

STRIVE

Report Series No.66

Nutrient and Ecosystem Dynamics in Ireland's Only Marine Nature Reserve (NEIDIN)

STRIVE

Environmental Protection
Agency Programme

2007-2013

Environmental Protection Agency

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EPA STRIVE Programme 2007–2013

**Nutrient and Ecosystem Dynamics in Ireland's
Only Marine Nature Reserve (NEIDIN)**

(2007-FS-B-4-M5)

STRIVE Report

Prepared for the Environmental Protection Agency

by

School of Biological, Earth and Environmental Sciences, University College Cork

Authors:

Mark Jessopp, Rob McAllen, John O'Halloran and Tom Kelly

ENVIRONMENTAL PROTECTION AGENCY

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

Telephone: +353 53 916 0600 Fax: +353 53 916 0699

Email: info@epa.ie Website: www.epa.ie

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The EPA STRIVE 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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Details of Project Partners

Dr Mark Jessopp*

School of Biological, Earth and Environmental
Sciences
Environmental Research Institute
University College Cork
North Mall
Cork
Ireland
Email: mjessopp@gmail.com

Dr Rob McAllen

School of Biological, Earth and Environmental
Sciences
University College Cork
North Mall
Cork
Ireland
Email: r.mcallen@ucc.ie

Prof. John O'Halloran

School of Biological, Earth and Environmental
Sciences
University College Cork
North Mall
Cork
Ireland

Dr Tom Kelly

School of Biological, Earth and Environmental
Sciences
University College Cork
North Mall
Cork
Ireland

Dr Robert Barber

Centre for Microfluidics and Microsystems
Modelling
Science and Technology Facilities Council
Daresbury Science and Innovation Campus
Warrington WA4 4AD
UK

Mr Kevin Barry

Civil and Environmental Engineering
Environmental Informatics Unit
University College Cork
Cork
Ireland

***Current address:**

Coastal & Marine Research Centre
Environmental Research Institute
University College Cork
Irish Naval Base
Haulbowline
Cork
Ireland

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Executive Summary

Humans now strongly influence almost every major aquatic ecosystem, and their activities have dramatically altered the fluxes of growth-limiting nutrients from the landscape to receiving waters. Increased incidence of algal blooms and necrotic patches in jewel anemone colonies suggest that anthropogenic nutrient enrichment may be negatively impacting Ireland's only statutory marine reserve, Lough Hyne. This project aimed to address the nutrient and ecosystem dynamics within Lough Hyne, with additional reference to the candidate special areas of conservation at Tragumna and Tranabo Bays.

Water quality and nutrient analysis was conducted monthly for 23 months. Initial high values of total nitrogen at the beginning of the study reduced over the course of the year, but remained much higher than historical values. The atomic ratio of nitrogen to phosphorus in water samples greatly exceeded the 16:1 ratio for optimum phytoplankton growth, suggesting that the coastal environment is phosphorus limited. There were no significant differences in nutrient levels between Lough Hyne and adjacent nearshore coastal areas, suggesting that high nutrient levels are part of a wider coastal problem, and not from localised inputs. Potentially eutrophic conditions where $TN^1 > 350 \text{ mg/m}^3$ and $TP^1 > 30 \text{ mg/m}^3$ occurred in 101 and 27 out of 131 samples, respectively, indicating a high degree of nitrogen enrichment in coastal waters. Bloom conditions (where phytoplankton cell abundance exceeded 10^6 cells/l) occurred on 27 sampling occasions.

Phytoplankton assemblages were studied for 18 months in Lough Hyne and the adjacent coast, and the influence of nutrients on structuring phytoplankton assemblages was investigated. Lough Hyne had higher phytoplankton abundances, yet lower Shannon–Weiner diversity, indicating a proliferation of relatively few dominant species. Non-metric multidimensional scaling plots showed a general separation of reserve and adjacent coastal areas, with

1. TN, total nitrogen; TP, total phosphorus.

significant differences between Lough Hyne and adjacent coastal areas being detected. Lough Hyne tended to be characterised by higher abundances of tintinnids, microflagellates and dinoflagellates, while locations outside Lough Hyne had overall higher abundances of diatom species. Diatom abundance correlated with chlorophyll *a* and the phosphorus to silicon ratio, suggesting that phosphorus may be the limiting nutrient to diatom production. Dinoflagellates correlated with salinity, temperature, and total nitrogen, indicating that the high nitrogen levels observed in marine waters favour dinoflagellate production.

A series of phytoplankton growth and microzooplankton grazing experiments were run in Lough Hyne and Tranabo Bay to investigate the extent to which top–down and bottom–up processes influence the observed differences in phytoplankton assemblages noted between Lough Hyne and adjacent coastal areas. Negative phytoplankton growth rates were observed in both locations, indicating that microzooplankton grazing was greater than phytoplankton growth at the time of the experiment. Microzooplankton grazing in Tranabo Bay was high, while in Lough Hyne the grazing rate was weak and non-significant. The phytoplankton growth rate was much higher in samples containing mesozooplankton grazers, suggesting mesozooplankton grazing on the abundant ciliates and heterotrophic dinoflagellates, which in turn reduced overall grazing pressure on phytoplankton. This suggests that top–down processes play a greater role in structuring phytoplankton assemblages at Lough Hyne.

Finally, the catchment and hydrodynamics of Lough Hyne were characterised. Catchment areas for Lough Hyne, Tranabo Bay, and Tragumna Bay were calculated as 2.89, 0.37 and 11.77 km^2 , respectively. Given that Tragumna Bay has a large catchment relative to its size, it may be more susceptible to anthropogenic nutrient enrichment associated with

runoff into its coastal waters. A two-dimensional, depth-averaged hydrodynamic model of Lough Hyne was developed that successfully modelled the unique 8-h ebb and 4-h flood tides observed in the lough. A revised tidal flushing time of 15 days was calculated. However, complete flushing of the lough was estimated at approximately 80 days, effectively double that of earlier estimates.

Along with Environmental Protection Agency reporting

of eutrophic status in estuaries along the south and south-east coast of Ireland, it is apparent that nutrient enrichment of nearshore coastal waters is widespread, and also adversely affects a number of areas in the south-west of Ireland. Exceptional algal mats have been noted in Clonakilty and Rosscarbery Estuaries as well as the Blue Flag beach at Inchydoney, highlighting the importance of reducing nutrient loadings and conducting regular monitoring.

1 Introduction

1.1 Background

Humans now strongly influence almost every major aquatic ecosystem, and their activities have dramatically altered the fluxes of growth-limiting nutrients from the landscape to receiving waters. Unfortunately, these nutrient inputs can have a profound negative effect upon the quality of surface waters worldwide (Smith, 2003).

Freshwater eutrophication and its effects on algal-related water quality are well understood and research continues to advance rapidly. However, our understanding of the effects of eutrophication on estuarine and coastal marine ecosystems is much more limited. This gap represents an important research need. Ecosystem responses to eutrophication depend on both export rates (flushing, microbially mediated losses through respiration, and denitrification) and recycling/regeneration rates within the coastal waters. The mitigation of the effects of eutrophication involves the regulation of inorganic nutrient (primarily nitrate and phosphate) inputs into receiving waters. Even though coastal systems can be hydrologically complex, the biomass of marine phytoplankton nonetheless appears to respond sensitively and predictably to changes in the external supplies of nitrogen and phosphate. These responses suggest that efforts to manage nutrient inputs to the seas will result in significant improvements in coastal zone water quality. Appropriately scaled and parameterised nutrient and hydrological controls are the only realistic options for controlling phytoplankton blooms, algal toxicity, and other symptoms of eutrophication in coastal ecosystems. However, regular monitoring of such inputs and detailed baseline information is paramount in this regard (Pinckney, 2001).

Lough Hyne Marine Nature Reserve in West Cork is one of Ireland's premier marine heritage sites. It was designated as Europe's first (and Ireland's only) marine reserve in 1981 to protect the rich biodiversity that occurs within its depths. This biodiversity is largely

due to the high habitat diversity caused by the highly variable flow regime that occurs within the marine reserve (from 3 m/s to virtually nothing). This is due to the 'Rapids', a narrow shallow constriction through which all tidal exchange occurs. The Rapids cause a unique asymmetrical tide (4 h flood, 8.5 h ebb (Bassindale et al., 1948)). The tidal restriction seen within Lough Hyne generates long water retention times, suggested to be as long as 41 days for complete flushing (Johnson et al., 1995). A seasonal thermocline, associated with temperature rather than salinity gradients (Thain et al., 1981), also develops in the deeper Western Trough area of the Lough resulting in severe hypoxia and anoxia for several months over the summer (McAllen et al., 2009). Over 300 papers have been published on the biota of Lough Hyne over the last 100 years; however, only a small proportion of these have provided any systematic data on water quality with a view to potential impacts on the marine reserve and its flora and fauna.

This lack of baseline data is potentially critical in terms of sustaining the integrity, biodiversity monitoring and potential climate change issues of this unique site. Lough Hyne is a very popular tourist attraction, especially during the summer months, and the need for confidence in the water quality is obviously of interest with regards to human health. However, concerns over the nutrient input and water quality of the Lough Hyne Marine Nature Reserve have been expressed by academic and government officers (National Parks and Wildlife Service). Increased occurrences of algal blooms within the lough have been reported in recent years, and may be a sign of nutrient enrichment leading to eutrophication effects.

Lough Hyne is relatively simple in its hydrography with a well-defined basin linked to the open sea by a tidal channel, which facilitates small-scale studies. In comparison with other coastal systems, tidal advection plays a lesser role in Lough Hyne, but at the same time represents a natural system with considerably greater complexity than experimental mesocosms. As such, findings from Lough Hyne can be placed in a broader

context, allowing extrapolation and comparison with other coastal systems. The use of two further candidate Special Areas of Conservation (SAC) sites in this study to the east of Lough Hyne at Tranabo and Tragumna Bays provides a wider context to this coastal nutrient status study. Tranabo is directly east of Lough Hyne and shares a very similar geological landscape, and has a small local community. Tragumna Bay is situated between Lough Hyne and Gokane Point. At the western end of the bay is Trallspean, a popular tourist beach with a substantial freshwater runoff across the beach and a small number of local residents. At the eastern end of the bay is the large village of Tragumna itself. All locations have salinity above 34 practical salinity units, and are characterised as fully marine rather than estuarine.

1.2 Project Objectives

This project aimed to address the nutrient and ecosystem dynamics within Ireland's only statutory marine reserve with additional reference to the

candidate SACs at Tragumna and Tranabo Bays. Specifically, the main objectives were to:

- Review and collate the limited literature and data of nutrient input available for Lough Hyne and surrounding area;
- Characterise the catchment area and boundaries surrounding these coastal waters by the use of a geographic information system (GIS) and examine any particular areas of risk;
- Characterise the hydrodynamics and variable flow regime of Lough Hyne;
- Assess water quality indicators at various sites within the study area, in particular nutrient status (total nitrogen, total phosphorus, silicates) and environmental parameters (salinity, temperature, dissolved oxygen and chlorophyll *a*); and
- Examine the influence of nutrients and environmental variables on the ecosystem dynamics, in particular phytoplankton assemblages.

2 Water Chemistry

2.1 Background

The total primary production and biomass of phytoplankton is directly related to nutrient loadings from land, as well as release from sediments, and the subsequent availability of these nutrients in the water column (Philippart et al., 2000; Cloern, 2001; Hu et al., 2001). Excess nutrients may be utilised by primary producers such as phytoplankton, resulting in increased biomass and density, as well as prolonged phytoplankton blooms. There are, however, thresholds where the capacity for assimilation of nutrient-enhanced production is exceeded, with water quality degradation the ultimate result (Rabalais, 2002; Rabalais et al., 2009). Loss of submerged aquatic vegetation due to decreased light levels (Valiela et al., 1997) and reduced oxygen levels in bottom waters due to microbial decomposition of particulate organic matter (Diaz and Rosenberg, 2008) are two of the more ecologically problematic results of such coastal eutrophication.

It is generally accepted that nitrogen is the limiting nutrient in marine systems (Nixon et al., 1996), in contrast to freshwater systems where phosphorus is regarded as the limiting nutrient (Schindler, 1974). However, anthropogenic nutrient enrichment has led to an 18–80 times increase in phosphorus and a 6–50 times increase in nitrogen levels in riverine inputs to estuarine systems relative to pristine conditions, with 2–6 times greater phosphorus, and 1.5–4.5 times greater nitrogen relative to the turn of the last century (Conley, 1999). The present balance of nitrogen and phosphorus is such that the nitrogen to phosphorus ratio of freshwater inputs to marine systems has increased to greater than that required for optimal plant growth (16:1 on an atomic basis, Justic et al., 1995; Howarth, 1996), with the ratio of nutrients also playing a vital role in the type of phytoplankton assemblages present in an area. The atomic silicon to nitrogen to phosphorus ratio of marine diatoms is about 16:16:1 when nutrient levels are sufficient (Redfield et al., 1963; Brzezinski, 1985). Decreasing the silicon to nitrogen ratio may reduce the potential for diatom

growth in favour of noxious flagellates (Officer and Ryther, 1980), and long-term decreases in silicon to phosphorus ratios have been associated with blooms of non-siliceous algae in coastal waters worldwide (Smayda, 1990).

While diatoms grow rapidly, have short lifetimes, and are a high-quality food source for primary consumers (Brett and Müller-Navarra, 1997), flagellates are frequently poor foods for most grazers and can lead to many undesirable effects. Excessive flagellate growth that is not grazed can lead to the de-oxygenation of the water column as organic matter sinks and decays, while some species are known to produce toxins that can lead to fish kills and shellfish poisoning in man (James et al., 1999). In Ireland, blooms of *Karenia mikimotoi* have caused mortalities in farmed salmon in Dunmanus Bay and mortalities of farmed clams off the coast of Sligo (Carmody et al., 1996). The dinoflagellate *Heterosigma akashiwo* has also caused mortality in caged fish in Ireland (ICES, 1991). Aquaculture operations are particularly sensitive to such blooms, since farmed or caged fish and shellfish cannot move away from affected areas.

Historically, assessment and management of eutrophication has been based on simple diagnostic measurements such as the mean winter nutrient concentrations against a reference threshold, an empirical approach that has been used in freshwater systems (Carlson, 1977). However, naturally occurring high nutrient levels, particularly in areas of coastal upwelling along the western boundary of continental land masses support rich communities where nutrient-enhanced production may be assimilated by higher trophic levels. Pitta et al. (2009) also found that excess nutrients around fish farms may effectively be transferred up the food web through microzooplankton grazing of phytoplankton biomass. Secondary production and, to a point, the quantity of fish harvested from an area are proportional to nutrient concentration, but only to a threshold, above which fishery yields may decline (Nixon and Buckley, 2002), so high nutrient levels are not in themselves always a

bad thing. The Water Framework Directive (WFD) states that at 'high' status, physico-chemical elements must be within their natural background ranges. High nutrient concentration is, therefore, regarded as cause for concern, necessitating detailed assessment of the biological response and the presence of undesirable disturbance. Nutrient concentrations in excess of baseline levels are now regarded as the first in a series of diagnostic steps to assess the risk of eutrophication.

No regular monitoring of nutrients and water quality has been undertaken at Lough Hyne since 1994. Johnson et al. (1995) found a net tidal input of dissolved inorganic phosphorus and significant inputs of dissolved inorganic nitrogen and silicon from freshwater sources to the lough. Concurrent with an increased frequency of red tide events observed in recent years at Lough Hyne (personal observation), it is also generally accepted that there is an increased

temporal and spatial frequency of nearshore blooms of benign, noxious and toxic flagellate species worldwide (Hallegraeff, 1993). The purpose of this study was therefore to monitor nutrient levels in Lough Hyne and the adjacent coastal area to determine whether nutrient enrichment is leading to the increased frequency of phytoplankton blooms, and to compare current levels with historical data for the purposes of identifying long-term trends.

2.2 Methods

Water samples were collected monthly from six marine locations in Lough Hyne Marine Nature Reserve and adjacent coastal areas as well as the small freshwater inputs to these areas (Fig. 2.1, Table 2.1) from January 2008 to November 2009. In marine locations, an integrated water sample was collected using a hose sampler (Qin and Culver, 1996; Dolan and Gallegos, 2001; Johnson and Costello, 2002; Rodriguez et al.,

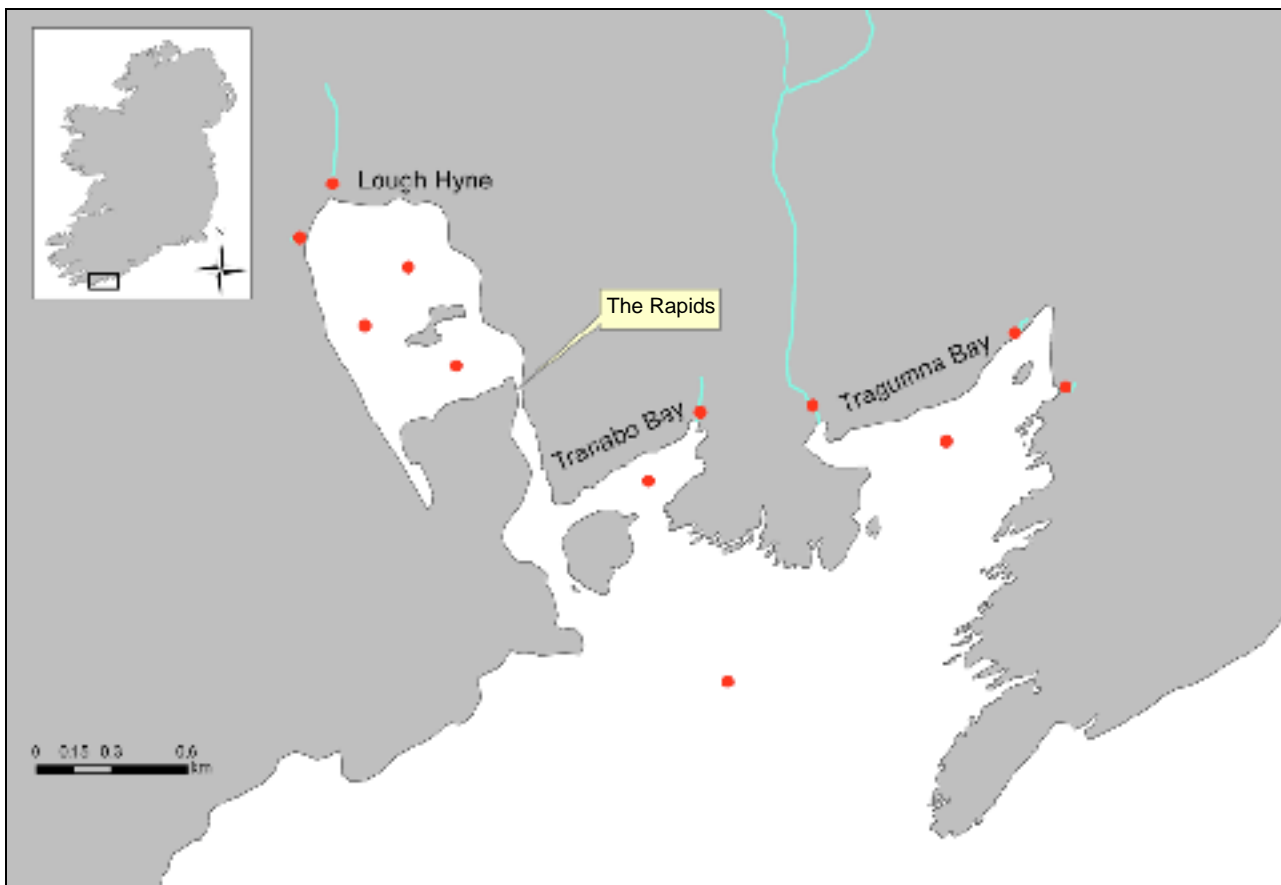


Figure 2.1. Sampling locations in Lough Hyne Marine Nature Reserve, Tranabo Bay, Tragumna Bay and adjacent coastal area, also showing location of freshwater inputs.

Table 2.1. Sampling locations. Darker shaded cells represent marine locations, lighter shaded cells represent freshwater inputs.

Location	Latitude	Longitude
Lough Hyne, South Basin	51° 29.994' N	9° 17.941' W
Lough Hyne, Western Trough	51° 30.015' N	9° 18.211' W
Lough Hyne, North Basin	51° 30.21' N	9° 18.099' W
Lough Hyne, Kelly's Pier	51° 30.238' N	9° 18.457' W
Lough Hyne, North Quay	51° 30.37' N	9° 18.375' W
Tranabo Bay	51° 29.763' N	9° 17.221' W
Tranabo Bay	51° 29.882' N	9° 17.106' W
Tragumna Bay	51° 29.841' N	9° 16.124' W
Tragumna Bay, Trallispean	51° 29.908' N	9° 16.675' W
Tragumna Bay, beach	51° 30.122' N	9° 15.934' W
Tragumna Bay, boat slip	51° 29.977' N	9° 15.834' W
Coast	51° 28.868' N	9° 17.427' W

2003; Cartensen et al., 2004) from the surface to 10 m depth, and a 1-l subsample was collected. Samples from freshwater inputs were taken by lowering 1-l sample bottles directly into streams. Water samples were immediately taken back to Cork (approx 1.5 h drive), for analysis of total nitrogen, total phosphorus, silicate and chlorophyll *a* by the University College Cork Aquatic Services Unit. Total phosphorus was determined following digestion of unfiltered sample with persulphate and sulphuric acid (Murphy and Riley, 1962), total nitrogen was determined following persulphate oxidation with potassium persulphate and boric acid (Grasshoff et al., 1983), and silicates by a manual colorimetric method (Parsons et al., 1984). Chlorophyll *a* was measured spectrophotometrically following overnight extraction of pigments in methanol (Her Majesty's Stationery Office, 1980). Associated salinity, water temperature and dissolved oxygen readings were taken with environmental probes at the time of sample collection. Daily rainfall data were obtained via Met Éireann (<http://www.met.ie>), using the weather station on Sherkin Island.

Additional sediment samples were collected before and after formation of the seasonal thermocline in Lough Hyne to determine the role of sediments in storing nutrients. Divers collected samples from 10-

20- and 30-m depths in the Western Trough, and at approximately 18 m depth in the North and South Basins of the lough. These samples were immediately frozen and later analysed for total Kjeldahl nitrogen (ammonia + organic nitrogen, but not oxidised nitrogen (nitrate + nitrite)), and total phosphorus.

2.3 Results

The freshwater replacement rate, ρ , of the bays can be calculated using the difference in salinity between coastal and bay waters according to the equation (adapted from Johnson et al., 1995):

$$\rho = \tau(S_c - S_b) / S_b \quad \text{Eqn 2.1}$$

where τ is the tidal replacement rate of the bay, S_c is the salinity of coastal water, and S_b is the salinity of water in the bay. [Table 2.2](#) shows the calculated freshwater replacement rate of the bays studied. Lough Hyne has a freshwater replacement rate of 0.112 per year, or a freshwater flushing time of just under 9 years. Tranabo Bay has a freshwater replacement rate of 4.69 per year (freshwater flushing of 77 days), and Tragumna Bay 0.915 per year (freshwater flushing of just over 1 year). It is apparent that Tranabo Bay, on account of its small volume, is most susceptible to freshwater nutrient input, although this is mitigated by its high tidal replacement rate (410

Table 2.2. Salinity and calculated freshwater replacement rates (per year) for the bays in the study.

Location	Average salinity (±SD)	τ (per year)	ρ (per year)
Coast	34.49 ± 0.412		
Lough Hyne	34.06 ± 0.543	8.85 ¹	0.112
Tranabo Bay	34.1 ± 0.607	410.11 ²	4.69
Tragumna Bay	34.33 ± 0.479	196.23 ²	0.915

¹Johnson et al. (1995).
²Jessopp et al. (2007).

times per year), meaning that water in the Bay is completely replaced on less than a daily basis, preventing build-up of freshwater nutrient inputs. Lough Hyne, Tranabo Bay and Tragumna Bay all have salinity only slightly below that of the adjacent coastal water, making them marine rather than estuarine in nature.

Freshwater inputs show higher levels (and greater variability between months) of all nutrients than the marine locations, particularly total nitrogen and silicates (Table 2.3, Fig. 2.2). However, given the high salinities and low freshwater replacement rates in the bays studied, the overall contribution of nutrients from the freshwater inputs to coastal waters is minimal.

No significant differences were detected between marine locations for nutrients (total nitrogen, total phosphorus and silicon). However, great variability was observed in nutrients from freshwater inputs. Lough Hyne tended to have lower total nitrogen and total phosphorus levels than Tranabo and Tragumna Bays, while silicon levels were roughly similar, possibly illustrating the effects of both a small water catchment area and no agriculture in the immediate vicinity. The

presence of agricultural activities in the catchment for Tranabo and Tragumna Bays will explain the higher nutrient loading of freshwater inputs to these areas. There was a significant difference in chlorophyll *a* levels between locations. Tukey's pairwise comparisons failed to resolve the differences, but there was a general trend for Lough Hyne to have higher chlorophyll *a* levels than other marine locations (Fig. 2.2, Table 2.4).

Table 2.4. ANOVA¹ of chlorophyll *a* levels in marine sampling locations. Data from January 2008 to November 2009.

	df	MS	F	P
Location	5	53.8	2.650	0.026
Error	126	20.3		
Total	131			

¹ANOVA, analysis of variance.

There was a significant effect of sampling month on nutrient concentration, with higher concentrations of nitrogen and phosphorus in winter months when

Table 2.3. ANOVA¹ of total nitrogen, total phosphorus and silicon for marine versus freshwater samples.

	df	Total nitrogen			Total phosphorus			Silicon		
		MS	F	P	MS	F	P	MS	F	P
Marine/Fresh	1	134.646	255.760	<0.001	0.00858	24.67	<0.001	151.283	1512.14	<0.001
Error	262	0.526			0.000348			0.1		
Total	263									

¹ANOVA, analysis of variance.

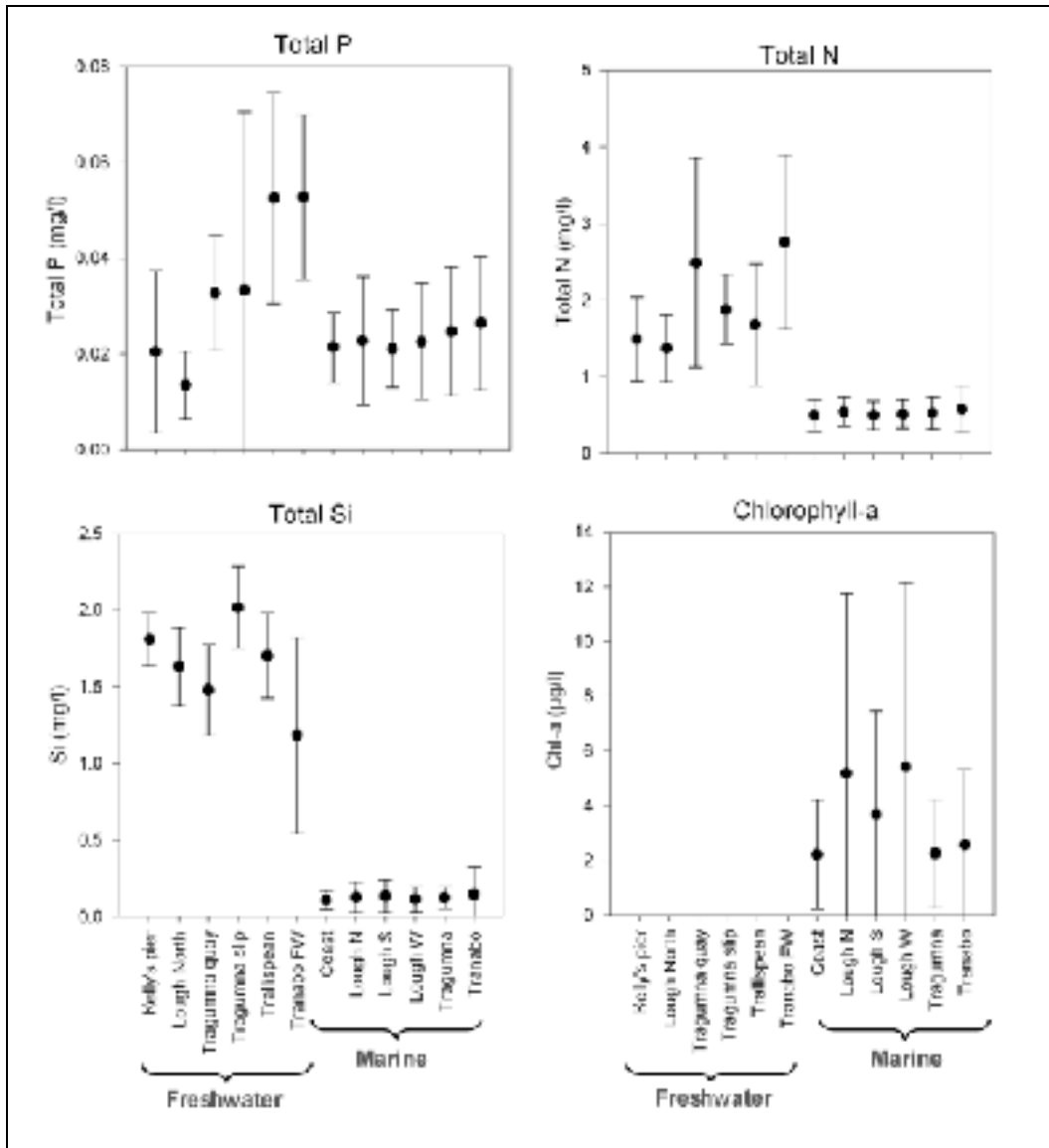


Figure 2.2. Nutrients (total nitrogen (total N), total phosphorus (total P), and total silicon (total Si)) and chlorophyll a levels for marine sampling locations (at salinity ~34.1) and their freshwater inputs. Data from January 2008 to November 2009 ± standard deviation.

phytoplankton growth becomes light and temperature limited. Lower nutrient levels occurred over spring/summer months coinciding with high phytoplankton abundance (Fig. 2.3). Molar ratios of total nitrogen to total phosphorus (Fig. 2.4) in marine water samples all exceeded the 16:1 Redfield ratio for optimum phytoplankton growth, suggesting that phosphorus is the limiting nutrient in this system.

The high total nitrogen to total phosphorus ratios observed led to an investigation of whether the current nutrient levels are consistent with previous data from

the same area. Total nitrogen and total phosphorus data are available courtesy of Prof. Mark Johnson (National University of Ireland, Galway) from investigations into the nutrient economy of Lough Hyne during 1992–1993. A comparison of 1992–1993 (unpublished) data with data collected during 2008–2009 shows that total nitrogen is considerably higher, while total phosphorus is slightly lower than previous levels (Fig. 2.5). To investigate possible causes of the high nitrogen values compared to historical data, regression of rainfall with total nitrogen values was

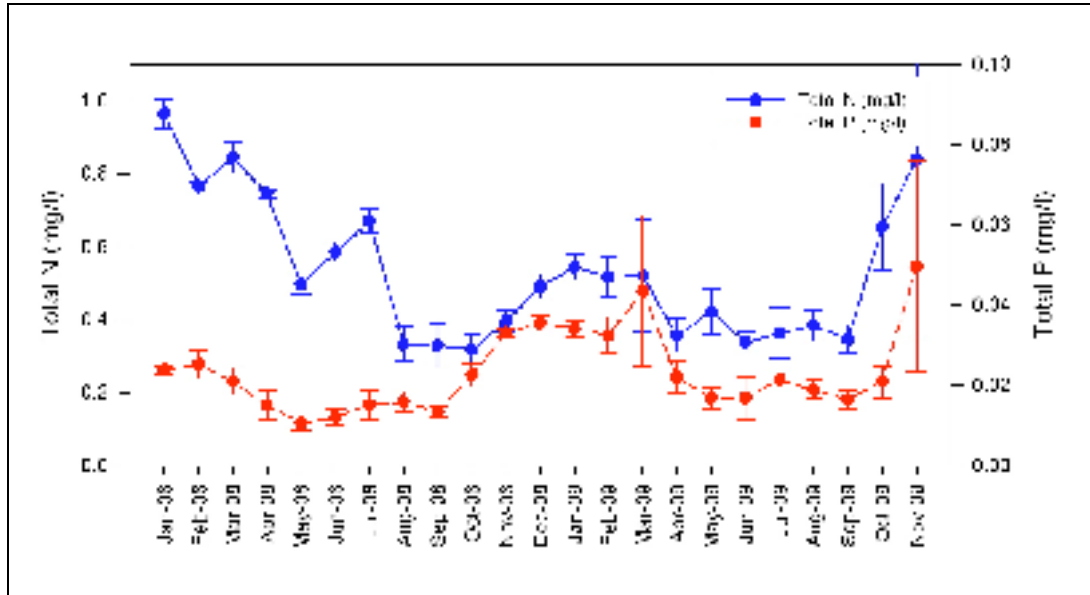


Figure 2.3. Total nitrogen (Total N) and total phosphorus (Total P) ± standard deviation for marine locations by month. Note difference in scale between both.

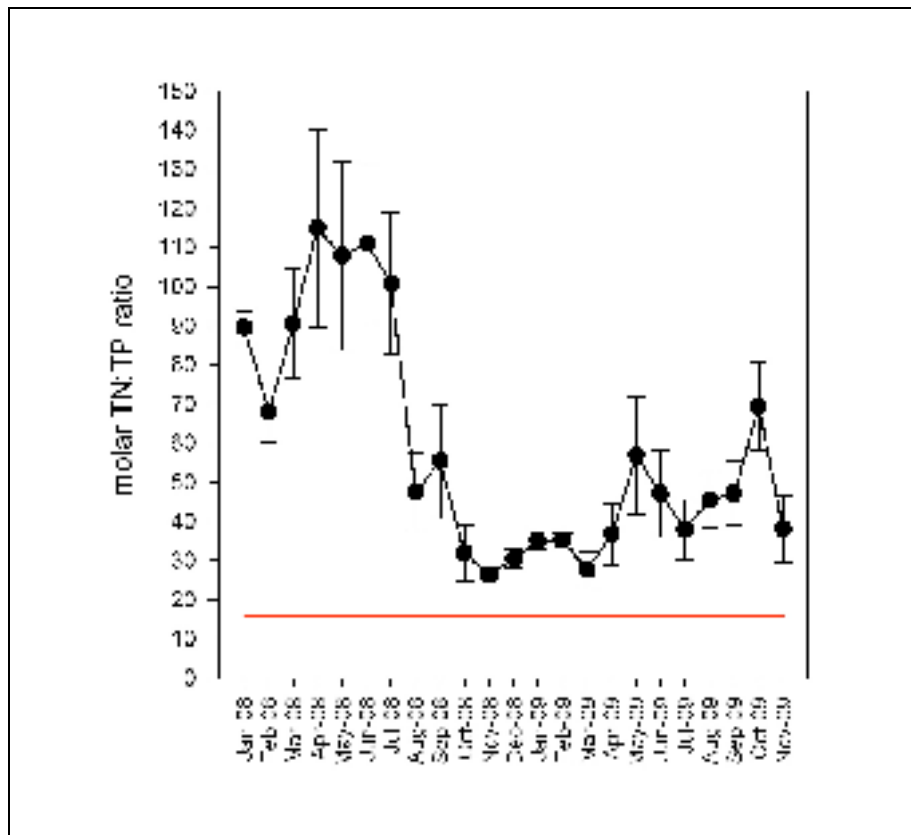


Figure 2.4. Molar ratios of total nitrogen (TN) to total phosphorus (TP) in marine samples. Red line indicates the 16:1 Redfield ratio for optimum phytoplankton growth.

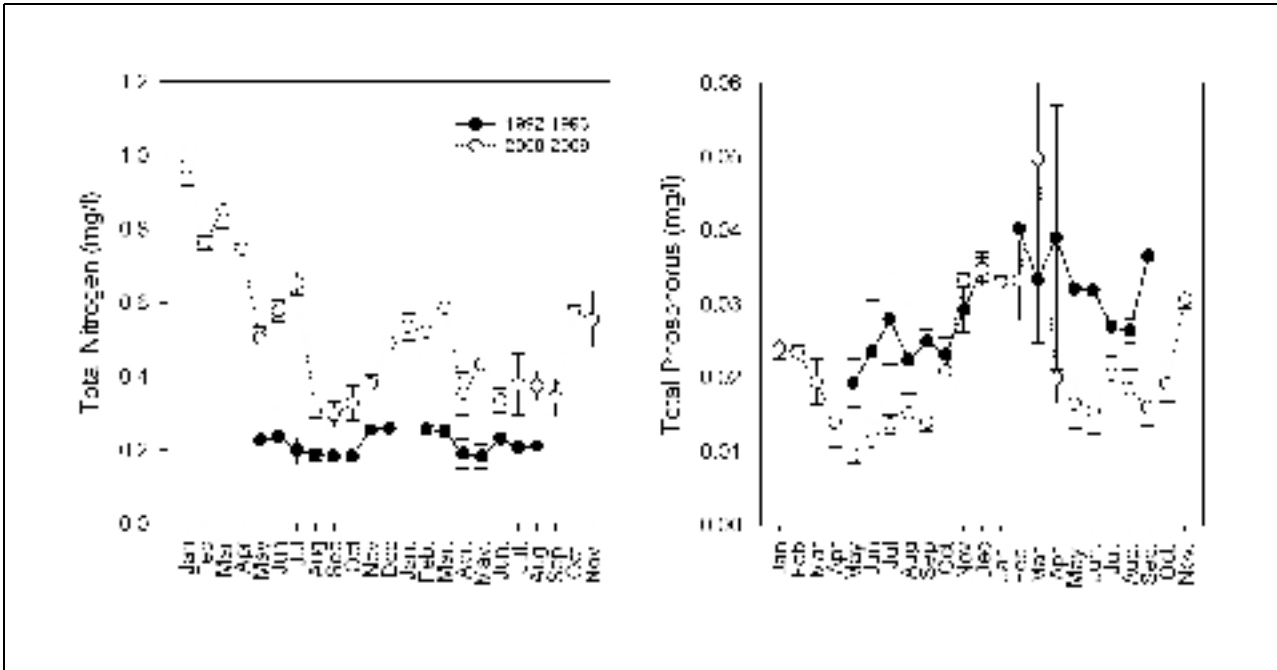


Figure 2.5. Comparison of 1992–1993 (filled circles) and 2008–2009 (open circles) data for total nitrogen and total phosphorus. Average salinity in Lough Hyne during 1992–1993 was 34.27 (Johnson, 1995), while average salinity during 2008–2009 was 34.06 (Table 2.2). Values represent mean nutrient concentration \pm standard deviation taken from marine waters in Lough Hyne and tidal inputs.

conducted. No significant relationship between nitrogen loading and either total or average rainfall for 7 days prior to sampling (total rainfall $R^2 = 5.4\%$, $P = 0.299$, average rainfall $R^2 = 5.4\%$, $P = 0.297$) or 30 days prior to sampling (total rainfall $R^2 = 0.1\%$, $P = 0.903$, average rainfall $R^2 = 0.0\%$, $P = 0.95$) was found (Fig. 2.6).

Nutrient analysis of diver-collected sediment samples showed that sediments in the South Basin had higher

nitrogen but lower phosphorus content than sediments from the North Basin, while samples from the Western Trough highlighted a marked increase in sediment nutrient loading with depth (Table 2.5).

The seasonal thermocline was present in the Western Trough of Lough Hyne in both 2008 and 2009 (Fig. 2.7). During the thermocline period, dissolved oxygen readings declined from around 25 m depth to complete de-oxygenation of the water at 30 m. In 2008,

Table 2.5. Total Kjeldahl nitrogen (ammonia + organic nitrogen, but not oxidised nitrogen (nitrate + nitrite)) and total phosphorus from diver-collected sediment samples taken after formation of the seasonal thermocline. Samples taken from 30 m in the Western Trough represent sediments taken from the anoxic zone.

Location	Total phosphorus (mg/g)	Kjeldahl nitrogen (mg/g)
South Basin, ~18 m	0.427	1.981
North Basin, ~18 m	0.516	0.832
Western Trough, 10 m	0.297	0.842
Western Trough, 20 m	0.453	1.687
Western Trough, 30 m	0.525	3.299

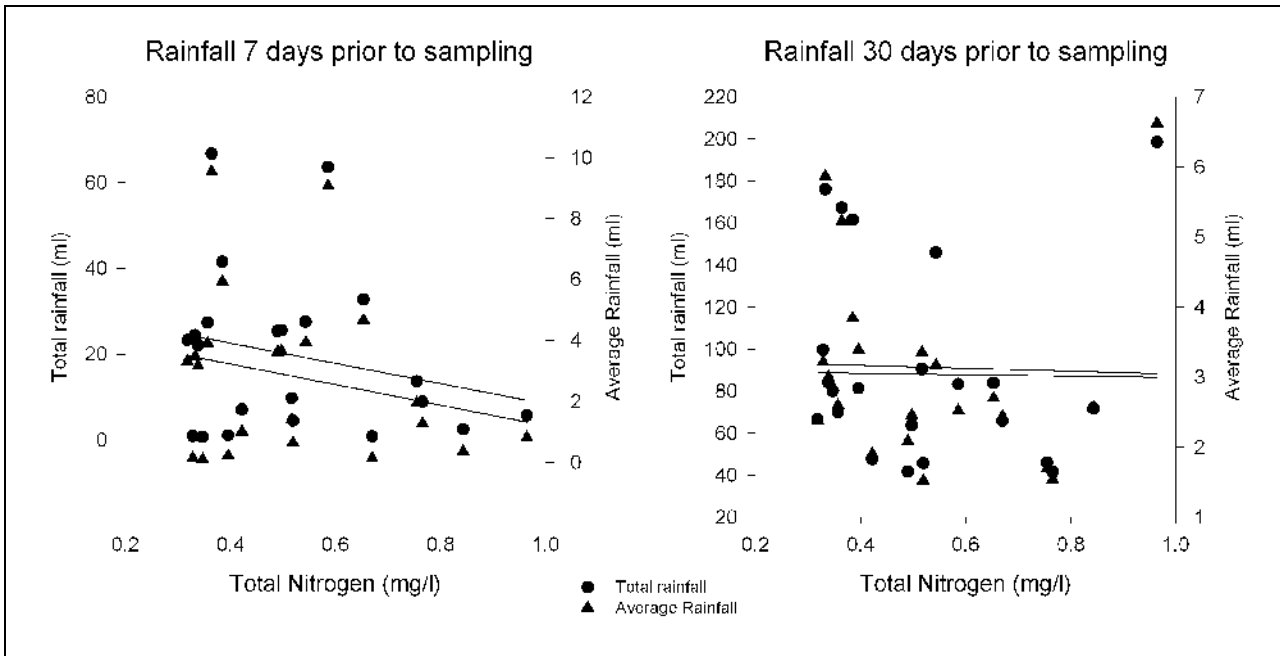


Figure 2.6. Scatter plot and regression line for total (filled circles) and average (filled triangles) rainfall versus total nitrogen in marine water samples January 2008 to October 2009. Regression of total nitrogen versus: total rainfall 7 days prior to sampling $R^2 = 5.4\%$, $P = 0.299$; average rainfall 7 days prior to sampling $R^2 = 5.4\%$, $P = 0.297$; total rainfall 30 days prior to sampling $R^2 = 0.1\%$, $P = 0.903$; average rainfall 30 days prior to sampling $R^2 = 0.0\%$, $P = 0.95$.

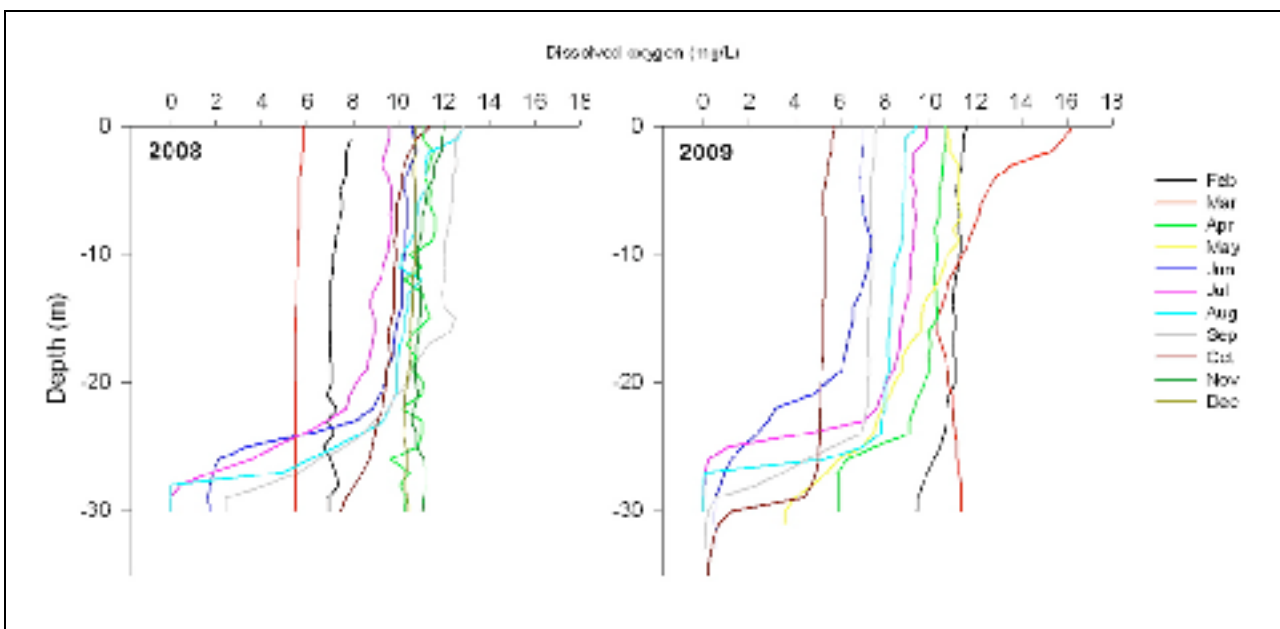


Figure 2.7. Seasonal development of thermocline showing dissolved oxygen (mg/l) with depth (m) in the Western Trough of Lough Hyne for 2008 and 2009.

the thermocline had not developed by sampling at the end of April, and equipment failure meant that no readings could be taken in May. The thermocline was already established by the June sampling period and had broken down by October. The thermocline developed earlier and lasted longer in 2009, with dissolved oxygen readings showing a marked reduction from 25 m depth in April and lasting through October. The thermocline had broken down some time before the November sampling.

2.4 Discussion

Under the European Union (EU) WFD, Member States must ensure that surface water bodies meet 'good' ecological status by 2015. In marine systems, this 'good' ecological status extends to at least 1 nautical mile from the coast for biological quality elements, and 12 nautical miles for physico-chemical quality elements (including nutrients). Guidelines for assessment of nutrient enrichment under the WFD follow the Oslo/Paris Convention (for the Protection of the Marine Environment of the North-East Atlantic) (OSPAR), which uses a comparison of winter mean nutrient levels against a reference threshold. Dissolved inorganic forms of nitrogen (nitrite + nitrate + ammonia) are used, with 'good' status defined as mean winter nutrient levels $<20 \mu\text{M}$ in coastal waters (Devlin et al., 2007b). Irish regulations set values of $12 \mu\text{M}$ and $18 \mu\text{M}$ (at salinity 34.5) for 'high' and 'good' ecological status, respectively (SI No. 272 of 2009). Nutrient analysis undertaken for this fellowship, however, determined total nitrogen (sum of all dissolved, particulate, organic and inorganic nutrients), as dissolved inorganic forms represent only a fraction of the nitrogen that may be biologically useful and that may contribute to phytoplankton growth, size structure, and community composition (Anita et al., 1991; Peierls and Paerl, 1997). While many aquatic organisms can consume and cycle dissolved organic nitrogen (Amon and Benner, 1994), particulate forms can also be ingested by zooplankton and converted to dissolved inorganic forms (Ikeda et al., 1982), making this component of the total nitrogen pool biologically available to phytoplankton. Furthermore, studies in freshwater lakes have found that total nitrogen and total phosphorus are much better predictors of algal biomass and production than nitrates or soluble

reactive phosphorus (Ryding and Rast, 1989), and the total nitrogen to total phosphorus ratio correlates well with measures of nutrient deficiency such as growth-based bioassays (Dodds and Prisco, 1990). Unfortunately, a direct comparison of dissolved inorganic nitrogen and total nitrogen levels is not possible as the ratio of dissolved inorganic to total nutrients is highly variable, particularly at low concentrations ($<5 \text{ mg/l}$, Dodds, 2003). Thresholds for 'good' ecological status are not available for total nitrogen and total phosphorus under OSPAR, but values from the literature suggest that total nitrogen values of $350\text{--}400 \text{ mg/m}^3$ and total phosphorus of $30\text{--}40 \text{ mg/m}^3$ indicate eutrophic conditions, and total nitrogen $>400 \text{ mg/m}^3$ hypertrophic conditions in coastal marine systems (Smith et al., 1999). Total nitrogen values $>350 \text{ mg/m}^3$ occurred in 101 out of 131 samples, while total phosphorus values $>30 \text{ mg/m}^3$ occurred in 27 samples, indicating a high degree of nitrogen enrichment in the nearshore coastal waters of south-west Ireland.

It was initially thought that the high total nitrogen values in marine and freshwater samples (Fig. 2.3) were a result of particularly high rainfall resulting in nutrients leaching from the ground and entering streams and thus to the coastal waters. However, no simple correlation between total nitrogen and total phosphorus existed with rainfall, suggesting that agricultural practices (e.g. timing of fertiliser inputs, slurry spreading) may have a greater influence on nutrient levels in coastal waters, or that correlations with rainfall are operating on a different timescale. Mallin et al. (1993) found, using a more extensive time series, that rainfall was significantly correlated with nitrate concentrations and phytoplankton productivity in a coastal estuary following a 2-week time lag. The effect of season on nutrient uptake by phytoplankton may also be a factor in not finding a correlation between nutrient levels and rainfall. During winter months when reduced light and temperature levels are suggested to limit phytoplankton growth, nutrients will not be taken up as readily as in the warmer summer months, when accelerated phytoplankton growth results in increased uptake of nutrients.

Molar ratios of total nitrogen to total phosphorus (Fig. 2.3) in marine water samples all exceeded the 16:1

Redfield ratio for optimum phytoplankton growth, averaging a ratio of 59:1, and this suggests that phosphorus is the limiting nutrient in this system. This finding is counter to many studies suggesting nitrogen as the limiting nutrient in marine systems (Ryther and Dunstan, 1971; Howarth, 1988; Oviatt et al., 1995; Nixon et al., 1996), although silicon and phosphorus limitation may occur in anthropogenically nitrogen-enriched nearshore regions (Dortch and Whittedge, 1992; Conley, 2000; Sylvan et al., 2006). The discrepancy may also lie in the use of molar ratios of total nitrogen and total phosphorus in this study, and their limited use in marine studies. A review of total nitrogen and total phosphorus data available in the marine literature found ratios ranging from 5:1 to 310:1, with an average of 37:1 (Downing, 1997), indicating that nitrogen is probably not the limiting nutrient in over 70% of these studies. While the average total nitrogen to total phosphorus ratio of 59:1 found in this study is quite high, it still lies within the range previously reported for total nutrient levels in marine waters. Analysis of total nutrients gives better measurements of nutrient supply than soluble, inorganic nitrogen and phosphorus alone, and is often used to distinguish nitrogen from phosphorus limitation in freshwaters (Downing, 1997; Cole, 2009), suggesting that marine stoichiometry studies are lagging behind similar freshwater research.

Clear changes in the molar ratios of nitrogen to phosphorus in Lough Hyne have become apparent from historical data. Previous data on total nitrogen and total phosphorus show molar ratios in the range 7:1–45:1, with an average of 19:1 (Prof. Mark Johnson, unpublished data). This suggests that Lough Hyne fluctuated between nitrogen and phosphorus limitation at various times, while the current study found molar ratios consistently in excess of 16:1, suggesting that nitrogen was not a limiting nutrient at any time during the study. Interestingly, while nitrogen was consistently higher than previous levels, phosphorus concentration was observed to be lower than historical data, and may reflect changes in agricultural practices with reduced phosphorus inputs through fertilisers.

The relatively high levels of nitrogen and phosphorus in sediment samples indicate that sediments may play an important role in storing excess nutrients in the

lough. Total Kjeldahl nitrogen was higher in sediments from the South Basin than in those from the North Basin and at similar depth in the Western Trough, which is likely to reflect different flow and sedimentation rates in these areas. Bell and Barnes (2002) reported highest sedimentation rates in the South Basin, followed by the Western Trough, with lowest sedimentation rates in the North Basin where currents were also lowest. Increased nitrogen and phosphorus levels with depth in sediment samples highlight the decreasing uptake of nutrients by primary producers with increasing depth as light becomes a limiting factor in phytoplankton growth and reproduction. The positive relationship between nutrient levels and depth in marine sediments reflects similar findings of increased dissolved nutrient concentrations with depth in bottom waters in the Baltic sea (Koop et al., 1990), and in water samples from Lough Hyne (Prof. Mark Johnson, unpublished data).

Closely linked to nutrient dynamics is the environmental variability within an ecosystem. A seasonal thermocline develops in the deeper Western Trough area of Lough Hyne, resulting in severe hypoxia and anoxia for several months over the summer (Kitching, 1990). De-oxygenation of the water column below the thermocline results in both mass mortality of sessile benthic fauna, and movement of mobile fauna out of the depleted oxygen zone (McAllen et al., 2009), structuring the benthic community seasonally. This thermocline is associated with temperature rather than salinity gradients (Thain et al., 1981), and developed earlier and persisted longer in 2009 than in 2008, most likely in response to more stable weather conditions in the second year of the study. Earlier studies show that the thermocline typically forms over summer, persisting from June to October (Kitching et al., 1976; Kitching, 1990). However, more recent studies have shown the thermocline to form earlier and persist longer (April–November, McAllen et al., 2009), a trend confirmed by the present study. Increased nutrient inputs increase the amplitude of fluctuations in the water column oxygen content (Oviatt et al., 1986), and Johnson (1995) suggested that this implies that, if nutrient inputs to Lough Hyne were increased, there might be expansion of the anoxic zone during periods of intense stratification to depths which are currently always

supplied with oxygen. This would result in knock-on effects, such as death of sessile fauna and reduction in the area of seabed suitable for colonisation. Despite the higher nitrogen levels recorded in Lough Hyne during this study, the seasonal thermocline and anoxic zone appear to remain consistent at approximately 25 m depth. However, anoxic conditions are now occurring earlier and persisting longer than previously recorded. Development of an oxythermocline has been a regular seasonal characteristic of the lough for many decades, and there is no reason to believe that this has not been occurring since the lough became fully marine some 4,000 years ago (Buzer, 1981). This suggests that it is unrelated to nutrient enrichment *per se*. Similar episodic hypoxic events have also been reported in fjords that become stratified in summer due to development of stable thermoclines (e.g. Jørgensen, 1980). However, nutrient enrichment may be influencing the duration of the oxythermocline in the lough, promoting earlier formation and greater persistence of anoxic conditions, highlighting the importance of further regular monitoring.

Detailed information on dissolved oxygen, salinity, temperature and nutrients, as well as on potential indicators of eutrophication such as chlorophyll, adds highly valuable data to studies such as this. While spot sampling of these parameters was conducted as part of the fellowship, the benefits of using automated, in-situ instrumentation is recognised. Left in situ on a mooring buoy, data can be recorded at timescales

otherwise unachievable. Such monitoring systems have been used quite widely in the UK and Northern Ireland in a range of projects associated with water quality and its potential influence on the ecology of aquatic systems. Along the west coast of Scotland, they have been used around aquaculture installations as a warning system of potentially harmful toxic blooms, and data are also used to produce predictive models of blooms for effective management to minimise their impacts. The Department of Agriculture and Rural Development in Northern Ireland (DARDNI) uses in-situ monitoring to provide continuous high-resolution data on basic environmental parameters and algal abundance to help monitor and manage eutrophic and threatened water bodies. Additional long-term monitoring is also conducted within Northern Ireland's only designated marine reserve at Strangford Lough. Unfortunately, in the Republic of Ireland, water quality monitoring systems of this nature are rare, although a pilot system has been deployed in the Liffey Estuary, measuring salinity, temperature, dissolved oxygen and nitrate, as well as incorporating automated water samplers for nutrient and phytoplankton samples (O'Donnell et al., 2008). It is becoming more apparent for the need for such systems from both a water quality monitoring perspective and to develop management strategies for reducing the potential impacts of anthropogenic inputs on resident biota to comply with the EU WFD.

3 Phytoplankton–Nutrient Interactions: Influence of Nutrients on Phytoplankton Biodiversity and Assemblage Structure

3.1 Background

Phytoplankton community composition has an important role in upper-ocean food-web structure and nutrient cycling. Factors influencing species-specific phytoplankton growth and mortality rates, such as nutrient availability, temperature, and salinity, can alter natural phytoplankton community composition, with knock-on ecosystem effects (such as grazing and decomposition). If growth of readily grazed phytoplankton, such as large diatoms, is favoured, trophic transfer and nutrient cycling will take place largely in the water column as they can provide a rich food source for fish and shellfish. However, if less-readily grazed dinoflagellate species are favoured, trophic transfer will be poor as the relatively large amounts of unconsumed algal biomass will ultimately settle to the bottom, stimulating microbial decomposition and oxygen consumption (Devlin et al., 2007a). This leads to hypoxic conditions and development of dead zones in the marine environment (Diaz and Rosenberg, 2008).

Some 90 species of phytoplankton described to date have the capacity to produce potent toxins that have been associated with fish kills (e.g. Azanza et al., 2008; Hall et al., 2008; Kempton et al., 2008) or poisoning in man through accumulation in fish and shellfish (e.g. Blanco et al., 2007; Lindahl et al., 2007). In addition, some otherwise non-toxic, large chain-forming diatoms can damage fish gills, through clogging or overproduction of mucous substances when in high abundances. Blooms tend to be dominated by one or two highly abundant species, accounting for as much as 95–99% of local phytoplankton biomass (Paerl, 1988). The specific nutrient requirements and ability of different species to assimilate different forms of dissolved and particulate nutrients, or fix atmospheric nitrogen, can determine the structure of assemblages. For example, the ability of nitrogen-fixing cyanobacteria to fix gaseous nitrogen may allow them

to proliferate under conditions where dissolved inorganic or organic nitrogen is depleted but other nutrients, such as phosphorus and iron, are sufficiently available (Glibert, 2007). Additionally, where high nitrogen or phosphorus ratios relative to silicon occur, a shift away from diatom-dominated assemblages has been shown (Officer and Ryther, 1980; Smayda, 1990).

In an Irish context, general oxygen conditions in estuarine and coastal waters are very good, with 99.4% of total surveyed area having dissolved oxygen levels sufficient to support aquatic life (O'Boyle et al., 2009). However, it is generally accepted that there is an increased temporal and spatial frequency of nearshore blooms of benign, noxious and toxic flagellate species (Hallegraeff, 1993), and hypoxic dead zones (Diaz and Rosenberg, 2008). Aquaculture operations are particularly sensitive to these blooms, since farmed or caged fish and shellfish cannot move away from affected areas. Therefore, understanding how environmental parameters influence the overall phytoplankton community composition is of great importance for predicting and avoiding conditions that may lead to the proliferation of undesirable species for both aquaculture and human health. The aim of this study was, therefore, to investigate the role of environmental conditions in shaping phytoplankton community structure, and to identify the conditions under which known problematic species proliferate at Lough Hyne.

3.2 Methods

Water samples were collected from a 5-m rigid inflatable boat (RIB) at six marine locations, previously described in [Section 2.2](#). Integrated water samples were collected using a hose sampler (Qin and Culver, 1996; Dolan and Gallegos, 2001; Johnson and Costello, 2002; Rodriguez et al., 2003; Cartensen et al., 2004), from the surface to 10 m depth, and a 60-ml

subsample was preserved using Lugol's acidified iodine solution (Parsons et al., 1984) for later identification of phytoplankton taxa. A further 1-l sample was collected for nutrient analysis (total nitrogen, total phosphorus, total silicates and chlorophyll *a*) as described in [Chapter 2](#). Associated salinity, water temperature and dissolved oxygen readings were taken with environmental probes at the same time.

Preserved phytoplankton samples were decanted into 25-ml settlement chambers and allowed to settle overnight before identification using a Nikon TS-2000 inverted microscope. Phytoplankton taxa were identified following Thomas (1997), Berard-Therriault et al. (1999), Horner (2002) and Larink and Westheide (2006), and additionally Cupp (1943) for marine diatoms and Dodge (1982) for marine dinoflagellates.

Individual species abundances were used to create a Bray–Curtis similarity matrix. Abundances were square-root-transformed to test for differences between sampling locations due to high abundances of dominant species, while still allowing some of the less abundant species to influence assemblage structure (Clarke and Warwick, 2001). It was expected that phytoplankton assemblages would vary over time, particularly in response to abiotic seasonal cues such as sea temperature and hours of daylight. Samples were therefore a priori separated into spring (March–May), summer (June–August), autumn (September–November) and winter (December–February) seasonal groups. Two-dimensional non-metric multidimensional scaling (nMDS) plots were used to explore the multivariate patterns of assemblages (Clarke and Warwick, 2001), and permutational multivariate analysis of variance (PERMANOVA+) was used to test for differences in assemblages between areas and seasons on the basis of Bray–Curtis similarities between samples (Anderson et al., 2008). The SIMPER routine (PRIMER 6, Plymouth Marine Laboratory) was used to identify specific phytoplankton taxa that contribute to the greatest dissimilarity between assemblages, using log-transformed abundances so that less-abundant species could contribute to overall differences between groups.

In order to investigate the role of nutrients and other environmental variables in structuring phytoplankton assemblages, the BEST routine in PRIMER was used to find the subset of environmental variables that best explains the multivariate phytoplankton assemblage structure. Environmental variables were transformed where appropriate to reduce large variances, and normalised before running the BEST routine. Principal component analysis (PCA) was used to visualise the multivariate separation of environmental data, and individual species abundance values overlaid in bubble plots to identify environmental conditions that may promote production of known toxic phytoplankton species.

3.3 Results

One hundred and seventy-one phytoplankton taxa were identified during the study. There were significant effects of sampling location and season on univariate measures of species richness, diversity and abundance, but no interaction between the two effects, indicating that seasonal effects were consistent across sampling locations ([Table 3.1](#)). Tukey's pairwise comparisons indicated that autumn and summer seasons had significantly greater species richness than spring, which in turn had greater species richness than winter. Winter samples also had significantly lower abundances than samples taken in spring, summer and autumn. While pairwise tests failed to resolve the significant differences in abundance between locations, in general there was a pattern of higher overall abundances within Lough Hyne compared with adjacent locations in the open seas. A reverse pattern was observed in the Shannon–Wiener index of diversity, with greater diversity observed in samples from outside (Tranabo, Tragumna and coastal waters) compared with locations within Lough Hyne, indicating that the observed higher abundances in the lough were due to a proliferation of relatively few dominant species.

Non-metric multidimensional scaling plots showed a general clustering of reserve and adjacent coastal areas in terms of phytoplankton assemblages ([Fig. 3.1](#)). These groupings were tested with PERMANOVA+ analysis. Sampling location nested within area (Lough Hyne versus adjacent coast)

Table 3.1. ANOVA¹ for species richness (S), Shannon–Wiener diversity (H') and abundance (N, log-transformed to remove heterogeneity) across temporal and spatial scales. Au: autumn; Wi: winter; Sp: spring; Su: summer; C: coast; To: Tranabo; Ta: Tragumna; N: North Basin; S: South Basin; W: Western Trough.

	df	S		H'		ln (N)	
		F	P	F	P	F	P
Location	5	0.59	0.706	4.05	0.002	3.75	0.004
Season	3	26.53	<0.001	2.42	0.072	18.02	<0.001
Location × Season	15	0.84	0.634	1.09	0.379	1.28	0.235
Error	83						
Total	106						
		Au = Su > Sp > Wi		C = Ta = To > N = W = S		Au = Sp = Su > Wi	

¹ANOVA, analysis of variance.

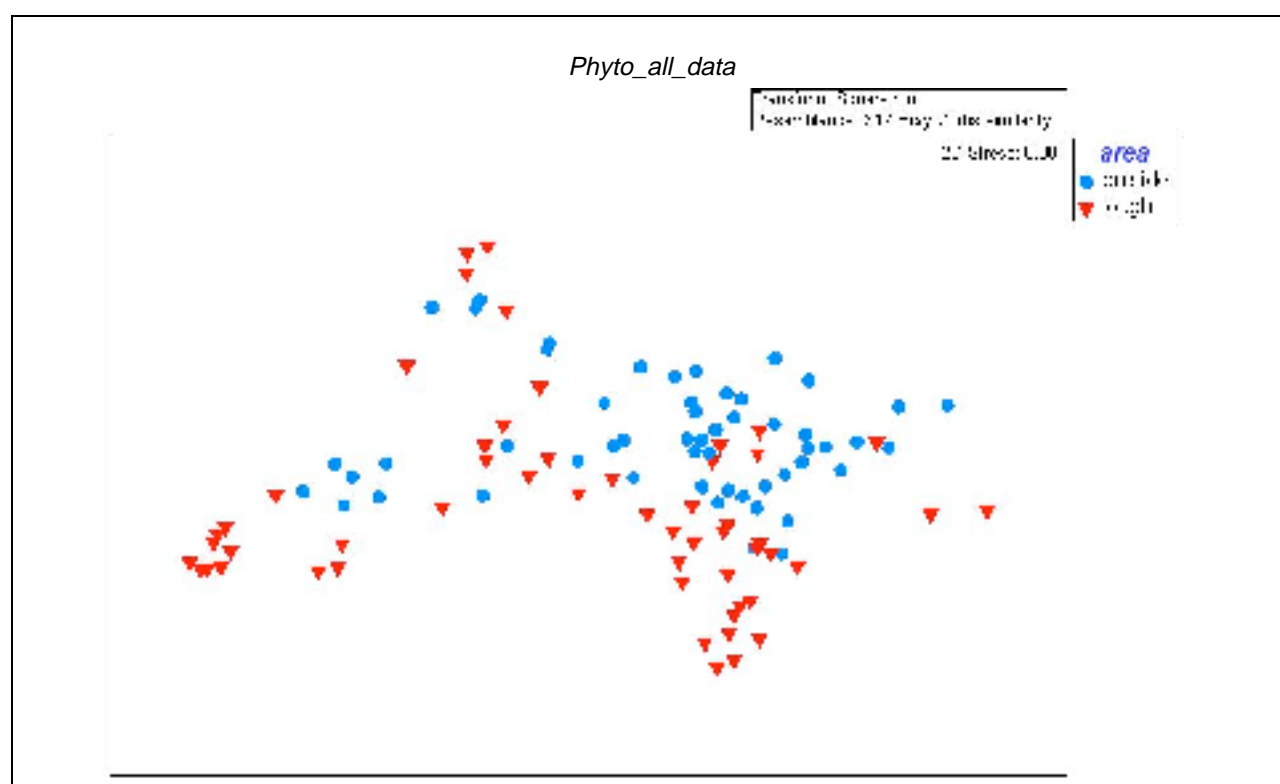


Figure 3.1. Non-metric multidimensional scaling plot of phytoplankton assemblages showing general clustering of samples from Lough Hyne and adjacent coastal areas.

showed no significant differences in assemblage structure between locations within each area (df = 4, pseudo-F = 0.49816, P > 0.9), so locations inside and outside Lough Hyne were pooled for subsequent analysis. This highlighted significant differences

between areas and seasons, with a significant interaction between the two (Table 3.2). Pairwise tests of the interaction showed that Lough Hyne and adjacent areas were distinct from each other in all seasons excluding summer.

Table 3.2. Results of PERMANOVA¹ analysis of phytoplankton assemblages in reserve versus non-reserve areas.

	d.f.	MS	Pseudo-F	P
Area	1	12803	6.2209	0.001
Season	3	17139	8.3279	0.001
Area × Season	3	3924.2	1.9068	0.001
Error	99			
Total	106			

¹PERMANOVA+, permutational multivariate analysis of variance.

The SIMPER routine was then run to determine which species contributed most to the observed difference in assemblage structure between Lough Hyne and the adjacent locations. Lough Hyne tended to be characterised by higher abundances of tintinnids, microflagellates and dinoflagellates, in particular *Heterocapsa* sp., *Scrippsiella* sp. and *Gyrodinium* sp., as well as chain diatoms of the *Chaetoceros* group. Locations outside Lough Hyne had overall higher abundances of diatom species, in particular *Skeletonema costatum*, *Thalassiosira* sp., *Paralia sulcata*, *Navicula* sp., *Cylindrotheca closterium* and *Pseudo-nitzschia delicatissima*.

The global BEST routine was then run to investigate the degree to which environmental variables influence phytoplankton assemblage structure. Overall, phytoplankton assemblages correlated with increasing temperature, chlorophyll *a* and the phosphorus to silicon ratio (global test statistic, $\rho = 0.512$, $P < 0.01$). When considered separately, diatom assemblages correlated with chlorophyll *a* and the phosphorus to silicon ratio ($\rho = 0.508$, $P < 0.01$), suggesting that phosphorus may be the limiting nutrient to diatom production. Dinoflagellate assemblages correlated with salinity, temperature and total nitrogen ($\rho = 0.593$, $P < 0.01$), indicating that the high nitrogen levels observed in marine waters throughout the fellowship ([Chapter 2](#)) are favouring dinoflagellate production.

Considering the potential negative impacts associated with blooms, where suitable abundances were available, correlations with environmental variables were investigated. Principal component analysis was conducted on environmental variables, and scaled

species abundances for samples overlaid on the resulting plot ([Fig. 3.2](#)). High abundances of the diatom *Pseudo-nitzschia delicatissima* and the dinoflagellate *Dinophysis acuminata* both occurred under conditions of increasing salinity and total nitrogen, while the toxic dinoflagellate *Amphidinium* sp. showed increased abundances, in particular with the increasing phosphorus to silicon ratio. The large, highly setose chain diatom *Chaetoceros danicus* showed highest abundances under conditions of increased phosphorus and temperature, and abundance of the harmful dinoflagellate *Karenia mikimotoi* correlated with conditions of increased salinity and nitrogen to phosphorus ratio.

3.4 Discussion

The higher abundances, yet lower Shannon–Wiener diversity observed in Lough Hyne samples, indicate a proliferation of relatively few dominant species. Blooms tend to be dominated by one or a few, highly abundant species, resulting from species-specific growth and mortality rates. Bloom conditions, or those where phytoplankton abundance (excluding *Phaeocystis* species) exceeded 10^6 cells/l (following Devlin et al., 2007a), occurred twice as frequently in lough samples as in coastal samples (18 versus nine samples, respectively), and two or fewer species contributed over 90% of total phytoplankton abundance in 25 of these bloom samples. The higher phytoplankton abundance inside Lough Hyne is also consistent with the findings of Su et al. (2004) who found that chlorophyll *a* and phytoplankton cell numbers were significantly greater in poorly flushed areas of a tidal lagoon. However, they found no

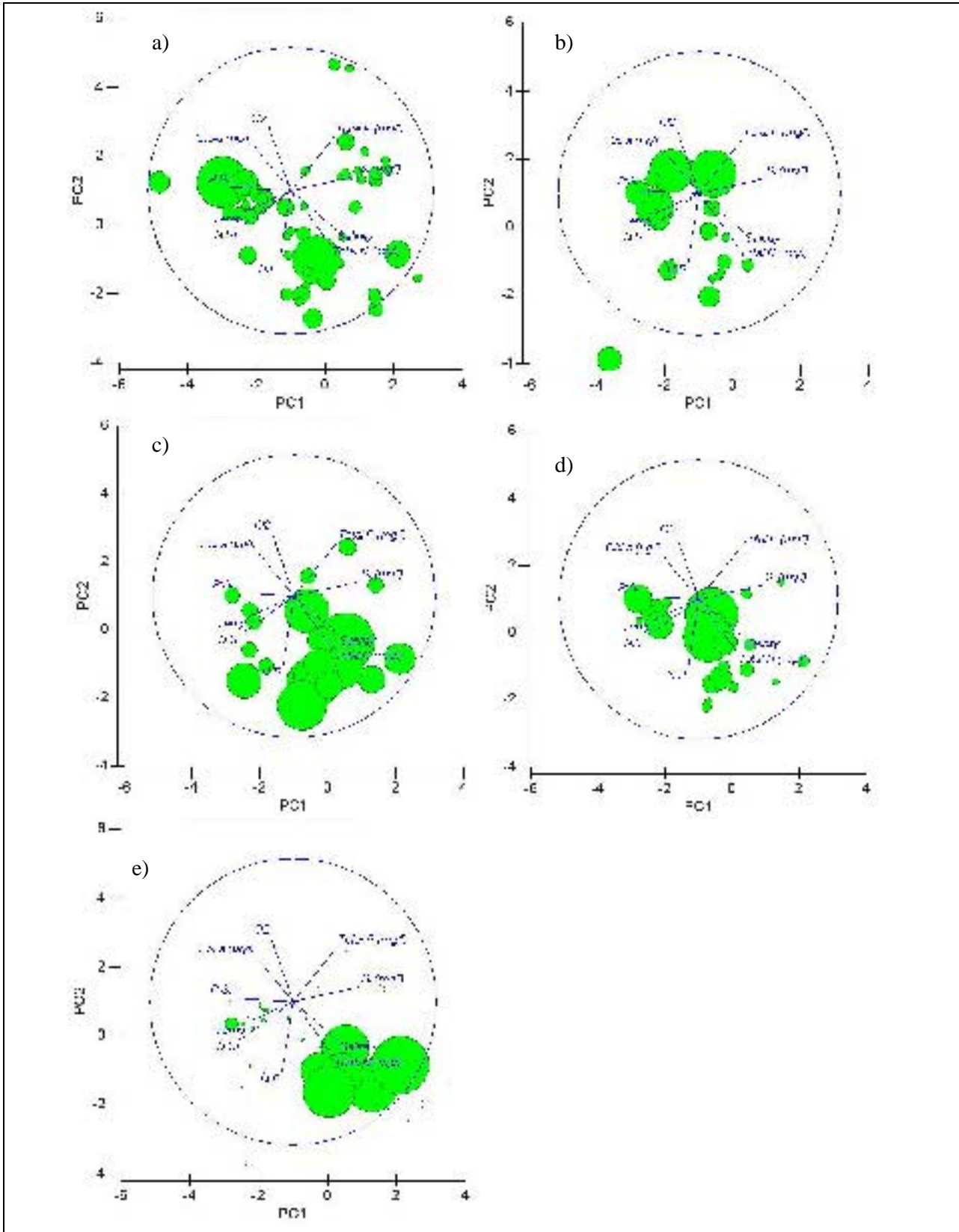


Figure 3.2. Principal component analysis of environmental variables with species abundances overlaid for a) *Amphidinium* sp., b) *Chaetoceros danicus*, c) *Dinophysis acuminata*, d) *Karenia mikimotoi*, and e) *Pseudo-nitzschia delicatissima*.

differences in species richness or diversity, and cluster analysis showed grouping determined by sampling time and not sampling location or flushing regime. This study found significant differences in both diversity and assemblage structure between reserve and non-reserve phytoplankton communities, across a relatively small spatial scale (<5 km), and supports similar findings for previous studies of phytoplankton (Johnson and Costello, 2002), meroplankton (Jessopp and McAllen, 2007), and holoplankton (Rawlinson et al., 2005) assemblages in the same area.

A longer water residence time in a restricted coastal area can potentially lead to a build-up of nutrient inputs from land (Tett et al., 2003). The catchment area for Lough Hyne is very small (2.89 km², see [Chapter 5](#)) and, despite the long flushing time of the bay, there were no regional differences in nutrient loading of total nitrogen, total phosphorus or silicates ([Chapter 2](#)). Therefore, the observed difference in phytoplankton community structure between Lough Hyne and the adjacent coastal waters is most likely due to some other factor. There was no significant difference in salinity between Lough Hyne and the adjacent coastal waters, but the slightly higher surface water temperatures in Lough Hyne may explain much of the overall higher phytoplankton abundance observed. Hydrodynamics and water residence times are also very different between Lough Hyne and adjacent coastal areas ([Chapter 5](#)), and vertical stability of the water column is suggested as an important variable determining the prevalence of dinoflagellates over diatoms. This is because the ability of dinoflagellates to undertake vertical migrations to acquire nutrients or optimum photosynthetic conditions confers a competitive advantage (Smayda and Reynolds, 2001). High densities of chain-forming diatoms, particularly *Chaetoceros socialis*, which was particularly abundant in samples, are also more likely to coagulate (Jackson, 1990), increasing their downward flux (Smetacek, 1985).

However, assemblage differences are likely due to a combination of bottom-up and top-down processes affecting species-specific growth and mortality. Microzooplankton grazing rates were much higher in Tranabo Bay than in Lough Hyne ([Chapter 4](#)), which will exert a greater top-down control on phytoplankton

assemblages, particularly on those species that are preferentially grazed. At the same time, mesozooplankton predation on microzooplankton, appeared to release phytoplankton from grazing pressure, resulting in an increased production rate, particularly in Lough Hyne (see [Chapter 4](#) for a more complete discussion on this).

The degree to which some individual phytoplankton species proliferate under different environmental conditions was illustrated in [Fig. 3.2](#). Multiple interacting physical, chemical, and biotic factors lead to the development and persistence of phytoplankton blooms, and it is apparent that no individual environmental factor was singularly responsible, or dominated bloom formation. It is unsurprising that some known coastal species such as *Karenia*, *Pseudo-nitzschia* and *Dinophysis* spp. correlated with increasing salinity. Other recent work has investigated the relationship between harmful algal bloom (HAB) species and eutrophication in Irish waters, with initial results showing that low biomass of HAB species does not indicate high nutrient levels. However, identifying conditions where toxic or otherwise problematic species undergo rapid cell division and growth may lead to cost-effective monitoring of the health of coastal waters. From a monitoring perspective, the ability to predict and control blooms relies on knowledge of a range of environmental data, such as temperature, turbidity, salinity, dissolved oxygen, light, and nutrient levels, that are readily measured in the field using portable meters, or in-situ loggers. Use of in-situ measuring devices is fairly limited in Ireland, although it is expected that these systems will become more widely used in the future as has occurred in the UK for monitoring water quality parameters under the auspices of the WFD (EPA, 1999). Under bloom conditions, targeted identification of phytoplankton can be undertaken, possibly reducing the frequency of monitoring that requires time-consuming expert taxonomic identification.

An interesting example is seen in abundance patterns of *Pseudo-nitzschia* spp. Although not true of all populations, some *Pseudo-nitzschia* populations have been found to produce domoic acid (Hasle, 2002; Maldonado et al., 2002), and has been confirmed in Irish waters (Cusack et al., 2002). Bioaccumulation of

this toxin in shellfish has been linked to amnesic shellfish poisoning (ASP) (Todd, 1993). *Pseudo-nitzschia* spp. proliferated under conditions of high salinity and total nitrogen along with increasing silicon and low dissolved oxygen. A threshold level of 50,000 cells/l is recommended by the Irish Marine Institute in its National Biotxin Monitoring Programme to begin flesh testing for ASP. This threshold was exceeded in 11 samples (approximately 10% of all samples), occurring at all sampling locations in July and September 2008, and reaching abundances of over 3 million cells/l. While Lough Hyne is a no-take marine reserve, and Tranabo and Tragumna Bays are candidate SACs with no aquaculture, the implications for human health are minimal, as shellfish in this area are not for human consumption. However, nearby Roaringwater Bay is an area of intensive oyster and mussel aquaculture, and is likely to experience much the same coastal nutrient and environmental conditions. High abundances of *Pseudo-nitzschia* spp. in this area can have major consequences, with possible cessation of shellfish harvesting and loss of revenue to aquaculture. While bloom formation may be prevented by low water residence time (Paerl et al., 1998), Roaringwater Bay has a flushing time in the region of 1.3 days, compared with 1.8 days for Tragumna Bay and 0.89 days for Tranabo Bay (Jessopp et al., 2007), indicating that the area is likely to experience blooms simultaneously with Lough Hyne.

Such a proliferation of cells can also reduce water clarity, with subsequent loss of submerged aquatic vegetation due to decreased light levels (Valiela et al., 1997), and reduced oxygen levels in bottom waters, due to microbial decomposition of particulate organic matter (Diaz and Rosenberg, 2008). While blooms of benign, noxious and toxic flagellate species are becoming more frequent (Hallegraeff, 1993),

identifying conditions where blooms are likely to occur is not only useful in targeting monitoring efforts, but in taking measures to prevent bloom formation. Possible mechanisms lie in minimising nutrient availability, decreasing light levels, water residence time and temperature, or increasing predation on phytoplankton species. Pumping surface waters to depth will remove phytoplankton from optimal light and temperature growth conditions. This may be an option in high-risk areas or areas of intensive aquaculture, but these typically occur in coastal bays and estuaries with no temperature stratification or euphotic zone. Physical removal of nutrient-rich bottom sediments by suction dredging is costly and will have impacts on benthic communities. Aeration or mixing of the water column may help maintain an oxidising environment, which shifts the chemical balance away from soluble phosphorus to insoluble forms that settle to the bottom, making phosphorus less available to algae in surface waters. Easily the most effective means of limiting nutrient availability would be improvement of catchment management and reduced point inputs such as use of fertilisers. However, diffuse sources of nitrogen and phosphorus (leaching of existing nutrients in soils to rivers, etc.) mean that a time lag in the region of decades may be expected before any overall reduction in nutrient levels entering coastal waters will become apparent. For example, despite an 86% decrease in phosphorus input from point sources, no trend in diffuse phosphorus loss has been detected, and there is still no overall reduction in phosphorus in streams 10 years later (Andersen et al., 2005).

Following identification of the environmental conditions most likely to stimulate blooms of toxic or otherwise problematic species, it would be useful and timely to generate criteria for designating 'bloom-sensitive' areas, and to incorporate these into management strategies for coastal marine habitats.

4 Phytoplankton Growth and Microzooplankton Grazing Rates

4.1 Background

Significant differences in phytoplankton assemblages have been found between Lough Hyne and the adjacent coastal area ([Chapter 3](#)), mirroring differences observed in meroplankton (Jessopp and McAllen, 2007) and holoplankton (Rawlinson et al., 2005) assemblages in the area. However, nutrient levels appear to be similar between these areas, indicating that, while high nutrient levels may be promoting phytoplankton blooms, other factors are responsible for the overall structuring of phytoplankton communities.

Key to the structuring of plankton communities is the balance between bottom-up and top-down processes of production and mortality. Phytoplankton production is limited by suitable availability of nutrients, temperature and light (e.g. Rhee and Gotham, 1981; Pennock and Sharp, 1994), while mortality from cell lysis and grazing pressure will heavily influence the final community structure (e.g. Kivi et al., 1993; Brussaard et al., 1995). Previous studies at Lough Hyne have highlighted differences in both phytoplankton (Johnson and Costello, 2002) and zooplankton (Rawlinson et al., 2005; Jessopp and McAllen, 2007) assemblages between Lough Hyne and its adjacent coastal waters, suggesting local differences in both bottom-up and top-down processes.

Factors regulating bottom-up control of phytoplankton growth can be easily measured in situ using standard environmental probes to measure light intensity, temperature, salinity, turbidity, and nutrient levels. In fact, the deployment of automated units for measuring a suite of environmental parameters over wide spatial scales and at fine temporal resolution is fast becoming a cornerstone of marine monitoring work globally. For more top-down pressures on assemblage structure, the incubation of natural phytoplankton populations in mesocosms has been widely used to determine net phytoplankton growth and grazing mortality (e.g.

Calbet (2001), Calbet and Landry (2004) and references therein). The use of bottle incubations has increased our understanding of gross phytoplankton growth rates, but the separation of phytoplankton communities from the surrounding area means that nutrients can quickly become limiting. The addition of nutrients at concentrations that saturate gross phytoplankton growth rates solves this problem, but incubations will then not represent in-situ growth conditions. Dialysis membranes allow nutrient exchange between enclosed phytoplankton communities and the surrounding water, and incubation of natural phytoplankton assemblages in dialysis mesocosms has become recognised as one of the most reliable approaches to estimate the in-situ growth rates (Furnas, 1990).

The grazing pressure on marine phytoplankton can be further divided into two components: that grazed by the microzooplankton (20–200 μm) and by the mesozooplankton (200 μm to 20 mm) (Dussart, 1965). Microzooplankton grazing consumes, on average, 67% of phytoplankton production (Calbet and Landry, 2004), and is able to exert top-down control of phytoplankton populations (Irigoien et al., 2005). Conversely, the long-held belief that many numerically dominant members of the mesozooplankton, in particular calanoid copepods, are herbivores has been challenged by the fact that microzooplankton can form a considerable part of the copepod diet (Kleppel, 1993). This results in a potential relaxing of phytoplankton grazing mortality under relatively high copepod abundances (Stibor et al., 2004). The extent to which micro- versus mesozooplankton grazing affects the structure of phytoplankton communities can therefore be determined by calculating phytoplankton growth in response to exposure to these different components of the plankton.

Natural populations of phytoplankton were incubated in situ both inside Lough Hyne and in adjacent coastal waters outside the lough to investigate the relative

contribution of phytoplankton growth, microzooplankton grazing and mesozooplankton grazing on structuring phytoplankton assemblages.

4.2 Methods

In-situ mesocosm studies were conducted in Lough Hyne Marine Nature Reserve and in the adjacent Tranabo Bay, south-west Ireland. Both bays are fully marine, with minimal freshwater input. Lough Hyne is approximately 1 km long and 0.5 km wide, and consists of North and South Basins approximately 20 m deep connected by a deeper (50 m) trough in the western part of the reserve. The reserve is connected to the ocean through Barloge Creek, via a shallow (5 m at high water), narrow (25 m) channel known as The Rapids through which tidal exchange occurs. The presence of a rock sill in The Rapids modifies the usual semi-diurnal tidal cycle, resulting in an asymmetric tide with ebb flow lasting approximately twice as long as flood, and a flushing time in the region of 41 days (Johnson et al., 1995). Tranabo Bay is located immediately to the east of Lough Hyne and is approximately 0.5 km across with a wide south-facing entrance and depths in the range of 5–10 m. Flushing time is in the region of 0.89 days (Jessopp and McAllen, 2007).

Mesocosms with a volume of 500 ml were made using dialysis membrane tubing with a molecular weight cut-off of 12,500 to allow diffusion of nutrients across the membrane (so that incubations did not become nutrient limited). Dialysis tubes were hydrated by soaking them in 1- μ m-filtered sea water for 12 h prior to use, and sealed at each end with plastic bag closures.

At each location, an integrated water sample from the surface to 10 m was obtained using a hose sampler, and passed through a 200- μ m mesh to exclude meso- and macrozooplankton. One-litre and 50-ml subsamples were taken for nutrient analysis (total nitrogen, total phosphorus and total silicates) and phytoplankton identification, respectively. Water column variables of temperature, salinity and dissolved oxygen were recorded using environmental probes. Water from the same location and filtered to 1 μ m, was used to create dilutions of 12.5%, 25%, 50%, 75%, 87.5% of unfiltered to filtered water. For each dilution,

a 500-ml initial sample was taken to determine chlorophyll *a* levels at the beginning of the incubation, and three replicate 500-ml dialysis bags were attached to a frame suspended approximately 2 m below the water surface and incubated in situ for 24 h. Two additional replicates of unfiltered sea water (thus containing mesozooplankton grazers) were incubated alongside dilution replicates to estimate the effect of mesozooplankton grazing on phytoplankton growth rates. A vertical zooplankton tow from 10 m to the surface was also conducted at each location using a 40-cm diameter 200- μ m mesh net at the beginning of the experiment to determine the composition and abundance of mesozooplankton grazers. The contents of the net cod end were preserved in 4% sea-water-buffered formalin, and standardised to known volume before being subsampled. Zooplankton were identified and enumerated under a binocular dissecting microscope.

Following 24 h incubation, dialysis bags were opened and a 25-ml subsample removed and preserved with Lugol's acidified iodine (Parsons et al., 1984) for subsequent phytoplankton identification using a Nikon TS2000 inverted microscope. The remainder of the sample (approx. 475 ml) was filtered onto Whatman GF/F filters and, following acetone extraction, analysed spectrophotometrically for chlorophyll *a* (Parsons et al., 1984).

Net growth rates, μ (per day) for each replicate dilution were calculated as:

$$\mu = (\ln Chl_{t_{24}} - \ln Chl_{t_0}) / t_2 - t_1 \quad \text{Eqn 4.1}$$

where $t = 24$ h and Chl_{t_0} and $Chl_{t_{24}}$ correspond to the initial and final chlorophyll *a* concentrations (mg/m^3), respectively.

Linear regression ($y = a + bx$) of growth rate plotted against proportion of unfiltered sea water was used to calculate phytoplankton gross growth rate ($k = y$ intercept) and microzooplankton grazing pressure ($g_{\text{micro}} =$ negative slope of the relationship) according to Landry and Hassett (1982). Grazing rates by mesozooplankton (g_{meso}) were calculated as the difference between net growth rates observed in unfiltered sea water and those calculated from the regression equation for $x = 1$ (Sommer et al., 2005).

Phytoplankton samples were decanted into 25-ml settlement chambers and allowed to settle overnight before identifying and enumerating all phytoplankton species present using a Nikon TS2000 inverted microscope at 200× magnification. Analysis of phytoplankton assemblage structure was carried out using PRIMER 6 statistical software. Phytoplankton abundances in dilution replicates were adjusted to compensate for dilution (to individuals/l of 200 µm filtered water), and Bray–Curtis similarity on square-root-transformed abundances was used to allow less abundant species to contribute to overall assemblage similarity.

4.3 Results

Dilution experiments were initially conducted in early June 2009, but chlorophyll *a* levels in samples were too low for accurate spectrophotometric measurement, and analysis of water samples showed very low phytoplankton abundances in both locations. The experiment was rerun on 7–8 July 2009. Environmental conditions at the beginning of the incubations including nutrient concentrations are given in [Table 4.1](#). Total nitrogen, total silicates, and temperature were slightly higher in Lough Hyne, but the lower levels in Tranabo Bay were not considered low enough to be limiting to phytoplankton growth.

Negative phytoplankton growth rates were observed in almost all replicates in both locations, indicating that microzooplankton grazing was greater than phytoplankton growth ([Fig. 4.1](#)). At Lough Hyne, the relationship between dilution and phytoplankton growth (a measurement of microzooplankton grazing

rates) was weak and non-significant (slope = 0.129, $R^2 = 0.027$, $P = 0.5$), while in Tranabo Bay, the relationship was strong and significant (slope = 1.0801, $R^2 = 0.5438$, $P < 0.01$). The phytoplankton growth rate was observed to be much higher in unfiltered sea-water samples containing mesozooplankton grazers (red triangles, [Fig. 4.1](#)), suggesting mesozooplankton grazing on ciliates and heterotrophic dinoflagellates, which in turn reduced microzooplankton grazing pressure.

Linear regression ($y = a + bx$) of growth rate plotted against proportion of unfiltered sea water gave estimated values of phytoplankton gross growth rate of $-0.2568/\text{day}$ and $-0.145/\text{day}$, while microzooplankton grazing pressure was calculated as $0.129/\text{day}$ and $1.0801/\text{day}$ for Lough Hyne and Tranabo Bay, respectively. Phytoplankton growth rate in unfiltered sea-water samples was much higher than predicted by the dilution/growth relationship (triangles, [Fig. 4.1](#)). This suggests mesozooplankton grazing on ciliates and heterotrophic dinoflagellates, which in turn reduced grazing pressure by microzooplankton.

Both micro- and mesozooplankton grazers were enumerated from 200-µm screened sea-water samples and vertical zooplankton tows. These showed particularly high abundances of tintinnids, heterotrophic dinoflagellates and copepod nauplii in samples from Lough Hyne compared with Tranabo Bay. Lough Hyne also had greater abundances of copepods, particularly *Oithona* sp. and *Temora longicornis*, while Tranabo Bay had higher abundances of the cladoceran *Podon* sp. ([Table 4.2](#)).

Table 4.1. Water column variables recorded at the beginning of dilution incubations.

	Lough Hyne	Tranabo Bay
Temperature (°C)	16.6	14.1
Salinity (pss)	31.7	33
Dissolved oxygen (mg/ml)	9.72	10.22
Chlorophyll <i>a</i> (mg/m ³)	1.590	1.079
Total nitrogen (mg/l)	0.506	0.316
Total phosphorus (mg/l)	0.022	0.024
Total silicon (µg/l)	0.119	0.082

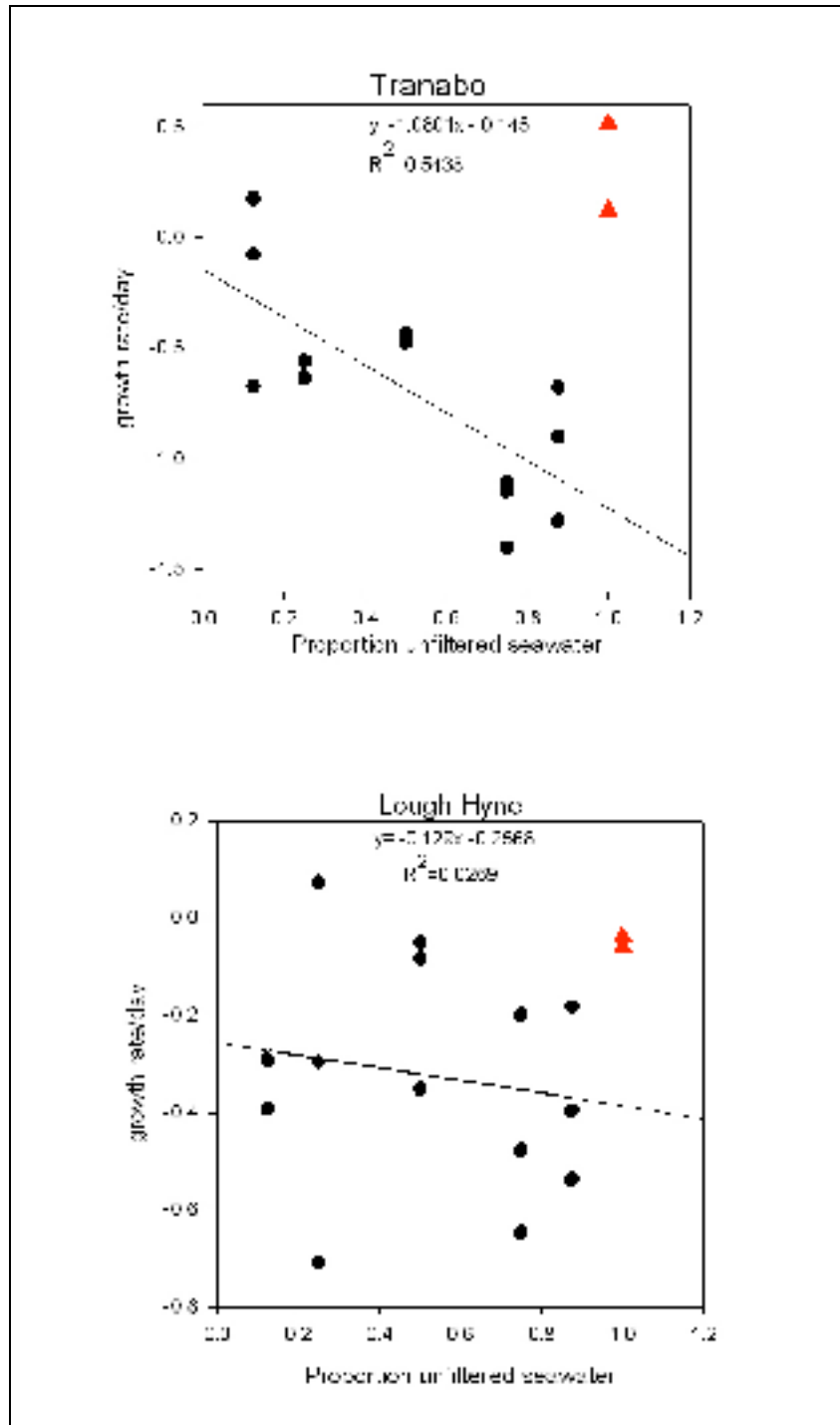


Figure 4.1. Net growth rates of phytoplankton across different dilutions. The slope of the regression indicates microzooplankton grazing pressure. Triangles indicate growth rates in unfiltered sea water, with the difference between measured and predicted growth (regression line) giving a measure of mesozooplankton grazing pressure.

Analysis of phytoplankton assemblage structure using the ANOSIM routine in PRIMER software showed significant differences in phytoplankton communities between Lough Hyne and Tranabo Bay (Global R =

0.939, P= 0.002). Non-metric multidimensional scaling plots were used to visualise differences between replicates in multivariate space (Fig. 4.2). Within each location, similarity to the original pre-incubation sample

Table 4.2. Abundance (individuals/litre) of common microzooplankton grazers found in 200-µm screened sea-water samples, and mesozooplankton grazers found in vertical zooplankton tows at Lough Hyne and Tranabo Bay.

Species	Lough Hyne	Tranabo Bay	Potential diet
Mesozooplankton			
<i>Podon</i> sp.	0.15	0.51	Large diatoms ¹
Gastropod larvae	0.46	0.60	Microflagellates and <i>Navicula</i> ²
<i>Oithona</i> sp.	2.27	0.87	Preferentially on ciliates ³
<i>Temora longicornis</i>	7.43	0.20	Diatoms, dinoflagellates, tintinnids ⁴
<i>Oikopleura</i> sp.	0.19	0.12	Small phytoplankton and picoplankton ⁵
<i>Chaetognatha</i>	0.03	0.02	Mainly copepod nauplii and copepodites, some tintinnids and rotifers ⁶
Microzooplankton			
Copepod nauplii	160	20	Large ciliates, diatoms and dinoflagellates ^{7,8,9}
Tintinnids	10,800	3,600	Diatoms, dinoflagellates, other small tintinnids ¹⁰
Unidentified ciliates	80	40	
<i>Gymnodinium</i> sp.	7,120	2,360	Ingestion of diatoms by heterotrophic protists commonly observed ¹¹
<i>Gyrodinium</i> sp.	160	40	
Unidentified naked dinoflagellates	1,400	1,360	
<i>Protoperidinium</i> sp.	80	120	
Unidentified armoured dinoflagellates	720	800	

¹Jagger et al. (1988).

²Zehra and Perveen (1991).

³Castellani et al. (2008).

⁴Dam and Lopes, (2003); Koski et al. (2005).

⁵Shiganova (2005).

⁶Tönnesson and Tiselius (2005).

⁷Paffenhöfer (1971).

⁸Turner et al. (2001).

⁹Hygum et al. (2000).

¹⁰Capriulo (1982).

¹¹Jeong et al. (2004) and references therein.

decreased with decreasing proportion of unfiltered water, indicating differential microzooplankton grazing pressure on certain phytoplankton groups.

For the more common species found in samples, the relationship between growth rate and microzooplankton grazing showed great variability in which species were heavily grazed and those which were not (Fig. 4.3, Table 4.3). *Pseudo-nitzschia delicatissima* and *Cylindrotheca closterium* were

heavily grazed. Significant grazing of pennate diatoms only occurred in Tranabo Bay, while microflagellates and *Skeletonema costatum* showed a significant effect of grazing only in Lough Hyne. *Chaetoceros* sp. appeared to be heavily grazed in Lough Hyne, although the relationship was not significant at the P = 0.05 level. *Rhizosolenia* sp., *Thalassiosira* sp., and *Licmophora* sp. all showed no significant effect of grazing in either location.

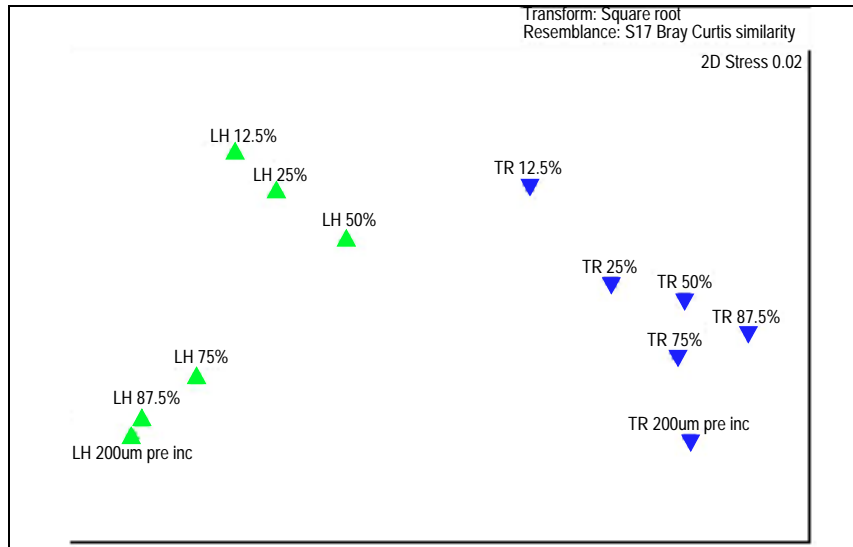


Figure 4.2. Non-metric multidimensional scaling plot of phytoplankton assemblages from pre-incubation 200-µm filtered water and replicates of different dilutions at Lough Hyne (green symbols) and Tranabob Bay (blue symbols).

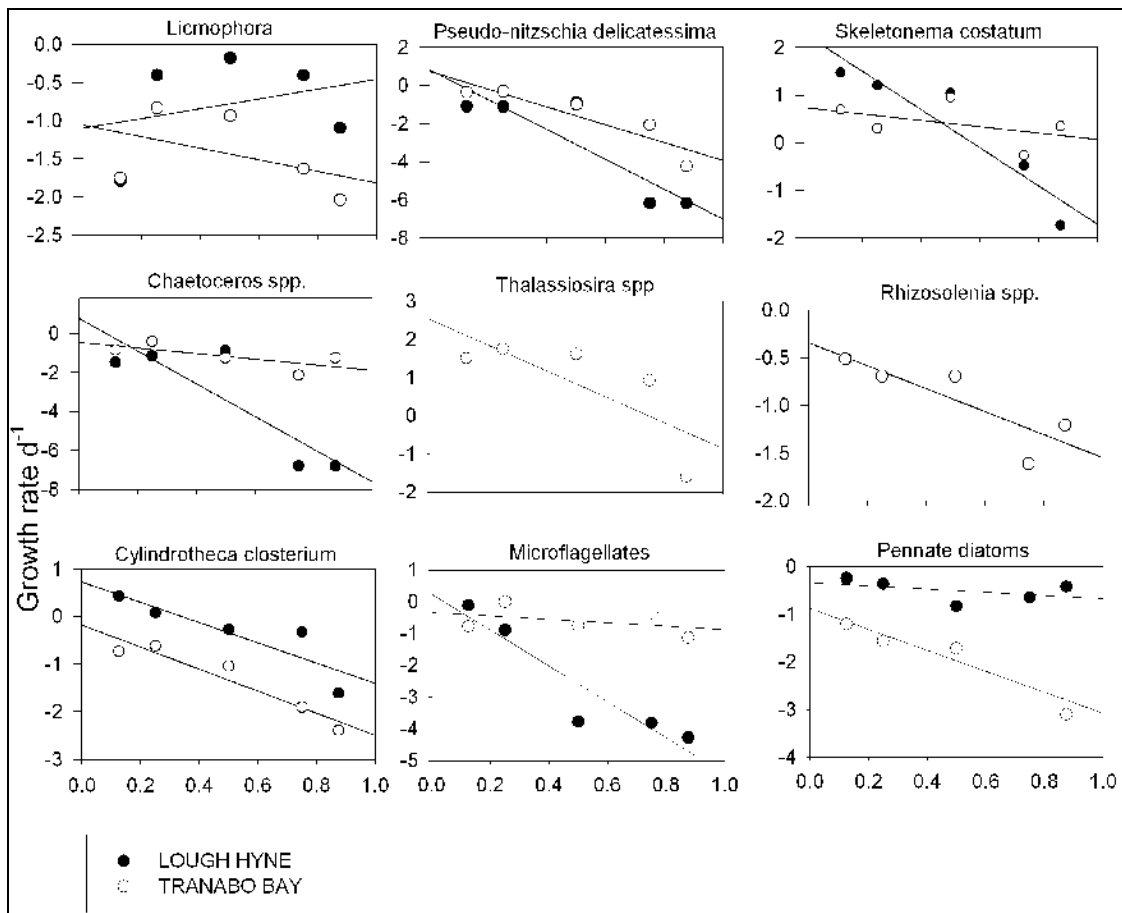


Figure 4.3. Grazing rates (per day), calculated by linear regression of growth rate against proportion of unfiltered water for individual phytoplankton species in Lough Hyne and Tranabob Bay.

Table 4.3. Gross growth and microzooplankton grazing rates determined by linear regression ($y = a - bx$) of growth rates against dilution for selected phytoplankton species at Lough Hyne and Tranabo Bay, July 2009. Values in bold indicate a significant effect of grazing at the $P = 0.05$ level.

	Tranabo bay		Lough Hyne	
	Gross growth (per day)	Micro grazing g_{micro} (per day)	Gross growth (per day)	Micro grazing g_{micro} (per day)
<i>Pseudo-nitzschia delicatissima</i>	0.754	4.668	0.820	7.810
<i>Chaetoceros</i> sp.	-0.460	1.434	0.763	8.358
<i>Cylindrotheca closterium</i>	-0.180	2.3125	0.718	2.122
<i>Licmophora</i> sp.	-1.059	0.757	-1.097	-0.640
<i>Rhizosolenia</i> sp.	-0.340	1.204		
<i>Skeletonema costatum</i>	0.741	0.673	2.296	3.995
<i>Thalassiosira</i> sp.	2.523	3.381		
Pennate diatoms	-0.877	2.196	-0.331	0.345
Microflagellates	-0.327	0.542	0.248	5.636

4.4 Discussion

Negative phytoplankton growth was observed both in Lough Hyne and Tranabo Bay, which seems unusual for the time of year that the experiment was conducted (late July) when phytoplankton growth conditions should be optimal (O'Boyle and Silke, 2009). In an extensive search of the literature, Calbet and Landry (2004) found only 29 instances out of 788 paired observations of phytoplankton growth and microzooplankton grazing where negative phytoplankton growth rates occurred. Although most of these occurred in oceanic waters of temperate/sub-polar regions, instances of temperate coastal and estuarine waters were also found. The reason for the observed negative growth at this time of year is unclear and would benefit from further study. However, one possible explanation is the presence of high abundances of microzooplankton grazers in samples, particularly copepod nauplii and tintinnids. Copepod nauplii will graze a number of taxa and size classes, including bacteria (Roff et al., 1995), chain diatoms and naked dinoflagellates (Paffenhöfer, 1971) and large ciliates and dinoflagellates (Turner et al., 2001), and were particularly abundant in Lough Hyne with 160 individuals/l occurring in sea-water samples. Tintinnids, which were abundant in both locations (3,600 individuals/l in Tranabo Bay, and 10,800 individuals/l in Lough Hyne), are heterotrophic, with a

diet consisting largely of picoplankton and dinoflagellates but also grazing on diatoms in small amounts (Stoecker et al., 1981; Bernard and Rassoulzadegan, 1993; Kamiyama, 1997; Kamiyama et al., 2004). The higher abundance of copepod nauplii and tintinnids in Lough Hyne may also explain much of the variability observed in growth rate, and no discernible effect of dilution compared with Tranabo Bay.

PRIMER analysis shows a clear distinction between phytoplankton communities in Lough Hyne and Tranabo Bay. Local conditions may explain much of this difference. Lough Hyne was observed to have slightly higher surface water temperatures and lower salinity, which may promote differential growth of certain phytoplankton groups over others. The long water retention time and incomplete tidal mixing in Lough Hyne may also provide more stable growing conditions, a factor that has previously been identified as influencing turnover in meroplankton communities (Jessopp et al., 2007). However, a top-down effect is also likely to be contributing to the observed phytoplankton assemblage differences. While *Pseudo-nitzschia delicatissima* and *Cylindrotheca closterium* were heavily grazed at both locations, *Skeletonema costatum* and microflagellates only showed significant grazing rates in Lough Hyne, and pennate diatoms

only appeared to be grazed in Tranabo Bay. All other commonly occurring, abundant species in dilution replicates showed no effect of microzooplankton grazing, suggesting strong species-specific top-down structuring of phytoplankton assemblages in this region.

The high phytoplankton growth observed in unfiltered sea-water samples (containing mesozooplankton grazers) also suggests a reduction in the microzooplankton grazing pressure on phytoplankton which may be explained by mesozooplankton grazing preferentially on ciliates and heterotrophic dinoflagellates. Copepods are predicted to occupy a higher trophic level in areas that are nutrient rich but with low silicon to nitrogen ratios and dominance by unpalatable or harmful algae (Sommer and Stibor, 2002; Sommer et al., 2002), and ciliates have been shown to be selectively preyed upon by copepods in coastal waters (Calbet and Saiz, 2005). Neither location is considered to be nutrient limiting, and both have relatively low nitrogen to silicon ratios (see [Table 4.1](#)) as well as high copepod abundances. Water from Lough Hyne had copepod abundances of over 10 individuals/l, while Tranabo Bay had abundances of approximately 1.3 individuals/l. In particular, both locations had high abundances of

Temora longicornis and *Oithona* sp., both known grazers of ciliates (Lampitt and Gamble, 1982; Dam and Lopes, 2003; Koski et al., 2005; Castellani et al., 2008), which will have reduced the grazing pressure on diatoms from these heterotrophs. Similar examples are available in the literature, with copepod grazing on protozoans resulting in increased phytoplankton biomass after experimental copepod addition (Vadstein et al., 2004).

It is clear from the results of the experiment that top-down processes determine the overriding structure of phytoplankton assemblages. High abundances of ciliates and heterotrophic dinoflagellates in both locations exert a strong grazing pressure on phytoplankton observed in the negative phytoplankton gross growth rates and high grazing rates of individual species. This is offset by high abundances of mesozooplankton grazers, which occupy a higher trophic level than autotrophic phytoplankton grazers. Mesozooplankton therefore exert a strong top-down control of the microzooplankton grazing community, which in turn enables sustainable phytoplankton growth. Indeed, unfiltered sea-water samples were actually observed to have positive phytoplankton growth rates, supporting this conclusion.

5 Catchment and Hydrodynamics

5.1 Background

Lough Hyne has long been regarded as a natural laboratory because of its wide range of habitats and flow regimes across a relatively small spatial scale. However, the hydrodynamics have been little studied since early work in the 1940s and 1950s, where water movement in The Rapids and the South Basin of the lough were characterised by the use of a Watts current meter and subsurface drift drogues (Bassindale et al., 1948, 1957). Even at this early stage, it was quickly recognised that flow dynamics play an important role in structuring the communities present in an area.

Using drift drogues, Bassindale et al. (1957) demonstrated surface currents during flood tide up to 0.37 m/s at Whirlpool Cliff, reducing to 0.033 m/s by the time water reaches the Western Trough. Ebb tides were typically slower, reaching a maximum of 0.15 m/s in the middle of the South Basin. Currents around the Western Trough have typically been recorded as <0.007 m/s at all stages of the tidal cycle (Kitching and Ebling, 1967; Bell, 2001). Further data from current meters deployed at discrete locations within Lough Hyne have additionally shown maximum flow at Whirlpool Cliff of up to 2 m/s during flood tides, and at minimum levels in the North Basin where they were below threshold levels for equipment measurement, <0.0039 m/s (Bell and Barnes, 2002).

Clearly, there is a need to collate all the available information on currents to build up an overall picture of the hydrodynamics of Lough Hyne. This would not only provide researchers with valuable information linking flow characteristics to ecological communities, but could provide the basis for risk management and monitoring in the event of pollution events such as oil spills (an example of which occurred with the sinking of the Kowloon Bridge near Lough Hyne in 1986). Computer-based hydrodynamic modelling has been widely used for this purpose, providing simulations that can be validated by few direct measurements in the field, and has been successfully applied in a variety of systems around the world (e.g. Johnson et al., 1991;

Gillibrand, 2001; Tsanis and Boyle, 2001; Ellien et al., 2004).

A two-dimensional, depth-averaged hydrodynamic model was therefore created to compute flow velocities and tidal height variations within Lough Hyne with a view to obtaining overall information on flow characteristics. Furthermore, to aid in risk assessment, the catchment areas of Lough Hyne and the candidate SACs at Tranabo and Tragumna Bays were calculated.

5.2 Methods

Techniques for calculating catchment area based on Ordnance Survey Ireland maps are available through the Spatial Analyst extension in ArcGIS. Contour lines for the area were digitised, and a three-dimensional Digital Elevation Model (DEM) created. The *Flow Direction* tool was used to create a raster data file and the *Basin* tool subsequently used to produce a new raster of catchment areas. This was then converted to a polygon and the area of each polygon calculated.

A two-dimensional, depth-averaged hydrodynamic model was set up to compute flow velocities and tidal height variations within Lough Hyne using Mike 21 proprietary software (Danish Institute Hydraulics). Bathymetric data of Lough Hyne and Barloge Creek were available from a multi-beam survey conducted in 2005 (Fig. 5.1), with bathymetry for The Rapids supplemented by data from Bassindale et al. (1948). The model was generated in 5-m grids using standard values from the literature for bed roughness and eddy viscosity. Boundary conditions for the model used spring tide levels at Barloge Creek (such that changes in water level propagate through the entire grid system and drive the model). Tide heights in Barloge Creek (and Lough Hyne for model validation) were measured using water-level loggers (HOBO U20 Water Level Data Logger, ONSET Computer Corporation), with barometric pressure compensation using atmospheric pressure data from a WMR200 weather station based in the nearby University College Cork Renouf

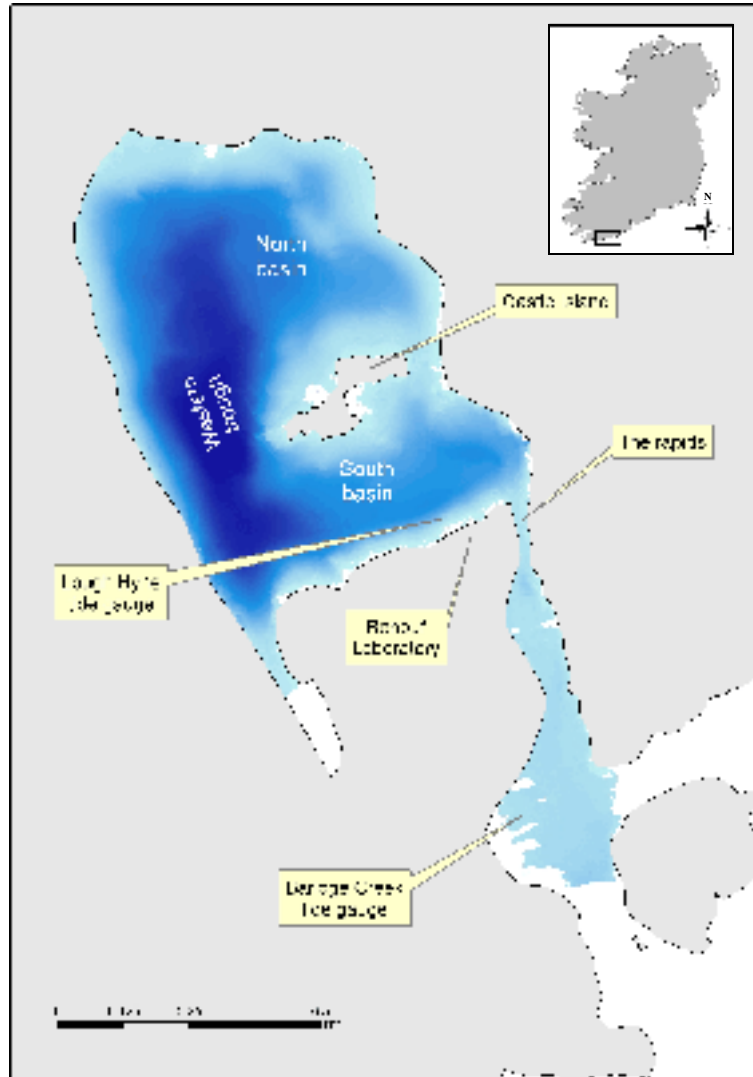


Figure 5.1. Lough Hyne Marine Nature Reserve, showing bathymetry (darker shading in deeper parts of the lough) and location of tide gauges. White areas indicate lack of bathymetric data either because of shallow depth or obstructions in the way of surveying equipment.

Laboratory. Water-level logger data were levelled to the Malin Head datum using a levelling stick to a nearby temporary global positioning system (GPS) benchmark. Given the minimal freshwater inputs to Lough Hyne and subsequent freshwater flushing time of just under 9 years (see [Chapter 2](#)), as well as its sheltered location, the model used no wind forcing and assumed no source discharges (i.e. no freshwater inputs into the lough in the model). The hydrodynamic model was run in 2-s time steps over a spring tide, modelling water movement from 9 to 11 June 2009.

The turnover time of water in Lough Hyne can be defined as the time taken for the total mass of material

within the lough to be reduced to a factor of e^{-1} (i.e. 0.37) of its original mass (Prandle, 1984). A simulation was run using a repeating spring tide boundary condition over a 90-day period, i.e. every single tidal cycle over the 90 days is a spring tide.

5.3 Results

Overlaying the calculated catchment areas on the original Ordnance Survey Ireland map, it is apparent that both Lough Hyne and Tranabo Bays have a relatively small catchment relative to their size (2.89 and 0.37 km², respectively). Tragumna Bay has a much larger catchment area (11.77 km²) and includes

Lough Abisdealy, a freshwater lake south of Skibbereen. Catchment areas for the bays were calculated using spatial analyst tools in ArcGIS.

The Mike 21 software successfully modelled the asymmetric tide observed in Lough Hyne based on boundary conditions outside the lough in Barloge Creek. However, there was a relatively poor match between the measured and modelled tidal height data in the lough, with the model consistently overestimating tidal heights inside the lough (max. error 15 cm, [Fig. 5.2](#)).

Modelled water flow for Lough Hyne shows minimal water movement in the North Basin during all states of tide, and not exceeding 0.004 m/s. Water movement in the Western Trough is also minimal except during the peak of flood tides with maximum modelled velocity occurring in the shallow water along the western shore ([Fig. 5.3](#)). Most water movement in the lough occurs in the South Basin, with highest current speeds modelled in The Rapids and Whirlpool Cliff. Relatively high modelled current speeds also occur along the southern shore of the lough and in the shallow water on the

south of Castle Island. During ebb tide, water movement in the South Basin rarely exceeds 0.06 m/s, with highest current speeds in the shallow waters along the southern shore of the lough ([Fig. 5.4](#)). During peak flow of flood tides, current speed at the end of The Rapids exceeds 1 m/s, rapidly dropping to 0.1–0.2 m/s by the time water reaches Whirlpool Cliff. Current speeds along the south shore and the south side of Castle Island remain relatively high throughout the flood tide. Development of a gyre occurs immediately to the north-west of The Rapids, with lough water rejoining water entering from The Rapids. This leads to a large area of low water movement immediately to the west of the gyre that persists throughout flood tide ([Fig. 5.5](#)).

The water turnover (flushing time) of Lough Hyne was defined as the time taken for the total mass of material within the lough to be reduced to a factor of e^{-1} (i.e. 0.37) of its original mass (Prandle, 1984), and was calculated as 15 days. However, complete replacement of the lough water took in the region of 80 days ([Fig. 5.6](#)).

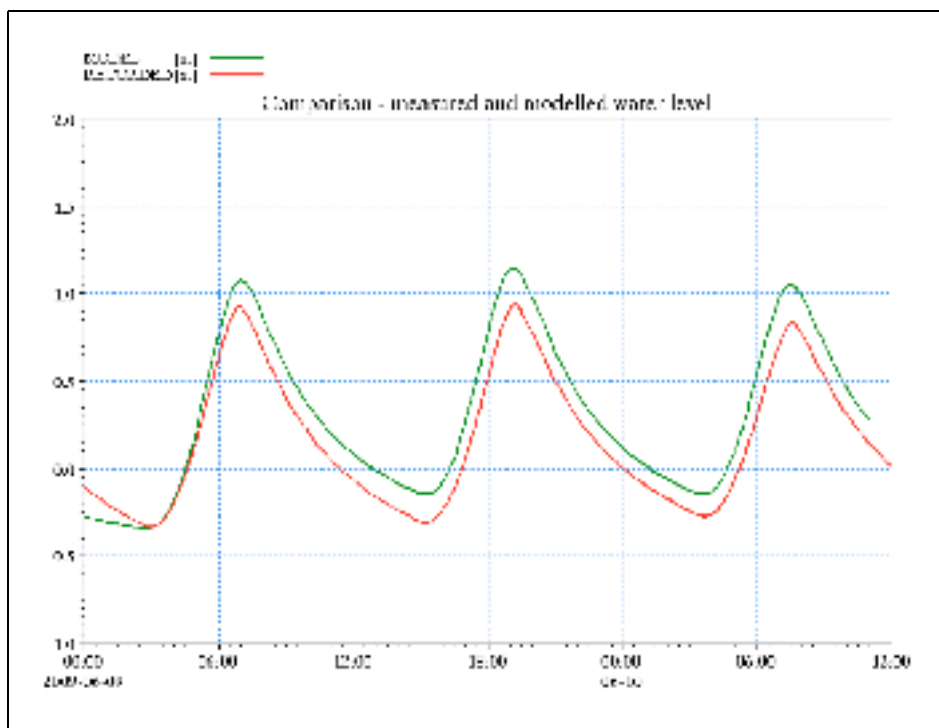


Figure 5.2. Comparison of measured and modelled water level inside Lough Hyne as an indication of how well the model reflects the true hydrodynamics of the lough.

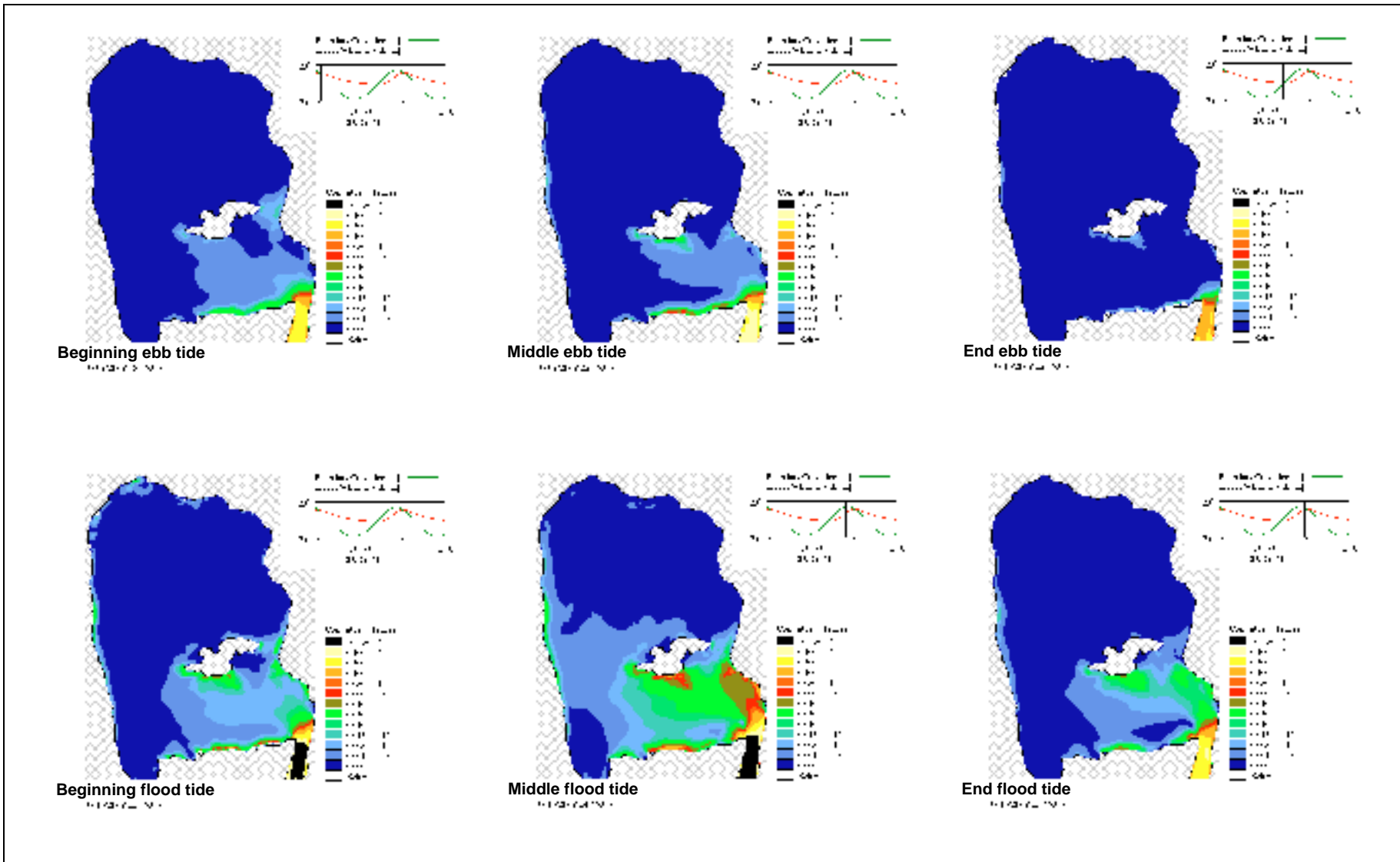


Figure 5.3. Modelled flow of Lough Hyne. Green line representing boundary conditions is measured tidal state outside Lough Hyne in Barloge Creek. Model WL in Lough Hyne is the modelled tidal state inside Lough Hyne. Black vertical bar indicates state of tide and are taken at the beginning, middle and end of both ebb and flood tides. Current speeds in meters per second.

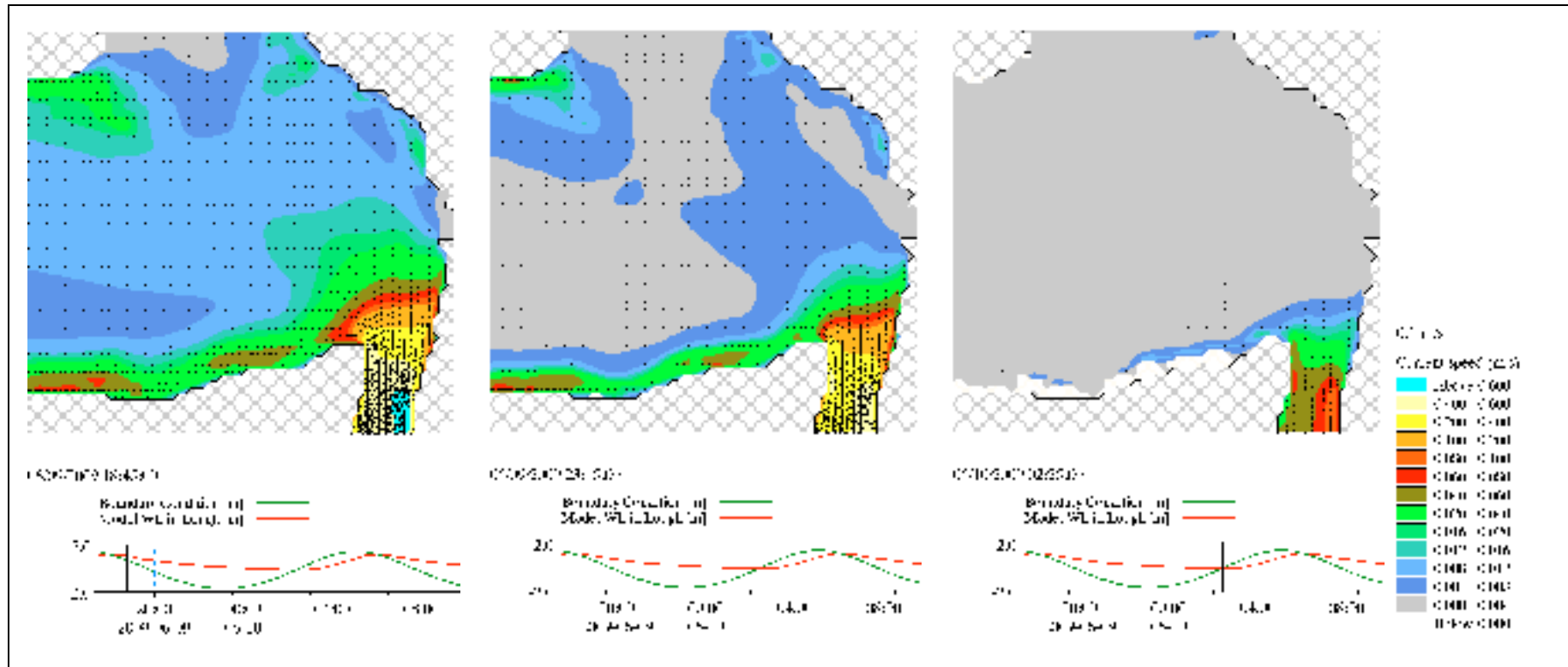


Figure 5.4. Modelled current speed and velocity vectors in Lough Hyne at the beginning, middle and end of ebb tide. The green line representing boundary conditions is measured tidal state outside Lough Hyne in Barloge Creek, while the red 'Model WL in Lough' shows the modelled tidal state inside Lough Hyne to which the current speeds refer. Black vertical bar indicates timing of image capture. Current speeds in metres per second, and black markings indicate speed and direction of water flow, but may not be fully visible at figure resolution.

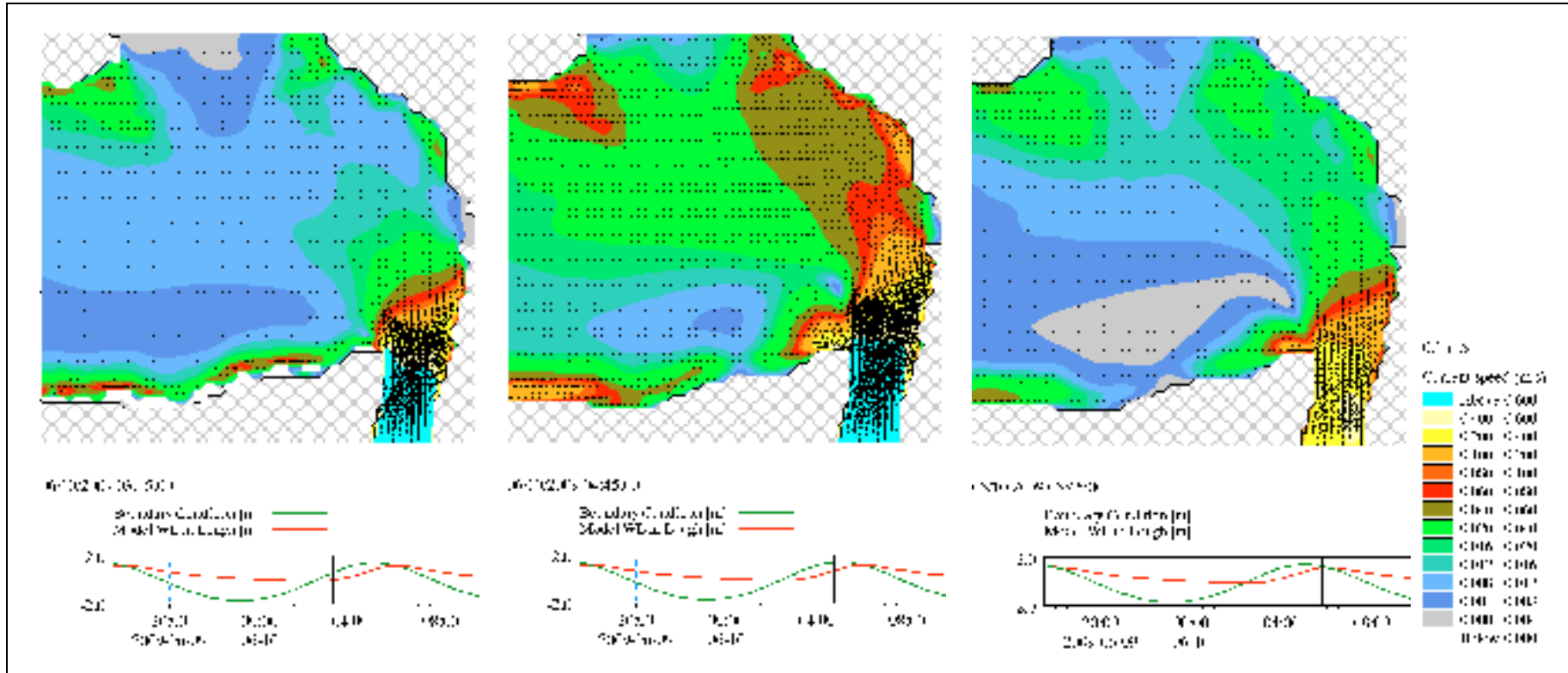


Figure 5.5. Modelled current speed and velocity vectors in Lough Hyne at the beginning, middle and end of flood tide. The green line representing boundary conditions is measured tidal state outside Lough Hyne in Barloge Creek, while the red 'Model WL in Lough' shows the modelled tidal state inside Lough Hyne to which the current speeds refer. Black vertical bar indicates timing of image capture. Current speeds in metres per second, and black markings indicate speed and direction of water flow, but may not be fully visible at figure resolution.

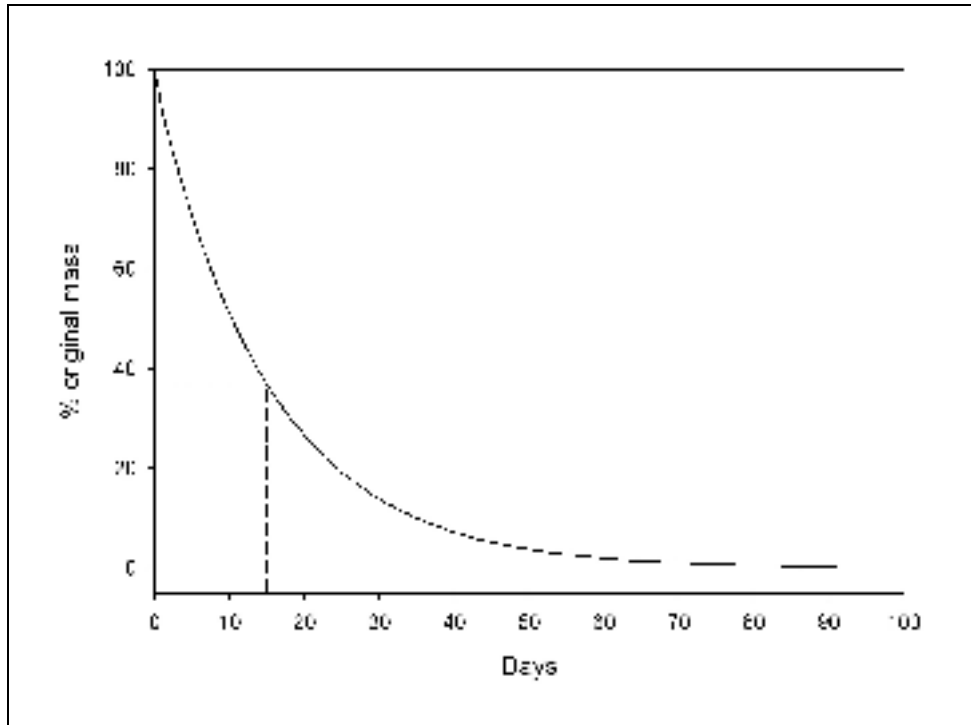


Figure 5.6. Results of flushing time simulation. Simulation was run over 90 days using a repeating spring tide boundary condition (i.e. every single tidal cycle over the 90 days is a spring tide). Line shows the percentage of original water mass in the lough with successive tidal flushing. Flushing time based on original water mass falling below 37% of original mass is indicated by reference line.

5.4 Discussion

While Lough Hyne and Tranabo Bay have small catchment areas relative to their size, Tranabo Bay has a much higher freshwater replacement rate on account of its small size and shallow depth, making it more vulnerable to anthropogenic nutrient enrichment. However, the catchment areas surrounding Tranabo Bay are not heavily cultivated, and the small freshwater inputs and high tidal flushing rate (see [Chapter 2](#) for tidal and freshwater replacement rates) of the bay mean that any nutrient run-off (however small) will be quickly flushed to coastal waters and large persistent algal blooms are unlikely. Tragumna Bay has a large catchment area relative to its size, and a small resident population, making it susceptible to anthropogenic nutrient enrichment associated with run-off into its waters. Again, small freshwater inputs and high tidal flushing mean that large or persistent blooms are unlikely in this area. The beach at Trallspean has consistently obtained Blue Flag status as testament to the water quality in the area.

The hydrodynamic model coped well with predicting the asymmetric tides in Lough Hyne. However, there was a relatively poor match between modelled and measured tidal height data, reflecting difficulties in obtaining accurate bathymetric data in The Rapids, suggesting that future models would benefit from a re-survey of The Rapids. Results from the model show for the first time an overall picture of water movement in Lough Hyne. Modelled current speeds were consistent with those reported by Bassindale et al. (1948) for The Rapids, Bell (2001) for the Western Trough, and Bell and Barnes (2002) for the North Basin, where current speeds were consistently modelled as below 0.004 m/s. The model also highlighted the development of an anticlockwise gyre immediately to the north-west of The Rapids, and an area of low flow to the west of this in the South Basin. Bassindale et al. (1957) describe an anticlockwise movement of water around the South Basin, using drift drogues, that is also consistent with this finding.

The tidal flushing time of Lough Hyne was calculated at 15 days. However, complete tidal replacement of the lough water took in the region of 71 days for 99% replacement. This represents a significant improvement on previous estimates. The flushing time of Lough Hyne was previously approximated at 12 days using the tidal prism method (Jessopp and McAllen, 2007). However, this assumes that the system is well mixed and that tides exclusively flush the system (Dyer and Taylor, 1973). While fresh water input is minimal, it is clear that the underlying assumption of complete tidal mixing is not met in Lough Hyne. Johnson (1995) calculated that, due to the asymmetric tide and incomplete water mixing, actual exchange with each tide is only 23% of the overall tidal volume, and factored this into a tidal prism model to give a revised tidal replacement rate for the lough of 41 days. According to the simulation, at 41 days, 93% of the lough volume is replaced by tidal flushing, and complete flushing occurs at around 80 days, a figure double that of the previous best estimate.

Obviously, a two-dimensional, depth-averaged hydrodynamic model represents a simplified version of Lough Hyne, and cannot account for differences in water movement at depth, or changes in hydrodynamics following development of the seasonal thermocline observed at the lough (McAllen et al., 2009, and [Chapter 2](#)). However, the current model represents a significant improvement in our ability to characterise water movement in the lough, and relates flow characteristics to sedimentation rates and resident biota. Readily identified areas of differing flow

can be used for experimental work investigating flow-mediated differences in biology, such as cirral length in barnacles (e.g. Li and Denny, 2004) and algal growth rate (e.g. Lapointe and Ryther, 1979). Furthermore, understanding the movement of water in and out of Lough Hyne can be used to identify the likely path of pollutants in the water column should they be released either inside or outside the reserve, and can inform best deployment of mitigation measures. The total primary production and biomass of phytoplankton is directly related to nutrient loadings from land and release from sediments, and subsequent availability of these nutrients in the water column (Philippart et al., 2000; Cloern, 2001; Hu et al., 2001). Higher nutrient levels in coastal waters compared with historical data have resulted in increased frequency and duration of phytoplankton blooms in Lough Hyne and likely increased sedimentation as ungrazed phytoplankton biomass dies and settles to the bottom. Correctly parameterised models will be critical in assessing the movement and impact of nutrients and sediment through the system, and will be useful for integrating nutrient monitoring data into regional catchment management plans under the WFD.

Progress in the development of the two-dimensional model in this study has prompted further research into the area, with funding to develop a full three-dimensional model of water movement in the lough secured. Temperature, tide, and flow data collected as part of this study will be utilised in developing this new model which aims to improve upon the current model, and include seasonal thermocline effects on water movement.

6 Recommendations

The Marine Strategy Framework Directive (adopted in June 2008) is intended to protect more effectively the marine environment across Europe. It aims to achieve 'good' environmental status of the EU's marine waters by 2021 and to protect the resource base upon which marine-related economic and social activities depend. The Marine Strategy Framework Directive constitutes the environmental component of the EU's future maritime policy, and is designed to complement the objectives of the WFD which requires surface freshwater and groundwater bodies – such as lakes, streams, rivers, estuaries and coastal waters – to achieve ecologically 'good' status by 2015.

Defining and maintaining 'good' environmental status requires knowledge of the changes taking place in coastal and offshore waters, and whether those changes are the result of natural variation or are induced by man's activities. Monitoring water quality and ecosystem effects from changes in status is paramount, and additionally helps fulfil reporting requirements under the WFD.

6.1 Water Chemistry

The increased concentration of nitrogen in coastal waters compared with that of previous studies is an obvious cause for concern. Nutrient enrichment is the major contributor to coastal eutrophication and subsequent negative impacts on ecosystems. Further work is recommended for the monitoring of nitrogen levels in Irish coastal waters. Detailed analysis of water samples to determine the relative contribution of ammonia, nitrate, nitrite, dissolved organic, inorganic, particulate, etc., forms to the total nitrogen pool may help identify their sources and highlight seasonal changes in their contribution to phytoplankton blooms. Monthly samples are insufficient for discriminating between years, since pulse inputs can be easily missed and phenomena such as nutrient-stimulated blooms occur over much shorter timescales (days to weeks). At the same time, the cost of monitoring at increased temporal scales is prohibitive to long-term studies. It is recommended that infrastructure funding

be sought for automated samplers to be deployed in strategic locations to monitor a suite of water quality parameters at timescales that would otherwise be unachievable through point sampling.

The methanol extraction method for chlorophyll *a* determination used in this study does not correct for phaeo-pigments. SI 272 of 2009 provides chlorophyll assessment thresholds for both methanol and acetone extraction methods, citing a median value of 5 µg/l during the March–September growing season for 'high' and 10 µg/l for 'good' status. However, it is strongly recommended that future studies use the acetone extraction method for chlorophyll *a* determination so that results are consistent with other EU WFD monitoring and reporting.

6.2 Phytoplankton Biodiversity

A total of 171 phytoplankton taxa were identified during the study of nutrient and ecosystem dynamics in Ireland's only statutory marine reserve. Despite the increased availability of literature to support taxonomic identification, the task still requires time-intensive taxonomic skills that would be logistically difficult to incorporate into any realistic framework for widespread monitoring. The Irish Marine Institute conducts regular monitoring of toxic phytoplankton around the coast, particularly in areas of aquaculture. This programme represents a unique opportunity for collaboration and data sharing to help meet monitoring and reporting obligations under the WFD.

This study made a first attempt to correlate phytoplankton biodiversity and proliferation of problematic species with environmental variables. While chlorophyll *a* levels are not an entirely satisfactory indicator of trends in phytoplankton production, there is potential to use historical data to extend the time series of environmental variables and increase the likelihood of finding strong correlations. Satellite-derived data may provide useful data, despite the large spatial scale and the additional problems in resolving data for nearshore coastal waters. There is

considerable experience with this methodology in the UK, offering the possibility of a common Irish/UK approach.

6.3 Risk Assessment

The production of a two-dimensional, depth-averaged hydrodynamic model represents a considerable improvement in our ability to characterise water movement and relate flow characteristics to resident biota in the lough. The power to link catchment area dynamics with the likely path of pollutants in the water column will be invaluable in producing effective risk assessments and contingency plans to limit environmental impacts from pollution events. However, this represents a first step in obtaining a full understanding of the true hydrodynamics of the lough. Development of a correctly parameterised three-dimensional model of water movement in the lough,

including seasonal water stratification, will also enable a better understanding of the fate of nutrients entering the reserve from freshwater sources. Despite only having small freshwater inputs, the high concentration of nutrients entering from freshwater sources and the long flushing time of Lough Hyne mean that nutrients are likely to be retained for much longer than in Tranabo and Tragumna Bays. This may result in increased frequency and duration of phytoplankton blooms in Lough Hyne, and likely increased sedimentation as ungrazed phytoplankton biomass dies and settles to the bottom. A three-dimensional model will be instrumental in assessing the movement and impact of nutrients and sediment through the system, and will be useful for integrating nutrient monitoring data into regional catchment management plans under the WFD.

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Acronyms

ANOVA	Analysis of variance
ASP	Amnesic shellfish poisoning
DARDNI	Department of Agriculture and Rural Development in Northern Ireland
DEM	Digital Elevation Model
EU	European Union
GIS	Geographic information system
GPS	Global positioning system
HAB	Harmful algal bloom
nMDS	Non-metric multidimensional scaling
OSPAR	Oslo/Paris Convention (for the Protection of the Marine Environment of the North-East Atlantic)
PCA	Principal components analysis
PERMANOVA+	Permutational multivariate analysis of variance
RIB	Rigid inflatable boat
SAC	Special Area of Conservation
TN	Total nitrogen
TP	Total phosphorus
WFD	Water Framework Directive

An Gníomhaireacht um Chaomhnú Comhshaoil

Is í an Gníomhaireacht um Chaomhnú Comhshaoil (EPA) comhlachta reachtúil a chosnaíonn an comhshaoil do mhuintir na tíre go léir. Rialaímid agus déanaimid maoirsiú ar ghníomhaíochtaí a d'fhéadfadh truailliú a chruthú murach sin. Cinntímid go bhfuil eolas cruinn ann ar threochtaí comhshaoil ionas go nglactar aon chéim is gá. Is iad na príomh-nithe a bhfuilimid gníomhach leo ná comhshaoil na hÉireann a chosaint agus cinntiú go bhfuil forbairt inbhuanaithe.

Is comhlacht poiblí neamhspleách í an Gníomhaireacht um Chaomhnú Comhshaoil (EPA) a bunaíodh i mí Iúil 1993 faoin Acht fán nGníomhaireacht um Chaomhnú Comhshaoil 1992. Ó thaobh an Rialtais, is í an Roinn Comhshaoil agus Rialtais Áitiúil a dhéanann urraíocht uirthi.

ÁR bhFREAGRACHTAÍ

CEADÚNÚ

Bíonn ceadúnais á n-eisiúint againn i gcomhair na nithe seo a leanas chun a chinntiú nach mbíonn astuithe uathu ag cur sláinte an phobail ná an comhshaoil i mbaol:

- áiseanna dramhaíola (m.sh., líonadh talún, loisceoirí, stáisiúin aistrithe dramhaíola);
- gníomhaíochtaí tionsclaíocha ar scála mór (m.sh., déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta);
- diantalmhaíocht;
- úsáid faoi shrian agus scaoileadh smachtaithe Orgánach Géinathraithe (GMO);
- mór-áiseanna stórais peitreal.
- Scardadh dramhúisce

FEIDHMIÚ COMHSHAOIL NÁISIÚNTA

- Stiúradh os cionn 2,000 iniúchadh agus cigireacht de áiseanna a fuair ceadúnas ón nGníomhaireacht gach bliain.
- Maoirsiú freagrachtaí cosanta comhshaoil údarás áitiúla thar sé earnáil - aer, fuaim, dramhaíl, dramhúisce agus caighdeán uisce.
- Obair le húdaráis áitiúla agus leis na Gardaí chun stop a chur le gníomhaíocht mhídhleathach dramhaíola trí chomhordú a dhéanamh ar líonra forfheidhmithe náisiúnta, díriú isteach ar chiontóirí, stiúradh fiosrúcháin agus maoirsiú leigheas na bhfadhbanna.
- An dlí a chur orthu siúd a bhriseann dlí comhshaoil agus a dhéanann dochar don chomhshaoil mar thoradh ar a gníomhaíochtaí.

MONATÓIREACHT, ANAILÍS AGUS TUAIRISCIÚ AR AN GCOMHSHAOIL

- Monatóireacht ar chaighdeán aer agus caighdeán aibhneacha, locha, uisce taoide agus uisce talaimh; leibhéil agus sruth aibhneacha a thomhas.
- Tuairisciú neamhspleách chun cabhrú le rialtais náisiúnta agus áitiúla cinntiú a dhéanamh.

RIALÚ ASTUITHE GÁIS CEAPTHA TEASA NA HÉIREANN

- Cainníochtú astuithe gáis ceaptha teasa na hÉireann i gcomhthéacs ár dtiomantas Kyoto.
- Cur i bhfeidhm na Treorach um Thrádáil Astuithe, a bhfuil baint aige le hos cionn 100 cuideachta atá ina mór-ghineadóirí dé-ocsaíd charbóin in Éirinn.

TAIGHDE AGUS FORBAIRT COMHSHAOIL

- Taighde ar shaincheisteanna comhshaoil a chomhordú (cosúil le caighdeán aer agus uisce, athrú aeráide, bithéagsúlacht, teicneolaíochtaí comhshaoil).

MEASÚNÚ STRAITÉISEACH COMHSHAOIL

- Ag déanamh measúnú ar thionchar phleananna agus chláracha ar chomhshaoil na hÉireann (cosúil le plannanna bainistíochta dramhaíola agus forbartha).

PLEANÁIL, OIDEACHAS AGUS TREOIR CHOMHSHAOIL

- Treoir a thabhairt don phobal agus do thionscal ar cheisteanna comhshaoil éagsúla (m.sh., iarratais ar cheadúnais, seachaint dramhaíola agus rialacháin chomhshaoil).
- Eolas níos fearr ar an gcomhshaoil a scaipeadh (trí cláracha teilifíse comhshaoil agus pacáistí acmhainne do bhunscoileanna agus do mheánscoileanna).

BAINISTÍOCHT DRAMHAÍOLA FHORGHNÍOMHACH

- Cur chun cinn seachaint agus laghdú dramhaíola trí chomhordú An Chláir Náisiúnta um Chosc Dramhaíola, lena n-áirítear cur i bhfeidhm na dTionscnamh Freagrachta Táirgeoirí.
- Cur i bhfeidhm Rialachán ar nós na treoracha maidir le Trealamh Leictreach agus Leictreonach Caite agus le Srianadh Substaintí Guaiseacha agus substaintí a dhéanann ídiú ar an gcrios ózóin.
- Plean Náisiúnta Bainistíochta um Dramhaíl Ghuaiseach a fhorbairt chun dramhaíl ghuaiseach a sheachaint agus a bhainistiú.

STRUCHTÚR NA GNÍOMHAIREACHTA

Bunaíodh an Gníomhaireacht i 1993 chun comhshaoil na hÉireann a chosaint. Tá an eagraíocht á bhainistiú ag Bord lánaimseartha, ar a bhfuil Príomhstíúrthóir agus ceithre Stíúrthóir.

Tá obair na Gníomhaireachta ar siúl trí ceithre Oifig:

- An Oifig Aeráide, Ceadúnaithe agus Úsáide Acmhainní
- An Oifig um Fhorfheidhmiúchán Comhshaoil
- An Oifig um Measúnacht Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáide

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag ball air agus tagann siad le chéile cúpla uair in aghaidh na bliana le plé a dhéanamh ar cheisteanna ar ábhar imní iad agus le comhairle a thabhairt don Bhord.

Science, Technology, Research and Innovation for the Environment (STRIVE) 2007-2013

The Science, Technology, Research and Innovation for the Environment (STRIVE) programme covers the period 2007 to 2013.

The programme comprises three key measures: Sustainable Development, Cleaner Production and Environmental Technologies, and A Healthy Environment; together with two supporting measures: EPA Environmental Research Centre (ERC) and Capacity & Capability Building. The seven principal thematic areas for the programme are Climate Change; Waste, Resource Management and Chemicals; Water Quality and the Aquatic Environment; Air Quality, Atmospheric Deposition and Noise; Impacts on Biodiversity; Soils and Land-use; and Socio-economic Considerations. In addition, other emerging issues will be addressed as the need arises.

The funding for the programme (approximately €100 million) comes from the Environmental Research Sub-Programme of the National Development Plan (NDP), the Inter-Departmental Committee for the Strategy for Science, Technology and Innovation (IDC-SSTI); and EPA core funding and co-funding by economic sectors.

The EPA has a statutory role to co-ordinate environmental research in Ireland and is organising and administering the STRIVE programme on behalf of the Department of the Environment, Heritage and Local Government.