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Fish Assemblages as Indicators of Water Quality in the Middle Thames Estuary, England (1980–1989)

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ABSTRACT: Fish abundance and environmental data collected over ten years (1980–1989) from the middle Thames estuary, England, were analyzed to detect temporal trends in fish populations and relationship with environmental parameters, and to assess water quality. Fish were collected from the cooling water intake screens of West Thurrock power station, situated 35.5 km below London Bridge, in the mid-estuary. Marine species abundance were highly seasonal, with peaks in December–March for herring (*Clupea harengus*), sprat (*Sprattus sprattus*), 3-spined-stickleback (*Gasterosteus aculeatus*), and poor cod (*Trisopterus minutus*); July–August for flounder (*Platichthys flesus*); and September–December for sand goby (*Pomatoschistus minutus*), whiting (*Merlangius merlangus*), bass (*Dicentrarchus labrax*), plaice (*Pleuronectes platessa*), and dab (*Limanda limanda*). Bimodal seasonal patterns of peaks or unclear seasonality in abundance characterized marine estuarine-dependent sole (*Solea solea*), Nilsson's pipefish (*Syngnathus rostelattus*) (April/May and September/October), and pouting (*Trisopterus luscus*) (May and November/December); the estuarine smelt (*Osmerus eperlanus*) (October and January) and the catadromous eel (*Anguilla anguilla*) (June and October). There was substantial variation in the abundance of common species over the period of ten years, with herring, sand goby, flounder, and plaice showing a stable abundance in 1980–1984, increasing sharply in 1985–1986, and then decreasing successively through the remainder of the decade (1987–1989). The first half of the decade was a period of higher abundance for less tolerant species such as smelt, sprat, and poor cod, while the second half showed higher abundances of species tolerant to harsh environmental conditions such as sand goby, flounder, eel, and plaice. A general pattern of stable fish populations with a slight trend of deterioration was found to emerge over the years, related to the number of species and quantities of common species. Multivariate techniques of principal component and canonical correspondence ordinations were used for assessing relationships between fish populations abundance and environmental variables. The most significant environmental variables correlated with fish species were temperature and dissolved oxygen. High abundances of flounder were associated with high temperature, while high abundance of poor cod, sprat, herring, and 3-spined-stickleback were associated with high dissolved oxygen, flow, ammonical nitrogen, and low temperature. Plaice, whiting, sand goby, bass, and dab were preferentially found in high salinity and suspended solids, while smelt and sole were likely to prefer average values or showed no clear preferences.

Introduction

The tidal Thames is a major urbanized and industrialized estuary draining into the North Sea and carrying effluents from sewage works and industries from Greater London. Pollution caused major declines in fish and other biota until improvements in sewage treatment in the 1960s. One of the most striking features of the recovery from pollution has been the return of fish species (Wheeler 1969, 1979; Huddart and Arthur 1971). The increasing species diversity has been accompanied by changes in fish community structure. An attempt to commercially harvest eels and the presence of substantial populations of smelt, which had been commercially exploited in the 1800s (Wood 1982), are examples of these changes. Andrews (1984) described improvement, between 1975–1980, in the number of fish species. Summer catches on screens at West Thurrock Power Station in 1968–1969 were usually nil or one species, whereas

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a decade later 10 to 15 species were normally present, while the number of species recorded in the winter almost tripled. The period 1976–1980 was characterized by increases in fish population size, animal fecundity, and species diversity, and can be related to the improved effluent quality of the modernized major Sewage Works (Andrews and Rickard 1980).

An underlying assumption in estuaries management is that altered habitats contain altered biological communities, and that species richness is inversely proportional to degree of deterioration. The use of biota in the monitoring and assessment of aquatic systems is attaining greater importance in detecting anthropogenic impacts (Gray 1989; Loeb 1994; Deegan et al. 1997). In this context, fish assemblages have been used because they are known to change in composition as their habitats are modified. The marked cycles of fish abundance in estuaries, mainly those marine estuarine-dependent, with a consistent seasonality, appear to related to intrinsic biotic interactions and respond to seasonal variation in environmental conditions and could confound annual trends if not properly understood. Long-term trends may be correlated with stress arising from slight incremental changes in environmental conditions. Long-term variations in fish abundance provides an important framework assessing the influence of water quality trends on fish assemblages.

The goal of this paper is to assess the feasibility of using fish assemblages as biological indicators of water quality in the Middle Thames estuary. One objective is to characterize the temporal distribution of the 15 most abundant fish species and to evaluate the link between environmental attributes and community structure by assessing seasonal and long-term changes in fish catches from West Thurrock Power Station intake water as sampling tools over the period 1980–1989. Analyses of power stations data enable important predictions as they can catch large number of fish, but each site has unique features depending on the position in the estuary (Henderson 1989). This method offers a useful means to obtain regular, quantitative samples, irrespective of weather conditions, and has been used successfully in many cases (Van den Broek 1979; Henderson 1989; Maes et al. 1998). The following questions are addressed: Do well-defined patterns of change in community structure exist? Do community patterns correspond with large-scale and/or local environmental gradients? Does community structure change over time and are these changes associated with environmental degradation? We hypothesized that there would be close correspondence between fish assemblage structure and temporal trend in water quality.

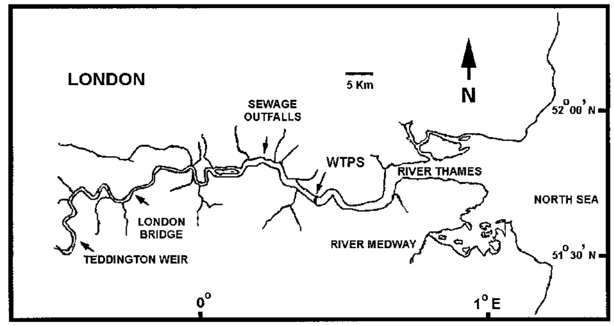

Fig. 1. Map showing the location of the sampling site (West Thurrock Power Station = WTPS) in the Middle Thames estuary, England.

Materials and Methods

Fish were collected from the cooling water intake band screens of West Thurrock Power Station (WTPS), situated on the north bank of the middle Thames estuary, 35.5 km downstream of London Bridge and about 17 km downstream from outfalls of the two major sewage treatment works serving London (Fig. 1). The cooling-water stream passes through a 4.3 m diam intake culvert into a large well from which lead six band screens, each connected to a pump. The culvert mouth is protected by a series of vertical slats, each about 30 cm apart, to prevent the entry of logs and other large extraneous matter. When all pumps are operating the input velocity is 3.2 m s^{-1}.

Standardization of data was achieved by routine sampling for 4 h, starting half an hour before ebb tide, on a fortnightly basis with few exceptions, from January 1980 to December 1989. Plastic netting bags (approximately 1-mm mesh size), held under the outlet from the screen washing channel to the main collecting duct, were emptied of accumulated fish. Fish were identified and counted. The total catch was converted to catch per unit effort (CPUE) by taking into consideration how many of the intake pumps were in operation during the sampling period. For comparative purposes, CPUE was estimated as the number of fish 0.545 millions m^{-3}, that is, 100 million gallons of water as $E = 100 \times A/5(P \times L)$, where E = expected number of raised individuals of a species in 0.545 millions m^3 of water pumped, A = observed number for individuals of a species, L = duration of the survey (h), and P = the number of pumps in operation with each one rated at 27,250,000 m^3 h^{-1}. This volume of water (0.545 millions m^3) corresponds to 5 pumps operating during 4 h sampling (correcting factor = 100/5)

The 15 most abundant species were grouped by life-cycle category and monthly mean abundances computed. Three species (pogge, *Agonus cataphrac-*

TABLE 1. Basic statistics and component loadings from Principal Components Analysis on log(x + 1) transformed environmental parameters in the middle Thames estuary, between 1980–1989. Only those values that are significantly correlated ($p < 0.01$) with a component are shown. SD = standard deviation.

Environmental Variables	Mean	SD	Ranges (Min–Max)	Axis 1	Axis 2
Salinity (psu)	10.8	3.9	3.8–19.3	−0.88	
Temperature (°C)	14.0	4.9	5.4–22.2	−0.87	
Flow ($m^3 s^{-1}$)	59	43.0	5–177	0.87	
Ammonical nitrogen ($mg l^{-1}$)	0.26	0.24	0–1.23	−0.82	
Dissolved oxygen (% saturation)	51.2	11.2	27–76	0.59	0.52
Suspended solids	91	67.5	18–486		0.73
pH	7.4	0.20	7.1–8.4		−0.52
Eigenvalues				3.4	1.1
% Variance explained				48.4	16.4

tus, common sea snail, *Liparis liparis,* and thin lipped grey mullet, *Liza ramada*) despite ranking among the 15 most abundant species in some years of the decade, were not included in this study because their overall abundance did not rank among the top 15 throughout the entire decade. Current literature was used to define life-cycle categories (Claridge et al. 1986; Loneragan et al. 1989): catadromous (C) = migrates from freshwater to the sea to breed; estuarine (E) = typically occurring and breeding in estuaries; freshwater (F) = typically occurring and breeding in freshwater; marine straggler (MS) = typically breeding in marine environments outside estuaries rarely occurring in estuaries; marine estuarine-dependent (MED) = marine spawning species found in large numbers in estuaries at certain periods of their life-cycle.

The following environmental parameters from National Rivers Authority (Thames Region) recorded at the same period of the fish sampling for WTPS area were used: pH, suspended solids ($mg l^{-1}$), temperature, dissolved oxygen (% saturation), ammonical nitrogen ($mg l^{-1}$), salinity (psu), and flow of water ($m^3 s^{-1}$) over Teddington Weir.

Logarithmic transformations, log(x + 1), of environmental parameters and fish abundance as CPUE were performed to meet assumptions of normality and homocedasticity for statistical tests and to reduce the bias of abundant species. One-way analyses of variance (ANOVA) were used to test for annual changes of fish abundance. Multiple range tests a posteriori Tukey were used to contrast means. Principal components analysis (PCA) were performed on environmental parameters and species abundance. A biplot of components scores (samples date) and factor loads (species) was performed to detect patterns. Canonical correspondence analysis (CCA) was used to detect and define temporal phases of environmental variation and relate these phases to changes in fish assemblage composition.

Results

Environmental Parameters

Environmental values, dispersion, statistics, and PCA scores are presented in Table 1. The first principal component accounted for 48.4% of the total variance and was labeled a seasonal Summer-Winter axis (Fig. 2). The first axis (ENV 1) from the PCA portrayed an ordination contrasting the high values of temperature and salinity, and low values of dissolved oxygen, ammonical nitrogen, and flow in July–September with the reverse situation in January–March. The second component (ENV 2) accounted for 16.4% of the variation and was positively correlated with dissolved oxygen and suspended solids, and negatively correlated with pH. This axis (ENV 2) contrasted high pH and low dissolved oxygen and suspended solids in April/July with the reverse situation in October/December.

Significant differences were found in at least one of the years of the decade for flow, pH, suspended solids, and dissolved oxygen (Table 2). Flow was highest in 1981 and 1982 and lowest in 1989. Suspended solids were highest in 1986 and lowest in 1981, 1982, and 1983. Dissolved oxygen was highest in the first half of the decade (1980–1984) while pH showed the opposite, being highest in 1985, 1987, 1988, and 1989.

Seasonal Variation

During December to February, herring, sprat, 3-spined-stickleback, and poor cod predominated (Fig. 3). Flounder was the dominant species from June to September, and sand goby, whiting, bass, plaice, and dab were co-dominants September to December. Smelt reached its greatest abundance from October to January. Bimodal patterns of peaks or unclear seasonality characterized the marine estuarine-dependent sole, Nilsson's pipefish, pouting, and catadromous eel (Fig. 3).

Multivariate analyses was used to identify associations of species in relation to their seasonal cycles

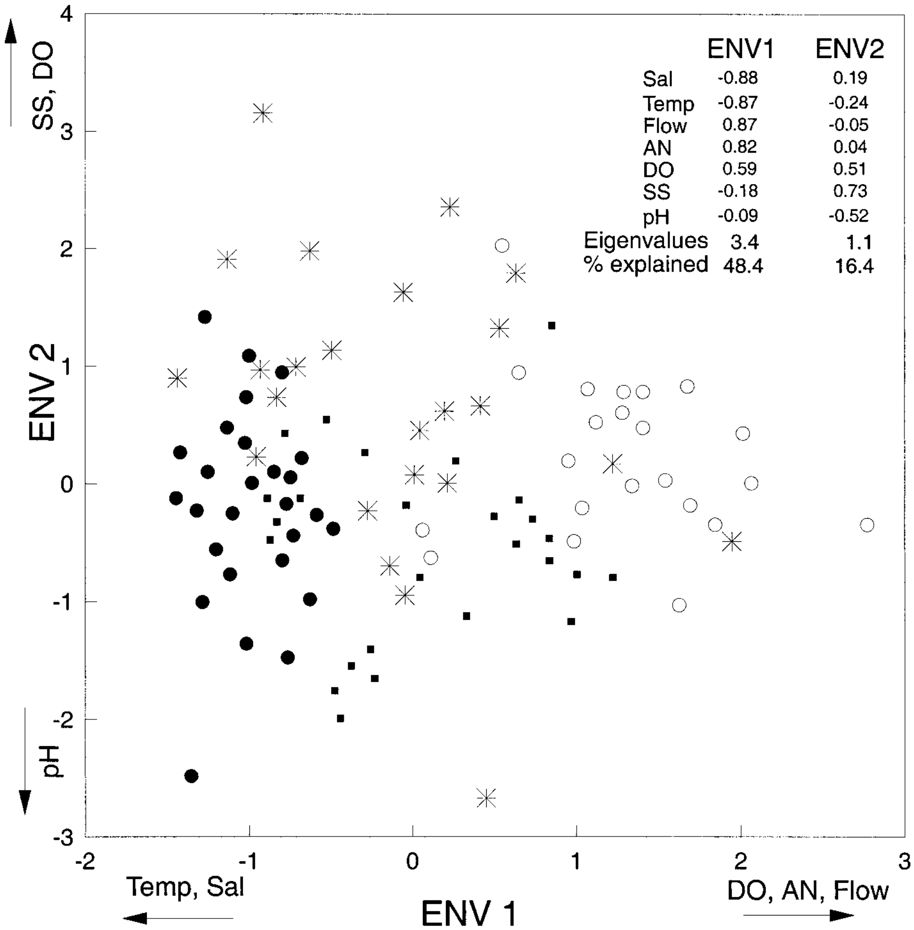

Fig. 2. Factor loads and sample date scores on the first two components from PCA on environmental parameters in the middle Thames estuary, 1980–1989. Environmental parameters: pH; SS = suspended solids; Temp = temperature; DO = dissolved oxygen saturation; AN = ammoniacal nitrogen; Sal = salinity; Flow = Flow of water over Teddington Weir. Monthly dates (○ January–March; ■ April–June; ● July–September; * October–December).

of abundance. Principal components analysis of the monthly abundances of the 15 most numerous species, yielded 4 axes with eigenvalues exceeding 1.0, explaining 68.8% of the variance. The first axis (SP1) from the PCA of fish abundance explained 35.8% of the variation and was significantly correlated with the abundance of dab, whiting, sand goby, plaice, and bass. SP1 portrayed an ordination contrasting the abundance of dab, whiting, sand goby, plaice, and bass in October/December samples with the scarcity of these species in the April–May–June samples (Fig. 4). The second axis (SP2) accounted for 15.4% of the variation and was positively correlated with 3-spined-stickleback, poor cod, sprat, pouting, and herring, and negatively with flounder. Axes 3 and 4 appear to be related

TABLE 2. F-values from one-way ANOVA and significant yearly differences of log(x + 1) transformed environmental parameters in the middle Thames estuary, from 1980 to 1989. Levels of significance: * = $p < 0.05$; ** = $p < 0.01$; ns = no significance.

Environmental Variables	F-value	Tukey Test
Salinity (psu)	1.0 ns	
Temperature (°C)	0.2 ns	
Flow ($m^3 s^{-1}$)	2.7*	1981, 1982 > 1989
Ammoniacal nitrogen (mg l^{-1})	0.3 ns	
Dissolved oxygen (% saturation)	3.9**	1980, 1981, 1982, 1983, 1984 > 1987, 1988
Suspended solids (mg l^{-1})	2.7*	1986 > 1981, 1982, 1983
pH	4.8**	1985, 1987, 1988, 1989 > 1981

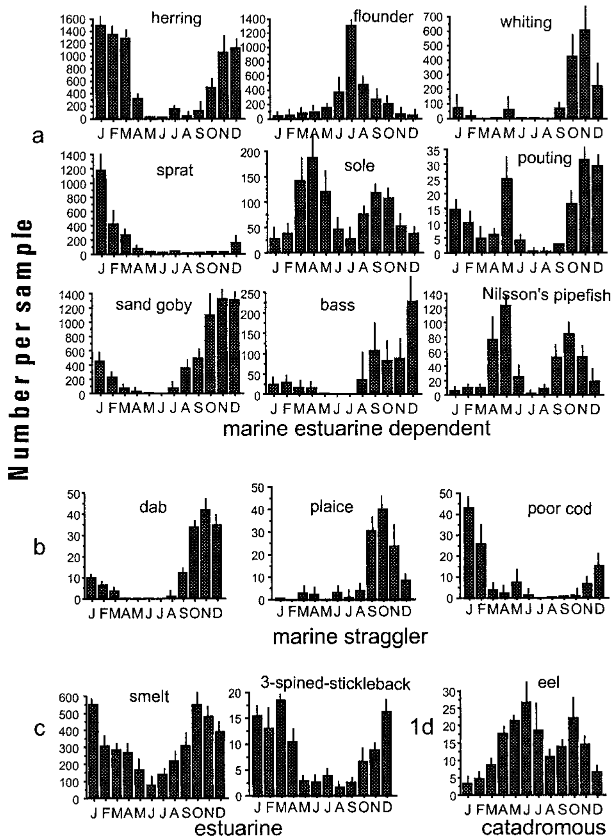

Fig. 3. Monthly means (+1 SE) for the abundances of the 15 most numerous fish species in the middle Thames estuary, 1980–1989. (a) Marine estuarine-dependent. (b) Marine straggler. (c) Estuarine. (d) Catadromous.

largely to species which showed bimodal or irregular seasonality of distribution, like sole, Nilsson's pipefish, and smelt. In summary, this distinctive sequential distribution corresponds to the seasonal changes in the relative abundances of the 15 common species and four types of structure of fish community are shown: December–January–February–March samples positioned to the upper extreme of SP2 contained a high proportion of 3-spined-stickleback, poor cod, sprat, and herring; July–August–September is predominated by flounder; September–October–November–December samples contained high proportion of dab whiting, sand goby, plaice, and bass; and April–May–June was a period of overall low fish abundance or a more balanced fish composition.

Among Year Variation

Every year in the decade, the 15 most abundant species in any one year contributed between 98.5% and 99.5% to the total catch but changed in rank (Table 3). Herring, sand goby, smelt, and flounder ranked among the top 4 species in most years but variations between years were evident (Table 3). Herring ranked first in abundance in most years (1980, 1981, 1983, 1986, and 1987), while smelt was dominant in 1982 and 1984, flounder in 1985, and sand goby in 1988 and 1989. Smelt or sprat assumed second place in the first five years of study being replaced by sand goby in most of the last five years. Bass, which earlier ranked between sixth and tenth, occupied second place in 1989.

The dominant and subdominant species represented less than 50% of the catch in most of the years of study with the exception of 1985–1988, when they were above 50%. Overall there was substantial variation in the abundance of the 15 most common species over the 10-yr period (Table 3; Fig. 5). Herring, sand goby, and plaice showed a stable abundance in 1980–1984, increasing sharply in 1986, then decreasing successively through the rest of the decade (1987–1989). Similarly, flounder showed highest abundance in 1985, while in 1987 eel and 3-spined-stickleback followed by a decreasing trend to the end of the study period.

The first half of the decade was the period of highest abundance for smelt (1980–1984), sprat (1980–1984), pouting (1980 and 1983), and poor cod (1980 and 1984). These among year differences were found to be highly significant in many instances (Table 4). For example, for smelt the average numbers of fish per sample for 1980, 1982, and 1984 were greater than in the period 1985–1989. For sprat, abundances were significantly higher between 1980–1984 compared with 1985–1989. However, an increase in abundance was shown by sand goby with a highly significant difference between low values of 1980–1984; 1989 and high values of 1985–1988.

The overall mean yearly abundance decreased from 2,286 fish in 1980 to 1,762 fish in 1984, and then increased to a peak of 3,569 fish in 1986. From 1986 onward there was a gradual decrease to a low of 1,386 fish (Table 3). For 1980–1983, the number of species recorded each year range from 49–54, whereas from 1984–1989 it falls to 35–44. Changes in the community structure are also shown in plots of the number of species per geometric class (Fig. 6). Rare species in geometric class I (abundance of 1 individual) fell from above 30 species in 1980–1983, to about 20 species in 1984–1988, and then showed a slight rise to about 25 species in 1989.

Influence of Environmental Parameters on Fish Abundance

The canonical correspondence analysis revealed that the most significant environmental variables associated with fish abundance were temperature and dissolved oxygen (Table 5). Correlations be-

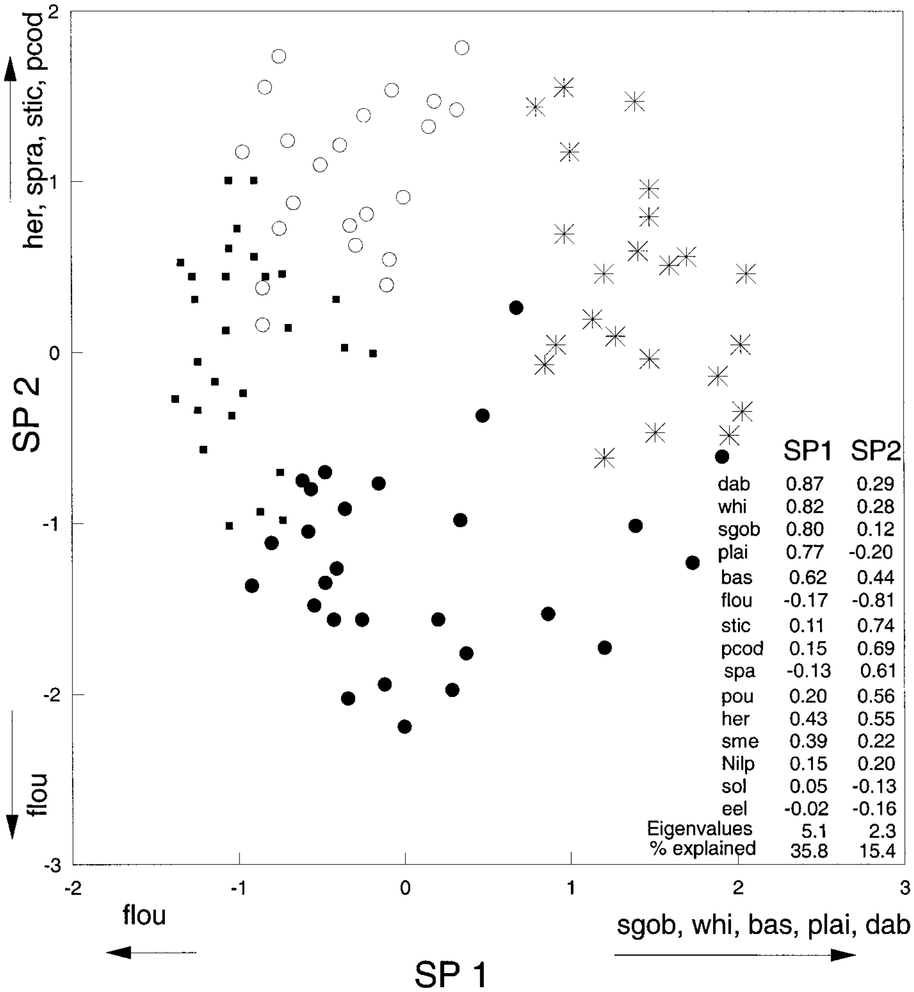

Fig. 4. Sample date scores on the first two components from PCA on abundance of 15 most numerous fish species in the middle Thames estuary, 1980–1989. Fish species: her = herring; sgob = sand goby; flou = flounder; spra = sprat; whi = whiting; bas = bass; dab = dab; plai = plaice; stic = 3-spined-stickleback; pcod = poor cod. Monthly dates (○ January–March; ■ April–June; ● July–September; * October–December).

tween species and the 4 environmental axes were high for the first (0.80) and second (0.75) axes, and lower for the third (0.65) and fourth (0.29) axes. Finally, only 25.4% of the total inertia of the species matrix was explained by the 7 factors included in the analysis. Figure 7 represents the ordination plot showing the months and the species distribution in relation to the environmental parameters, as determined by CANOCO. Each arrow represent a factor and determines a direction in the diagram, obtained by extending the arrow in both directions. The projections of a species on this axis shows its preference for high or low values of this environmental gradient (Ter Braak 1986). The closer the species to the vector, or other species, the stronger the relationship, while the relative position along the vector will give the type of effect (i.e., increasing abundance with high or low values for the environmental variable). Although four axes are determined within the analysis, only axes 1 and 2 were plotted as they accounted for the 86.4% of the variability explained.

Axis 1 separates Summer samples, mainly July and August, on the right side, in opposition to Winter samples from December to March on the left side (Fig. 7). The major source of patterned variation in the data is a marked shift in fish community structure between Summer and Winter, along axis 1, coincident with changes in temperature which was inversely related to dissolved oxygen. Flounder was associated with high temperature and pH, and low dissolved oxygen and ammonical nitrogen values. Poor cod, sprat, 3-spined-strickleback, and herring were associated with high flow, dissolved oxygen, and ammonical nitrogen, and low temperature and salinity. Plaice, sand

TABLE 3. Top 15 most abundant fish species in any one year in the middle Thames estuary to number of individuals as CPUE, from 1980 to 1989 (% of all fish below). SE = standard error.

Rank	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1980–1989
1	her	her	sme	her	sme	flou	her	her	sgob	sgob	her
	26	31	25	32	26	34	35	38	33	21	26
2	sme	spra	her	sme	spra	sgob	sgob	sgob	her	bass	sgob
	21	19	20	15	22	27	33	30	22	18	20
3	sgob	sme	flou	spra	her	her	flou	flou	flou	her	sme
	18	15	17	12	17	16	10	10	17	17	14
4	flou	whi	sgob	sgob	sgob	sme	sme	sme	sme	flou	flou
	11	10	11	12	10	8	7	8	9	12	13
5	spra	spra	whi	flou	flou	whi	whi	sol	sol	whi	spra
	6	6	10	11	7	4	5	3	6	8	8
6	sol	flou	spra	whi	sol	Nilp	spra	bas	whi	sme	whi
	6	6	7	9	6	3	3	2	4	6	6
7	whi	sol	sol	sol	whi	sol	sol	spra	Nilp	sol	sol
	5	4	3	2.6	3	3	2	2	2	5	4
8	Nilp	Nilp	Nilp	bas	bas	spra	plai	whi	pog	Nilp	bas
	2	0.9	3	2.1	2	2	1	2	1.2	5	2
9	pout	mull	bas	Nilp	Nilp	bas	Nilp	eel	bas	spra	Nilp
	1	0.8	1	2	2	2	0.7	1.1	1	2	2
10	dab	dab	eel	pout	pcod	plai	eel	stic	spra	pog	eel
	1	0.6	0.7	1.3	1	0.7	0.7	0.8	1	1	0.7
11	pcod	eel	pcod	eel	pout	eel	pog	Nilp	dab	eel	pout
	0.8	0.5	0.3	0.6	0.9	0.6	0.6	0.8	1	1	0.5
12	eel	bas	dab	pcod	pog	dab	dab	plai	eel	stic	dab
	0.6	0.5	0.3	0.4	0.7	0.2	0.5	0.7	0.9	0.5	0.5
13	bas	pou	stic	stic	stic	stic	snai	pog	plai	dab	plai
	0.5	0.4	0.3	0.3	0.4	0.2	0.4	0.6	0.6	0.5	0.5
14	stic	stic	pog	pog	eel	snai	stic	dab	stic	pout	stic
	0.4	0.4	0.1	0.3	0.4	0.2	0.3	0.6	0.4	0.4	0.4
15	snai	plai	pout	mul	dab	pcod	pout	snai	pout	mul	pcod
	0.3	0.4	0.1	0.2	0.3	0.2	0.3	0.3	0.3	0.3	0.3
15 spp—%	99.2	98.5	99.0	99.0	98.9	99.5	99.3	99.4	99.1	98.6	98.6
no. spp	51	49	51	54	39	35	37	40	41	44	79
CPUE ± SE	2,286 ± 285	2,086 ± 379	1,730 ± 273	2,136 ± 366	1,762 ± 490	2,334 ± 550	3,569 ± 906	2,757 ± 547	2,121 ± 261	1,386 ± 156	2,145 ± 135
Samples	20	24	23	24	13	14	14	13	19	22	186

Species: her = herring; sgob = sand goby; sme = smelt; flou = flounder; spra = sprat; whi = whiting; sol = sole; bas = bass; Nilp = Nilsson's pipefish; eel = eel; pou = pouting; dab = dab; plai = plaice; stic = 3-spined-stickleback; pcod = poor cod; pog = pogge; snai = common sea snail; mul = thin lipped grey mullet.

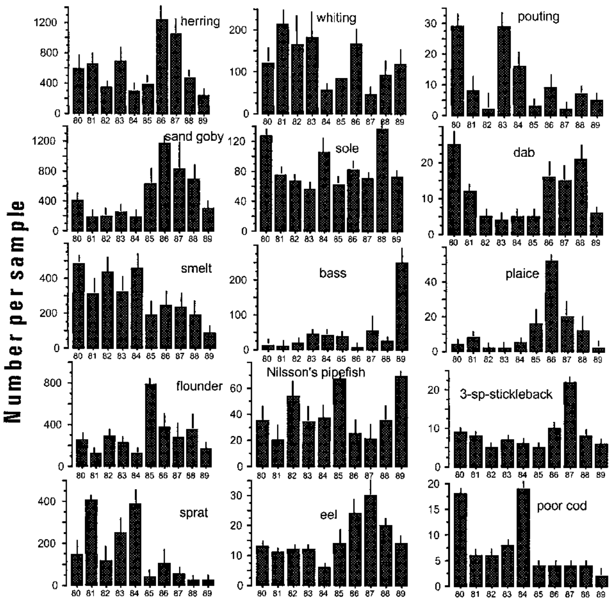

Fig. 5. Yearly mean abundance (+1 SE) for the 15 most numerous fish species in the middle Thames estuary, 1980–1989.

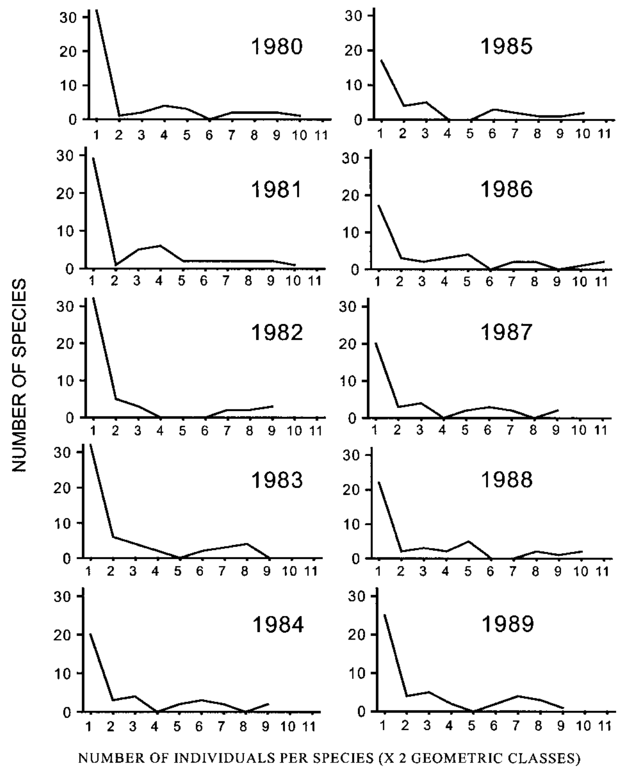

Fig. 6. Number of species against individuals per species in geometric classes in the middle Thames estuary, 1980–1989.

goby, bass, dab, and whiting were preferentially found in high salinity and suspended solids and low pH. Smelt and sole were likely to prefer average values or showed no clear preferences.

Discussion

The most noticeable seasonal change (a decrease) in both number of species and individuals occurred in summer because of the decrease in water quality which normally accompanies rising temperatures. Environmental parameters in the middle Thames estuary varied according to period of the year and influenced fish community composition and abundance. The greatest abundance of flounder occurred in July–August when temperature and salinity were highest, and flow and dissolved oxygen were lowest; Elliott et al. (1988) found poor water quality in Forth estuary, Scotland, during summer, with the fish fauna being dominated by flounder. According to CANOCO, the most important factor associated with the distribution of fish species is temperature, followed by dissolved oxygen. The increases in abundance of sand goby, whiting, bass, plaice, and dab in Au-

TABLE 4. F-values from one-way ANOVA and significant yearly differences of log(x + 1) transformed fish abundance species in the middle Thames estuary, from 1980 to 1989. Levels of significance: * = $p < 0.05$; ** = $p < 0.01$; ns = no significance.

Species	F-value	Tukey Test
Herring	3.3*	1986–1987 > 1980–1985; 1988–1989
Sand goby	3.2*	1986 > 1985; 1987–1988 > 1980–1984; 1989
Smelt	5.5**	1980; 1982; 1984 > 1985–1989
Flounder	3.6*	1985 > 1980–1984; 1986–1989
Sprat	5.4**	1980–1984 > 1985–1989
Whiting	1.5 n.s.	—
Sole	1.9 n.s.	—
Bass	6.2**	1989 > 1984 > 1980–1982; 1986
Nilsson's pipefish	0.8 n.s.	—
Eel	3.7*	1986–1988 > 1980–1985; 1989
Pouting	6.3**	1980l; 1983–1984 > 1982; 1985; 1987–1989
Dab	0.6 ns	—
Plaice	7.9**	1986 > 1987 > 1980–1984; 1989
3-spined-stickleback	5.1**	1987 > 1980–1986; 1988–1989
Poor cod	3.5*	1980; 1984 > 1981–1983 > 1985–1989

TABLE 5. Summary of the CCA performed on the abundance of fish species. Significant factors were selected by a stepwise procedure analogous to forward elimination in multiple regression analysis.

	Axes				
	1	2	3	4	
Correlation of environmental variables					
Temperature	0.63	0.42	−0.15	−0.01	
Dissolved oxygen	−0.53	−0.31	−0.33	−0.06	
Flow	−0.25	−0.49	0.18	−0.03	
Ammoniacal nitrogen	−0.22	−0.56	0.12	−0.12	
Suspended solids	−0.17	0.22	0.14	−0.15	
pH	0.15	−0.03	0.25	0.08	
Salinity	0.06	0.67	−0.16	−0.03	
Summary statistics for ordination axes					
Eigenvalues	0.049	0.026	0.006	0.002	
Species-environment correlations	0.80	0.75	0.65	0.29	
Cumulative percentage of variance					
of species data	19.1	29.2	31.7	32.9	
of species-environment correlations	56.6	86.4	93.7	96.4	
Sum of all unconstrained eigenvalues					0.254
Sum of all canonical eigenvalues					0.086

tumn coincides with decreasing temperature and increasing dissolved oxygen. In winter, characterized by high river flow, dissolved oxygen and ammonical nitrogen, and low salinity and temperature, the fish community is dominated by herring, sprat, 3-spined-stickleback, and poor cod. A correlation revealed by the statistical analyses does not however indicate a direct casual relationship that is explained by physiological tolerance of the species to the measured variable. Demonstrating a direct casual relationship requires specific experiments, which was beyond the scope of the present study. However, some insight to the species preferences may be obtained. Dissolved oxygen is not generally a limiting factor for the occurrence of fish in the estuary, as it was in the first half of the century (Wood 1982). Pomfret et al. (1991) found that dissolved oxygen levels <4.5 mg l^{-1} coupled with temperatures >15°C acted as a barrier to fish movement, however this is not the case for all species. Alabaster et al. (1991) tabulated values of median minimum dissolved oxygen levels over 1, 10, and 40 km of the Thames estuary during the third quarter of the year, only 4/12 of the values exceeded 3.5 mg l^{-1} between 1986 and 1989, compared with 11/12 in the preceding period (1982–1985), indicating improved water quality between these two periods. O'Reilly Wiese et al. (1997) found that a decline in metal accumulation in the sediment of the middle Thames estuary and an increase in Manganese concentration has been attributed to increases in the dissolved oxygen in the estuarine waters resulting from the increased efficiency of the sewage treatment works. During the 10 yr of these study at West Thurrock, the mean annual saturation level of dissolved oxygen was 51.2%, within a range of 27–76%. In summary, temperature, salinity, dissolved oxygen, ammonical nitrogen, and flow were the major factors changing seasonally, the remaining, pH and suspended solids, showed relatively low seasonal changes and did not influence the markedly seasonal fish community.

Potter et al. (1986) found from studying consistency of seasonal changes in fish community in the Severn Estuary that the cyclical pattern were not driven directly by temperature, salinity, or freshwater discharge but were a reflection of sequential immigrations of different species, mainly marine estuarine-dependent, and that the composition and abundance of fish fauna were modified to some degree by extremes in environmental variables. A study along longitudinal reaches of the Elbe estuary (Thiel et al. 1995) found temperature to be the best predictor of the total abundance while salinity influenced the species richness. Marshall and Elliott (1998) also found that salinity had a greater influence on the species composition within the Humber estuary than temperature and that salinity influenced the distribution of fish through their salinity tolerance. It is axiomatic that the environmental variables play an initial role in structuring the fish assemblage but biological interaction are then superimposed on that structure. Moreover, biological factors, such as predator-prey interaction and prey distribution, will affect fish distribution patterns. The present study has suggested associations between environmental variables and fish abundance, but both interspecific and intra-specific biotic interactions remain to be studied in this system. There are also dynamic patterns of migration in and out of the area by species

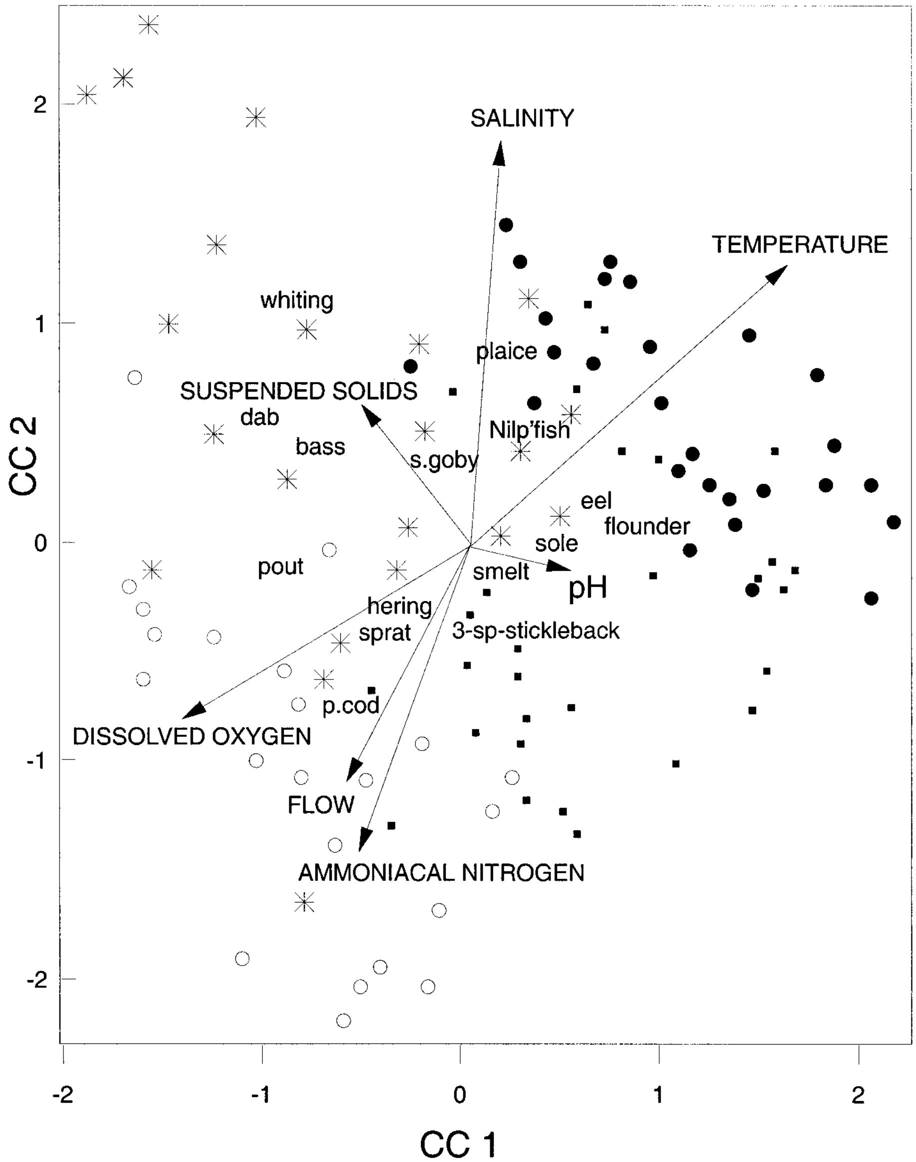

Fig. 7. Ordination diagram (triplot) from canonical correspondence analysis including fish species, environmental parameters (represented by vectors) and the samples coded by monthly dates (○ January–March; ■ April–June; ● July–September; * October–December).

which use the estuary as nursery grounds, with each species responding in a particular way to the internal, biological aspects of life cycle. The interspecific variability can also be related to differences in the methods by which most of these species are transported from their spawning grounds to upstream nursery areas in the estuary. Species such as herring, sprat, and bass, which appear at a relatively small size in the Severn estuary (Potter et al. 1986), probably use passive and selective tidal transport to enter and pass up the estuary (Fortier and Leggett 1982; Norcross and Shaw 1984). By contrast, species such whiting, which are represented by individuals with a larger modal length, have been described as entering their nursery areas through "an active migration of juveniles rather than a passive denatant drift of planktonic larvae" (Cooper 1980, 1983). The sequential replacement of species during this period of high abundance, mainly in Autumn and Winter, could be of value in reducing the likelihood of competition for space and food in the shallows of the middle estuary at this time. A similar conclusion was reached by Weinstein et al. (1980) and Potter et al. (1986).

The seasonal pattern of the most abundant species in the middle Thames estuary was similar to that described for the middle reaches of other western Europe estuaries. The high occurrence of flounder in July–August coincides with peaks in the Ythan (Scotland) and Tamar (southwest England) estuaries, comparable to the Baltic and North Sea coastal areas where the flounder is a summer visitor (Dando 1984). New recruits (30–40 mm Total Length—TL) first appeared in the middle estuary in June, but, as early as May, smaller individuals (10–15 mm TL) from migrations from the coastal spawning areas were observed in the upper estuary in seine collections (Araújo et al. 1999). These small juveniles were not sampled at the West Thurrock screens. Gadoids, whiting, and pouting, showed similar seasonal patterns, peaking in September–December, and differing from poor cod which peaked in December–March. Gobies from the *P. minutus* complex are the most abundant species on the coast of northwest Europe. The increase in the numbers during Autumn and early Winter in the Thames estuary do not match the situation described in the Medway estuary (Van den Broek 1979) and Severn estuary (Claridge et al. 1985), where it is believed that the decline of gobies in the winter reflect an offshore movement towards warmer waters as the temperature in the shallows fell to a low level. Juveniles of bass in most British estuaries are expected in high number during their autumnal inshore migration. This situation in the Thames is in agreement with the findings of Claridge and Potter (1983) and Hardisty and Huggins (1975) for the Severn estuary. The December to March herring and sprat peak in the Thames is almost matched in the Forth-Firth estuary in Scotland (Elliot et al. 1990) but differs from the Severn in southwest England (Hardisty and Huggins 1975) where these clupeids, probably from a completely separate unit of stock, peaks between September and November. Fluctuations in abundance of herring and sprat in Thames estuary are associated both with seasonal migrations and with the level of spawning success each year in the North Sea (Andrews et al. 1982). The annual bimodal peaks of sole in the Thames estuary in March–April and in September parallels the situation in the Wadden Sea, Netherlands (Creutzberg and Fonds 1971), Severn estuary (Claridge and Potter 1987), and is similar to that found in Medway estuary, the largest tributary of the lower Thames estuary situated approximately 40 km below West Thurrock Power Station (Van den Broek 1980). Eels are well known for their long migration from spawning grounds in central-west Atlantic Ocean to the estuaries in north-west Europe; they arrive in spring when environmental conditions are less harsh, then enter and remain in freshwater for periods of up to 20 yr as adults (Huddart and Arthur 1971). Naismith and Knights (1988) detected, for the Thames estuary, peaks of eels as elvers and small juveniles between May and June.

The differences in species composition and diversity among the first and second half of the decade supported the idea that an slightly increasing deterioration of water quality in the Middle Thames estuaries took place in the 1980s. The relatively high-quality water condition in 1980–1984 characterized by a more diverse and higher abundance of several less tolerant fish species that included smelt, poor cod, and sprat, was replaced by other species such sand goby and flounder, more tolerant to harsh environmental conditions, and a lower evenness due to a few high dominant species in 1985–1989. Flounder had its greatest recorded dominance in summer, 1985 to 1988, with a similar high summer dominance in 1976–1979 (Andrews 1984). Flounder are known to be tolerant of widely changing environmental conditions. Numbers of common species like smelt, sprat, and poor cod fell over the decade, coinciding with decreasing dissolved oxygen and flow. Smelt is often regarded as an indicator of improving water quality and has recently returned (in 1989) to the Forth estuary (Pomfret et al. 1991) following its disappearance in the 1960s. Previously abundant in the Tyne (Davis 1983), its return to that estuary in northeast England may be a possibility as water quality improves. According to Wheeler (1969), smelt are common in the Thames in spring, spawn in the neighboring estuaries of the Rivers Crouch and Blackwater, and, since 1968, the Thames water has been of sufficient quality to allow this species to pass from the sea to upstream of London (Wood 1982). Maximum abundances for bass and Nilsson's pipefish coincided with lowest overall numbers of fish in 1989. Andrews (1984) found a trend of increasing numbers of species of fish in the 1970s. In the 1980s the opposite pattern was observed with a decreasing trend in the number of species over the decade resulting from a decrease in diversity and shifts in population structure, and this could be associated with lower dissolved oxygen and flow in the end of the decade.

Differences in both rare and common species suggest the change in the community structure from a more diverse and stabilized period in 1980–1983 to a less diverse period in 1984–1988, and somewhat of a return to the former pattern but with lower abundance of species in 1989. These changes cannot, however, be categorically related to effects of pollution. Other factors, such as environmental disturbance (e.g., natural variations in river discharge, water temperature, or dissolved oxygen) can alter the community structure equilibrium.

The effect of pollution will alter the natural sequence of periodic use of estuarine systems by the marine estuarine-dependent and other fish species. Changes in community structure from the fish catches at West Thurrock power station suggests a more stable community in 1980–1983, followed by a trend of deterioration in species richness in 1984–1989. Years 1980–1983 showed increased diversity with higher numbers of rare species and less common species, characterizing a more stable community. On the other hand, the years of 1985, 1986, and 1987, with few rare species and higher abundances of common species characterized a more disturbed community. An increased relative abundance of species known to be tolerant of widely changing environmental conditions and stress factors, e.g., flounder and sand goby, as well as decreased relative abundance of intolerant species, e.g., smelt and sprat, indicates a trend of slight deterioration of fish habitat during the latter part of the decade.

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