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Seasonal and between-year variations of fish populations in the middle Thames estuary: 1980–1989

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Abstract Fish samples collected at the cooling water intake screens of West Thurrock power station located 35.5 km downstream of London Bridge on the Thames estuary during the decade 1980–1989 were analysed. Seasonal and long-term changes in the abundance of the 15 most numerous fish species and in several fish community parameters were analysed. The majority of species were highly seasonal in their distribution and abundance. Species diversity was lower in the summer (May–August) compared with spring/winter (October–February). Evidence of long-term changes in species diversity and community structure over the decade is presented. The changes were consistent with a period of relative stability (1980–1984) followed by a period of change (1985–1989) and may reflect a deterioration in water quality in the second quinquennium. It is argued that the monitoring of fish communities in estuaries should be based on a multi-metric approach as no single indicator alone can describe the complex community structure.

KEYWORDS: estuary, fish, populations, seasonal, Thames, yearly.

Introduction

The Thames estuary has, since the 1960s, provided a classic example of the recovery of an estuary from gross pollution. This recovery has been monitored chemically, but one of its most striking features has been the return of many fish species to the estuary, culminating in the appearance of the salmon in the late 1970s. Andrews (1984) described the changing patterns of fish species diversity and abundance from 1975 to 1980. During the subsequent 10 years, species diversity has stabilized but the population structure has continued to vary.

This paper has two aims. The first is to describe the seasonal and annual variation in the abundances of the 15 most numerous species in the fish community of the middle Thames estuary, which contribute 98.5% of the total fish sampled over the period 1980–1989. Because regular seasonal cycles of abundance are established, the comparison on a year-by-year basis needs to distinguish inter- and intra-year variations and this is attempted. Secondly, measurements of different attributes of the full fish community during the decade will be analysed. Long-term shifts in community structure need to be understood because they may

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be correlated with stresses arising from changing environmental conditions. Because such changes in community structure are likely to precede more fundamental changes in species diversity, they could provide an early warning of habitat or water quality deterioration. Thus, once baseline community structure has been described, a continued monitoring programme should be able to detect future perturbations

Methods

Fish were collected from the cooling water intakes screens of West Thurrock Power Station, which is situated on the north bank of the middle Thames estuary, 35.5 km downstream of London Bridge and 17 km downstream of the outfall from Beckton Sewage Treatment Works, which is the major works serving north London. Fish sampling from power stations has been used with considerable success to obtain data on fish communities in England (Wheeler 1969; Huddart & Arthur 1971a,b; Van den Broek 1979, 1980). However, the methods of estimating fish abundance using fish entrained on screens can be biased because fish may not be caught in proportion to their relative abundance in the habitat (McHugh 1967). Possible selectivity may occur in the relative ability of fish of different size and species to escape, although the range of size of fish caught, from large eels to small gobies, suggests that fish are unable to withstand entrainment irrespective of size. The use of conventional sampling techniques in large estuaries is made difficult by the presence of extensive areas of mud and large tidal range and action. The National Rivers Authority carried out trawling near the West Thurrock Power Station simultaneously with sampling from the power station screens and found no significant differences between the two sampling methods except that the screens yielded a greater number of fish species (M. Thomas, personal communication). Another potential source of error is the state of the tide and the variable number of pumps in operation. To minimize these problems a standardized sampling technique was adopted. Fish were collected from the intake screens for 4 h commencing 0.5 h before low water on a fortnightly basis over the 10-year period. The total catch was converted to catch-per-unit-effort by taking into consideration the number of intake pumps in operation during the sampling period.

Fish were identified, counted and total lengths of all flatfish, clupeids, gadoids and smelt were measured to the nearest mm. Species were categorized using definitions widespread in the literature (Claridge, Potter & Hardisty 1986; Loneragan, Potter & Lenanton 1989) where: catadromous = migrating from fresh water to the sea to breed; estuarine = typically occurring and breeding in estuaries; freshwater = typically occurring and breeding in fresh water; marine straggler = typically breeding in marine environments outside estuaries rarely occurring in estuaries; marine estuarine dependent = marine species found in large numbers in estuaries at certain periods of their life cycle.

Comparisons of abundance measurements were performed in terms of seasonal changes, assessed as monthly averages. Analyses of variance (ANOVA) were used to test for significant changes in seasonal abundance. Multivariate analysis was then used to identify associations of species in relation to their seasonal cycles of abundance. Principal components analysis (PCA) and cluster analysis were performed on the abundances of the 15 most numerous species. For cluster analysis, there are a number of agglomerative hierarchical methods available and choice of an appropriate similarity measure is crucial (Pielou 1984). After preliminary trials, the City

Block measure recommended by Boulton (1988), based on the absolute values of the differences among all $\log_{10}(x + 1)$ transformed variables, was found to be the most suitable. A bi-plot of component scores and factor loads was carried out to find relationships between the sampling dates and to link them with the temporal changes in fish species.

Between-year variations in the relative abundance of the 15 most numerous species were examined, followed by an analysis of long-term changes in the entire fish community. Calculations based on fish abundance were performed using $\log_{10}(x + 1)$ transformation of the raw data. The following parameters of the fish community structure were used: number of species and individuals; species richness (D) (Margalef 1969); two heterogeneity indices of diversity, Simpson's index (SIM) and Shannon–Wiener index (H') (Krebs 1989) and the Evenness function (J') (Pielou 1966). In addition, the yearly cumulative percentage curves for the top 15 species were plotted.

Results

1 *The 15 most abundant species*

(a) Two-way analysis of variance. ANOVA showed that the mean abundance of almost all of the 15 most abundant species differed significantly both monthly and yearly (Table 1). The

Table 1. F-values and levels of significance from ANOVA of $\log_{10}(x+1)$ transformed fish abundance of the 15 most numerous species in the middle Thames estuary, from January 1980 to December 1989

Common name	Scientific name	Main effects: Month 11 d.f.	Main effects: Year 9 d.f.	2-Way interaction: month × year 99 d.f.
Marine estuarine-dependent				
Herring	*Clupea harengus* L.	38.6**	8.6**	2.1**
Sand goby	*Potamoschistus minutus* (Pallas)	101.1**	4.2**	3.3**
Flounder	*Pleuronectes flesus* L.	9.3**	4.6	3.0**
Sprat	*Sprattus sprattus* (L.)	44.5**	15.3**	4.5**
Whiting	*Merlangius merlangus* (L.)	94.2**	6.4**	2.6**
Sole	*Solea solea* (L.)	16.3**	5.6**	2.8**
Bass	*Dicentrarchus labrax* (L.)	45.7**	19.3**	2.1**
Nilsson's pipefish	*Syngnathus rostellatus* Nilsson	21.5**	3.4**	1.8**
Pouting	*Trisopterus luscus* (L.)	11.9**	9.8**	2.5**
Marine straggler				
Dab	*Limanda limanda* (L.)	47.2**	2.6*	1.6*
Plaice	*Pleuronectes platessa* L.	36.3**	21.8**	2.6**
Poor cod	*Trisopterus minutus* (L.)	29.0**	3.4**	1.8**
Estuarine				
Smelt	*Osmerus eperlanus* (L.)	15.7**	14.9**	2.0**
Three-spined stickleback	*Gasterosteus aculeatus* L.	12.1**	4.9**	0.9
Catadromous				
Eel	*Anguilla anguilla* (L.)	5.3**	1.6	1.2

d.f., degrees of freedom.

Levels of significance: *, $P < 0.05$; **, $P < 0.01$.

higher *F*-values and significances shown for monthly comparisons indicate that for all species, there is at least one monthly mean that differs highly significantly from the other means. For yearly comparisons, all species except eel, *Anguilla anquilla* (L.), and dab, *Limanda limanda* (L.), showed at least one year mean that was highly significantly different from the others. Highly significant but much lower *F*-values were also shown by month × year interactions in all species but eel, dab and threespine stickleback, *Gasterosteus aculeatus* L. These results indicate that the differences in monthly abundances in the 10-year period were significant and that monthly abundances pattern for these species were not the same every year.

(b) Seasonal variation. Given that the abundances of species were influenced primarily by month, monthly abundance data were pooled for the 10-year sampling period (Fig. 1a–d). Marked variations were found between monthly means for most of the 15 most numerous species with a unimodal distribution, except in three, sole, *Solea solea* (L.), Nilsson's pipefish, *Syngnathus rostellatus* Nilsson, and eel, which exhibited a bimodal seasonal distribution.

Analysis of the temporal separation in the occupation of the estuary by the five species accounting for 81.2% of the total fish sampled (Fig. 2) indicated that herring, *Clupea harengus* L., and sprat, *Sprattus sprattus* (L.), predominated from January to March, flounder, *Pleuronectes flesus* L., from June to August and sand goby, *Potamoschistus minutus* (Pallas), and herring from October to December. Of the remaining top 15 species smelt, *Osmerus eperlanus* (L.), was the least changeable in ranking, occupying second place from April to July and falling to third at other times. Three-spined stickleback and poor cod, *Trisopterus minutus* (L.), reached their highest abundances in the winter whereas whiting, *Merlangius merlangus* (L.), bass, *Dicentrarchus labrax* (L.), dab and plaice, *Pleuronectes platessa* L., peaked in the late autumn (September–December).

Length-frequency histograms for the nine commercial species during their peak months in the estuary (Fig. 3) showed that most populations consisted of small fish. Modal length classes ranged from 4–5 cm in flounder and sole, to 14 cm in whiting. The histograms for flounder, sole, dab and to a lesser extent smelt show two modes corresponding to the 0+ and 1+ age classes, but the high contribution of the 0+ age class in the length-frequency histograms indicated that the great majority of fish are from the previous spring–summer spawning.

(c) Multivariate analysis of seasonal variation. Principal components analysis of the monthly abundances of the 15 most numerous fish, yielded five components with eigenvalues exceeding 1.0, which accounted for 72.2% of the variance (Table 2). Components I and II accounted for 48.6% of the total variation (Table 2). Component I was related to the abundances of dab, sand goby, whiting, plaice and bass whilst the second component contrasted the high abundances of threespine stickleback, sprat, herring and poor cod with the greatly reduced abundance of flounder. Components III–V appear to be associated with species that show bimodal or irregular seasonality of distribution.

A seasonal basis for the variance between the abundances of fish was demonstrated by a hierarchical classification of the data on fish abundance on each sample date (Fig. 4). This analysis produced a clear primary dichotomy between spring/summer and autumn/winter and then four large clusters corresponding to the period of estuary occupation by the common species: (1) summer (July–August); (2) spring (April–May–June); (3) winter to early spring

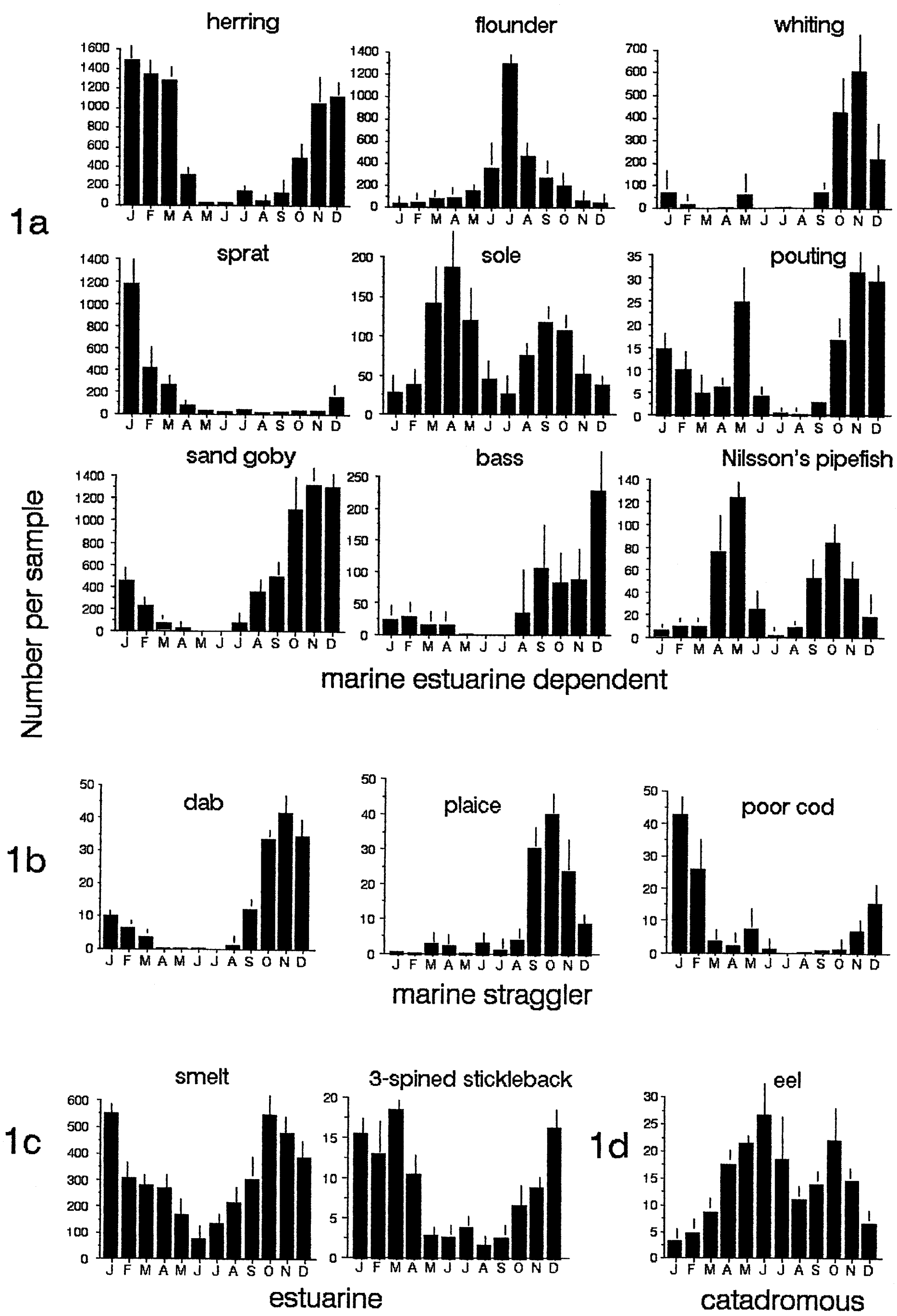

Figure 1. Monthly means (+1 standard error) for the abundances of the 15 most numerous fish species in the middle Thames estuary, between 1980 and 1989. 1a – marine estuarine dependent; 1b – marine straggler; 1c – estuarine; 1d – catadromous.

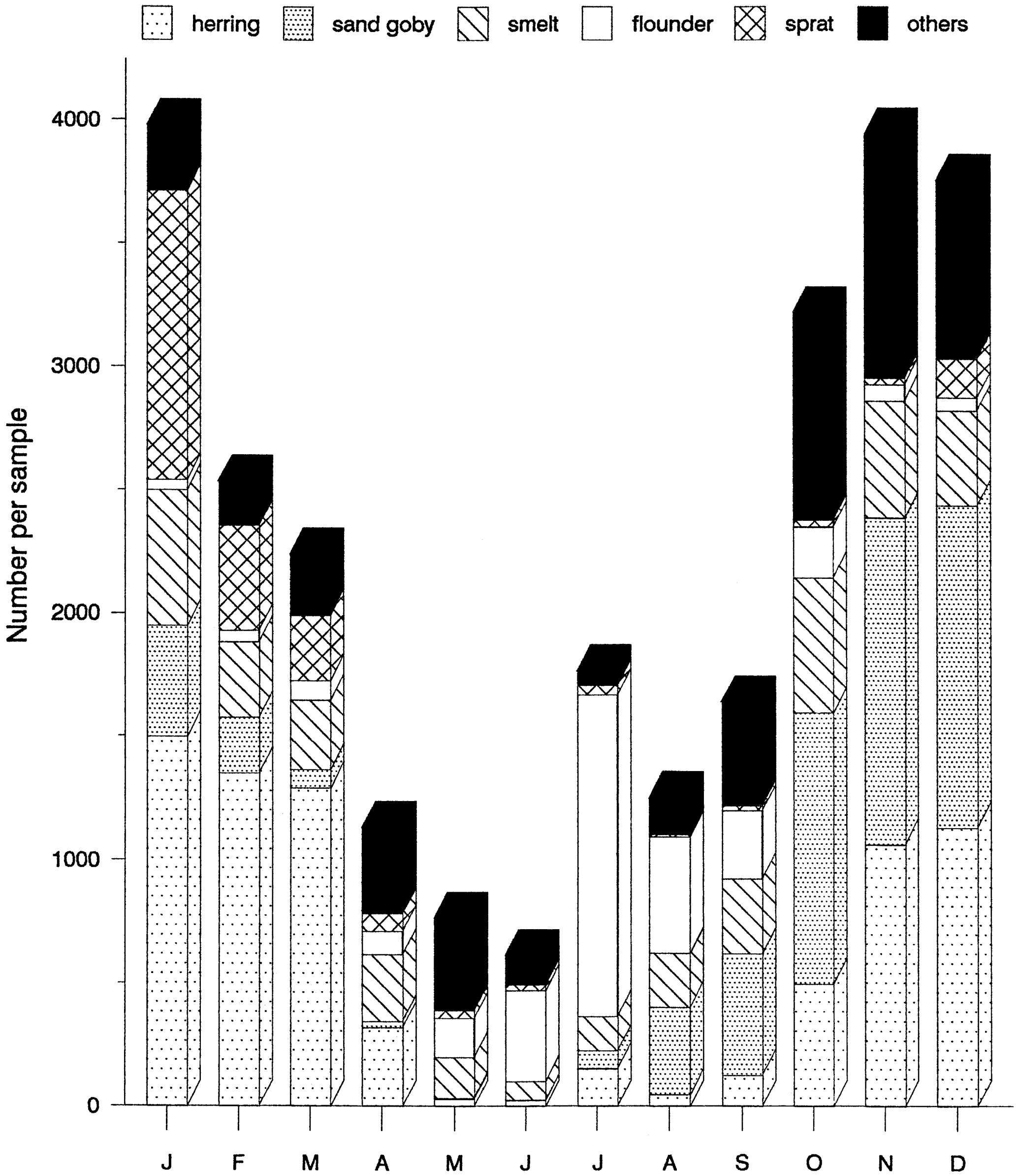

Figure 2. Monthly abundances of the most numerous fish species in the middle Thames estuary, from 1980 to 1989.

(January–February–March); (4) autumn to early winter (September–October–November–December).

A plot of PCA scores by date (Fig. 5) confirmed the seasonal basis of the hierarchical cluster analysis. An anticlockwise temporal pattern can be followed from September–October–November samples in the extreme right to, in sequence: December, middle right; January–February–March, upper centre; April–May–June, extreme left; July and August, through middle

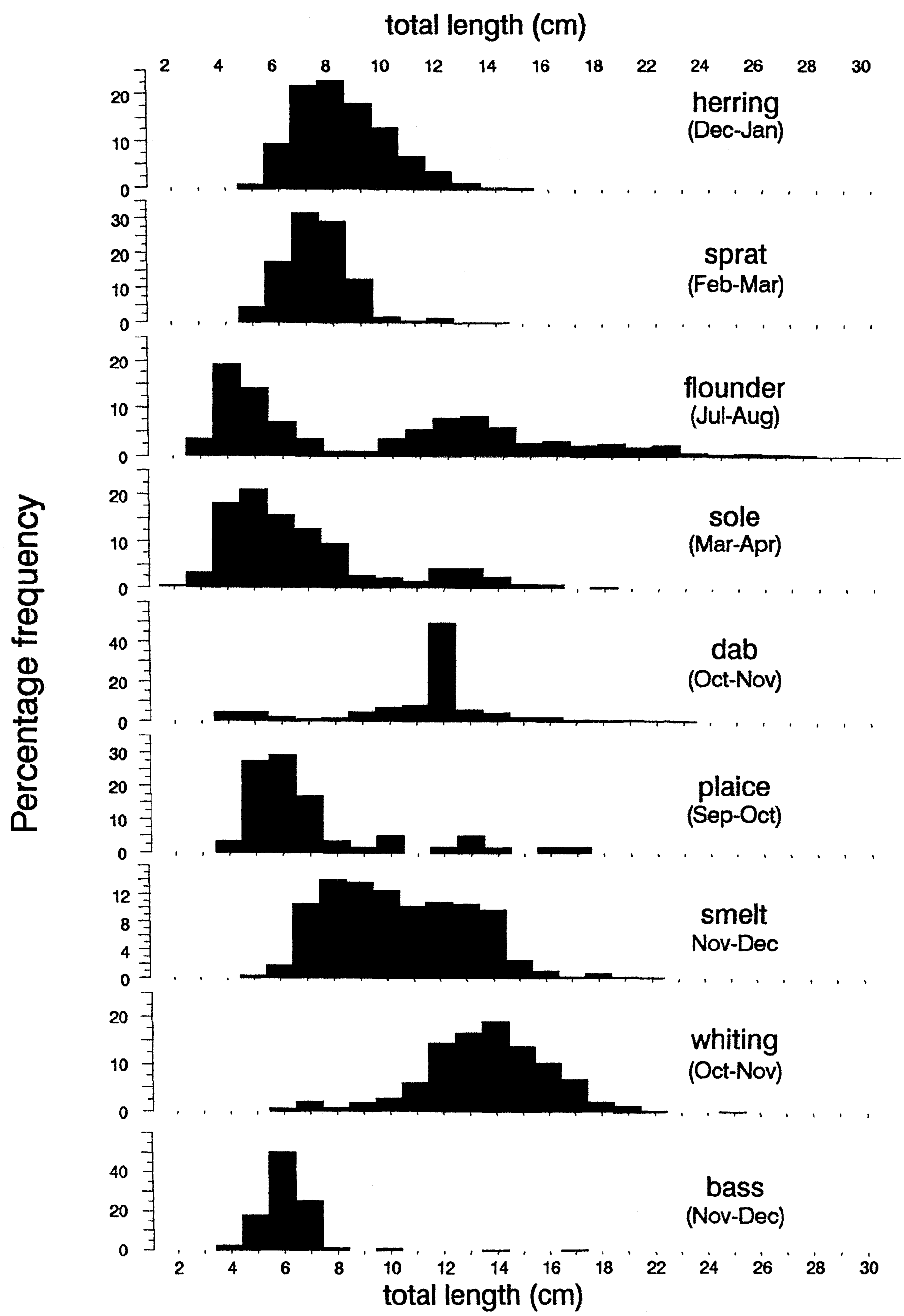

Figure 3. Length-frequency histograms for nine of the most numerous fish species in the middle Thames estuary during the two months when each species reaches maximum abundance.

Table 2. Components loads from PCA on $\log_{10}(x+1)$ transformed fish abundance in the middle Thames estuary, between 1980 and 1989 (values less than 0.50 are omitted)

Species	Axis 1	Axis 2	Axis 3	Axis 4	Axis 5
Herring	–	0.70	–	–	–
Sand goby	0.82	–	–	–	–
Smelt	–	–	–	–	0.61
Flounder	–	–0.50	–0.62	–	–
Sprat	–	0.71	–	–	–
Whiting	0.78	–	0.50	–	–
Sole	–	–	–	–	0.79
Bass	0.59	–	–	–	–
Nilsson's pipefish	–	–	–	0.67	–
Eel	–	–	–	0.72	–
Pouting	–	–	0.78	–	–
Dab	0.83	–	–	–	–
Plaice	0.76	–	–	–	–
Three-spined stickleback	–	0.84	–	–	–
Poor cod	–	0.50	0.57	–	–
Eigenvalues	5.1	2.1	1.3	1.2	1.0
% Variance explained	34.3	14.3	8.8	7.8	7.0

left to lower centre; and finally back to autumn, lower right. This distinctive sequential distribution corresponded to seasonal changes in the relative abundances of the 15 common species.

Overall, cluster analysis and PCA gave similar results, which confirms the robustness of the methods. The differentiation between clusters 2 and 4 corresponded closely with component 1 from the PCA results, while the differentiation between clusters 1 and 3 corresponded closely with component 2.

(d) Between-year variation. There was substantial variation in the abundance of the common species over the decade (Fig. 6). The significance of these variations were tested using the Student–Newman–Keuls (SNK) test (Araujo 1992). The abundances of several species including herring, smelt, sand goby, flounder, eel, plaice and three-spined stickleback showed a relative stability in 1980–1984 but underwent highly significant substantial changes during the period 1985–1989. Herring, sand goby, flounder, eel, plaice and stickleback first of all increased in abundance, peaking in 1985, 1986 or 1987, and then decreased for the rest of the decade (1987–1989). Smelt, sprat and poor cod, on the other hand, were significantly ($P \leqslant 0.05$) less abundant from 1985 to 1989 whilst bass produced a remarkable peak of abundance in 1989.

Every year of the decade, the 15 most abundant species contributed between 98.5% and 99.5% to the total catch but interchanged in rank (Table 3). Herring, sand goby, smelt and flounder ranked amongst the top four species in most years but variations between years were evident. Either herring or smelt were the most numerous species in the first 5 years (1980–1984). Herring remained predominant in 2 of the following 5 years (1985–1989) but there was

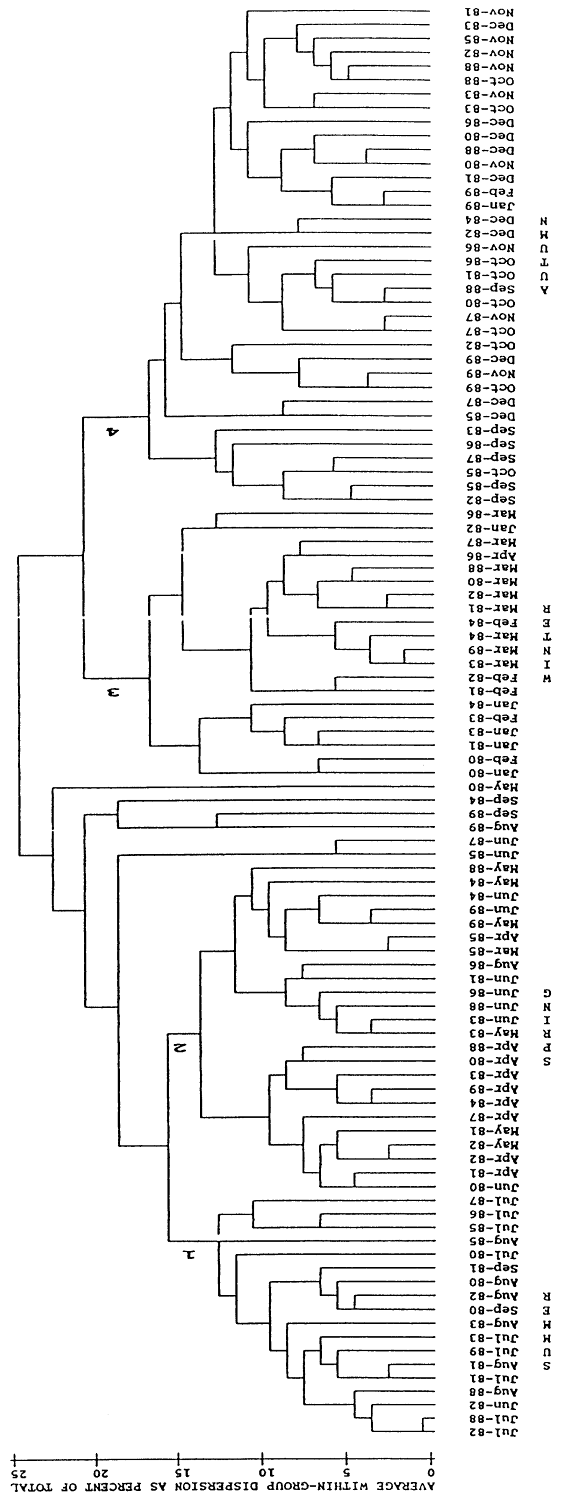

Figure 4. Hierarchical clustering of monthly sampling dates on abundances of the 15 most numerous fish species in the middle Thames estuary, from 1980 to 1989. Average linkage with City Block measure on $\log_{10}(x + 1)$ transformed data.

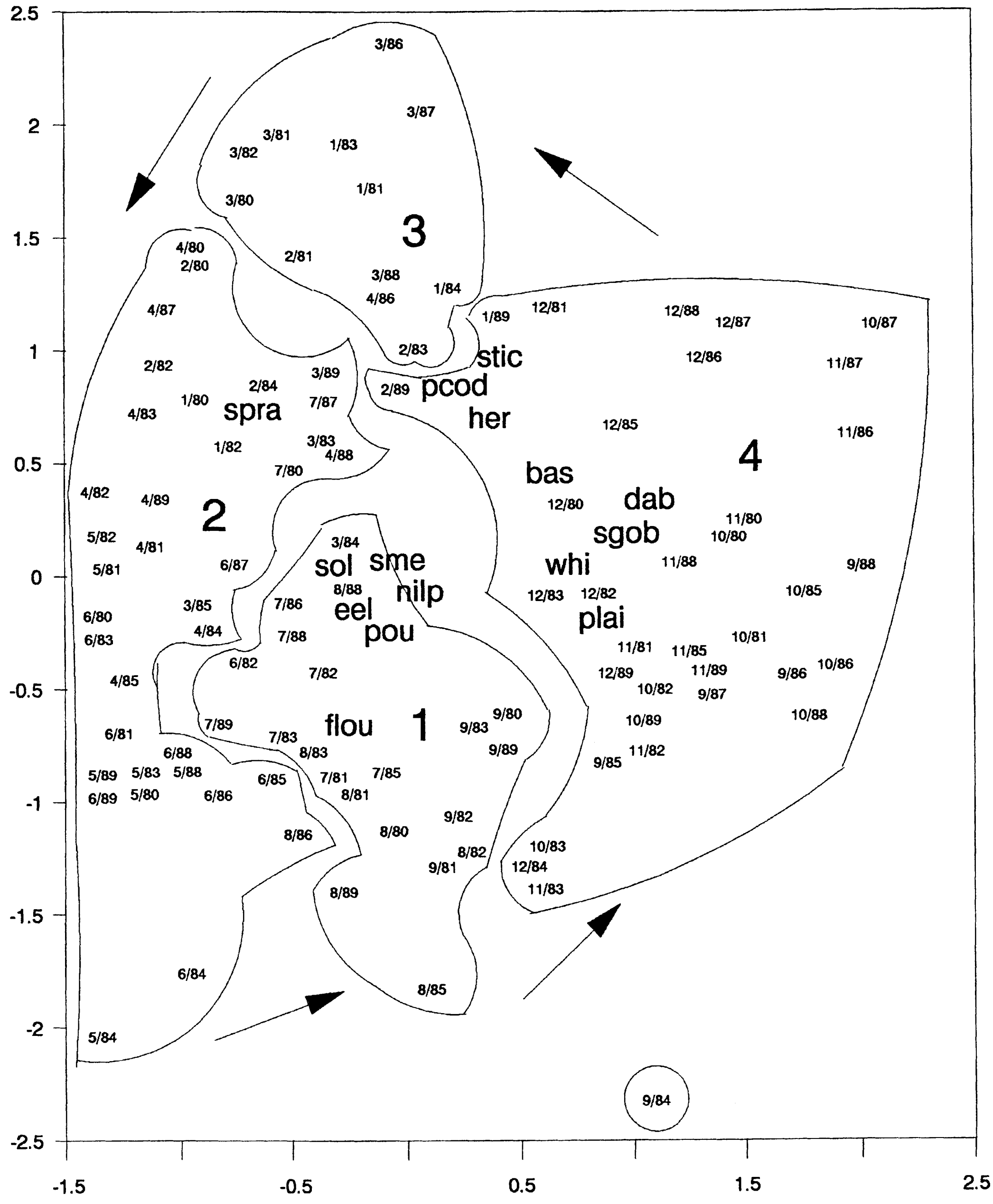

Figure 5. Factor loads and sampling dates scores on the first two components of PCA on abundance of the 15 most numerous fish species in the middle Thames estuary, from January 1980 to December 1989. Clusters 1–4 as in Figure 4. Key: bas, bass; dab, dab; eel, eel; flou, flounder; her, herring; nilp, Nilsson's pipefish; pcod, poor cod; plai, plaice; pou, pouting; sgob, sand goby; sme, smelt; sol, sole; spra, sprat; stic, stickleback; whi, whiting.

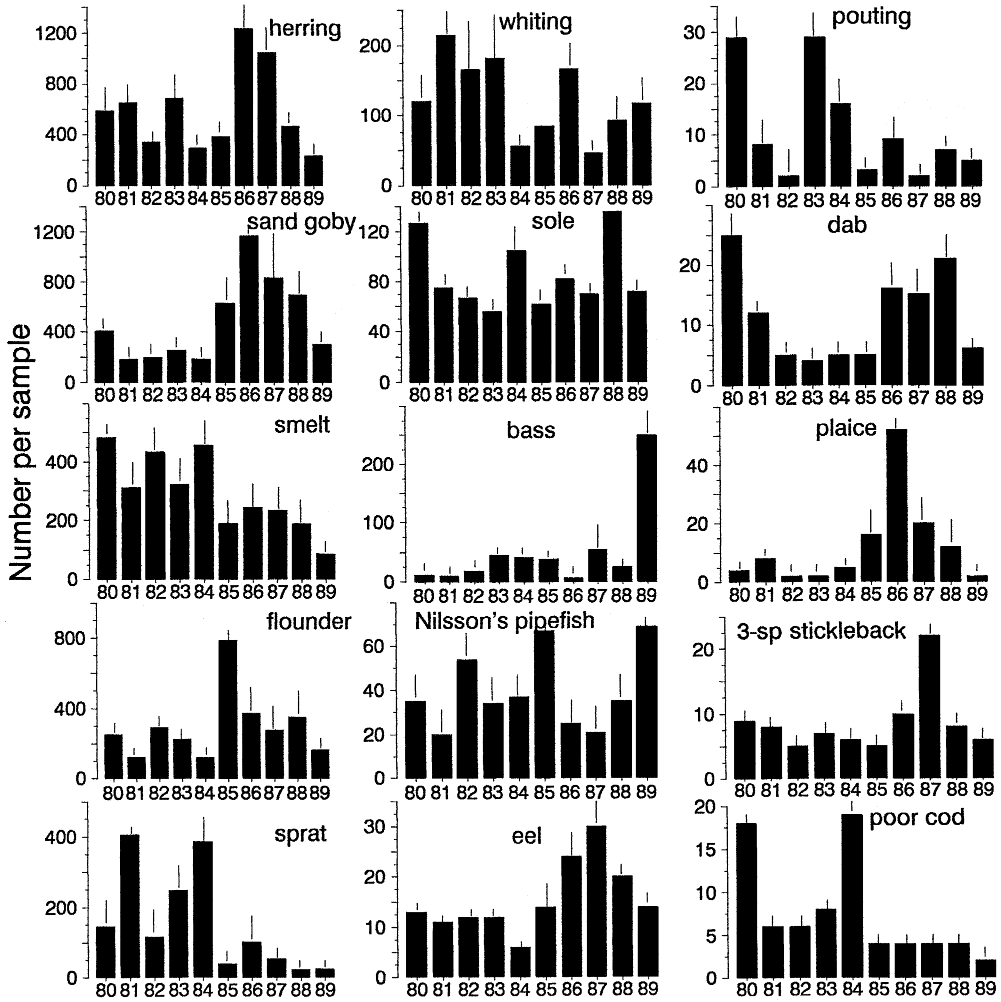

Figure 6. Yearly mean abundances (+ 1 standard error) for the 15 most numerous fish species in the middle Thames estuary, between 1980 and 1989.

a notable rise to prominence by flounder and sand goby in the other years. Smelt abundance fell from 1–3 ranking in 1980–1984 to 4–6 in the second half of the decade. Sprat, ranked 2–6 in the first 5 years, fell to 6–10 in the second 5 years, whilst bass, which usually ranked between 6 and 12, occupied second place in 1989. The relative contribution to the total by the five most abundant species were: herring ranging from 16% (1985) to 38% (1987); sand goby, 6% (1981) to 33% (1988); smelt, 7% (1986) to 26% (1984), flounder, 6% (1981) to 34% (1985), and sprat 22% (1984) to 1% (1988). The dominant and subdominant species accounted for less than 50% of the total catch between 1980 and 1984 and in 1989, but rose to above 50% from 1985 to 1988.

Table 3. Summary of sample data from West Thurrock Power Station during the decade 1980–1989

	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1980–1989
No. samples	20	24	23	24	13	14	14	13	19	22	
No. species	51	49	51	54	39	35	37	40	41	44	79
Mean CPUE	2286	2086	1730	2135	1762	2334	3569	2757	2121	1386	2145
% Contribution top 15 species	99.2	98.5	99.0	99.0	98.9	99.5	99.3	99.4	99.1	98.6	98.6
Top 6 species in rank order											
1	Herring	Herring	Smelt	Herring	Smelt	Flounder	Herring	Herring	S. globy	S. goby	Herring
2	Smelt	Sprat	Herring	Smelt	Sprat	S. goby	S. goby	S. goby	Herring	Bass	S. goby
3	S. goby	Smelt	Flounder	Sprat	Herring	Herring	Flounder	Flounder	Flounder	Herring	Smelt
4	Flounder	Whiting	S. goby	S. goby	S. goby	Smelt	Smelt	Smelt	Smelt	Flounder	Flounder
5	Sprat	S. goby	Whiting	Flounder	Flounder	Whiting	Whiting	Sole	Sole	Whiting	Sprat
6	Sole	Flounder	Sprat	Whiting	Sole	N. pipefish	Sprat	Bass	Whiting	Smelt	Whiting

(e) Cumulative percentage. In 1980–1984, the first of the most abundant species represented between 25% and 32% of all fish, rising above 33% in 1985–1988, and falling to only 21% in 1989 (Fig. 7). The cumulative percentage up to the second, third and fourth most abundant species amounted to about 47%, 63% and 74% of all fish in 1980–1984; 63%, 76% and 82% in 1985–1988; and 39%, 56% and 68% in 1989, respectively. From 1985 to 1988 the community structure changed from the pattern common to the first 5 years but then reverted towards it in 1989. The greater part of the differences between the patterns of 1980–1984 and 1985–1988 was due to changes in the relative contributions of the seven most abundant species to the total number of fish.

2 *Community structure and diversity*

(a) Number of individuals and species. The mean catch-per-unit-effort (CPUE) for all sample dates in the decade was 2145 (SE 135; range 139–13 928). The overall yearly abundance of individuals per unit effort decreased from 2286 in 1980 to 1762 fish sample^{-1} in 1984 (Table 3). It then rose to a peak of 3569 fish sample^{-1} in 1986 before a gradual fall to a low of 1386 fish sample^{-1} in 1989. Table 3 also shows that from 1980 to 1984, the number of species recorded each year ranged from 39 to 54 but fell to 35–44 from 1985 to 1989. The mean number of species from all sample dates was 17 (SE 0.38; range 6–28). When seasonality of occurrence was taken into account (Table 4), a marked difference in the mean number of species recorded annually in samples from the summer (10–15) and winter (21–23) was apparent. Different aspects of seasonality were then examined for trends both within and between years over the study period.

(b) Species richness and diversity indices. Monthly changes in values for these parameters throughout the decade are shown in Fig. 8 and SNK tests of the significance of these variations were carried out by Araujo (1992). [Mean values (x) from all samples are given with the standard error (SE) and range (R).]

Species richness index (D): $x = 2.20$, SE = 0.04, $R = 0.64$–3.44.

Not unexpectedly, D-values were high (> 2.2) in winter and low (< 1.7) in summer. The differences between June–August and September–May were highly significant ($P \leqslant 0.01$). Comparing D for different years, there was some indication that lower summer troughs and lower winter peaks occurred more frequently between 1984 and 1989. This pattern was similar to that observed for the number of species.

The Shannon–Wiener index (H'): $x = 1.47$, SE = 0.03, $R = 0.50$–2.20.

There was a highly significant variation ($P \leqslant 0.01$) between low summer values (notably July, $x = 1.0$) and the peaks of April–May ($x = 1.68$) and September–October ($x = 1.7$). As with D, the lowest H' values were recorded in 1985–1989.

Simpson's index (SIM): $x = 0.33$, SE = 0.01, $R = 0.12$–0.81.

Seasonality was not marked, but annual peaks of SIM values in January–February and July were usually apparent. On 10 occasions in these months, this index exceeded 0.5, meaning

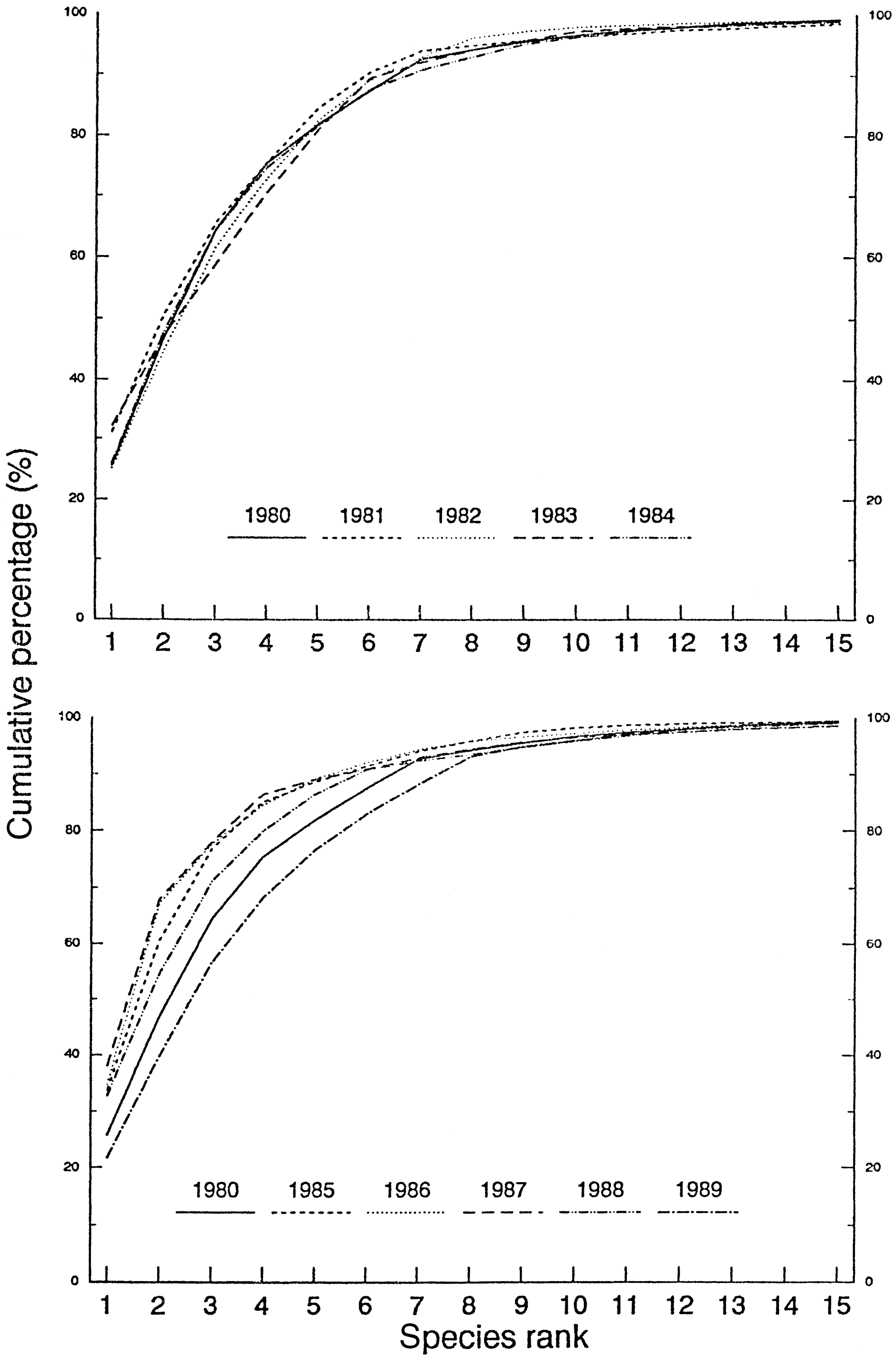

Figure 7. Yearly cumulative percentages of the 15 most abundant fish species in the middle Thames estuary, from 1980 to 1989.

Table 4. Number of fish species per sample in the middle Thames estuary, in summer and winter months between 1980 and 1989 (*n*, number of samples)

	Summer (May–August)			Winter (October–February)		
Year	Average	Range	*n*	Average	Range	*n*
1980	14	10–18	9	23	15–26	9
1981	13	10–16	8	22	15–30	11
1982	15	11–19	8	22	18–27	9
1983	13	8–18	8	23	20–26	10
1984	14	12–16	3	22	22	1
1985	10	9–11	4	23	16–30	5
1986	10	6–15	4	25	23–28	5
1987	12	10–14	3	23	18–25	5
1988	12	9–16	9	23	21–26	6
1989	11	8–15	9	23	18–27	6

that a single species constituted over 50% of the fish community, but generally values were much less, indicative of a lack of overall dominance within the estuary. There were no clear trends over the period 1980–1989.

Evenness (J'): $x = 0.53$, SE $= 0.01$, $R = 0.19$–0.78.

Seasonal and between-year patterns of J' values paralleled those of H'. May and September peaks occurred when fish numbers were low and distributed relatively evenly between species.

(c) Summary. Overall, one annual peak in late autumn/early winter was recorded for number of individuals, number of species and richness. Annual double peaks were recorded for Shannon–Wiener index and evenness, in autumn and spring, and for Simpson's index, in January and July. It may be concluded that seasons (monthly comparisons) had highly significant effects on the number of species, number of individuals and richness, and a significant effect on diversity indices (H' and *SIM*) and evenness. Long-term variation (yearly comparisons) could be detected in the number of individuals, numbers of species, species richness and in H'.

Discussion

Many marine teleosts enter and remain within estuaries for a period of time, particularly during the early part of their life cycles, and often in very large numbers (Blaber & Blaber 1980; Potter, Loneragan, Lenanton, Chrystal & Grant 1983). Other species, such as smelt, remain in the estuary throughout their lives or, like eels and flounder, migrate through the estuary from and to fresh water for breeding and feeding.

The middle Thames estuary was severely polluted throughout the first half of this century, but the return of fish was recorded by Andrews & Rickard (1980) amongst others. The initial phase began in 1964 following water quality improvements resulting largely from the reconstruction of a major tideway sewage treatment works at Crossness (dry weather flow

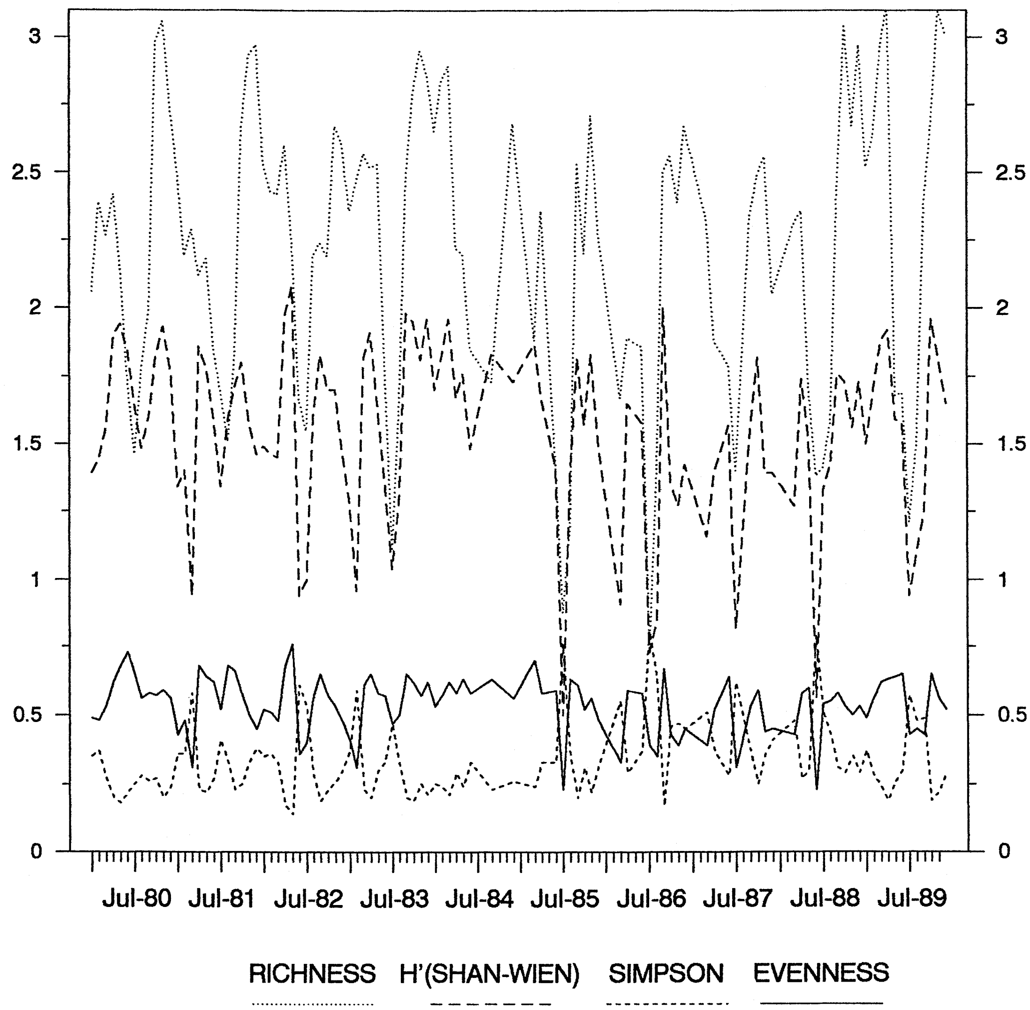

Figure 8. Monthly fish community parameters in the middle Thames estuary, from January 1980 to December 1989. (Richness, 77.; Shannon–Weiner (H'), – – – –; Simpson **77;** Evenness ———).

500 000 $m^3 day^{-1}$). A seasonal pattern developed in which increasingly abundant and diverse winter populations, mostly of young, marine–estuarine-dependent species departed in the spring to leave a small number of resident and migrant species between May and August. In summer, and despite an overall return to aerobicity, dissolved oxygen levels remained very low in the middle estuary, rarely rising above 5% saturation. Further improvements in water quality were brought about by the upgrading of a second, larger sewage treatment works at Beckton (dry weather flow 810 000 $m^3 day^{-1}$). This contributed to a second phase of recolonization between 1974 and 1980 when summer stocks increased with minimally 12 species, including smelt, eel and flounder, and the total diversity rose to over 90 species (Andrews & Rickard 1980). The level of dissolved oxygen, especially in the critical third or summer quarter, was clearly a key

factor in providing acceptable conditions for fish, and since the mid 1970s a 10% minimum was normally achieved at this time of year. During the 10 years of this study at West Thurrock in the middle estuary, the mean annual saturation level of dissolved oxygen was 52%, within a range of 26–76% (Araujo 1992).

The marked cycles of abundance demonstrated by West Thurrock samples between 1980 and 1989, appear to reflect a true seasonality in the levels of stocks and relate primarily to migrations into and out of the estuary by essentially non-resident species, mainly the marine estuarine-dependent herring, sprat, flounder, sand goby and other less abundant fish. Most of the common species exhibited a consistent seasonality but a few had rather ill-defined abundance patterns, occurring either all year round or in some period without consistency.

The four seasonal phases identified by multivariate analyses were characterized by changes in abundances of chiefly 10 species which contributed to an annual sequence in the structure of the fish community:

1 winter (Jan.–Mar.), dominated by herring, sprat, three-spined stickleback and poor cod;
2 spring (Apr.–Jun.), characterized by the lowest abundances of most species;
3 summer (Jul.–Aug.), dominated by flounder;
4 autumn (Sep.–Dec.), dominated by sand goby, whiting, bass, dab and plaice.

Smelt, sole and eel were present in the estuary in reasonable numbers throughout the year.

Andrews (1984) recorded that between 1976 and 1980 the top seven species in the estuary were, in descending order: whiting, sand goby, smelt, flounder, sprat, whiting and sole. The most remarkable change was the switch from whiting to herring in the first rank. Both species appeared in the estuary during autumn and winter and their numbers were probably more related to spawning successes in the North Sea than to reduced pollution (Andrews & Rickard 1980; Andrews, Aston, Rickard & Steel 1982). The increase in herring observed in the present study followed the imposition in 1977 of a 6-year moratorium on the North Sea fishery for this species but, at the same time, its persistence in the middle estuary during summer since 1980 must also reflect the improved water quality.

The Thames winter peaks of both herring and sprat were matched in the Forth estuary (Elliott, O'Reilly & Taylor 1990) but not in the Severn estuary. Here, separate western clupeid stocks produce peaks of herring numbers between September and November, and of sprat in mid winter and early spring to summer (Hardisty & Huggins 1975). The Thames summer flounder peak coincided with those in the Tamar (Hartley 1947) and Ythan (Summers 1979) estuaries but again the Severn differed, with a later flounder peak typically between September and November. By contrast, the seasonality of bass and pouting, *Trisopterus luscus* (L.), in the Thames was similar to that recorded in the Severn (Claridge & Potter 1983, 1984). Peak eel numbers in the Thames estuary between May and June (Naismith & Knights 1988) were added to in the present study by a further peak in October.

The results of between-year variations in abundance and the cumulative abundance curves indicate a shift from a relatively stable pattern of abundances for 12 of the most numerous fishes in the first quinquennium to the second, where striking rises and/or falls in the abundances of species are apparent. As for community composition, there was a fall in the annual number of species recorded from 1984. The decline was among the rarer species, which accounted for 1.5% or less of the total community abundance. This finding could have been affected by the somewhat reduced number of samples taken in 1984–1987, but this appears unlikely to have been a significant factor as 1987, with 13 samples, yielded comparable species diversity to 1988, with 19 samples.

Unperturbed communities have a relatively high number of rare species and a greater evenness of species abundance and few superabundant species (Hellawell 1986). The large number of rare species, lower abundance of dominants and co-dominants and higher evenness recorded during 1980–1983 suggests a period of community stability and minimum perturbation. This appears to be followed by a period of deterioration as rare species declined and many of the top species exhibited erratic peaks of high abundance post 1984. In 1989, conditions appear to revert to those of the 1980–1984 period, although this year may have been exceptional because of temperature, leading to the extremely high numbers of bass in the estuary.

There has been some interest in the use of species diversity indices for the establishment of water quality criteria (Wilhm & Dorris 1968). The consensus is that species diversity is inversely proportional to pollution and that high indices imply greater complexity of energetic pathways, being associated, therefore, with higher stability. According to Livingston (1976), the use of species diversity as an indicator of pollution could be misleading unless done carefully, because the effect of pollution could simply alter the natural sequence of periodic use of estuarine systems by dominants without substantially altering the overall species diversity. In terms of the practical application of diversity indices for the detection and evaluation of pollution, it is evident from this study that indices are seasonally variable in the middle Thames estuary and these variations must be considered when attempting to assess pollution stress. This problem could be overcome if a combination of indices which reflect the different components of diversity are selected based on the previously observed seasonality of the community to be monitored. In the Thames, such indices could include the number of species caught and CPUE during the year as a whole, or the peaks and troughs of species numbers and individuals, and values for derived indices (D, H', *SIM* etc.) obtained in various months during the year. Alternatively, the use of the indices could be restricted to a specific time of year at a time of perceived maximum pollution stress. In the middle Thames estuary this would be the third quarter of the year (July–September), when oxygen levels in the river normally reach a minimum for the year.

The abundance of fish fell quickly in early spring, when the most dominant species started moving away from the middle estuary. Richness showed a similar seasonal variation to the number of individuals and species, because they changed in the same way almost at the same time, but a distinct seasonal change occurred in the apportionment of individuals within the species. This was reflected in the different pattern of variation in the indices of diversity (H' and *SIM*) and in the evenness, which presented double annual peaks. Evenness and the Shannon–Wiener index may be the most useful measure of pollution stress, especially in the critical period of summer when few species remain.

An increasing trend for richness 'troughs' during summer throughout the decade resulted from a true decrease in the number of species and shifts in population structure. This trend was contrary to that observed for the period 1975–1980 by Andrews (1984), who noted an increasing richness in the temporal series. The range in values of richness and other indices reported during this study confirmed the high seasonal variation of the middle Thames estuary. Because evenness showed parallel trends to H', differences in the latter were largely due to changes in the equitability of allotment of individuals, rather than to differences in the number of species. Overall, H' values ranged from 0.5 to 2.20. The lowest recorded were between 0.5 and 0.7 in July 1985, 1986 and 1987, which could indicate a deterioration of the river in these periods. Direct comparisons with other estuaries are useful in identifying major differences of fish migratory seasonality and species diversity. However, it is doubtful whether the differences in diversity indices values can be used to indicate relative levels of pollution stress, because these values are more likely to reflect the natural variability in estuarine physical, chemical and biotic conditions and the different stock origins of the marine–estuarine-dependent species which migrate into and out of the various estuaries.

It was demonstrated that the initial recovery of an estuary from gross pollution can be monitored effectively using representative fish samples such as those obtained in this study from power station intake screens. (Andrews *et al.* 1982). This recovery has been monitored in the middle Thames estuary since the 1960s and the fish samples showed major changes in species diversity and abundance. Between 1980 and 1989, the river Thames continued to receive effluents from sewage treatment works but oxygen levels remained adequate to support fish populations even during the critical third quarter of the year. The complexity of the estuarine fish community with its marked seasonality of distribution and abundance makes it difficult to detect the effects of subtle changes in water quality on the fish community. However, the various analyses carried out suggest that the improvements recorded by Andrews (1984) were maintained during the first half of the study decade (1980–1984) but that there was evidence on several counts of increasing instability and possible deterioration in the period 1985–1989. With regard to possible deterioration, it is pertinent to note that in Alabaster, Gough & Booker's (1991) tabulated values of median minimum dissolved oxygen levels from boat-run data over 1, 10 and 40 km of the 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). No one metric of the fish community is capable of demonstrating these changes on its own. The multimetric approach adopted in this study is recommended for monitoring pollution impacts in complex communities such as the middle Thames estuary and could provide guidelines for the establishment of environmental quality objectives and pollution indices based on estuarine fish community structures.

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