

The Irish Sea: Nutrient status and phytoplankton

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Abstract

Historical nutrient and phytoplankton data from the Irish Sea are reviewed in the light of recent studies. Mean late winter concentrations of dissolved inorganic nitrogen (DIN as $\text{NO}_3^- + \text{NO}_2^-$), dissolved inorganic phosphate (DIP as PO_4^{3-}) and silica (Si as SiO_2) in offshore near-surface waters are 8.3, 0.7 and 6.6 μM , respectively. Concentrations in inshore waters of the eastern Irish Sea can reach 57 μM DIN, 5 μM DIP and 17 μM Si. The northwards residual flow through the Irish Sea ($\approx 5 \text{ km}^{-3} \text{ d}^{-1}$) is estimated to deliver $\approx 82 \times 10^3 \text{ t}$ DIN and $12 \times 10^3 \text{ t}$ DIP during the winter period. The annual freshwater inputs of DIN (including ammonium) and DIP are 123 and $9 \times 10^3 \text{ t}$, respectively. Offshore waters of the western Irish Sea are enriched with DIN and DIP (≈ 3.0 and 0.4 μM , respectively) relative to Celtic Sea shelf break concentrations but salinity DIN relationships show that measured winter concentrations are lower than predicted. Denitrification is considered a key process limiting nitrogen enrichment of the Irish Sea.

The onset and duration of the production season is controlled by the sub-surface light climate. Differences in depth and tidal mixing in the Irish Sea give rise to regional variation in the timing and length of the production season. Maximum spring bloom biomass in coastal and offshore waters of the western Irish Sea (23 and 16 mg chlorophyll m^{-3} , respectively) compares with values of up to 44 mg chlorophyll m^{-3} in Liverpool Bay and elevated production and biomass in the latter is attributed to enrichment. There is no evidence that enrichment and changes in nutrient ratios have caused major shifts in phytoplankton composition in Liverpool Bay. Species of *Phaeocystis* are found throughout the region in most years and together with other microflagellates can dominate the spring bloom. Red tides of dinoflagellates are rare events in the Irish Sea but regular monitoring of phytoplankton in the vicinity of shellfish beds has revealed the presence of toxin-producing dinoflagellates in the Irish Sea.

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1. Introduction

The Irish Sea, located on the north western European continental shelf, is bounded by the land masses of the UK and Ireland (Fig. 1). The

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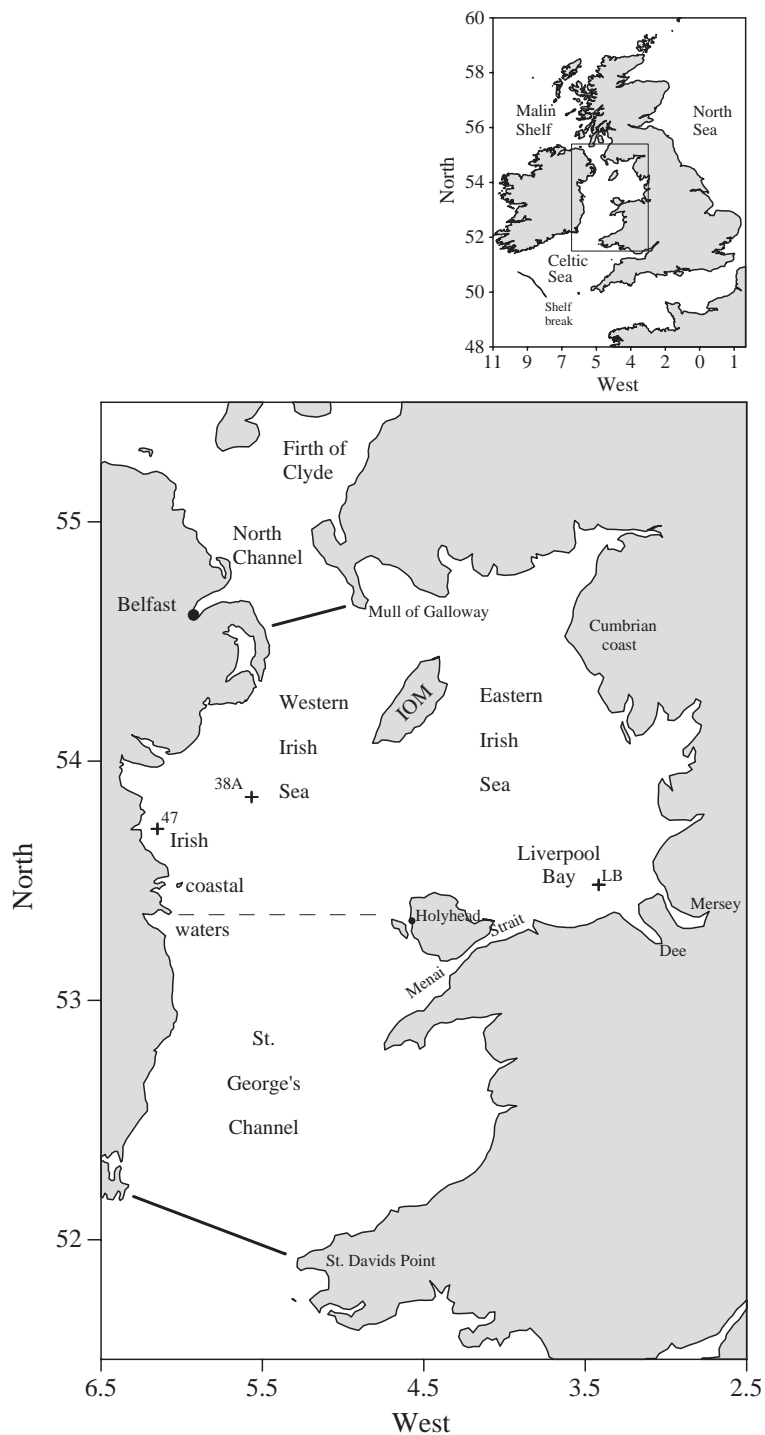


Fig. 1. A map of the Irish Sea showing key locations and sampling stations (+) mentioned in the text. The DARD offshore mooring station is at station 38A. The solid lines mark the southern and northern boundaries of the Irish Sea. The Dublin to Holyhead section is shown by the dashed line.

geographical limits of the sea are usually taken to be between 52° N (St David's Head to Carnsore Point) and 54° 40' N (Mull of Galloway). This small coastal sea has a volume of 2430 km³, which is <10% of the volume of the North Sea. To the east of the region, the water is generally <50 m deep and there are extensive shallow (\approx 20 m) coastal areas. Waters in the west are generally deeper and a trough 80 to 100 m deep extends north south through the western Irish Sea.

Despite its small size, the natural resources of the Irish Sea are of considerable economic importance. The 1998 value of fish and *Nephrops norvegicus* (Norwegian lobster) landings, for example, has been estimated as £ 43 million (Connolly and Molloy, 2000). However, coastal marine ecosystems of Northern Europe are under pressure from global change (e.g. climate variation, nutrient enrichment and toxic pollution) which threatens these resources. As the marine environment is modified by global change, it will be important to develop strategies to effectively manage natural marine resources and protect our natural wildlife heritage. Such strategies must be based on scientific understanding of which parts of the environment are changing and how this impacts on ecosystem structure and function. Documenting the current status of the marine environment is an important first step, since this provides the baseline against which future change can be quantified.

Many coastal regions are enriched with plant nutrients (Van Bennekom et al., 1975; Van Bennekom and Wetsteijn, 1990; Riegman et al., 1992; Hickel et al., 1993; De Jonge et al., 1996). For the Irish Sea, the risk of enrichment is compounded by its semi-enclosed nature. The region is relatively isolated from open shelf and oceanic waters and exchange is constrained by two channels. St George's Channel in the south connects the Irish Sea to the Celtic Sea and the North Channel links the Irish Sea with the inner Malin Shelf to the north. In the context of the Den Haag workshop on eutrophication, the purpose of this paper is to define the current nutrient status of the Irish Sea in relation to external sources and describe aspects of Irish Sea phytoplankton relevant to the eutrophication issue.

2. Methods

For the purposes of this paper, published material is reviewed in the light of recent studies and data collected by the Department of Agriculture and Rural Development (DARD) in Northern Ireland. Details of the methods used by DARD are given in Gowen et al. (1995) for temperature and salinity, dissolved inorganic nutrients, chlorophyll and primary production. In 1995, DARD established a mooring in the western Irish Sea at 53°51'N 05°34'W. In March 1997 the mooring was moved to its present location at 53°47'N 05°38'W (Fig. 1). The mooring was a standard 'U' shape with the instrument arm supporting two automated in situ water samplers (McLane, Woods Hole, USA) that were deployed at \approx 12 m for nutrients (McLane RAS 3-48N) and \approx 14 m for microplankton (McLane RAS 500). Mercuric chloride (to give a final concentration of 20 mg l⁻¹) and acidic Lugol's iodine were used to preserve water samples for dissolved inorganic nutrients and phytoplankton, respectively. More recently a recording CTD (Seabird Electronics Inc. Washington USA) was deployed at 16 m.

3. General oceanography of the Irish Sea

Transport through the region is generally considered to be northwards (Bassett, 1909) with water from the Atlantic and Celtic Sea providing the source water for the Irish Sea. Early estimates of flow through the Irish Sea (1.3 and 1.15 km d⁻¹ for the southern entrance and Dublin to Holyhead section, respectively) were made by Knudsen (cited by Bowden, 1950). Using a modification of the salt budget approach used by Knudsen, Bowden (1955) estimated the mean flow across the Dublin to Holyhead line to be 0.3 km d⁻¹ and concluded that the higher values of Knudsen were over-estimates because they included longitudinal transport of salt into the Irish Sea. Using a value of 0.3 km d⁻¹ and a cross sectional area of 7.1 km² for the Dublin to Holyhead section (Bowden, 1950), the volume transport would be 2.1 km³ d⁻¹. Brown (1991) reported a mean residual flow of \approx 1.5 cm s⁻¹ in the Celtic Sea (51° N and 7° W) from an unpublished study by Sherwin. This is equivalent to 1.3 km d⁻¹, i.e. the

same as the estimate of Knudsen, reported by Bowden (1955), and gives a volume transport of $8.1 \text{ km}^3 \text{ d}^{-1}$ across the southern entrance. More attention has been paid to flow through the North Channel. Here, outflow is largely on the eastern, Scottish side with a weaker inflow along the Northern Ireland coast. Dickson and Boelens (1988) reviewed estimates of volume transport and concluded that the net transport was between 2 and $8 \text{ km}^3 \text{ d}^{-1}$. Using the conservative tracers salt and caesium-137, Simpson and Rippeth (1998) estimated flow through the Irish Sea to be between 3.5 and $5.2 \text{ km}^3 \text{ d}^{-1}$. These values compare with estimates of $8.6 \text{ km}^3 \text{ d}^{-1}$ derived from recording current meter measurements (Brown and Gmitrowicz, 1995) and $6.7 \text{ km}^3 \text{ d}^{-1}$ from a 15-mo study of HF radar and ADCP measurements by Knight and Howarth (1998). For the purposes of this paper a value of $5 \text{ km}^3 \text{ d}^{-1}$ has been assumed. The overall residence time of water in the Irish Sea is in the order of 12 mo, although Dickson and Boelens

(1988) present estimates for different areas within the sea. It is evident, however, that local meteorological conditions (particularly wind forcing) have a major influence on flow through the two channels and hence volume transport and residence time (Knight and Howarth, 1998).

The bathymetry of the Irish Sea, regional differences in tidal amplitude and freshwater input give rise to distinct hydrographic areas (Gowen et al., 1995). Lowest salinities are measured in the eastern Irish Sea (Fig. 2), which reflects the pattern of freshwater inflow. Of the total riverine discharge of $31 \text{ km}^3 \text{ y}^{-1}$ into the Irish Sea, $24.9 \text{ km}^3 \text{ y}^{-1}$ (80%) flows into coastal water of the eastern Irish Sea (Bowden, 1955). In addition to this freshwater inflow, Bowden (1955) calculated that the annual rainfall over the sea added an additional 10.6 km^3 freshwater. To the west of the region, the spatial distribution of salinity shown in Fig. 2 indicates a tongue of more saline water extending northwards

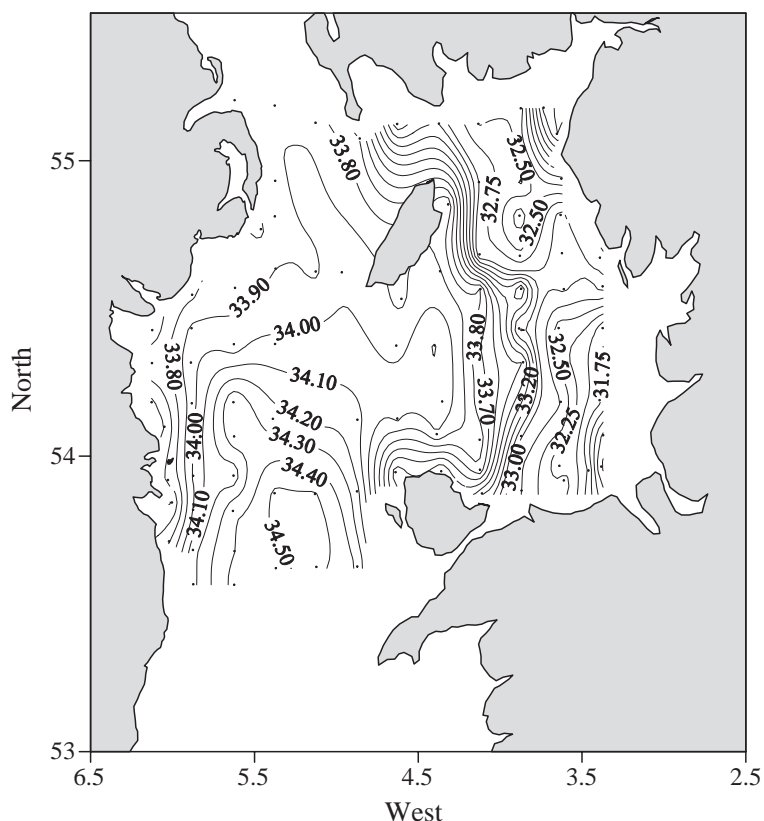


Fig. 2. The near-surface distribution of salinity in the Irish Sea during January 2000. The contour intervals are 0.25 between 30 and 33 and 0.1 between 33 and 34.5.

through the western Irish Sea. This appears to be a consistent winter feature (Matthews, 1914; Lee, 1960; Gowen et al., 2002) and supports the view that the bulk of the flow is to the west of the Isle of Man (Ramster and Hill, 1969). The distribution of salinity also suggests limited exchange between the eastern and western Irish Sea although radionuclide distributions indicate some east west transport (Leonard et al., 1997) probably north of the Isle of Man. Deep water and weak tidal flows ($\leq 25 \text{ cm s}^{-1}$) south west of the Isle of Man, allow the seasonal development of stratification (Gowen et al., 1995; Horsburgh et al., 2000). In this area, the density gradients associated with a dome of cold bottom water drive a near-surface gyre (Hill et al., 1994) which may be important in retaining planktonic organisms within the stratified region (White et al., 1988). The transition between the stratified and mixed waters is marked by a tidal mixing front (Simpson and Hunter, 1974). In the two channels, turbulence generated by strong tidal flows is sufficient to keep the water column vertically mixed throughout most of the year.

4. Dissolved inorganic nutrient concentrations and supply

4.1. The annual cycle

The annual cycle of dissolved inorganic nutrients in the Irish Sea with maximum and minimum concentrations in winter and summer, respectively, is typical of northern European coastal and shelf seas and reflect the seasonality of biological production and breakdown. Following from Ryther and Dunstan (1971) and cell quota arguments (Tett and Droop, 1988) nitrogen is widely assumed to be the nutrient most likely to limit phytoplankton growth in the Sea. For the Irish Sea, Gibson et al. (1997) suggested that the pattern of DIN and DIP draw-down during the spring, with DIN becoming depleted before DIP, provided *prima facie* evidence for nitrogen being the limiting nutrient.

Recent synoptic winter surveys of the Irish Sea show a marked heterogeneity in the spatial distribution of near-surface nutrients with highest concentrations in the eastern Irish Sea (Fig. 3). Kennington et al. (1998) reported maximum concentrations of 46.4

μM DIN, 1.7 μM DIP and $>12.5 \mu\text{M}$ Si for coastal waters off the Cumbria coast in March 1997. Gowen et al. (2000) measured concentrations of 29.2 μM DIN, 1.6 μM DIP and 4.6 μM Si (salinity 32.36) in Liverpool Bay although in inshore waters of the bay winter concentrations of up to 57.1 μM DIN, 5.2 μM DIP and $>16.7 \mu\text{M}$ Si were reported by Kennington et al. (1998). Winter concentrations of dissolved nutrients are generally lower in the western Irish Sea. In Irish coastal waters (Station 47, Fig. 1), Gowen et al. (2000) reported values of 9.5 μM DIN (salinity 34.46), 0.8 μM DIP, 5.0 μM Si (salinity 34.57) for March 1997. For the period 1998 to 2002, mean March/ early April concentrations (moored sampler and discrete samples) of the three nutrients in offshore near-surface waters of the western Irish Sea were 8.3 μM DIN, 0.7 μM DIP, 6.6 μM Si.

4.2. External sources

The main external sources of dissolved nutrients to the Irish Sea are marine (Atlantic) and freshwater (riverine and atmospheric). Quantifying these source terms provides an insight into the relative magnitude of any anthropogenic influence. The Atlantic sets the overall background nutrient levels for the Irish Sea and deviations from Atlantic water concentrations will therefore reflect internal cycling and the influence of anthropogenic nutrient sources. Close to the shelf break in the Celtic Sea ($7^\circ 40' \text{W}$) Cooper (1961) measured near-surface concentrations of 0.6 to 0.7 μM DIP and 3.5 to 4.0 μM Si in mid-March 1955. Gowen et al. (2002) report data from UK surveys undertaken in January/February 1994, February 1998 and January 1999 which have characterised winter concentrations in surface waters at the shelf break. For January and February, DIN is typically between 6.3 and 8.8 μM (mean 7.7 μM , $n=135$) and DIP and Si concentrations range from 0.4 to 0.7 μM (mean 0.5 μM , $n=21$) and 2.3 – 4.2 μM (mean 2.8, $n=21$), respectively.

Deriving a robust estimate for the Atlantic source term is not a trivial task and at present is constrained by a lack of understanding of key processes. Using $5 \text{ km}^3 \text{ d}^{-1}$ for volume transport together with the mean winter shelf break concentrations, the daily input from the Atlantic can be estimated as 540 t DIN, 78 t DIP and 840 t Si. Clearly, the greatest potential for the supply of dissolved nutrients from the Atlantic is

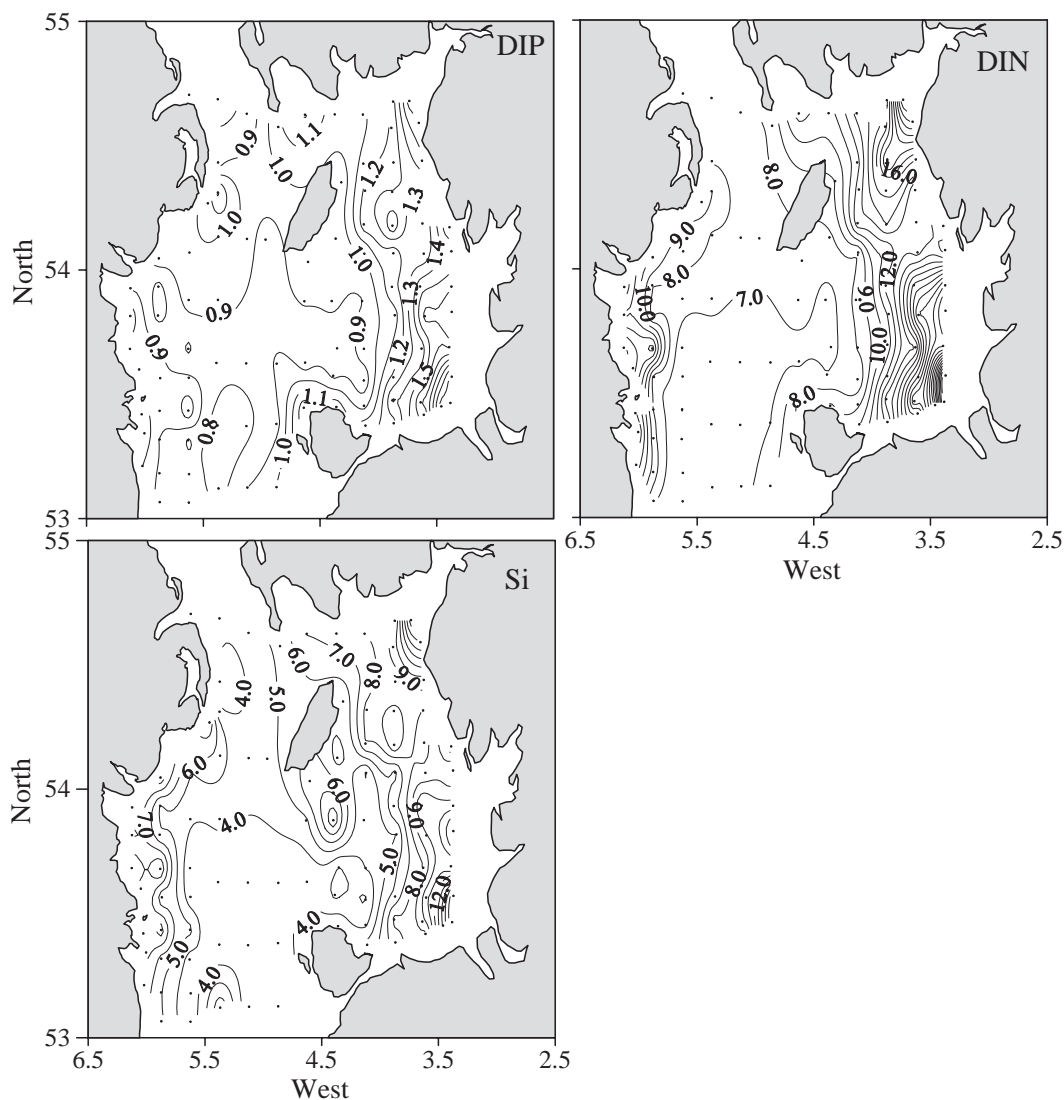


Fig. 3. The spatial distribution of dissolved inorganic nutrients (μM) in near-surface waters of the Irish Sea during January 2000. For DIP the contour interval is $0.1 \mu\text{M}$ and for DIN and Si the contour interval is $1.0 \mu\text{M}$.

winter when concentrations are at or near their annual maximum. However, attempts to extrapolate to an annual Atlantic supply term introduce further uncertainty. Details of the winter build-up of nutrients through deep off-shelf mixing are lacking, the outer shelf region is one of weak flows (Pingree, 1993) and the presence of a shelf break salinity front during winter (Hydes et al., 2004) may indicate restricted on-shelf transport. Finally, the timescale for transport of water from the shelf break into the Irish Sea may be

up to one year. One consequence of the latter is the potential for nutrient cycling and removal by sedimentation and burial and denitrification in the case of DIN as Atlantic water is transported across the shelf and through the Celtic Sea. The presence of low winter nitrate ($\approx 5.5 \mu\text{M}$) in near-surface waters of the Celtic Sea (Hydes et al., 2004) may reflect the presence of 'old Atlantic water' from which DIN has been removed. Winter water entering the Irish Sea might therefore have a DIN concentration of ≈ 5.5

μM rather than the $7.7 \mu\text{M}$ measured at the shelf break. Transport of dissolved nutrients into the Irish Sea would be much less during spring and summer due to the growth of phytoplankton but would be replaced by the advection of particulate and dissolved organic nutrients.

Assuming winter shelf break concentrations are established by November and that the period of supply is 5 mo, then a crude estimate of the annual Atlantic source term would be $82 \times 10^3 \text{ t DIN}$, $12 \times 10^3 \text{ t DIP}$ and $127 \times 10^3 \text{ t Si}$. The OSPAR quality status report for the Celtic Seas for the year 2000 (OSPAR, 2000a) gives estimates for the Atlantic supply of N and P as greater than 100 million tonnes and 28 million tonnes, respectively. These values seem implausible (the annual Atlantic supply of N to the greater North Sea is only estimated as 4.1 million t (OSPAR, 2000b) and are likely to be the result of reporting error. Based on a volume transport of $5 \text{ km}^3 \text{ d}^{-1}$, the annual volume transport through St George's Channel would be 1825 km^3 . Dividing this volume into the OSPAR Atlantic N source term ($100 \times 10^6 \text{ t}$) gives an Atlantic water concentration of 54.8 g m^{-3} ($3914 \mu\text{M DIN}$). For DIP, the Atlantic source concentration would be 15.3 g m^{-3} equivalent to $495 \mu\text{M}$. Clearly these large estimates cannot be correct and the supply of nutrients from the Atlantic must be much less than those given in the OSPAR quality status report.

4.3. Freshwater

Freshwater (riverine, industrial and domestic) inputs of DIN (including ammonium) and DIP to the Irish Sea are currently $\approx 80 \times 10^3$ and $7.0 \times 10^3 \text{ t}$ per year, respectively (OSPAR, 2001). The Si input to the north western Irish Sea from Irish rivers is $\approx 9.0 \times 10^3$ from Irish rivers (C. Gibson, pers. comm., 2002). The annual loading of Si from UK rivers is $22 \times 10^3 \text{ t}$ (UK Environment Agency). The atmospheric inputs of N and P are 43 and $2 \times 10^3 \text{ t}$ (Gillooly et al., 1992). There is also a substantial input of riverine nutrients into the Celtic Sea, which could contribute to the total riverine input to the Irish Sea. It would therefore appear that the freshwater input of nitrogen to the Irish Sea is of a similar magnitude to the natural marine input. This contrasts with the North Sea where the supply of Atlantic N represents 70% of the total (marine, freshwater and atmospheric) input (OSPAR, 2000b).

The eastern Irish Sea is clearly enriched with all three nutrients relative to shelf break concentrations and the influence of freshwater inflow on nutrient concentrations in the eastern Irish Sea is evident from salinity nutrient relationships (Fig. 4). For all three nutrients there is a significant ($P < 0.01$, least-squares linear regression) negative relationship reflecting high concentrations in freshwater relative to Atlantic water. The situation in the western Irish Sea is less clear. The

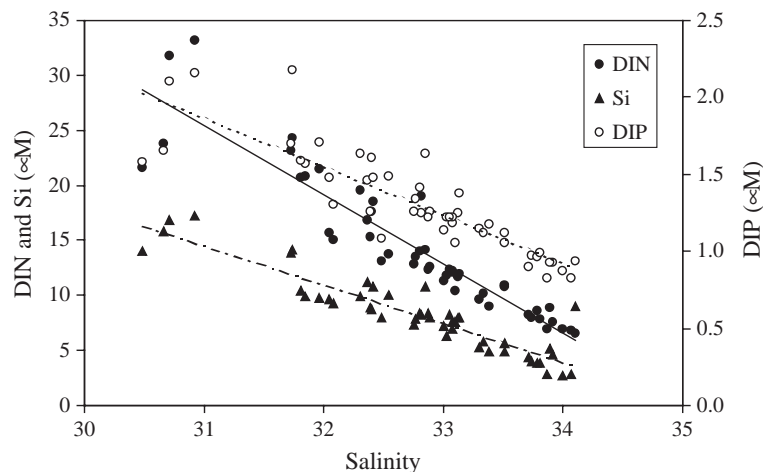


Fig. 4. Salinity-nutrient relationships for data from near-surface waters of the eastern Irish Sea in January 2000.

region is enriched with DIP and Si relative to the shelf break region but to a lesser extent than the eastern Irish Sea. January and February concentrations (1998 to 2002 moored sampler and discrete near-surface samples) of DIP and Si ranged from 0.6 to 0.9 μM (mean 0.8 μM , $n=78$) and from 3.1 to 9.7 μM Si (mean 6.5 μM , $n=103$), respectively. For both nutrients, concentrations were significantly higher than those measured at the shelf break (ANOVA \log_{10} transformed data, $P<0.01$). With respect to DIN in offshore waters of the western Irish Sea, January and February, (1998 to 2002 moored sampler and discrete samples) concentrations ranged from 4.1 – 11.1 μM . The mean 7.5 μM ($n=103$) was close to the mean shelf break value of 7.7 μM although there was a small but significant difference between the two data sets (ANOVA \log_{10} transformed data, $P=0.04$). By March/ early April (prior to the spring bloom) concentrations of offshore western Irish Sea DIN had increased (mean 8.3 μM , $n=80$) and were significantly higher (ANOVA \log_{10} transformed, $P<0.01$) than January and February Irish Sea and shelf break concentrations. Assuming that the January/February shelf break concentrations represent the winter maximum for that region, it would appear that in the Irish Sea, concentrations of DIN increase throughout the winter period.

The contribution of freshwater nutrient sources to winter nutrient concentrations in the western Irish Sea is less apparent than in the eastern Irish Sea. Foster (1984) failed to find a significant salinity-nitrate relationship in the western Irish Sea and Gibson et al. (1997) concluded that riverine sources only contributed 11% to the winter build-up of DIN. For the recent DARD data (1998 to 2002 discrete and sampler data) only Si gave a significant ($P<0.01$) negative regression against salinity (Fig. 5) during the period of winter nutrient accumulation (September to March). However, the mooring data reveal short-term events (days) during which increases in nutrient concentrations are associated with reductions in near-surface salinity. This suggests that riverine sources of nutrients may be important in ‘topping up’ winter levels in the western Irish Sea.

Between 18 and 26 February 2002, near-surface salinity decreased from 34.21 to 33.87. Over the same period concentrations of all three nutrients increased. Si increased by 1.1 μM (from 6.8 to 7.9 μM), which

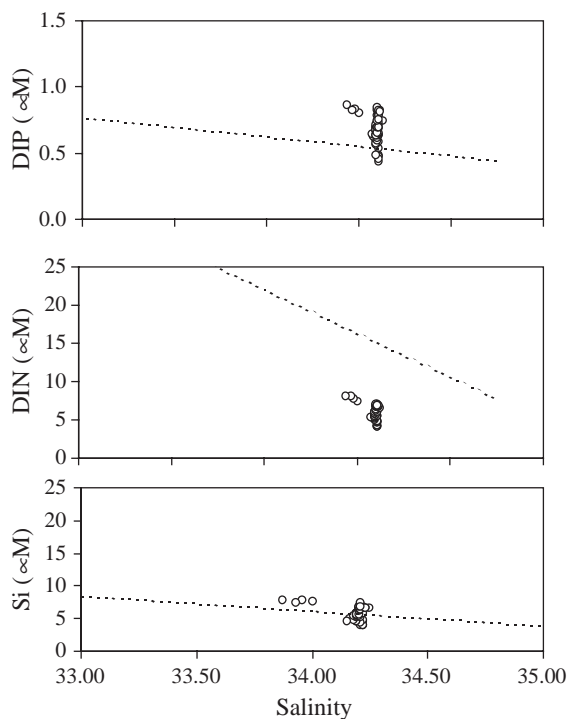


Fig. 5. Salinity-nutrient relationships for data from discrete samples and the moored sampler collected between September and March 1998 to 2002. The dashed line represents the theoretical mixing line between winter nutrient concentrations in freshwater and surface water at the Celtic Sea shelf break.

compares with a predicted increase of 0.8 μM , assuming a freshwater Si concentration of 83 μM (R. Foy pers. comm., 2002). The similarity between the measured and predicted increase in Si is reflected in the data in Fig. 5, which show that for a given salinity, measured concentrations of Si are close to the theoretical Si salinity mixing line.

For DIP, the measured increase of 0.1 μM is much higher than the 0.03 μM predicted from a 1% reduction in salinity and freshwater concentration of 3.0 μM (data from the Rivers Boyne and Liffey, OSPAR, 2001). This apparent over-estimate of DIP input is reflected in the comparison between measured concentrations and the theoretical mixing line (Fig. 5). For a given salinity, most of the measured concentrations plot above the theoretical mixing line between Atlantic water and freshwater. One reason for this may be that freshwater DIP is only one part of the total freshwater phosphorus load. For the Boyne and Liffey, total P (particulate and dissolved) is ≈ 4.2

μM although the final concentration of DIP will depend on exchange processes between dissolved and particulate phosphorus.

Dissolved inorganic nitrogen shows the opposite pattern to that of DIP. The measured increase of $1.4 \mu\text{M}$ is less than the increase of $2.1 \mu\text{M}$ predicted from a 1% decrease in salinity and a freshwater concentration of $211 \mu\text{M}$ (nitrate and ammonium data from the Rivers Boyne and Liffey, OSPAR, 2001). This under-estimate is also reflected in Fig. 5, which shows that for a given salinity, all of the measured DIN concentrations fall below the theoretical mixing line between Atlantic water and freshwater. The mean January/February (1998 to 2002 discrete and moored sampler data) concentration of DIN for which there are corresponding salinity data is $6.6 \mu\text{M}$ (salinity 34.20). The predicted concentration for this salinity is $15.1 \mu\text{M}$. Removal of DIN by denitrification in estuaries and the transport of 'old' Atlantic water into the Irish Sea would reduce source concentrations of DIN but denitrification in Irish Sea sediments may also be an important process by which comparatively low DIN concentrations are maintained in the western Irish Sea. Rates of sediment denitrification have been measured at the Irish coastal station 47 and offshore station 38A. During spring and summer 1997, Gowen et al. (2000) measured denitrification rates of between 6 and $7 \mu\text{mol m}^{-2} \text{h}^{-1}$ at the inshore station. Trimmer et al. (1999) measured rates of between 6 and $48 \mu\text{mol m}^{-2} \text{h}^{-1}$ (mean $21 \mu\text{mol m}^{-2} \text{h}^{-1}$, $n=6$) between February and July 1998 at the offshore station. These values equate to between 0.05 to 0.4 mol y^{-1} and compare with a rate of $0.3 \text{ mol m}^{-2} \text{y}^{-1}$ derived by Simpson and Rippeth (1998) using the LOICZ budgeting procedure.

4.4. Historical and recent surveys

Historical (e.g. Jones and Folkard, 1971) and recent (Kennington et al., 1997, 1998; Gowen et al., 2002) surveys of the eastern Irish Sea and Liverpool Bay indicate that this area has been enriched for at least 35 y. Jones and Folkard (1971) undertook a major study of the eastern Irish Sea during the 1960s, and for February 1967 measured maximum surface concentrations of $22.5 \mu\text{M NO}_3^-$ (salinity 31.18), $2.0 \mu\text{M DIP}$ (salinity 32.32) and $16.7 \mu\text{M Si}$ (salinity 31.00). Additional data on the nutrient status of

Liverpool Bay come from studies in 1970/71 by Abdullah and Royle (1973) and in 1975 by Foster et al. (1977). The study by Slinn (1974) is the earliest comprehensive study of dissolved nutrients in the western Irish Sea. In February 1965 and 1968 Slinn (1974) measured concentrations of <4 to $5 \mu\text{M DIN}$, 0.6 to $0.7 \mu\text{M DIP}$ and 6.0 to $7.0 \mu\text{M Si}$. The nitrate values are consistent with concentrations of 5 to $6 \mu\text{M NO}_3^-$ reported for St. George's Channel ($\approx 30 \text{ km}$ off Holyhead) by Ewins and Spencer (1967). Concentrations of DIN (<6 to $>8 \mu\text{M}$) measured by Slinn (1974) in March 1966 were higher than those in January/ February and supports the view of a continual build-up of winter DIN in the Irish Sea. The February concentrations of ≈ 4 to $5 \mu\text{M DIN}$ measured by Slinn (1974) in 1965 and 1968 are lower than the current January/February mean concentrations at the Celtic Sea shelf break ($7.7 \mu\text{M}$) and in offshore waters of the western Irish Sea ($7.5 \mu\text{M}$). This suggests that the elevation in western Irish Sea winter DIN has occurred since the 1960s. Foster (1984) measured a concentration of $10.7 \mu\text{M}$ in December 1975 and Gillooly et al. (1992) reported a concentration of $\approx 8.0 \mu\text{M}$ for January/ February 1990. These survey data are too few to properly assess trends in nutrient levels but recent analysis of the Isle of Man time-series established by Slinn in the 1950s provides good evidence for an increase in DIN ($\approx 3.0 \mu\text{M}$) and DIP ($\approx 0.4 \mu\text{M}$) levels in the Irish Sea (Allen et al., 1998; Gowen et al., 2002). This increase took place during the 1960s and 1970s and may have been associated with increased riverine concentrations (Gowen et al., 2002) although Evans et al. (2003) suggest that climate variation may also influence nutrient levels in the Irish Sea. Data collected over the last 4–5 years indicate that there is no trend in winter DIN concentrations and winter levels of DIP may be decreasing.

5. Phytoplankton

5.1. Production

In the western Irish Sea, differences in depth and tidal mixing influence the timing of the phytoplankton production season (Gowen et al., 1995). This gives rise to what appears to be a wave of growth extending

out from Irish coastal waters as the production season begins progressively later offshore and in the North Channel (Fig. 6). The start of the production season is characterised by a spring bloom with a peak between March and May. For Irish coastal waters and offshore waters of the western Irish Sea, spring bloom chlorophyll can reach 23 and 16 mg m⁻³, respectively (Gowen and Bloomfield, 1996). Spring bloom chlorophyll concentrations appear to be higher in Liverpool Bay. Gowen et al. (2000) reported a maximum spring bloom biomass of 43.9 mg chlorophyll m⁻³ in May 1997. There are, however, few data with which to compare this value and judge whether it is typical. Spencer (1972) recorded a mean chlorophyll concentration of 0.33 mg m⁻³ (based on sampling at 30 stations) during a 2-d survey in May 1970. This seems particularly low compared to the 43.9 mg m⁻³ quoted above and the concentrations of up to 7.0 mg m⁻³ (chlorophyll+pheopigment) measured by Foster et al. (1982) in early May 1977 and up to 38.0 mg chlorophyll m⁻³ in April 1997 by Kennington et al. (1998).

Estimates of the annual production of phytoplankton for the Irish Sea are limited. To date the study by Gowen and Bloomfield (1996) is the most comprehensive but was restricted to the western Irish Sea. Here, annual production was estimated as 140 g C m⁻² in offshore stratified waters and 194 g C m⁻² in Irish coastal waters and the North Channel. These values are comparable with estimates from the North Sea (Joint and Pomroy, 1993) comparing similar water types. There are few published measurements of primary production for the eastern Irish Sea. In Liverpool Bay, Gowen et al. (2000) measured a maximum rate of 3.2 g C m⁻² d⁻¹ during the spring bloom in 1997 and based on 9 values, estimated annual production as 182 g C m⁻², which is low compared to the 250 to 300 g C m⁻² y⁻¹ for continental coastal waters of the North Sea (Joint and Pomroy, 1993).

Summer production is probably limited by DIN availability throughout most of the Irish Sea although the deep North Channel is an exception. Here, Gowen et al. (1995) measured a mean DIN concentration of 4.1 µM (range 2.1 to 6.1 µM, n=17) in near-surface waters during June to August 1992 and 1993. Offshore waters to the west of the region are characterised by low summer biomass in

surface waters and there is frequently a sub-surface chlorophyll maximum. On 22 June 1999 for example, concentrations of chlorophyll at depths of 1 and 20 m were 1.5 and 8.1 mg m⁻³, respectively. Gowen et al. (2000) reported a mean summer (June – August) biomass of 2.5 mg chlorophyll m⁻³ (0.6 to 4.2 mg m⁻³, n=19) for Irish coastal waters in 1997. This compares with an overall mean of 3.6 mg m⁻³ (0.0 to 11.4 mg m⁻³, n=109) for all DARD chlorophyll data (June to August 1992 to 2002) from station 47 in Irish coastal waters. Offshore, for the same months and over the same period, the mean euphotic zone (upper 20 m) concentration was 1.9 mg m⁻³ (0 to 9.7 mg m⁻³, n=88) and summer concentrations are significantly lower (log₁₀ transformed data ANOVA, *P*<0.01) than those measured at the coastal site. In July and August 1996, Kennington et al. (1997) measured maximum concentrations of 12 and 25 mg chlorophyll m⁻³ in the vicinity of the Dee and Mersey river estuaries but 3 to 8 mg m⁻³ in more open waters of Liverpool Bay. At station LB in Liverpool Bay, Gowen et al. (2000) reported a mean summer (1997) biomass of 8.8 mg m⁻³ (4.1 to 13.6 mg m⁻³, n=29).

The accumulation of DIN over winter fuels most of the spring phytoplankton bloom and enrichment might be expected to increase spring bloom production and standing stock. On the basis of a comparative study of sites in Irish coastal waters and Liverpool Bay (Gowen et al., 2000) concluded that this was the case. For offshore waters of the western Irish Sea there are no pristine stratified areas with which comparative studies can be undertaken and there are no historical production data with which to compare with those reported by Gowen and Bloomfield (1996). It is evident from recent observations in this offshore region that most of the winter DIN in the euphotic zone is utilised by phytoplankton for growth. Post-bloom euphotic zone concentrations are typically <0.5 µM and this implies that the excess winter DIN (relative to concentrations measured by Slinn in the 1960s) is utilised by phytoplankton, i.e. spring bloom production has increased. Furthermore, despite a high degree of variability in the data, recent analysis of the Isle of Man chlorophyll time-series indicates a statistically significant increase in spring bloom chlorophyll (Hartnoll et al., 2002).



Fig. 6. Spatial and temporal variation in the development of the 1992 spring bloom (measured as daily production, mg C m^{-2}) in the western Irish Sea. The contour interval is 250 mg C m^{-2} .

5.2. Species composition

One of the earliest studies of the seasonal distribution of phytoplankton (diatoms and dinoflagellates) was undertaken in 1949/1950 and 1951/1952 by Williamson (1952, 1956) and provide early records of the occurrence of particular species in the Irish Sea. During the late 1950s through to the mid 1970s, Liverpool Bay was the main focus of study on phytoplankton in relation to nutrient supply (Spencer, 1972; Foster et al., 1982) and algal blooms (Jones and Haq, 1963; Jones and Folkard, 1971; Helm et al., 1974). For more offshore waters, Beardall et al. (1982) and Coombs et al. (1993) report limited observations on phytoplankton composition in the vicinity of the western Irish Sea front. More recently, McKinney et al. (1997) undertook a detailed study of diatom abundance in 1995 (April to August) at the DARD mooring site. McKinney et al. (1997) recorded a total of 39 species of diatoms. *Skeletonema costatum* was the most abundant spring bloom species and in order of abundance, species of *Chaetoceros*, *Pseudonitzschia* and *Thalassiosira* were also important components of the bloom. Based on limited sampling of the 1997 spring bloom, Gowen et al. (2000) found that *Guinardia delicatula* was the dominant diatom at both the Irish coastal station 47 and the DARD offshore mooring site. These studies together with microscope analysis of samples collected in recent years using the DARD moored sampler indicate that there is considerable inter-annual variability in bloom composition. Diatoms appear to dominate the bloom in most years (although the dominant species varies from year to year) but microflagellates can represent an important component of the spring bloom (as in 1997) and in 2001 dominated the spring bloom.

On the basis of a comparative study of Liverpool Bay and Irish coastal waters, Gowen et al. (2000) concluded that there was little evidence for enrichment and perturbation of nutrient ratios having induced changes in species composition in Liverpool Bay. In both locations blooms of microflagellates (including *Phaeocystis* spp.) preceded the 1997 spring diatom bloom and summer populations were characterised by mixed assemblages of diatoms and flagellates. *Phaeocystis*, which is widely regarded as a nuisance alga has been present in the eastern Irish Sea at least since the

1950s (Williamson, 1956; Jones and Haq, 1963). Species of *Phaeocystis* appear to be present in this region in most years (Spencer, 1972; Foster et al., 1982; Kennington et al., 1999) and have also been observed in the western Irish Sea (Gowen et al., 2000). Helm et al. (1974) reported a bloom of the dinoflagellate, *Karenia mikimotoi* (= *Gyrodinium aureolum*) in the eastern Irish Sea during the autumn of 1971. Mortalities of benthic invertebrates were associated with the bloom but not directly attributed to it. No subsequent blooms of this alga have been reported for the Irish Sea although blooms of *K. mikimotoi* have been reported in Firth of Clyde sea lochs in 1980 (Jones et al., 1982) and at the Islay front on the Malin Shelf in August 1996 (Gowen et al., 1998). Finally, there have been no reports of large persistent surface summer blooms of this alga at the western Irish Sea front similar to those reported at tidal fronts in the English Channel (Pingree et al., 1975).

The phytoplankton studies outlined above provide important background information on the species present in the Irish Sea and short-term inter-annual variability (at least in offshore western Irish Sea waters). However, the short duration of most studies and the different methods of sample collection used preclude any assessment of long-term changes in phytoplankton species in the Irish Sea. It is only in the last 8 to 10 years that regular sampling to develop time-series of phytoplankton species has been established in the region. The UK Environment Agency in collaboration with the University of Liverpool Port Erin Marine Laboratory on the Isle of Man have initiated a sampling programme in the eastern Irish Sea (see Hartnoll et al., 2002) and DARD has established a programme in the western Irish Sea. In addition, the Isle of Man Government began a bloom watch programme in 1992. In accordance with EU Directive (EC 91/492) requiring member states to monitor phytoplankton composition in the vicinity of shellfish beds, there are national schemes that encompass coastal waters of the Irish Sea. Taking the Northern Ireland monitoring programme as an example, a total of 16 nuisance/toxin-producing species have been identified to date (Table 1) and since the programme was started in 1993, positive bioassay tests for algal toxins have resulted in periodic closure of shellfish beds (A. McKinney, pers. comm., 2002). These time-series are too short to determine

Table 1

A list of nuisance and toxin-producing algae recorded in coastal waters of Northern Ireland since 1993

| Species |
|---|
| <i>Alexandrium</i> spp. |
| <i>Dictyocha speculum</i> |
| <i>Dinophysis acuminata</i> |
| <i>Dinophysis acuta</i> |
| <i>Dinophysis norvegica</i> |
| <i>Dinophysis rotundata</i> |
| <i>Karenia mikimotoi</i> (<i>Gyrodinium aureolum</i>) |
| <i>Gymnodinium</i> spp. |
| <i>Heterosigma akashiwo</i> |
| <i>Lingulodinium polyedra</i> |
| <i>Noctiluca scintillans</i> |
| <i>Phaeocystis pouchetti</i> |
| <i>Prorocentrum lima</i> |
| <i>Prorocentrum minimum</i> |
| <i>Protoperdinium</i> spp. |
| <i>Pseudonitzschia</i> spp. |

whether there have been long-term changes in the Irish Sea phytoplankton.

6. Conclusions

1. On an annual basis freshwaters contribute $\approx 50\%$ of the total external supply of DIN to the Irish Sea.
2. The Irish Sea is enriched with anthropogenic nutrients. In offshore waters of the western Irish Sea winter levels of DIN and DIP have increased by ≈ 3.0 and $0.4 \mu\text{M}$, respectively, since the late 1950s/early 1960s. Current late winter concentrations are typically $\approx 8 \mu\text{M}$ DIN, $0.7 \mu\text{M}$ DIP and $5\text{--}6 \mu\text{M}$ Si. Winter nutrient levels in the eastern Irish Sea are higher relative to the western region and can reach $57 \mu\text{M}$ DIN, $5 \mu\text{M}$ DIP and $17 \mu\text{M}$ Si.
3. Elevated production and phytoplankton biomass in Liverpool Bay is attributed to nutrient enrichment but enrichment does not appear to have resulted in a major shift in species. Spring bloom production has probably increased in the western Irish Sea and the Isle of Man time-series provides some evidence for this.
4. Nuisance and harmful species of phytoplankton have been present in the Irish Sea since at least the late 1950s. Current monitoring in the vicinity of shellfish beds has identified a range of nuisance/

harmful species in Irish Sea coastal waters but a lack of historical data precludes any assessment of long-term trends in the composition of Irish Sea phytoplankton.

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