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REPORT

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National Rivers Authority
Thames Region

on

Water Quality and Freshwater Flow in the Thames Tideway in relation to Salmon Migration, with particular reference to the effect of low flow in 1990

by

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Executive Summary

A statistical examination of data on both water quality in the Thames estuary and on the count of salmon **Salmo salar L.** trapped in fresh water above the head of the tide in 1982-1990, has established that:

1) The annual percentage return of parr and smolts as 1 sea-winter fish (grilse) in the period July to September (0.33%) was positively correlated with the median average daily freshwater flow at Teddington. The return, which was average at 19.5 m^3s^{-1}, was reduced to 10% of the average at 6 m^3s^{-1} and to 1% of the average at 2 m^3s^{-1} (Figure 3; page 10).

2) The annual return for the whole year was directly related to the return in July to September, so that the reduction in return in the summer months was not fully compensated for by later returns in the autumn and winter (Equation 7; page 16).

3) In September, when the flow averaged 14.1 m^3s^{-1} for the whole period, the annual percentage return was also negatively related to the extent and duration of low concentrations of dissolved oxygen (DO) and to high water temperature. When a 60 km length of estuary was at a 90%ile value of borderline lethal combinations of DO and temperature, the return was 50% of average, and when the length was 70 km, the return was zero. The length of the estuary at a high temperature (90%ile >21.5°C, coupled with shorter lengths at higher temperatures), rather than the length at low DO (10%ile <3.5 mg l^{-1}, coupled with shorter lengths at lower concentrations), was the more important factor (Figure 5; page 13).

4) For the period, 1987-1990, the effect of flow in reducing the monthly percentage annual return was greatest at low DO. The flow that was associated with a nil monthly return was 6.5 m^3s^{-1} at a minimum 95%ile concentration of DO of 3.5 mg l^{-1}, but was 12.7 m^3s^{-1} at 3 mg l^{-1} (Equation 4; page 15). Similar results were obtained with weekly data (Equation 7; page 16).

5) Weekly catches (normalised) increased with increase in river flow (Equation 11; page 18) and increase in tidal height (Equation 12; page 18).

6) Weekly rates of migration increased with increase in flow; the flow for zero rate was 0-7.8 m^3s^{-1}, depending upon the years examined (Table VI; page 20).

7) Daily rates of migration increased with increase in tidal height (Equation 13; page 20).

Note: Conclusions relating to flow are high-lighted in the text of the report.

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CONTENTS

Water Quality and Freshwater Flow in the Thames Tideway in relation to Salmon Migration, with particular reference to the effect of flow in 1990.

1. INTRODUCTION

The environmental requirements of upstream migrant Atlantic salmon **Salmo salar** L. in the estuary of the River Thames have been described in terms of the concentration of dissolved oxygen (DO), expressed as median and 95%ile excedence values, during the whole period of migration, and over different distances, for the years 1982-1984 (Alabaster & Gough, 1986). They have also been further identified in terms of DO, water temperature, freshwater flow and tidal height for the period 1982-1989 (Alabaster, Gough and Brooker (in press). The present analysis includes data for 1990.

2. METHODS

2.1. WATER QUALITY

The sources of data on water quality for 1990 are essentially as those already reported for the 29 sites sampled by boat along the 140 km length of the estuary in 1982-1984 (Alabaster & Gough, 1986) although the frequency of the sampling was halved, as in 1985-1989, to an average of one per station per week. For a large proportion of samples, DO was not expressed as mg l^{-1}, but the concentration was calculable in most cases from the percentage air saturation value, the temperature and the salinity (from Truesdale & Gameson, 1957) leaving a wastage of only two records.

In addition, quarter-hour measurements of DO and water temperature were available, as for the years 1987-1989, from each of seven automatic sampling sites on the estuary, located from 30 km upstream of London Bridge to 40 km downstream. Because of the tidal flow past each site, up to four measurements were available each day at any point within the limits of the tidal excursion of about 10 km both landward and seaward of each site.

Use was also made of the mean daily freshwater flow (ADF) of the river Thames gauged at Kingston (Teddington) and the tidal height observed at Teddington weir.

The present data analysis repeated previous methods including, where possible, the estimation on a daily basis of the lengths of estuary at given DO's and temperatures. In addition, since the minimum DO was not necessarily correlated with the highest water temperature, the potential lethality of the combination of the two for each sample was expressed, arbitrarily, as the difference between the temperature and the 1000-minute median lethal temperature to salmon smolts at the measured DO, as detailed by Alabaster, Gough and Brooker (in press), the equation being:

$$\ln\ln O = -0.513 + 0.046\,T \qquad (1)$$

where O is the lethal DO (mg l^{-1}) and T is the temperature (°C).

2.2. SIMULATED DATA ON DISSOLVED OXYGEN AND WATER TEMPERATURE

Because of the paucity of boat-run data on water quality, an attempt was made to interpolate missing values. Since there appeared to be a strong link between values for adjacent sites on the same day and since temporal changes were gradual, it was assumed that the temperature on a given day could be modelled as a mean temperature for the day, plus a deviation which depended only upon the reach number. The pattern of deviations was fitted by a systematic search for a least squares fit to the points actually observed.

It was found that, as with previous years' data, the variance of the daily temperature was reduced to a lesser extent by the model than was that of the DO, the proportion explained for 1990 data being 40.8% for temperature and 70.7% for DO.

The mean temperature or DO was found for each day by fitting the observed points on each day to the profile already chosen. The residuals were then calculated and inspected. One large residual was noticed for temperature, corresponding to a reading of 10°C for reach 2 on 26 September, 1990. This was removed from the data and the model re-calibrated. There was then only one residual exceeding 1 °C. For the DO model, the residuals were relatively larger, two exceeding 2 mg l^{-1}, but no suspect data values were identified.

Having obtained a simulated value for every day when values were observed, values for the remaining days were interpolated. Finally, annual, weekly and monthly summaries were obtained of the percentile distributions in each zone and of the total distances represented by zones having a given DO and temperature, or lethal combination of DO and temperature.

A similar excercise was carried out using data from the fixed stations. Whilst there was generally reasonably good agreement between the two models for DO, there were some differences between them with temperature for some years; maximum values for the fixed stations were lower than those for the boat-sampling data in 1987 and 1988, and slightly higher than them in 1990. The means for the two models are shown in Appendix I.

2.3. SALMON

Juvenile salmon have been stocked into the River Thames, many as marked or tagged parr and smolts (Table I) and, until 1990, have returned almost exclusively (95% of smolts and 92% of parr) as 1-sea-winter fish (grilse). In 1990, however, almost half of those trapped and aged were 2 sea-winter fish.

Table I. Annual numbers of salmon stocked as smolts and parr and annual percentage return as 1-sea-winter fish (grilse) in the R. Thames

Year	No. of smolts	% return[1]	No. of parr	% return[2]
1981	5000	1.5	45500	0.09
1982	2800	1.0	35800	0.10
1983[3]	7448	0.2	85937	0.03
1984	7810	0.3	73334	0.03
1985	22538	0.6	70565	0.06
1986	14500	0.1	79342	0.15
1987	28063	0.7	100703	0.06
1988	35165	0.1	108925	0.04[4]
1989	53521	0.1	-	-

1. In year of stocking plus one.
2. In year of stocking plus two.
3. The numbers are revised from Alabaster & Gough (1986).
4. The figure is revised from Alabaster, Gough & Brooker (in press).

The total return of smolts has ranged up to 1.68%, depending upon the batches used, whilst that of parr has been up to 0.16%. An angular transformation was used to normalise the distribution of some of the data on the percentage return (Bartlett, 1947).

The passage of the fish through the estuary from 1983 onwards was estimated from the number intercepted at the trap at Molesey; returns during 1982 and early 1983 were estimated from electric fishing at the trap site, prior to its construction. The annual, monthly and weekly totals were expressed as the percentage return of parr and smolts as grilse and 2-sea-winter fish. The monthly and weekly totals were also used both un-transformed and after being changed in one of two ways, each to avoid the bias caused by numbers being greatest during the middle of the season. First they were expressed, for each period, as a proportion of the average for all years from 1984-1989 and, in some cases, normalised for annual variations. Secondly, they were expressed, for each year, as a cumulative percentage over the season, and then further transformed to units of standard deviation (probit units) so that the increment in each week - i.e. the rate of migration - could be expressed as probits per day. These measures of the fish counts were used as dependent variables in linear multiple regression analyses, using freshwater flow, DO, water temperature, salinity and tidal height as independent variables. Unless otherwise stated, variables were included in the stepwise regression only if they were significant at $P > 0.05$.

3. RESULTS

3.1. WATER QUALITY AND FLOW

Table II. Median minimum DO and median maximum temperature over different lengths of the Thames Estuary in July-September (from the boat-run data), and median average daily freshwater flow (ADF) at Teddington

Year	DO (mg l^{-1})			Temperature (°C)			Median ADF
	1km	10km	40km	1km	10km	40km	(m^3 s^{-1})
1982	3.8	4.1	4.8	20.3	20.2	19.9	15.7
1983	3.5	3.7	4.6	21.5	21.6	21.2	16.5
1984	3.6	3.8	4.9	22.5	22.3	21.0	9.9
1985	3.2	3.5	5.5	18.9	18.7	18.3	26.9
1986	2.8	3.0	4.2	19.9	19.6	18.7	19.7
1987	1.8	2.0	3.8	19.8	19.7	19.2	18.0
1988	3.0	3.2	3.9	19.4	19.3	19.0	20.3
1989	2.2	2.6	3.9	22.2	21.9	21.0	8.1
1990	3.7	3.9	5.1	20.2	19.9	19.8	4.6

The overall water quality in the Thames estuary in July to September, 1982-1989, together with the river flow, is summarised in Table II.

The median DO and temperature have been compiled as before (Alabaster

& Gough, 1986) by calculating the percentile frequency distributions for each station, plotting the median against distance, and interpolating the length of estuary at that value. In general, the DO has been low, especially in 1987, whilst the temperatures have been relatively high, especially in some years when river flows have been low, as in 1984 and 1989.

3.2. SALMON

The total numbers of salmon caught or found in the river in 1982-1989 are shown in Table III. They were generally rather low, but in 1988 a relatively high number was trapped and electric fished, despite a relatively low DO in July to September; perhaps the high number is attributable to the relatively low temperature and relatively high river flow that prevailed.

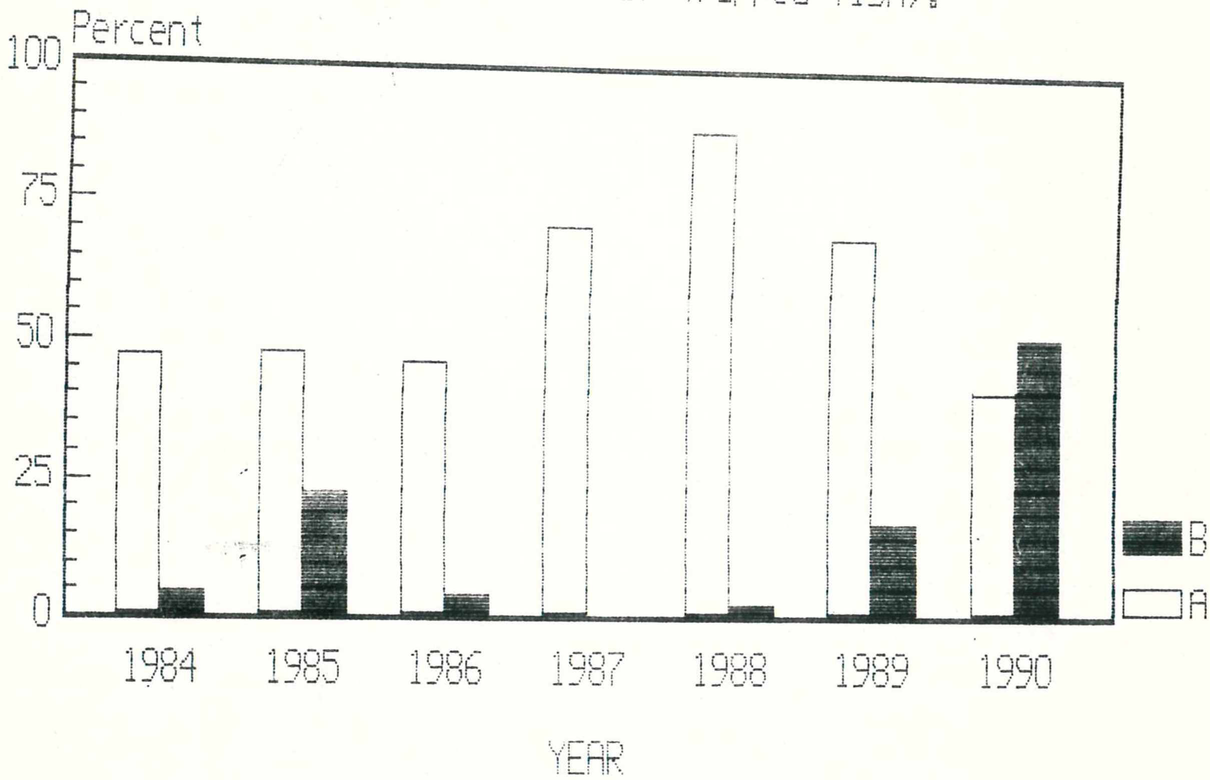
Table III. Annual numbers of adult salmon in the River Thames (total numbers of 2-sea-winter fish shown in parenthesis)

Year	Alive (trapped or angled or electric fished)	Found dead or moribund	Total
1982	122	6	128
1983[1]	74	16	90
1984[1]	103	3	106(2)
1985	69	6	75(8)
1986	157	19	176(3)
1987	47	11	58
1988	316	7	323(5)
1989[2]	122	10	132(15)
1990	147	7	154(32)
Total	1157	85	1242(65)

1. The numbers are slightly revised from Alabaster & Gough (1986)
2. The numbers are slightly revised from Alabaster, Gough & Brooker (in press).

Those trapped and aged in 1984-1990 comprised only about half (63%) of the total from all sources of all ages and, of these, only a small proportion was 2-sea-winter fish, except in 1990 (Fig. 1).

Fig.1. Trapped salmon, 1984-1990. A, 1- and 2-sea-winter fish (% fish from all sources and ages). B, 2-sea-winter fish (% 1- and 2-sea-winter trapped fish).



The monthly distribution of trap catches over the whole period is shown in Fig. 2. The 2-sea-winter fish tended to arrive about one month earlier than the grilse, the maxima occurring in July and August, respectively. Their distributions were approximately normal.

As with the overall monthly distribution (Fig. 2), the cumulative percentage of grilse trapped during each year (1984-1990) was approximately normal, but correlation coefficients were significant for monthly accumulated data only for 1984 ($P = 0.025-0.01$) and 1985 ($P = 0.05-0.025$), using the test for normality of Filliben (1975). This may be due to the fact that the DO's during these two years were the highest of the period (Table II) and therefore caused fewer perturbations in the rate of migration than the lower DO's during the rest of the time. None of the correlation coefficients for the distributions on a weekly cumulative basis was significant, presumably because of perturbations in the rate of migration caused by short-term fluctuations in environmental factors. The same applies to the coefficient for cumulative daily catch, which was calculated for 1988 when the largest number of fish was trapped.

3.3. ANNUAL PERCENTAGE RETURN OF PARR AND SMOLTS AS GRILSE

The percentage return of parr and smolts as adults is the best measure of the run of fish in trying to relate the passage of fish to environmental factors in different years, since it takes account of the different availability of fish in different years.

3.3.1. 3-month period, July-September, 1982-1990

The annual total percentage return of parr and smolts as grilse in 1982-1990 (Table I), and their return in the summer months, both tended to increase with the DO and flow, and to decrease with the temperature, as expressed in Table II, although generally not significantly. The exception was for the logarithm of return in July to September, which was positively correlated with the logarithm of median flow in the same period ($P = 0.01-0.001$). The equation is:

$$\log_{10} P_{j-s} = -2.975 + 1.953 \times \log_{10} F_{j-s} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where P_{js} is the percentage return of parr and smolts as grilse in July-September and F_{j-s} is the median ADF in the same period. It accounts for 0.64 of the variance, but other factors are probably also important since the residuals of the variances were not distributed normally (Filliben, 1975). The relationship indicates that, overall, the percentage return was average (0.33%) at a flow of 19 $m^3 s^{-1}$, was

Fig.2. Percentage distribution of salmon trapped in 1984-1990. A, 1-sea-winter fish. B, 2-sea-winter fish.

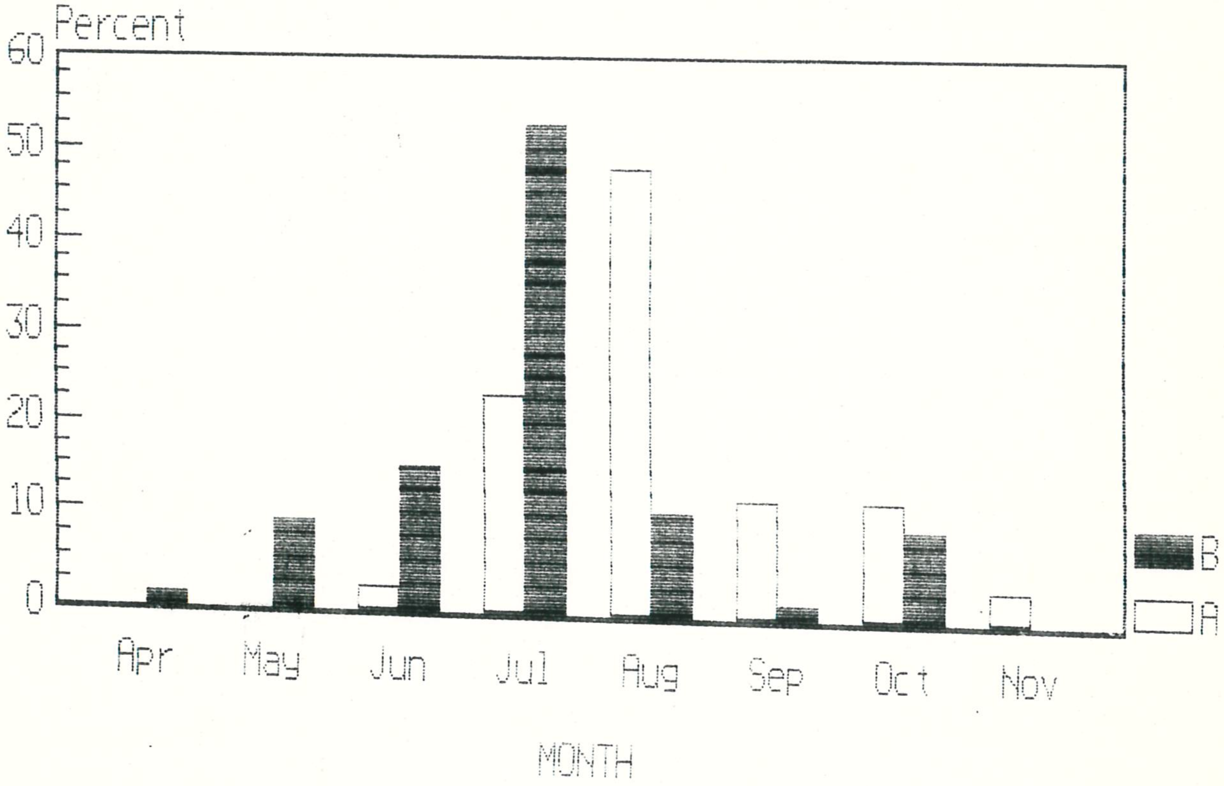
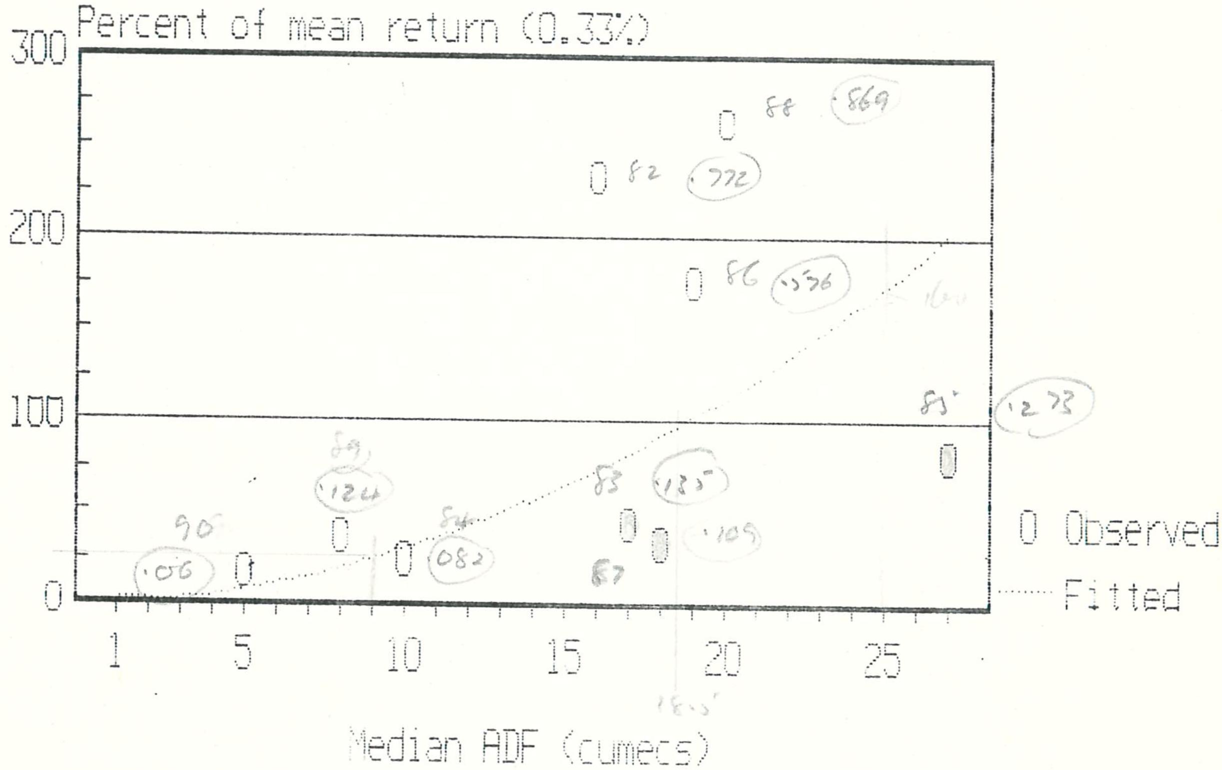


Fig.3. Annual percentage return of parr and smolts as trapped grilse in July to September in relation to median average daily flow (ADF) at Teddington.



reduced to 10% of the average at 6 m^3 s^{-1} and to 1% of the average at 2 m^3 s^{-1}; it is illustrated in Fig. 3.

The returns of parr were very much smaller than, and poorly correlated with those of smolts, and their exclusion from the regression made a small difference to the results.

Exclusion of data for 1982, when there was no trapping, and for 1983, when trapping started in July, made little difference to the results, as is to be expected with caculations based upon a 3-month period.

All the results are summarised in Table IV.

Table IV. Regression of $\log_{10}$ annual percentage return of parr and smolts as grilse in July to September on $\log_{10}$ ~~mean~~ ADF (m^3 s^{-1}) median

*, P = 0.05-0.01; **, P = 0.01-0.001

Intercept	Regression coefficient	Variance accounted for (r^2)	Notes
		1982-1990	
-2.975	1.953	(0.64)**	(1)
-2.583	1.734	(0.56)*	(2)
-2.596	1.734	(0.60)*	(3)
-3.591	2.355	(0.61)*	(4)
		1983-1990	
-2.960	1.881	(0.70)**	
-2.568	1.665	(0.61)*	(2)
-2.581	1.663	(0.60)*	(3)
		1984-1990	
-2.978	1.920	(0.72)*	
-2.565	1.658	(0.60)*	(2)
-2.586	1.675	(0.60)*	(3)

(1) Plotted in Fig. 3.

(2) Including fish of unknown age in freshwater, assuming an average percentage return for a given year.

(3) Including fish of unknown age in freshwater, assuming the proportion and percentage return of those of known age in a given year.

(4) Excluding parr-derived smolts.

Of the grilse that were trapped, some (19%) were of unknown age in freshwater. An attempt was made, therefore, to allow for these fish by assuming that their rate of return was 1) at the average for all fish of known freshwater age in the year of return, and 2) in proportion to the proportions of grilse of parr and smolt origin, and their respective rates of return in the year of return. These allowances also made little difference to the results. (Table 10)

3.3.2. 4- and 8-weekly periods in July-September, 1982-1990

When the months of July to August were considered together in pairs, the logarithmic relation found with flow for the 3-month period, July to September was not evident, except for August and September, combined (P = 0.05-0.01). The equation is:

$$\log_{10} P_{a-s} = -0.132 + 1.624 \times \log_{10} F_{a-s} \quad \text{....................(3)}$$

where P_{a-s} is the percentage return in August and September and F_{a-s} is the corresponding average ADF in $m^3 s^{-1}$. It accounts for only 0.33 of the variance and is illustrated in Fig. 4.

Similar results were obtained excluding 1982, and both 1982 and 1983; for these two cases, respectively, the intercepts are -0.159 and -0.165, the constants of proportionality are 1.606 and 1.629, and the variances accounted for are 0.35 and 0.36, which are much lower than those for the 3-month period given in Table IV.

When all 4-weekly periods were combined, weak relationships were found between the percentage return, expressed as a percentage of the mean for a given week over the 9-year period (and normalised for year) and the length of estuary at a 90%ile value of 1) borderline lethal combinations of DO and temperature (according to Equation 1), and 2) temperatures of 21.5°C. Much more significant results were obtained when September was considered alone, particularly for temperature. The results are summarised in Table V. The equation for 1982-1990 indicates that a nil return of fish is obtained when the distance is 69.8 km. This is illustrated in Fig. 5. A similar result is obtained excluding 1982 and 1983. **It may be noted that the flow in September was 14.1 $m^3 s^{-1}$, which is rather lower than for the 3-month period as a whole, and that a different relationship might be appropriate at a different range of flows.**

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Fig.4. Annual percentage return of parr and smolts as trapped grilse (August and September in relation to median monthly average daily flow (ADF) at Teddington.

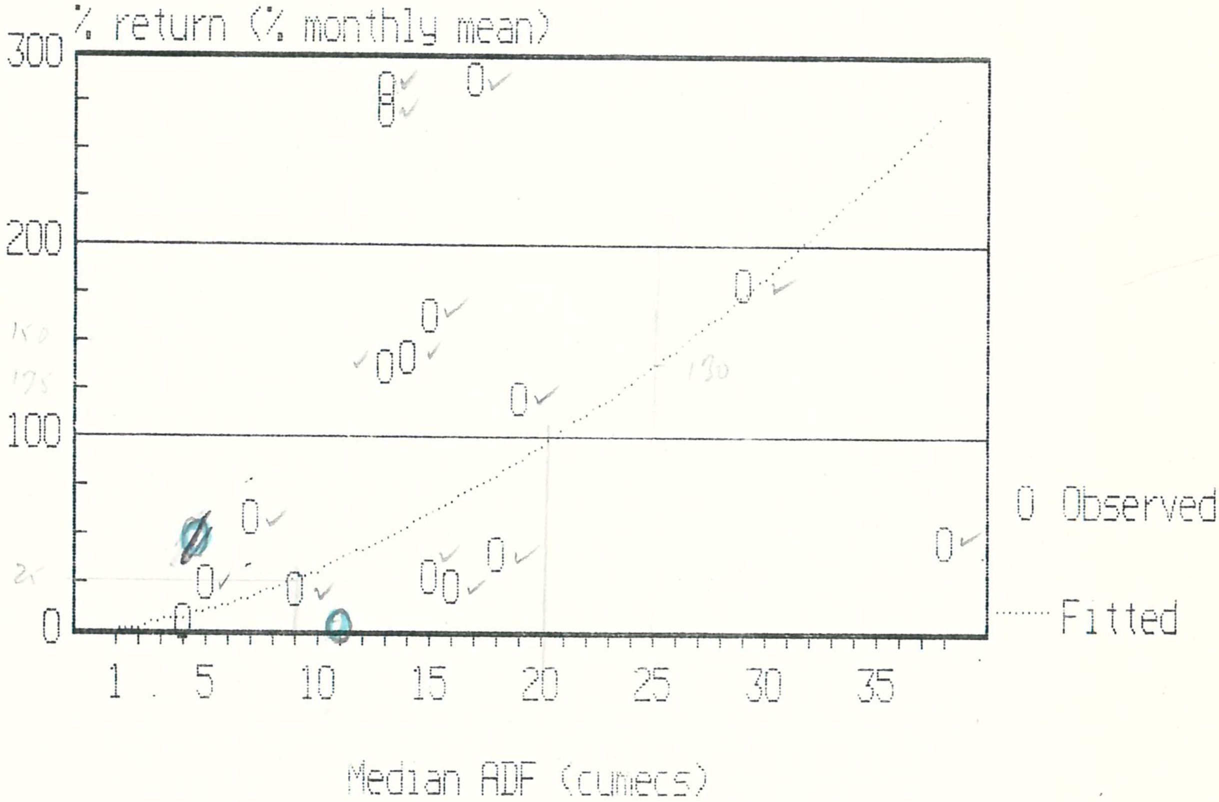


Fig.5. Annual % return of parr and smolt as trapped grilse in September in relation to the length of Estuary at a 90%ile lethal combined DO & temperature.

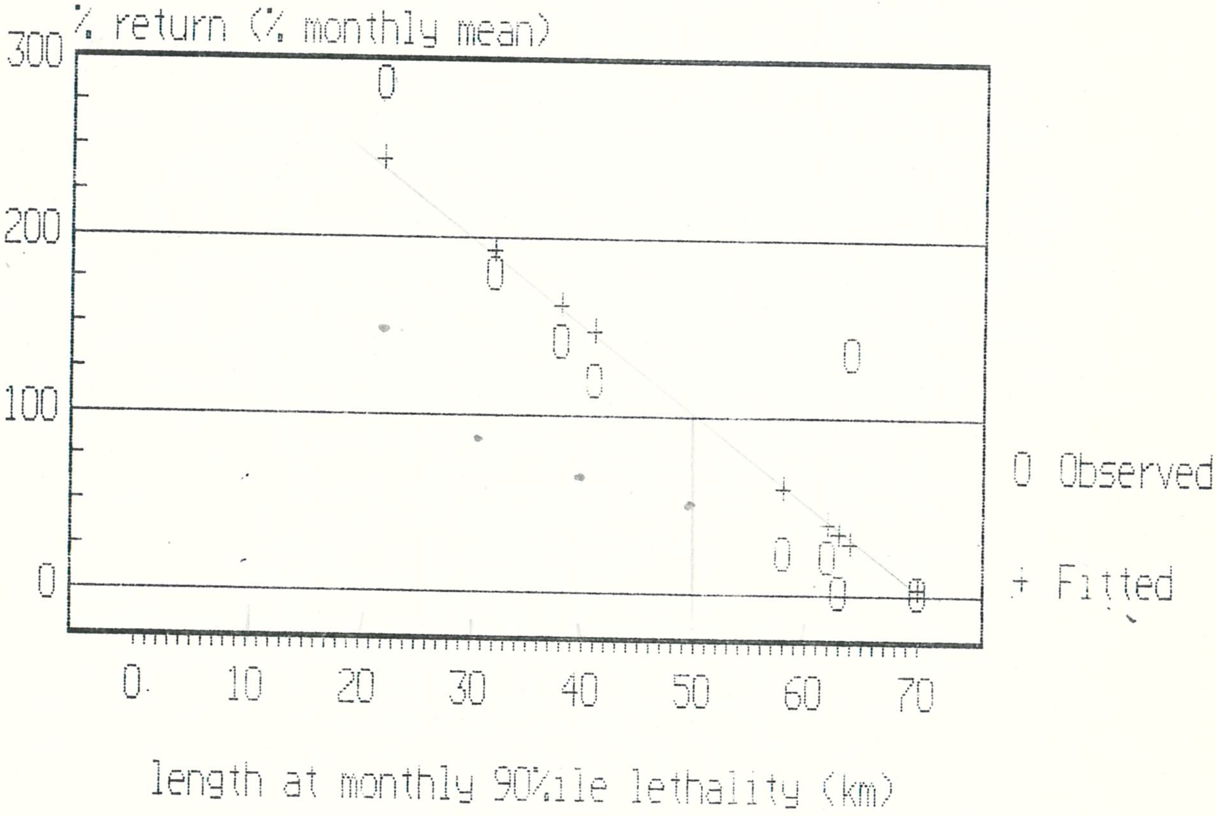


Table V. Linear multiple regression of return of parr and smolts as grilse in all 4-weekly periods in July-September, 1982-1990, as a percentage of the respective means for all years and also normalised for month of year. *, P = 0.05-0.01; **, P = 0.01-0.001; ***, P < .001; N.I., not included in regression (variance accounted for is shown in parenthesis)

Intercept	REGRESSION COEFFICIENT: Length at 90%ile lethality of zero	REGRESSION COEFFICIENT: Length at 90%ile temperature of 21.5°C	Distance for no return (km)	Notes
	July, August & September, 1982-1990			
130.5	N.I.	-0.922(0.14)*	141.5	
5.2	-2.074(0.18)*	N.I.		(1)
	August & September, 1982-1990			
292.6	-3.578(0.32)*	N.I.	82.9	
	September, 1982-1990			
354.9	-5.087(0.77)**	N.I.	69.8	(2)
4.43	-2.64 (0.51)*	N.I.		(1)
1.95	N.I.	-1.371(0.80)**		(1)
	September, 1983-1990			
381.5	-5.917(0.96)***	N.I.	64.5	
9.33	-4.76 (0.71)**	N.I.		(1)
	September, 1984-1990			
9.05	-4.62 (0.71)*	N.I.		(1)

(1) Logarithmic units used.

(2) Plotted in Fig. 5.

3.3.3. 4-weekly periods in July-September, 1987-1990

An analysis was carried out on the data collected at the seven fixed sampling points in 1987-1990. The lowest weekly 95%ile DO values of all the stations in each week were averaged for each calendar month, together with the corresponding 5%ile water temperatures. The latter are often, but not necessarily, the highest 5%ile temperatures, because the highest temperatures are not necessarily correlated with the lowest DO's. The reasoning behind these choices was that, although the fish were likely to be affected where the DO was at a minimum and the temperature at a maximum, any successful passage of fish at such locations would probably occur when the DO was at the upper end of its range, whilst the temperature was at the lower end of its range. The median monthly daily average freshwater flow was also calculated. A significant result was obtained with flow and DO (P = 0.05-0.01 in both cases), which accounted for 0.34 and 0.36 of the variance, respectively, according to the following equation:

$$P_m = -4.836 + 0.095 \times F_m + 1.207 \times DO_m \quad \text{.....................(5)}$$

where P_m is the 4-weeky percentage return (expressed as a percentage of the corresponding 4-weekly mean for the period 1982-1989), F_m is the corresponding mean ADF, as $m^3 s^{-1}$, and DO_m is the corresponding mean of the lowest weekly 95%ile DO's in any of the fixed stations.

Equation 5 indicates that, at the mean 4-weekly ADF of 12.7 $m^3 s^{-1}$ that prevailed during the period, the percentage return was average at a minimum 95%ile DO of 3.58 mg l^{-1}, and nil at 3.01 mg l^{-1}.

It also shows that as the DO is reduced, the return is more affected by low flows; at 3.5 mg l^{-1}, for example, the return is average at 15.2 $m^3 s^{-1}$ and zero at 6.5 $m^3 s^{-1}$, whereas at 3 $m^3 s^{-1}$ it is average at 20.2 $m^3 s^{-1}$ and zero at as high as 12.7 $m^3 s^{-1}$.

3.3.4. Weekly periods

Over the whole period 1982-1990, using the boat-run data, there was no significant correlation of weekly return of grilse with temperature and DO, or with river flow and tidal height, perhaps because too few water samples were taken, averaging only about a score per week for most of the period.

For the years taken singly, only 1982 showed a significant positive correlation between the weekly return and river flow (P = 0.01-0.001) accounting for 0.63 of the variance, the equation being:

$$P_w = -3.237 + 0.376\ F_w \quad \text{....................................(6)}$$

where P_w is the weekly return as a proportion of the average and F_w is the corresponding weekly mean ADF. **It indicates a zero return at a flow of 8.6 $m^3 s^{-1}$.**

Only 1985 showed a significant positive correlation with tidal height (P = 0.05-0.01) accounting for 0.51 of the variance, the equation being:

$$P_w = -12.28 + 3.44\ H_w \quad \text{....................................(7)}$$

where H_w is the average weekly tidal height in metres.

For the years 1987-1990, however, using data from the fixed stations, a significant correlation was found for the return of grilse with both river flow and the minimum 95%ile DO at the station chosen as having the lowest DO (P = 0.01-0.001 in both cases), the amount of the variance being accounted for being 0.18 and 0.12, respectively. The equation is:

$$P_w = -2.675 + 0.069 \times F_w + 0.703 \times DO_w \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

where the symbols are as in Equations 6 & 7.

This equation is similar to Equation 5 for 4-weekly rates of return, but the flows at which the return is zero are slightly lower; that for a DO of 3 mg l^{-1} is 8.2 $m^3 s^{-1}$ compared with 12.7 $m^3 s^{-1}$, whilst that for 3.5 mg l^{1} is 3 $m^3 s^{-1}$ compared with 6.5 $m^3 s^{-1}$.

Somewhat similar results were obtained for the relation between the return of grilse and the 50%ile and 95%ile values for the differences between the observed DO's and the lethal values calculated from Equation 2, although the amount of the variance accounted for and the level of significance were generally lower.

3.3.5. Whole year

Grilse continued to be caught from October to December, and the total percentage return of smolts as grilse for the whole year followed the same trend as that for July to September, suggesting that, when a below-average return was obtained in the summer, it was not necessarily compensated for at the end of the season. Since the return of different strains of fish is likely to be different in terms of both percentage and timing (Bailey & Saunders, 1984), a comparison has been made between the total return for the year of the stock of smolts from the Cynrig Hatchery, which was used in all years except 1987, 1988 & 1990, and the corresponding return in July to September. There was a significant relation between the two (P = 0.05), accounting for 0.86 of the variance, the equation being:

$$P_y = 0.27 + 1.86 \; P_{j-s} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

where P_y is the total return for the year and P_{j-s} is the return in July to September.

This equation implies that, were the return in the summer nil, the return for the year would be only 27% of the average observed in the period 1982-1989 (15-40% based on the Standard Error).

3.3.6. Summary

The annual return of parr and smolts as grilse in July to September, 1982-1990 was reduced with reduction in freshwater flow at Teddington and was not fully compensated for during the rest of the year.

Within the period 1984-1990, the monthly return in September was reduced with an increase in the extent of the estuary at which the DO and, particularly, temperature were borderline for the survival of salmonid fish.

Within the period 1984-1990 the weekly return in July to September was reduced with reduction in both flow and the minimum 95%ile DO at the fixed monitoring station having the lowest values.

3.4. PROPORTIONAL CATCH FOR THE PERIOD, 1982-1990

Although the percentage return of parr and smolts is the best measure of the runs of fish, the total number of adults captured on their upstream migration can provide additional information when normalised for annual variation. The present analysis is restricted to monthly and weekly values for the years 1987-1990, expressed as a percentage of the mean for 1982-1990 in order to make some allowance for the variation in catches during the season.

3.4.1. 4-weekly periods

For 4-weekly data, the mean ADF accounts for 0.36 of the variance ($P = 0.05-0.01$), whilst the lowest weekly 95%ile DO of all fixed stations also accounts for 0.36 of the variance ($P = 0.01-0.001$); the equation is as follows:

$$C_m = -7.27 + 0.145 \times F_m + 1.821 \times DO_m \quad \text{.......................(8)}$$

the symbols being analagous to those in Equation 5 for percentage return. The results for Equations 5 and 9 are quite similar. **The flow at which the catch is zero, for a DO of 3 mg l^{-1}, is 12.5 $m^3 s^{-1}$ compared with 12.7 $m^3 s^{-1}$, and for a DO of 3.5 mg l^{-1}, the flow is 6 $m^3 s^{-1}$ compared with 6.5 $m^3 s^{-1}$.**

Further normalising the catch data to try to allow for the variation between years gives the following result, which accounts for 0.56 of the variance ($P = 0.01-0.001$):

$$C_m = 0.06 + 0.058 \times F_m \quad \text{......................................(9)}$$

This indicates a nil catch at 1.03 $m^3 s^{-1}$.

3.4.2. Weekly periods

Over the whole period 1982-1990, there was no significant correlation of weekly return of grilse with temperature and DO, using the boat-run data, or with river flow and tidal height, perhaps because too few water samples were taken, averaging only about a score per week for most of the period.

For the years taken singly, only 1982 showed a significant positive correlation between the weekly return and river flow ($P = 0.01-0.001$) accounting for 0.63 of the variance, the equation being:

$$P_w = -3.237 + 0.376\ F_w \qquad (10)$$

where P_w is the weekly return as a proportion of the average and F_w is the corresponding weekly mean ADF. **It indicates a zero return at a flow of 8.6 $m^3\ s^{-1}$.**

This approach, therefore, supports in a general way some of the main conclusions on the effect of flow and DO that were drawn from analysis of the percentage return of fish.

Only 1985 showed a significant positive correlation of catch with tidal height ($P = 0.05-0.01$) accounting for 0.51 of the variance, the equation being:

$$P_w = -12.28 + 3.44\ H_w \qquad (11)$$

where H_w is the average weekly tidal height in metres.

3.5. RATE OF MIGRATION WITHIN A SEASON

By assuming a normal distribution of intermittent catches of fish during the season, and expressing the cumulative number of fish trapped at intervals during the season as probit units, it is possible to describe the rate of migration without bias and thus to relate it to environmental factors. It's potential value for this purpose is greatest for short intervals of time.

3.5.1. Weekly periods

For the years 1987-1990 the rate of migration was significantly affected by flow; the relationship is shown in Fig. 6.

The results for the different years are summarised in Table VI.

Depending upon the year and number of years included in the regression, **the flow for a nil rate of migration varies from zero to 7.8 $m^3\ s^{-1}$**. This range brackets the corresponding values for weekly number of fish caught (Equation 9).

Fig.6. Weekly rate of migration of trapped Grilse in July to September in relation to mean weekly average daily flow (ADF) at Teddington, 1987-1990.

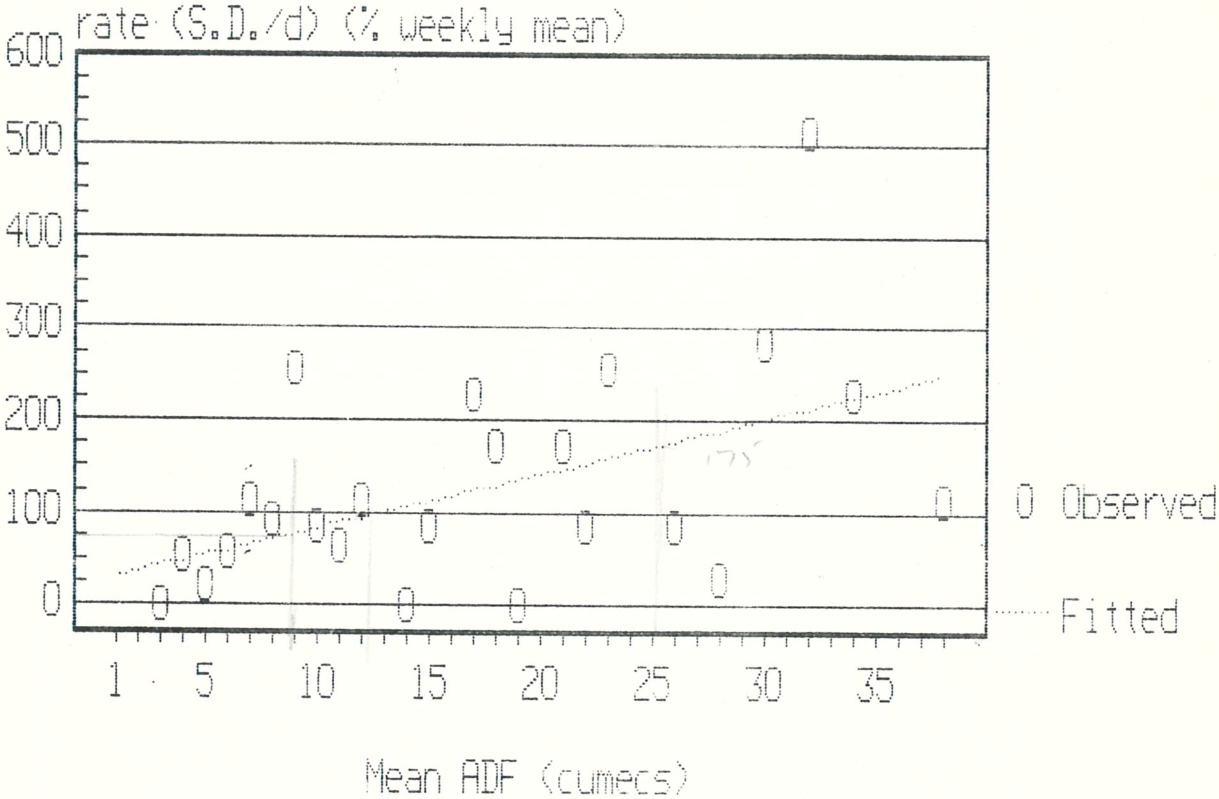


Table VI. Relation between weekly rate of grilse migration in the River Thames, July-September, 1987-1990 and average daily flow at Teddington. *, P = 0.05-0.01; **, P = 0.01-0.001; ***. P = <.001. The proportion of the variance (r^2) that is accounted for is shown in parenthesis

YEAR	Intercept	Regression coefficient	Flow for nil rate (m^3 s^{-1})
1988	-0.031	0.004(0.45)*	7.8
1988(1)	-0.045	0.006(0.53)**	7.5
1990	-0.029	0.13 (0.25)*	2.2
1987-1988	0.008	0.002(0.16)*	4.0
1988-1989	0.0	0.003(0.33)*	0.0
1987-1989	0.005	0.002(0.25)**	2.5
1988-1990	0.006	0.002(0.30)***	3.0
1987-1990(2)	0.008	0.002(0.26)***	4.0

(1) Lice-infested fish only

(2) Plotted in Fig. 6.

3.5.2. Daily periods

Generally, the daily trap catch data do not lend themselves to close analysis. This is because the values are often low or zero, or even missing because the trap was not visited every day, and also because the results are sometimes complicated by electric fishing carried out downstream of the trap. In 1988, however, there were many consecutive days when fish were trapped.

In that year, there was a marked tendency for lice-infested fish to be trapped on days close to the time of peak spring tides. Altogether, 82% were trapped when tides were higher than the mean of 3.88 m at Teddington, and a significant relation was found between the daily rate of migration and the maximum daily tidal height ($P < 0.001$) accounting for 0.67 of the variance, the equation being:

$$R_d = -0.874 + 0.239\ L_{max} \quad \text{.................................(11)}$$

where R_d is the daily rate of migration of lice-infested grilse and L_{max} is the maximum daily tidal height in metres.

It is likely that this factor also operated in other years to increase the variability of the results.

from July to September

3.6. CATCHES AND FLOW IN 1990

The impact of low flows on runs of fish can be illustrated by the daily record in 1990, when both flows and catches were at their lowest for the whole period studied, whilst the DO was relatively high and the temperatures relatively low. The situation in July to September is illustrated in Fig. 7, combining results for grilse and 2-sea-winter fish. Trap catches were low and sparse in July, and even more so in August. Electric fishing carried out below the trap at Molesey at the end of August showed that there had been a small accumulation of (14) fish, which had evidently passed through the estuary, but had not entered the trap. A subsequent electric-fishing at the end of September, after flows had remained very low, showed that there was virtually no further accumulation of fish. During this period, the rate of migration of grilse has been shown to fall off with reduction in flow (Table VI; third line). Subsequently, there were increases in flow in October, November and December, and more fish were caught, although a large proportion (63%) was electic-fished rather than being trapped (Fig. 8).

3.7. FISH MORTALITIES

Of the fish found dead or moribund (Table III), more than half were located in the tidal Thames, mostly in July when the greatest number of fish was trapped. The monthly totals for July each year, when expressed as a percentage of the total trapped and found dead, show some tendency to be highest for those months when the percentages of samples, predicted from Equation 2 as being potentially lethal, were also highest. The average mortality was 35% for the years 1986, 1987 and 1989, when the average frequency of lethal DO and temperature was 73%, whilst it was only 2% for the other years when the frequency was only 35%. Three fish were found dead in the estuary in August (in 1987 and 1989) when the frequency of potentially lethal conditions was 73%, whereas in the remaining years, with no mortality, it was only 41%.

4. DISCUSSION AND CONCLUSIONS

4.1. GENERAL INTERPRETATION OF RESULTS

There is considerable difficulty in describing, in reasonably simple terms relevant to the passage of fish, the information on environmental factors operating in the Thames estuary. This is due partly to the large temporal and spatial variations, coupled with a paucity of data on water quality, especially during some seasons when the highest temperatures and lowest DO's prevailed. Furthermore, there is great uncertainty about the timing and rate of passage of salmon through the estuary and into the fish trap, both of which determine the conditions to which the fish are exposed. There is also the problem of expressing the return of fish without bias when dealing with catches that tend to maximise during the middle of the season for a particular run of fish of a given sea-age. For these reasons, a large proportion of the variance in the catch or return of fish is expected to be unaccounted for by regression analysis.

4.2. RELATION BETWEEN RUNS OF FISH AND ENVIRONMENTAL FACTORS

The overall success of the regression analysis is summarised in Table VII in terms of the maximum variances that have been accounted for.

Table VII. Summary of the most significant and largest variances (r^2) accounted for in the regression analysis of the return of parr and smolts as grilse to the Thames estuary. *, P = 0.05-0.01; **, P = 0.01-0.001; ***, P<0.001

Period	Significant independent variable	Dependent variable: Percentage return	Proportion of mean catch	Rate of migration
July-Sept.	Flow	0.70**		
August-Sept.	Flow	0.36*		
Sept.	Temperature)	0.80**		
4-weekly(1)	Flow)	0.34*)	0.36*)	
	DO)	0.36*)	0.36**)	
	Flow		0.56**	
Weekly	Flow		0.63**	0.53**
	Flow)	0.18**)		
	DO)	0.12**)		
	Tidal height		0.51*	
Day	Tidal height			0.67***

(1) July to September

It shows that the percentage return of parr and smolts as adults, on a weekly, monthly and seasonal (July to September) basis, is correlated with flow. It also shows that catches and the rate of migration are correlated with flow on a weekly basis. Other significant environmental factors

Fig. 7. Daily flow and number of grilse and 2-SW salmon trapped and electric-fished at Molesey (July-Sept.) 1990.

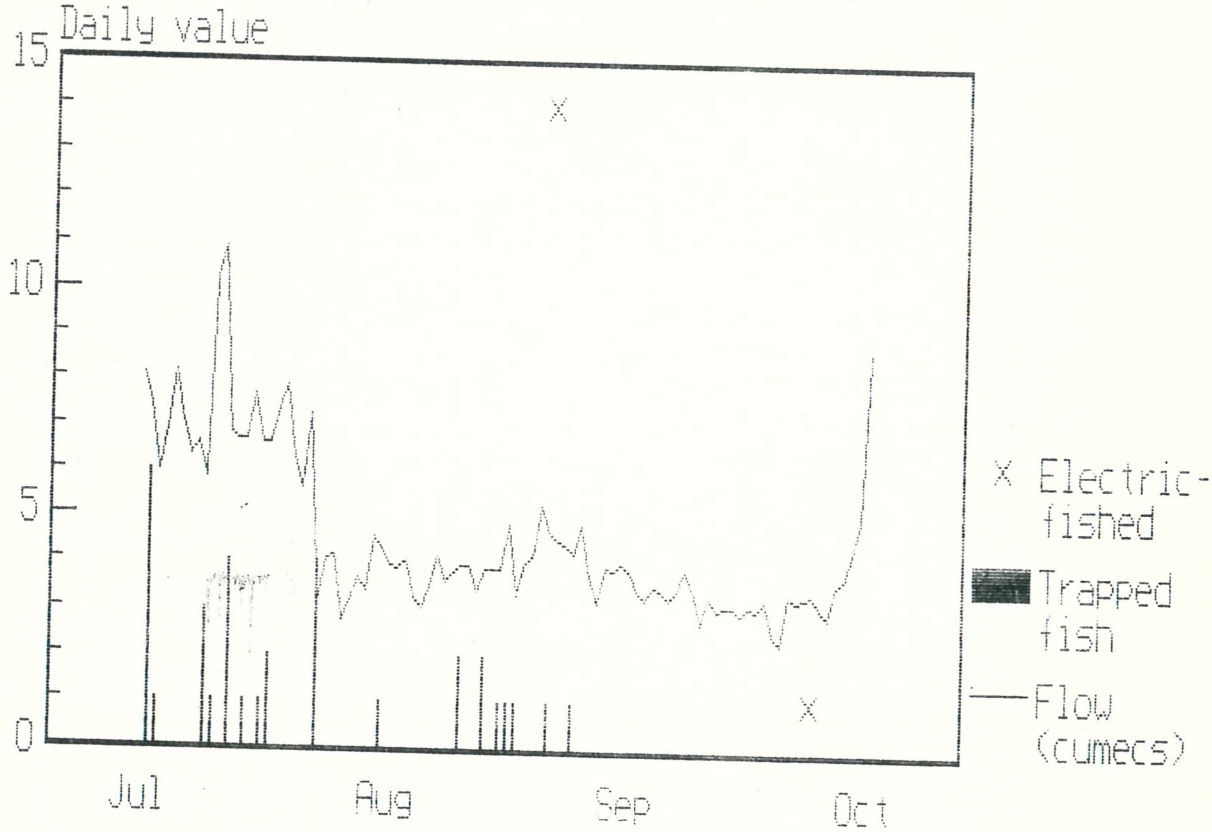
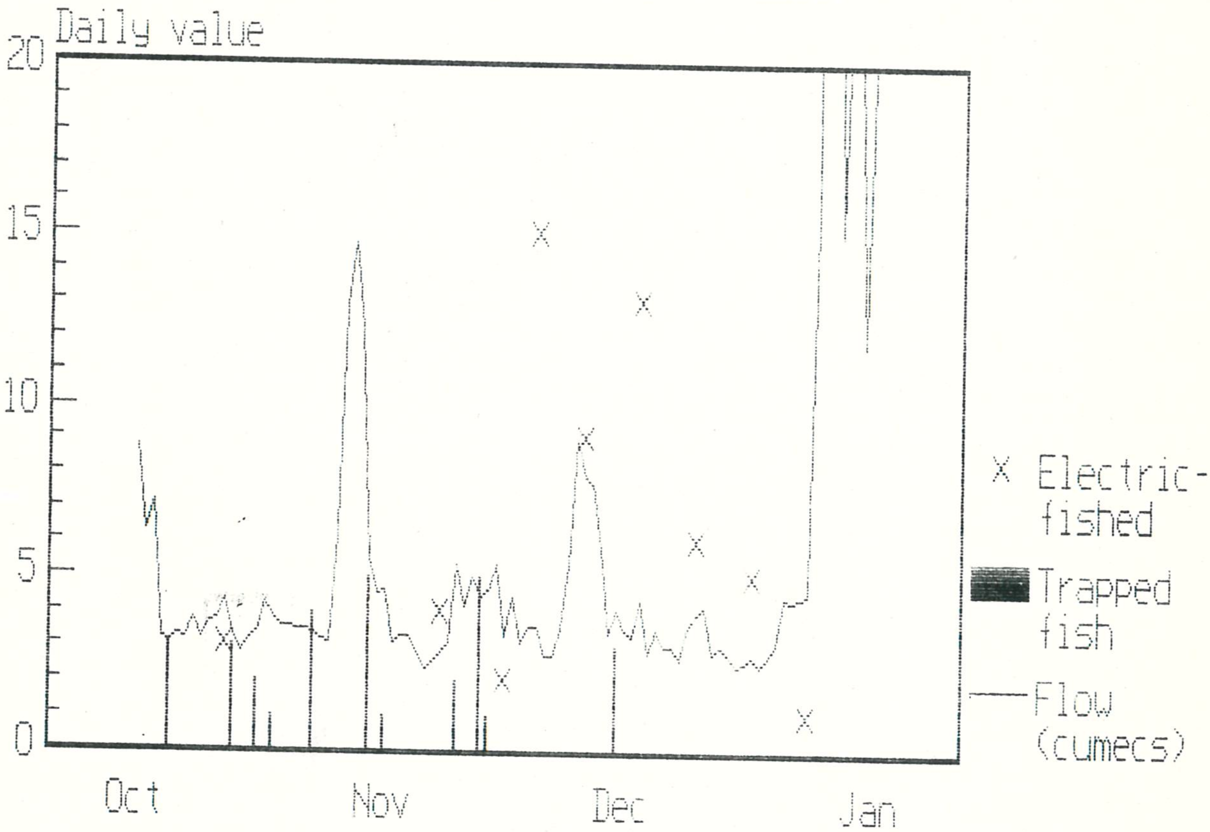


Fig. 8. Daily flow and number of grilse and 2-SW salmon trapped and electric-fished at Molesey (Oct.-Dec.) 1990.



identified are: water temperature, DO and daily tidal height, the first two of which are shown to interact with the effect of flow, the return being reduced by an increase in the length of estuary where given low DO's (<3 mg l^{-1}) and high temperatures (>21.5°C) prevail.

4.3. IMPACT OF LETHAL FACTORS

The relationships found with temperature and DO, and the mortalities of fish in the estuary, are consistent with the known lethal effects of high temperature, combined with low DO, and are probably causal in a general sense, bearing in mind that the values for which the correlations were found were accompanied by some much higher temperatures and much lower DO's.

4.4. VALIDITY AND PREDICTIVE VALUE OF CORRELATIONS

The importance of river flow in affecting the movement of fish into and within rivers is well established (e.g. Banks, 1969; Milner, 1990), and it is likely that this is the effect that has been detected in the present study, although it is possible that the amount of fresh-water entering at the head of the tide also had an effect in attracting fish into and through the estuary itself.

The rate of migration is often increased in the presence of increased river flow, but then may decline below the average. This is probably due to limited availability of fish to enter the river downstream of the point of measurement, as found with trap catches at the head of the tide on the River Coquet, Northumberland (Alabaster, 1970) and on the River Axe (Alabaster, 1989).

Furthermore, although a large proportion of the run may enter at relatively low flows during the summer, the total for the year may be reduced at very low summer flows. In the River Coquet, the annual total count of salmon was related to the total flow in the river (Alabaster, 1970); in the River Tywi, South Wales, there was a significant reduction in successful entry during the particularly dry summer of 1989 (Clarke **et al.**, 1991); the low catch of grilse in the River Frome in 1976 was thought to have been caused by low base flows (Welton **et al.**, 1989; Milner, 1990); and tracking of tagged salmon has demonstrated a reduced entry of fish into estuaries in the South of England at very low flows (D. Solomon, personal communication).

The present results for the Thames, relating salmon runs to river flow are, therefore, in general agreement with data for other rivers, although the influence of other factors in the Thames has been demonstrated.

Provided that future flow régimes in the Thames result from characterisics within the range of historical rainfall/run-off that obtained in the period 1982-1990, and that abstraction rates and estuarine temperatures and DO's also remain within the ranges used to establish the relationships between fish runs and flow, there is little doubt that similar relationships to those described in this report would continue to apply.

It should be noted that there is a very large scatter about the regressions of fish runs on environmental factors, as illustrated for flow and DO in Figs. 3-6. There would, therefore, be considerable error involved in making any precise predictions based upon these relationships.

ACKNOWLEDGEMENTS

The author wishes to acknowledge the help given by staff of the National Rivers Authority, Thames Region, particularly Mr. P. J. Gough, who supplied information on the fish stocking and recapture programme, and Mr. K. Farmer, who provided data on water quality, freshwater flow and tidal height. The author is also most grateful to Mr. W. J. Brooker (of Brooker and Garland) for developing the software necessary to interpret and summarise the data on water quality.

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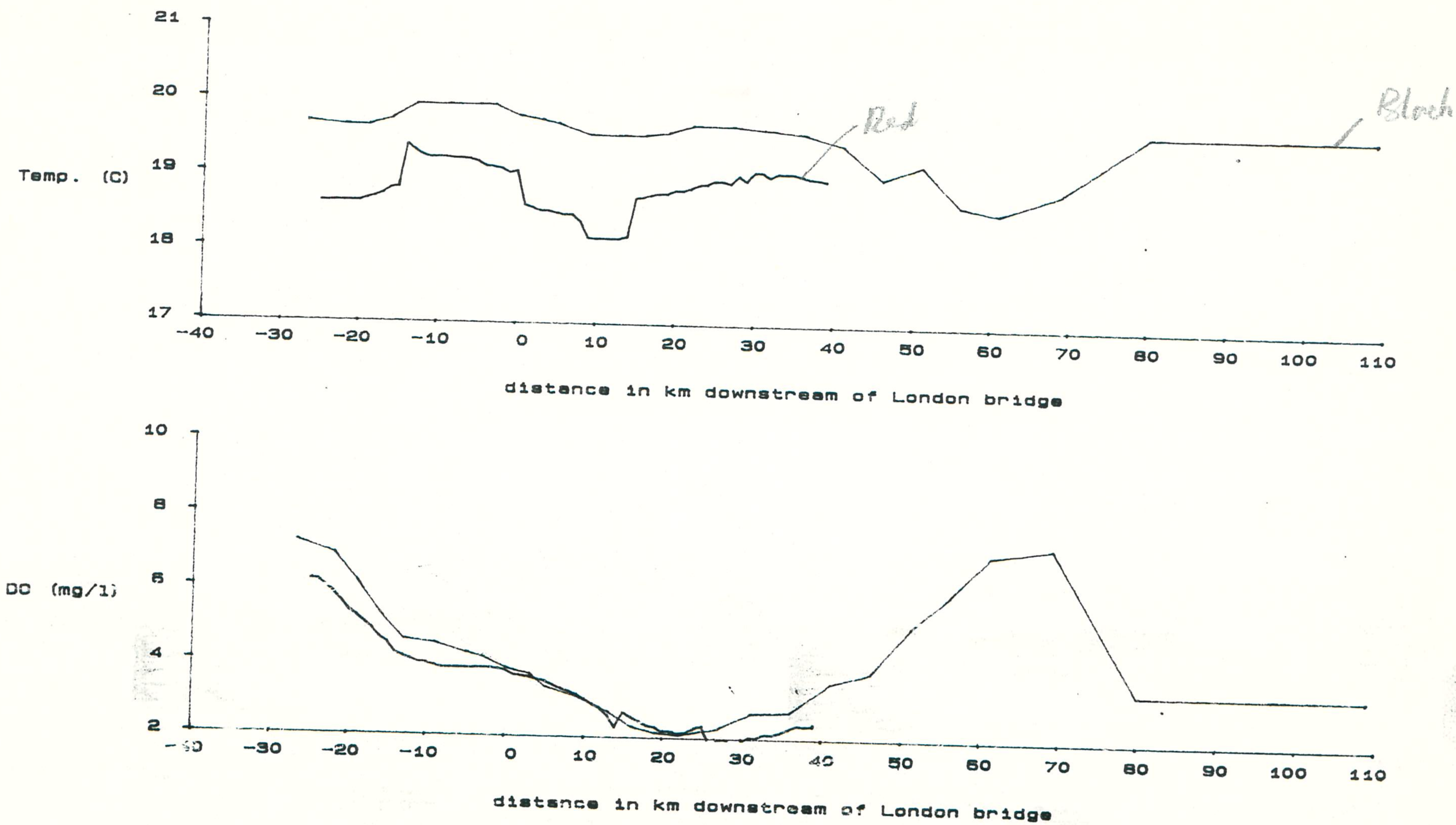
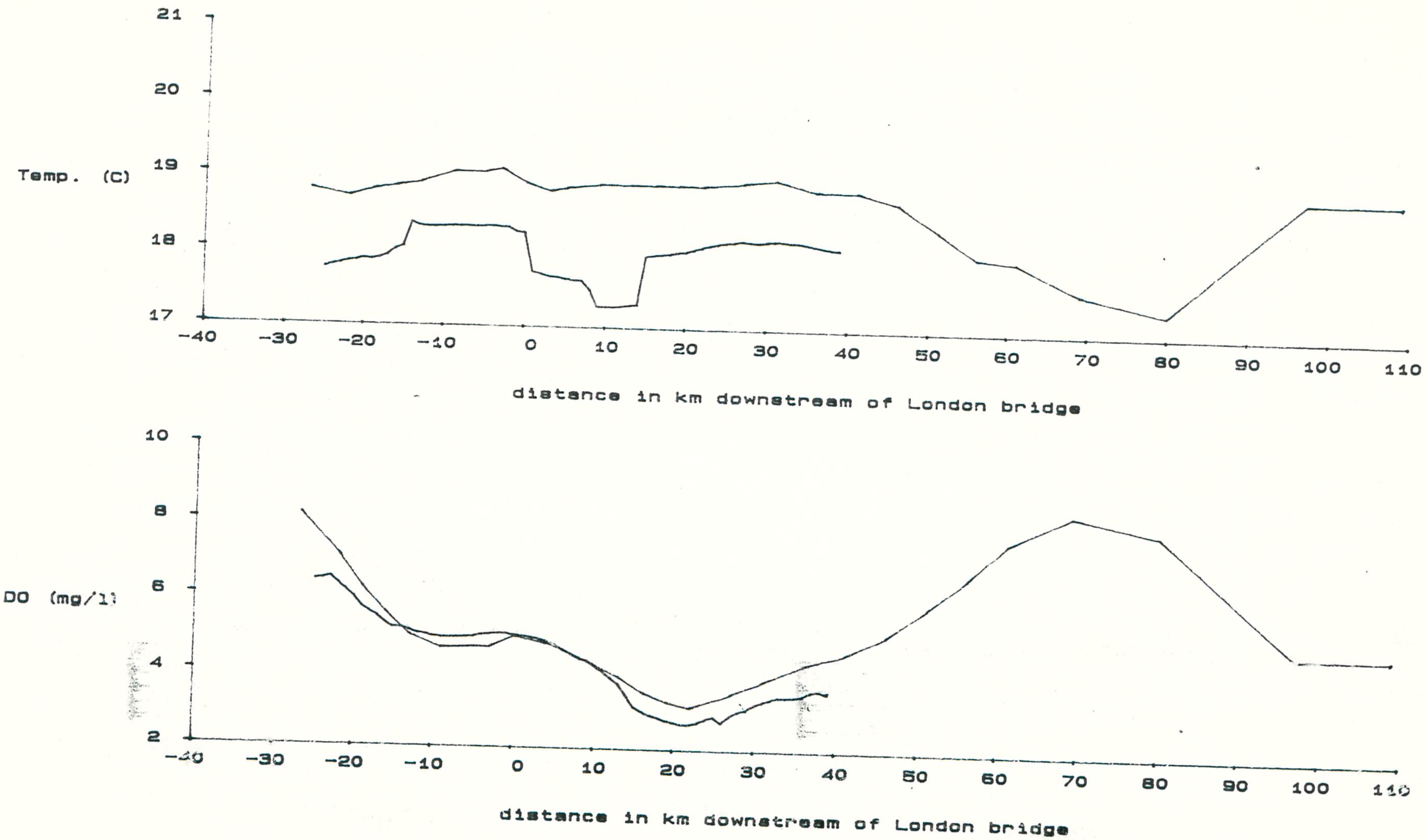
APPENDIX I

Comparison of mean DO and temperature from boat-run data (covering the whole estuary) and fixed station data (covering the middle reaches of the estuary) for 1987-1990

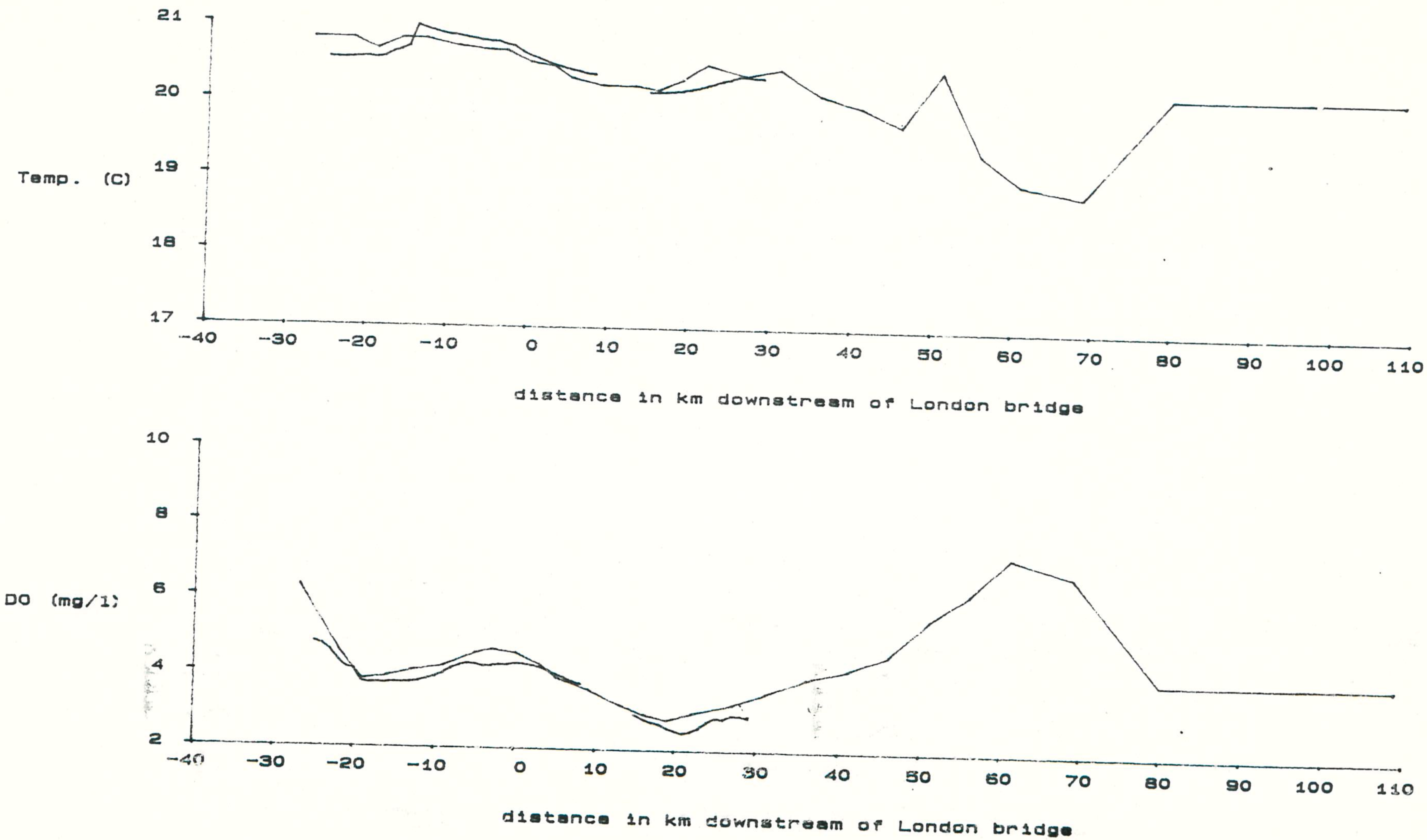


Comparison of means for July-September 1987. model for boat data (black). fixed site data (red)



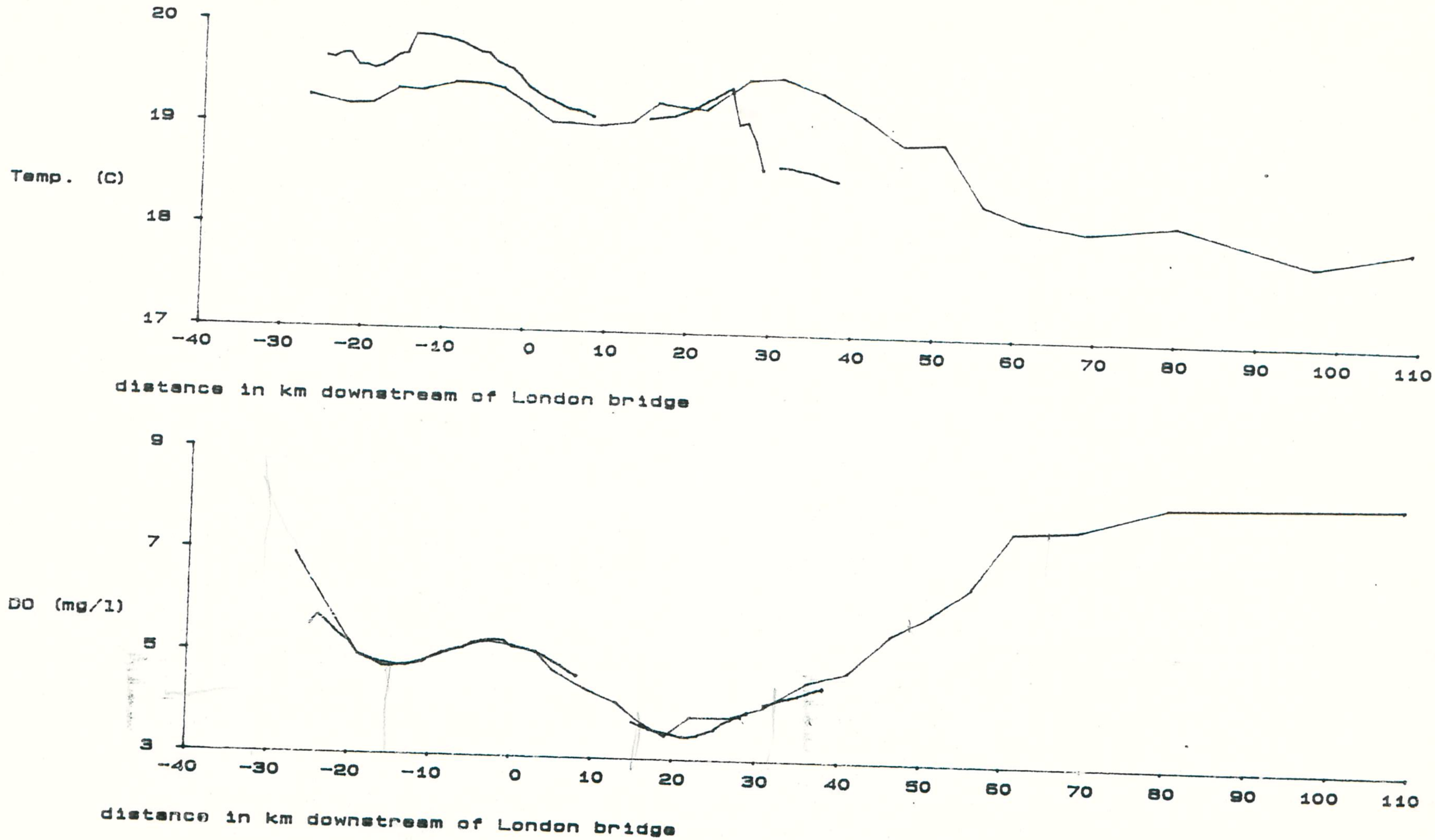
Comparison of means for July-September 1988, model for boat data (black), fixed site data (red)

30

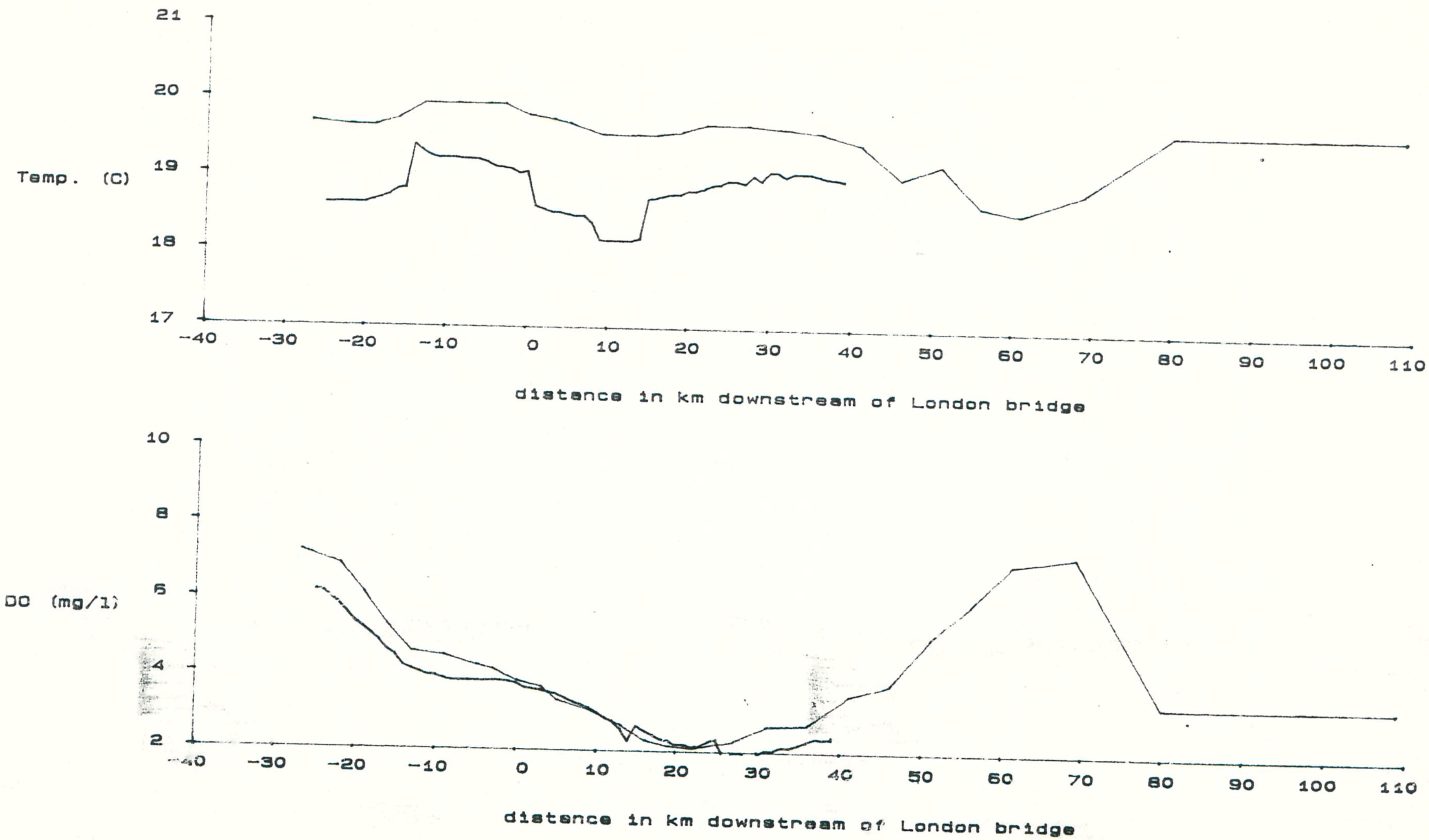


Comparison of means for July-September 1989, model for boat data (black), fixed site data (red)

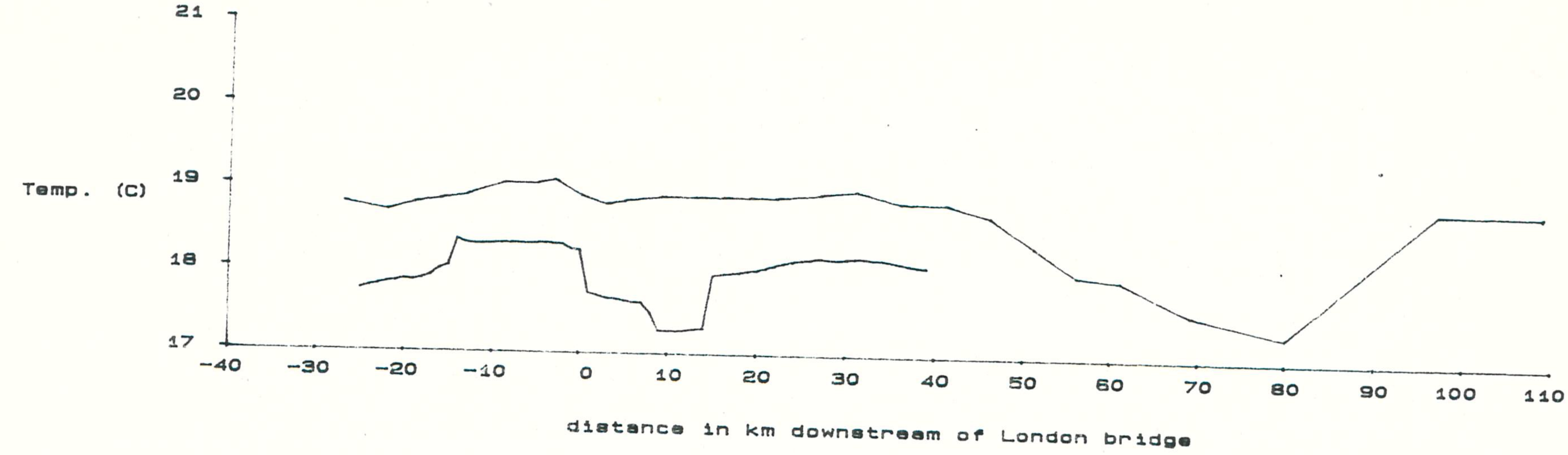
81

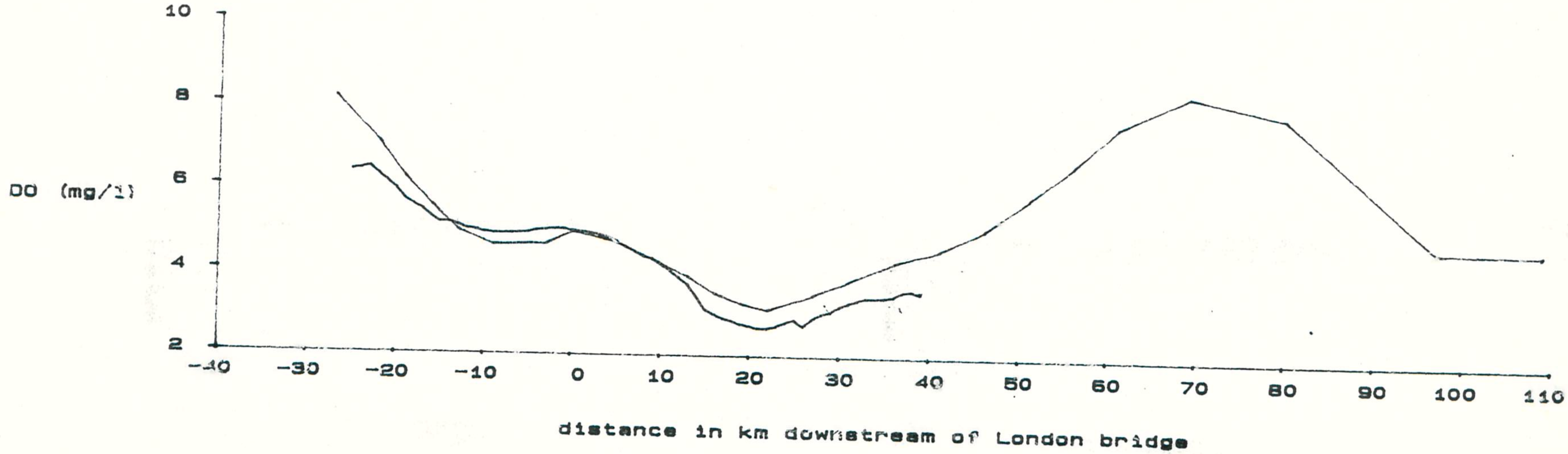


Comparison of modelled profile for boat data (black) with means for fixed site data, June-Sept. 1990

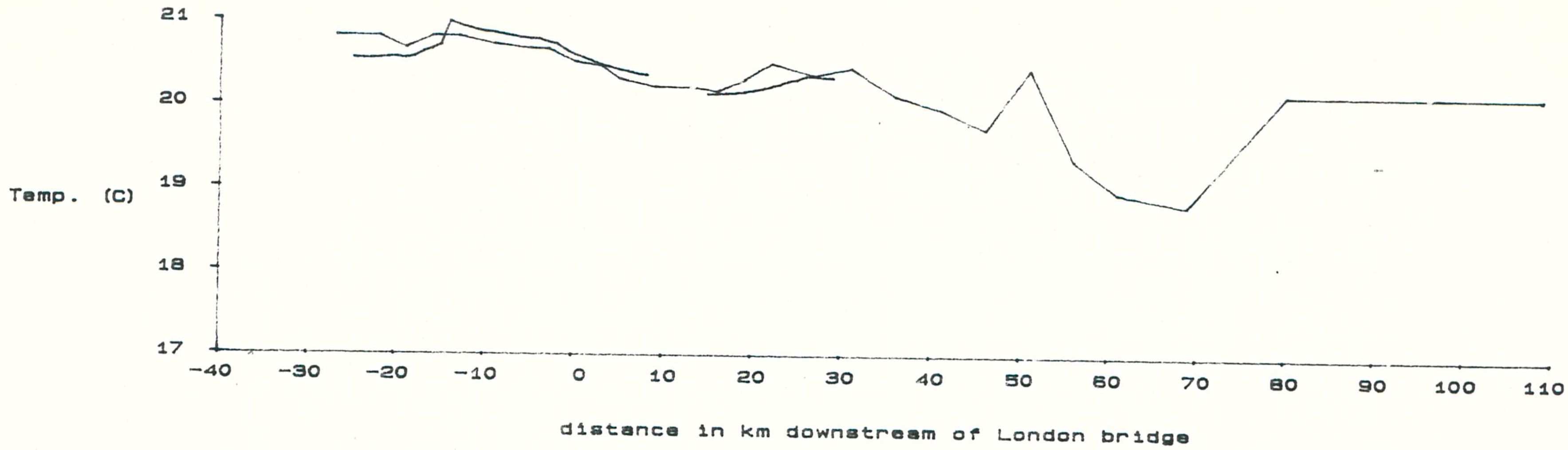


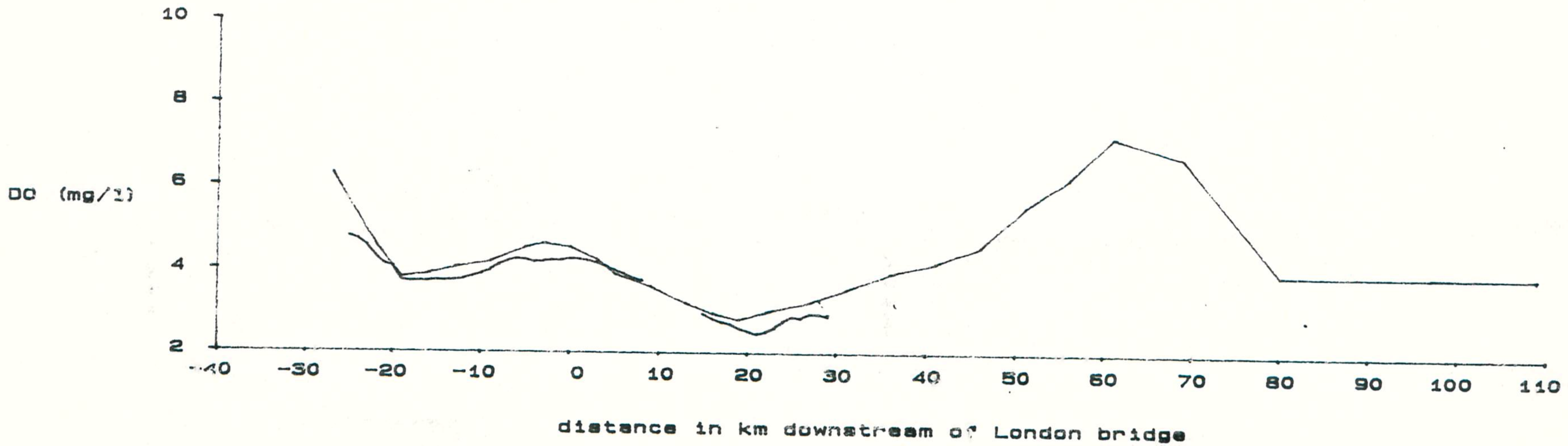
Comparison of means for July-September 1987, model for boat data (black), fixed site data (red)





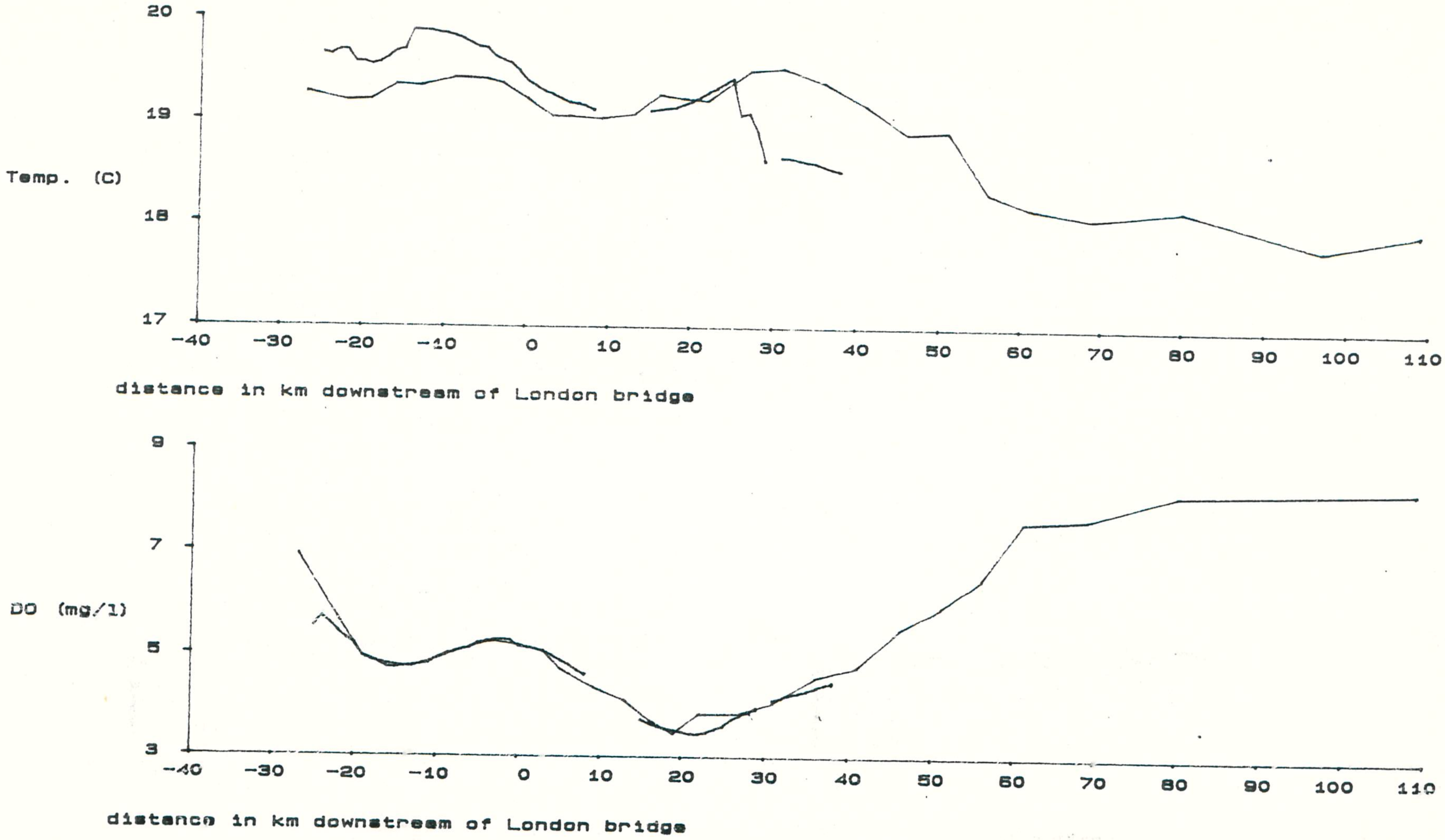
Comparison of means for July-September 1988. model for boat data (black). fixed site data (red)





Comparison of means for July-September 1989, model for boat data (black), fixed site data (red)

85



Comparison of modelled profile for boat data (black) with means for fixed site data, June-Sept. 1990