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Report No. **249**

# Catchment Management Support Tools for Characterisation and Evaluation of Programme of Measures

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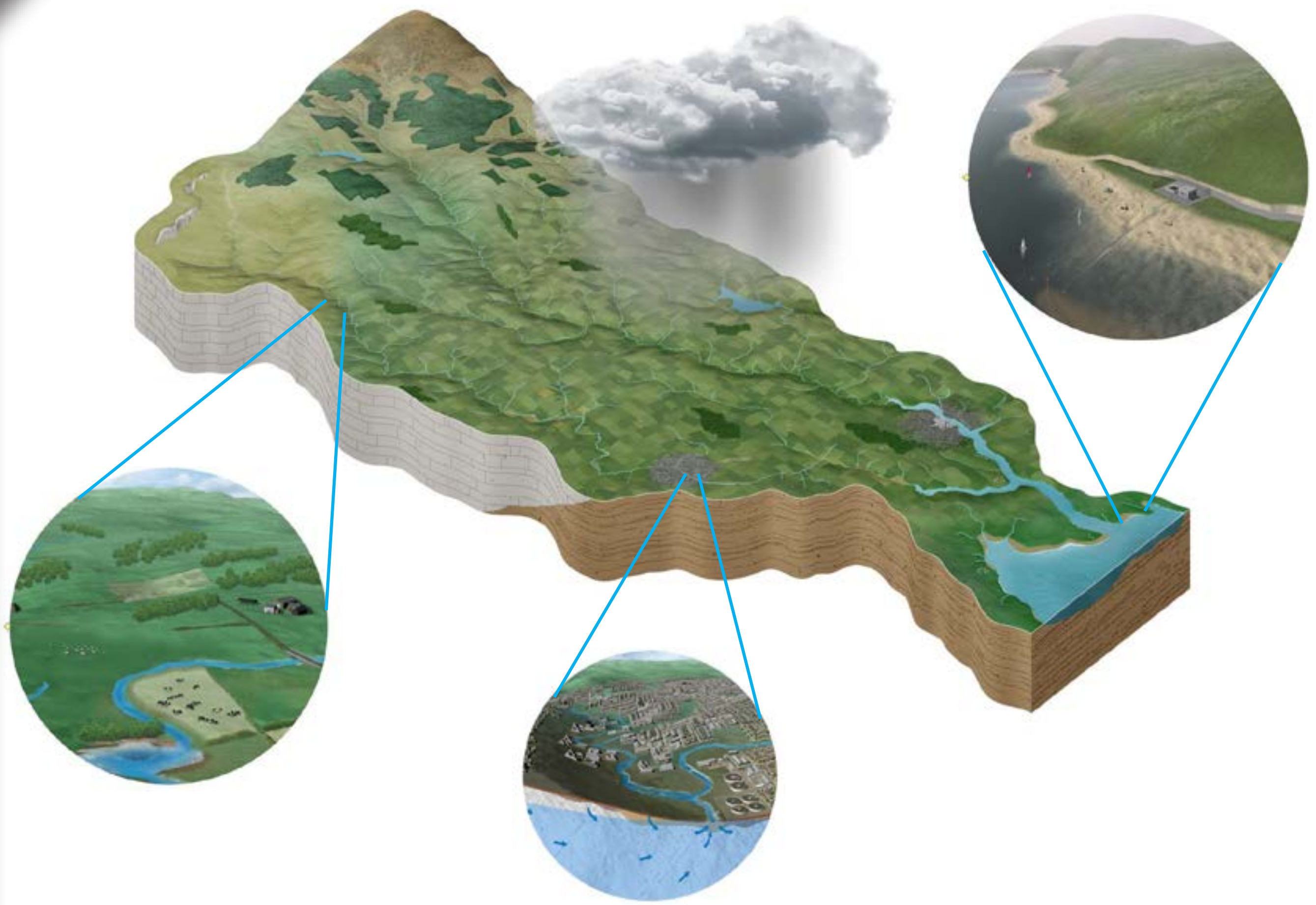

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Government of Ireland

**ENVIRONMENTAL PROTECTION AGENCY**

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- Office of Environmental Enforcement
- Office of Evidence and Assessment
- Office of Radiation Protection and Environmental Monitoring
- Office of Communications and Corporate Services

The EPA is assisted by an Advisory Committee of twelve members who meet regularly to discuss issues of concern and provide advice to the Board.

EPA RESEARCH PROGRAMME PROGRAMME 2014–2020

# Catchment Management Support Tools for Characterisation and Evaluation of Programme of Measures

# (CatchmentTools Project)

# (2013-W-FS-14)

# EPA Research Report

Prepared for the Environmental Protection Agency

by

University College Dublin

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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.

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# Contents

# List of Figures

# List of Tables and Boxes

## Tables



## Boxes

# Executive Summary

Nutrient enrichment and eutrophication can negatively impact on freshwater ecosystems, estuarine and coastal waters. As a result of improvements in nutrient management and regulation, there has been a large reduction in total phosphorus, total ammonia and total nitrogen emissions from Irish catchments in recent decades. However, half of Irish river water bodies still require improvements to bring them to Good status, as required by the Water Framework Directive (WFD) (2000/60/EC). The Catchment Management Support Tools for Characterisation and Evaluation of Programme of Measures project, or CatchmentTools project, developed data analysis tools and models for assessing nutrients in Irish catchments to support catchment scientists and managers to (1) characterise nutrient sources, pathways and receptors in catchments and (2) assess potential mitigation measures.

The Source Load Apportionment Model (SLAM) is the flexible framework developed by the CatchmentTools project to estimate the nutrient load from various sectors entering water bodies, following attenuation or treatment. The SLAM results quantify nutrient losses from both point discharges (municipal wastewater treatment plants, industry and septic tank systems) and diffuse sources (pasture, arable, forestry, peatlands, etc.). Hydrogeological controls have a strong impact on nutrient fluxes, particularly in rural catchments. Flow pathways have been represented in the diffuse agricultural and septic tank systems modules by incorporating results from the Catchment Characterisation Tool (CCT) and the Source Apportionment of Nutrients in Irish Catchments for On-Site Effluent (SANICOSE) models, respectively.

The SLAM framework characterises sources of phosphorus (P) and nitrogen (N) emissions to water at a range of scales, from sub-catchment to national, by synthesising pressure datasets and physical landscape characteristics to predict emissions from point and diffuse sources. The predicted annual nutrient emissions were assessed against monitoring data for 16 major river catchments covering 50% of the area of Ireland. At the national scale, model results indicate that total average annual emissions to surface water in Ireland are over 2700 $t\,yr^{-1}$ of P and 82,000 $t\,yr^{-1}$ of N. These values are lower than previous national estimates, in part due to the model significantly underestimating loads calculated from monitoring data in some catchments. The inclusion of the results in the Environmental Protection Agency's WFD characterisation process, alongside numerous other national datasets and local knowledge, facilitated the assessment of nutrient load information in a logical, structured, consistent and comparative way across the country. The proportional contributions from individual sources show that the main sources of P are from municipal wastewater treatment plants and agriculture, with wide variations across the country related to local anthropogenic pressures and the hydrogeological setting. Agriculture is the main source of N emissions to water across all regions of Ireland.

A pilot study in the Suir catchment highlighted that a small proportion (13%) of the catchment area requires a reduction in P emissions to achieve Good status. In these areas, model results can be used in conjunction with knowledge from local authorities and investigative assessments gathered through the WFD characterisation process to identify significant pressures that contribute excessive nutrient loads.

By synthesising large amounts of information, the SLAM framework predicted the dominant sources of nutrients at regional and local scales, contributing to the national nutrient risk assessment of Irish water bodies.

# 1 Introduction

## 1.1 Catchment Management

Identifying appropriate measures to address eutrophication remains a major challenge across Europe, where many river and lake water bodies are still failing to meet Water Framework Directive (WFD) objectives (EU, 2000). The management of diffuse sources of nutrients in rural catchments is of interest globally, as environmental objectives compete with the increasing demand for food production. In Ireland, integrated catchment management has been used to implement a systems-based approach for assessing and managing freshwater ecosystems (Daly *et al*., 2016). Characterisation of water bodies for the second cycle of the WFD has been undertaken, including evaluation of physical, hydro-chemical and ecological characteristics of water bodies in conjunction with a risk assessment of pressures, to determine the pollution pathways and impacts. These assessments used results from water quality models (e.g. Gill and Mockler, 2016; Mockler *et al*., 2016) to ensure that the detailed field investigations and determination of measures are efficiently targeted and that decision makers are better informed about the effectiveness of measures and the possible response of water bodies to future actions (Ní Longphuirt *et al*., 2016).

## 1.2 Nutrient Transport and Attenuation

Water mobilises and transports nutrients through the landscape; the potential for natural attenuation of nutrient amounts varies considerably with hydrological settings, transport pathways and type of nutrient (Archbold *et al*., 2016). For instance, nitrate is typically delivered to streams via subsurface pathways (Kröger *et al*., 2007; Tesoriero *et al*., 2009). In contrast, the majority of phosphorus from diffuse sources is driven by storm events and delivered via overland flow (Jordan *et al*., 2005), although significant quantities may also be delivered via tile drainage (Monaghan *et al*., 2016; Zimmer *et al*., 2016) and groundwater pathways (Mellander *et al*., 2016) with individual hot-spots of nutrient loss, or critical source areas, contributing a relatively high proportion of the nutrients exported from the landscape (Pionke *et al*., 2000). As hydrology is a key driver of nutrient delivery at catchment scale, all relevant hydrological processes should be adequately represented in a water quality model (Medici *et al*., 2012).

## 1.3 Load Apportionment Modelling

In cases where water quality is impacted by excess nutrients, load apportionment modelling can support the proportional and pragmatic management of water resources. There are two broad approaches to load apportionment modelling: (1) load-orientated approaches that apportion origin based on measured in-stream loads (Grizzetti *et al*., 2005; Greene *et al*., 2011; Grizzetti *et al*., 2012); and (2) source-orientated approaches where amounts of diffuse emissions are calculated using models typically based on export coefficients from catchments with similar characteristics (MCOS, 2002; Jordan and Smith, 2005; Smith *et al*., 2005; Campbell and Foy, 2008; Ní Longphuirt *et al*., 2016). The load apportionment model developed by the Catchment Management Support Tools for Characterisation and Evaluation of Programme of Measures project, or the CatchmentTools project, takes the latter approach, enabling estimates of the relative contribution of sources of nitrogen (N) and phosphorus (P) to surface waters in catchments without in-stream monitoring data. Instead of developing a model that would require calibration with monitoring data, the model developed here integrates information on point discharges, diffuse sources (pasture, arable, forestry, etc.), and catchment data, including hydrogeological characteristics where applicable. This allows the model to be applied throughout Ireland, independently of the availability of measured in-stream data.

## 1.4 Project Aims

Significant changes in the magnitude and sources of P in Irish rivers have occurred over the last two decades, due to both improvements in wastewater treatment works and changes in land management practices (O’Boyle *et al*., 2016), altering the relative contributions from point and diffuse sources (Ní Longphuirt *et al*., 2016). As regulation of point discharges continues to reduce emissions from point sources, other sources of nutrients may start to control water quality in these areas and these must be prioritised for management. The CatchmentTools project aimed to quantify the sources of P and N emissions in Irish rivers in order to support the identification of such potential pressures resulting in eutrophication.

There were two separate components to the CatchmentTools project, as the original proposal was expanded to incorporate an extension of the Environmental Protection Agency (EPA)-funded Pathways Project (Archbold *et al*., 2016) in order to integrate that project's diffuse agricultural model into EPA systems (Work Package 1) and update the model's land cover data (Work Package 2). The project participant, Dr Ian Packham, completed these work packages in the first 20 months in collaboration with members of the EPA's Informatics and Catchments Units.

The main CatchmentTools project objectives were to:

- develop a national load apportionment framework and evaluate its performance in predicting nutrient loads in Irish rivers by comparing the outputs of the model with measured in-stream loads (Work Packages 5–7);
- identify the main sources of nutrients in Ireland at national, regional and local scales (Work Package 8);
- compare and contrast the main sources and delivery pathways of agricultural and wastewater emissions and support the EPA characterisation process (Work Package 4);
- demonstrate scenario analyses to support integrated catchment management (Work Package 9); and
- provide training and documentation for EPA and other technical staff (Work Package 3).

# 2 Developing Load Apportionment Models

## 2.1 Introduction

Where surface waters are impacted by excess nutrients, understanding their sources is key to the development of effective, targeted mitigation measures. Modelling can be used in these areas, in conjunction with knowledge from local authorities and investigative assessments, to identify significant pressures that contribute excessive nutrients to surface waters. In Ireland, nutrient emissions are the main drivers of surface waters not achieving the required Good status, as defined by the WFD. Hence, the CatchmentTools project developed a model to predict the sources of nutrients contributing to these emissions and to assess future pressures and the likely effectiveness of targeted mitigation scenarios. This Source Load Apportionment Model (SLAM) (Mockler *et al*., 2016) supports catchment managers by providing scientifically robust evidence to back up decision making in relation to reducing nutrient pollution. The SLAM is a source-oriented model that calculates the N and P exported from each sector (e.g. pasture, forestry and wastewater discharges) that contribute to overall nutrient loads in a river. The model output is presented as maps and tables that show the proportions of nutrient emissions to water attributed to each sector in each sub-catchment.

## 2.2 The Source Load Apportionment Model Framework

The SLAM framework incorporates multiple national spatial datasets relating to nutrient emissions to surface water, including land use and physical characteristics of the sub-catchments (Table 2.1). Separate modules were developed for each type of nutrient source to facilitate upgrading and comparisons with new data or methods (Figure 2.1). For example, in the current version (v. 2.05) of the framework, two of the original modules have been upgraded with output from more advanced export-coefficient-based models. The agriculture (pasture and arable) and septic tank systems modules use spatial outputs from the Catchment Characterisation Tool (CCT) (Archbold *et al*., 2016) and the Source Apportionment of Nutrients in Irish Catchments for On-Site Effluent (SANICOSE) models (Gill and Mockler, 2016), respectively. Each of the modules for point and diffuse sources are described in detail below in sections 2.3 to 2.8. The

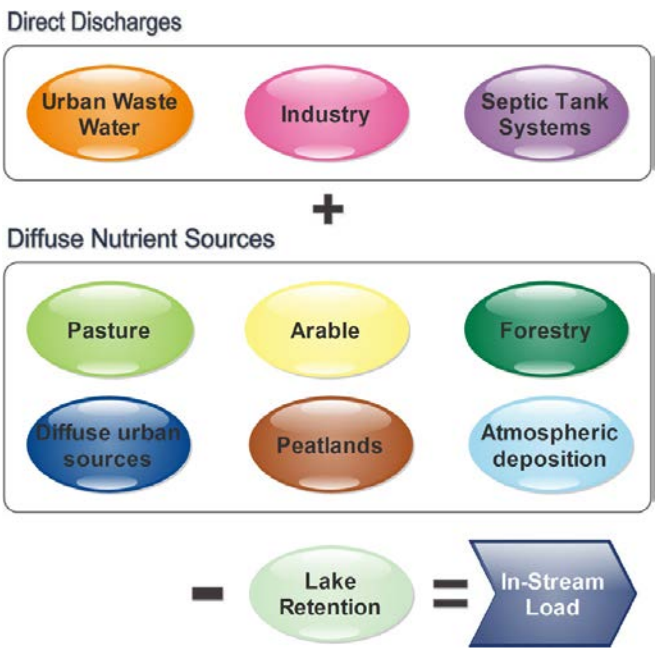


**Figure 2.1. Sub-models of the SLAM framework.**

**Table 2.1. Data sources for the SLAM framework (v. 2.05)**

| Sub-model | Input data and source |
|---|---|
| Waste water discharges | 2014 Annual Environmental Report data (EPA, 2015) |
| | 2014 EPA Licensing Enforcement and Monitoring Application (LEMA) |
| Diffuse urban sources | 2012 CORINE land cover (Lydon and Smith, 2014) |
| Industrial discharges | Section 4 licence limits (EPA, 2015) |
| | 2011–2013 PRTR database (EPA, 2015) |
| Septic tank systems | Non-sewered house dataset and surface water bodies (EPA, OSI) |
| | Karst feature vulnerability and subsoil permeability (GSI) |
| Pasture (diffuse agriculture) | 2012 LPIS (DAFM dataset) |
| | 2010 agricultural census data (Central Statistics Office, 2010) |
| Arable (diffuse agriculture) | 2012 LPIS (DAFM dataset) |
| | 2010 agricultural census data (Central Statistics Office, 2010) |
| | Good Agricultural Practices (GAP) Regulations (Government of Ireland, 2014) |
| | Fertiliser application rates (Lalor *et al*., 2010) |
| Forestry | 2012 CORINE land cover (Lydon and Smith, 2014) |
| Peatlands | 2012 CORINE land cover (Lydon and Smith, 2014) |
| Atmospheric deposition | Lake segment areas (EPA dataset) |
| | N deposition map (Henry and Aherne, 2014) |

**CORINE, Coordination of Information on the Environment; PRTR, Pollutant Release and Transfer Register; OSI, Ordnance Survey, Ireland; GSI, Geological Survey Ireland; DAFM, Department of Agriculture, Food and the Marine.**

total annual nutrient load at the outlet of each sub-catchment ($L_i$) was calculated as:

$$L_i = (\text{Point}_i + \text{Diffuse}_i) \times (1 - \text{Lake}_i) \qquad (2.1)$$

where

$\text{Point}_i$ = sum of nutrient loads discharged from wastewater treatment plants, industrial discharges and emissions from septic tank systems;

$\text{Diffuse}_i$ = sum of diffuse nutrient losses from agriculture, forestry, peatlands, urban areas and atmospheric deposition; and

$\text{Lake}_i$ = estimated nutrient lake retention factor.

A summary of the models and data sources for each component of Equation 2.1 as implemented in SLAM v. 2.05 is provided in this chapter. Further details of the model development and application are available in Mockler *et al*. (2016), and the framework structure and user interface are described in Mockler (2016). The SLAM technical documentation is available for download on http://erc.epa.ie/safer/reports.

Sections 2.3–2.8 present details of each of the point and diffuse modules in the SLAM framework. In section 2.9 the performance of the model is assessed by comparison with monitoring data. In the last section of this chapter (section 2.10), the model's performance and main sources of uncertainty are discussed.

## 2.3 Wastewater Discharges

The calculation of total annual emissions from wastewater discharges is the summation of the loads emitted from wastewater treatment plants (WWTPs) and the loads that are generated in the agglomeration and discharged without treatment. The annual agglomeration load, $\text{Agglom}_{N,P}$ (kg yr$^{-1}$), was therefore calculated as:

$$\text{Agglom}_{N,P} = \text{Agglom}_{\text{WWTP}} + \text{Agglom}_{\text{untreated}} \qquad (2.2)$$

where

$\text{Agglom}_{\text{WWTP}}$ = load discharged from WWTP for N or P (kg yr$^{-1}$); and

$\text{Agglom}_{\text{untreated}}$ = untreated sewerage from agglomeration for N or P (kg yr$^{-1}$).

The estimation of nutrient loads from WWTPs used the best available data for each plant following international best practice (OSPAR, 2004). The preferred source was the actual nutrient load emissions reported for WWTPs based on the 2014 Annual Environmental Reports (AERs), where available. If an AER was not available for a WWTP, then the secondary data source, the EPA Licensing Enforcement and Monitoring Application (LEMA), was used in the calculation to estimate annual emission values. $Agglom_{WWTP}$ is typically the major component of the total agglomeration load, and was calculated as:

$$\text{Agglom}_{\text{WWTP}} = \begin{Bmatrix} \text{AER}_{N,P}, \text{where AER}_{N,P} \text{available} \\ \text{PE} \times \text{RATE}_{N,P} \times \text{TREAT}_{N,P}, \\ \text{where AER}_{N,P} \text{ unavailable} \end{Bmatrix} \quad (2.3)$$

where

$AER_{N,P}$ = reported annual emission for N or P (kg yr$^{-1}$) in AER;

PE = population equivalent, as reported in LEMA;

$RATE_{N,P}$ = nutrient production rate for N or P (kg yr$^{-1}$); and

$TREAT_{N,P}$ = treatment efficiency factor based on WWTP treatment level.

Estimates of nutrient production rates ($RATE_{N,P}$) from 2014 AER data indicated about 12 g person$^{-1}$ day$^{-1}$, or 4.38 kg yr$^{-1}$, for N and 2 g person/day, or 0.73 kg yr$^{-1}$, for P. These figures are in line with international guidance values (Guidline 4, OSPAR, 2004). Treatment efficiency factors ($TREAT_{N,P}$) were related to treatment level (OSPAR, 2000), and are under review for Irish WWTPs.

The second component of the calculation of emissions from wastewater discharges estimates the annual nutrient loads from untreated sewerage ($Agglom_{untreated}$), which can include any loss from the sewer network from combined sewer overflows, also referred to as storm water overflows, and emergency overflows. $Agglom_{untreated}$ was calculated as follows:

$$\text{Agglom}_{\text{untreated}} = \frac{\text{LoadIN}_{\text{WWTP}}}{(100 + \%\text{LOSS})} \times \%\text{LOSS} \quad (2.4)$$

where

$LoadIN_{WWTP}$ = annual load at inlet of WWTP for N or P (kg yr$^{-1}$); and

%LOSS = percentage of the total agglomeration load discharge by storm water overflows.

As with $Agglom_{WWTP}$, the preferred data source was the AER. When values for $LoadIN_{WWTP}$ were not reported in the AERs, an estimate based on population equivalents was calculated; when a value for %LOSS was unavailable, a default of 3% was used.

## 2.4 Industrial Discharges

Industrial discharges were estimated from one of two sources, depending on the facility licence. Facilities where industrial discharges are licensed by the EPA report their annual emission values to the Pollutant Release and Transfer Register (PRTR). An average of 3 years (2011–2013) of total nitrogen (TN) and total phosphorus (TP) (kg yr$^{-1}$) values reported were used for each facility. Facilities that are licensed by local authorities (under section 4 licences) generally do not report annual emissions and so the licence limits were used to estimate an annual value (OSPAR, 2004), as:

$$\text{Industry}_{N,P} = \text{Reported}_{N,P} \text{ OR } (25\% \times L_{\max}) \quad (2.5)$$

where

$Reported_{N,P}$ = annual nutrient emission load for N or P reported (kg yr$^{-1}$); and

$L_{max}$ = maximum allowable licensed nitrogen load for N or P (kg yr$^{-1}$).

## 2.5 Septic Tank Systems

A conceptual model based on export coefficients was developed specifically for the SLAM framework to estimate nutrient losses from domestic wastewater treatment systems (referred to as septic tank systems in this study). The SANICOSE model (Gill and Mockler, 2016) synthesises over a decade of field studies on on-site systems in Ireland across many different soil types (Gill *et al*., 2007, 2009a,b,c; Sulleabhain *et al*., 2009; O'Luanaigh *et al*., 2012; Donohue *et al*., 2015) and combines factors relating to the efficiency of the septic tank systems with attenuation factors for the hydrogeological flow pathways, based on the diffuse pollution factors developed in the Pathways Project (Archbold *et al*., 2016). Three different conceptual pathways, through which loads from septic tank systems can reach surface water bodies, were considered:

- *Pathway 1:* inadequate percolation, i.e. surface pathway direct to surface water body;
- *Pathway 2:* near surface (soils and subsoils) pathway;
- *Pathway 3:* groundwater pathway.

The SANICOSE model quantifies the annual nutrient contribution for each septic tank system at their specific locations, as estimated from geographical information system (GIS) data on property locations and sewered areas. See Gill and Mockler (2016) for further details on the septic tank system module structure and parameters.

## 2.6 Diffuse Agricultural Losses

The key pressure input dataset for the agriculture module (i.e. the CCT) is the Land Parcel Identification System (LPIS) from the Department of Agriculture, Food and the Marine (DAFM). The DAFM collects data from farmers who record the land use and crop description of each field they own, allowing for accurate identification of land use in a spatial context. These data were combined with DAFM data on N and P loads based on the Animal Identification System for cattle and Central Statistics Office data for sheep. As the LPIS is an administrative database relating to agricultural payment schemes, the data required pre-processing before use in the geospatial model (Zimmermann *et al*., 2016).

The CCT is an annual average export coefficient model calculating leaching rates based on methods from existing models for N (Shaffer *et al*., 1994; del Prado *et al*., 2006) and P (Heathwaite *et al*., 2003). In addition, the model applied pathway-dependent attenuation coefficients related to the hydrogeological conditions, which were inferred from GIS maps of relevant properties including soil drainage, subsoil permeability and depth to bedrock. These coefficients were determined following a literature review and expert elicitation for the two pathway categories grouped into (1) “near surface” pathways, including overland and drain flow, and (2) groundwater (Archbold *et al*., 2016). The CCT calculated N and P losses from diffuse agriculture ($\text{DiffAgri}_{\text{N,P}}$) using a mass balance calculation as follows:

$$\text{DiffAgri}_{N,P} = \text{Leached}_{N,P} \times [(\text{NS} \times \alpha_{N,P}) + (\text{GW} \times \beta_{N,P} \times \phi_{N,P})] \quad (2.6)$$

where

$\text{Leached}_{N,P}$ = loads leached from the soils for N or P ($\text{kg yr}^{-1}$);

$\alpha_{N,P}$ = near-surface pathway factors for N or P;

$\beta_{N,P}$ = groundwater pathway factors for N or P;

$\phi_{N,P}$ = groundwater bedrock transport factor for N or P;

NS = fraction of load to surface water via near surface pathway; and

GW = fraction of load to groundwater (= 1 – NS), where:

$$\text{NS} = \frac{P_e - R}{P_e}$$

$$\text{GW} = \frac{R}{P_e}$$

where

$P_e$ = annual effective precipitation; and

$R$ = average annual recharge.

Note that both $P_e$ and R data were taken from the Geological Survey of Ireland (GSI) Groundwater Recharge Map (Hunter Williams *et al*., 2013).

The calculation of $\text{Leached}_{N,P}$ from pasture and arable, near surface pathway ($\alpha_{N,P}$), groundwater pathway ($\beta_{N,P}$) and groundwater bedrock transport factors ($\phi_{N,P}$) for N and P are outlined below.

### 2.6.1 Phosphorus leaching calculation and export coefficients

The CCT-P model was loosely based on the Phosphorus Indicator Tool (PIT) (Heathwaite *et al*., 2003), which was developed in the UK to estimate P losses from agricultural soils to surface waters. For both pasture and arable land cover, the CCT-P model estimated the applied nutrients using the maximum allowable fertilisation rates (Government of Ireland, 2014). In addition to the applied nutrients, a value of Teagasc soil P index 3 was assumed, which is equivalent to a Morgan’s P value of $8\,\text{mg l}^{-1}$ and $6.5\,\text{mg l}^{-1}$ for arable and pasture, respectively. $\text{Leached}_P$ was then calculated as 1% of the applied and soil P loads. The pathway coefficients ($\alpha_P$ and $\beta_P$) were modified from the PIT model to match available nutrient monitoring data in Irish agricultural catchments (Table 2.2). The P groundwater factors ($\beta_P$) were related to the depth to bedrock, except in areas of peat soils (Table 2.3). The CCT-P model assumed that there is no attenuation of P in Irish aquifers. Further information on the development of the CCT-P model is available in Archbold *et al*. (2016 and references therein).

**Table 2.2. Phosphorus near-surface pathway factors**

| Soil type | P near-surface factor |
|---|---|
| Clayey soil classified as wet | 0.4 |
| Sandy soil classified as dry | 0.2 |
| Peat | 0.4 |
| Drain flow | 0.7 |

**Table 2.3. Phosphorus groundwater pathway factors**

| Depth to bedrock | P subsoil factors |
|---|---|
| X Extreme (0–1 m and near karst features)* | 0.4 |
| E Extreme (1–3 m)* | 0.15 |
| 3–5 m* | 0.05 |
| 5–10 m* | 0.02 |
| > 10 m* | 0.01 |
| *Exception peat subsoils | 0.9 |

### 2.6.2 *Nitrogen leaching calculation and export coefficients*

In the CCT-N model, the $Leached_N$ from pasture was calculated using the NCYCLE_IRL (del Prado *et al*., 2006) modelled values for groupings of fertiliser application rate, soil drainage type and pasture type. The LPIS provided applied rates of N (kg ha$^{-1}$ yr$^{-1}$) at farm level (see Zimmermann *et al*., 2016). Diffuse nutrient losses from arable land were calculated similarly to the Nitrogen Risk Assessment Model for Scotland (NIRAMS) (Dunn *et al*., 2004). The CCT-N model estimated the available (net) nutrients using the maximum allowable fertilisation rates (Government of Ireland, 2014), atmospheric deposition and average off-take values. Denitrification varies by soil texture, with rates of 5%, 15% and 75% applied to sandy, loamy or clay/peaty soils, respectively. $Leached_N$ was calculated using the Nitrate Leaching and Economic Analysis Package (NLEAP) model (Shaffer *et al*., 1994):

$$\text{Leached}_N = \text{Available}_N \times (1 - \exp\left[-K \times \left(\frac{\text{WAL}}{\text{SATC}}\right)\right]) \tag{2.7}$$

where

$\text{Available}_N$ = available (net) N (kg ha−1 yr−1);

$K$ = leaching coefficient (0.7 for sandy soils and 1.2 for other soils);

WAL = water available for leaching (mm yr−1), estimated from $P_e$; and

SATC = soil saturated capacity (mm yr−1) estimated from Anthony *et al*. (1996) based on the soil drainage classification in the Irish National Soils Map (Teagasc *et al*., 2006).

For both pasture and arable areas, nutrient reduction factors ($\alpha_N$, $\beta_N$, and $\varphi_N$) were then applied to the leached amount of nutrients ($\text{Leached}_N$) to predict the final losses to water ($\text{DiffAgri}_N$). The coefficients representing the delivery of N via near-surface pathways ($\alpha_N$) were linked to subsoil permeability, as N tends to move through the subsoils before arriving at the surface water receptor (Table 2.4.). In addition, a map of the possible location of land drains (Mockler *et al*., 2014) indicated a preferential delivery pathway for nitrate in low-permeability subsoils. Groundwater export coefficients ($\beta_N$) were determined following a literature and expert elicitation review (Packham *et al*., 2015). These coefficients vary by subsoil permeability and depth to bedrock (Table 2.5), both available as maps from GSI. The bedrock attenuation coefficient ($\varphi_N$) was linked to aquifer bedrock units with the potential for denitrification, mostly due to the presence of pyrite (Table 2.6).

## 2.7 Other Diffuse Nutrient Sources

The 2012 CORINE (Coordination of Information on the Environment) (Lydon and Smith, 2014) level 3 land cover data were used in the forestry, peatlands and urban sub-models (Table 2.7). Various export coefficients for forestry, peatlands and diffuse urban (MCOS, 1999) as outlined in Table 2.7 were then applied in each of the modules to estimate their annual nutrient emissions to water. Nutrient export coefficients linked to CORINE land cover classes have been used in many studies to estimate annual load apportionment values (e.g. Grizzetti *et al*., 2012 and references therein). In the SLAM framework, the diffuse nutrient emissions from forestry, peatlands and urban areas were calculated as:

$$\text{Diffuse}_{N,P} = \text{Area} \times \text{Export}_{N,P} \tag{2.8}$$

where

Area = area of the land cover category from CORINE 2012 (ha); and

$\text{Export}_{N,P}$ = export coefficient for N or P (kg ha$^{-1}$ yr$^{-1}$).

**Table 2.4. Nitrate near-surface pathway factors**

| Subsoil permeability | N near-surface factor |
|---|---|
| Low | 0.2 |
| Low and likely to have land drains | 0.7 |
| Moderate | 0.55 |
| High | 1 |
| N/A | 0.95 |
| Water/lake/rock | 0.95 |

**Table 2.5. Nitrate groundwater pathway factors**

| Subsoil permeability (depth to bedrock) | Low | Moderate | High | N/A (DTB < 3 m) |
|---|---|---|---|---|
| 0–1 m | 1.0 | 1.0 | 1.00 | 1.0 |
| 1–3 m | 0.60 | 0.95 | 1.00 | 0.95 |
| 3–5 m | 0.20 | 0.90 | 1.00 | – |
| 5–10 m | 0.05 | 0.85 | 1.00 | – |
| > 10 m | 0.01 | 0.75 | 1.00 | – |

**Table 2.6. Nitrate groundwater bedrock pathway factors**

| Bedrock unit* | Transport factor |
|---|---|
| Unit 1a, Unit 1b | 0.65 |
| All other bedrock units | 1 |

### *2.7.1 Atmospheric deposition*

In the SLAM framework, atmospheric deposition on land was accounted for in each diffuse module, either explicitly (i.e. for diffuse agriculture) or implicitly (e.g. in the forestry export coefficients). In addition, direct deposition on open water was represented in the model. The EPA lake segment dataset was used to represent open water, which includes lakes with a cumulative area of 1333 km$^2$. $Export_N$ (Equation 2.8) was calculated spatially for all lakes from a map of atmospheric deposition of N (Henry and Aherne, 2014), with an average rate of deposition on lakes of 9.4 kg N ha$^{-1}$ yr$^{-1}$. For P, there is typically less systematic spatial variation in deposition rates, with the global average and overall geometric mean deposition rate of TP reported as 0.43 and 0.27 kg ha$^{-1}$ yr$^{-1}$, respectively (Tipping *et al.*, 2014). In this study, a uniform rate of 0.5 kg ha$^{-1}$ yr$^{-1}$ TP deposition ($Export_P$) was assumed based on data from Northern Ireland (Jordan, 1997).

## 2.8 Lake Retention

For the SLAM framework, a simple lake retention model was implemented that reduces loads from catchments draining through all lakes above a threshold size. Following the EPA's characterisation process (EPA, 2005), small lakes were identified as

**Table 2.7. Nutrient export rates in the SLAM model (v. 2.05) for urban, forestry and peat land cover**

| Land cover | CORINE code | Area (km$^2$) | Area of Ireland (%) | Rates (kg ha$^{-1}$ yr$^{-1}$) | |
|---|---|---|---|---|---|
| | | | | N | P |
| *Urban* | | | | | |
| Continuous urban fabric | 111 | 31 | 0.0 | 5 | 1.4 |
| Discontinuous urban fabric | 112 | 1119 | 1.6 | 5 | 0.86 |
| Industrial or commercial units | 121–124 | 130 | 0.2 | 5 | 1.88 |
| Mine, dump, construction sites | 131–133 | 3 | 0.0 | 5 | 2.15 |
| Green urban areas, sport and leisure | 141, 142 | 36 | 0.4 | 5 | 1.4 |
| *Forestry* | | | | | |
| Broadleaved, coniferous, mixed forest | 311–313 | 3765 | 5.3 | 5.42 | 0.33 |
| Natural grassland, moors, heathland | 321, 322 | 1411 | 2.0 | 5.42 | 0.33 |
| Transitional woodland–shrub | 324 | 2898 | 4.1 | 3.71 | 0.565 |
| *Peat* | | | | | |
| Inland marshes | 411 | 194 | 0.3 | 2 | 0.325 |
| Peat bogs | 412 | 10,338 | 14.7 | 2 | 0.2 |

having an area of less than 50 ha and retention factors were not applied. The retention factors developed during studies in the Lee catchment (Sullivan *et al*., 1995) were applied to catchments upstream of lakes, with $Lake_{iN} = 0.1$ and $Lake_{iP} = 0.24$ (see Equation 2.1).

## 2.9 Comparison with Monitoring Data

The SLAM results were compared with monitoring data to assess the model's performance prior to its extension to cover the entire country using the R "stats" and "graphics" packages (R Core Team, 2016). Sixteen major river catchments covering 50% of the area of Ireland (Figure 2.2a) were selected, based on the availability of both monitoring data and loadings information. These catchments are in the national riverine inputs monitoring programme that is managed by the Irish EPA. The design of the programme followed the Comprehensive Study on Riverine Inputs and Direct Discharges (RID) principles (OSPAR, 1998). O'Boyle *et al*. (2016) provide details of the sampling and analysis methodologies for the TP and TN concentration data used in this study. The locations of the flow and nutrient concentration monitoring stations (Table 2.8) are largely at the tidal limits of rivers and they are generally upstream of the large wastewater treatment plant discharges associated with the major coastal urban centres. It was preferable to test the model in areas dominated by diffuse sources of nutrients, as load emission estimates from large direct discharges on Irish coasts are based on detailed annual monitoring and reporting and are more reliable than estimates of diffuse emissions.

The loadings information for diffuse and point sources used in this study relate to 3 years, 2012–2014, and

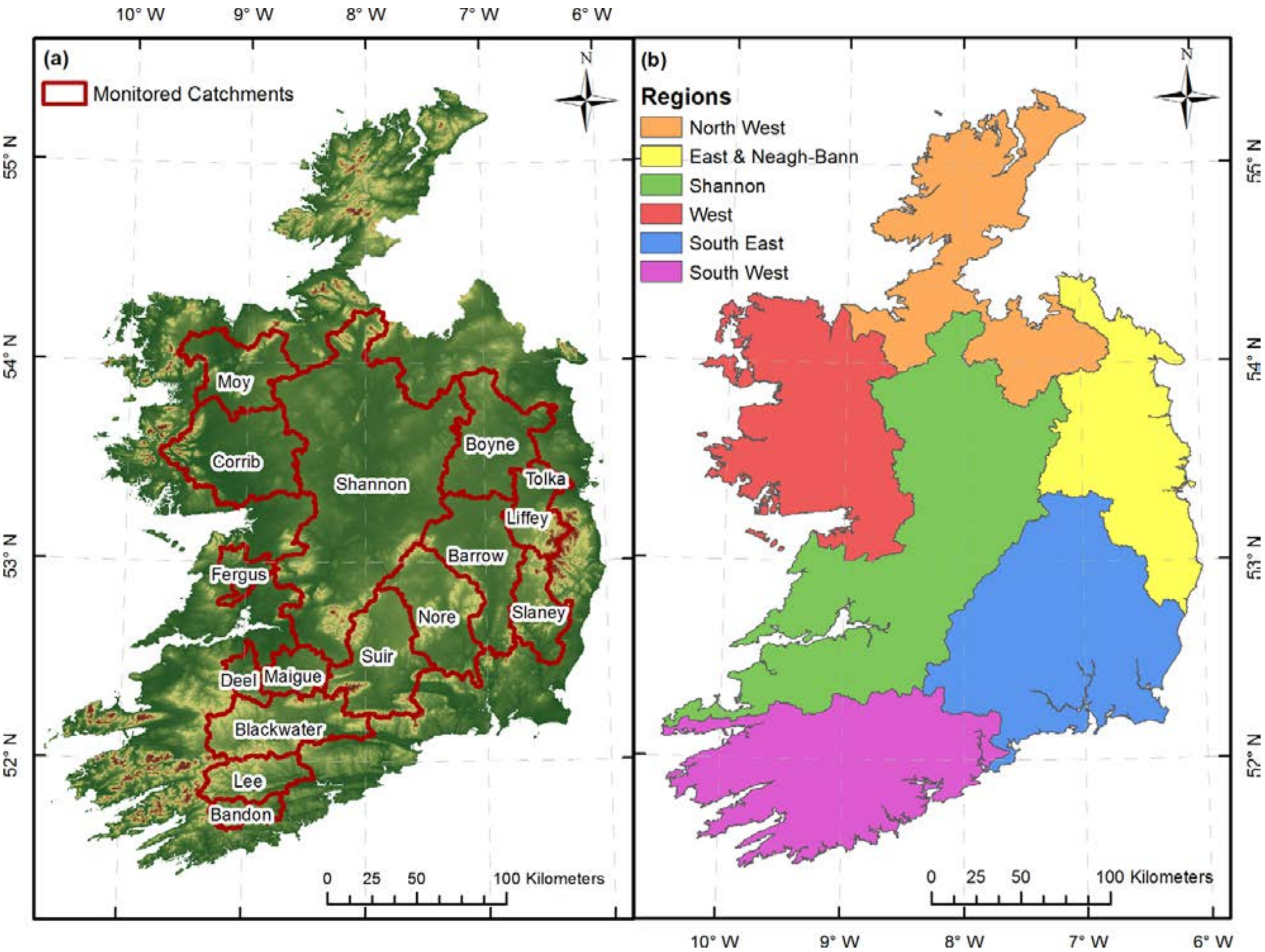


**Figure 2.2. (a) Locations of 16 catchments with monitored total nitrogen and phosphorus emissions to water. (b) Catchment regions based on previously defined river basin districts.**

hence monitoring data for only these years were used to evaluate the model performance. In most catchments, the wettest year of this period was 2014, with 2013 being the driest (Figure 2.3). The long-term annual flows were within the ranges of annual flows for these 3 years in all the study catchments except for the Bandon catchment, which has had a notable increase in flows in recent years, possibly due to issues with changes in the rating at this station (Figure 2.3). As flow data were not available for the Corrib catchment for the study period, the 1990–2011 long-term average (104 $m^3 s^{-1}$) was assumed for each year.

Annual loads were calculated as the product of the flow-weighted annual mean concentration of TP or TN and the annual flow (see O'Boyle *et al*., 2016). Monitoring of flow and nutrients occurred at separate locations along the rivers so, to calculate the loads, the flow values were scaled by the ratio of the areas draining to the nutrient and flow monitoring stations. There was less than a 20% difference in the monitored area for all catchments except for the Slaney and Suir catchments (Table 2.8). The SLAM results provide a reasonable representation of the variance of the 3-year annual average loads (Figure 2.4a,b), with satisfactory coefficient of determination ($r^2$) for annual TP ($r^2 = 0.78$, $p = < 0.01$, $n = 16$) and TN ($r^2 = 0.82$, $p = < 0.01$, $n = 16$). The error bars highlight the interannual variability in the measured emissions that is not captured by the model. Figure 2.4c,d indicates the individual results for each test catchment. These results compare well with other nutrient modelling studies, such as the InVEST nutrient delivery ratio model that was applied in the UK (Redhead *et al*., 2018), which also found a wide variation of model accuracy among 36 study catchments.

The model tends to underestimate P loads, particularly in the Deel, Bandon, Maigue, Lee and Blackwater catchments, that is to say, primarily in areas in the south and south-west of Ireland where iron-rich soils facilitate P mobilisation (Mellander *et al*., 2016), a process that is not yet captured by the agriculture module (CCT-P). The underestimate of P is especially large in the Blackwater catchment, where the EPA's catchment assessment has identified that excess phosphate leading to eutrophication is a significant issue of concern in a number of water bodies. Forestry is the most common significant pressure in the Blackwater catchment and it has been identified as a potentially significant pressure in over 10% of river water bodies that are *At Risk* of not meeting their WFD objectives, more than any other catchment in the country. According to the EPA's draft catchment assessment, insufficient protective measures for felling is a significant issue, including clearfelling activities with inadequate buffer strips and lack of silt traps, which result in excess siltation and excess nutrients in

**Table 2.8. Chemistry and hydrometric monitoring station codes and catchment areas**

| River | Nutrient monitoring station | Area ($km^2$) | Hydro station | Area ($km^2$) |
|---|---|---|---|---|
| Bandon | 20B02–0900 | 515 | 20002 | 424 |
| Barrow | 14B01–3500 | 2804 | 14029 | 2778 |
| Blackwater | 18B02–2600 | 2384 | 18002 | 2334 |
| Boyne | 07B04–2200 | 2624 | 7012 | 2408 |
| Corrib | 30C02–0460 | 3103 | 30061 | 3136 |
| Deel | 24D02–1450 | 489 | 24029 | 486 |
| Fergus | 27F01–0700 | 554 | 27002 | 511 |
| Lee | 19L03–0700 | 1177 | 19013 | 796 |
| Liffey | 09L01–2350 | 1119 | 9022 | 848 |
| Maigue | 24M01–0900 | 807 | 24008 | 806 |
| Moy | 34M02–1100 | 1949 | 34001 | 1975 |
| Nore | 15N01–2400 | 2427 | 15006 | 2418 |
| Shannon[a] | 25S01–2600/25S01–2900 | 11,619 | 25055; 25001; 25075 | 10,817; 646; 10,782 |
| Slaney | 12S02–2350 | 1321 | 12001 | 1031 |
| Suir | 16S02–2700 | 2629 | 16011/16009[b] | 2144/1583[b] |
| Tolka | 09T01–1150 | 149 | 09037 | 138 |

**[a]Flow monitoring at Ardnacrusha, Annacotty, and Shannon tailrace at Parteen Weir.**

**[b]Upstream flow monitoring station 16009 (Suir2) on the Suir River used where data were unavailable at station no. 16011.**

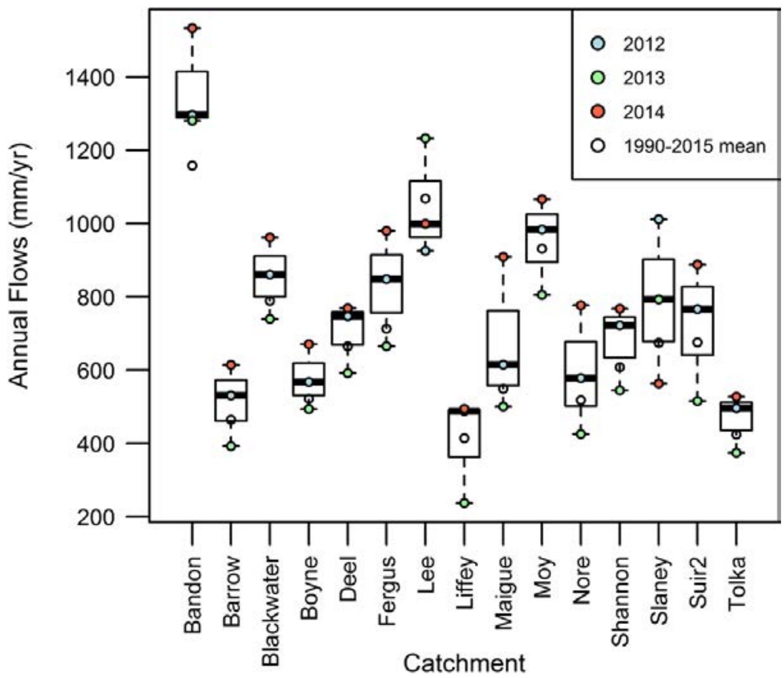


**Figure 2.3. Boxplots of area normalised annual flow (mm year$^{-1}$) for the study period, with annual values indicated for 2012 (blue), 2013 (green), 2014 (red) and the 1990–2015 long-term mean flow (black).**

water bodies. The further development of the forestry component of the SLAM framework to reflect felling activities may improve the estimation of P emissions in the Blackwater catchment.

The model also underestimates N loads, particularly in the Slaney, Barrow and Blackwater catchments. Some underestimation was expected, as each sector model includes only major sources of nutrients and does not incorporate incidental losses that may occur throughout the year. Furthermore, the parameterisation of the CCT model, which is the dominant component of the SLAM N results, aimed to reduce "type 1 errors", in which agriculture would be incorrectly identified as causing nutrient emissions. This may have resulted in the underestimation of annual emissions in some catchments. The underestimate of N is especially large in the Slaney catchment. EPA river monitoring data indicate that the N concentration levels are very high throughout the Slaney and increase moving down along the main channel with corresponding increases in flow, indicating that the N emissions are from diffuse sources. Of the 16 catchments in the study, the level of N concentrations from the EPA's WFD monitoring data are second only to the Nore catchment; however, the Nore catchment estimates for annual N load emissions from monitoring data are lower than for the Slaney (Figure 2.4). This indicates that the load calculation from monitoring data may be an overestimation, potentially due to the timing of water quality monitoring samples.

## 2.10 Model Performance and Uncertainties

Inconsistencies between individual SLAM results and measured in-stream loads may be due to several reasons, including input data issues, unknown source(s) not accounted for in the model (e.g. accidents or non-compliant farmyards) or inadequate monitoring data. Uncertainties in a model-based study, such as this, can arise in (1) model context, (2) model structure, (3) input (forcing) data and (4) identification of parameter values (Walker *et al*., 2003). Uncertainties have not been quantified in this study; however, each source is discussed qualitatively in this section.

### *2.10.1 Model context*

It is important that the context in which the model results are used, including assumptions and boundary conditions, is justifiable, to ensure that the model is not applied outside its intended scope. The SLAM predicts the annual emissions of P and N to water, and does not include inter- or intra-annual variability. Changes due to hydrological variability and groundwater lag

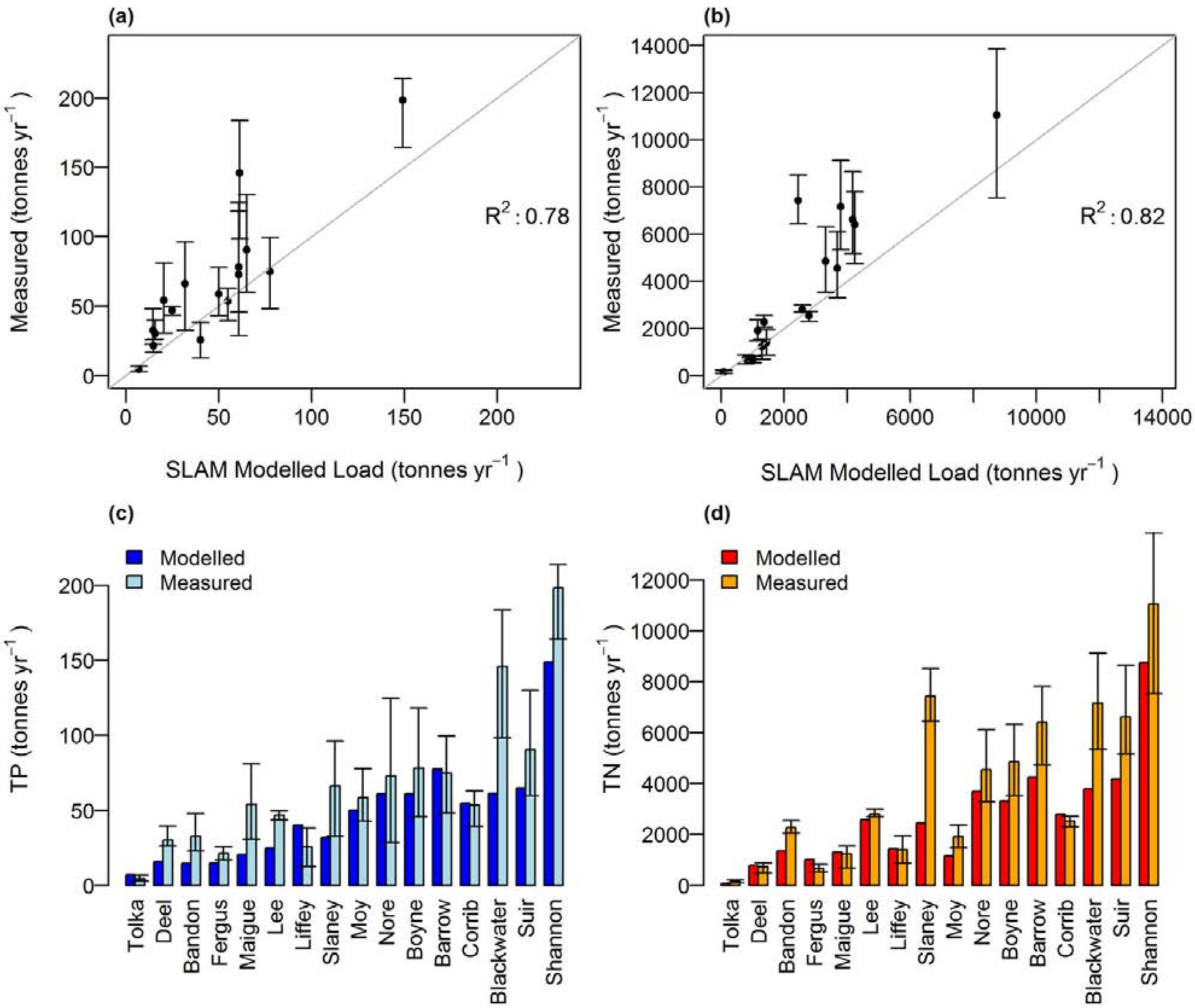


**Figure 2.4. Modelled SLAM nutrient emissions of (a) total phosphorus and (b) total nitrogen compared with average measured annual nutrient fluxes from 2012 to 2014 (error bars show the range of measured loads). Bar charts of modelled and measured (c) total phosphorus and (d) total nitrogen for each catchment (ordered by increasing catchment area).**

times are therefore not explicitly captured. This is in contrast to statistical load apportionment modelling, which develops functional relationships between nutrient concentrations and discharge monitoring data (e.g. Greene *et al*., 2011). Therefore, the SLAM results are not directly suitable for assessing pressures in these cases e.g. identifying sources of high nutrient concentrations at low flows. However, the chosen modelling approach does facilitate predictions in ungauged or poorly gauged catchments, facilitating the range of spatial assessment produced in this study.

### 2.10.2 Model structure

Several nutrient sources have not been included in the current version of the framework, such as sewer misconnections, which are potentially significant sources in urban areas (Ellis and Butler, 2015), and leaching of N from abandoned landfill sites. In addition, unknown sources and emerging pressures, including from phosphate dosing of raw water supplies, are also present in many catchments. These issues will inform the direction of model development and will drive new research and data collection to improve model performance.

### 2.10.3 Input (forcing) data

Several key input data sets to the SLAM framework, including LPIS and the annual environmental reports for WWTPs and industrial discharges, are collected and maintained for other management-oriented purposes and were not originally quality controlled for use in a national nutrient model. Zimmermann *et al*. (2016) outlined the administrative, spatial and thematic limitations of using the LPIS geodatabase for spatial modelling. Similar difficulties were encountered with other national datasets that required tailored data quality reviews prior to their use in the SLAM. Furthermore, the structures of data sources changed periodically to meet the requirements of the data's primary purpose and, as a result, the model framework needed to be revised. This lack of control or first-hand knowledge of input data can result in unknown uncertainties being present in the model results.

### *2.10.4 Identification of parameter values*

The model evaluation presented here and the development of the CCT that calculated the agricultural emissions are based on national monitoring data. However, the uncertain nature of low temporal resolution monitoring programmes, including the monthly regime used in this study, is well researched (Johnes, 2007; Cassidy and Jordan, 2011; Jiang *et al*., 2014; Snelder *et al*., 2017). This is particularly relevant for P, as more than 80% of P emissions occur in only 10% of the year during high-flow events (Ockenden *et al*., 2016) and so are likely to not be adequately captured by low temporal resolution monitoring data. It is predicted that, just like the monitoring data, the SLAM model underpredicts the actual annual P emissions. However, the environmental quality standards are also based on this data and have been shown to reflect the impact of nutrients on river ecology (Donohue *et al*., 2006).

### *2.10.5 Pressure information*

As the results of the SLAM framework are not calibrated to monitoring data, the performances of the sub-models are dependent on high-quality input data. Close liaison with the data owners and local authorities is vital to ensure meaningful results. The LPIS data, for example, that are used for calculating agricultural emissions provide superior reliability and accuracy when compared with the previously used agricultural census data. However, the LPIS has only been pre-processed for geospatial modelling for a single year (2012) on account of limited resources. Quality control of the national databases is time-intensive and any remaining errors or omissions will impact on results. However, the synthesis of the substantial number of national databases by the framework results in a powerful tool for assessing the relative fate of nutrients in the Irish water environment.

The heterogeneity of the urban environment makes the identification of export coefficients more difficult compared with other land cover types (White and Hammond, 2006, 2009). Several sources may not be captured by this approach, including localised practices and incidental spills. For example, a review of sewer misconnections by Ellis and Butler (2015) found typical rates of misconnection in the UK and Ireland ranging from 1 to 6%. Recent investigative assessments undertaken separately by both Dublin City Council and South Dublin County Council showed that 8% of houses were misconnected. Hence, sewer misconnections are a potential source of nutrient losses from urban areas not currently included in the model.

### *2.10.6 Emerging pressures*

Phosphate dosing of raw water supplies began for the first time on a trial basis in the south-west of Ireland in November 2016 to control plumbosolvency in mains water. This has the potential for significant contributions to P concentrations in surface waters, particularly due to mains water leakage, as has been seen in other countries where the practice has been widespread for decades (Gooddy *et al*., 2017). Phosphate dosing should be included in future iterations of this P load apportionment research.

# 3 National Nutrient Source Apportionment Results

Load apportionment results by sector were analysed nationally for six regional (formerly river basin) districts (Figure 2.2b) and at a local scale for 583 sub-catchments ranging in area from 24 to 390 $km^2$. These results have been published in *Science of the Total Environment* (Mockler *et al*., 2017b).

## 3.1 National Overview

### *3.1.1 Main sources of phosphorus in Irish rivers*

The average annual P emissions to surface water in Ireland were estimated at over 2700 $t\,yr^{-1}$. Source contributions varied by region (Table 3.1), with municipal wastewater discharges and pasture dominant overall. At the regional level, the clear dominance of wastewater in the East (78%) reflects the distribution of the population, which is clustered around the capital city, Dublin. Pasture is the dominant diffuse source of P, contributing up to 47% at the regional level. Forestry and peatlands were estimated to contribute up to 13% and 23%, respectively, of P emissions in some regions, whereas contributions from septic tank systems and other licensed discharges (i.e. industrial discharges) were low across all regions, representing less than 3% of P emissions.

The SLAM estimate of total P emissions from Ireland is less than the previously reported annual national emissions to the OSPAR (Oslo–Paris Convention for the Protection of the North-East Atlantic) Commission for the years 2011–2015, due in part to the model significantly underestimating loads calculated from monitoring data in some catchments. In addition, the OSPAR calculation methods can result in overestimations in that the linear extrapolation of catchment loads upstream of OSPAR monitoring stations to downstream areas results in some duplication of point source emissions.

### *3.1.2 Main sources of nitrogen in Irish rivers*

Agriculture is the main source of N in Irish rivers, similar to other countries, including the UK (Bowes *et al*., 2014) and across Europe (Bøgestrand *et al*., 2005). In Ireland, average annual N emissions to water were estimated at over 82,000 $t\,yr^{-1}$, which, like P, is slightly lower than previously reported national emissions to the OSPAR Commission for the years 2011–2015. Pasture was the dominant source overall (Figure 3.1b, Table 3.2) and N emissions were more spatially uniform than P emissions, as nitrate from diffuse sources is typically delivered to streams via subsurface pathways, with links between increasing nitrate concentrations and groundwater contributions (Tesoriero *et al*., 2009). Emissions from arable land reflected the locations of the most crop-intensive areas in the more freely draining soils of the country in the East (14%) and South East (20%). The proportion of emissions of N from septic tank systems was low on average (2%), with higher contributions in the North West (5%) and West regions (4%), reflecting the relatively high density of non-sewered properties in these areas. Contributions from wastewater were low across all regions (< 7%) except for the East (33%), the latter due to the high proportion of the population living in this region.

### *3.1.3 Point vs diffuse sources at local scale*

Figure 3.2a,b illustrates the range of nutrient export rates of P and N emissions to water for each of the 583 sub-catchments in Ireland and the percentage contributions from point sources (Figure 3.2c,d). Point sources of nutrients were classified as wastewater, other licensed discharges and septic tank systems. Farmyards as point sources are also likely contributors to emissions to water but are not included in the model (although they are somewhat implicit in the CCT). The locations of urban areas and the associated wastewater and industrial discharges drive the highest emission rates of P (Figure 3.2a,c). Mid-ranging P export rates (0.25–0.5 $kg\,ha^{-1}\,yr^{-1}$) typically coincide with agricultural lands with poorly draining soils. However, agricultural intensity has a dominant impact on the magnitude of the total emission rates for N, with the majority of emissions coming from the East and South of the country reflecting the coincidence of higher intensity agricultural land on more freely draining soils (Figure 3.2b,f).

**Table 3.1. Phosphorus emissions to water by region and percentage contribution from sources**

| Region | Area ($km^2$) | P total ($t\,yr^{-1}$) | Wastewater (%) | Other licensed discharges (%) | Diffuse urban (%) | Septic tank systems | Pasture (%) | Arable (%) | Forestry (%) | Peatlands (%) | Deposition on water (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| North West | 9842 | 264 | 13 | 1 | 4 | 3 | 47 | 1 | 12 | 15 | 4 |
| East (and Neagh-Bann) | 8458 | 1015 | 78 | 0 | 7 | 1 | 8 | 2 | 2 | 1 | 0 |
| South East | 12,850 | 378 | 28 | 2 | 7 | 2 | 38 | 8 | 12 | 3 | 0 |
| South West | 11,181 | 416 | 39 | 2 | 5 | 1 | 31 | 2 | 11 | 8 | 1 |
| Shannon | 18,014 | 422 | 24 | 1 | 5 | 2 | 43 | 1 | 13 | 6 | 4 |
| West | 10,458 | 271 | 8 | 0 | 4 | 2 | 43 | 0 | 13 | 23 | 8 |
| Total | 70,803 | 2766 | 42 | 1 | 5 | 1 | 29 | 2 | 9 | 7 | 2 |

**Table 3.2. Nitrogen emissions to water by region and percentage contribution from sources**

| Region | Area ($km^2$) | N total ($t\,yr^{-1}$) | Wastewater (%) | Other licensed discharges (%) | Diffuse urban (%) | Septic tank systems | Pasture (%) | Arable (%) | Forestry (%) | Peatlands (%) | Deposition on water (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| North West | 9842 | 4286 | 7 | 1 | 1 | 5 | 59 | 3 | 9 | 10 | 5 |
| East (and Neagh-Bann) | 8458 | 13,000 | 33 | 1 | 2 | 2 | 45 | 14 | 2 | 1 | 1 |
| South East | 12,850 | 20,594 | 4 | 1 | 1 | 2 | 69 | 20 | 2 | 1 | 0 |
| South West | 11,181 | 19,551 | 7 | 0 | 0 | 2 | 77 | 9 | 2 | 2 | 0 |
| Shannon | 18,014 | 17,171 | 6 | 1 | 1 | 2 | 78 | 3 | 4 | 2 | 3 |
| West | 10,458 | 7589 | 3 | 0 | 1 | 4 | 74 | 1 | 5 | 9 | 4 |
| Total | 70,803 | 82,190 | 10 | 1 | 1 | 2 | 69 | 10 | 3 | 2 | 2 |

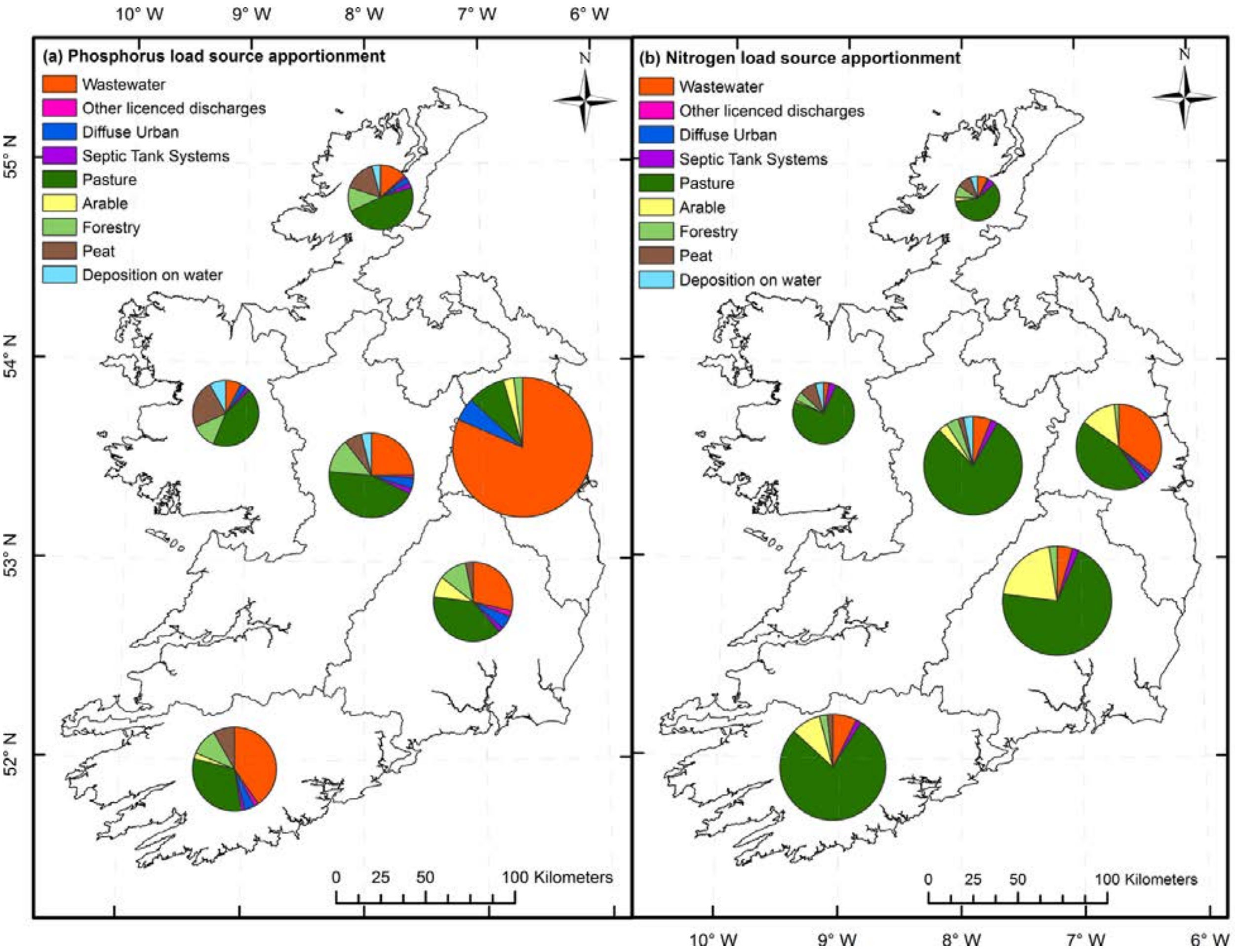


**Figure 3.1. Load apportionment of (a) phosphorus and (b) nitrogen emissions to water by region. The size of the pie indicates the relative total nutrient emissions.**

## 3.2 Comparisons of Nutrient Sources and Pathways

### *3.2.1 Impact of pressure vs pathway on emissions from pasture*

To explore the main drivers of nutrient emissions from pasture, relationships between the modelled P and N losses (kg ha$^{-1}$ yr$^{-1}$) and indicators of pressure (livestock units per hectare) and delivery pathway (percentage area of poorly drained soils) in the 583 sub-catchments were examined in an R pairs plot (R Core Team, 2016). The results (Figure 3.3) show that:

- There is a strong inverse relationship between the modelled P and N load emissions from pasture in the 583 sub-catchments ($r^2 = 0.71$, $p = < 0.001$). These contrasting delivery mechanisms in the conceptual models of P and N for diffuse agriculture reflect the scientific understanding of key nutrient delivery mechanisms present in Irish conditions.
- Phosphorus emissions from pasture increase with the percentage area of poorly drained soils ($r^2 = 0.87$, $p = < 0.001$), whereas N emissions decrease ($r^2 = 0.65$, $p = < 0.001$).
- There is further contrast between P and N source pressures and the consequent emissions, as there is a strong increasing relationship between N emissions from pasture and livestock units ($r^2 = 0.78$, $p = < 0.001$), whereas the relationship with P is weakly negatively correlated ($r^2 = 0.43$, $p = < 0.001$).

These relationships emphasise that P emissions from pasture are not driven by the magnitude of the pressure (indicated by the livestock units), as hydrogeological conditions have an overriding impact on transport and attenuation (Mellander *et al*., 2015).

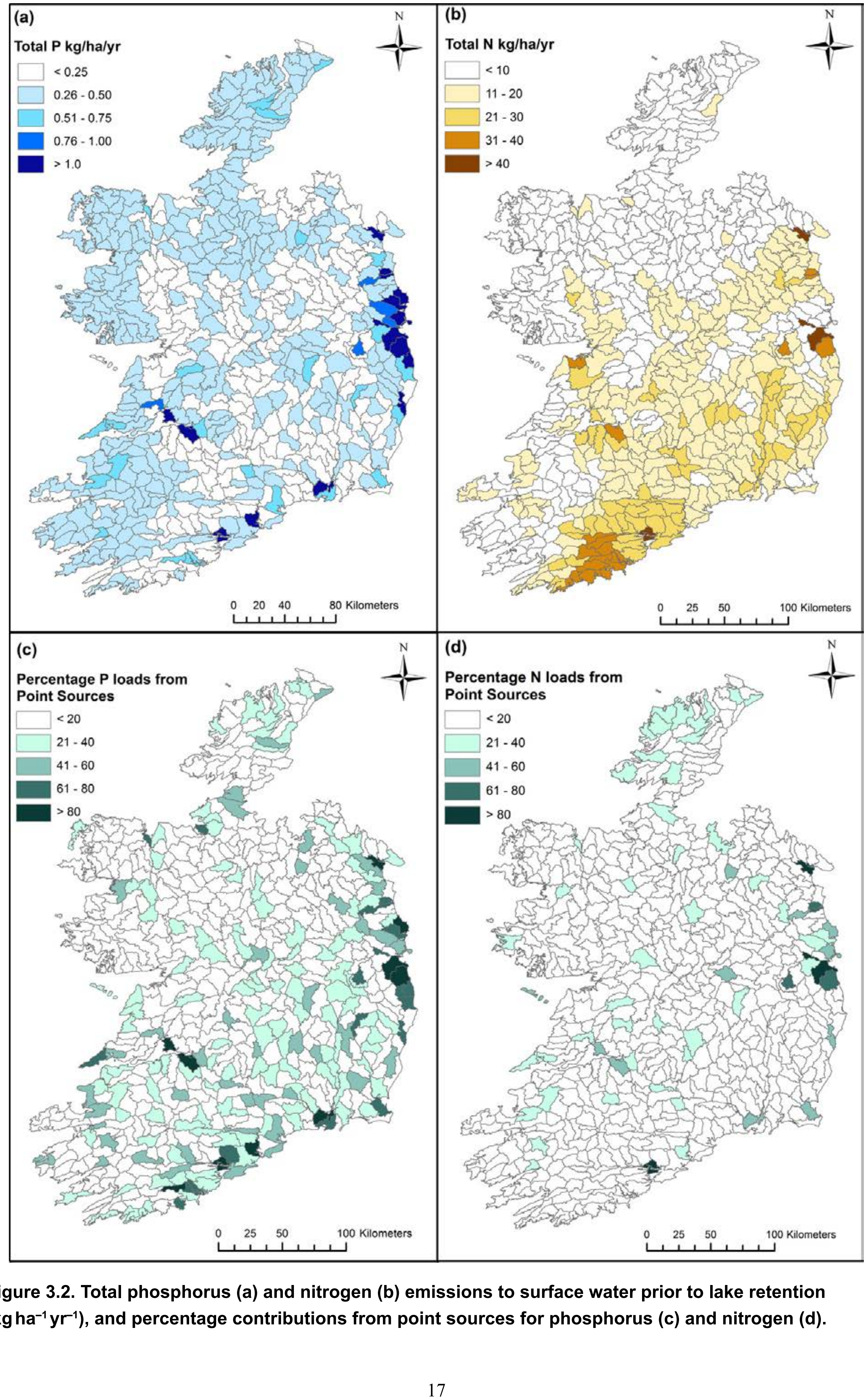


**Figure 3.2. Total phosphorus (a) and nitrogen (b) emissions to surface water prior to lake retention ($kg\,ha^{-1}\,yr^{-1}$), and percentage contributions from point sources for phosphorus (c) and nitrogen (d).**

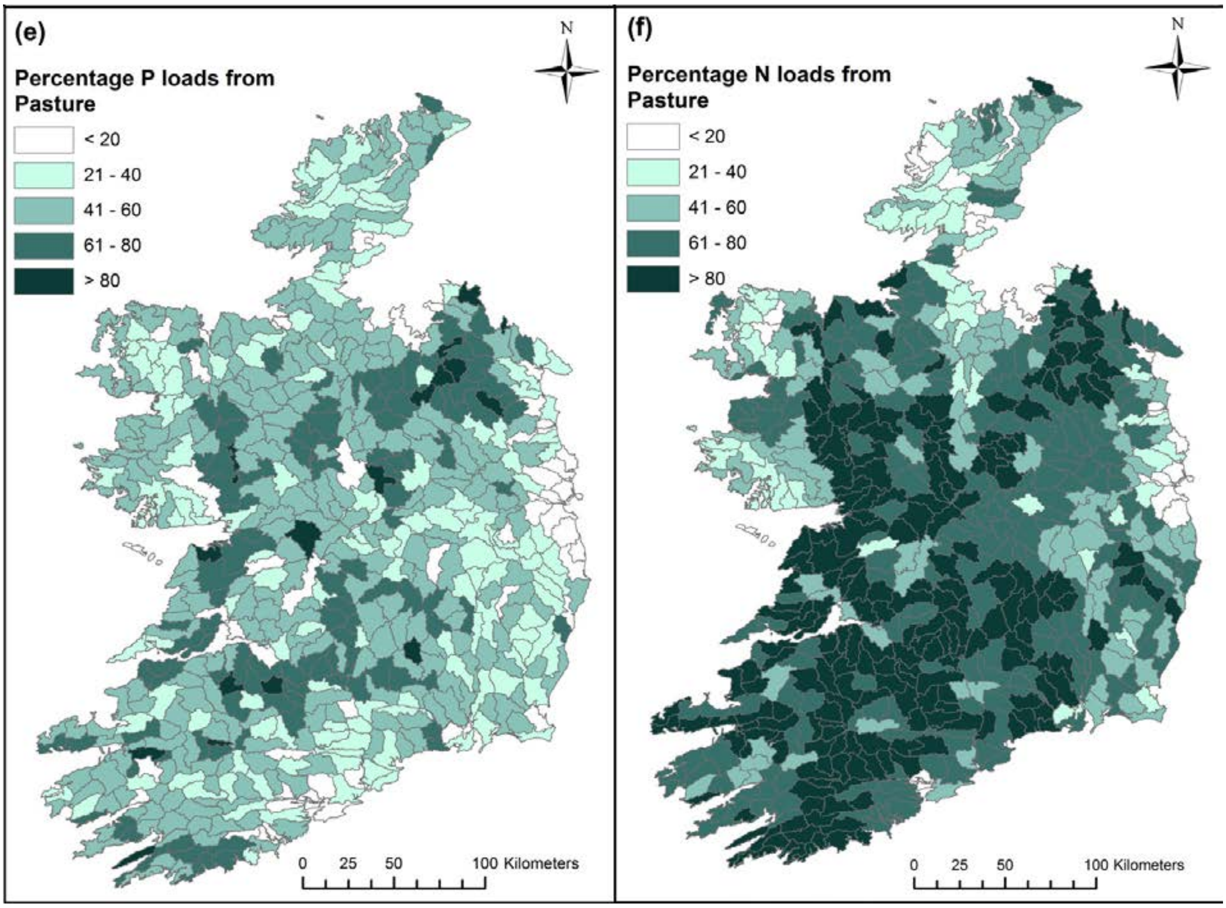


**Figure 3.2. Continued. Percentage contributions from pasture for phosphorus (e) and nitrogen (f) for 583 sub-catchments.**

In fact, the majority of diffuse P emissions come from a relatively small proportion of these poorly drained soils (critical source areas). Thus, to be effective from a water quality perspective, tailored N and P mitigation options are required that consider the local source–pathway–receptor relationships. For example, measures for reducing N emissions typically need to focus on managing source loads, as interrupting the pathway is challenging (Deakin *et al.*, 2016).

### *3.2.2 Municipal wastewater treatment vs septic tank systems*

Municipal wastewater treatment in Ireland has improved significantly in recent years, driven in part by European legislation, including the Urban Waste Water Directive (91/271/EEC) (EU, 1991). Phosphorus emissions from wastewater have decreased by 40% from the reported emissions from wastewater in 1999 (OSPAR, 2000), over which time there has been an increase in Ireland’s population of 0.8 million (21%). Most of the population, over 3 million people, are connected to sewerage systems and there are over 1000 authorised wastewater treatment plants across the country. Industrial discharges are also connected to some of these plants, resulting in a total population equivalent (p.e.) of 4.6 million being treated annually. The average treatment efficiency rate (percentage of P and N removed) is estimated as 62% and 56% for P and N, respectively.

The remainder of the population in Ireland, over 1.4 million people, uses septic tanks or package treatment systems for domestic wastewater treatment (referred to in this study as septic tank systems), and this number is rising, with a 20% increase recorded in the 9-year period from 2002 to 2011 (Central Statistics Office, 2013). These 500,000+ individual systems generate over 950 $t\,yr^{-1}$ of P and 5800 $t\,yr^{-1}$ of N, respectively, assuming 1.9 $kg\,P\,yr^{-1}$ and 11.62 $kg\,yr^{-1}$ N per household. These were modelled by the SANICOSE model (Gill and Mockler, 2016), which was implemented nationally, producing estimated nutrient emissions from each septic tank system that were

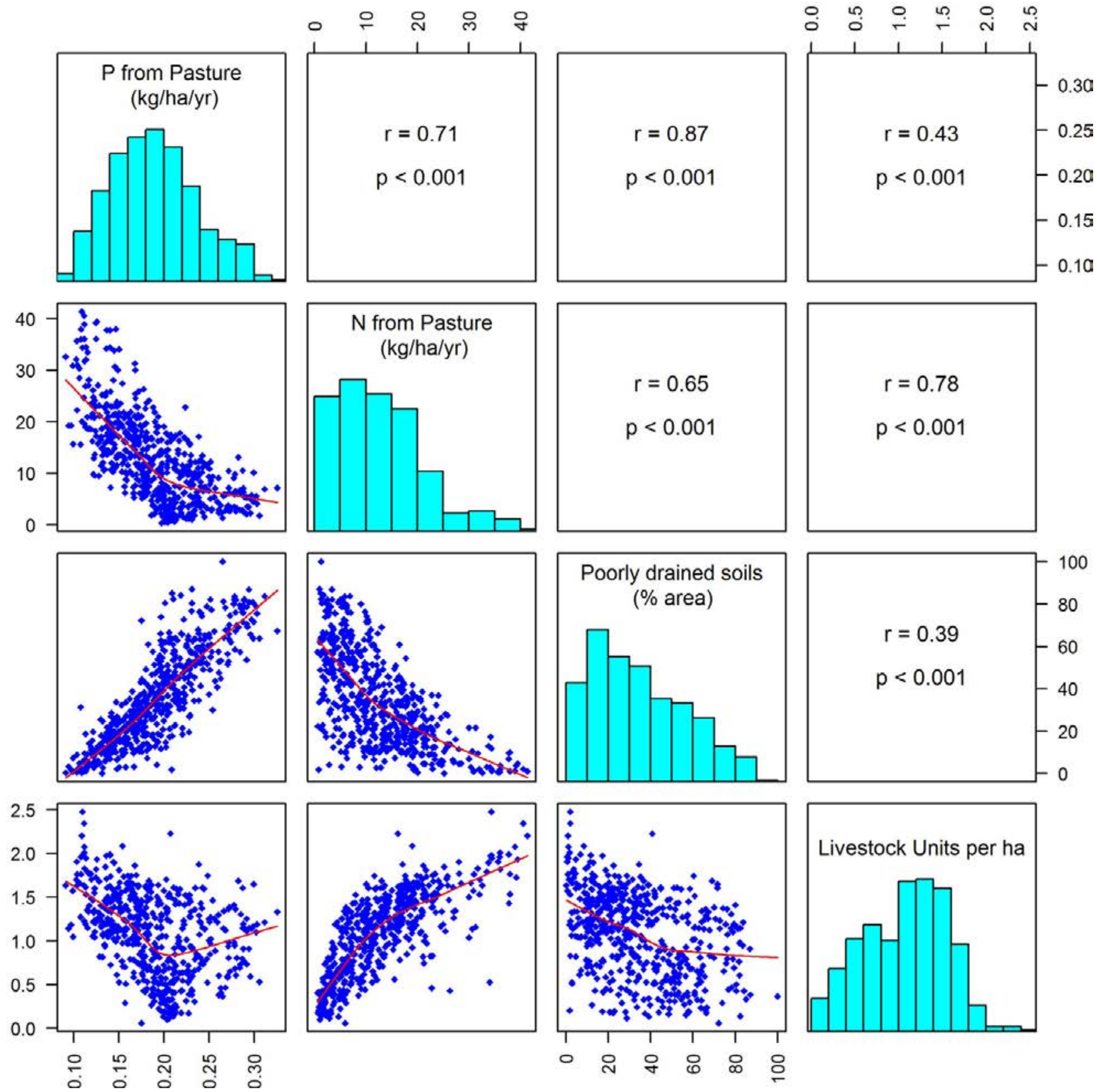


**Figure 3.3. Relationships between phosphorus loads from pasture (kg ha$^{-1}$ yr$^{-1}$), nitrogen loads from pasture (kg ha$^{-1}$ yr$^{-1}$), the area of pasture with poorly drained soils (%) and the livestock units per ha for 583 sub-catchments. This pairs plot (R Core Team, 2016) shows histograms in the diagonal panels, with correlation plots for each pair of variables shown in the lower panels and the corresponding Spearman's rank-order correlation coefficient (*r*) and significance (*p*) for each shown in the mirrored upper panel.**

fed into the SLAM framework. The modelled average treatment efficiency rates of these systems were 95% and 67% for P and N, respectively. It can be seen that, on average, the N treatment efficiency rate is comparable to that from wastewater treatment plants, while the P treatment rate by septic tank systems is superior. The average sub-catchment contributions were 2% and 3% for N and P, respectively. However, the treatment efficiency from septic tank systems varies widely, and underperforming systems have the potential to cause impact in small streams, particularly in areas of poor permeability during low-flow periods, when there is little baseflow for dilution (Archbold *et al*., 2010; Withers *et al*., 2012). In areas with a high density of septic tank systems (over 19 per km$^2$), their contributions to annual nutrient loads can be up to 22% for P and 13% for N (Gill and Mockler, 2016). Advances in techniques to identify the contributions of pollution from human sources (e.g. Richards *et al*., 2017) and their application in Irish catchments (Bedri *et al*., 2016; Flynn *et al*., 2016) will provide valuable data to validate and refine these source apportionment estimates.

### *3.2.3 Wastewater treatment plants vs storm water overflows (combined sewer overflows)*

There are over 1000 storm water overflows (often referred to as combined sewer overflows) in Ireland that discharge storm water and may also discharge untreated wastewater from urban areas drained by combined sewerage systems. In the SLAM, emissions from the wastewater module include discharges from treatment plants and storm water overflows. The SLAM uses annual values in the 2014 AERs, where available, to estimate emissions from storm water overflows and otherwise assumes a proportion of the collected load from the agglomeration. The SLAM results indicate that storm water overflows account for 5% of the total P emissions in Ireland (12% of the wastewater emissions) and 1% of N emissions (10% of the wastewater emissions). However, there are significant uncertainties with these estimates, as the actual losses are dependent on complex network-specific characteristics including precipitation patterns, the connected impervious area, the rainfall-runoff rate, and the storage volume in the sewer network. Studies of emissions from individual storm events using detailed monitoring and hydrodynamic modelling (e.g. Quijano *et al*., 2017) are required to fully characterise the complex discharges from storm water overflows in agglomerations and resulting water quality impacts. Following a recent review of low-cost monitoring technologies used in Irish sewer networks (Morgan *et al*., 2017), further research on monitoring and treating storm water overflows in Irish sewer networks is planned, which could provide network-specific data to improve this model.

### *3.2.4 Groundwater vs surface water pathways*

On average, the SLAM model estimates that the groundwater pathway contributed approximately 5% of P and 25% of N to surface waters, increasing up to 70% of P and 80% of N in some hydrogeologically susceptible sub-catchments. This calculation used the SLAM modules for agriculture (pasture and arable) and septic tank systems, which calculated the emissions to surface waters through two pathway categories: (1) “near surface” pathways including overland and drain flow; and (2) groundwater. By including these pathways in the conceptual models of nutrient transport and attenuation, the three-dimensional relationships of sources, pathways and receptors in catchments are accommodated.

To achieve successful outcomes, water quality management strategies must be tailored to the local hydrogeological conditions and main pollutant pathways. Deakin *et al*. (2016) outlined two contrasting examples, showing that in a freely draining karstified catchment with predominantly subsurface pathways, measures must target managing inputs to groundwater, whereas in a catchment underlain by poorly draining soils, the transport of P by overland flow and interflow, and from small point sources, were key issues and so measures were required to intercept these pathways and mitigate discharges.

# 4 Models Supporting Catchment Management

## 4.1 Introduction

The SLAM results have been analysed at a range of scales and coupled with other models and assessments. For example, the SLAM has been used to characterise existing and previous water quality conditions, including:

- assessing the current sources of nutrient emissions to Ireland's water bodies; and
- evaluating changes in sources of nutrient emissions in recent decades.

The SLAM framework also provides capabilities for scenario analyses to support integrated catchment management in Ireland, including:

- local-scale scenario analyses to identify potential nutrient reduction options to achieve Good status in nutrient-impacted water bodies; and
- regional-scale scenario analyses to assess the impact of future projections of land cover and land use change, population increases and wastewater treatment improvements.

This chapter includes an overview of the characterisation and scenario analyses undertaken by the CatchmentTools project to support integrated catchment management in Ireland. Firstly, the model integration into the EPA's WFD characterisation process is outlined (section 4.2), followed by a summary of the trends in nutrient emissions to estuaries (section 4.3). Section 4.4 details the scenario analysis undertaken in the Suir catchment, and finally there is a brief introduction to an on-going collaboration that is developing regional water quality projections for the Greater Dublin Area based on land use change scenarios for 2026 (section 4.5).

## 4.2 Load Apportionment for Catchment Characterisation

In order to improve water management in Ireland, the Irish EPA has substantially strengthened the evidence base on which decisions are made by implementing a rigorous risk-based approach to the water body characterisation and assessments required under the WFD (Daly *et al*., 2016). The purpose of these assessments was to determine the significant pressures impacting on water bodies that are *At Risk* of not meeting their WFD objectives. The significant pressures are those that are hydrogeologically connected to the water body and need to be addressed before the water quality will improve. Determining which of the multitude of pressures within a water body are significant is important, so that measures can be more efficiently and specifically targeted to achieve water quality improvements.

Characterisation is a multi-disciplinary task requiring a variety of datasets, many of which are not currently captured or accessible in a centralised system. The EPA has developed a WFD application that provides a single point of access to catchment data, which will be useful for many catchment science and management purposes, not just those that are specific to the WFD. The application is accessible currently through EDEN (https://wfd.edenireland.ie/) and is available to EPA staff as well as to staff in other public agencies. Much of the information is also more widely available through a new public website, www.catchments.ie. The SLAM framework was developed to support the proportional and pragmatic assessment of every sub-catchment within this national characterisation process. The national nutrient source apportionment results, as outlined in Chapter 3, were produced at sub-catchment scale and integrated into the EPA's WFD characterisation process (Daly *et al*., 2016) by the EPA's Catchment Science and Management Unit during 2016 and 2017 (Figure 4.1). The source apportionment results were included in the catchment assessments alongside other national datasets, including ecological status and trends in ecological and chemical monitoring data; information on land use, pressures, pathways and the sensitivity of receptors; licence, enforcement, audit and inspection information from regulatory agencies; and local, on-the-ground knowledge from the local authorities and fisheries agency staff (Daly *et al*., 2016). Inclusion of the SLAM results into this process facilitated the assessment of nutrient load information in a logical, structured,

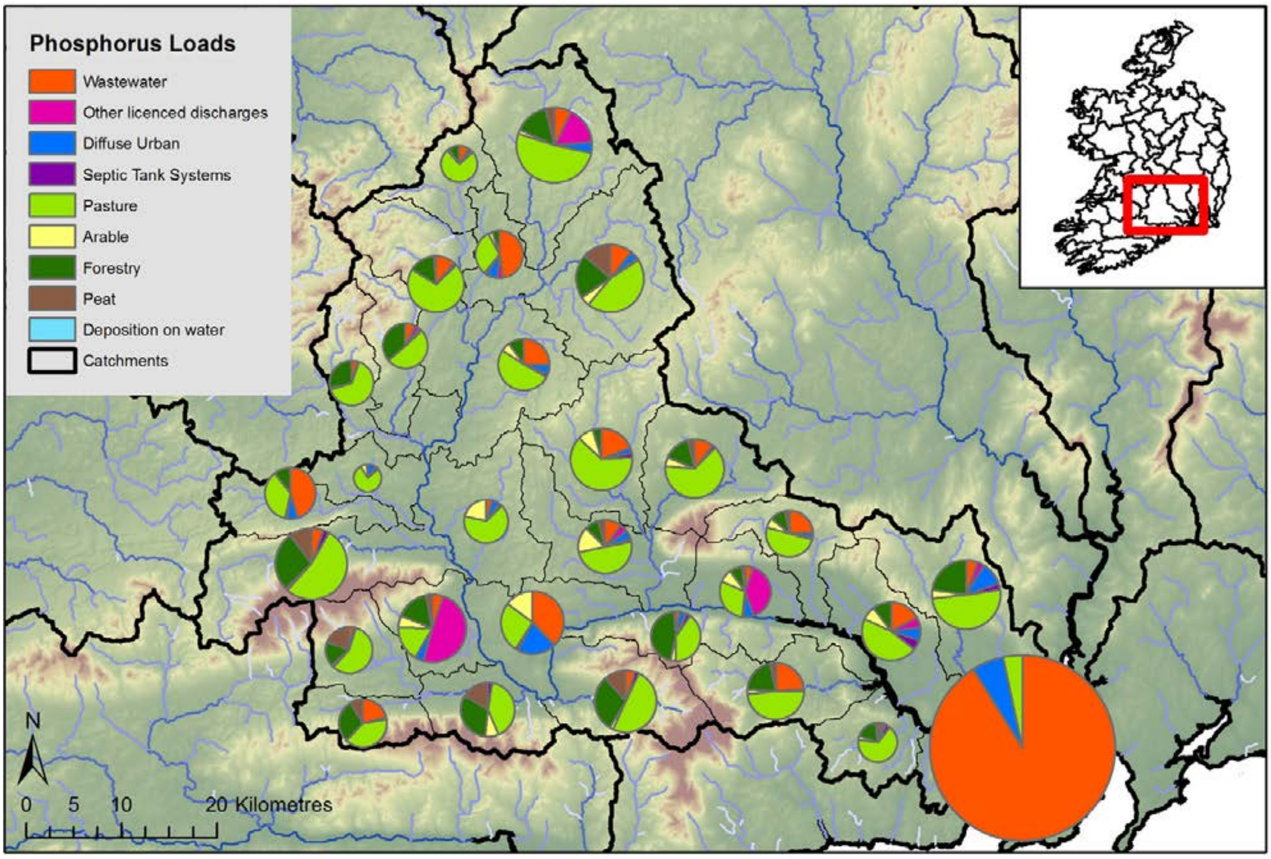


**Figure 4.1. Phosphorus load apportionment results for the Suir catchment (size of pie indicates relative contribution to annual loads from each sub-catchment) (step 2).**

consistent and comparative way across the country and has therefore enabled robust and practical use of the available information. This systems-focused approach is vital for integrated catchment management and effective WFD implementation (Voulvoulis *et al*., 2017). The model results, however, were only one indicator used to identify the significant pressures. During the WFD characterisation process, the results were interpreted by catchment scientists along with the other national datasets listed above. Furthermore, the SLAM results were only used in cases in which chemical and ecological monitoring data, local knowledge or other information indicated that excess nutrients were impacting on a water body. This process ensured that the several sources of uncertainty (see section 2.10) and the model under- and over-estimations would not result in the incorrect identification of significant pressures.

The design of measures requires integrating hydrological and social science assessments to ensure that decision makers have the best information when evaluating cost-efficiency and effectiveness (Psaltopoulos *et al*., 2017), and models such as the SLAM provide some of the necessary information to feed into these assessments. For example, the annual percentage contribution of loads from septic tank systems may be small overall at the sub-catchment scale, but their impact in small stream headwaters can be significant during low-flow periods (Withers *et al*., 2012). Source apportionment models, such as the SLAM, can provide an indication of sources of emissions at regional or sub-catchment levels but are not suitable for detailed, site-specific assessments. Local investigative assessments are therefore required prior to implementation of specific mitigation strategies.

## 4.3 Trends in Nutrient Emissions to Estuaries

A collaborative study (Ní Longphuirt *et al*., 2016) examined the dynamic nature of anthropogenic pressures at catchment scale and the resulting impacts on Irish estuaries by modelling loading information spanning over a decade. This study traced N and P flows from the source to the coastal zone to determine the effectiveness of mitigation efforts and enhance the understanding of response trajectories.

Nutrient load apportionment for 18 river systems for two time periods, 2000 and 2013, were produced and linked with estuarine water quality parameters. Measured P inputs showed a significant reduction in 15 catchments, with only four rivers showing a concurrent reduction in N. In most of the catchments, the greatest overall contributor to N and P loads was diffuse sources. Nevertheless, the considerable reductions in P were attributed to reductions in both diffuse and point sources, highlighting the effectiveness of measures already implemented. The reductions in N loads have been more modest and were largely related to agricultural improvements. Parallel improvements in estuarine water quality were evident in 8 of the 18 catchments, highlighting the complexity of response mechanisms in estuaries. The impact of measures intended to reduce nutrient loadings, thereby improving estuarine water quality, can be impeded by nutrient cycling processes and modulating factors such as light and residence time. This study emphasised that a holistic view must be taken along the freshwater–marine continuum to ensure that nutrient imbalances are not created in downstream coastal areas.

## 4.4 Load Reduction Assessment and Local Scenario Analyses

The Suir pilot study (Mockler *et al*., 2016) evaluated the potential load reductions that could be achieved from alternative mitigation options and focused on wastewater treatment plants and agricultural runoff in a nutrient-enriched water body. This study aimed to demonstrate the use of the SLAM to identify potential sector-level measures in the Suir catchment, including:

- assessment of the nutrient load reductions required to return all sub-catchments to Good WFD status;
- evaluation of the SLAM results for 29 sub-catchments of the Suir for N and P; and
- an example of using the SLAM results to identify potential appropriate measures for a sector by quantifying load reduction scenarios.

### 4.4.1 *The Suir study catchment*

The Suir is a 3500 $km^2$ catchment in the south-east of Ireland, with 29 sub-catchments (Figure 4.2), some of which have unsatisfactory water quality. The catchment land use is predominantly agriculture, mainly pasture, with an average stocking rate of 1.4 livestock units $ha^{-1}$. The total population is approximately 200,000, and the average density of septic tank systems in the catchment is 8 per $km^2$. The largest town is Waterford at the mouth of the Suir estuary, with a population of 56,000 in 2016.

### 4.4.2 *Load assessment methodology*

Where a water body or sub-catchment was identified as being *At Risk* of not achieving Good WFD status due to high nutrient concentrations, a load reduction assessment was carried out (Figure 4.3) as follows:

- Step 1: Assessment of the in-stream load reduction required using an in-stream load estimation method and the nutrient environmental quality standard, or a surrogate/equivalent proxy, to achieve the required WFD objective, typically Good status. This was carried out at (1) water body or sub-catchment level and (2) catchment scale, taking the transitional and coastal (TRaC) water bodies into consideration.
- Step 2: Comparison of in-stream loads and the load apportionment model results with consideration of the possible sources of additional loads that have not been modelled (e.g. incidents and accidents) where there are notable differences.
- Step 3: Identification of scenarios to achieve load reduction and issues or areas for investigative assessments.

### 4.4.3 *Load reduction targets*

As environmental quality standards (EQS) have not been set in legislation for TP, EQS values for molybdate-reactive phosphorus (MRP) were used as a conservative proxy in step 1. Based on mean values, the EQS values are 0.0025 mg P $l^{-1}$ and 0.0035 mg P $l^{-1}$ for High and Good status boundaries in rivers, respectively (Government of Ireland, 2009). Although the contribution of MRP to TP may vary widely in discharges (e.g. EPA, 2015), assuming that all of the

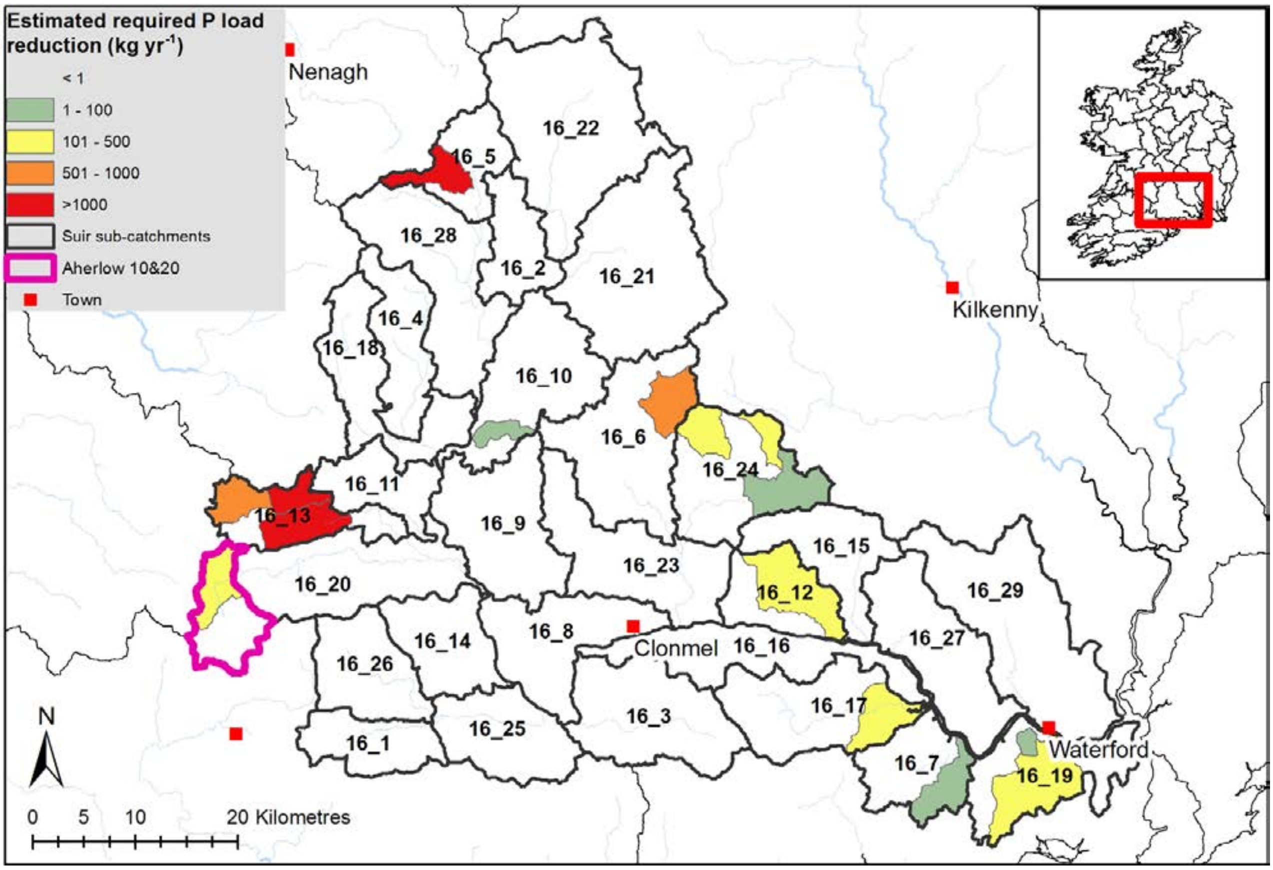


**Figure 4.2. Load reduction required for phosphorus loads to attain Good status based on an annual average concentration of 0.035 mg l$^{-1}$ (step 1).**

TP is biologically available in the form of MRP is a conservative approach. In other words, if the TP load meets the MRP EQS, and MRP is only a fraction of the TP load, then the MRP requirements will be met.

In the Suir catchment, the total load reduction required to reduce the average annual concentration of P below the threshold for Good of 0.035 mg l$^{-1}$ was calculated as 8.4 t yr$^{-1}$ of TP. This is equivalent to a reduction of 7% of the TP load emissions from the entire catchment. However, these load reduction targets are confined to 13% of the catchment area (22 water bodies), with 5% of this area (eight water bodies) estimated to require reductions of more than 0.5 t yr$^{-1}$ of TP (Figure 4.2). In fact, most of the required load reductions (55%) are limited to an area of only 39 km$^2$ (two water bodies) in two of the 29 sub-catchments (Ara_SC_010 and Fishmoyne_SC_010). This analysis emphasises the presence of individual hot-spots of nutrient loss, or critical source areas, within a catchment that contribute a high proportion of the nutrients exported from the landscape (Pionke *et al*., 2000).

### *4.4.4 Local scenario analysis: Aherlow example*

The sub-catchment area of two water bodies, Aherlow 10 and 20 (pink outlined area in sub-catchment 16_20, Figure 4.2) was selected for assessment of possible reduction measures. The area's land cover is predominantly pasture, with two wastewater treatment plants servicing p.e.s of 465 p.e. and 46 p.e., both with primary treatment. Following the above method, an assessment of alternative mitigation measures was undertaken in the *At Risk* area of the sub-catchment Suir_SC_090. Measures related to upgrading wastewater treatment plants to either secondary or tertiary treatment were evaluated using nutrient reduction factors dependent on treatment level (OSPAR, 2000). For this example, enhancement of buffer strips was selected as the potential measure to mitigate against diffuse P losses in overland flow based on reported P removal rates (e.g. Hoffmann *et al*., 2009; Sharpley *et al*., 2009). The effectiveness of buffer strips in controlling P in surface runoff is highly dependent on how they are placed and managed

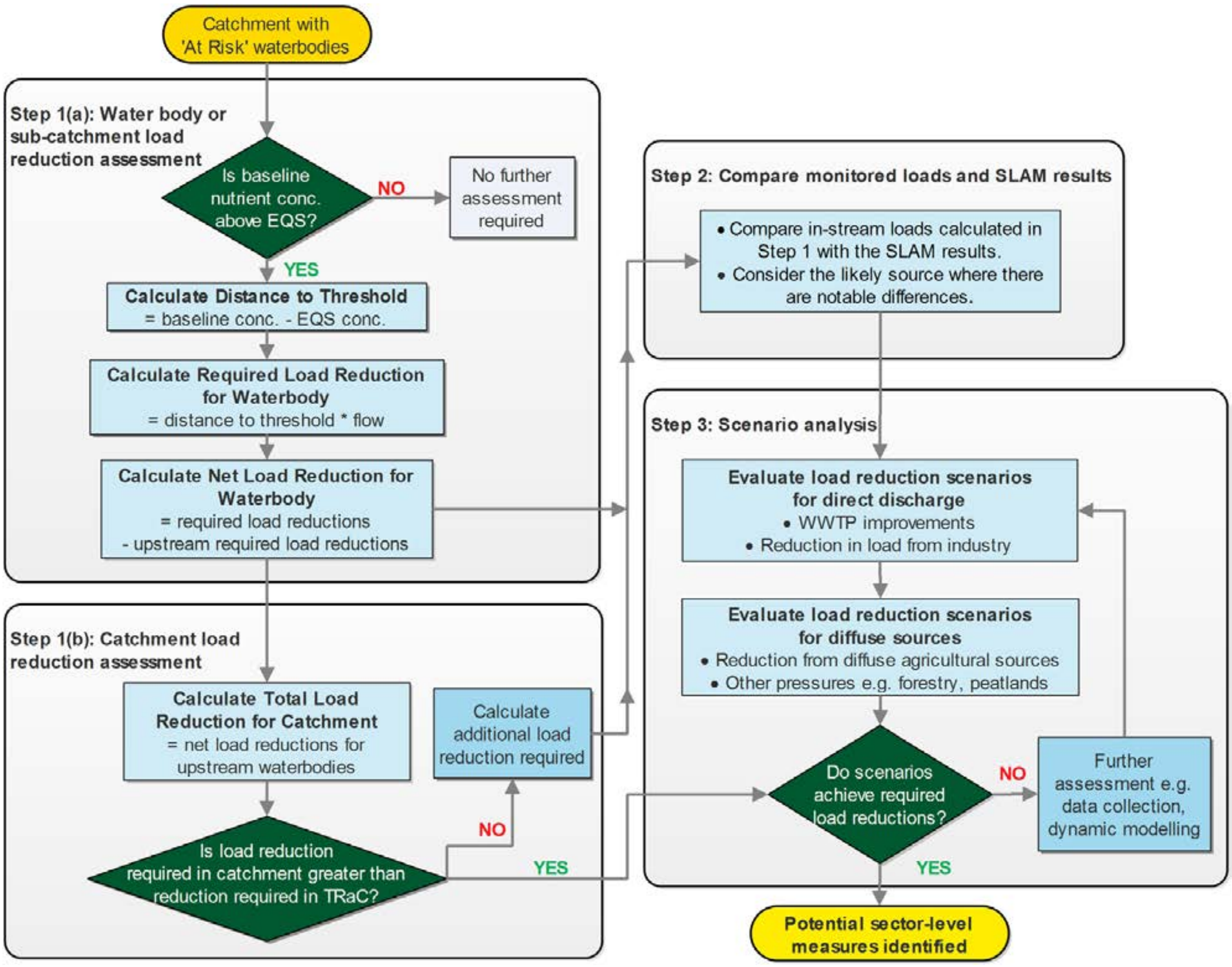


**Figure 4.3. Process flow chart to identify nutrient load reductions required and potential sector level measures.**

(Dorioz *et al*., 2006) and is typically a function of width, slope, soils and hydrogeological conditions (Collins *et al*., 2016). Overall, the enhancement of buffer strips was identified as a viable potential measure for the agricultural sector in this example.

The results from the load reduction assessment and scenario analyses were as follows:

- Step 1: Loading calculations using monitoring data indicated that a reduction of 150 kg yr$^{-1}$ is required to reduce the P concentration to below the WFD Good threshold of 0.035 mg l$^{-1}$.
- Step 2: For this sub-catchment area, the SLAM results predicted 18% lower loads compared with monitoring data. As discussed above, these load differences may be due to model or input data inaccuracies or an unknown nutrient source not accounted for in the model. Hence, local knowledge and investigative assessments would be required to adequately assess the conditions.
- Step 3: Assuming that investigative assessment was undertaken and the SLAM results are representative of the loads in the sub-catchment, the total load reduction required is equivalent to 58% reduction from wastewater emissions or a 13% reduction in losses from pasture. Box 4.1 outlines the three scenario options.

Importantly, losses of nutrients vary depending on farm management practices (e.g. Doody *et al*., 2014), and local hydrological flow paths (e.g. Ryan and Finnan, 2015; Thomas *et al*., 2016), which are not captured by the national assessment tool detailed here. In order to identify significant pressures and potential measures in a water body, all available evidence should be considered in conjunction with the SLAM results, including knowledge from local authorities and investigative assessments gathered through the WFD characterisation process.

**Box 4.1. Three scenarios for phosphorus reduction in the Aherlow sub-catchment**

**1 Improvement of wastewater treatment**

The total load from the two wastewater treatment plants is calculated as 226 kg yr$^{-1}$. Using nutrient reduction factors dependent on treatment level (OSPAR, 2000), upgrading these plants to secondary or tertiary treatment would result in a load reduction of approximately 70 or 190 kg yr$^{-1}$, respectively. Hence, scenario (1) would be able to achieve the required load reduction of 150 kg yr$^{-1}$.

**2 Reduction in P losses from pasture**

The evaluation of measures to achieve the 13% reduction in losses from pasture, i.e. a reduction from ~0.2 kg ha$^{-1}$ yr$^{-1}$ to 0.17 kg ha$^{-1}$ yr$^{-1}$, is more difficult compared with scenario (1), as limited data are available on the performance of targeted measures in Irish catchments. In the Aherlow 10 and 20 sub-catchment area, the transfer pathways for P were identified by the CCT as predominantly near surface (Figure 4.4). These high-risk areas include pasture land cover with poorly drained soils. Based on reported removal rates in the literature, the enhancement of buffer strips was identified as a viable potential measure for the agricultural sector to achieve the required load reduction of 150 kg yr$^{-1}$ in this sub-catchment. However, the success would depend on the applicability of the buffer strips to local conditions and the specific details of the measure's design, implementation and maintenance. Any additional measures should therefore be evaluated locally in liaison with local authorities and land owners.

**3 Combined reductions from wastewater and pasture**

Cost-effectiveness analysis is integral in the implementation of the WFD (Joyce and Convery, 2009). Given the capital investment required for scenario (1) and the uncertainty of scenario (2), an evaluation by multi-criteria decision analysis (not undertaken in this study) may identify an optimal acceptable solution that is a combination of measures targeted at wastewater emission and losses from pasture.

## 4.5 Regional Scenario Analyses

A collaborative study is under way with the University College Dublin (UCD) School of Environmental Policy that aims to assess how projected changes in population and land use in the East region of Ireland may impact on water quality by 2026, which is the end of the second WFD management cycle. This research will demonstrate how two independent models, developed for the same study region, are coupled to estimate nutrient losses for different regional development scenarios. Coupling existing and tested models for a region offers an effective solution for the application of state-of-the-art models from different disciplines in an integrated manner. In this collaboration, the SLAM framework has been linked with the Monitoring Land Use Cover and Dynamics (MOLAND) land use model (Barredo and Demicheli, 2003) to evaluate the impact of land use change on water quality.

### *4.5.1 Case study: the Greater Dublin Region*

The Greater Dublin Region is Ireland's most densely populated region with a population of ~2 million within an area of 7815 km$^2$. Its three main catchments are the Nanny–Delvin, Avoca–Vartry and Liffey–Dublin Bay, stretching over 3567 km$^2$. Because of improvements in nutrient management and regulation, there has been a large reduction in TP in particular, and reductions in other nutrient emissions to the Irish Sea from these catchments (O'Boyle *et al*., 2016).

### *4.5.2 SLAM coupling with MOLAND*

The MOLAND land use model has been developed by the Research Institute for Knowledge Systems as part of an initiative of the European Commission Joint Research Centre (Barredo and Demicheli, 2003). It generates alternative future scenarios informing urban planners and policymakers on the possible

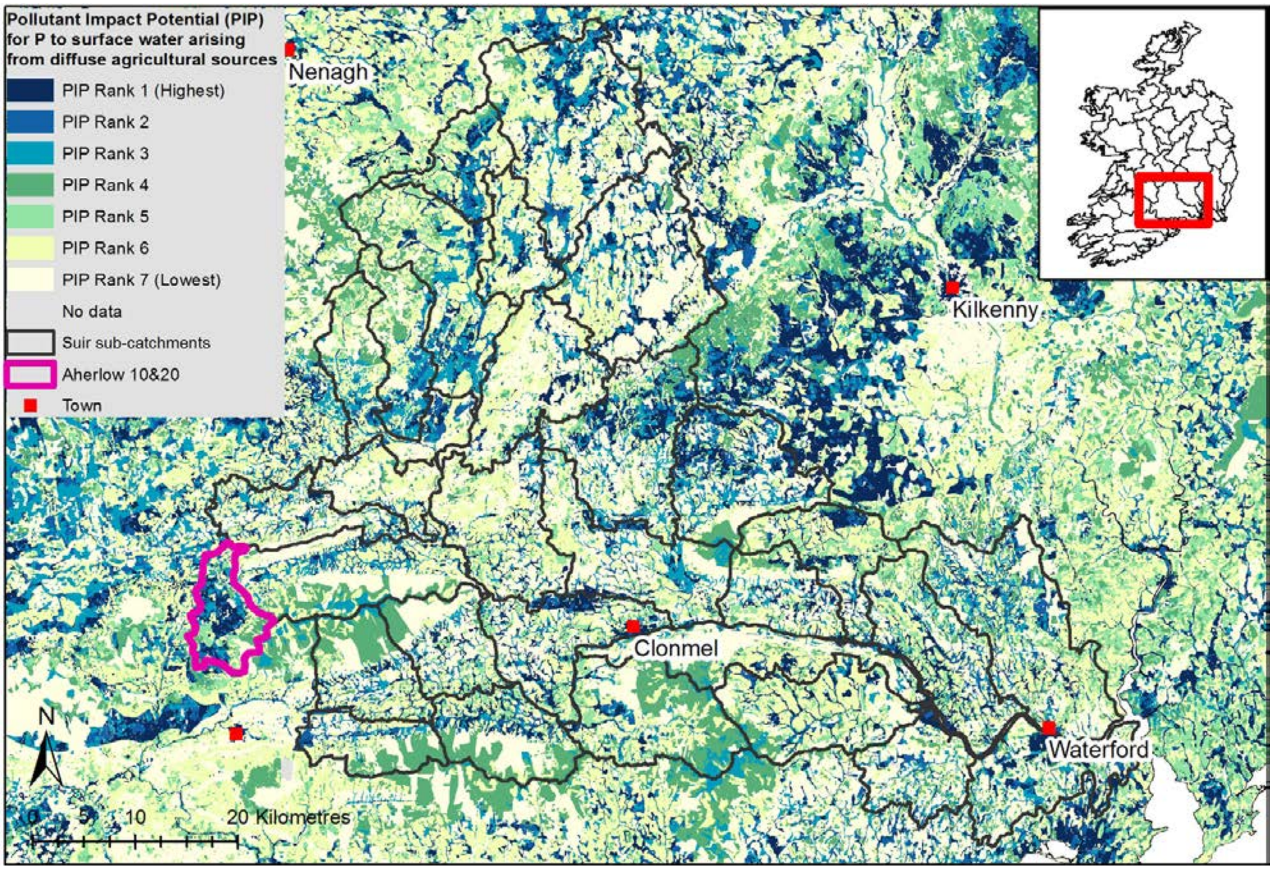


**Figure 4.4. Pollution impact potential map for phosphate to surface water arising from diffuse agricultural sources, with dark blue areas indicating the highest risk (step 3).**

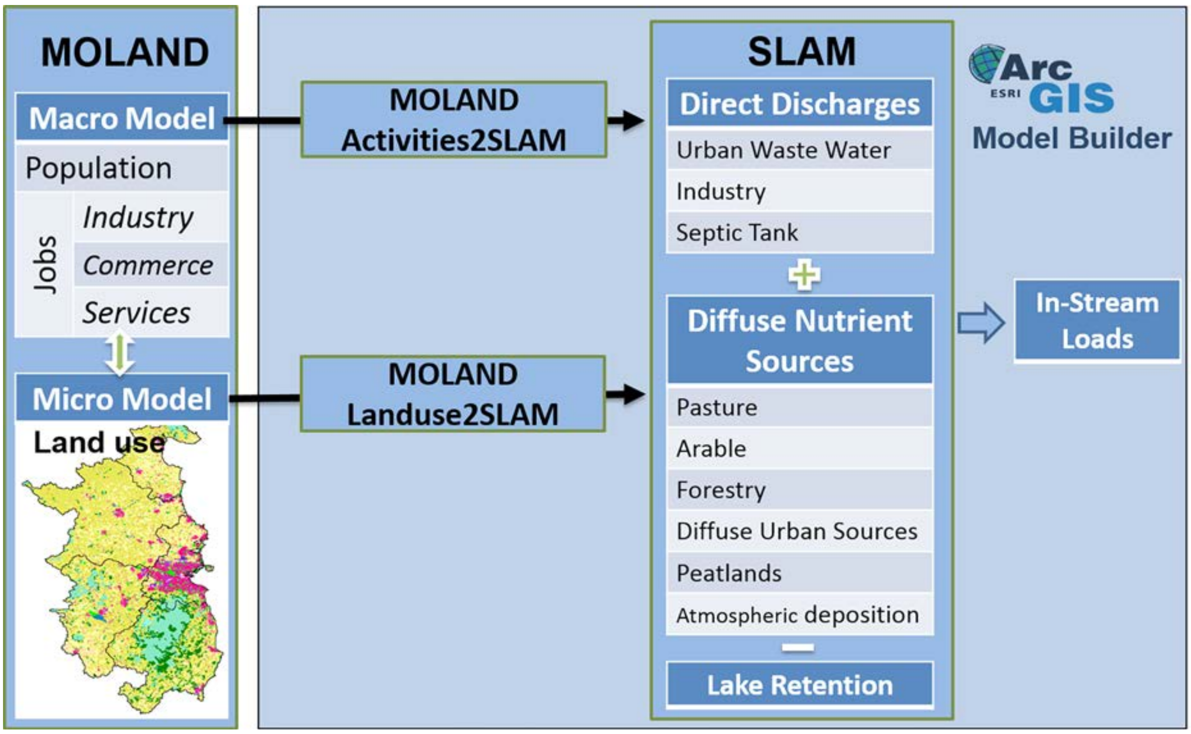


**Figure 4.5. The MOLAND–SLAM coupling framework.**

implications of their land use change decisions. The MOLAND was calibrated for the Greater Dublin Region for a number of years with available datasets (1990, 1996, 2000 and 2006) (Shahumyan *et al*., 2009) and it formed an important part of the review of the Dublin and Mid-East Regional Planning Guidelines.

In this study, the land cover change projections, estimated by MOLAND for the Greater Dublin Region, were incorporated into the inputs of the SLAM framework to estimate annual nutrient losses from diffuse sources for the future scenario alternatives (Figure 4.5). In addition, population and employment projections from MOLAND were used to estimate emissions from direct discharges. These models had independent development paths. Therefore, keeping them separate and not changing their source codes was important to ensure that the integrated suite remained compatible with the future versions of both models.

Initial results highlighted that urbanisation will reduce emissions from agriculture by varying levels, driven by projected reductions in agricultural land cover in the three catchments (Shahumyan *et al*., 2017). Further analyses are planned that will evaluate population increases and the associated changes to municipal wastewater discharges, including the effects of upgrades to treatment plants, to quantify projections of water quality change in this region. This research will continue after the end of the CatchmentTools project, and the results will be disseminated through peer-reviewed publications.

# 5 Conclusions

The CatchmentTools project developed data analysis tools and models to support catchment scientists and managers to (1) characterise nutrient sources, pathways and receptors in catchments and (2) assess potential mitigation measures. The main output of the project was the SLAM framework, which was developed to characterise sources of P and N emissions to water at a range of spatial scales from sub-catchment to national by synthesising land use and physical characteristics to predict emissions from point and diffuse sources. The SLAM results have been analysed at a range of scales and coupled with other models in order to improve understanding of catchment dynamics. For example, the dynamic nature of anthropogenic pressures at catchment scale were examined using loading information spanning over a decade to explore the resulting impacts on Irish estuaries (Ní Longphuirt *et al*., 2016). At a local scale, Mockler *et al*. (2016) illustrated a simple assessment of potential mitigation measures in a nutrient-enriched water body. Upgrading the SLAM framework with new models and data will continue in order to support integrated catchment management in Ireland.

The SLAM results were included in the EPA's WFD characterisation process for the second cycle of the WFD, which facilitated the assessment of nutrient load information in a logical, structured, consistent and comparative way across the country. The SLAM results were included in this process, in which chemical and ecological monitoring data, local knowledge or other information indicated that excess nutrients were impacting on a water body. The model results were interpreted by catchment scientists along with the other national datasets including ecological status and trends in ecological and chemical monitoring data; information on land use, pressures, pathways and the sensitivity of receptors; licence, enforcement, audit and inspection information from regulatory agencies; and local, on-the-ground knowledge from the local authorities and fisheries agency staff. This process ensured that the several sources of uncertainty (see section 2.10) and the significant model under- and over-estimations in some catchments would not result in the incorrect identification of significant pressures.

Catchment management can be supported by modelling at a range of scales and levels, all of which can reduce the resources required to analyse substantial amounts of information. The national nutrient source apportionment results from the SLAM framework indicated the following:

- Agriculture was the dominant source of N across all catchments, whereas the dominant sources of P emissions varied by land use and hydrogeological setting.
- P emissions from pasture were mainly driven by hydrogeological conditions, not pressure, highlighting that mitigation options should aim to interrupt the local source–pathway–receptor relationships.
- P emissions from wastewater are dominant in highly populated areas. However, wastewater treatment has significantly improved in recent decades, over-compensating for population increases.
- The highest N emissions were in the south and south-east and are attributed to relatively intensive agricultural activities on freely draining soils.
- Annual nutrient loads from septic tank systems and industrial discharges are comparatively low at regional and sub-catchment scales. However, detailed investigative assessments are recommended where localised or low-flow impacts are suspected.

These model results contributed to the characterisation and risk assessment of all Irish water bodies undertaken by the EPA, which included a wealth of monitoring data and local knowledge, in order to identify the dominant sources of nutrients at regional and local scales.

## 5.1 Deliverables and Dissemination

The SLAM toolbox and input database are available for research use (with consideration of data use restrictions). A technical user document is available online: http://erc.epa.ie/safer/

Recent publications have focused on the use of the SLAM model results to explore the interactions between sources of nutrients and long-term changes over time, as well as the interactions between nutrient emissions from rivers and the downstream impacts on transitional and coastal waters (see Appendix 1). Further publications are at preparation and review stages. The key publications to date are:

- Sources of nitrogen and phosphorus emissions to Irish rivers: estimates from the Source Load Apportionment Model (SLAM) (Mockler *et al.*, 2017b).
- Nutrient load apportionment to support the identification of appropriate Water Framework Directive measures (Mockler *et al.*, 2016).
- Modeling the pathways and attenuation of nutrients from domestic wastewater treatment systems at a catchment scale (Gill and Mockler, 2016).
- Linking changes in nutrient load source to estuarine responses: an Irish perspective (Ní Longphuirt *et al.*, 2016).

On account of the multidisciplinary nature of the research topic, the CatchmentTools project has contributed to several additional collaborative publications:

- The Irish Land-Parcels Identification System (LPIS): experiences in ongoing and recent environmental research and land cover mapping (Zimmermann *et al.*, 2016).
- What have we learned from over two decades of monitoring riverine nutrient inputs to Ireland's marine environment? (O'Boyle *et al.*, 2016).

Peer-reviewed conference papers detailing the project deliverables have been presented at international conferences, including:

- Development of a nutrient load apportionment modelling toolbox (Mockler, 2016).
- CCT: a simple prioritisation tool for identifying critical source areas for managing waterborne pollutants (Packham *et al.*, 2016).

Dissemination to the wider community has been on-going through presentations at Irish conferences and WFD-related meetings. In addition, a newsletter article outlining the Suir source apportionment results was published online: www.catchments.ie/news.

# 6 Recommendations

## 6.1 Model Development and Maintenance

The CatchmentTools project aimed to synthesise the best available national research and data to estimate and apportion the sources of N and P in Irish surface waters. The SLAM framework was developed as a modular system to facilitate updating of pressure data and upgrading of sector models. Because of limited resources of the project, some of the models are still based on simple emission factors. For example, there is a growing body of research on nutrient emissions from forestry and peatlands that has not yet been incorporated into a national sector model. As our understanding of the interactions between land cover, land use and hydrogeological connections grows, further research findings can be incorporated into the SLAM framework. Where feasible, it is recommended that future related research projects are advised to produce national spatial results of nutrient emissions that can be incorporated into the SLAM framework.

### *6.1.1 Pressure information*

As the SLAM framework is a source-oriented method, its performance is highly dependent on high-quality pressures information. National databases of pressures support the development of powerful analyses for assessing the relative fate of nutrients in the Irish water environment. Quality control of the national databases is time-intensive; however, any errors or omissions that remain in the datasets will impact on results. It is therefore recommended that the development of quality-controlled databases of pressure information is continued.

The diffuse agricultural models in the SLAM v. 2.04 use 2012 data from the LPIS. It is recommended that this land use information is maintained and kept up to date. In addition, the 2012 CORINE land cover should be updated to 2016 when available.

### *6.1.2 Links with on-going projects*

The EPA has recently funded a new project, Catchment Models and Management Tools for Diffuse Contaminants (Sediment, Phosphorus and Pesticides): DIFFUSE project (Mockler *et al.*, 2017b), which will explore novel approaches to modelling diffuse sources of emissions (including from sediment and P). Understanding connectivity in the landscape is a vital component of characterising the source–pathway–receptor relationships for water-borne contaminants, and so is a priority in this research. Deliverables from the DIFFUSE project, where applicable, will be compatible with the SLAM framework.

ESManage is an on-going EPA-funded project that is creating an ecosystems services modelling framework that will further develop an existing dynamic water quality model, the Catchment Modelling Tool (Mockler *et al.*, 2014). As the SLAM model results provide input data required for this dynamic model, it is recommended that a tool be developed to loosely couple the SLAM framework to the Catchment Modelling Tool. Such a tool will reduce the resources needed to set up dynamic water quality simulations in Irish catchments.

## 6.2 Future Research Needs

### *6.2.1 Model uncertainty*

There are many potential sources contributing to model uncertainties and the under- and over-predictions of annual nutrient emissions when compared with load estimations from monitoring data. The issues impacting on model performance vary among catchments depending on the dominant processes and the degree to which the local conditions relate to the underlying assumptions of the model calculations. There are opportunities for improvements to be made to the input data and model structure across all of the sectors in the modelling framework that would reduce model uncertainty (details of the wastewater, urban emissions, forestry and peatland sectors are discussed below). Moreover, the development of the SLAM framework to provide a quantification of the propagation of uncertainty would identify the components to prioritise and could provide an indication of the accuracy and applicability of the model that would improve the communication of the SLAM results for decision making. In addition, an increased sampling frequency of the monitoring data used for evaluation would reduce uncertainty in the evaluation of the results.

### *6.2.2 Wastewater*

Emissions from agglomerations can include discharges from treatment plants, emergency overflows and storm water overflows. Studies of emissions from individual storm events using detailed monitoring and hydrodynamic modelling (e.g. Quijano *et al*., 2017) are required to fully characterise the complex discharges from storm water overflows in agglomerations and resulting water quality impacts. The SLAM relies on reported emission values in the AERs; however, values are often not available for storm water overflows. Where no values are available, the SLAM includes an estimated load, proportional to the load generated in the agglomeration. Following a recent review of low-cost monitoring technologies used in Irish sewer networks (Morgan *et al*., 2017), further research on monitoring and treating storm water overflows in Irish sewer networks is required that could provide network-specific data to improve the SLAM estimates.

### *6.2.3 Urban emissions*

Phosphate dosing of raw water supplies to control plumbosolvency in mains water has the potential to significantly contribute to P concentrations in surface waters due to mains water leakage and increased loads from municipal wastewater treatment plants and septic tank systems, as has been seen in other countries where these practices have been widespread for decades (Gooddy *et al*., 2017). The model of diffuse urban emission should include this new source in future iterations of this research.

### *6.2.4 Forestry and peatlands*

Forestry accounts for over 10% of Ireland's land cover and over half of this is on blanket peat. The HYDROFOR project found that forestry operations, particularly clearfelling and windrowing activities, have significant impacts on the aquatic environment. Windrowing, for example, mobilises significant quantities of P and sediment (Clarke *et al*., 2015). In the three HYDROFOR study sites, both total suspended solid (TSS) and P concentrations were highest when nearly 100% of the forests were clearfelled (Kelly-Quinn *et al*., 2014). It is recommended that the findings of this and other studies on emissions from forestry (e.g. O'Driscoll *et al*., 2014) are extrapolated to the national level and incorporated into the SLAM framework.

### *6.2.5 Monitoring data*

To gain a deeper understanding of critical time periods for ecosystems and the impact of scaling in catchment monitoring, it is recommended that nested catchment monitoring of chemistry and ecology is undertaken. This monitoring could be enhanced by including source-tracking to quantify the impact of pressures.

### *6.2.6 Flow–chemistry–ecology interactions*

A major deficit in the understanding catchment processes relates to how nutrients and sediment influence ecology. It is recommended that any future research exploring this complex topic includes modelling of flow–chemistry–ecology interactions in order to extrapolate the understanding gained from study catchments to a broader Irish context.

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# Abbreviations

| | |
|---|---|
| **AER** | Annual Environmental Report |
| **CCT** | Catchment Characterisation Tool |
| **CORINE** | Coordination of Information on the Environment |
| **DAFM** | Department of Agriculture, Food and the Marine |
| **EPA** | Environmental Protection Agency |
| **EQS** | Environmental quality standard |
| **GIS** | Geographic information system |
| **GSI** | Geological Survey of Ireland |
| **LEMA** | Licensing Enforcement and Monitoring Application |
| **LPIS** | Land Parcel Identification System |
| **MOLAND** | Monitoring Land Use Cover and Dynamics (model) |
| **MRP** | Molybdate-reactive phosphorus |
| **N** | Nitrogen |
| **OSPAR** | Oslo–Paris Convention for the Protection of the North-East Atlantic |
| **P** | Phosphorus |
| **p.e.** | Population equivalent |
| **PRTR** | Pollutant Release and Transfer Register |
| **SANICOSE** | Source Apportionment of Nutrients in Irish Catchments for On-Site Effluent model |
| **SLAM** | Source Load Apportionment Model |
| **TN** | Total nitrogen |
| **TP** | Total phosphorus |
| **UCD** | University College Dublin |
| **WFD** | Water Framework Directive |
| **WWTP** | Waste water treatment plant |

# Appendix 1 Project Outputs

| Peer-reviewed journal articles | | |
|---|---|---|
| 2016 | Modelling the pathways and attenuation of nutrients from domestic wastewater treatment systems at a catchment scale. Environmental Modelling & Software, 84, 363–377. | Laurence W. Gill and Eva M. Mockler |
| 2016 | The Irish Land-Parcels Identification System (LPIS): Experiences in on-going and recent environmental research and land cover mapping. Biology and Environment, 116B(1), 53–62. | Jesko Zimmermann, Reamonn M. Fealy, Kevin Lydon, Eva M. Mockler, Phillip O'Brien, Ian Packham, Gavin Smith and Stuart Green |
| 2016 | Nutrient load apportionment to support the identification of appropriate Water Framework Directive measures. Biology and Environment, 116B(3), 245–263. | Eva M. Mockler, Jenny Deakin, Marie Archbold, Donal Daly and Michael Bruen |
| 2016 | What have we learned from over two decades of monitoring riverine nutrient inputs to Ireland's marine environment? Biology and Environment: Proceedings of the Royal Irish Academy, 116B(3), 313–327. | Shane O'Boyle, Rebecca Quinn, N. Dunne, Eva M. Mockler and Sorcha Ní Longphuirt |
| 2016 | Linking changes in nutrient source load to estuarine responses: an Irish perspective. Biology and Environment, 116B(3), 295–311. | Sorcha Ní Longphuirt, Eva M. Mockler, Shane O'Boyle, Caroline Wynne and Dagmar Brigitte Stengel |
| 2016 | Assessing the relative importance of parameter and forcing uncertainty and their interactions in conceptual hydrological model simulations. Advances in Water Resources, 97, 299–313. | Eva M. Mockler, K.P. Chun, G. Sapriza-Azuri, M. Bruen and H.S. Wheater |
| 2017 | Sources of nitrogen and phosphorus emissions to Irish rivers and coastal waters: estimates from a nutrient load apportionment framework. Science of the Total Environment, 601–602, 326–339. | Eva M. Mockler, Jenny Deakin, Marie Archbold, Laurence Gill, Donal Daly and Michael Bruen |
| **Peer-reviewed conference papers** | | |
| 2015 | Understanding hydrological flow paths in conceptual catchment models to improve water quality modelling. Proceedings of the Irish National Hydrology Conference. | Eva M. Mockler, Fiachra E. O'Loughlin and Michael Bruen |
| 2015 | Assessing the Applicability of the Revised Universal Soil Loss Equation (RUSLE) to Irish Catchments. IAHS Publ. 367, 99–105. IAHS, Wallingford, UK. | A. Rymszewicz, E. Mockler, J. O'Sullivan, M. Bruen, J. Turner, E. Conroy, M. Kelly-Quinn, J. Harrington and D. Lawler |
| 2016 | CCT: A simple prioritisation tool for identifying critical source areas for managing water-borne pollutants. Proceedings of the 8th Biennial Meeting iEMSs. | I. Packham, M.A. Archbold, E.M. Mockler, A. Mannix, D. Daly, J. Deakin and M. Bruen |
| 2016 | Development of a Nutrient Load Apportionment Modelling Toolbox. Proceedings of the 8th Biennial Meeting iEMSs. | Eva M. Mockler |
| 2017 | What are the main sources of nutrient inputs to Ireland's aquatic environment? Proceedings of IAH (Irish Group) Conference "Developments in Irish Hydrogeology in a Changing Water Services and Planning Environment", Tullamore. | Eva M. Mockler, Jenny Deakin, Marie Archbold, Donal Daly and Michael Bruen |
| 2017 | Exploring the effects of regional development scenarios on nutrient emission: coupling land use model MOLAND with the Source Load Apportionment Model. Proceedings of the 15th Computers in Urban Planning and Urban Management (CUPUM) Conference. | H. Shahumyan, E.M. Mockler, B. Williams and M. Bruen |

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|---|---|---|
| **Presentations** | | |
| 2014 | Catchment management support tools for water quality modelling: spatial data & hydrologic connectivity. Conference of Irish Geographers, UCD, 8–10 May 2014. | Eva M. Mockler |
| 2016 | Modelling the sources of nutrients in irish catchments. ESAI Environ Conference, University of Limerick, 22–24 March 2016. | Eva M. Mockler |
| 2016 | Development of a Nutrient Load Apportionment Modelling Toolbox. 8th International Congress on Environmental Modelling & Software, Toulouse, France, 10–14 July 2016. | Eva M. Mockler |
| 2016 | CCT: A simple prioritisation tool for identifying critical source areas for managing water-borne pollutants. 8th International Congress on Environmental Modelling & Software, Toulouse, France, 10–14 July 2016. | Michael Bruen |
| 2016 | The Source Load Apportionment Model (SLAM): A framework to support the identification of appropriate WFD nutrient measures. Invited seminar, Agri-Food & Biosciences Institute (AFBI), Belfast, September 2016. | Eva M. Mockler |
| 2017 | What are the main sources of nutrient inputs to Ireland's aquatic environment? IAH, Tullamore, April 2017. | Eva M. Mockler |
| 2017 | Exploring the effects of regional development scenarios on nutrient emission: coupling land use model MOLAND with the Source Load Apportionment Model. 15th Computers in Urban Planning and Urban Management (CUPUM) Conference. | H. Shahumyan and Eva M. Mockler |
| **Conference posters** | | |
| 2014 | Rainfall, catchments, N & P: where models say our water will be. Catchment Science Summer School, Aberdeen. | Eva M. Mockler |
| 2015 | Quantifying conceptual hydrological flow paths across heterogeneous conditions using a tailored catchment model. EGU, Vienna. | Eva M. Mockler and M. Bruen |
| 2015 | The CatchmentTools Project. Catchment Science Conference, Wexford. | Eva M. Mockler, I. Packham, M. Archbold, J. Deakin, D. Daly and M. Bruen. |
| 2017 | Sources of nitrogen and phosphorus emissions to Irish rivers: estimates from the Source Load Apportionment Model (SLAM). EGU, Vienna. | Eva M. Mockler, Jenny Deakin, Marie Archbold, Donal Daly and Michael Bruen |
| **Public dissemination** | | |
| 2016 | Newsletter article – What's flowing into the Suir? Results from nutrient load apportionment modelling. | Eva M. Mockler |
| **Model deliverables** | | |
| 2017 | SLAM Toolbox (ArcGIS) | Eva M. Mockler |
| 2017 | SLAM documentation | Eva M. Mockler |

**AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL**
Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

## Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

**Rialú:** *Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

**Eolas:** *Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.*

**Tacaíocht:** *Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.*

## Ár bhFreagrachtaí

### Ceadúnú
Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:
- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha)*;
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

### Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil
- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

### Bainistíocht Uisce
- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

### Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol
- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil *(m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

### Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn
- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

### Taighde agus Forbairt Comhshaoil
- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

### Measúnacht Straitéiseach Timpeallachta
- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

### Cosaint Raideolaíoch
- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- 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 cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

### Treoir, Faisnéis Inrochtana agus Oideachas
- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol *(m.sh. Timpeall an Tí, léarscáileanna radóin)*.
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

### Múscailt Feasachta agus Athrú Iompraíochta
- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

### Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil
Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:
- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- Oifig um Chosaint Radaíochta agus Monatóireachta Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

# Catchment Management Support Tools for Characterisation and Evaluation of Programme of Measures

Authors: Eva M. Mockler and Michael Bruen

## Identifying Pressures

Nutrient enrichment and eutrophication can negatively impact freshwater ecosystems and estuarine and coastal waters. A load apportionment modelling framework was developed to characterise sources of phosphorus and nitrogen emissions to water at a range of spatial scales from sub-catchment to national. The resulting Source Load Apportionment Model (SLAM) quantifies nutrient losses from both point discharges (urban wastewater, industry and septic tank systems) and diffuse sources (pasture, arable, forestry, peatlands, etc.). Agriculture is the main source of nitrogen emissions to water across all regions of Ireland. The main sources of phosphorus are from wastewater and agriculture, with wide variations across the country related to local anthropogenic pressures (i.e. arising from human activity) and the hydrogeological setting. By synthesising large amounts of information, the SLAM framework predicted the dominant sources of nutrients at regional and local scales, contributing to the national nutrient risk assessment of Irish water bodies.

## Informing Policy

Results from this project informed the assessment of the 583 sub-catchments in Ireland within the national Water Framework Directive (WFD) characterisation process. These assessments were carried out by the EPA, with assistance from local authorities, Inland Fisheries, and other public bodies, to determine the significant pressures impacting water bodies that are At Risk of not meeting their WFD objectives. A significant pressure is one that is impacting Ireland's water quality in a particular water body, and which needs to be addressed before the water quality will improve. Determining which pressures are significant is important so that measures can be specifically targeted to achieve water quality improvements. The source apportionment results were interpreted by catchment scientists, along with the other national datasets including ecological status and trends in ecological and chemical monitoring data; information on land use, pressures, pathways and the sensitivity of receptors; licence, enforcement, audit and inspection information from regulatory agencies; and local, on-the-ground knowledge from the local authorities and fisheries agency staff.

## Developing Solutions

The data analysis tools and models developed for assessing nutrients in Irish catchments were used by catchment scientists to support the characterisation of nutrient sources, pathways and receptors in catchments. These tools will continue to be used to assess potential mitigation measures in that they provide capabilities for scenario analyses to support integrated catchment management in Ireland, including;

- local-scale scenario analyses to identify potential nutrient reduction options to achieve Good status in nutrient-impacted water bodies; and
- regional-scale scenario analyses to assess the impact of future projections of land cover and land use change, population increases and wastewater treatment improvements.

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