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Assessing Recent Trends in Nutrient Inputs to Estuarine Waters and Their Ecological Effect

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Comhshaol, Pobal agus Rialtas Áitiúil
Environment, Community and Local Government

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EPA Research Programme 2014–2020

Assessing Recent Trends in Nutrient Inputs to Estuarine Waters and Their Ecological Effect

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EPA Final Report

Prepared for the Environmental Protection Agency

by

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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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Executive Summary

Increases in the nutrient loads into estuarine and coastal systems have resulted in a concurrent biological response with an increase in the occurrence of micro- and macroalgal blooms. In fact, moderate changes in phytoplankton biomass and the frequency of blooms, due to nutrient enrichment, have contributed to over 20% of transitional waters being classed as having a less than “good” ecological status, as assessed under the European Union Water Framework Directive (WFD). At present, 36% of the Irish transitional waters and 67% of the coastal waters monitored have a “good” or “high” status; therefore, a large proportion of systems require improvement.

The main objective of this project was to trace the historic nitrogen (N) and phosphorus (P) flows from the source to the coastal zone not only to enable a determination of the effectiveness of recent mitigation measures, but also to enhance the current understanding of response trajectories. The results will assist with the future targeting of actions to be applied specifically in light of current and future programmes of measures in the context of European directives and regulations (e.g. the WFD and the Marine Strategy Framework Directive).

Load apportionment modelling indicated that, in most systems, the greatest overall contributors to N and P loads are diffuse sources. However, reductions in both diffuse and point sources have resulted in considerable reductions in P, highlighting the effectiveness of the measures that have been applied. Reductions in N loads have been more modest and are largely related to agricultural improvements. The more widespread reduction in riverine P inputs and the concurrent high and increasing N to P ratios, in both riverine inputs and estuarine systems, are indications of the imbalance of nutrient reduction, which may have deleterious impacts on the transport of nutrients to the outer coastal zone, even though estuarine ecosystem health may be improved.

The application of the Dynamic Combined Phytoplankton and Macroalgal (DCPM) box model to two Irish estuaries elucidated the importance of the hydrological regime in determining the growth of opportunistic green macroalgae in marine-dominated estuarine systems. Seasonal oscillations in monitored river flow rates can alter nutrient transfer from the catchment to the estuary, thus increasing the relative contribution of P from adjacent marine waters to estuarine systems. Load reduction scenarios indicated that, in such systems, P load reduction will result in a minimal impact on the macroalgal biomass of the system, while substantial N removal would be required before a biological response could be attained. The hydrological complexity of estuarine systems that has been demonstrated suggests that a portfolio of separate, but complementary, management approaches may be required to address eutrophication in these estuaries.

This study has shown that, in the Irish context, the impact of measures to reduce nutrient loadings is largely dependent on load source and input magnitude, as well as on nutrient cycling processes and modulating factors, such as light and residence time. The influence of measures, cycling and physical controls will evolve through the estuarine continuum from fresh to marine water, highlighting the need to consider the impact of measures on each river–estuarine system in the context of these control shifts.

Next page The top section of the infographic details the sources of the nutrient loads for 18 Irish catchments, as identified through load apportionment modelling, the measured reduction in riverine inputs and the corresponding changes in estuarine parameters between 2000 and 2013. The table at the bottom identifies the changes that have occurred in each individual estuarine and coastal system and the corresponding drivers of nutrient change.

TOP NUTRIENT LOAD SOURCES FROM THE 18 CATCHMENTS STUDIED

ARABLE	PASTURE	ADDITIONAL SOURCES	WASTEWATER TREATMENT PLANTS (WWTP)
Organic and inorganic fertiliser are applied to land used to grow crops	Organic and inorganic fertiliser are applied to land for animal grazing	Industrial waste, diffuse urban, domestic wastewater treatment plants, peat, forestry, deposition on water	Point sources of municipal waters
11% N – 2% P	**73% N – 28% P**	**8% N – 22% P**	**8% N – 48% P**

RIVERINE INPUTS

60% Reduction in **P** inputs from rivers to transitional and coastal systems from 2000 to 2013 in the catchments studied

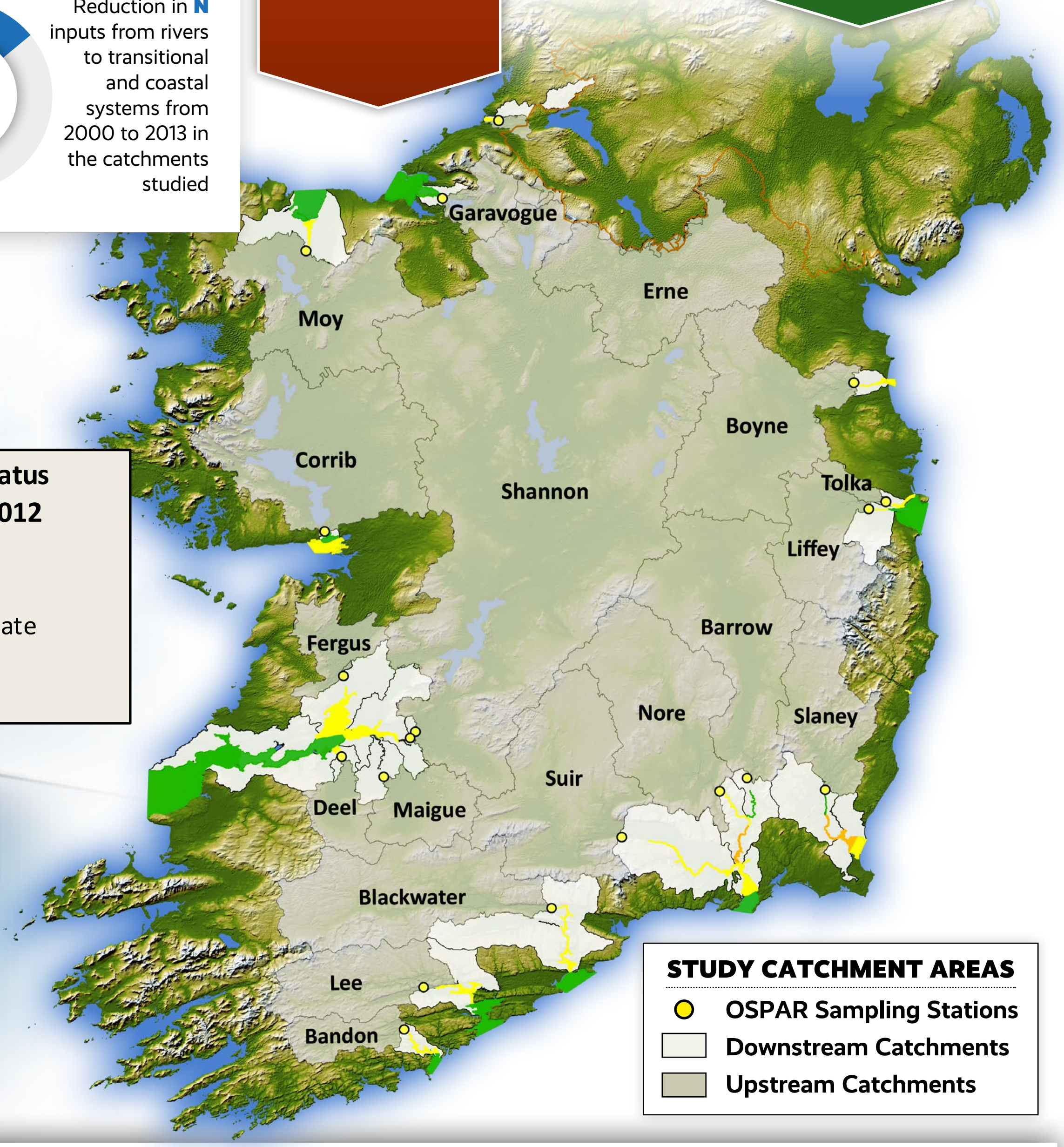
14% Reduction in **N** inputs from rivers to transitional and coastal systems from 2000 to 2013 in the catchments studied

ESTUARINE PARAMETERS

66% Reduction in MRP in transitional waters from 2000 to 2013 in the catchments studied

0% Reduction in DIN in transitional waters from 2000 to 2013 in the catchments studied

28% Reduction in chlorophyll in transitional waters from 2000 to 2013 in the catchments studied



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CATCHMENT →		BANDON	LEE	BLACKWATER	SUIR	BARROW/ NORE	SLANEY	LIFFEY	TOLKA	BOYNE	ERNE	GARAVOGUE	MOY	CORRIB	DEEL	MAIGUE	FERGUS	SHANNON
MAIN DRIVER OF NUTRIENT LOAD CHANGE	N	Arable	Pasture	Pasture	Pasture	Pasture	Pasture	WWTP	WWTP	Pasture	Pasture	Pasture	Pasture	Pasture	Pasture	Pasture	Pasture	Pasture
	P	Industry	WWTP	Pasture	Pasture	Pasture	Pasture	WWTP	WWTP	Pasture	Pasture	WWTP	Industry	Pasture	WWTP	Pasture	WWTP	Industry
RIVERINE INPUTS	N	↔	↔	↓	↔	↓	↔	↔	↓	↓	↔	↔	↔	↔	↔	↔	↔	↓
	P	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↔	↔	↓	↓	↓	↓
ESTUARINE NUTRIENTS	N	↑	↓	↔	↔	↓	↔	↑	↓	↔	↓	↓	↓	↓	↔	↔	↔	↔
	P	↑	↔	↓	↔	↓	↔	↓	↓	↑	↔	↔	↓	↓	↓	↔	↔	↔
ESTUARINE CHLOROPHYLL	C	↓	↓	↓	↔	↓	↔	↔	↑	↔	↔	↓	↓	↓	↓	↔	↔	↓

This infographic was produced as part of the EPA Research Report 184 (more information at: www.epa.ie)

1 General Introduction

1.1 Anthropogenic Pressures on Estuarine and Coastal Ecosystems

Anthropogenic activities related to agricultural, human and industrial waste, and land use changes have extensively altered global patterns of elemental cycling and increased flows of nitrogen (N) and phosphorus (P) from land to surface waters in the last few decades. While various elements can limit plant growth at a given place and time, the productivity of most aquatic ecosystems is controlled by the concentration, molecular form and stoichiometry of these two macronutrients (Butcher, 1947; Officer and Ryther, 1980). Thus, knowledge of the sources of N and P, and their consequential impacts on surface water recipients and biological elements, is essential for our understanding of ecosystem responses to anthropogenic pressures.

Nutrients from land transit through the continuum formed by soils, groundwater, rivers, lakes, estuaries and coastal marine areas, and impact on each system in succession. The magnitude of the deleterious impact on surface waters is determined by a number of modulating factors, such as flow regimes, temperature, precipitation, connectivity with adjacent systems and hydrological regimes (Bouman *et al*., 2013). In turn, the level of nutrient assimilation by biological components, coupled with biochemical nutrient cycling, will act to retain or transform a significant fraction of the nutrients transported into a system (Billen *et al*., 1991). Nutrient pressures, through their influence on the building blocks of aquatic systems, namely primary producers, can alter and shape food webs and thus strongly determine ecosystem structure (Borum and Sand-Jensen, 1996; Nielsen and Richardson, 1996).

Currently, eutrophication negatively affects rivers, lakes and estuaries worldwide, and accounts for the foremost aquatic ecosystem management problem (Selman and Greenhalgh, 2009). Eutrophication is expressed through the development of phytoplankton blooms, which can be harmful, the development of macroalgal blooms, a reduction in oxygen levels through the water column and, as previously mentioned, alterations to upper trophic levels.

In Ireland, blanket mitigation measures have been applied to reduce nutrient losses from agriculture, domestic municipal waste water and industrial sources. Small-scale studies have indicated that these measures have led to a decrease in nutrient loadings to some surface water systems (Greene *et al*., 2011; O'Dwyer *et al*., 2013). However, the reduction in the transport of nutrients from sources to surface waters after mitigation measures is expected to vary depending on catchment characteristics, including forestry cover, agriculture and the degree of urbanisation. Furthermore, natural factors, such as geology, soils, climate and hydrology, will largely determine background water quality and the legacy accumulation of anthropogenic nutrients in soils (Jordan *et al*., 2012; Taylor *et al*., 2012; Vermaat *et al*., 2012).

The specific response of estuarine and coastal systems to decreases in diffuse and point source loads can also differ greatly because of their inherent chemical, biological and physical gradients, and complex biogeochemical cycles. Estuaries can act as a source of nutrients, especially P (Deborde *et al*., 2007; Van Der Zee *et al*., 2007) and silica (Legovic *et al*., 1996; Cabeçadas *et al*., 1999), as a result of organic material recycling and the desorption and diffusion of P from sediment pore waters during early diagenesis (Deborde *et al*., 2008; Delgard *et al*., 2012). In addition, estuaries may act as a sink or a source of N depending on the nitrification–denitrification and ammonification–anammox balances (Abril *et al*., 2000; Garnier *et al*., 2006; Seitzinger *et al*., 2006). Finally, biological assimilation can also act to filter nutrients as they pass through the estuarine system; with the reduction of limiting nutrients, such as P, this filter can be reduced, leading, in some cases, to an export of N to adjacent marine systems (Paerl *et al*., 2004).

1.2 The Response of Primary Producers to Anthropogenic Pressures

High levels of nutrient availability increase the growth of algal biomass and often result in a shift in the dominant primary producer, for example from seagrass-dominated systems to the faster growing and, more importantly, bloom-forming, opportunistic macroalgae and/or phytoplankton (Coutinho *et al*., 2012). Phytoplankton are recognised as sensitive biological indicators of anthropogenic pressure and, in particular, chlorophyll concentrations are used worldwide as a proxy for biomass (Lacouture *et al*., 2006). However, the use of taxonomic composition and structure combined with chlorophyll concentrations, as required by the Water Framework Directive (WFD), provide a better understanding of the implications of anthropogenic forcings on transitional and coastal waters (Brito *et al*., 2012).

A further consequence of excess nutrient loading is an increase in the frequency of phytoplankton blooms. Blooms occur if biomass levels are outside what is considered the normal range for a given area (Carstensen *et al*., 2004). In particular, the frequencies of harmful algal blooms of species that are considered toxic have been increasing worldwide (Van Dolah, 2000). Some of these species are considered a serious health risk to humans and can have important impacts on shellfish production.

The magnitude of the response to nutrient availability, and the type of algae that react, will depend largely on physical and biological constraints, such as light, residence time, grazing and ocean exchange (Cloern, 2001; Carstensen *et al*., 2011; O'Boyle *et al*., 2015). For example, the proliferation of fast-growing opportunistic macroalgae can often be a result of hydrological regimes, such as short residence times, which do not allow enough time for the growth of large phytoplankton blooms and also result in the flushing of phytoplankton to adjacent coastal waters with each tidal cycle. This, coupled with the preference for sheltered sites and ideal sediment conditions, can lead to the proliferation of large seasonal macroalgal mats. Their areal extent and density can also result in the displacement of other species, a reduction in biodiversity and large oscillations in dissolved oxygen (DO).

Therefore, understanding the interaction between anthropogenic pressures and primary producers, in the context of mediating factors, is an essential precursor to planning remediation measures and understanding recovery rates. This will assist in the development of approaches that incorporate ecological principles into management and restoration activities (Stanley *et al*., 2010).

1.3 Estuarine Status in the Irish Context

Irish transitional and coastal systems represent a combined area of over 14,000 km^2. According to the most recent assessment (2010–2012) undertaken by the Environmental Protection Agency (EPA), 36.3% of Irish transitional waters are considered to have a "high" or "good" ecological status, while 67.4% of coastal waters have a "high" or "good" status (EPA, 2015). In terms of area, this means that 45% of the area of transitional waters and 93.6% of coastal waters are considered of "good" to "high" status.

The ecological status of transitional and coastal systems, as determined by the WFD, is based on specified biological [phytoplankton, benthic invertebrates, macroalgae, angiosperms (seagrass and saltmarsh) and fish (transitional waters only)] and physico-chemical (DO, inorganic N, P and specific pollutants) quality elements, and an assessment of hydromorphological alterations. Ecological status is classified into five categories ("high", "good", "moderate", "poor" and "bad"), which are defined by the degree of deviation from a reference condition. Biological elements that are sensitive to anthropogenic forcings, such as fish, phytoplankton and marine macrophytes, are often responsible for a moderate classification or worse in transitional waters. In the case of coastal waters, it is often benthic invertebrates and DO that are the main causes of a reduced status classification.

The main environmental objectives for transitional and coastal waters in Ireland are "to restore those waters which are at less than good ecological status and to protect those waters which are at high or good ecological status" (EPA, 2015). In order to meet these objectives, a concise understanding of the functioning of these waters must be coupled with the successful implementation of the measures that will result in their successful achievement.

1.4 Drivers for Estuarine Management

The modification of the natural supply of nutrients from rivers into transitional and coastal systems in the last few decades and the consequential degradation of surface water systems at a European level have resulted in the development of various platforms, such as the European Union (EU) WFD (2000/60/EC;

EC, 2000), the Marine Strategy Framework Directive (MSFD; 2008/56/EC; EC, 2008) and the Oslo–Paris Convention for the Protection of the North-East Atlantic (OSPAR), which are aimed at assessing, and setting targets for the improvement of, ecological and environmental status. OSPAR has provided a quantitative dataset of loadings from rivers to transitional and coastal waters for the last 25 years. The initial analysis suggests decreasing trends in many of these systems, which indicates a potential reduction in nutrient loads. These improvements are more than likely the result of blanket mitigation measures, applied to reduce nutrient losses from agricultural, domestic and industrial sources under the Nitrates Directive (91/676/EEC; EC, 1991b), the Urban Waste Water Treatment Directive (91/271/EEC; EC, 1991a), the Water Quality Standards for Phosphorus Regulations [Statutory Instrument (S.I.) No. 258/1998; Government of Ireland, 1998] and the Good Agricultural Practice Regulations (S.I. No. 101/2009; Government of Ireland, 2009).

While blanket measures can be effective, the selection of future measures for estuarine and coastal waters should be based on a well-developed understanding of (1) the effectiveness of previous measures and (2) how pressures interact with environmental and physical factors and impact on biological receptors. This will require a multidisciplinary approach that examines the interaction between the disturbance of biogeochemical cycles, the resultant fluxes to surface water systems and the impact on biological processes. Observational monitoring and time series, are not only required for reporting purposes, but are also essential tools for detecting, measuring and understanding these interactions and responses.

In Ireland, monitoring programmes over the last two to three decades have provided a database of information which can be synthesised to elucidate the influence of nutrient reduction measures on river inputs to transitional and coastal waters. Concurrently, it can provide a means of determining not only the changes in estuarine systems, but also their connectivity to pollutants emanating from land-based anthropogenic activities. Ultimately, these long-term datasets are important resources for augmenting our understanding of the mechanisms that mediate ecosystem restoration (Cloern *et al*., 2015). Linking and understanding oscillations and trends in water quality through an analysis of these parameters will in turn inform future national policy decisions and provide a background for understanding the possible implications of future scenarios of climate change and/or increased anthropogenic pressures relating to growth in population, industry or agriculture. This is particularly relevant in the context of future demands for food production and strategic national plans, such as Food Harvest 2020 and Food Wise 2025.

1.5 Overall Aims of this Research

The main objectives of this project were to identify trends in nutrient concentrations in Irish estuarine and coastal waters, and to investigate their implications for the ecological status of these ecosystems. The analysis of historical datasets and the identification of the responses of ecosystems to changes in nutrient loadings should inform future decisions in the context of EU directives (the WFD, MSFD and Nitrates Directive). The project includes four main objectives:

- to collate and perform a detailed assessment of environmental, physico-chemical and biological data, and organise these data into accessible database format;
- to interpret trends and the relationship between specific factors (environmental, physico-chemical and biological); and to assess the ecological influence of tighter controls on nutrient inputs, and identify cumulative effects and loading thresholds;
- to identify susceptible and key ecosystems that require more extensive monitoring and/or nutrient control;
- to develop a tool for forecasting potential symptoms in the event of changing loading inputs and waste water treatment; and to identify recommendations and appropriate measures for the future improvement of water quality in general and for site-specific situations.

2 Linking Nutrient Load Apportionment, River Nutrient Input Trends and Estuarine Consequences

2.1 Overview

Anthropogenic pressures have led to problems of nutrient over-enrichment and eutrophication in estuarine and coastal systems in the Irish environment. Since 1998, a number of EU Directives have been implemented in Ireland resulting in significant measures to curtail nutrient losses and improve water quality. A load apportionment model (LAM) coupled with multidecadal monitoring of nutrient inputs from rivers to estuaries allow for a comparison between the effectiveness of these measures and trends in nutrient delivery to estuarine and coastal waters. Concurrent monitoring of biological and chemical parameters in estuarine and coastal systems promotes an understanding of the response of systems to changes in nutrient loads (Figure 2.1).

The Blackwater Estuary, which drains a large agricultural catchment on the south coast of Ireland, was chosen as a first case study to assess the links among alterations in nutrient loads, river inputs and changes in estuarine conditions in 1990, 2000 and 2010.

The objectives of this study were to (1) determine whether or not decreases in overall loads and changes in load apportionment to the estuarine catchment have occurred in the last 20 years; (2) examine potential links among trends in calculated catchment nutrient loads, measured river loads and downstream estuarine concentrations; (3) determine the impacts of any changes in physico-chemical and biological parameters within the estuarine system; and (4) identify the measures that have been most effective in reducing nutrient loss from the catchment to the estuary. The results of this work have been published in the journal *Science of the Total Environment*, which is available as open access (Ní Longphuirt *et al.*, 2015a).

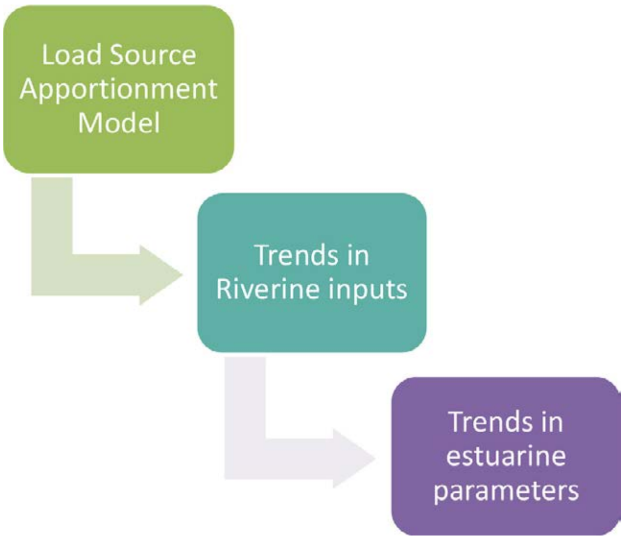

Figure 2.1. Schematic of the analysis pathway for identifying the impact of nutrient loads on estuarine functioning.

In addition to this, a data-driven analysis and narrative of the trends in nutrient load apportionment from 18 Irish catchments, the concurrent trends in measured riverine loads and the responses of downstream estuarine water bodies over a 14-year period (2000–2013) are also presented. We attempt to disentangle the biophysical and chemical factors that constrain or maintain the status of Irish estuarine water bodies and identify systems in which mitigation measures that relate to diffuse or point sources have resulted in an improvement in water quality. This national study is being prepared for a special issue of *Biology and Environment: Proceedings of the Royal Irish Academy*.

These analyses have provided a context for the identification of the nutrient sources that drive water quality in estuarine systems at a catchment scale and the shift in sources since the introduction of national measures to improve water quality. Furthermore, they will allow an understanding of the possible timing and direction of estuarine system responses to load oscillations through multidecadal timescales. Therefore, this study will assist and inform management decisions related to the targeting and prioritising of mitigation measures.

2.2 Methods

2.2.1 Load apportionment modelling

Load apportionment modelling provides a challenge in that the complexity of the model is limited by the availability of the data and knowledge of specific processes.

Data relating to diffuse and, indeed, point sources of nutrients have, historically, been sparse; however, the greater focus on reporting and the creation of extensive databases recently means that LAMs will continue to improve.

The quantification of nutrient load apportionment to the Blackwater catchment was based on historic reporting procedures, which were undertaken to comply with requirements under OSPAR. In order to identify trends, load calculations were undertaken for 1990, 2000 and 2010.

These years were chosen because the largest body of information was available for this period. A detailed account of load calculations for diffuse sources (inorganic and organic fertilisers, land use and unsewered populations) and point sources [waste water treatment plants (WWTPs) and industry] of nutrients is given in Ní Longphuirt *et al.* (2015a). In cases for which actual datasets of point discharges and pathway processes were unavailable, coefficients have been applied based on commonly agreed methods and previously measured rates (O'Sullivan, 2002; OSPAR, 2011).

In the national study, the determination of load apportionment involved the use of a newly developed LAM (Mockler *et al*., submitted). While the 2000 dataset allowed the use of the method undertaken in the Blackwater study, the more comprehensive 2013 dataset allowed for a more extensive analysis. A detailed account of these additional calculations can be found in Mockler *et al*. (submitted).

2.2.2 Trends in riverine inputs

Water samples were collected monthly from the 18 rivers by the EPA and analysed to give monthly nutrient concentration data for total phosphorus (TP), molybdate reactive phosphorus (MRP), total nitrogen (TN), total oxidised nitrogen (TON) and ammonia (NH_3). Nutrient concentrations were measured in accordance with *Standard Methods for the Examination of Water and Wastewater* (APHA *et al*., 2005). These data were combined with instantaneous flow data to produce a flow-weighted mean concentration (FWMC) value for each nutrient. The nutrient input of each specific nutrient transported by a river was estimated by taking the product of the FWMC divided by the total flow.

The annual input (in tonnes/year) for each parameter was then calculated by multiplying the FWMC by the annual mass flow for each river and dividing by an annual mass flow normalisation factor to remove the effects of oscillations in flow, and hence rainfall/weather conditions, and allow comparison with the load source apportionment. Nutrient inputs for the River Shannon were measured at Ardnacrusha and the Parteen Weir, as the river splits into two sections at this point. These inputs are reported as Shannon OC (old channel) and Shannon TR (trail race), respectively.

2.2.3 Trends in estuarine parameters

The EPA has been monitoring Irish estuarine systems on a seasonal winter–summer basis since the 1980s. A number of monitoring sites in each of the estuaries were sampled yearly: once in the winter and three times during the productive period between May and September. Samples for the analysis of total chlorophyll and nutrients were collected using 2-litre Hydro-Bios Ruttner bottles at the surface and 0.5 m from the bottom. DO saturation, together with temperature, salinity and depth, were recorded using a Hydrolab DataSond. Chlorophyll pigments were analysed using 'Hot Methanol' protocols from the Standing Committee of Analysts (1980). NH_3, TON and MRP were measured as for the river samples. Water transparency at each station was measured using a 25-cm diameter Secchi disc. Dissolved inorganic nitrogen (DIN) is reported as the sum of TON and NH_3.

2.2.4 Statistical trend analysis

Temporal trends in both river loads and physiochemical parameters in each estuary were undertaken using non-parametric seasonal Mann–Kendall tests (Hirsch *et al*., 1991) using the R Platform and TTAinterface Trend Analysis package (R TTA) (Devreker and Lefebvre, 2014). The river load data were analysed as an overall annual trend. However, this tool also allows the identification of temporal trends while taking into consideration seasonal variations; thus, it considers the trends within individual months (except all data for January) before combining the trends to give an overall annual trend. In the case of the Blackwater riverine inputs and the estuarine data from all systems, seasonal trends were analysed in this manner for each of the parameters tested to account for the relative importance of seasonality and weather conditions (e.g. storm events and rainfall) on nutrient concentration in the estuary. In the Blackwater Estuary, for which DIN showed a linear regression with salinity (suggesting a conservative relationship between these two parameters), mixing diagrams were also used to examine the trend in DIN normalised for salinity in the outer coastal zone (which has a salinity of 34). All trends were considered significant at a *P*-value of lower than 0.05.

2.3 Results

2.3.1 A case study of the Blackwater system

The calculated nutrient LAM for the Blackwater catchment shows a decoupling of the reduction patterns for N and P between 1990 and 2010 (Table 2.1). A slight (2%) increase in N load estimations between 1990 and 2000 is evident, followed by an 18% decrease between 2000 and 2010. In comparison, P loadings were reduced by 9% between 1990 and 2000, and by a further 20% between 2000 and 2010. The load reductions and relative decreases were considered to be in line with European observations (Bouraoui and Grizzetti, 2011; Windolf *et al.*, 2012).

The reductions are likely to be largely related to decreases in diffuse agricultural loadings to the catchment and coincided with a dramatic decrease in inorganic fertiliser application rates, which decreased by 30% and 53% for N and P, respectively, between 2000 and 2010 (Table 2.1). The second most important factor contributing to these reductions emanates from a decrease in nutrients from sheep, as the number of sheep decreased from 205,104 in 1990 to 65,120 in 2010.

The number of cattle remained stable over the two decades between 1990 and 2010, at 741,457 ± 1807; cattle were the main source of diffuse organic nutrient loadings in this catchment, and, after inorganic fertiliser use, were the second largest source of overall loadings to the catchment.

Substantial improvements in the treatment of domestic waste water have been achieved throughout the catchment, and the percentage of households connected to municipal WWTPs has increased greatly. This improved level of treatment has, however, been offset by a 50% increase in the population over the period of this study. As a consequence, nutrients emanating from domestic sources have remained relatively stable over the 20 years between 1990 and 2010.

Significant downwards trends in measured river inputs to the estuary were found for TN, TON, TP and MRP from 2000 to 2010, while no change in either N or P levels is evident before 2000 (Table 2.2). A more detailed analysis of the trends for the 2000–2010 period revealed that if aggregated for the summer period only, no significant trends are evident. However, for winter periods, statistically significant downwards trends are apparent for TN, TON, TP and MRP inputs.

The molar ratio of TN to TP in river inputs showed contrasting trends for these two decades. While the TN to TP ratio decreased slightly between 1990 and 2000, there was a strong increase from 2000 to 2010, which was again only present in winter. This reflects the stronger downwards trend in P relative to N inputs.

Table 2.1. Calculated nutrient load source apportionment for the Blackwater Estuary

	N (tonnes/year)			P (tonnes/year)		
Nutrient	**1990**	**2000**	**2010**	**1990**	**2000**	**2010**
Organic fertiliser	5829	5635	5278	172	167	155
Inorganic fertiliser	5327	5729	3983	148	118	55
Unsewered rural pop	113	107	87	12	11	9
WWTP	78	83	110	21	23	25
Forestry	122	119	103	7	7	6
Woodland/woodland scrub	46	59	78	7	9	12
Peatlands	13	10	9	2	2	2
Urban areas	9	10	11	2	2	3
Background losses	265	260	254	17	17	17
Total loadings	11,537	11,753	9659	372	339	267

Organic fertiliser relates to manure production from cattle and sheep.
Pop, population.

Table 2.2. Results of seasonal Mann–Kendall statistical analysis of trends in nutrient inputs from the Blackwater River to the estuary

		1990–2000		2000–2010					
		Annual trend		Annual trend		Summer trend		Winter trend	
Parameter	Slope units	Agg method	Sen's slope	Agg method	Sen's slope	Agg method	Sen's slope	Agg method	Sen's slope
TN	T/Y	90th percentile	171.46	Max	**–79.58[b]**	90th percentile	–53.14	Max	**–76.48[a]**
NH_3	T/Y	90th percentile	0.14	Mean	–0.10	Median	0.25	90th percentile	–0.26
TON	T/Y	90th percentile	43.60	90th percentile	**–65.16[a]**	90th percentile	–34.62	90th percentile	**–72.01[a]**
TP	T/Y	Mean	1.44	90th percentile	**–2.27[c]**	Median	–2.57	90th percentile	**–2.62[c]**
MRP	T/Y	Median	0.11	90th percentile	**–1.02[b]**	Median	–1.93	90th percentile	**–1.26[b]**
Flow	m^2/s	Max	**5.55[a]**	90th percentile	1.96	Median	–6.25	90th percentile	–3.81
N:P	NU	Mean	**–5.76[b]**	Median	**17.14[c]**	Median	8.75	Mean	**17.02[c]**

The method of monthly aggregation of data was determined by the TTAinterface R package through the use of ANOVA to determine the best relationship fit between the possible aggregation methods and the data. The 2000–2010 dataset was also analysed separately for summer and winter trends. Statistically significant trends are highlighted in bold.

[a]$P<0.05$.

[b]$P<0.01$.

[c]$P<0.01$.

Agg, aggregation; max, maximum; N:P, N to P ratio; NU, no unit; T/Y, tonnes/year.

Estuarine parameters revealed varying responses to the decrease in nutrient inputs. Significant downwards trends in MRP concentrations are evident in 10 out of 18 stations for the 1992–2010 period. If the data for the two decades are analysed separately, no significant changes are apparent between 1992 and 2000, while significant trends are evident in six stations for the 2000–2010 period (Figure 2.2). No significant trends were identified in DIN concentrations for any of the estuarine stations. However, mixing diagrams

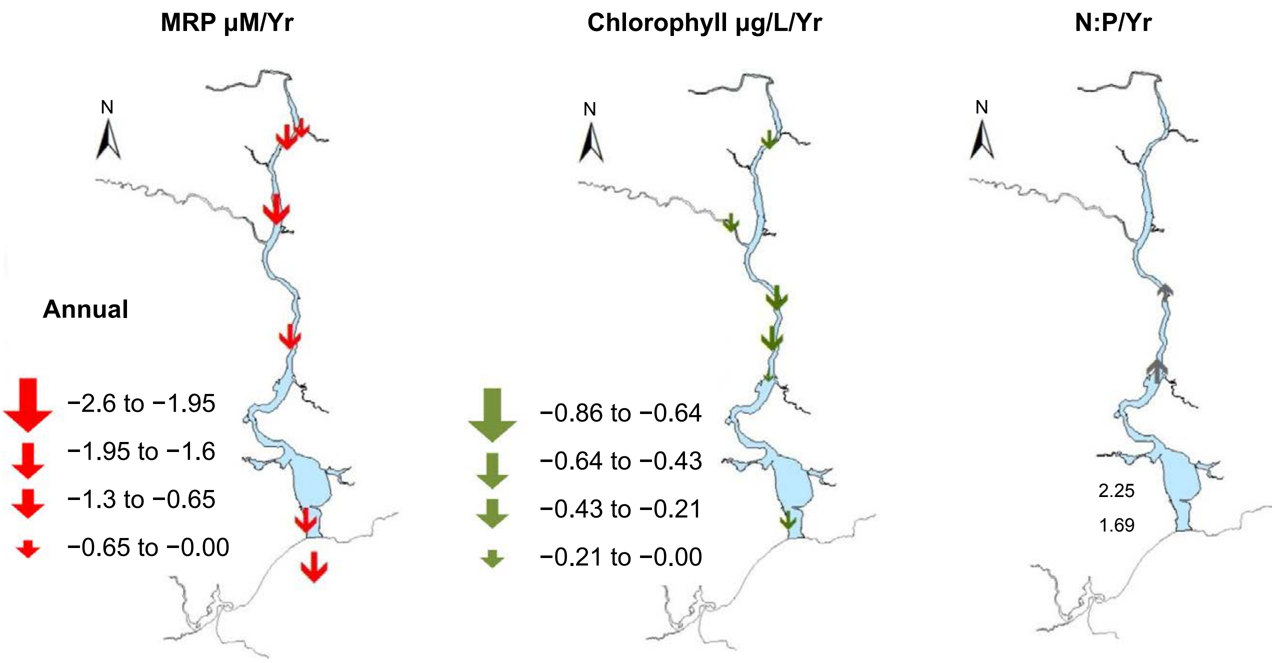

Figure 2.2. Statistically significant trends in MRP, chlorophyll and the N to P ratio (N:P) for the 2000–2010 period.

(which consider that salinity versus DIN has a constant linear relationship) used to analyse overall annual trends revealed an increase in DIN between 2000 and 2010, if normalised to a salinity of 34 (Sen's slope trend = 0.0206 µmol/L per year, $P = 0.007$). This signified a 22% increase which, if applied to the data, results in an increase from 2.17 ± 1.4 µmol/L (average for the 1999–2001 period) to 2.65 µmol/L.

At all times, the N to P (N:P) ratios remained above 16, suggesting that P was the limiting nutrient in the system throughout the monitoring period. A significant increase in the N:P ratio was evident for two of the stations monitored between 1992 and 2010 and between 2000 and 2010. The concentration of chlorophyll, a proxy for phytoplankton biomass in the water column, significantly decreased annually in six stations across the Blackwater Estuary.

2.3.2 *Linking changes in nutrient load apportionment to estuarine responses: an Irish perspective*

The Blackwater case study was extended to include 18 additional catchments and to provide a more national indication of the change in nutrient loads, riverine inputs and estuarine parameters. The study focused on a shorter timescale (2000–2013) that encompassed the timeframe within which the majority of directives, Irish regulations and associated measures were put in place. The results highlight the varying responses in estuarine systems to load reductions.

In the 18 catchments studied, N emanated mainly from diffuse sources in both 2000 (90%) and 2013 (92%) (Figure 2.3). However, diffuse N sources were less important in catchments with large agglomerations (e.g. Liffey). By contrast, diffuse sources represented less

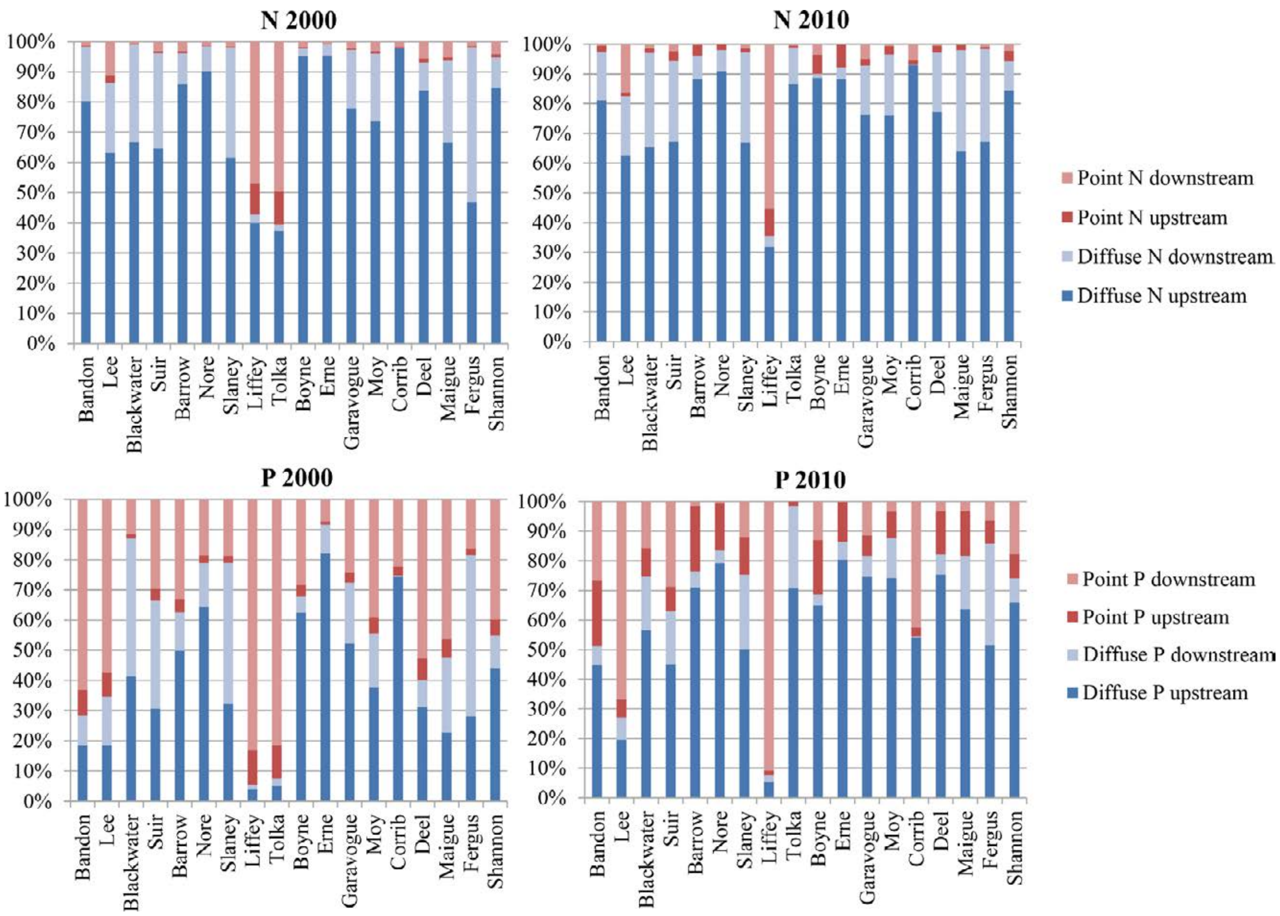

Figure 2.3. Calculated nutrient load source apportionment for the 18 catchments studied. 'Point N' and 'Point P' refer to the point sources of these nutrients (i.e. WWTPs and industry) that enter the estuarine system. 'Diffuse N' and 'Diffuse P' refer to the sources of these nutrients from agriculture, septic tanks, runoff and atmospheric deposition. 'Upstream' sources are those upstream of the station at which river loads to the estuary are calculated (above zero salinity), while 'downstream' sources refer to those that are downstream of this point up to the coastal zone.

than 58% (in 2000) or 70% (in 2010) of all P entering estuarine waters. There was a large variability in the importance of diffuse P to individual estuarine systems in 2000, with diffuse sources ranging from 5% to 92% of all P sources (Figure 2.3). In 2010, the importance of diffuse P sources increased in most systems, reflecting the magnitude of the decrease in point P sources which was more than that of the decrease in diffuse sources. Catchments with large point P sources were, in general, linked to large agglomerations, as observed for N (Figure 2.3).

The separation between up- and downstream sources highlights the importance of nutrient transport from the catchment directly encompassing the estuarine system. Specifically, in the case of point sources, downstream sources make up a large proportion of the downstream load because large agglomerations and industry are located close to the river mouth (e.g. Liffey, Lee and Tolka). In the case of diffuse sources, the relative influence of downstream sources is often dependent on the size of the catchment up- and downstream, and the length of the estuarine system.

The LAM indicates that absolute point sources of N and P decreased by 7% and 5%, respectively, between 2000 and 2010 for all the catchments studied. Concurrently, the modelled diffuse sources of N and P decreased by 30% and 37%, respectively. On average, agriculture represented 94% and 89% of the diffuse N load in 2000 and 2010, respectively, and was split between pasture (95% in 2000; 88% in 2010) and arable (5% in 2000; 12% in 2010) land. With regard to P, the importance of agriculture to diffuse sources was lower than for N: agriculture represented 63% and 59% of the diffuse P load in 2000 and 2010, respectively. However, unlike for N, the relative amounts from pasture (90%) and arable (10%) land were equal for both years.

The importance of loads from WWTPs to point sources remained stable for N and P for both 2000 and 2010 (ranging from 78 to 86%), reflecting the stable ratio between waste water from domestic and industrial sources, and the concurrent decrease in both sectors in the 10-year period.

The N:P ratio of the LAM to all catchments increased between 2000 and 2010 (with the exception of the Garavogue), from an average ratio of 35.2 in 2000 to 58.9 in 2010. An analysis of the data indicated that for both 2000 and 2010 the N:P load ratio was strongly linked to the importance of agriculture for the TN load in the 18 catchments (Figure 2.4). The relationship between these two factors changed between 2000 and 2010, reflecting the higher N:P load emanating from agriculture in 2010 (Table 2.3). The same relationship

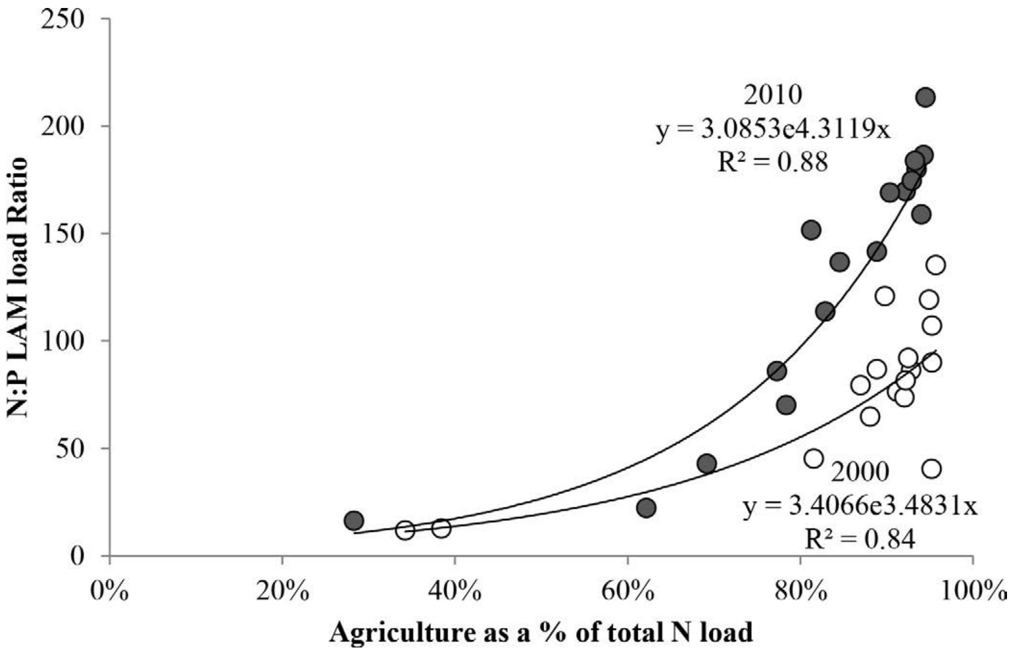

Figure 2.4. Relationship between the importance of agriculture to the overall load of the catchment and the N:P load ratio, as determined by a LAM. Grey dots represent 2010 data, while white dots represent 2000 data.

Table 2.3. N:P ratios for nutrients emanating from agriculture, WWTPs and industrial waste. An increase in the focus on P resulted in an increase in N:P ratios from all sectors

	N:P ratio	
Sector	**2000**	**2010**
Agriculture	170 ± 92	289 ± 189
WWTP	10 ± 4	23 ± 15
Industrial waste	10 ± 7	44 ± 65

was not true for P; this suggests that the agricultural N load apportionment was the driving force behind the N:P ratios of the nutrient loads.

Reductions (or increases in the case of Cork and Bandon) in LAM N loadings were mainly due to diffuse source load oscillations (Table 2.4). An exception was the Tolka catchment which showed an almost complete removal of point source loads. In the case of P, the split was catchment dependent: nine catchments exhibited a reduction in P that was related to point sources, and for eight catchments, P decreases were mainly caused by reductions in diffuse sources. In the case of one catchment, the Barrow, diffuse and point source reductions had an equal impact on the overall calculated load reduction.

Nationally, measured nutrient inputs to estuarine systems from upstream rivers significantly decreased between 2000 and 2013 (Figure 2.5). Reductions in P (TP or MRP) were observed in 15 of the 18 catchments studied, and most rivers showed consistent decreases in TP and MRP from 2005 onwards. In the systems that showed a significant trend, the reductions resulted in a 48% decrease in TP in the 14-year period of study (on the basis of an average of the data from the 2000–2002 and 2011–2013 periods). The largest significant decreases in TP and MRP (in kg P/km^2 per year) were recorded for the Maigue Estuary followed by the neighbouring Deel, the Tolka and the Blackwater. Two systems (the Moy and the Corrib) did not show any significant decreases in either TP or MRP.

Reductions in N inputs were identified in only four of the catchments studied, with improvements again evident from c. 2005 onwards in a number of systems (data not shown). Within these four catchments, the average decrease in TN was approximately half of that observed for MRP (24%). Improvements in N inputs were always associated with concurrent improvements in P load. Significant reductions in NH_3 inputs were evident in six systems and indicate reductions in organic sources of N to the systems (Figure 2.5). As a result of the disparity between the N and P inputs, there was a statistically significant increase in the TN to TP and/or the MRP:TON input ratios in five of the catchments studied (Figure 2.5).

The response time with regard to reducing P inputs was almost immediate in six of the estuarine systems, with significant decreases in estuarine MRP corresponding to decreases in upstream inputs and concentrations (Figure 2.6). However, there was a decrease in estuarine MRP without a corresponding reduction in riverine inputs in two other systems (Moy and Corrib). These results, combined with the LAM results (Table 2.4), suggest that, within these systems, large reductions in downstream point sources are more likely to have caused the decrease in P than inputs from the upstream catchment. MRP concentrations increased in two catchments (Bandon and Boyne) in the polyhaline zones of the systems. In both cases, inputs of MRP from the upstream river had decreased; this, again, indicates that more localised sources of P were probably more important with regard to influencing the nutrient trends. Of the estuarine systems encompassed by this study, only four had a "moderate" status as a result of high MRP concentrations and three of these (Liffey, Tolka and Deel) showed significant decreasing MRP trends, while one (Maigue) exhibited a non-significant, decreasing trend.

Only six estuaries had a decreasing trend for DIN and two (Liffey and Bandon) had increasing trends. Decreasing N inputs and associated improvements in the downstream estuary were only evident for one system, the Tolka. The Blackwater, Boyne, Barrow–Nore and Shannon estuaries showed no significant changes in estuarine conditions, even with a decrease in riverine N inputs, highlighting the complexity of nutrient cycling in estuarine systems. DIN concentrations are not considered a parameter in the WFD classification of transitional water bodies of less than 30 salinity. However, 5 out of the 18 systems studied had DIN concentrations that exceeded the good–moderate assessment boundary. Of these, both the Liffey and Bandon estuaries exhibited increases in DIN.

Estuarine chlorophyll concentrations decreased in eight of the estuarine systems studied, and this can be linked,

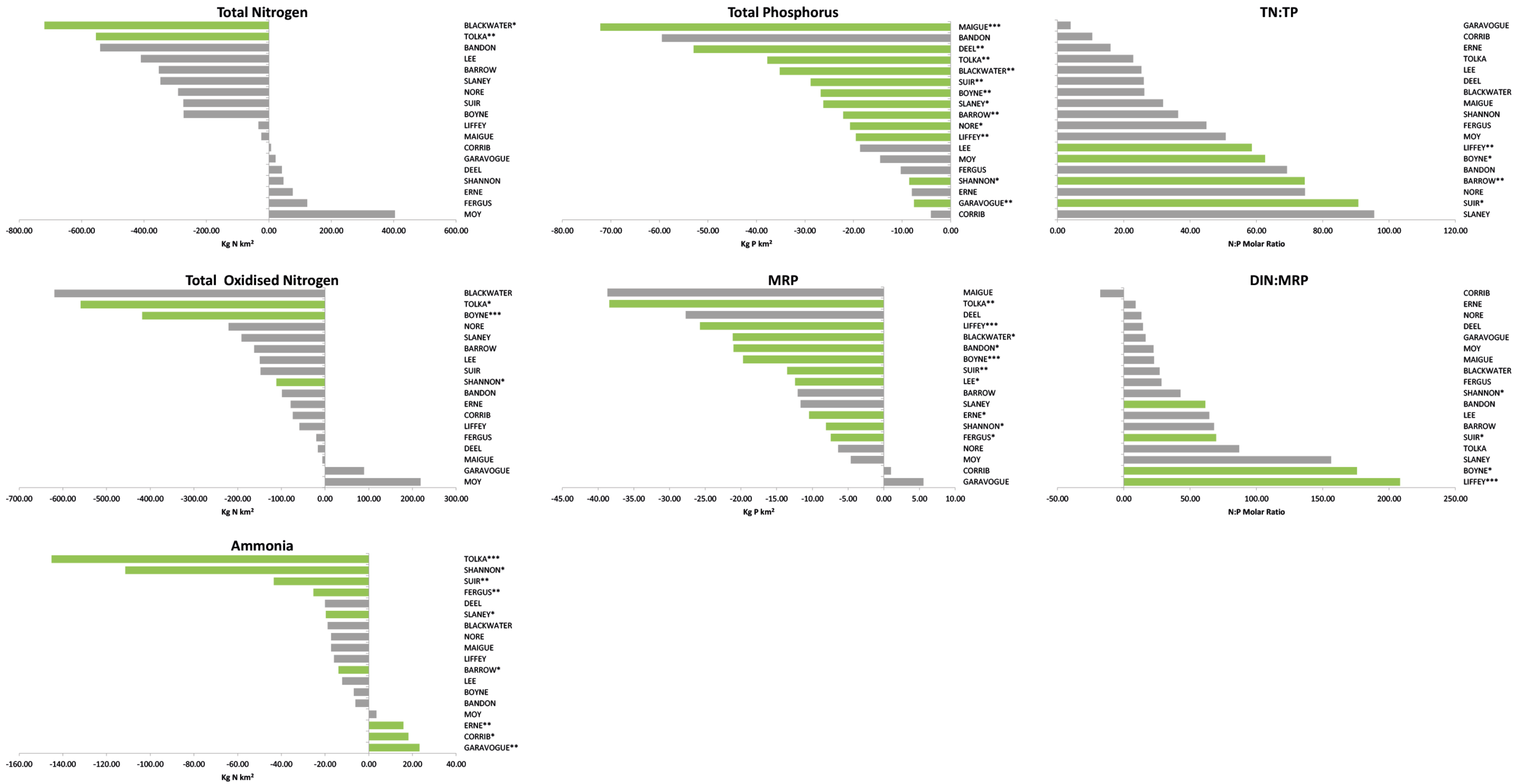

Figure 2.5. Relative nutrient load reduction between 2000 and 2002, and 2011 and 2013 in the 18 catchments studied. Green bars represent reductions found to be statistically significant (Mann–Kendall Trend Analysis), while the level of significance is denoted as follows: *$P<0.05$, **$P<0.01$, ***$P<0.001$.

Table 2.4. Synopsis of the trends in load apportionment (not statistically tested), riverine nutrient inputs and estuarine parameters for the 18 catchments studied

Catchment	LAM trends, % change in source (change relative to overall model change is shown in brackets)				LAM trends, % change in source (change relative to overall model change is shown in brackets)				Riverine input trends (2000–2013)				Water body	Estuarine trends		
	N 2010 greatest contributor	Overall decrease	N diffuse	N direct	P 2010 greatest contributor	Overall decrease	P diffuse	P direct	TN	DIN	TP	MRP		DIN	MRP	Chl
Bandon	Diffuse downstream	12%	11% (90%)	73% (10%)	Diffuse upstream	–76%	–56% (–21%)	–83% (–79%)					Mesohaline			
													Polyhaline			
													Mixoeuhaline			
Cork	Diffuse upstream	17%	11% (59%)	48% (41%)	Point downstream	–39%	–52% (–47%)	–31% (–53%)					Mesohaline			
													Polyhaline			
													Mixoeuhaline			
Blackwater	Diffuse upstream	–17%	–19% (–100%)	161%	Diffuse upstream	–48%	–55% (–100%)	2%					Mesohaline			
													Polyhaline			
													Mixoeuhaline			
Suir	Diffuse upstream	–23%	–24% (–100%)	13%	Diffuse upstream	–53%	–55% (–70%)	–48% (–30%)					Mesohaline			
													Polyhaline			
													Mixoeuhaline			
Barrow	Diffuse upstream	–11%	–11% (–96%)	–11% (–4%)	Diffuse upstream	–52%	–41% (–50%)	–67% (–50%)					Mesohaline (B and N)			
Nore	Diffuse upstream	–24%	–25% (–100%)	–2%	Diffuse upstream	–43%	–40% (–73%)	–56% (–27%)					Polyhaline (B and N)			
Slaney	Diffuse upstream	–20%	–21% (–100%)	12%	Diffuse upstream	–61%	–63% (–81%)	–54% (–19%)					Mesohaline			
													Polyhaline			
													Mixoeuhaline			
Liffey	Point downstream	–20%	–34% (–72%)	–10% (–28%)	Diffuse upstream	–37%	–12% (2%)	–39% (–98%)					Mesohaline			
													Polyhaline			
													Mixoeuhaline			
Tolka	Diffuse upstream	–86%	–64% (–30%)	–100% (–70%)	Diffuse upstream	–92%	0%	–100% (–100%)					Mesohaline			
													Polyhaline			
													Mixoeuhaline			

Table 2.4. Continued

Catchment	LAM trends, % change in source (change relative to overall model change is shown in brackets)				LAM trends, % change in source (change relative to overall model change is shown in brackets)				Riverine input trends (2000–2013)				Water body	Estuarine trends		
	N 2010 greatest contributor	Overall decrease	N diffuse	N direct	P 2010 greatest contributor	Overall decrease	P diffuse	P direct	TN	DIN	TP	MRP		DIN	MRP	Chl
Boyne	Diffuse upstream	–33%	–39% (–100%)	199%	Diffuse upstream	–41%	–40% (–66%)	–43% (–34%)					Mesohaline			
													Polyhaline			
													Mixoeuhaline			
Erne	Diffuse upstream	–73%	–75% (–100%)	209%	Diffuse upstream	–94%	–5% (100%)	64%					Mesohaline			
													Polyhaline			
													Mixoeuhaline			
Garavogue	Diffuse upstream	–57%	–59% (–100%)	13%	Diffuse upstream	–19%	–4% (–18%)	–43% (–82%)					Mesohaline			
													Polyhaline			
													Mixoeuhaline			
Moy	Diffuse upstream	–51%	–50% (–96%)	–56% (–4%)	Diffuse upstream	–55%	–25% (–27%)	–87% (–73%)					Mesohaline			
													Polyhaline			
													Mixoeuhaline			
Corrib	Diffuse upstream	–27%	–26% (100%)	149%	Diffuse upstream	–42%	–19% (–100%)	100%					Mesohaline			
													Polyhaline			
													Mixoeuhaline			
Deel	Diffuse upstream	–26%	–23% (–82%)	–70% (–18%)	Diffuse upstream	–65%	–27% (–17%)	–89% (–83%)					Mesohaline			
													Polyhaline			
Maigue	Diffuse upstream	–24%	–21% (–82%)	–76% (–9%)	Diffuse upstream	–74%	–55% (–35%)	–91% (–65%)					Mesohaline			
Fergus	Diffuse upstream	28%	30% (99%)	15% (1%)	Diffuse upstream	–40%	–35% (–75%)	–53% (–25%)					Mesohaline			
													Polyhaline			
Shannon	Diffuse upstream	–42%	–44% (96%)	–37% (–4%)	Diffuse upstream	–55%	–27% (–32%)	–69% (–68%)					Mesohaline			
													Polyhaline			
													Mixoeuhaline			

Green boxes indicate a statistically significant downward trend, red boxes indicate a statistically significant upward trend and light blue boxes indicate that the trend is not significant.
Chl, chlorophyll.

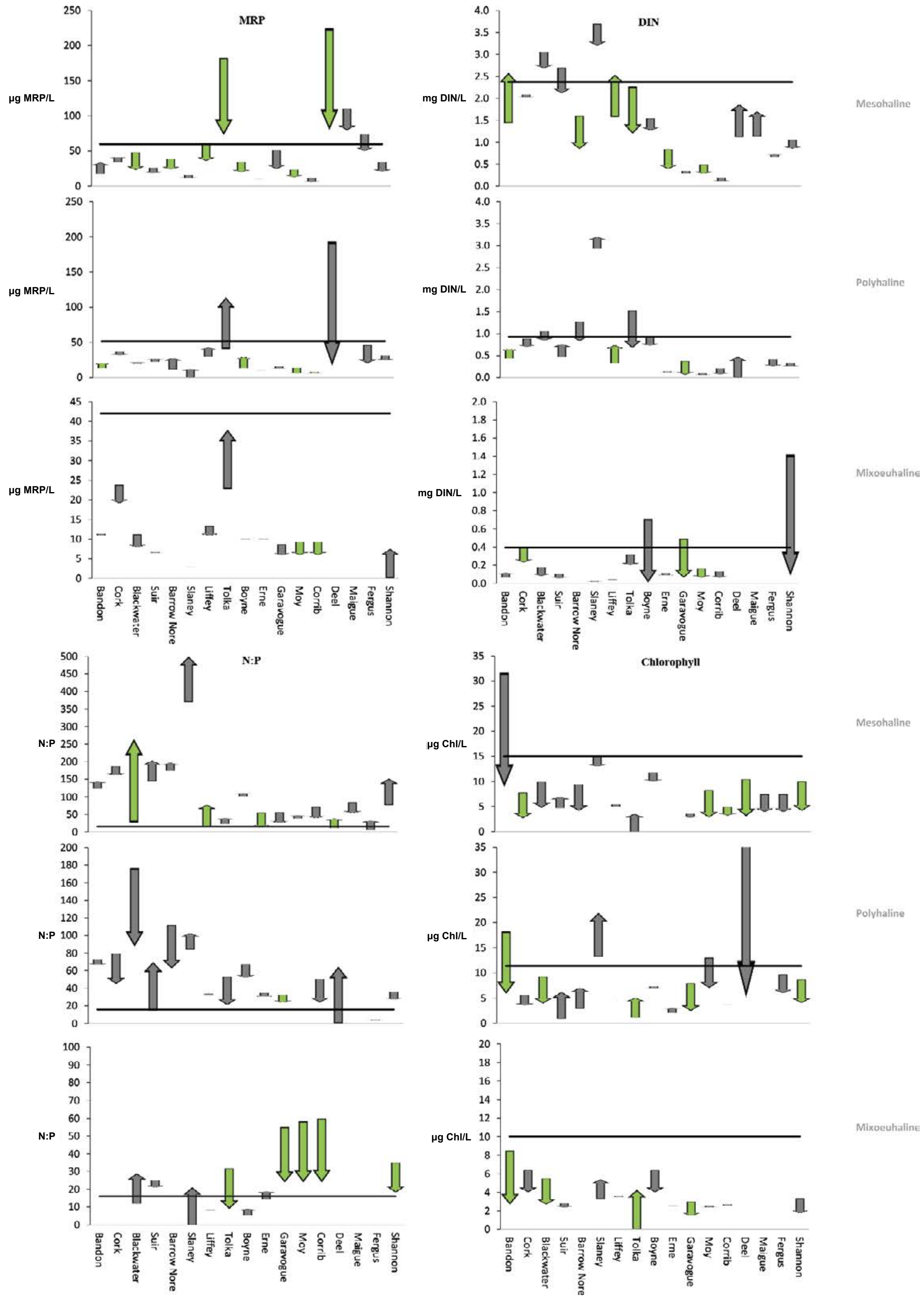

Figure 2.6. Historic trends in estuarine parameters from 2000 to 2013 for the 18 catchments studied. The arrows represent trajectories of concentrations as calculated by the Sen's estimator (R TTA tool) from 2000 to current concentrations (median 2011–2013). Green arrows represent statistically significant trends. Solid black lines represent the WFD good-median boundary for MRP, DIN and chlorophyll (this differs depending on salinity). Note: each water body was split into three salinity bands for the purpose of the trend analysis: mesohaline (0–17), polyhaline (17–30) and mixoeuhaline (>30). If a water body is not represented in one of the graphs (e.g. Maigue mixoeuhaline), it is because there were no stations in the particular salinity band. The scale of the y-axes differ for some parameters.

in most cases, to decreases in N or P influxes and/or concentrations. Chlorophyll significantly increased in only one system (the Tolka).

2.4 Discussion

2.4.1 The role of policy in reducing nutrient loads

The effectiveness of policies and measures enacted to improve water quality can only be assessed by monitoring programmes undertaken after the policies and measures have been implemented. The striking and significant reduction in riverine nutrient inputs in the majority of the catchments studied, and the concurrent improvement in estuarine concentrations, is hence an indication of the success of the policies implemented to reduce nutrient inputs over the last two decades.

A larger and more widespread decrease in P nutrient reductions than N reductions was evident from the riverine inputs and the estuarine datasets (Figures 2.5 and 2.6; Table 2.5). In the case of the Blackwater catchment, and indeed nationally, these results suggest that mitigation measures, which mostly focused on P reductions, have been effective (Figure 2.7). As early as 1998, the Local Government (Water Pollution) Act 1977 (Water Quality Standards for Phosphorus) Regulations 1998 led to the introduction of nutrient management planning at local authority level as part of a suite of measures to maintain or improve water quality. The regulations were unique in Europe in that they included a requirement for a direct ecological assessment of the impact of eutrophication. The regulations led to the introduction of nutrient management planning at the local authority level. Agricultural application rates of P were limited to replacement values which consider the levels of P available in the soil (based on Morgan's soil test) and hence a targeted approach with implications at a localised level has ensued (Coulter and Lalor, 2008; Wall *et al*., 2011).

The LAM results reveal that wide-scale reductions in diffuse agricultural loadings have had a substantial influence on the load reductions observed (see Figures 2.4 and 2.5, and Table 2.4). Land for grassland-based dairy and mixed livestock comprises 90% of utilised agricultural land in Ireland (which represents 56% of total land use) (Wall *et al*., 2011) and, as a result, the implications of inorganic fertiliser reduction measures are considered a key reason for the observed large reductions in nutrient loads on a national scale.

The Good Agricultural Practice Regulations (2009), which are key to the management strategy for Ireland's implementation of the Nitrates Directive, were the first to impose limits on the magnitude, application, timing, rates, storage and placement of inorganic fertilisers and organic manures containing both N and P (Taylor *et al*., 2012). The organic loading cap for N is 170 kg organic N/ha per year, with a derogation possible to 250 kg organic N/ha per year and inorganic application rates calculated to ensure that the maximum does not surpass a TN level of 226 kg of N/ha per year. These regulations limit not only organic N, but also, by association, organic P application rates.

As a result of these measures, there has been a trend towards relying on "high N" fertiliser compounds rather than "high P" and potassium (K) compounds, while the use of N-only fertiliser has also increased (Lalor *et al*., 2010). Consequently, there has been a larger decrease in the usage of P and K, than of N, fertilisers. A survey of Irish farms shows that N usage for grassland increased after 1995, but then steadily decreased between 1999 and 2008; this is broadly in line with changes in national N fertiliser consumption. For P and K, steady reductions in sales and usage have been apparent since 1995 (Lalor *et al*., 2010). Further measures which have reduced N transport to surface water but which are, as yet, not covered in the LAM include minimum requirements for on-farm infrastructure for slurry and manure storage, and housing facilities. During the season in which rainfall is highest (i.e. 15 September to 31 January), closed spreading periods, during which the application of organic and inorganic fertilisers are prohibited, have reduced the incidental loss of organic and inorganic fertilisers and have been shown to limit the impact of agricultural wastes on water quality during these periods (Flynn *et al*., 2016). Indeed, this major

Table 2.5. Combined percentage reduction in N and P for all 18 catchments, as determined by the LAM, riverine inputs (all catchments upstream of estuaries) and all estuarine systems (receiving waters)

	Reduction for all catchments (%)	
	N	P
LAM	7	51
River inputs	14	59
Estuarine concentration	0	66

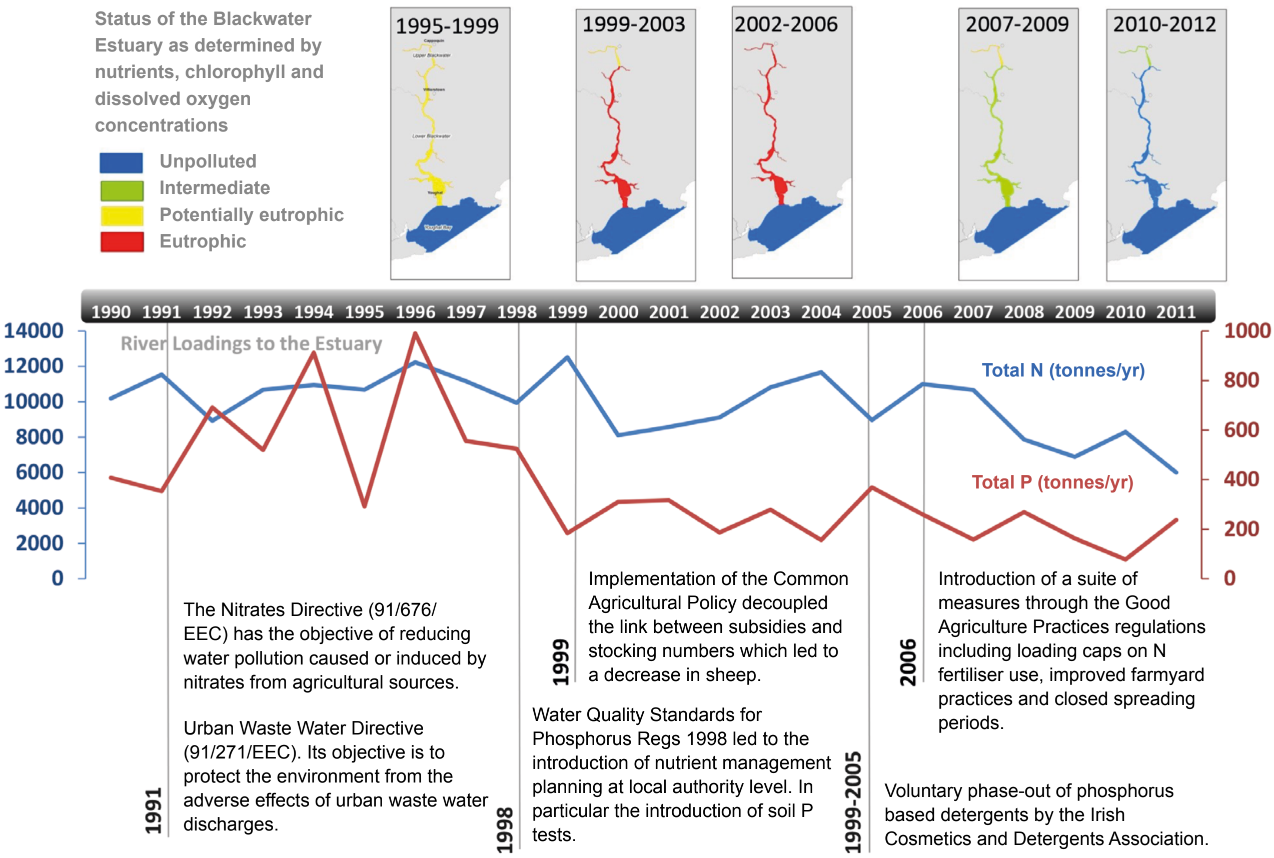

Figure 2.7. A representation of (from top to bottom) the improvement in eutrophication status, the reduction in measured riverine N and P inputs between 1990 and 2011, and the main (national) drivers of nutrient reductions in the Blackwater estuarine system in southern Ireland.

control of winter application rates was reflected in the trend analysis of river inputs to the Blackwater Estuary, whereby annual trends were largely driven by winter decreases in N and P.

In addition, the voluntary phase-out of the use of phosphate-based detergents by the Irish Cosmetics and Detergents Association (ICDA) between 1999 and 2005 is not captured in the LAM calculations, but will have had a significant impact on river P inputs.

Improvements in waste water treatment have been undertaken nationally since the implementation of the Urban Waste Water Treatment Directive in 1991 (EC, 1991a), through the Urban Waste Water Treatment Regulations 2001–2010. A further national measure to prevent and reduce pollution by urban waste water discharges was the introduction of a licensing and authorisation process for such discharges in 2007. The decrease in the importance of point P sources in the LAM between 2000 and 2010 indicates the substantial impact of improved treatment and controls in WWTPs and the industrial sector within this time frame.

2.4.2 *Nutrient response timing and direction: the importance of nutrient cycling and mitigation factor*

The relationship between decreases in N loads and riverine inputs and estuarine responses is extremely variable (Table 2.4) and highlights the complexity of recovery trajectories in estuarine and marine ecosystems (Duarte *et al*., 2009, 2015; Ní Longphuirt *et al*., 2015a). Overall reductions in P, calculated from the LAM or riverine inputs, were much greater than the reductions in N, and downstream MRP responses within the time frame of the study are, in general, significant. The inconsistent responses of some estuarine systems to nutrient load oscillations may be the result of a number of processes. A decrease in the input of a limiting nutrient, which, in the majority of systems, is P, may reduce overall estuarine primary production. This could cause a negative feedback response, whereby no change or even an increase in nutrient concentrations occurs. For example, in the Bandon Estuary, chlorophyll concentrations decreased concurrently with riverine P inputs, while increases in both MRP and DIN concentrations in the estuary were evident. The significant decrease in pelagic primary production in this estuary would result in a consequential decrease in N and P assimilation. This could explain the observed increase in nutrients. The direct effect of reducing P inputs on the phytoplankton biomass in the Bandon Estuary reinforces the findings of O'Boyle *et al*. (2015). This work described the importance of modulating factors in the responses of estuarine primary producers to nutrient conditions. The Bandon Estuary is not limited with regard to either light or residence time and so will respond very strongly to either an increase or a reduction in nutrient inputs. This in turn will impact on the uptake, cycling and retention of nutrients in the system. Similarly, the Blackwater Estuary, also considered to be relatively unlimited by mitigating factors, exhibited a significant reduction in chlorophyll with a corresponding reduction in N and P inputs. The estuarine concentration of P was affected by the reduction in P inputs, while the lack of any reduction in the estuarine concentration of N is thought to have been due to the decrease in biological uptake rates. Nutrients received from the catchment system are filtered through both benthic and pelagic primary production within an estuarine system.

A shift in the relative biomass of primary producers, and subsequent alterations to the burial and regeneration of organic matter, will reduce the amount of a nutrient that is retained within a system and, likewise, exported to the coastal zone (Paerl *et al*., 2004). Furthermore, reductions in primary production can reduce denitrification rates, as the carbon supply to the benthic system can decrease (Fulweiler *et al*., 2007). The impact of moderating factors could also explain the lack of a biological response, in some estuarine systems, to the decreases in inputs and estuarine concentrations. Physical factors, such as residence time, ocean exchange and light availability, can have a more important role with regard to controlling primary production than high nutrient concentrations; thus, even if concentrations and loads decrease, the impact on growth is limited (O'Boyle *et al*., 2015). This may explain the historically low chlorophyll concentration and lack of response to nutrient controls in the Upper Blackwater Estuary, Lower Suir Estuary, Maigue Estuary, Fergus Estuary, Shannon Estuary, Lower Corrib Estuary, Erne Estuary and Liffey Estuary.

Seven water bodies (the Upper Bandon, Lower Bandon, Lower Blackwater, Upper Suir, Lower Slaney, Moy and Deel) were classed as being predominantly influenced by nutrients, with residence time and light conditions being considered secondary (O'Boyle *et al*., 2015). In the current study, biological responses to reductions in nutrient concentrations were observed in four out of these seven water bodies. In the remaining three systems (the Upper Bandon, Lower Slaney and Upper Suir), high chlorophyll concentrations, as a result of persistently high nutrient concentrations, were evident. These systems, although showing signs of nutrient-related problems, would be expected to respond well to tighter nutrient load controls.

The complex nutrient cycling that occurs in estuarine sediments will further compound the response of nutrient concentrations, and indeed primary production, to reductions in nutrient inputs. The accumulation of internal nutrient pools and their subsequent release from estuarine sediments can maintain nutrient concentrations at high levels in estuarine systems, even if loadings have been reduced (Boynton *et al*., 1995; Conley *et al*., 2000; Carstensen *et al*., 2006). Internal sediment pools of N can take up to 10 years to decrease (Christensen *et al*., 1994) and, as such, could alter the importance of N fluxes from the sediment to the water column. In the case of P, desorption from suspended and benthic sediments at high salinities is considered to be a relatively important source of estuarine P and this can also negate reductions in external inputs (Balls *et al*., 1992). This phosphate buffer mechanism could be an important factor in the Suir–Nore–Barrow and Slaney systems, in which suspended sediment levels can be quite high. In these systems, MRP–salinity curves are bell shaped and increases in MRP between 10 and 20 salinity confirm the importance of these nutrient pools.

Nutrient cycling in estuarine sediments is also important for moderating the response of the system to seasonal changes in nutrient loads. In the Blackwater system for example, changes in riverine nutrient inputs mainly occur in winter and this demonstrates the influence of closed spreading periods. Interestingly, such reductions in winter appear to have implications for biological responses in summer. The results suggest that the sequestration of nutrients in benthic and intertidal sediments during winter periods, and indeed between years, may have implications even in summer during which inputs may appear to be stable. The amplitudes and expanses of such processes are important for determining the time required for estuarine nutrient concentrations to respond to implemented measures.

Finally, the importance of downstream point sources and adjacent systems on estuarine nutrient concentrations was shown to be an important factor in a number of estuaries. An example of this is the Garavogue catchment. A reduction in N, but not P, was observed in riverine inputs to the Garavogue Estuary. However, inconsistent with this, no reductions in either nutrient were noted in the mesohaline zone. Significant reductions in N and chlorophyll were, however, observed in the polyhaline and mixoeuhaline zones. These reductions could have been linked to reductions in the point source inputs due to improvements in the Sligo WWTP that discharges to the estuary. A similar reduction in lower estuarine nutrient concentrations was observed in the Moy Estuary; in this case, reductions in estuarine concentrations were not preceded by reductions in riverine inputs. These improvements are, again, undoubtedly related to the upgrading of a WWTP, namely the plant in Ballina in c. 2008.

For the Liffey and Tolka Estuaries, which have catchments containing the agglomeration of Dublin, negative changes were evident. There was an increase in DIN in the Liffey Estuary; salinity–DIN plots suggest that this decrease was linked to the impact of the Ringsend WWTP at the mouth of the estuary. Concurrently, chlorophyll concentrations in the Tolka Estuary have been increasing since 2000, and there has been very little change in the large opportunistic macroalgal blooms that occur in summer. This is contrary to the large decrease in riverine inputs of both P and N. The Tolka Estuary is largely controlled by exchange with the adjacent Liffey Estuary and Dublin Bay; hence, the undesirable biological response of the primary producers is more than likely related to its proximity to the WWTP outlet, combined with the provision of P from the high-salinity waters of outer Dublin Bay. The importance of marine sources of P for a similar marine-dominated system was described in detail by Ní Longphuirt *et al*. (2015b).

In addition, shifting baselines related to climatic change or large-scale hydromorphological changes mean that the restoration of systems to pre-disturbance ecosystem status may, in some cases, be unachievable (Duarte *et al*., 2009; Carstensen *et al*., 2011).

2.4.3 The influence of load source on determining the nutrient landscape of estuarine systems

The results highlight the importance of nutrient load source for determining the nutrient landscape of estuarine systems. High DIN concentrations in the meso- and polyhaline sections of some systems (Bandon, Lee, Blackwater, Suir–Nore–Barrow, Slaney and Boyne) were coupled with low MRP concentrations, and resulted in relatively high N:P ratios, which are deemed to be more than the ratios expected for estuarine and coastal systems. These catchments receive more than 90% of their N load from agricultural sources. The importance of this link is more prevalent in the context of the increase, since 2000, in the N:P load ratio from agriculture (Table 2.3). With the exception of the Upper Slaney system, these systems are also all classified as having "moderate" or "poor" status under the WFD. This classification is the result of a diminished biological status rather than high nutrient concentrations, as P levels in these systems are below the good–moderate WFD boundary level. N, on the other hand, is not considered when classifying transitional water bodies and so the status is solely reliant on the response of biological and related biochemical [(DO, biological oxygen demand (BOD)] elements. Interestingly, if DIN was included it would not alter the status of most of the systems, as the biological responses are sufficient. The Slaney system is the exception to this, as a biological response was not evident in the upper estuarine systems. This is probably because of the very low residence times (> 1 days) for nutrients in this system, which allow nutrients to pass through the system at a speed that is faster than phytoplankton growth rates.

High and increasing N:P ratios have led to the exacerbation of outer coastal eutrophication problems in a number of European systems (Paerl *et al*., 2004; Kronvang *et al*., 2005, van Beusekom, 2005). A recent study in the North Sea provides evidence of a link between large imbalances in N and P levels and major consequences for the growth, species composition and nutritional quality of marine phytoplankton (Burson *et al*., 2016). As in the Irish context, this was linked to the disconnection between N and P fertiliser application rate reductions (Glibert *et al*., 2014) and the more effective removal of P from domestic and industrial waste water (Grizzetti *et al*., 2012). The latter is also evident in Ireland; however, the N:P ratio increase for waste water was much smaller than it was for agriculture (Table 2.3).

Therefore, the effective control of eutrophication requires consideration of not only loads of N and P individually, but also their relative amounts, in order to ensure the effective reduction of the levels of nutrients transported to both estuarine and subsequent coastal zones. While mitigation strategies often serve a dual function through the targeted reduction of one nutrient and a resulting concurrent reduction of another, focusing on mitigating individual pathways by identifying critical sources of N and P can help to target individual reductions if necessary (Melland *et al.*, 2014).

A number of downstream mixoeuhaline systems are considered N limited, particularly in summer (e.g. the Liffey, Tolka and Boyne systems), while in some systems N:P ratios are decreasing because of nutrient controls (e.g. the Garavogue, Moy, Corrib, Erne and Shannon systems). A shift from P to N limitation along the freshwater–marine continuum is widely accepted (Howarth and Marino, 2006). However, the implications for management measures in the estuary and upstream catchment are important for the management of eutrophication through the entire system (Paerl, 2009).

2.5 Conclusions

Studies that trace N and P flows from their source to the coastal zone do not only allow the determination of the effectiveness of mitigation measures, but also enhance the understanding of response trajectories. This will assist the future targeting of the actions to be applied specifically in light of current and future programmes of measures. In most systems, the greatest overall contributors to N and P loads are diffuse sources. However, reductions in both diffuse and point sources have resulted in considerable reductions in P, highlighting the effectiveness of the measures that have been applied. However, reductions in N loads have been more modest and are largely related to agricultural improvements. The high and increasing N:P ratios in river inputs and estuaries are an indication of the imbalance in nutrient reduction and this may have deleterious impacts on the transport of nutrients to the outer coastal zone. In the Irish context, this study has shown that the impact of measures to reduce nutrient loads is largely dependent on not only load source, but also nutrient cycling processes and modulating factors, such as light and residence time. The importance of winter load reductions, due to closed fertiliser spreading periods, has led to both winter and summer estuarine improvements, thus demonstrating the importance of such measures for estuarine remediation. The influence of measures, cycling and physical controls evolves through the estuarine continuum from fresh to marine water, highlighting the need to consider the impact of measures on each river–estuarine system in the context of these control shifts.

3 Detangling the Link Between Phytoplankton Community Structure and Hydrological, Light and Nutrient Controls in the Irish Context

3.1 Overview

With regard to the detrimental impacts of nutrient enrichment in estuarine and coastal zones, phytoplankton communities are one of the first biological elements to respond. Chlorophyll concentration, a proxy for phytoplankton biomass, is often used as an indicator of enrichment and also for the determination of trophic status. High levels of biomass, due to the formation of blooms, can be detrimental to the health of estuarine ecosystems (Smayda, 2004) through a reduction in water quality and DO, which can create unsuitable conditions for the survival of other flora and fauna.

However, the response of the phytoplankton community to nutrient loadings is not limited to chlorophyll concentration alone, but also includes structural changes related to the composition, abundance, frequency and intensity of algal blooms. Alterations to any of these constituents can modify the energy supply and food quality that fuels production in food webs. In turn, this can impact on nutrient and energy fluxes, fisheries, aquaculture, and microbial processes (Houde and Ruthford, 1993; Bacher *et al*., 1998; Cloern *et al*., 2014).

As explored by O'Boyle *et al*. (2015) and confirmed in Chapter 2 of this report, chlorophyll concentrations in Irish estuarine and near coastal systems are controlled by nutrient inputs and mitigating factors such as light and residence time. To further extend this concept, analyses of the impact of these factors on the entire phytoplankton community structure (biomass, composition and abundance) would deepen our understanding of the impacts of anthropogenic nutrient loadings on primary producers.

The objectives of this study were (1) to create a phytoplankton tool (the "Phyto Index") that encompasses all the structural components of the phytoplankton community; (2) to compare this tool with corresponding environmental data for the purpose of identifying the parameters that impact on the phytoplankton community; and (3) to investigate the phytoplankton composition and blooming species dataset with the view to elucidating the link between driving factors and the bloom species.

The results of this chapter will, firstly, provide the basis for a detailed phytoplankton metric which could be incorporated into the reporting structure for the WFD. Secondly, an analysis of blooming events will augment our understanding of the factors that drive the presence of certain bloom species in different water bodies in Ireland.

3.2 Current Phytoplankton Status Determination

The importance of structural changes in phytoplankton communities due to anthropogenic activities has been recognised by the WFD through the inclusion of biological indicators. The ecological quality status of phytoplankton should be assessed using indicators of biomass; the frequency and duration of blooms, and the abundance and composition of phytoplankton data (see EC, 2000, Annex V, Tables 1.2.3 and 1.2.4).

The current Irish method for WFD monitoring of estuarine and coastal waters is a two-stage process consisting of assessments of phytoplankton abundance, and bloom frequency and biomass. Firstly, the median and 90th percentile chlorophyll concentrations of phytoplankton are determined (EPA, 2010). The reference conditions and class boundaries are salinity dependent, and the reference conditions for fully saline waters are 3.33 mg/L, ecological quality ratio (EQR) = 1 (EPA, 2008). These findings are then combined with assessments of the taxonomic abundance of dominant taxa and bloom frequency over an assessment period of 6 years (EPA, 2008). The tool first calculates the frequency of individual taxon concentrations that exceed 500,000 cells/L, at salinities of ≤ 17, or 250,000 cells/L, for coastal waters of salinities above 17, over the 6-year period (on the basis of four samples per year for each water body). Reference conditions are considered to be met if there is only one fail every 3 years, the high–good boundary will be surpassed if there is a fail every 2 years, and the good–moderate boundary will be surpassed if there is a fail every year (or on 25% of sampled dates). National EQRs are then calculated by dividing the reference values by the observed values.

3.3 Conceptualisation of a New Phytoplankton Index (Phyto Index)

While changes in chlorophyll level and bloom frequency represent a direct community response to nutrient enrichment, the inclusion of abundance and community structure information in assessment approaches, through the distribution of individuals to species, conveys additional information on the composition of the community. It also indicates possible changes in structure due to alterations in factors that influence the community as a whole, such as nutrient availability and light conditions. The inclusion of community structure also allows the inclusion of heterotrophic species that are not always represented by chlorophyll measurements (Domingues *et al*., 2008). Furthermore, a multimetric index is often considered more robust than its component metrics (Lacouture *et al*., 2006). The proposed Phyto Index takes elements of the original EPA blooming tool and the Integrated Phytoplankton Index (IPI) developed by Spatharis and Tsirtsis (2010) to create a tool that will be compatible with current methods of estuarine water body classification (i.e. the EPA blooming tool), and also comparable to environmental and physical forcings in Irish estuarine and coastal waters.

3.3.1 Phyto Index development

The first step in the development of the multimetric index was the determination of which ecological indices to include, along with chlorophyll concentrations and abundance of dominant taxa. A number of ecological indices, which determine diversity and evenness, were calculated for the dataset. The results of these calculations were then divided on the basis of salinity (i.e. above and below 17 salinity) and compared with the abundance of dominant taxa in order to determine their monotonicity (consistent increase or decrease) with this metric and hence the level of ecological disturbance (Table 3.1). With regard to a measurement of evenness, the E2 index had the highest correlation with abundance and, therefore, this was considered representative of community structure for the Phyto Index.

The second step was the development of reference and class boundaries (high–good, good–moderate, moderate–poor and poor–bad, as per WFD characterisations)

Table 3.1. Log regression analysis of the relationship between evenness and diversity indices and the abundance of the dominant taxa

	Below 17 salinity		Above 17 salinity		Reference
	Equation	R2	Equation	R2	
Evenness indices					
E1	$y=-0.075\ln(x)+1.4896$	0.57	$y=-0.083\ln(x)+1.5805$	0.62	Pielou (1975)
E2[a]	$y=-0.089\ln(x)+1.502$	0.70	$y=-0.108\ln(x)+1.6733$	0.73	Sheldon (1969)
E3	$y=-0.09\ln(x)+1.457$	0.67	$y=-0.108\ln(x)+1.6265$	0.70	Ludwig and Reynolds (1988)
E4	$y=-0.0562\ln(x)+0.9$	0.06	$y=-0.029\ln(x)+1.0526$	0.21	Ludwig and Reynolds (1988)
E5	$y=-0.036\ln(x)+1.049$	0.25	$y=-0.053\ln(x)+1.215$	0.40	Ludwig and Reynolds (1988)
Diversity indices					
Shannon H’	$y=-0.053\ln(x)+2.0641$	0.03	$y=-0.053\ln(x)+2.2604$	0.02	Shannon and Weaver (1949)
Menhinick’s	$y=-0.006\ln(x)+0.1033$	0.34	$y=-0.007\ln(x)+0.1144$	0.34	Menhinich (1964)
Simpson’s	$y=0.0271\ln(x)+0.072$	0.07	$y=0.0243\ln(x)+0.0646$	0.05	Ludwig and Reynolds (1988)
Margalef	$y=0.0871\ln(x)+0.0424$	0.06	$y=0.1882\ln(x)+0.7288$	0.14	Margalef (1958)
Gleason	$y=0.0807\ln(x)+0.2006$	0.05	$y=0.1813\ln(x)+5.669$	0.13	Ludwig and Reynolds (1988)

[a]The E2 index had the highest correlation with abundance.

for each of the three indices, that is, the chlorophyll, abundance and E2 indices. These indices encompass biomass, abundance and the composition of blooms, as required by the WFD. In the case of chlorophyll, the reference conditions (which are salinity dependent) and boundaries were taken from the METRIC project (EPA, 2008) and the currently used EPA bloom frequency tool. A new five-point scale was developed for abundance based on the single-species phytoplankton blooming tool currently used by the EPA and the full phytoplankton dataset available for Irish estuarine waters (2007–2013). The median values for all estuaries that never failed in a 6-year period and were also classed as "unpolluted" according to TSAS classification (2007–2012) were considered the reference condition (Table 3.2).

The high–good boundary value was set as the reference value plus 50% of the reference value. The upper third quartile was considered the good–moderate boundary for estuaries with a salinity of more than 17, while the moderate–poor boundary was the boundary for bloom conditions, as determined by the phytoplankton blooming tool. The poor–bad boundary was the upper third quartile of all national datasets plus 1.5-times the interquartile range value [outliers were determined by the method developed by Tukey (1977) and used by Spartharis and Tsirtsis (2010)]. Because E2 showed a relationship with the log abundance, the boundaries for this index were calculated from the limits of the five-point scale developed for abundance.

Finally, for each metric, boundary conditions were converted into a normalised EQR by first converting the data to a numerical scale between 0 and 1, where boundaries were not equidistant. These values were then transformed into an equal-width class scale between 0 and 1. The EQR values of the three metrics were calculated for each of the sampling points (date–phytoplankton composite samples) available for all the water bodies sampled (Table 3.3). The Phyto Index was calculated as the average of the chlorophyll, blooming tool, and combined abundance and evenness (which represent community composition) metrics. All metrics were used in the calculations if based on a 6-year period, and only three metrics (chlorophyll, 0.5 × abundance and 0.5 × evenness) were used if only single water body or date data points were being considered (Table 3.3).

3.3.2 *Calibration of the Phyto Index with the current EPA blooming tool*

In order to test the validity of the Phyto Index (metrics: chlorophyll, blooming frequency, and abundance and evenness), the results were compared with the five assessment classes of the blooming tool (metrics: blooming frequency and chlorophyll) over the 2007–2012 period. The newly proposed index performed well against the EPA tool currently used to determine the ecological status of phytoplankton for the WFD (Figure 3.1). The two tools showed a linear correlation ($R^2 = 0.90$). The newly developed Phyto Index tended to give lower EQR values, particularly for the high-status water bodies. An examination of the current EPA tool statuses and the statuses determined by the new Phyto

Table 3.2. Reference and class boundaries of cell abundance for the most abundant species, developed for salinities above and below 17. Boundaries are based on the 2007–2012 phytoplankton dataset for Irish estuarine and coastal waters

Salinity	High	Good	Moderate	Low	Bad	Reference
<17	0–22,500	22,500–73,000	73,000–500,000	500,000–937,000	937,000–upper limit	15,000
>17	0–12,000	12,000–34,750	34,750–250,000	250,000–308,000	308,000–upper limit	8000

Table 3.3. Grouping of the metrics of the Phyto Index. The abundance, E2 and chlorophyll metrics can be combined and compared with environmental data; bloom frequency can be added if a 6-year average for reporting under the WFD is considered

Metric	Abundance	E2	Chlorophyll	Bloom frequency
Grouping	Site- and date-specific Phyto Index is comparable with environmental data 6-year average			Determined from 6 years of data

Index indicated that, of the 95 water bodies compared, 55 had the same status, 39 had a lower status, and 1 had a higher status (Broadmeadow: poor to moderate) than the Phyto Index. Of the 40 water bodies that had a different status from the Phyto Index, 33 changed from high to good. The water bodies that altered in status were then compared with the overall WFD classification (which includes a number of biological and chemical metrics) for the 2010–2012 period. With the current classification method, the phytoplankton status classification was above that of the overall status level in 35 out of 95 cases. However, with the new method, only 19 water bodies differed from the overall WFD status. Hence, the use of the additional metrics to determine phytoplankton status has led to a greater level of agreement between phytoplankton and the other biological and chemical indicators that are used to determine water body status under the WFD.

The inclusion of additional metrics for community structure has resulted in a more robust method, but also allows a higher degree of sensitivity to changes in the structure of the community (Garmendia *et al.*, 2013). For instance, a large abundance of small cells may not be captured by chlorophyll concentrations and may be under the cut-off considered to be a "bloom event", but could still have consequences for ecosystem health and overlying consumers in the ecosystem food web. In the case of the Argideen Estuary for example (sampled once in 2007 and three times in 2010), high abundance levels and low community evenness were not captured by chlorophyll concentration values and the status thus moved from moderate to poor.

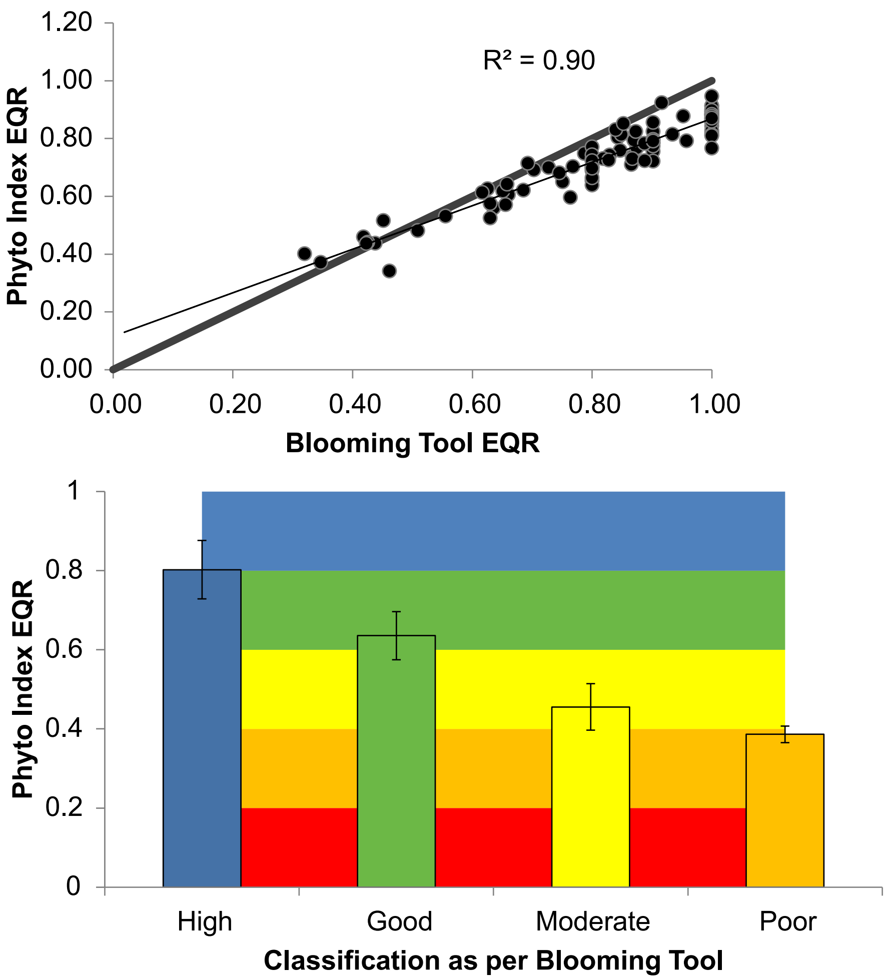

Figure 3.1. Linear comparison of the newly developed Phyto Index (metrics: chlorophyll, blooming frequency and abundance, evenness) with the currently used EPA blooming tool (metrics: blooming frequency and chlorophyll) (top panel), and the Phyto Index EQRs (averages and standard deviations) for the water bodies grouped by the classifications described previously (bottom panel).

3.4 Linking the Phyto Index to Nutrients and Forcing Parameters

A principal components analysis (PCA) was undertaken on the dataset (2011–2013) to test the influence of environmental factors on the Phyto Index (R platform, FactoMineR-package). The PCA extracted nine components; however, only the first two, which represented 51% of the variance, are presented (Figure 3.2). An analysis of environmental variables indicates that the main axis of variation represents the transition from high to low nutrient concentrations along the salinity gradient from fresh to marine water. The variables with the highest loading on the first axis (axis 1) were DIN (0.95), silicic acid (0.90), salinity (–0.86) and the N:P ratio (0.87).

The second component of variation appears to represent the transition from areas with low to high residence time (0.83) and light conditions (0.78). This indicates that, as residence time increases, so does the ratio of mixing depth to photic depth. This is probably a reflection of the hydromorphology of estuaries, as those which are longer and deeper are more likely to have a higher mixing depth to photic depth ratio than those with low residence times which are, by nature, shorter and shallower. This relationship is very interesting as, in both cases, one moderating factor offsets the other. Therefore, when residence time is high, low light levels prevent a response. However, when light levels are high, the residence time is low and moderates the response of phytoplankton. This almost "Catch-22" relationship is extremely interesting with regard to explaining why a number of Irish estuaries do not respond to high levels of nutrients, and complements the work and theories of O'Boyle *et al*. (2015).

The Phyto Index vector was located almost directly opposite the nutrient vectors indicating the almost linear response of the Phyto Index to nutrient concentrations. The results differ from those of O'Boyle *et al*. (2015), who found that chlorophyll median and 90th percentile concentrations were deflected from the nutrient vectors because of the influence of residence time and light conditions.

These Phyto Index results suggest that a multimetric index may capture the negative response of the community structure to high nutrient levels, which are not necessarily shown if biomass measurements are considered alone.

An example of this would be the Upper Liffey Estuary. While the chlorophyll EQR alone indicated a good status, E2 and, in particular, abundance EQRs were quite low. The low EQR values suggest that the community was

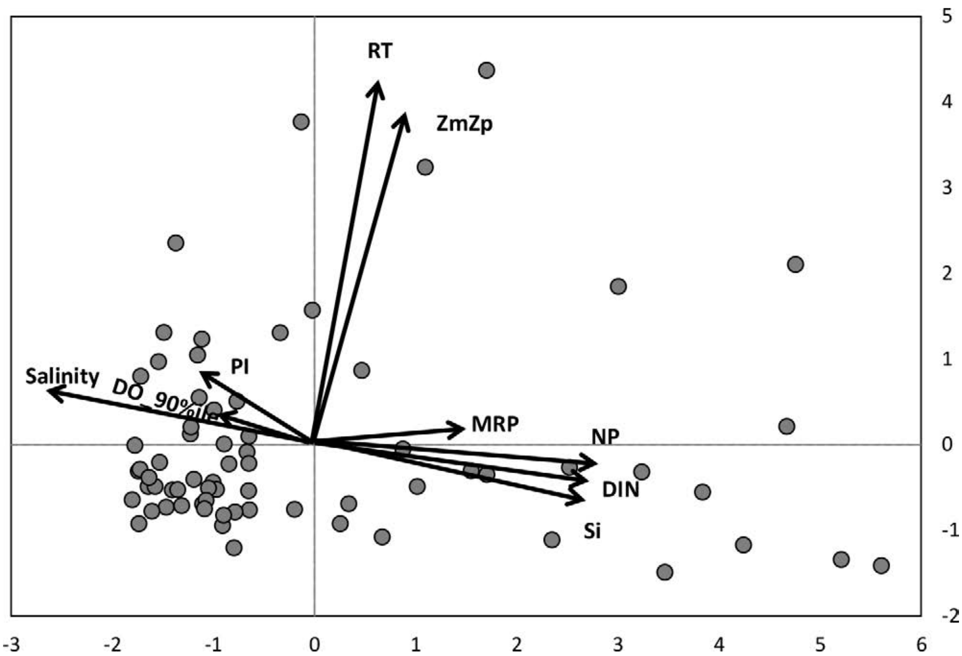

Figure 3.2. Results of PCA to determine the relationship between physico-chemical parameters and the Phyto Index. NP, N to P ratio; RT, residence time; Si, silicic acid; Zm:Zp, mixing depth to photic depth ratio.

not evenly distributed among species, but was dominated by one species and the abundance of cells was high. The largest blooms in the system were dominated by Euglenophyceae and Cryptophyceae in most cases. However, in August 2011, the harmful bloom-forming dinoflagellate *Lingulodinium polyedrum* was most abundant. High abundances of phytoplankton can be found in systems, even when chlorophyll concentrations are low (Domingues and Galvão, 2007). In other systems, heterotrophic species, which do not have photosynthetic pigments, can make important contributions to the phytoplankton bloom and these are not considered through chlorophyll analysis alone (Domingues *et al*., 2008). Heterotrophs are currently not considered in the current bloom frequency tool if chlorophyll alone is considered as a proxy for biomass, and this is also a limitation of the current Phyto Index. The proposed Phyto Index tool accounts for the heterotrophic community through the use of abundance and evenness measurement metrics.

3.5 Blooming Species in Irish Estuarine and Coastal Systems

The Irish phytoplankton dataset, while spatially comprehensive in its cover of Irish estuarine systems, does not allow for a comprehensive analysis of long-term trends or seasonal succession. Consistent sampling and phytoplankton species identification has been undertaken only since c. 2007, and the limitation of quarterly sampling points negates the possibility of annual and seasonal data analyses. Hence, analysis tools that explore the entire dataset in terms of the relationship between environmental and physical factors were applied. This allowed for some identification of the factors that determine the occurrence of bloom species in systems and the possible grouping of the datasets.

Approximately 80 species were responsible for blooming events in the Irish estuarine and coastal systems monitored between 2007 and 2013. Of these species, 50 are diatom species followed by 20 dinophyceaen species; the remaining 10 were microflagellates, Euglenophyceae, cyanophytes, chlorophytes, ciliates, Chrysophyta and chromophyte species (Table 3.4). The diatom *Chaetoceros* spp. *(Hyalochaete* type*)* followed by *Skeletonema* spp. were responsible for 18% and 10% of all blooms, respectively. Ten species accounted for 58% of all blooms recorded by the EPA's WFD sampling in Irish transitional and coastal waters between 2007 and 2013 (Table 3.4). Diatom species made up 7 out of the 10 most common species, along with one cyanophyte, one dinophyte and one flagellate species. The results suggest that blooms in Irish estuarine and near coastal waters are caused by the growth of a small number of species concurrent with results from other countries (e.g. Devlin *et al*., 2009).

3.5.1 Linking bloom species with environmental and physical parameters

To identify the environmental and physical parameters that have the greatest effect on the species responsible for blooms, a classification and regression tree (CART) method was applied (namely the rpart package, R platform). CART models are recursive partitioning or tree-based models which can help explore the structure of a dataset, while developing easy-to-visualise decision rules for predicting a categorical (classification tree) or continuous (regression tree) outcome. Recursive partitioning, which takes into account the distributional properties of the measures [see Hothorn *et al*. (2006) for a full description], was also applied to the blooming dataset (PARTY package, R platform). The analysis differentiated the data into nodes, which were compiled of groups of data.

The CART model

The parameters entered into the model included physical factors, such as temperature, salinity, residence time [see Hartnett *et al*. (2011) for calculations] and light availability [mixing depth to photic depth ratio (Zm:Zp); see O'Boyle *et al*. (2015) for calculations]. Nutrient concentrations and ratios (DIN, MRP, silicic acid and the N:P ratio) were also entered into the model and considered. The dependent variable was blooming species. The results indicated that DIN, Zm:Zp, salinity and silicic acid were the main factors contributing to the occurrence of specific blooming species (Figure 3.3). The small surf zone species *Asterionellopsis glacialis* was separated by the first split in the tree and was found in areas with high levels of light. The main bloom-forming species *Chaetoceros* spp. (*H*. type) occurred consistently in high-salinity areas (>34), and in areas (with a salinity of >32) where silicic acid concentrations were elevated. Diatoms require silicic acid for the production of their shells and thus high silicic acid concentrations would favour their growth over other species. *Skeletonema* spp., on the other hand, were found to bloom if the Zm:Zp was more than 0.73. They are also more likely

Table 3.4. Top 10 blooming species and the frequency of blooming events in the dataset (2007–2013; summers only)

Species	Higher group	No. of blooming events	Salinity		Zm:Zp		RT (days)		DIN (mg/L)		MRP (µg/L)		N:P	
			Average	±SD	Average	±SD	Average	±SD	Average	±SD	Average	±SD	Average	±SD
Chaetoceros spp. (*H.*)	Bacillariophyceae	115	27.5	10.0	0.9	0.7	19.0	18.3	0.3	0.5	16.2	14.8	46.8	80.2
Skeletonema spp.	Bacillariophyceae	66	25.1	11.1	1.1	1.2	20.6	15.4	0.7	1.0	16.0	11.5	72.9	106.0
Cryptophyte spp.	Cryptophyta	31	24.4	11.7	1.0	1.1	14.6	8.2	0.7	1.0	16.3	12.7	84.1	115.3
Microflagellates	Microflagellates	29	25.4	11.1	2.0	2.2	25.5	22.6	0.3	0.4	30.7	65.3	32.2	26.4
Asterionellopsis glacialis	Bacillariophyceae	26	21.4	12.7	0.6	1.2	10.2	7.2	0.6	0.8	21.5	21.9	57.5	65.6
Cylindrotheca closterium/ Nitzschia longissima	Bacillariophyceae	26	24.2	11.4	1.0	1.0	12.8	12.6	0.7	0.8	20.5	17.8	101.8	230.2
Leptocylindrus danicus	Bacillariophyceae	24	25.9	9.9	0.8	0.5	30.0	34.9	0.3	0.4	13.2	10.3	45.2	63.5
Thalassiosira spp. (20–50 µm)	Bacillariophyceae	20	22.9	14.2	2.8	2.5	32.3	18.4	0.9	1.3	20.7	15.7	86.5	128.0
Guinardia delicatula	Bacillariophyceae	17	28.4	5.6	1.5	1.7	19.5	13.2	0.4	0.4	16.4	17.2	60.1	78.7
Heterocapsa triquetra	Dinophyceae	17	24.0	9.4	0.6	0.2	17.5	9.0	0.5	0.7	22.8	20.3	42.1	49.8

to thrive than microflagellates if DIN values are low. Both *Chaetoceros* spp. *(H.* type*) and Skeletonema* spp. have been shown to have relatively low half-saturation constants for nitrate and, consequently, are less likely to be limited by the relatively low DIN concentrations found in high-salinity waters (Eppley *et al*., 1969). The final set of nodes identified indicate that at DIN values of less than 0.64 mg/L and salinity values of less than 32, the light conditions will determine whether *Cylindrothecae closterium* or *Heterocapsa triquetra* are the blooming species, with higher light conditions favouring *Cylindrothecae closterium*. This species has been reported to tolerate a wide range of salinities, from 12–50 (Johnson, 1977; Nche-Fambo, 2015).

The physical conditions (light availability, temperature, water movement) and chemical conditions (nutrients, oxygen), together with interspecific interactions (grazing and competition), often define the composition of phytoplankton communities in aquatic environments (Devlin *et al*., 2009). While nutrient concentrations primarily influence phytoplankton productivity and biomass, the resource ratio can affect the composition of phytoplankton communities (Sommer, 1994; Philippart *et al*., 2000). While the results here do not suggest an influence of nutrient ratios on the phytoplankton community, the importance of nutrient concentrations and light conditions is evident.

Recursive partitioning

The recursive partitioning analysis differentiated the data into nodes, which were compiled of groups of data and a significance (*P*) value was given for each split in the dataset (Figure 3.4). Light and DIN were the two factors that resulted in a partitioning of the data. The groups identified had similar traits (Figures 3.4 and 3.5). Group 13 was the first group identified and was separated from the other bloom events by particularly low light availability. These data points were compiled solely of diatom bloom events from the Mid-Suir Estuary where residence times are high and light conditions are low. DIN values and hence N:P ratios were also low during these nine bloom events. The conditions for group 12 (six species), which separated this group from the other bloom events, were relatively low salinity but high DIN values (Figures 3.4 and 3.5). This indicated more of a freshwater influence. While four of the bloom

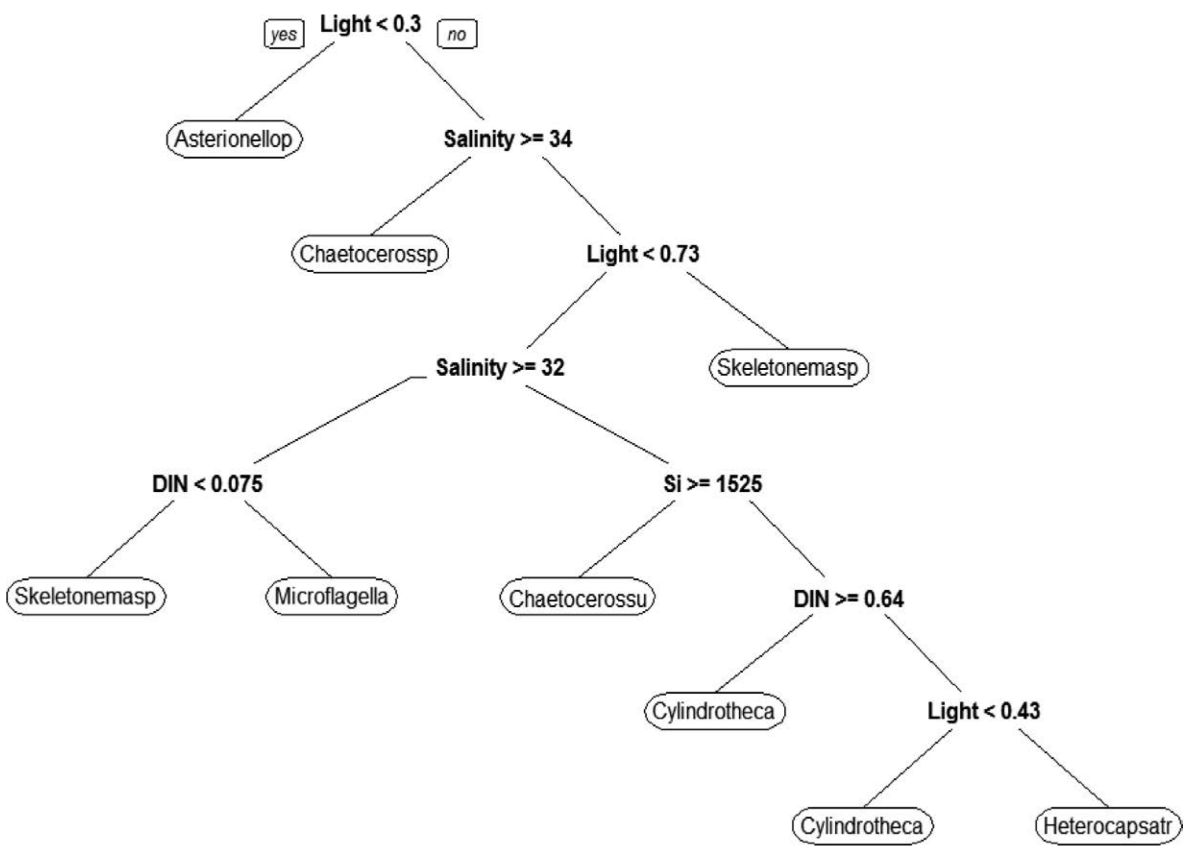

Figure 3.3. Classification tree produced for the partitioning of the bloom species relative to environmental and physical variables.

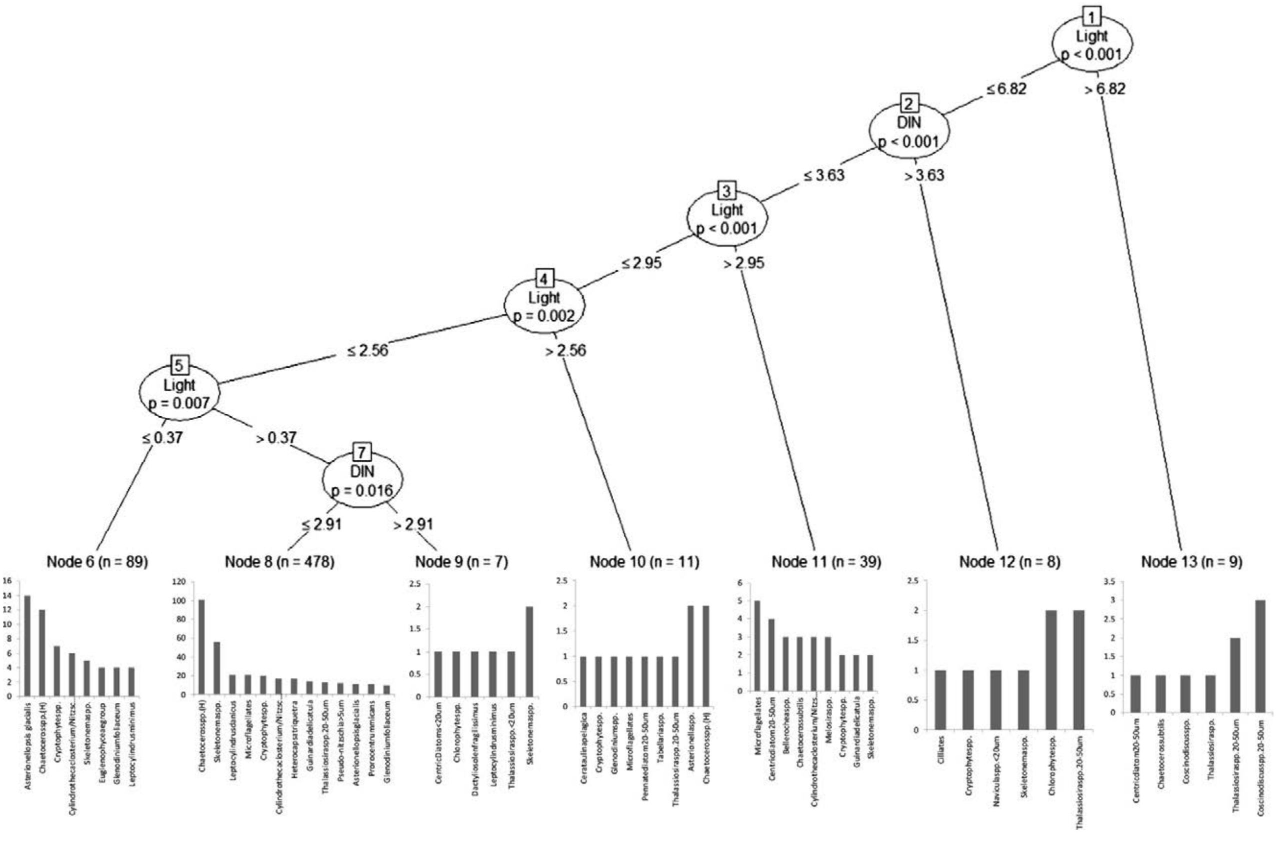

Figure 3.4. Regression tree produced for the partitioning of the bloom species relative to environmental and physical variables using recursive partitioning (the R-based PARTY package).

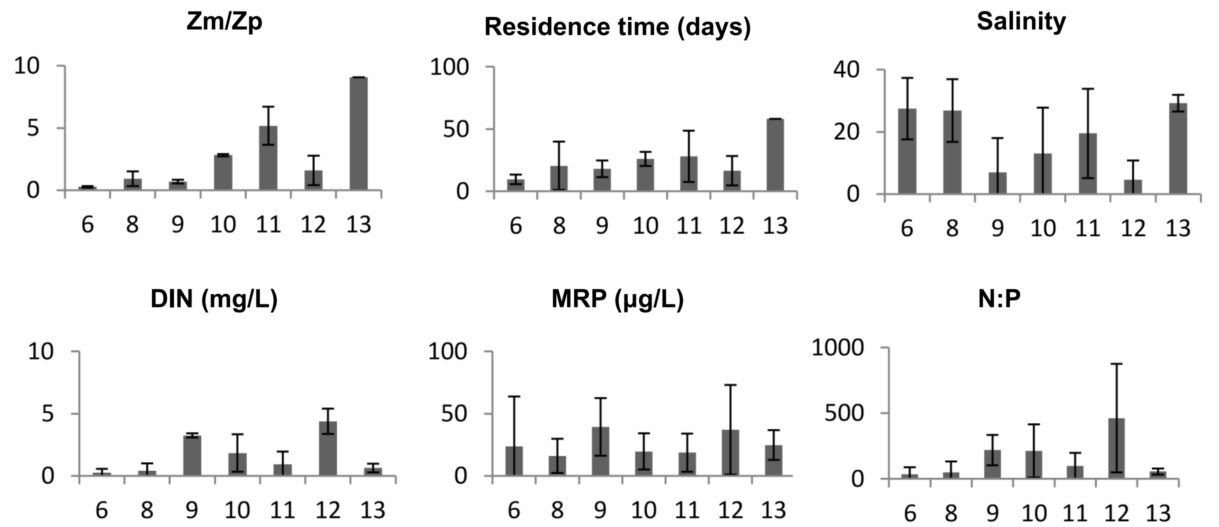

Figure 3.5. Physical and chemical parameters for the groups of blooming events differentiated by the recursive partitioning (PARTY) method. Bars represent average values and error bars represent standard deviations.

events were related to diatom species in this group, four were the result of blooms of ciliates, chlorophytes and cryptophytes, all of which are found in areas of high DIN concentrations; chlorophytes are often prolific in freshwater areas (Jendyk *et al.*, 2014). Group 11 (39 events) contained data points from the Shannon and Fergus Estuaries and the Suir system (New Ross Port, Barrow–Nore–Suir–Lower Suir) and was dominated by microflagellates (Figure 3.4). The low light availability in these areas separated this group from the other bloom events (Figure 3.5). Group 10 consisted of 11 data points and was made up of data from the Barrow–Nore–Suir (eight data points) system and the Cashen Estuary. This group is associated with a very narrow range of light conditions and residence times (Figure 3.5).

Group 9 was associated with high levels of light and nutrients, but relatively low levels of salinity (Figure 3.5). Group 8 was the largest group identified and was dominated by *Chaetoceros* spp., followed by the diatom *Skeletonema* spp. (Figure 3.4). This group was associated with relatively good light conditions, variable residence times, high levels of salinity and lower nutrient concentrations than the other groups (Figure 3.5). Group 6, for example, was dominated by diatom species. The species *Asterionellopsis glacialis*, which is considered a surf zone diatom, dominated group 6 (followed by *Chaetoceros* spp.; Figure 3.4). This group was associated with high levels of light, relatively high levels of salinity, relatively low residence times, low DIN values and the lowest average N:P ratio values (33.5 ± 54.9). The results of both analysis methods indicate that light and nutrient conditions are the main indicators of which species types dominate bloom occurrences in Irish transitional and coastal waters. In shallow coastal areas of Northern Europe, light, rather than the level of nutrients, is often the limiting factor and, hence, can influence the phenology of bloom occurrences (Iriarte and Purdie, 2004). This was also apparent in this study in which the light conditions had more of an influence on the partitioning of the dataset than nutrient levels. Furthermore, the recursive partitioning suggests that datasets can often be grouped in terms of their geographical proximity, as was the case for the Shannon and Fergus Estuaries and the Suir system. This is in agreement with studies of British waters, which suggest that community populations may be ubiquitous across marine types in systems of close proximity (Devlin *et al*., 2009).

It must be noted, however, that while species-specific strategic adaptations are selectively favoured in certain environments, the high variability of estuarine and coastal waters make concrete definitions difficult to attain (Devlin *et al*., 2009). Thus, the identification of responses to eutrophication-induced nutrient concentrations coupled with natural processes can be challenging (Devlin *et al*., 2009; Jaschinski *et al*., 2015). More system-specific studies, which follow long-term trends in high-frequency phytoplankton datasets, may give a more detailed and robust indication of the impacts of physico-chemical factors on phytoplankton communities (e.g. Coelho *et al*., 2015; Harding *et al*., 2015).

3.6 Conclusions

Assessment tools which encompass both the structure and quantitative biomass response of phytoplankton communities are required to comply with the EU WFD and support management policies. The Phyto Index proposed in this study appears to correlate well with existing methods and hence allows continuity and comparability with historic status classifications. In addition, it improves the level of agreement between the status of Irish water bodies and the overall WFD classification, thus suggesting that a more realistic indication of status is portrayed.

The exploration of the phytoplankton dataset was far from exhaustive but does indicate the importance of physical and chemical factors on the blooming species that occur in Irish estuarine and coastal systems. It also highlights the similarities between geographically close systems in terms of the bloom species found and the environmental conditions.

4 Modelling the Response of Irish Estuaries to Changing Nutrient Loads

The work completed for this section of the report has been published in the journal *Estuaries and Coasts* as:

Ni Longphuirt *et al.*, 2015b. Influence of hydrological regime in determining the response of macroalgal blooms to nutrient loading in two Irish estuaries. *Estuaries and Coasts* 39: 478–494 (DOI 10.1007/s12237-015-0009-5)

4.1 Abstract

Eutrophication and the development of persistent opportunistic macroalgal blooms are recognised as one of the main detrimental effects of increased anthropogenic pressures on estuarine and coastal systems. This study aimed to highlight the interplay between pressures and controlling physical factors on ecosystem functioning. The hypothesis that hydrological regime can control the growth of opportunistic macroalgae was tested with the study of two Irish estuaries, the Argideen and the Blackwater, with similar nutrient loading sources but divergent hydrological regimes. Seasonal monitoring data were initially examined, while the application of a pre-existing box model allowed a further analysis of the influence of residence time and nutrient load modifications on macroalgal growth. Seasonal oscillations in monitored river flow rates altered nutrient transfer from the catchments to the estuaries in both cases, as is shown through differences between winter and summer nutrient concentrations. In the Argideen, however, the relative contribution of P from adjacent marine waters was high due to the shorter residence times and greater influx of marine water into the estuary. Modelling studies showed that in the Argideen Estuary, P load reduction would have potentially minimal impact on macroalgal growth due to the shorter residence time which increased the influx of P from marine sources. N load reduction of 60% had a significant, albeit limited, impact on macroalgae and was insufficient in achieving the environmental objectives for this water body. For the more river-dominated Blackwater Estuary, modelled reductions in P resulted in a considerable decrease in biomass. Any further P decreases would accentuate the existing disparity in estuarine N:P ratios with possible repercussions for N transport to the coastal system. Hence, the hydrological complexity of estuarine systems demonstrated dictates that a portfolio of separate, but complementary, management approaches may be required to address eutrophication in these estuaries.

To avoid copyright infringement, the results of this particular section of the project are not presented in this report; however, the full manuscript is available online (http://link.springer.com/article/10.1007%2Fs12237-015-0009-5).

5 Conclusions

5.1 Implications of Historic Nutrient Reduction Measures for Riverine Inputs

The implementation of blanket measures to improve diffuse and point nutrient sources since 2000 have been effective in reducing nutrient loadings to many Irish catchments. The disparity between the overall N and P reductions (7% and 51%, respectively) calculated for the 18 catchments in this study mirrors the targeting of control measures to reduce P levels, because of its role as a limiting nutrient in most freshwater systems. The prominence of decreases in point source levels to overall P reduction, specifically in areas in which P sources are mainly diffuse, highlights the significance of improvements to waste water treatment over the intervening decade. This large improvement in waste water treatment has resulted in an increase in the relative importance of P from diffuse sources from 58% to 70% between 2000 and 2014, while N source apportionment has remained relatively stable (90–92% of N is from diffuse sources).

The smaller reduction in calculated N loads is mirrored by the modest reduction in N riverine inputs and highlights a decoupling of N and P transport along the land–sea continuum. This phenomenon is widespread in systems in which nutrient load reduction measures have been implemented. In the Irish context, this has resulted in a significant increase in the N:P ratio in riverine inputs, particularly in areas where agricultural loads dominate.

The case study of the Blackwater system highlighted the importance of winter riverine P inputs to overall annual reductions. In addition, in light of concurrent summer P inputs, and the reduction in chlorophyll concentrations in the Blackwater Estuary, it underlined the relevance of the targeted reduction of winter slurry spreading to the improvement of biological indicators during the productive summer season.

5.2 The Importance of Moderating Factors and Ecosystem Functioning to the Regulation of Estuarine Responses

Transitional and coastal water responses to nutrient input reductions varied considerably, confirming that nutrient cycling processes, physical factors and ecosystem functioning may modulate response mechanisms.

Nutrient cycling in Irish transitional and coastal waters is largely undocumented, but could potentially be important for the extent, timing and direction of nutrient responses. Important chemical processes include the desorption of P from estuarine sediments as salinity increases, and the stocking and subsequent release of N from estuarine sediments as inputs vary. Changes in the biological retention of nutrients by primary producers, because of a reduction in limiting nutrients such as P, could offset any reduction in N inputs, as noted for the Blackwater system, and have deleterious impacts on adjacent coastal areas as a result of alterations in nutrient transport and load ratios.

The concept that moderating factors, such as light and residence times, can curtail the response of primary producers to nutrient forcings in many Irish systems, highlighted in O'Boyle *et al*. (2015), was reinforced by the findings of the current study. The absence of a significant response to nutrient reduction was predicated on historically low chlorophyll concentrations in a number of estuaries. In turn, nutrient controls are expected to result in considerable reductions in chlorophyll levels if nutrient concentration is the main controlling factor for primary production.

The exploration of the phytoplankton dataset indicates that physical and chemical factors influence not only the biomass of phytoplankton communities, but also the community structure and species responsible for blooming events in Irish estuarine and coastal systems. It also highlights the similarities between geographically close systems in terms of the prevalent environmental conditions and bloom species.

This study highlights the importance of diverse ecosystem functioning on the response of systems to nutrient loads. In marine-dominated systems (e.g. the Arigdeen and Tolka systems), seasonal oscillations in nutrient delivery, coupled with low residence times, can result in an increase in P inputs from adjacent coastal waters. The modelling study undertaken here highlights the importance of this marine source for sustaining opportunistic macroalgal mats in specific systems. Furthermore, it shows that measures aimed at reducing anthropogenic P sources may not be effective at improving estuarine health in these marine-dominated systems. In such cases, considerable and targeted N reduction may, in fact, be the only effective measure; however, this may not be feasible for both technical and socio-economic reasons.

The Dynamic Combined Phytoplankton and Macroalgal (DCPM) model applied in this study is considered a useful tool for the identification of the possible implications of decreased nutrient loading; furthermore, it can be incorporated into programmes of measures through the identification of the most-limiting nutrient in at-risk systems and the identification of the necessary nutrient reductions required to improve status. In addition, it can also provide information on the functioning of systems with regard to the importance of marine nutrient sources versus riverine inputs, particularly in marine-dominated systems in which opportunistic green macroalgal blooms impact on overall ecosystem health.

5.3 Phytoplankton Tool Development

The development of a Phyto Index, which encompasses metrics that reflect both the structure and quantitative biomass response of phytoplankton communities and thus complies with EU WFD requirements, was also completed during the project. The Phyto Index correlates well with existing methods and hence allows continuity and comparability with historic status classifications. In addition, it provides a higher level of agreement with regard to the status of Irish water bodies and overall WFD classifications, suggesting that it provides a more realistic indicator of status.

6 Recommendations

6.1 Implications for Future Programmes of Measures

Detailed knowledge of nutrient pressures and sources in catchments is vital for catchment managers' efforts to reduce nutrient loadings and eutrophication in surface waters (Kronvang *et al*., 2016). However, just as relevant is an understanding of the response mechanisms of transitional and coastal waters to any measures that are implemented. As such, a retrospective approach, which identifies the links between measures and responses, will assist with the adoption of a more targeted approach to nutrient reduction. This is particularly relevant for the current Tier-2 sub-catchment characterisation being undertaken by the EPA's WFD Integration and Coordination Unit. The results of this project will feed directly into, and will assist in the analysis of, potentially significant pressures, the resilience of ecosystems and the likely response of estuarine systems to nutrient reductions.

The work will therefore help to inform management decisions in relation to targeting and prioritising mitigation measures which are socio-economically and technically feasible, while ensuring the best environmental return. This will provide a basis for understanding the possible consequences of further measures, or, alternatively, the required measures needed to improve status. Furthermore, it will help to elucidate the possible ramifications of increased policy-related pressures to augment agricultural outputs (Food Harvest 2020, etc.). The results of this study highlight a number of key points that should be considered when planning mitigation measures:

- The response mechanisms of transitional and coastal systems will be moderated by internal nutrient cycling and physical factors (light and residence times). These factors have been well defined in this study and that of O'Boyle *et al*. (2015) and should be considered when identifying the probable responses of systems to nutrient management. Some systems will respond well to nutrient reduction measures but, at the same time, will be very sensitive to any increases.
- Nutrient limitation can vary between systems and thus measures will need to be curtailed to reflect the most effective measure for each system and the geographical positioning of nutrient reduction measures.
- Response mechanisms and nutrient limitations will evolve along the estuarine continuum and thus measures need to account for the possible divergent implications of measures from land to sea.
- The indication that the N:P ratios of riverine inputs are increasing, and that this may have deleterious impacts particularly in coastal areas, suggests that dual nutrient reduction measures may be appropriate in a number of areas to bring N reduction in line with that of P reduction.
- The DCPM model has been applied to a number of Irish estuarine systems and has proved to be a useful tool for describing estuarine systems. In particular, it can provide information on the functioning of estuarine systems and the necessary load reductions required to improve status. In the case of marine-dominated systems impacted by opportunistic algal growth, the importance of marine sources of P could also be assessed. The model could therefore be a complementary tool for the characterisation work currently being undertaken at the catchment level in Ireland under the WFD.

6.2 Recommendations for Future Monitoring and Research Gaps

Eutrophication processes are controlled by complex interactions between many biological (grazing and growth rates), chemical (nutrient limitation) and physical (mixing and advection) factors, and the combinations of these factors are unique to any given estuary.

The results of this study have highlighted the importance of these processes to the response mechanisms of transitional and coastal waters. However, detailed information on these processes in terms of rates and resultant nutrient cycling have not yet been reported for Irish systems. The quantification and elucidation of these processes in an Irish context would complement the current understanding and allow a more detailed parameterisation of the ecosystem models currently being applied in the Irish setting. Gaps in the research have been identified for the following areas:

- the absorption and desorption of P from sediments in the estuarine setting;
- the stocking and release of N from benthic sediments and, in particular, nitrification–denitrification processes;
- the importance of nutrient flux rates for the cycling of all nutrients (N, silicic acid and P) in estuarine and coastal regions;
- direct primary production measurements of primary producers through estuarine systems;
- the timing of phytoplankton blooms;
- the importance of grazing.

In addition to further research in these areas, research into the confounding impacts of oscillating weather cycles and climate change would further increase the knowledge base for determining the probable outcomes of remediation actions.

Long-term monitoring datasets of Irish transitional and coastal systems have been key to the analyses undertaken during this study. While the results have provided an insight into the link between the anthropogenic nutrient inputs to estuarine systems and the subsequent responses, additional monitoring programmes could provide additional support to the conclusions reached and elucidate some further links between forcing factors and environmental responses. In particular, the following monitoring actions would be useful:

- Long-term high frequency monitoring of the timing and magnitude of phytoplankton primary production, biomass and community structure in key systems would elucidate the seasonal (spring/autumn) timing of blooms. The limitations of having only four samples per year was restrictive in the context of the current research because it excluded the application of phytoplankton tools that have previously been developed in Europe and that require a more comprehensive dataset. Higher frequency sampling in key systems would improve our understanding of the seasonal oscillations in Irish phytoplankton communities and the moderating factors that affect community structure.
- Concurrent high-frequency nutrient monitoring would contribute to our understanding of nutrient cycling and limitation.
- Data collection on light conditions and extinction coefficients in Irish estuarine systems would be particularly useful for defining moderating factors and identifying shifts in ecosystem functioning.
- The determination of both TP and MRP in estuarine samples would assist with the determination of the amount of P contained in sediment and organic components. This would be particularly relevant in areas where P desorption from sediment is thought to occur.
- The switch to acetone or high-performance liquid chromatography (HPLC) methods for analysing chlorophyll and related phaeopigments would bring current methods in line with acceptable global standards and would separate the relative contributions of living and dead biomass to total pigment concentration.

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Abbreviations

CART	Classification and regression tree
DCPM	Dynamic Combined Phytoplankton and Macroalgal Model
DIN	Dissolved inorganic nitrogen
DO	Dissolved oxygen
EPA	Environmental Protection Agency
EQR	Ecological quality ratio
EU	European Union
FWMC	Flow-weighted mean concentration
K	Potassium
LAM	Load apportionment model
MRP	Molybdate reactive phosphorus
MSFD	Marine Strategy Framework Directive
N	Nitrogen
NH_3	Ammonia
N:P	Nitrogen to phosphorus
OSPAR	Oslo–Paris Convention for the Protection of the North-East Atlantic
P	Phosphorus
PCA	Principal components analysis
R TTA	R Platform and TTAinterface Trend Analysis
S.I.	Statutory Instrument
TN	Total nitrogen
TON	Total oxidised nitrogen
TP	Total phosphorus
WFD	Water Framework Directive
WWTP	Waste water treatment plant
Zm:Zp	Mixing depth to photic depth ratio

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
- An Oifig um Cosaint Raideolaíoch
- 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.

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Assessing Recent Trends in Nutrient Inputs to Estuarine Waters and Their Ecological Effect

Authors: Sorcha Ní Longphuirt and Dagmar B. Stengel

Climate - Water - Sustainability
Identifying pressures • Informing policy • Developing solutions

Identify pressures

The factors and processes controlling the export of diffuse and point source pollution from land to surface water have been the focus of a number of large-scale research projects in the recent decades, and, as a result, are well understood in the Irish environment. During the current project, load apportionment modelling was used to identify nutrient pressures in the Blackwater catchment. National load apportionment outputs were also determined through collaboration with the EPA-funded Catchment Management Support Tools (CMST) Project, which aims to model temporal nutrient transfers to Irish catchments. The research outputs have increased our understanding of nutrient pressures on Irish estuarine and coastal waters.

Inform policy

The responsibilities of the EPA in relation to the Water Framework Directive were amended in July 2014 with the publication of the S.I. No. 350 of 2014 – European Union (Water Policy) Regulations 2014. This gave significant new responsibilities to the EPA, including: reviewing the impact of human activities; drafting environmental objectives; undertaking catchment characterisation; preparing template river basin management plans; and compiling common programmes of measures. The project has fed directly into Tier 2 sub-catchment characterisation being undertaken by the EPA and can assist in the analysis of potentially significant pressures, the resilience of ecosystem, and likely response of estuarine systems to nutrient reductions. The work, which is on-going, therefore has helped inform management decisions in relation to targeting and prioritising mitigation measures which are socio-economically and technically feasible while ensuring the best environmental return.

Develop solutions

The selection of effective measures for estuarine and coastal waters will be predicated on having a well-developed understanding of how pressures interact with environmental factors and impact on biological receptors. The current project has helped to disentangle the biophysical and chemical factors that constrain/maintain the status of water bodies through the use of a simple box model which can be run using different scenarios of projected nutrient loads (agricultural and urban waste water), and climate considerations (flow regimes and winter/summer loads).

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