PROC. N.S. INST. SCI. (1996)
Volume 41, Part 1 & 2, pp. 24-38.

Studies on the Phytoplankton and the Water Quality at Greenfield, CLWYD, U.K.

J. SITA DEVI AND J.S.S. LAKSHMINARAYANA
Department of Biology, Centre universitaire de Moncton,
Moncton, New Brunswick, E1A 3E9

A study of the phytoplankton of the Welsh Dee Estuary, a part of Liverpool Bay, is reported. Correlative studies of the phytoplankton and its biomass with those of the chemical parameters indicated relationships between periodicity of phytoplankton and water quality and the possible utilization of nutrients and some trace metals by the algae. The phytoplankton biomass judged by chlorophyll content ranged from 1.63 to 4.28 mg L-1. The species diversity, of the phytoplankton varied from 2.33 to 3.98 characteristic of the oceanic plankton. The water quality was found to be within acceptable limits.

Introduction

Burrows and Sharples (1972, 1973), Sharples (1972) studied the phytoplankton of the Liverpool Bay and Mersey estuaries. The working party report on sludge disposal in Liverpool Bay (W.P. Report, 1972a, 1972b) indicated that there should b e aregular programme to monitor the quality of sea water across the sludge dumping area and specifically to measure salinity, temperature, nutrients, plant pigments and quantitative floristic records of the phytoplankton. This paper reports data on the phytoplankton population and the physico-chemical quality of water collected in the spring summer and fall of 1974 in the Dee estuary near Greenfield, North Wales*.

Materials and Methods

Water and phytoplankton samples were collected on eight days at intervals of about one month at Station G, off shore near Greenfield (53° 18'N, 3° 13'W, Fig 1), between April and October. The surface water samples were collected at 30 minutes or 1 hour intervals to represent a part of the tidal cycle. The water samples were taken from a depth of 0.2 to 1.2 m from the surface when the tide was high but during low tides the depth of the samples was just a few centimeters.

Fig 1 Map of Dee estuary and surrounding waters.

* Full details of the results of chemical analyses, the taxonomy of the phytoplankton collected and the seasonal changes observed in this population are given in a Ph.D. thesis (Sita Devi, 1980) which can be consulted at the Bedford Institute of Oceanography, Dartmouth, Nova Scotia, B2Y 4A2.

Surface water samples were analysed for physical and chemical parameters by the Dee and Clwyd River Division (H.M.S.O. 1972). Methods of analysis of chlorophyll-α and phaeopigments (Strickland and Parsons, 1972) ammonia N and trace elements (Sita Devi, 1980) have been reported. The standard membrane filter technique was used for the detection of *Escherichia coli* (H.M.S.O. 1969).

The phytoplankton collection, fixation and enumeration were made on water samples (1L) as previously described (Sita Devi and Lakshminarayana, 1989). For benthic algal examination, mud samples were collected from exposed surfaces at low tide using a 2 cm diameter polyethylene cylindrical corer.

Additional data, analysis results and details of isolation of all phytoplankton collected, are given in supplementary material in the version of this paper on magnetic disc. This data is in tabular form, each table is numbered consecutively and all these tables are referred here in the format: Table XX*

Table I Water quality at Station G near Greenfield, Dee Estuary, U.K.

Characteristic	Units	Mean Value (S.D.)	Range	No. of Analyses
Temperature	deg. C	13.95 (3.2)	9.6 -18.3	50
pH	-	7.65	6.7 - 8.4	45
Salinity	o/oo	30.09 (2.85)	18.2 -33.2	51
B.O.D.	$\mu g\ L^{-1}$	3.7 (2.150)	0.8 -11.7	49
Dissolved oxygen	$\mu g\ L^{-1}$	8.26 (3.5)	1.6 -10.6	8
Phosphate	$ng\ L^{-1}$	8 (2)	0.007- .011	7
Ammonia nitrogen	$\mu g\ L^{-1}$	0.21 (0.12)	0.08 - .51	20
Silicate	$\mu g\ L^{-1}$	0.4 (0.4)	0.07 - 2.3	39
Total iron	$\mu g\ L^{-1}$	1.53 (0.9)	0.21 - 4.14	51
Soluble iron	$\mu g\ L^{-1}$	0.14 (.04)	0.11 - 0.21	6
Total manganese	$\mu g\ L^{-1}$	0.13 (.03)	0.1 - 0.18	32
Total Zinc	$\mu g\ L^{-1}$	0.24 (0.16)	0.05 - 0.98	51
Soluble Zinc	$\mu g\ L^{-1}$	0.13 (0.14)	0.03 - 0.86	45
Chlorophyll	$\mu g\ L^{-1}$	2.43 (1.31)	0.06 - 5.41	51

Results

Physico-chemical characteristics of the water samples. Analyses of water samples collected at station G near Greenfield are given in Table I. As expected water temperatures rose in April and declined in September. In addition to the determinations given in Table I analyses for nickel and cobalt gave values of about 0.2 $\mu g\ L^{-1}$; copper concentration were lower (~ 0.1 $\mu g\ L^{-1}$) and cadmium values lower still (~20 $ng\ L^{-1}$). No correlation was observed between cadmium concentration and the tidal cycle and no changes were found in the copper, chromium and lead concentrations throughout the experimental period. Except for manganese and the elements quoted in the preceding sentence, the concentrations of trace elements were lower in summer than in spring.

A comparison with analyses of Irish Sea waters by other workers is given in Table IV*

Table II Monthly cell numbers, species identified and diversity indices for phytoplankton of the Dee estuary near Greenfield, North Water, U.K.

Date of Sampling (1974)	Mean number of species	Diversity (d)	Mean cell number L-1 ($x10^3$)	Mean chlorophyll-α ($\mu g\ L^{-1}$)
9, April	65	3.9875	81.2	1.84
7, May	72	3.0178	241.0	2.91
22, May	64	3.0089	306.0	4.28
28, June	52	3.2097	300.0	2.38
18, July	57	3.9804	276.0	2.85
15, August	42	2.3326	118.0	3.71
8, September	51	3.4468	105.0	1.63
15, October	49	2.9651	70.7	2.30

Table III Correlation coefficients between phytoplankton chlorophyll–a and physico–chemical parameters of water collected near Greenfield, North Wales, U.K.

Parameters	Log Phytoplankton cell numbers	Chlorophyll-a	Tidal Height	Silicate	Salinity
D. oxygen	-.629	.736	-	-	-
Chlorophyll-a	-.554	-	.547	-	-
Salinity o/oo	-	.519 (.669#)	(.733#)	-.811	-
Total iron	-.658#	.531 (-.822#)	.657#	-	-0.614
Plankton No.	-.647#	.577 (.909#)	-.725#	-	-
B.O.D.	-	-	.543	.692	-
Ammonia (N)	-	-	.578	-	0.673
Soluble iron	-	-	-	-0.596	-
Silicate	-.561#	-	-	-	-0.810
Phosphate	-	-	-	-	-0.673
Soluble zinc	-.511*	-	-	-	0.519

Correlation coefficients for parameters on samples taken in spring.
* Correlation coefficient for total zinc of samples collected in spring.

Composition and variation of the phytoplankton

In all 122 species of phytoplankton representing 108 Diatoms, 12 Dinoflagellates, 1 Hapatophyceae, and one representing the Prasinophyceae were counted. Diatoms, with 48 genera, formed the dominant part of the phytoplankton especially in April alternating in dominance with an unidentified microscopic algal group which was prevalent in October. The Summer and Spring phytoplankton changes in the Dee Estuary resemble that of the Irish Sea (Sita Devi, 1980). Blooms of *Phaeocystis pouchettii*, were observed during May (148,560 bladders L^{-1}) and July (120,690 bladders L^{-1}). the Dinoflagellates were the third important group contributing to the total phytoplankton. They were represented by 8 genera. During August this group increased in prevalence due to a bloom of *Noctiluca scintillans*. The maximum number of cells of this species recorded was 68,490 L^{-1}. A list of phytoplankton in alphabetical order (Table V*) and a list of those organisms that have been reported by other workers

Table IV Water Quality* at Station (G) Greenfield, Clwyd, U.K., Irish Sea and English Channel (*Excepting Water Temperature, pH, and Salinity all other parameter results are expressed in μgL^{-1} - Mean Values) at Station G Greenfield Dee Estuary, U.K.

ParameteR	Dee Estuary Greenfield Present Study	River Dee Queens ferry		Liverpool Bay	Liverpool Bay	More-con BE-Bay	North East Irish Sea	Cumberland Coast	Cardigan Bay	Western English
		1966-71 (1)	1970-71 (1)	(2)	(3)	(3)	(3)	(3)	(3)	(4)
W.T. (deg.C)	13.95	10.9	10.5	-	6.13-14.0	5.76-5.77	5.8-7.96	10.0-12.0	11.0-14.0	11.14-18.65
pH	7.65	-	-	-	-	-	-	-	-	-
S ‰	30.09				30.9-34.46	30.44-31.14	29.75-34.15	30.6-33.1	33.2-34.4	35.17-35.41
D.O.	8.26	9.8	9.6	-	-	-	-	-	-	-
B.O.D.	3.7	3.5	3.9	-	-	-	-	-	-	-
Si	0.39	3.8	3.9	0.25	0.3-16.7	11.9-12.2	5.3-14.4	-	1.0-3.0	0.05-2.64
NH_3-N	0.21	0.55	0.58	0.22	-		-	-	1.0-7.0	0.05-2.25
PO_4-P	0.008	0.63	0.56	0.065	0.25-1.16	1.14-1.19	0.59-1.98	0.1-3.0	0.1-.4	0.05-0.38
Fe(T)	1.53	1.85	1.14	-	-	-	-	-	-	-
Mn(T)	0.1	0.13	0.13	0.002	-		-		-	-
Zn(T)	0.24	-	-	0.1	-	-	-	-	-	-
Cu(T)	0.1	-	-	0.002	-	-	-	-	-	-
Pb(T)	0.1	-	-	0.0008	-	-	-	-	-	-
Cd(T)	0.04	-	-	0.001	-	-	-	-	-	-
Ni(T)	0.19	-	-	0.0009	-	-	-	-	-	-
Co(T)	0.15	-	-	-	-	-	-	-	-	-

1. O'SULLIVAN, A.J., 1975, Discharges of wastes into Liverpool Bay, 1971, In "Liverpool Bay - An assessment of present knowledge" N.E.R.C. Public. Series "C" No., 14:13-16.
2. BURROWS, E.M. and E.J. SHARPLES, 1972. Bio-assay of seawater and sludge, App. 17., W.P., Report, H.M.S.O., II:405-440. BURROWS, E.M. and E.J. SHARPLES, 1973, Bio-assay of seawater. App. A, W.P. Report, H.M.S.O., III:23-43.
3. JONES, P.G.W. and FOLKARD, A.R., 1971. "Hydrographic observations in the eastern Irish Sea with particular reference to the distribution of nutrient salts". J. mar. biol. Ass. U.K., 51, 159-182.
4. HOLLIGAN, and HARBOUR, 1977.

Table V List of Phytoplankton Recorded at Greenfield (G), Clwyd, U.K.

BACILLARIOPHYCEAE	
Order:	BACILLARIALES
Sub-order:	Coscinodiscineae
Family:	Coscinodiscaceae
	Melosira Agardh
	M. nummuloides Agardh;
	SP, S, A, N.
	M. juergensii Agardh;
	SP, S.
	Paralia Heiberg
	P. sulcata (Ehrenberg) Cleve;
	SP, S, N, D.
	Cyclotella Kutzing
	C. striata (Kutzing) Grunow in Cleve & Grunow;
	SP, S, A, O.
	C. Sp.;
	SP, S, A.
	Stephanodiscus Ehrenberg
	S. rotula (Kützing) *comb. nov.;*
	S. A. sD.
	Coscinodiscus Ehrenberg
	C. radiatus Ehrenberg;
	SP, S, sD.
	C. lineatus Ehrenberg;
	S, sD.
	C. marginatus Ehrenberg;
	SP, S, A, O, D.
	C. concinnus Wm. Smith;
	SP, sD.
	C. grani Gough;
	SP, S, N, D.
	C. eccentricus Ehrenberg;
	SP, S, sD.
	Actinocyclus Ehrenberg
	A. octonarius Ehrenberg var. *Octonarius;*
	SP, S, N, D.
	A. roperi (de Brebisson) Grunow;
	S.
	Roperia Grunow
	R. tessellata (Roper) Grunow ex Van Heurck;
	SP, S, sD.
	Thalassiosira Cleve
	T. nordenskioldii Cleve;
	SP, S, D.
	T. hyalina (Grunow) Gran.;
	SP, S.
	T. gravida Cleve;
	SP, B.
	T. decipiens (Grunow ex Van Heurck) Jorgensen;
	S.P, .S
	T. condensata Cleve;
	SP, S, A, sD.
	Hyalodiscus Ehrenberg
	H. scoticus (Kutzing) Grunow;
	SP, S, O, sD.
	Podosira Ehrenberg
	P. stelliger (Bailey) Mann;
	SP, S, A, T, D.
	Skeletonema Greville
	S. costatum (Greville) Cleve;
	SP, S, A, N, D.
	Stephanopyxis Ehrenberg
	S. turris (Greville) Ralfs in Pritchard;
	SP, A, N.
Family:	ACTINODISCACEAE
	Actinoptychus Ehrenberg
	A. senarius (Ehrenberg) Ehrenberg;
	SP, N.
Sub-order:	BIDDULPHINEAE
Family:	BIDDULPHIACEAE
	Biddulphia Gray
	B. aurita (Lyngbye) de Brebisson;
	SP, S, D.
	B. rhombus (Ehrenberg) Wm. Smith forma *rhombus;*
	S, A, N.
	B. regia (M. Schultze) Ostenfeld;
	SP, S.
	B. mobiliensis (Bailey) Grunow ex Van Heurck;
	S, N.
	B. sinensis Greville;
	S, A.
	B. laevis Ehrenberg;
	S, L.
	Eucampia Ehrenberg
	E. zodiacus Ehrenberg;
	SP, S, A, sD.
	Triceratium Ehrenberg
	T. favus Ehrenberg;
	SP, S, N.
	Ditylum Bailey

D. brightwellii (T. West) Gronow ex Van heurck;
SP.
Bellerochea Van Heurck
B. malleus (Brightwell) Van Heurck forma *malleus*;
SP, S, A, N, D.

Family: CHAETOCERACEAE
Chaetoceros Ehrenberg
C. boreale Bailey;
SP, S, A, B.
C. densum Cleve;
SP, S, A, O, D.
C. danicum Cleve;
SP, S, N, D.
C. decipiens Cleve;
SP, S, A, Ar.
C. lorenzianum Grunow;
S, A, N.
C. constrictum Gran;
SP, S, N.
C. laciniosum Schutt;
S, N.
C. debile Cleve;
SP, S, N, sD.

Sub-order: RHIZOSOLENINEAE
Family: BACTERIASTRACEAE
Bacteriastrum Shadbolt
B. hyalinum Lauder;
SP, S, A.

Family: LEPTOCYLINDRACEAE
Leptocylindrus Cleve
L. danicus Cleve
SP, S, A, N.
L. minimus Gran;
S, N.
Guinardia H. Peragallo
G. flaccida (Castracane) Peragallo;
S, A, N.
Schroderella Pavillard
S. delicatula (Peragallo) Pavillard;
SP, S, N.
Lauderia Cleve
L. borealis Gran;
SP, S, A, N.

Family: RHIZOSOLENIACEAE
Rhizosolenia Brightwell forma
R. alata Brightwell forma *alata;*
S, O, sD.
T. delicatula Cleve
S, N.
R. stolterfothii H. Peragallo;
SP, S, N, sD.
R. robusta Norman ex Pritchard;
SP, O.
R. shrubsolei Cleve;
SP, A, N.
R. setigera Brightwell;
SP, S, N, SD.
R. styliformis Brightwell;
SP, S, O, D.
R. hebetata forma *semispina* (Hensen) Gran;
S, O.

Sub-order: FRAGILARINEAE
Family: FRAGILARIACEAE
Fragilaria Lyngbye
F. pinnata Ehrenberg;
SP, S, L. sD.
F. oceanica Cleve;
SP, S, L, Ar, sD.
F. hyalina (Kutzing) Grunow ex Van Heurck;
SP, S, O.
F. schulzi Brockman;
A, L.
F. crotonensis (A.M. Edwards) Kitton;
SP, S, A.
Rhaphoneis Ehrenberg
R. surirella (Ehrenberg) Grunow ex Van Heurck;
SP, S, A, O.
Asterionella Hassall
A. japonica Cleve & Moller ex Gran;
SP, S, N, D.
Synedra Ehrenberg
S. affinis Kutzing;
S, L.
S. tabulata (Agardh) Kutzing;
SP, S, A.
S. pulchella Kutzing;
SP, O.
S. undulata (Bailey) Gregory;
SP, S, N.
Thalassionema (Grunow) Hustedt
T. nitzschioides Hustedt;
SP, N, sD.
Licmophora Agardh
L. gracilis (Ehrenberg) Brunow var. *gracilis;*
SP, S, A.
Grammatophora Ehrenberg
G. marina (Lyngbye) Kützing;
SP, S, A, L.

Sub-order: ACHNANTHINEAE
Family: ACNANTHACEAE
Achnanthes Bory
A. brevipes Agardh;
SP, S, A, L.
A. Sp.;
S, A.
Cocconeis Ehrenberg
C. scutellum Ehrenberg var. *Scutellum;*
SP, S, U.
C. placentula;
SP, S.
Rhoicosphenia Grunow
R. curvata (Kutzing) Grunow;
SP, S.
Sub-ordr: NAVIUCULINEAE
Family: NAVICULACEAE
Navicula Bory
N. crucigera (Wm. Smith) Cleve;
SP.
N. salinarum Grunow;
SP, S.
N. digito-radiata (Gregory) Ralfs in Pritchard;
S, A.
N. viridula (Kutzing) Kützing;
SP, S, A.
N. lyra Ehrenberg;
S, L.
N. cincta (Ehrenberg) Van Heurck;
S.
N. cryptocephala Kützing;
SP, S.
Dipleneis Ehrenberg
D. elliptica (Kutzing) Cleve;
S.
D. didyma (Ehrenberg) Cleve;
SP, S, A.
D. bombus (Ehrenberg) Cleve;
SP, S.
Pinnularia Ehrenberg
P. Sp.
SP.
Pleurosigma Wm. Smith
P. normanii Ralfs in Pritchard;
S, A.
P. aestuarii (de Brebisson ex

P. angulatum (Quekett) Wm. Smith;
SP, S.
Gyrosigma Hassall
G. Wansbeckii (Donkin) Cleve;
SP, S, A.
G. balticum (Ehrenberg) Cleve;
S, O.
G. fasciola (Ehrenberg) Cleve;
S.
Amphiprora Ehrenberg
A. alata (Ehrenberg) Kutzing;
SP, S.
A. paludosa Wm. Smith;
SP.
Family: GOMPHONEMACEAE
Gomphonema Hustedt
G. Sp;
SP.
Family: CYMBELLACEAE
Phaeodactylum Bohlin
P. tricornutum Bohlin
SP, S, A.
Amphora Ehrenberg
S.
A. spectabilis Gregory
A. coffeaeformis (Agardh) Kützing;
SP.
A. ovalis Kutzing;
SP, S, A.
Family: EPITHEMIACEAE
Epithemia de Brebisson
E. Kurgida (Ehrenberg) Kutzing;
SP, A.
Family: BACILLARIACEAE
Bacillaria Gmelin
B. paxillifer (O.F. Muller) Hendey;
SP, S, O.
Nitzschia Hassall
N. apiculata (Gregory) Grunow;
SP, S, A.
N. dubia Wm. Smith;
SP, S.
N. closterium (Ehrenberg) Wm. Smith;
SP, S, N.
N. filiformis Wm. Smith;
SP, A.
Sub-order: SURIRELLINEAE
Family: SURIRELLACEAE
Surirella Turpin
S. ovata Kutzing;
SP.

Kützing) Wm. Smith;
SP, S.
S. gemma (Ehrenberg) Kützing;
SP, S, A, O.

Class: DINOPHYCEAE
Order: PROROCENTRALES
Family: PROROCENTACEAE
Exuviaella Cienkowski
E. Sp.;
SP, S, A, sD.
Prorocentrum Ehrenberg
P. micans Ehrenberg
SP, S, A, sD.

Order: DINOPHYSIALES
Family: DINOPHYSIACEAE
Dinophysis Ehrenberg
D. Sp.;
SP, S, A, sD.

Order: GYMNODINIALES
Family: GYMNODINIACEAE
Gymnodinium Stein
G. Sp.;
SP, S, D.

Family: NOCTILUCACEAE
Noctiluca Suriray in Lamarck
N scintillans (Macartney) Ehrenberg;
SP, S, N, D.

Family: PERIDINIACEAE
Peridinium Ehrenberg
P. ovatum (Pouchet) Schütt;
SP, S, A, L, sD.

Family: GONYAULACACEAE
Gonyaulax Diesing
G. Sp.;
SP, S, A, sD.

Class: HAPTOPHYCEAE
Order: PRYMNESIALES
Family: PHAEOCYSTACEAE
Phaeocystis Lagerheim
P. pouchetti (Hariot) Lagerheim;
SP, S, D.

Order: PRASINOPHYCEAE
Family: HALOSPHAERACEAE
Halosphaera Schmitz
H. viridis Schm.;
SP.

Family: CERATIACEAE
Ceratium Schrank
C. furca (Ehrenberg) Clap. et Lachm.;
SP, S, D.
C. fusus (Ehrenberg) Dujard;
SP, S, sD.
C. macroceros (Ehrenberg) Vanhoffen;
SP, A, D.
C. tripos (O.F. Mull) Nitzsch.;
SP, S, A, sD.
C. longipes (Bailey) Gran;
A.

Legend:

Y = all seasons	Ar = arctic
SP = spring	L = littoral
S = summer	O = oceanic
A = autumn	U = ubiquitous
W = winter	T = tychopelagic
N = neritic	D = dominant
B = boreal	sD = sub-dominant

Table VI List of Phytoplankton common to station (G), Greenfield, Clwyd, U.K. and other coastal sea waters.

Species reported in this paper	Species reported in previous work now found at Greenfield Reference Numbers (see below)												
	1	2	3	4	5	6	7	8	9	10	11	12	13
Melosira nummuloides Agardh		x	x										
M. juergensii Agardh				x									
Paralia sulcata (Ehrenberg) Cleve	x			x	x			x		x			
Cyclotella striata (Kutzing) Grunow													
Coscinodiscus radiatus Ehrenberg	x	x	x	x	x								
Coscinodiscus lineatus Ehrenberg		x	x	x									
C. concinnus Wm. Smith				x						x			
C. grani Gough	x			x									
C. eccentricus Ehrenberg	x	x	x	x	x								
Thalassiosira nordenskioldii Cleve				x				x					x
T. gravida Cleve				x				x		x			
T. decipiens (Grunow ex Van Heurck) Jorgensen				x				x					
Podosira stelliger (Bailey) Mann	x		x		x								
Skeletonema costatum (Greville) Cleve					x			x					
Stephanopyxis turris (Greville) Ralfs in Pritchard					x								
Actinoptychus senarius (Ehrenberg)			x	x									
Biddulphia aurita (Lyngbye) Brebisson		x	x		x			x					
B. rhombus (Ehrenberg) forma rhombus		x	x		x			x					
B. regia (M. Schultze) Ostenfeld	x		x	x	x			x		x			
B. mobiliensis (Bailey) Grunow ex Van Heurck	x			x	x								
B. sinensis Greville				x	x			x	x	x		x	
B. Laevis Ehrenberg			x										
Eucampia zodiacus Ehrenberg				x	x		x	x		x			
Triceratium favus Ehrenberg			x										
Ditylum brightwelli (T. West) Grunow ex Van Heurck		x			x	x			x		x		
Bellerochea malleus Van Heurck forma malleus					x			x		x			
Chaetoceros densum Cleve				x									
C. danicum Cleve				x									

C. decipiens Cleve				x	x					x			
C. laciniosum Schütt				x									
C. debile Cleve				x			x						
Bacteriastrum hyalinum Lauder								x					
Leptocylindrus danicus Cleve	x			x	x		x	x					
L. minimus Gran							x	x					
Guinardia flaccida (Castracane) Peragallo	x			x	x			x		x			
Lauderia borealis Gran	x			x	x								
Rhizosolenia alata Brightwell forma alata				x			x	x		x			
R. delicatula Cleve	x			x	x		x	x					
R. stolterfothii H. Peragallo	x			x	x		x	x		x			
R. robusta Norman ex Pritchard				x				x					
R. shrubsolei Cleve	x	x		x				x				x	x
R. setigera Brightwell				x	x			x					
R. styliformis Brightwell				x				x		x		x	
Fragilaria oceanica Cleve		x			x								
F. crotonensis (A.M. Edwards) Kitton					x								
Asterionella japonica Cleve & Müller ex Gran				x	x			x		x		x	
Synedra affinis Kutzing		x											
S. tabulata (Agardh) Kutzing	x												
Thalassionema nitzschioides Hustedt	x			x			x						
Grammatophora marina (Lyngbye) Kutzing		x											
Achnanthes brevipes Agardh		x	x	x									
Cocconeis scutellum Ehrenberg var. Scutellum		x		x									
C. placentula Ehr.		x											
Navicula crucigera (Wm. Smith) Cleve		x											
N. digito-radiata (Gregory) Ralfs in Pritchard			x										
N. lyra Ehrenberg		x	x										
N. cryptocephala Kutzing					x								
Diploneis didyma (Ehrenberg) Cleve			x										
Pleurosigma angulatum (Quekett) Wm. Smith		x	x	x									
Gyrosigma balticum (Ehrenberg) Cleve		x											
G. fasciola (Ehrenberg) Cleve				x									
Amphiprora paludosa Wm. Smith			x										

Phaeodactylum tricornutum Bohlin					x							
Amphora coffeaeformis (Agardh) Kützing		x										
Bacillaria paxillifer (O.F. Müller) Hendey	x			x	x							
Nitzschia closterium (Ehrenberg) Wm. Smith		x		x	x		x	x				
Surirella ovata Kützing		x										
S. gemma (Ehrenberg) Kützing		x	x	x	x							
Prorocentrum micans Ehrenberg				x		x	x					
Noctiluca scintillans (Macartney) Ehrenberg				x	x							
Ceratium furca (Ehrenberg) Calp. et Lachm.				x	x	x						
Ceratium fusus (Ehrenberg) Dujard	x			x	x	x	x			x	x	x
C. macroceros (Ehrenberg) Vanhoffen				x	x	x					x	
C. tripos (O.F. Mull.) Nitzsch.				x		x					x	x
C. longipes (Bailey) Gran				x	x	x						x
Phaeocystis pouchetti (Hariot) Lagerheim	x			x	x							
Halosphaera viridis Schm.						x						

1. SYKES, J.B. and BONEY, A.D., 1970. Pollution and inshore phytoplankton. Mar. Poll. Bull. 1(3): 38-41.
2. GHAZZAWI, F.M., 1933. The littoral diatoms of the Liverpool and Port Erin shores. J. Mar. Biol. Ass. U.K. 19:165-176.
3. ODAM, C.S., 1951. Diatoms of the Thames Estuary. J. Quekett Microscopical Club, 3(4):225-236.
4. MOMMAERTS, J.P., 1969. On the distribution of major nutrients and phytoplankton in the Tamar estuary. J. Mar. Biol. Ass. U.K., 49, 749-765.
5. BURROWS, E.M. and SHARPLES, E.J., 1972. Bio-assay of seawater and sludge. App. 17, W.P. Report, H.M.S.O., II:405-440.
6. LUCAS, C.E., 1942. Continuous Plankton Records: Phytoplankton in the North Sea, 1938-1939. Part II. Dinoflagellates, Phaeocystis, etc. Hull, Bull. Mar. Ecol., 11:47-70.
7. HOLLIGAN, P.M. and HARBOUR, D.S., 1977. The vertical distribution and succession of phytoplankton in the Western nglish Channel in 1975 and 1976. J. Mar. Biol. Assoc., U.K., 57:1075-1093.
8. LUCAS, C.E., 1940. Ecological investigations with the continuous plankton recorder: The Phytoplankton in the Southern North Sea, 1932-1947. Hull. Bull. Mar. Ecol., 4:73-170.
9. WILLIAMSON, D.I., 1956. The plankton in the Irish Sea. 1951 and 1952. Hull. Bull. Mar. Ecol., IV:87-114.
10. HARDY, A.C., 1944. Explanation - Marine Ecology. Hull. Bull. Mar. Ecol., 1:1-XLii.
11. CHENG, C., 1941. Ecological relations between the Herring and the plankton off the North-East coast of England. Hull. Bull. Mar. Ecol., I:239-254.
12. WILLIAMSON, D.I., 1952. Distribution of plankton in the Irish Sea in 1949 and 1950. Proc. & Trans. Liverpool Biol. Soc., LVIII:1-45.
13. PEARCEY, F.G., 1985. Investigations on the movements and food of the Herring, with addition to the marine fauna of Shetland Island, Proc. royal Physical Soc. Edinburgh U.K., 8:389-415.

Table VII Welsh Dee Estuary: List of Algal Species Found on Mud Samples at Station (G) Greenfield, Clwyd, U.K.

	Dates of Collection					
Species Name	16/4	10/5	7/6	24/	23/8	23/9
Melosira nummuloides	P	P	A	A	P	P
M. juergensii	A	A	P	A	A	A
Paralia sulcata	P	P	A	P	A	P
Cyclotella striata	P	P	P	A	P	A
C. Sp.	A	A	A	P	A	A
Skeletonema costatum	P	A	A	P	P	A
Fragilaria pinnata	P	A	A	A	P	P
F. oceanica	A	A	A	P	P	P
F. hyalina	A	A	P	A	A	P
F. crotonensis	P	A	P	P	A	P
Raphoneis surirella	A	A	A	P	P	A
Synedra tabulata	A	A	A	P	A	A
S. pulchella	P	P	P	A	P	P
S. undulata	A	A	P	P	A	A
Licmophora gracilis	A	A	P	A	P	P
Grammatophora marina	A	A	A	P	A	P
Achnanthes brevipes	P	P	P	A	P	P
Cocconeis scutellum	A	P	P	A	P	P
C. placentula	P	P	A	P	A	A
Navicula crucigifera	P	A	A	A	A	A
N. salinarum	P	P	A	A	P	A
N. digito-radiata	A	P	A	P	P	A
N. viridula	P	A	P	P	A	A
N. lyra	A	A	P	A	A	A
N. cincta	A	A	P	A	A	A
N. cryptocephala	P	A	A	A	A	P
Diploneis elliptica	A	A	P	A	A	P
D. didyma	A	P	A	P	A	A
D. bombus	P	A	A	A	A	A
Pinnularia Sp.	A	P	P	A	P	A
Pleurosigma normanii	A	A	A	P	A	A
P. aestuarii	P	P	P	A	P	A
P. angulatum	P	A	A	A	A	P
Gyrosigma wansbeckii	P	A	P	A	A	P
G. balticum	A	P	A	P	P	A
Gomphonema Sp.	A	P	P	A	A	P
Phaeodactylum tricornutum	A	A	P	A	A	P
Amphora spectabilis	A	P	P	A	A	P
A. ovalis	P	A	A	P	A	A
Bacillaria paxillifer	A	A	P	A	A	P
Nitzschia apiculata	A	A	A	P	A	P
N. dubia	A	P	P	A	A	A
N. closterium	P	A	P	P	P	A
N. filiformis	P	A	A	A	A	P
Surirella ovata	P	A	A	P	A	A
S. gemma	A	P	A	P	P	P

P = Found; A = Not found.

Table VIII Correlation coefficients between phytoplankton pigments and chemical parameters in Welsh Dee Estuary, U.K.

	Spring			Summer
Parameters	Log Phytoplankton No.	Tidal Height	Chloro-phyll-a	Chloro-phyll-a
Silicate	-.561	-	-	-
Fe (T)	-.658	-.725	-.822	-
Zn (T)	-.511	-	-	-
Tidal Ht.	.867	-	-	-
Plankton No.	.647	-	.909	-
S (0/00)	-	.657	.669	.579
Chlorophyll-a	-	.733	-	-
B.O.D.	-	-	- 0.536	-

in the waters of the British Isles (Table VI*) can be found in the supplementary materials published on magnetic disc.

The dominant algal species in the waters of Dee Estuary that were collected were *Paralia sulcata, Coscinodiscus radiatus, C. marginatus, Actinocyclus octonarius* var. *octonarius, Thalassiosira nordenskioldii, Podosira stelligera, Bellerochea malleus, Skeletonema costatum, Biddulphia aurita, Rhizosolenia styliformis, Chaetoceros danicum, C. densum, Asterionella japonica, Noctiluca scintillans, Ceratium macroceros, Peridinium ovatum* and *Phaeocystis pouchetti.* A list of the plankton collected from the sea floor on six occasions between April and September are given in Table VII* in the supplementary materials.

Seasonal succession of phytoplankton associations based upon their presence or absence during different seasons showed that of the 34 species representing spring, summer and autumn *Coscinodiscus marginatus, Thalassiosira condensata, Podosira stelliger, Skeletonema costatum, Eucampia zodiacus, Bellerochea malleus, Chaetoceros densum, C. decipiens, Prorocentrum micans, Peridinium ovatum, Dinophysis* sp., and *Ceratium tripos* were the most common forms. *Rhizosolenia setigera, R. styliformis, R. stolterfothii, Asterionella japonica, Gymnodinium* sp., *Noctiluca scintillans, Ceratium furca, C. fusus, Phaeocystis pouchetti, Paralia sulcata, Coscinodiscus radiatus, C. eccentricus, Actinocyclus octonarius* var. *octonarius, Thalassiosira nordenskoldii, Hyalodiscus scoticus, Biddulphia aurita, Chaetoceros debile, C danicum* were the most common of the 42 species which occurred in spring and summer seasons. Out of the nine species of summer and autumn *Stephanodiscus rotula* and *Ceratium macroceros* were the most common algae. *Rhizosolenia alata* and *Coscinodiscus lineatus* were the dominant species of summer while *Coscinodiscus concinnus* and *Thalassionema nitzschioides* were commonly observed in spring. A correlation of the seasonal phytoplankton pigments and chemical parameters is given in Table VIII.

Biomass. During the period of study the chlorophyll-a concentration in the water varied from 0.38 $\mu g\ L^{-1}$ at 1900 h on April 9 to 5.41 $\mu g\ L^{-1}$ at 1000 h on July 18 and 5.21 $\mu g\ L^{-1}$ at 1015 h on August 15. In general higher concentrations were observed in the morning hours. The average concentration of this pigment on each of the eight sampling days lay in the range 1.63-3.71 mg L^{-1}, the highest value being in May and the lowest in September (Table II), revealing high phytoplankton production in summer. Regression analyses between chlorophyll-α and other measured parameters of the water (Table I) revealed positive correlations (Table III) between the pigment and salinity, dissolved oxygen and plankton cell numbers.

Species diversity and variation. The species diversity (d), (Parsons and Takahashi, 1973), of the Dee estuary phytoplankton varied from 2.33 to 3.99 (Table II) during the period of study.

The d values obtained are characteristic of oceanic plankton where d generally varies from 3.5 to 4.5 (Margalef, 1967).

Discussion

The Dee Estuary waters showed lower values of pH, silicate, nitrogen, orthophosphate, iron and manganese than the average values for the River Dee at Queensferry for the year 1966 - 1971 and 1970 - 1971 (O'Sullivan, 1975). The concentrations of silica, phosphate and ammonia nitrogen were higher than those of Liverpool Bay waters (Burrows and Sharples, 1973). The physico-chemical parameters at Greenfield thus lie between the values obtained for waters of Queensferry and Liverpool Bay. The phosphate and silicate values were also lower than those for Morecombe and Cardigan Bays, the Cumberland Coast and the North East Irish Sea (Jones and Folkard, 1971). Queensferry waters were influenced by the Dee river and polluted water discharges, while Liverpool Bay was principally oceanic in character.

The sludge that enters Liverpool Bay contains Fe, Zn, Cu, Mn, Pb, Cr, Ni, Cd, Hg, Phosphate, anionic detergents and chlorinated hydrocarbons (W.P. Report, 1973). The bio-assay of sea water by Burrows and Sharples (1973) indicated that *Laminaria saccharina* was more sensitive to copper than either *Phaeocystis* or *Skeletonema*. The toxic action of copper and zinc, when they occur together, is the same as that of copper and the toxic action of sludge is controlled by copper concentration (Burrows and Sharples, 1973). The indirect correlation was obtained between iron, silica, zinc and log phytoplankton numbers during the spring season which involved the trace metal utilization by the phytoplankton. There appeared to be no toxic effects on the populations of the phytoplankton.

Previous work (Spencer, 1972) revealed patchy distribution of phytoplankton in the surface waters of Liverpool Bay in 1970 but the chlorophyll concentration in the Dee estuary appears to be greater than in Liverpool Bay or in the Irish Sea between Wicklow and Dublin (Sykes and Boney, 1970). The phytoplankton is regarded as stable when d values are about 2.5 and in active growth when d lies in the range 3.5-4.0 (Margalef, 1967). If the water turbulence is strong as it is in the Dee estuary, the diversity in small volumes may be great and it will only stabilize when large volumes of water are examined (Margalef, 1967). In the work reported here where relatively small water samples were collected, such turbulence may be resulted in high diversity values and the observed inverse correlation between chlorophyll concentration and d values. An indirect correlation was obtained between iron, silica and zinc with log phytoplankton numbers during the spring, when probably involved trace element utilization by the phytoplankton. We conclude that in these waters there were little toxic effects on the phytoplankton population.

Acknowledgements

We thank Professor W.B. Stallworthy and Dr. S. Frost for their help. The work was supported by research grants given by the Université de Moncton, The National Research Council and the University of Salford.

References

Burrows, E.M. and **Sharples, E.J.,** 1972. Bio-assay of seawater and sludge. App. 17., W.P. Report, *H.M.S.O.,* II: 405-440.

Burrows, E.M. and **Sharples, E.J.,** 1973. Bio-assay of seawater. App. A, W.P. Report, *H.M.S.O.,* III: 23-43.

H.M.S.O., 1969. *The Bacteriological Examination of Water Supplies.* No 71, 1-115.

H.M.S.O., 1972. *Analysis of Raw, Potable and Waste Waters.* London.

Jones, P.G.W. and **Folkard, A.R.,** 1971. "Hydrographic observations in the eastern Irish Sea with particular reference to the distribution of nutrient salts". *J. mar. biol. Ass.* U.K., 51: 159-182.

MARGALEF, R., 1967. Some concepts relative to the organization of plankton. *Oceanogr. Mar. Biol. Ann. Rev.* edited by Harold Barnes, George Allen and Unwin Ltd., London., 5: 257-289.

O'Sullivan, A.J., 1975. Discharges of wastes into Liverpool Bay, 1971. In "Liverpool Bay - An assessment of present knowledge" *N.E.R.C. Public.* Series 'C' No., 14: 13-16.

Parsons, R.T. and **Takahashi, M.** 1973. *Biological Oceanographic Processes.* Pergamon Press, Oxford, pp. 1=-186.

Sharples, E.J., 1972. The use of phytoplankton for indication of the effects of waste disposal on water quality in Liverpool Bay. Ph.D. Thesis, University of Liverpool.

Sita Devi., J., 1980. Studies on the phytoplankton of Malpeque Bay, Prince Edward Island, Canada and the Welsh Dee Estuary, U.K. Ph.D. Thesis, University of Salford, Salford, Lancashire, U.K., pp. 572.

Sita Devi, J. and **Lakshminarayana, J.S.S.** 1989 Studies on the phytoplankton and the water quality of Malpeque Bay, Prince Edward Island, Canada. Proc. N.S. Inst. Sci., 39: 39-50.

Spencer, C.P., 1972. Plant nutrient and productivity study. *W.P. Report, H.M.S.O.,* 2: 359-402.

Strickland, J.D.H. and **Parsons, T.R.,** 1972. A practical handbook of sea water analysis. *Bulletin Fisheries Research Board of Canada,* No. 167: 310 pp.

Sykes, J.B. and **Boney, A.D.,** 1970. Pollution and inshore phytoplankton. *Mar. Poll. Bull.* 1: 38-41.

W.P. Report. 1972a. An abbreviation for out of Sight Out of Mind. Report of a working party on sludge disposal in Liverpool Bay. *Department of the Environment. H.M.S.O.,* I: 1-36.

W.P. Report. 1972b. An abbreviation for out of Sight Out of Mind. Report of a working party on sludge disposal in Liverpool Bay. *Department of the Environment. H.M.S.O.,* II: 1-486.

W.P. Report. 1973. An abbreviation for out of Sight Out of Mind. Report of a working party on sludge disposal in Liverpool Bay. *Department of the Environment. H.M.S.O.,* III: 1-104.

(Received 6 May 1993)