BENTHIC DIATOMS OF THE RIVER DEEL: DIVERSITY AND COMMUNITY STRUCTURE

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ABSTRACT

This paper compares the diversity and structure of the benthic diatom assemblages on boulder and cobble substrata and examines the influence of site and seasonal factors on diatom diversity in the River Deel, Co. Limerick. One hundred and ten diatom species were identified from the River Deel, with 85 species found on boulders over a two-year period and 102 species found on cobbles over a one-year period. There was little difference in the composition of the diatom community on boulders between sites. Some differences were noted between sites for cobbles, with a small number of species being more associated with certain sites than others. The absence of marked differences between the sites was attributed to the lack of longitudinal variation in the main channel of the River Deel. On both substrates, indicator species analysis showed that the abundance of most diatom species was not related to sampling date. On boulders, only fourteen species in 1999 and twenty-one species in 2000 had a significant association with any sampling date. Twelve cobble species had a significant association with a sampling date (principally May). There was little correspondence between significant indicator species on cobbles and boulders. The patterns of dominance of diatom species differed between the boulder and cobble substrates over the sampling period, and Detrended Correspondence Analysis (DCA) showed that diatom samples formed two distinct groupings based on substrate.

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INTRODUCTION

Benthic algae, or phytobenthos, live attached to or near substrata, such as stones, macrophytes and mosses, on lake and river beds. The term encompasses a great diversity of algal types, including *Bacillariophyta* (diatoms), *Cyanophyta* (blue-green algae), *Chlorophyta* (green algae) and *Chrysophyta* (golden algae) among others. In rivers, diatoms exceed all other groups combined in terms of species diversity. The small number of published studies on the diversity of phytobenthos in Irish rivers makes it difficult to compare results from the present study of a moderately eutrophic, calcareous river with those from similar Irish rivers. McDonnell and Fahy (1978) investigated the algae of the Inver, a small moorland stream in Co. Galway; Heuff and Horkan (1984) investigated the oligotrophic River Caragh; while Ní Chatháin *et al.* (2004) investigated the diatom assemblage at potential reference sites. However, little is known about the influence of environmental variables on phytobenthos in Irish rivers of varying typology and water quality or about the composition, distribution or spatial or temporal variation of these phytobenthos.

In contrast, a number of other European countries and the USA utilise phytobenthos for water quality–monitoring purposes in rivers (Whitton *et al.* 1991; Whitton and Rott 1996; Prygiel *et al.* 1999; Porter *et al.* 1993), mainly focusing on diatoms, which are the most diverse and numerous component of the phytobenthic assemblage, with well-documented ecological preferences (Lange-Bertalot 1979; Whitton *et al.* 1991; Cattaneo and Amireault 1992; Round 1993; van Dam *et al.* 1994; Whitton and Rott 1996; Kelly *et al.* 1998; Rott *et al.* 1998; Prygiel *et al.* 1999; Kelly 2000). The EU Water Framework Directive (WFD) (European Community 2000) has stipulated phytobenthos as one of the biological quality elements to be used to define the ecological status of rivers and lakes. This has presented a need for additional information on algal communities in our rivers, including their composition and diversity, the factors affecting their distribution and their potential as indicators of ecological status. The objective of this paper is to describe the diversity, structure and ecology of the benthic diatom community from a typical lowland Irish river.

The River Deel is a lowland, calcareous river, 52km long and encompassing a catchment area of 51,200ha, mainly in Co. Limerick. The River Deel serves agriculture, farming-based industries and urban water needs, while it also caters for amenity and game-angling interests. The catchment is one of the most intensively farmed in the country. Most

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soils in the catchment have an average extractable phosphorus level of 6–10mg l^{-1} (Limerick County Council 1990), and the Deel is regarded as slightly to moderately eutrophic (Lucey *et al.* 1999; Clabby *et al.* 2003). Sources of suspected impacts include sewage, industries and agriculture (Clabby *et al.* 2003). As a consequence, the River Deel has repeatedly performed poorly in biological investigations carried out by the Environmental Protection Agency (EPA), although some improvements were observed in the 2002 survey (Clabby *et al.* 2003). The benthic diatom assemblages of lowland, calcareous rivers such as the River Deel have not been previously investigated in Ireland.

This paper presents the results of a two-year survey of benthic diatom diversity in the River Deel. We investigated the structure of diatom assemblages on two different substrates in the river: boulders and cobbles. Cobbles are the recommended substratum for sampling of river diatoms for the purposes of water-quality assessment (Round 1993; Kelly *et al.* 1998; European Committee for Standardization 2003). We hypothesise that there are significant differences in the diatom communities on the two substrates and that there are significant seasonal and site differences in diatom diversity.

MATERIALS AND METHODS

STUDY SITES

Five sites were sampled on the main channel of the River Deel (Table 1). The sites were chosen because of the similarity of their substrata and bankside vegetation and the presence of riffle areas. Limestone boulder (>256mm diameter) and limestone cobble (≥ 64mm, ≤ 256mm diameter) (size categories as per European Committee for Standardization 2003) substrata were present and sampled at all five sites. Physico-chemical data for each site were supplied by Limerick County Council. Site 5 was located furthest upstream, while Site 1 was located furthest downstream, with approximately a 32-km distance between sites.

SAMPLING

Benthic diatoms from stone substrata (epilithon) were sampled monthly from boulders between March 1999 and October 2000. From May to October 2000, diatoms were sampled from cobbles. No samples could be collected in May, September or December 1999 or in July 2000 due to flooding. The methods for collecting epilithic diatoms from boulders followed those prescribed by the American Public Health Association (1995). Five boulders were collected at random from each site, a square area (5×5cm) was delineated on the boulder surface and the epilithic algae were removed with a scalpel. Detached algae were then washed into labelled 50-ml vials. Epilithic diatoms were collected from cobbles following the same methodology as that used for boulders: five cobbles that were free of sediments and macroalgal growth were sampled from riffle areas at each site. Epilithic diatoms were removed with a scalpel from a measured square or rectangular area marked on the surface of each cobble. The scalpel was used as some cobbles contained encrusted growths of algae due to the hardness of the river. The sample area on each cobble was also brushed vigorously with a toothbrush in a plastic tray with water to remove any remaining algal film, and the sample was then poured into a 50-ml plastic vial. Samples were brought back to the laboratory in a cooled bag and were stored in the dark at 4°C. Where possible, identification was carried out within one week of collection. Otherwise, samples were preserved in Lugol's iodine pending identification. Conspicuous macroalgal growths (primarily green algae) occurring at any of the sites were also collected and identified.

IDENTIFICATION AND ENUMERATION

Permanent slide mounts of diatoms collected from boulder and cobble substrates were prepared to aid identification and to quantify diatom frequency of occurrence. Samples were oxidised with 30% H_2O_2 and potassium dichromate (Kelly *et al.* 1998).

Table 1—Locations and chemistry data of five sampling sites on the River Deel, Co. Limerick.

Site	*Location*	*Grid ref.*	*Mean depth (cm)*	*pH range*	*Mean PO_4 (mg l^{-1})*	*Range PO_4 (mg l^{-1})*	*Mean NO_3 (mg l^{-1})*	*Range NO_3 (mg l^{-1})*	*Q value (1999)*
1	Inchirourke	R 340 495	42	7.5–8.7	0.176	0.06–0.30	11.08	4.03–14.65	3–4
2	Newbridge	R 335 452	45	7.6–8.5	0.176	0.07–0.29	9.95	4.47–14.23	3–4
3	Bridge downstream of Slewnawn Stream	R 312 362	49	7.8–8.4	0.189	0.09–0.32	9.27	4.34–13.01	3
4	Bridge upstream of Owenskaw River	R 319 291	31	8.0–8.7	0.130	0.04–0.20	11.97	5.27–15.56	–
5	'Broken Bridge'	R 360 270	35	7.8–8.7	0.128	0.07–0.20	13.65	4.83–16.17	3

Oxidised solutions of cleared diatom cell walls (valves) were mounted on glass microscope slides using Naphrax (Brunel Microscopes Ltd). Diatom valves were counted in random fields of view at ×1000 magnification using Nomarski optics until approximately 300 valves per slide were enumerated and identified. Identifications of prepared diatoms were made using primarily the monographs of Krammer and Lange-Bertalot (1986; 1988; 1991a; 1991b). Macroalgae and non-diatom microalgae were identified using the taxonomic works of Bourrelly (1966; 1968; 1981), Prescott (1964), Whitton *et al.* (2000), John *et al.* (2002) and Patrick and Reimer (1966; 1975). All identifications were to species level where possible, with green algae and blue-green algae identified mainly to genus level.

DATA ANALYSIS

For each species, two measures of occurrence were estimated: (a) % frequency, or the proportion of samples in which a species occurred; (b) % abundance, or the percentage of the total valve count contributed by that species. Indicator species analysis (IndVal) (Dufrêne and Legendre 1997) was used to determine the indicator value (*IV*) of diatom species on cobble and boulder substrates. In this procedure $IV_{ij} = RA_{ij} \times RF_{ij} \times 100$; where RA_{ij} is the relative abundance of species *j* in substrate *i*, and RF_{ij} is the relative frequency of species *j* in substrate *i*. The highest *IV* of a given species (*IVmax*) is taken as the overall *IV* of that species for that substrate. The *IVmax* values of individual species were tested for statistical significance using Monte Carlo permutation (1,000 permutations). The null hypothesis is that a given species has no *IV* (i.e. the *IVmax* is no greater than that expected by chance). Species diversity and evenness were calculated using Shannon's diversity index (H′) and MVSP version 3.11c (Kovach 1999). For comparison of diatom diversity between substrates and sites, species numbers were $\log_{10}$-transformed and compared using *t*-tests in the SPSS for Windows (version 10.0) statistical package. The indirect gradient analysis technique of Detrended Correspondence Analysis (DCA) (ter Braak and Šmilauer 1998) was used to assess the similarity of the diatom assemblages on boulder and cobble substrates.

In order to relate the diatom community to water quality, the Trophic Diatom Index (TDI) was calculated for both substrates. The TDI is a measure of the effect of nutrients, predominately phosphorus, on diatom assemblages (Kelly and Whitton 1995). It is computed using a 'weighted average' equation and is calculated as follows:

$$\mathrm{TDI} = (\mathrm{WMS} \times 25) - 25$$

where WMS = Weighted Mean Sensitivity, calculated as follows:

$$\mathrm{Index} = \frac{\sum_{j-1}^{n} a_j s_j v_j}{\sum_{j-1}^{n} a_j v_j}$$

where a_j = abundance (proportion) of taxon *j* in the sample, s_j = pollution sensitivity (1–5) of taxon *j*, and v_j = the *IV* (1–3) of species *j*.

The values of sensitivity (s_j) are as follows: 1 = favoured by very low nutrient concentrations; 2 = favoured by low nutrient concentrations; 3 = favoured by intermediate concentrations of nutrients; 4 = favoured by high concentrations of nutrients; and 5 = favoured by very high concentrations of nutrients.

Interpretation of the index requires the calculation of a second value, percent motile valves, and the rationale for the inclusion of this calculation is based on the fact that growth forms of diatoms are believed to provide information on non-nutrient factors influencing community composition, such as sedimentation (Kelly *et al.* 2001).

RESULTS

A total of 110 diatom species were identified from boulders and cobbles in the River Deel. Eighty-five diatom species were identified from boulders sampled at the five sites from March 1999 to October 2000 (Table 2). Diatom diversity on cobbles (102 species) was greater than that on boulders, even though cobble sampling was conducted only from May to October 2000. Only 63 diatoms were identified from boulders during this latter period. Significantly fewer ($P < 0.05$) diatom species were found on average per site per sampling date on boulders (28.1 ± 5.2) than on cobbles (31.7 ± 6.9). The majority of diatoms identified were pennate, with *Cyclotella meneghiniana* and *Melosira varians* the only centric species identified.

The relationships between frequency and mean % abundance of the principle diatom species on boulders and cobbles are shown in Fig. 1. Species occurring with high frequency were also generally more abundant, and these species dominated the diatom assemblage. The data set also includes species that were abundant but present in relatively fewer samples, such as *Fragilaria capucina*, as well as less abundant species that were nevertheless common, such as *Navicula lanceolata*, *Navicula saprophila*,

Table 2—Percentage frequency of occurrence (i.e. the proportion of samples in which a species occurred) of diatoms on boulders and cobbles in the River Deel, Co. Limerick.

Taxa	*Boulders*	*Cobbles*
Achnanthes conspicua A. Mayer	0.0	29.2
Achnanthes hungarica (Grunow) Grunow in Cleve & Grun.	0.0	20.8
Achnanthes lanceolata (Brébisson) Grun.	2.5	79.2
Achnanthidium biasolettiana Bukhtiyarova & Round	0.0	8.3
Achnanthidium minutissimum (Kützing) Czarnecki	100.0	100.0
Amphora inariensis Krammer	47.5	41.7
Amphora ovalis (Kützing) Kützing	3.8	4.2
Amphora pediculus (Kützing) Grunow	100.0	100.0
Caloneis bacillum (Grunow) Cleve	75.0	83.3
Cocconeis pediculus Ehrenberg	100.0	91.7
Cocconeis placentula Ehrenberg	100.0	100.0
Cyclotella meneghiniana Kützing	47.5	66.7
Cymatopleura solea (Brébisson) W. Smith	30.0	4.2
Cymbella affinis Kützing	5.0	4.2
Cymbella gracile (Ehrenberg) Kützing	0.0	12.4
Cymbella laevis Naegeli in Kützing	0.0	62.5
Cymbella lanceolata (Ehrenberg) Kirchner	15.0	8.3
Cymbella minuta Hilse ex Rabenhorst	63.8	87.5
Cymbella silesiaca Bleisch in Rabenhorst	6.3	12.5
Denticula tenuis Kützing	41.3	8.3
Diatoma ehrenbergii Kützing	2.5	4.2
Diatoma mesodon (Ehrenberg) Kützing	3.8	4.2
Diatoma moniliforme Kützing	0.0	33.3
Diatoma tenue Agardh	2.5	4.2
Diatoma vulgare Bory	100.0	66.7
Encyonema gracile Ehrenberg	1.3	0.0
Eunotia arcus Ehrenberg	1.3	8.3
Eunotia exigua (Brébisson ex Kützing) Rabenhorst	23.8	12.5
Eunotia incisa Gregory	0.0	8.3
Eunotia pectinalis (Kützing) Rabenhorst	1.3	4.2
Eunotia serra Ehrenberg	2.5	4.2
Fragilaria brevistriata Grun. in Van Heurck	0.0	4.2
Fragilaria capucina Desmazieres	28.8	45.8
Fragilaria capucina var. perminuta (Grunow) Lange-Bertalot	21.3	25.0
Fragilaria capucina var. vaucheriae (Kützing) Lange-Bertalot	20.0	25.0
Fragilaria fasciculata (C. Ag.) Lange-Bertalot	0.0	12.5
Fragilaria lapponica Grun. in Van Heurck	0.0	8.3
Fragilaria ulna var. acus (Kützing) Lange-Bertalot	0.0	20.8
Fragilaria virescens Ralfs	1.3	4.2
Frustulia rhomboides (Ehrenberg) De Toni	12.5	20.8
Gomphonema acuminatum Ehrenberg	3.8	8.3
Gomphonema angustum Agardh	11.3	79.2
Gomphonema augur Ehrenberg	1.3	4.2
Gomphonema clavatum Ehrenberg	50.0	50.0
Gomphonema gracile Ehrenberg	0.0	4.2
Gomphonema minutum (C. Agardh) C. Agardh	93.8	4.2
Gomphonema olivaceum (Hornemann) Brébisson	80.0	79.2
Gomphonema olivaceum var. minutissima Hustedt	0.0	8.3
Gomphonema olivaceum var. staurophorum (Panotocsek)	0.0	8.3
Gomphonema parvulum (Kützing) Kützing	78.8	91.7

Table 2 (*Continued*)

Taxa	*Boulders*	*Cobbles*
Gomphonema truncatum Ehrenberg	10.0	12.5
Gyrosigma acuminatum (Kützing) Rabenhorst	40.0	16.7
Gyrosigma attenuatum (Kützing) Rabenhorst	0.0	4.2
Melosira varians Agardh	26.3	37.5
Meridion circulare (Greville) Agardh	15.0	20.8
Navicula sp. 2	0.0	70.8
Navicula accomoda Hustedt	5.0	4.2
Navicula atomus (Kützing) Grunow	18.8	4.2
Navicula capitata var. hungarica (Grun.) R. Ross	1.3	0.0
Navicula capitatoradiata Germain	0.0	4.2
Navicula cari Ehrenberg	0.0	4.2
Navicula contenta Grun. in Van Heurck	7.5	20.8
Navicula cryptocephla Kützing	2.5	4.2
Navicula cryptotenella Lange-Bertalot	77.5	100.0
Navicula gregaria Donkin	100.0	91.7
Navicula lanceolata (Agardh) Kützing	91.3	100.0
Navicula menisculus Schumann	100.0	20.8
Navicula minuscula Grun. in Van Heurck	6.3	100.0
Navicula radiosa Kützing	2.5	87.5
Navicula reinhardtii (Grunow) Grunow in Cleve & Möller	8.8	4.2
Navicula rhynchocephala Kützing	2.5	4.2
Navicula saprophila Lange-Bertalot & Bonik	41.3	4.2
Navicula subminuscula Manguin	20.0	12.5
Navicula tripunctata (O.F. Müller) Bory	100.0	95.8
Navicula veneta Kützing	1.3	29.2
Nitzschia acicularis (Kützing) W. Smith	63.8	8.3
Nitzschia amphibia Grunow	30.0	4.2
Nitzschia constricta (Kützing) Ralfs in Pritch.	3.8	12.5
Nitzschia dissipata (Kützing) Grunow	93.8	91.7
Nitzschia filiformis (W. Smith) Van Heurck	0.0	4.2
Nitzschia fonticola Grunow in Van Heurck	2.5	12.5
Nitzschia inconspicua Grunow	2.5	4.2
Nitzschia linearis (Agardh) W. Smith	16.3	29.2
Nitzschia palea (Kützing) W. Smith	72.5	83.3
Nitzschia paleacea (Grunow) Grunow in Van Heurck	5.0	20.8
Nitzschia perminuta (Grunow) M. Perag.	0.0	4.2
Nitzschia recta (Hantzsch) Rabenhorst	0.0	8.3
Nitzschia sigmoidea (Nitzsch) W. Smith	3.8	4.2
Pinnularia borealis Ehrenberg	3.8	8.3
Pinnularia microstauron (Ehrenberg) Cleve	8.8	4.2
Pinnularia rupestris Hantzsch in Rabenhorst	0.0	4.2
Pinnularia viridis (Nitzsch) Ehrenberg	6.3	4.2
Planothidium lanceolatum (Bréb. ex Kützing) Round & Bukhtiyarova	61.3	0.0
Pseudostaurosira brevistriata (Grunow in Van Heurck) Williams et Round	2.5	0.0
Reimeria sinuata (Gregory) Kociolek & Stoermer	100.0	87.5
Rhizosolenia sp.	2.5	0.0
Rhizosolenia eriensis H.L. Smith	0.0	79.2
Rhoicosphenia abbreviata (C. Agardh) Lange-Bertalot	100.0	100.0
Stauroneis anceps Ehrenberg	2.5	4.2

Table 2 (*Continued*)

Taxa	*Boulders*	*Cobbles*
Staurosirella lapponica (Grunow in Van Heurck) Williams & Round	12.5	0.0
Surirella angusta Kützing	7.5	16.7
Surirella brebissonii Krammer & Lange-Bertalot	61.3	33.3
Surirella linearis W. Smith	0.0	4.2
Surirella ovalis Brébisson	2.5	20.8
Synedra acus Kützing	2.5	0.0
Synedra ulna (Nitzsch) Ehrenberg	100.0	70.8
Tabellaria fenestrata (Lyng.) Kütz. 1844	43.8	0.0
Tabellaria flocculosa (Roth) Kützing	31.3	4.2
Unidentified 1	3.8	5.3
Unidentified 2	0.0	4.2

Nitzschia palea, *Nitzschia dissipata* and *Reimeria sinuata*. Only 24 species (27%) occurred in 50% or more of the samples. Forty-one species (47%) occurred in less than 10% of samples.

On boulders, *Navicula gregaria*, *Cocconeis placentula*, *Navicula tripunctata*, *Cocconeis pediculus* and *Diatoma vulgare* dominated the diatom community. On cobbles, *Cocconeis placentula* and *Navicula tripunctata* were also among the dominant species, but *Achnanthidium minutissimum*, *Amphora pediculus* and *Navicula minuscula* were more common on cobbles than on boulders. Twenty-five species were found exclusively on cobble substrata, and eight on boulder substrata (Table 2). On the basis of frequency, *Gomphonema angustum*, *Navicula minuscula*, *Achnanthes lanceolata* and *Navicula radiosa* were more frequently encountered on cobbles than on boulders, while *Navicula menisculus*, *Gomphonema minutum*, *Nitzschia acicularis*, *Denticula tenuis* and *Navicula saprophila* were more frequently found on boulders than on cobbles. Some diatom species (*Cocconeis placentula*, *Cocconeis pediculus*, *Diatoma vulgare* and *Rhoicosphenia abbreviata*) were epiphytic on filaments of the green alga *Cladophora glomerata*, which grew attached to most boulders. At times, these species densely covered *Cladophora* filaments. IndVal analysis detected six diatom species with statistically strong associations with cobbles (Table 3). Three species were significantly associated with boulders, but the associations were generally not as strong as those for cobbles.

There was no significant difference in the numbers of diatom species recorded on cobbles between sampling dates. Significantly fewer ($P < 0.05$) diatom species were found on boulders (21.8 species) at all sites in June in both years than on other sampling dates (mean = 28.1 species). For both substrates, IndVal analysis of diatom occurrence showed that the abundance of most species was not significantly ($P \geq 0.05$) related to sampling date. On boulders, only 15 species in 1999 and 21 in 2000 had a significant ($P \leq 0.05$) association with any sampling date (Table 4). Four species (*Cocconeis pediculus*, *Navicula menisculus*, *Navicula tripunctata* and *Rhoicosphenia abbreviata*) showed the same significant pattern of seasonal distribution between the two years, attaining maximum abundance on the same or contiguous sampling dates in summer in both years. These species were also common on cobbles in summer, but were not significantly associated with the summer months of July to August. Twelve cobble species had a significant ($P \leq 0.05$) association with a sampling date, principally May (Table 4). There was little correspondence between significant indicator species on cobbles and those on boulders.

Differences between the abundance patterns of diatoms on boulders and cobbles for the months they were all sampled are illustrated by rank-abundance curves (Fig. 2). *Cocconeis placentula*, *Navicula gregaria* and *Navicula tripunctata* were the three most abundant diatoms on boulders in most months from May to October 2000. On cobbles, however, abundance patterns were more variable: *Achnanthidium minutissimum* was the most abundant diatom in May and June, but *Cocconeis placentula* became dominant thereafter. On boulders, the dominance of *Cocconeis placentula*, *Navicula gregaria* and *Navicula tripunctata* decreased over the sampling period, and the composition of the diatom community became more even, as evidenced by reduction in the slope of the species abundance curves and by increasing Shannon–Wiener diversity values over the sample period. No such trends were observed on cobbles. Shannon–Wiener index values for boulders and cobbles (Fig. 2) were tested for similarity using a Mann–Whitney U test and were not significantly different.

Similarities between diatom communities on cobbles and boulders were assessed by DCA (Fig. 3). The abundances of individual diatom species on both substrata were compared only for those

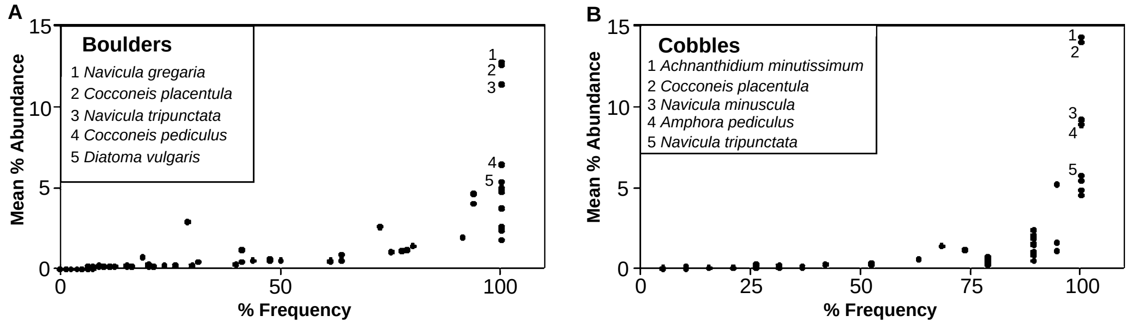

Fig. 1—Relationship between abundance and frequency of diatom species on boulder and cobble substrates in the River Deel, Co. Limerick.

months in which both were sampled (i.e. May to October 2000). Based on substrate, diatom assemblages formed two distinct groupings, which are separated on axis 1 of the DCA diagram (total inertia = 1.74; axis 1 = 0.38; axis 2 = 0.15). Axis 2 separated the samples on the basis of sampling date, an effect that is most marked for boulders, where May and June samples and September and October samples are separated into two groupings, with August samples interspersed between the two. Cobble samples form a single, more diffuse grouping, which nonetheless shows a differentiation between summer and autumn samples. Some species that were abundant on boulders in May and June, such as *Cocconeis placentula*, became more abundant on cobbles in September and October. The DCA analysis indicates that the diatom assemblage on cobbles in September and October bears more similarity to the diatom assemblage on boulders sampled in May and June than it does to the assemblage on contemporaneously sampled boulders. The DCA analysis also indicates that differences in the diatom community between substrates were consistently observed along the river channel and over the sampling period.

Values for the TDI index typically ranged between 60 and 80 in the River Deel (Table 5), indicating waters rich in orthophosphate, and all sites can be classified as moderately to fairly eutrophic (Dr M.G. Kelly, pers. comm.). TDI values did not differ significantly between the two substrata. TDI values revealed that boulder substrata had a generally higher percentage of motile species, which indicates that factors other than water quality, such as sedimentation, may be influencing the diatom assemblage (Table 5). The largest difference between the substrates lies in the species that strongly influence the TDI score. Boulder substrata had higher abundances of *Navicula lanceolata* and particularly *Navicula gregaria*, which are motile species. Other species influencing the TDI score included those that are commonly epiphytic or found in association with *Cladophora glomerata*, such as *Cocconeis placentula*, *Cocconeis pediculus*, *Diatoma vulgare*, *Gomphonema minutum* and *Fragilaria capucina*. In comparison, diatom species influencing the TDI score on cobble substrata included *Achnanthidium minutissimum*, *Amphora pediculus*, *Cocconeis placentula*, *Gomphonema minutum*, *Navicula lanceolata*, *Navicula gregaria*, *Navicula tripunctata*, *Nitzschia dissipata*, *Reimeria sinuata* and *Rhoicosphenia abbreviata*.

DISCUSSION

There are no diatom studies from rivers of similar trophic status in Ireland (i.e. moderately to fairly eutrophic rivers) with which to compare the results

Table 3—Indicator diatoms for boulder or cobble substrates in the River Deel, Co. Limerick (using IndVal analysis). Only those species that do not satisfy the null hypothesis of no *IV* ($P < 0.05$) are listed.

Substrate/Species	*% Frequency*	*IV*	*P*
Boulders			
Gomphonema minutum	93.8	100.0	0.01
Cymatopleura solea	30.0	97.6	0.01
Diatoma vulgare	100.0	88.2	0.01
Cobbles			
Reimeria sinuata	87.5	100.0	0.01
Gomphonema angustum	79.2	92.1	0.018
Achnanthes lanceolata	79.2	89.2	0.02
Amphora pediculus	100.0	81.6	0.01
Achnanthidium minutissimum	100.0	80.7	0.01
Cymbella minuta	87.5	76.7	0.015

of the present study. Documented Irish studies such as McDonnell and Fahy (1978) and Heuff and Horkan (1984) mainly identified diatoms to genus level, making comparisons difficult. The more recent survey of Ní Chatháin *et al.* (2004), a study of high-quality river sites in Ireland (50 sites sampled three times—autumn, spring and summer), identified 175 species. In comparison, Ní Chatháin and Harrington (2002) found 71 species in more oligotrophic, lowland sites (25 sites sampled during a single survey). As 110 species were identified from the River Deel, a pattern of reduced diversity in more enriched waters is evident; however, it is also important to note the timescales in which these

Table 4—*IVmax* values and dates of significant associations for boulder diatoms (B) in 1999 and 2000 and for cobble diatoms (C) in 2000. Only those taxa that do not satisfy the null hypothesis of no *IV* ($P < 0.05$) are listed.

Species	*Month*			*IVmax*		
	B '99	*B '00*	*C '00*	*B '99*	*B '00*	*C '00*
Achnanthes hungarica			May			76.0
Achnanthes lanceolata		Oct.			40.0	
Achnanthidium minutissimum	Nov.			26.7		
Amphora pediculus	Nov.			27.6		
Caloneis bacillum		Feb.			22.9	
Cocconeis pediculus	June	June		22.8	26.5	
Cocconeis placentula		May			19.0	
Cyclotella meneghiniana	July	Jan.		53.0	28.6	
Cymbella lanceolata	July			47.1		
Diatoma moniliformis			May			41.4
Diatoma vulgare		Sept.			18.2	
Fragilaria capucina		Aug.	May		44.8	62.7
Fragilaria capucina var. vaucheriae			May			60.3
Fragilaria fasciculata			May			60.0
Frustulia rhomboides		Aug.			40.0	
Gomphonema clavatum	Apr.			32.7		
Gomphonema olivaceum			May			51.5
Gomphonema olivaceum var. minutissima			June			50.0
Gomphonema truncatum		Aug.			60.0	
Meridion circulare	July	Apr.		32.6	80.0	
Navicula atomus		Oct.			61.5	
Navicula contenta			Sept.			77.9
Navicula gregaria	Apr.			30.3		
Navicula lanceolata		Sept.	May		22.2	43.0
Navicula meniscus	Mar.	Apr.		29.6	28.4	
Navicula saprophila	Nov.			49.7		
Navicula subminuscula			Aug.			65.3
Navicula tripunctata	June	June		25.2	15.5	
Nitzschia acicularis		Aug.			42.7	
Nitzschia amphibia	Aug.			34.7		
Nitzschia constricta		Aug.			60.0	
Nitzschia dissipata	Nov.		May	37.0		46.4
Nitzschia palea		Mar.			24.6	
Pinnularia viridis		Aug.			47.4	
Planothidium lanceolatum	July			28.3		
Rhizosolenia eriensis			Sept.			49.2
Rhoicosphenia abbreviata	Aug.	Aug.		28.9	28.1	
Tabellaria fenestrata		Oct.			33.6	
Tabellaria flocculosa		Feb.			39.5	

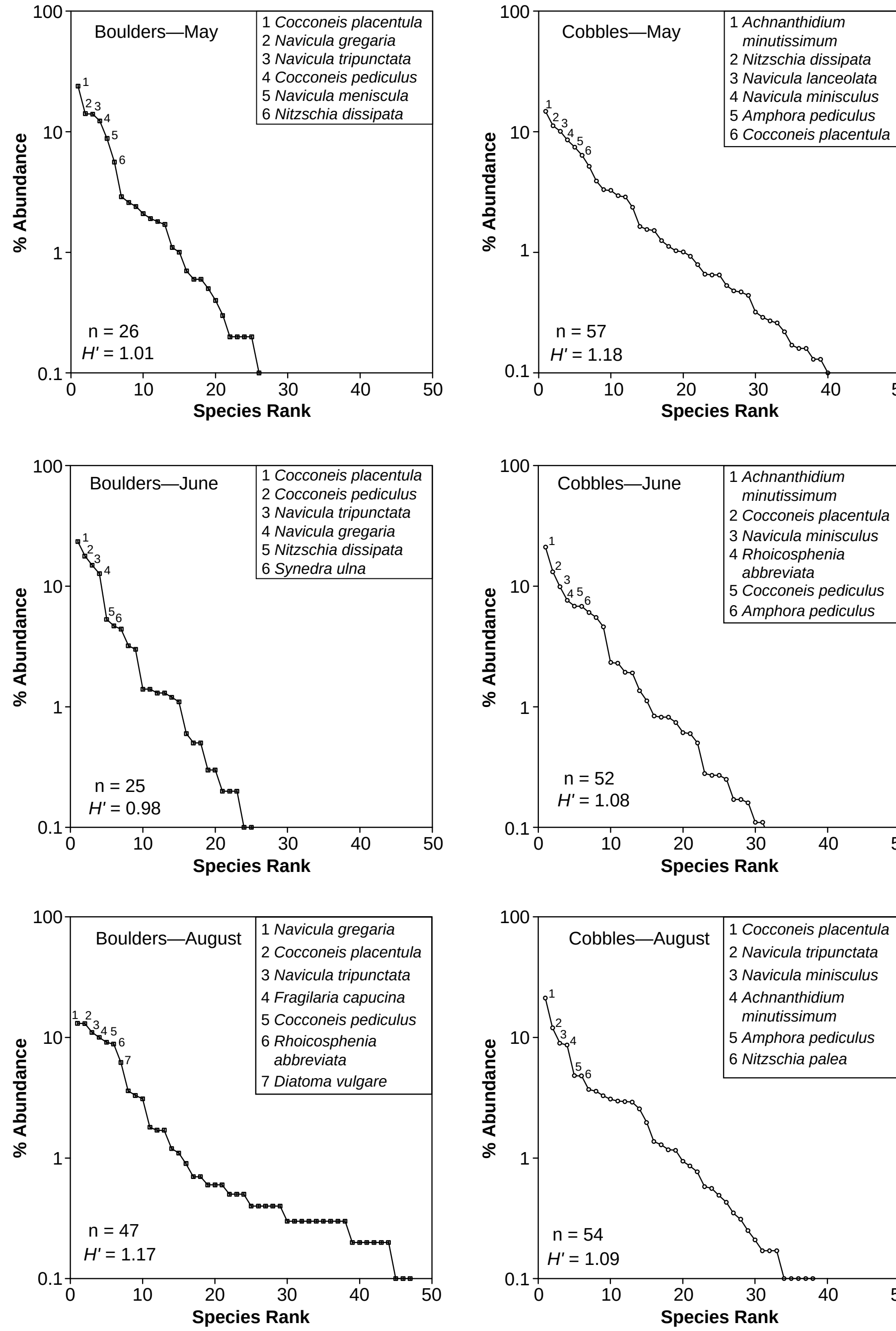

Fig. 2 (above and overleaf)—Rank-abundance curves for diatom species sampled on boulders and cobbles in the River Deel, Co. Limerick, from May to October 2000. n = number of diatom species; *H′* = Shannon–Wiener Index value.

studies were conducted, as studies conducted over longer periods of time can often yield greater species numbers. There are a number of studies of moderately eutrophic rivers from the UK with which to compare the River Deel, although no recent studies are available. Moore (1976 & 1977) identified 93 species from the River Avon and 117 species from a eutrophic tributary of the River Wylye.

The majority of the diatom species identified from boulder and cobble substrata in the River Deel are common in calcareous and eutrophic rivers in the UK and mainland Europe. Most species identified from cobble and boulder substrata are epilithic, but some are epipelic, common on silt-covered boulders, particularly in lowland streams such as the River Deel (e.g. *Navicula tripunctata* and *Navicula lanceolata*), and some are epiphytic species

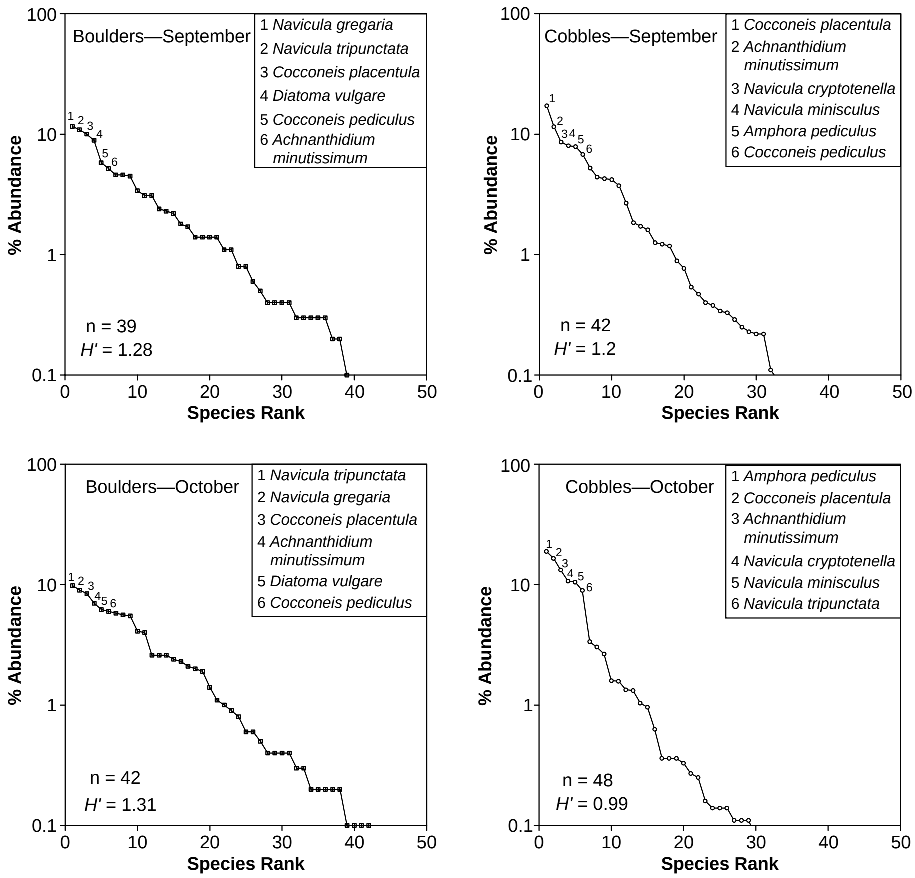

Fig. 2 (*Continued*)

common on *Cladophora* filaments. A few species, such as *Cyclotella meneghiniana*, are typical of the plankton of larger rivers. Widespread generalist species were found in the River Deel on both substrata; for example, *Achnanthidium minutissimum*, *Diatoma vulgare*, *Nitzschia dissipata* and *Rhoicosphenia abbreviata*.

The structure of the diatom assemblage from the River Deel agrees with findings in the literature, which indicate that diatom communities are dominated by a few species that occur frequently and a large number of rare species that occur occasionally, or sometimes only once (van Dam 1982; Round 1993; Kelly and Whitton 1995; Allott and Flower 1997; Goldsmith 2000).

The diatom community was very similar at all five sites, especially on boulders. In general, the most abundant diatom species were common to all five sites on both substrata. Most of the variation between the sites involved diatom species with frequencies of less than 10%. The similarity of the five sites was expected, because there is relatively little longitudinal variation in the River Deel in respect to geology, gradient, land use and water chemistry. In this regard, the River Deel is typical of many rivers in the lowland central plain of Ireland.

Sampling date had a highly significant influence on the composition of the diatom assemblages on both boulder and cobble substrata. On boulders, there was considerable similarity in the seasonal occurrence of some species between 1999 and 2000. In addition, a similar assemblage of diatom species was found on both boulders and cobbles during the summer of 2000. However, few species exhibited the same monthly patterns of abundance on both substrata. Exceptions were *Cocconeis placentula*, which was more abundant earlier in summer on both substrata, and *Gomphonema olivaceum*, *Nitzschia palea* and *Gomphonema clavatum*, which were more abundant in the autumn (September and October). In rivers, seasonal variation in environmental variables, such as flow due to flood events, can be considerable and can have much greater impact than in lakes (Allan 1995). Numerous studies have demonstrated that such changes can have a considerable effect on the

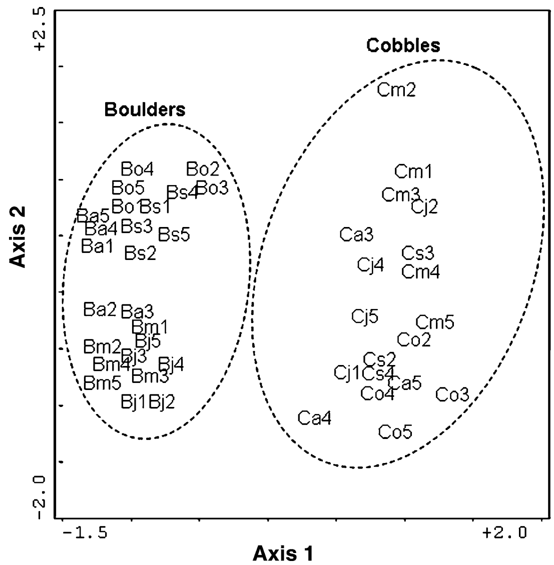

Fig. 3—DCA ordination of cobble (C) and boulder (B) diatoms from the River Deel, Co. Limerick, on a monthly basis from May to October 2000 (July excluded) at 5 sites (1 to 5). m = May; j = June; a = August; s = September; o = October.

composition and productivity of algal assemblages (Butcher 1932; Douglas 1958; Moore 1977; Esho and Benson-Evans 1984; Cox 1990; Allott and Flower 1997). Biotic factors, such as grazing and competition from larger macroalgae, are also significant. Douglas (1958) found that fluctuations in the population of the diatom *Achnanthes* sp. in March and April and the decline after the end of April were probably due to grazing by *Agapetus* (caddis fly). Heavy spates may substantially alter the composition of the diatom community by dislodging the more loosely attached species. However, there is no evidence of this effect in the aftermath of the flood in July 2000 in the River Deel.

The DCA ordination indicates that differences in the composition of the diatom communities between the substrates were maintained irrespective of sampling date or location along the river channel. Although similarities in diatom community composition can be seen between boulder and cobble substrates, the order and dominance of species differed between substrates, with the most obvious examples being the abundance of *Navicula gregaria* on boulder substrata in comparison with cobble substrata and the abundance of *Achnanthidium minutissimum* on cobble substrata in comparison with boulder substrata. Differences in the diatom community between the substrata may be related to a number of factors, such as variations in the surface characteristics of cobbles and boulders. The surface of boulders was generally more uneven than that of cobbles and permitted the accumulation of silt, which may have favoured macroalgae and more motile diatoms such as *Navicula* and *Nitzschia* species.

More likely, however, the difference between diversity indices/rank-abundance curves for the two substrata may reflect the fact that the 'dominant' taxon on boulders was not a diatom but the green alga *Cladophora glomerata*, and the gradual increase in diversity values on boulders may reflect the increasing dominance of this species. The difference between the two substrata may then be explained to some extent by the conceptual model of Biggs *et al.* (1998), as discussed in Yallop & Kelly (2006). Cobbles may be rolled more frequently and, hence, have an assemblage dominated by fast-growing pioneers (e.g. *Achnanthidium* spp., *Amphora pediculus*, *Cocconeis placentula*), whereas boulders are more stable and dominated by competitive species, such as *Cladophora*, which favour epiphytes (*Cocconeis* spp., *Rhoicosphenia*) and modify the microhabitat on the boulder to favour motile taxa (e.g. *Navicula*) (Yallop & Kelly 2006). This also provides an explanation for the results of the TDI, which showed a higher percentage of motile valves on boulders than on cobbles.

The TDI values agreed with the EPA classification of the River Deel as 'slightly to moderately eutrophic' (Lucey *et al.* 1999). In addition, TDI values did not appear to be greatly influenced by sampling date (due to minimal longitudinal variation in the Deel) or substrate. Therefore, diatoms could be useful for monitoring long-term changes in water quality in the River Deel.

The large gap in knowledge of the composition, diversity, structure and function of diatom assemblages, and of the phytobenthic assemblage as a whole, in Irish rivers has created a difficulty for the requirement to utilise phytobenthos for the assessment of good ecological status under the WFD. This study of the River Deel has attempted to address the lack of knowledge in relation to Irish river algae. Although the study was limited to one system, it does provide a starting point, from which wider, more detailed investigations of algal assemblages in Irish rivers have already been based (Ní Chatháin & Harrington 2002; Ní Chatháin *et al.* 2004). In particular, the study by Ní Chatháin *et al.* (2004) investigated potential reference conditions for Irish river types and surveyed the phytobenthos present at these minimally disturbed, high-quality sites. The study of the River Deel provided insights into methodologies employed for the sampling and enumeration of diatoms and also demonstrated the suitability of the diatom

Table 5—Comparison of TDI and percent motile scores for boulders and cobbles sampled between May and October 2000 (July excluded).

Month	*Site*	*Boulders*		*Cobbles*	
		TDI	*% Motile valves*	*TDI*	*% Motile valves*
May	1	79.2	48.8	71.1	40.4
	2	69.6	43.8	79.7	56.6
	3	71.7	45.8	82.8	38.5
	4	72.6	49.1	75.0	39.0
	5	71.8	46.6	70.3	47.9
June	1	70.8	39.7	68.3	30.5
	2	71.0	37.4	–	–
	3	77.5	42.1	65.3	26.9
	4	73.3	43.8	68.8	29.9
	5	70.6	42.5	75.0	26.8
August	1	57.7	33.5	–	–
	2	73.8	51.5	–	–
	3	76.4	39.6	76.9	38.3
	4	63.1	34.6	72.9	39.2
	5	61.9	30.2	74.8	23.2
September	1	70.9	39.4	–	-
	2	76.5	47.7	73.1	20.9
	3	78.7	45.5	77.2	31.5
	4	70.9	46.3	76.2	25.7
	5	71.6	43.4	–	–
October	1	69.7	41.5	–	–
	2	72.3	43.0	72.2	19.9
	3	67.4	41.6	73.0	27.7
	4	73.5	39.7	80.8	44.1
	5	73.9	46.2	78.6	7.3

assemblage for monitoring river water quality in Ireland. The similarities between the River Deel and other lowland rivers in the central plain of Ireland suggest that similar results may also be expected from these rivers.

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