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EFFECT OF SUSPENDED SOLIDS ON SALMON

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The effect of suspended solids and dissolved oxygen on salmon (*Salmo salar*, L.) in the Parrett estuary, Somerset, UK

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The mortality of salmon in the Parrett estuary is correlated with maximum concentrations of suspended solids, which can reach 57,000 mg/l. However, the mortality was probably caused by low concentration of dissolved oxygen that were associated with high concentrations of suspended solids and exacerbated by high water temperature.

Key words: *Salmo salar*; suspended solids; dissolved oxygen; temperature

I. INTRODUCTION

It has long been known that many adult salmon (*Salmo salar*, L) are picked up dead in the estuary of the River Parrett, and has sometimes been assumed that they were suffocated by high concentrations of suspended solids (SS) in the water, as recorded for example, in evidence given to the Salmon Commissioners in 1902. At the same time, however, concentrations of dissolved oxygen (DO) are known to have been low and their over-riding lethal effect is suspected. Data on water quality and catches of dead and live salmon have, therefore, been examined to investigate the rôle of these two factors in the mortality.

II. MATERIALS AND METHODS

Relevant data on the concentrations of SS, DO, biochemical oxygen demand (BOD), water temperature, freshwater flow and annual fish catch and mortality in the estuary have been obtained from the South Western Region of the National RiverssAuthority. Informatiom on daily catches of

fish has been provided by a local fishermen, Mr. R. H. G. Thorne. Also, predicted tidal height at Bridgwater, computed by the Institute of Oceanographic Sciences, has been utilised.

WATER QUALITY

Data on the concentrations of SS are available for the estuary near the time of high water for the years 1971 (twenty-two daily surveys), 1972 (eleven surveys), 1977 (one survey), 1978 (two surveys) and 1992 (one survey). They enable the maximum concentration to be determined during high water at West Quay, Bridgwater, near the head of the estuary. One of the surveys in 1978 and the one in 1992 also cover the distribution of concentrations along the estuary during the tidal cycle.

Dissolved oxygen, expressed as percentage of the air saturation value (ASV), was measured over a tidal cycle during one to five surveys a year from 1962 to 1978, 1983 and 1992, making 39 surveys in all. Almost all surveys (31) also show the distribution of DO along the estuary during the tidal cycle. The average values of DO for the period 1963-1970 for each of six sampling stations between between 8 km upstream of West Quay and 20 km downstream are given in Table I, together with the overall average. The frequency and distribution of sampling was unequal between stations and between surveys and there were wide fluctuations during the tidal cycle; thus the figures give only a very general idea of the DO conditions in the estuary. More samples were taken at West Quay than elsewhere; the minimum usually occured within two hours after high water and ranged between 2% and 55% ASV.

Measurements of water temperature and chloride were available for about half of the DO surveys from 1963, but mostly between 1972 and 1992, and chloride was also included for all 33 surveys for SS made in 1971 and 1972.

Concentrations of total ammonia were measured during all the surveys in 1971 and 1972 and during 10 other surveys in 1963 to 1978. During half of the latter group, synchronous measurements were also made of water temperature and pH value, so enabling the un-ionised ammonia to be calculated using tabulated values of percentage ionisation (Thurston, Russo & Emerson, 1979).

Sulphide measurements were available for the two surveys made in 1978.

For the survey in 1977, the depth of sampling was 1 m below the water surface, except when the water depth was less than 1.4 m when it was 0.6 m above the bed; no other details of sampling depth are given.

FRESHWATER FLOW

For one of the surveys in 1963, and from the year 1967, average daily flows were available for the main sources of freshwater to the Parrett estuary. These were: Haleswater, River Isle, River Tone, River Yeo and the River Parrett itself. In addition, from 1967 to 1977, an additional synthetic flow was available for the River Parrett at Langport, comprising the flows of the River Isle, River Yeo and River Parrett, together with an additional component for ungauged tributaries. This synthetic flow has been used unless otherwise stated.

FISH CATCHES

Annual catches of dead and live salmon were available from the statutory returns of licensed fishermen for the years 1962-1973. They averaged 23.7% for the whole period.

Records of daily catches made by Mr. Thorne were available for the years 1953-1992; they relate mainly to positions between Dunball and Combwich, located between 4 km and 12 km seawards of Bridgwater. Between 1953 and 1975, catches were made from a boat using a dip-net, and dead

fish were also noted and collected. From these figures the percentage dead was calculated. From 1976 catches were made mainly in batteries of funnel-shaped wicker traps (putts) facing up-stream to catch fish swimming actively with the ebb tide; these catches have been excluded in calculating the percentage dead. The average percentage for the years 1962-1973 is markedly higher (62.4%) than that calculated for the statutory returns; the data are considered to be more reliable than the statutory returns and have, therefore, been used exclusively in the current analysis.

DATA ANALYSIS

The general approach has been to find empirical relationships between fish mortality and water quality characteristics, using regression analysis. However, because of the lack of synchronicity in the data available, attempts have been made using pooled data, to find broad relationships and also to relate water quality to other germaine factors, such as tidal height and river flow, so as to be able to interpolate conditions that might have prevailed when SS and DO were not actually measured.

Suspended solids

Concentrations found in 1971 and 1972 tended to be low in winter, tidal maximum values at West Quay increasing to about 2000 mg l-1 in May, 4500 mg l-1 in June, 9000 mg l-1 in July and 12,500 mg l-1 in August (Fig. 1). The trends over the year were well fitted by a 3rd order polynomial curve of log10 maximum concentration of SS on day number ($P<0.001$), although there was a considerable scatter in the data. Similar results were obtained when including data for the later years. The residual variances about the polynomial curve describing the seasonal

variation in log10 SS were positively related to tidal height, presumably reflecting the effect of the tidal bore in bringing into suspension the solids settled on the bed during other phases of the tidal cycle.

The seasonal variation in log10 SS was also negatively related to freshwater flow ($P>0.001$), as well as being positively related to tidal height ($P<0.001$), the regression equation being:-

$$\text{Log10 SS} = 2.33 + 0.141\ H - 0.068\ F \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1),$$

where H is tidal height in feet and F is freshwater flow in m3 s-1, these two factors accounting for 0.35 and 0.22 of the variance, respectively. The effect of flow in reducing maximum concentrations is, presumably, mainly one of dilution.

Equation (1) has been used to estimate SS concentrations on all (40) days when fish were caught in 1971 and 1972, as well as in two other years (1967 and 1974) in which the mortality was relatively high.

Alternative equations were developed relating SS concentration to freshwater flow and number of tides before or after the spring maxima, so as to take account of solids behaviour that might be similar to that found in the estuary of the river Usk (Parker et al.,in press). However, although more of the variance (0.62) was accounted for on falling tides, less (0.53) was accounted for on rising tides, and only slightly more for combined data (0.60). These equations were, therefore, not used to interpolated missing values.

Biochemical oxygen demand

BOD, being an arbitrary measure of potential oxygen demand, cannot be directly related to actual DO that is measured at the same time as the samples for BOD are taken, although it can be used to indicate generally how SS might affect DO.

During the surveys of SS in 1971 and 1972, BOD was also measured. The maximum values for a given survey during May to August almost always coincided with maximum values for SS. Over the two years, maximum BOD was, not unexpectedly, positively correlated with maximum SS, and also negatively correlated with tidal height, the latter effect presumably being the result of increased dilution afforded by increased tidal volume.

DO measurements were not made during these two surveys, but were available for three others made in 1977, 1978 and 1992, together with data on both BOD and SS. In these, DO was negatively correlated with log10 concentration of SS ($P=0.01-0.001$), but not with BOD; the constant of proportionality was similar for the three surveys (-22.04, -26.86 and -22.97, respectively), although the overall concentrations of DO in the surveys were different. The data are summarised in Table II.

III.RESULTS

SUSPENDED SOLIDS

The average percentage dead over 1971 and 1972 was 66% in May, 65% in June, 59% in July and 86% in August, and was not significantly correlated with log10 maximum SS interpolated for the middle of the month using the polynomial equation. The number of fish involved, however, was low (71). By taking the catch data for the period 1953 to 1975, numbers were increased substantially and the relationship was then found to be significant ($P<0.05$).

Thus there is a general relation over the season between maximum concentration of SS and salmon mortality.

Catches of fish were synchronised with actual measurements of SS on only four occasions (in 1971) and involved only seven fish of which four were dead (57%). The median maximum concentration of SS for these four

occasions was 19,164 mg l-1. Thus the general conclusion from pooled data - that SS play a rôle in mortality - is supported by these few particular observations.

However, when synthesised data on SS (using Equation 1) are examined, concentrations associated with dead fish being caught are not consisently different from those associated with caches of live fish (Table III).

DISSOLVED OXYGEN

Table II indicates the likelihood that low DO, which is associated with high SS, is implicated in the fish mortalities in the estuary.

In 1963 and 1964 one-day surveys were carried out during the annual week-long shut-down of one of the main waste disharges to the estuary, as well as in the weeks both before and immediately following the shut-down. In 1963, the minimum DO during the shut-down was 36% ASV, whilst before and immediately following it, was 28% and 11% ASV, respectively; in 1964, the corresponding figures were 42%, 33% and 46% ASV, respectively. Thus the general effect of the waste on DO was evident despite variability in other germaine factors, the average DO being 39% ASV without the waste discharge and 29.5% ASV with it. During the (5-d) weeks within which the surveys were carried out the tides averaged 3.98 m without the waste and 3.95 m with it, a difference that would account for a difference in DO of only 0.2% ASV (based upon a positive significant relationship [$P<0.05$] found between DO and tidal height). It seems unlikely that the concentration of SS would have been so different under the two conditions as to have affected the DO to any great extent (no estimates are possible using freshwater flow, because records were not available for the years in question).

The mortality within the catch in these two years, however, was 50% with the discharge and 31.3%, without it. This suggests that low DO rather than high SS was primarily responsible for the difference in mortality, although a Chi2 test showed that the difference between the two conditions was not statistically significant.

Further calculations for conditions in which the DO was not always known, showed that the mortality during the week immediately before the shut-down, combined with that immediately after, was also 50%, and that, for the years 1963, 1964 and 1971, the mortality was 59% with the discharge and 50% without it. Again, however, the differences were not significant.

For 12 of the 41 tidal surveys made between 1962 and 1992, records were available for both minimum DO at West Quay and for the fish mortality in the estuary, although numbers were low (only 19 fish); a negative correlation found between mortality and DO was not significant. Numbers were increased (to 52) by including catches made both two days before and two days after each survey, the assumption being that the minima DO would be similar on all 5 days in each case. The correlation was now significant ($P<0.05$), accounting for 0.44 of the variance, a 50% mortality being associated with a minimum of 32.5% ASV and an extrapolated 94% mortality being associated with a minimum DO of zero.

On the four occasions when both maximum concentrations of SS and fish mortality were observed, the concentration of DO was estimated from the relationship found between DO and SS (Table II). It averaged 39.4% ASV and was associated with a total mortality of four out of seven fish (57%). Whilst not conclusive evidence of the dominant rôle of DO in causing fish mortality in the Parrett, because of the small number of fish involved, it does support the other evidence already given.

AMMONIA

Maximum values of un-ionised ammonia in the five surveys where both temperature and pH were measured, averaged 0.021 mg NH3 l-1. This is about 0.14 of the lethal threshold concentration (Alabaster, Shurben & Knowles, 1979) at a high DO (9 mg l-1) and about 0.23 of the threshold at a low value (3.5 mg l-1). A similar figure is obtained assuming that the temperature was 20°C and the pH 8.0 in all those cases where these two characteristics were not measured. It is probably safe to conclude, therefore, that ammonia did not contribute significantly to the lethality of the water when estimates of fish mortality were available, since at values of DO lower than 3 mg l-1, DO would have been the limiting factor.

SULPHIDE

The maximum concentration of sulphide found was <0.1 mg l-1. This is well below the value of 1.0 mg l-1 reported as lethal to Pacific salmon (EPA, 1973). It is unlikely, therefore, that sulphide contributed to the toxicity of the estuary.

VI. DISCUSSION

Whilst the mortality of salmon caught in the Parrett estuary is correlated with concentration of SS, there is no evidence of SS being a direct cause of the mortality that was found there. The values of SS that prevailed when dead fish were being found are very similar to those associated with catches of live fish, and not consistently higher, as would otherwise be expected were SS contributing significantly to mortality.

The concentrations of SS associated with dead fish are also much lower than those found to be lethal to rainbow trout (*Oncorhynchus mykiss*) under laboratory conditions. The equation relating pooled monthly salmon mortality to monthly maximum concentrations of SS would

predict a mortality of 34% at 1000 mg l-1 and 64% at 10000 mg l-1. Herbert (in Alabaster & Lloyd, 1982) found that rainbow trout survived one day in 80,000 mg l-1 silt from gravel washing, and that the concentration had to be raised to 160,000 mg l-1 to kill them within this period. The period of exposure of the fish to SS in the Parrett is not known, but it seems likely to be relatively short, lasting perhaps for only a few tidal cycles because the fish would be destined, not for the Parrett, but for other rivers in the area, such as the Usk, Wye and Severn, as shown by tagging experiments (Swain, 1982).

It is, perhaps, not surprising that salmon are able to withstand the very high concentrations of SS that occur in the Parrett estuary, since other rivers, such as the Usk, Wye and Severn itself, which also contain high concentrations have supported excellent runs of fish since records began. Presumably, the fish have had ample time to acclimatise to these extreme, but natural, conditions. It is true, however, that the maximum concentrations in the Parrett are particularly high for the UK; those in the Usk, for example are very much lower - of the order of 8000 mg l-1. Nevertheless, in the Bay of Fundy, Canada, where tides are even higher than those in the Severn estuary and concentrations range between 20,000 and 40,000 mg l1- in tidal rivers near the head of Cumberland Basin (Gordon & Desplanque, 1983), the rivers emptying into this part of the Bay all have salmon runs (J. A. Ritter, personal communication).

It should be pointed out that although maximum concentrations may extend throughout the water column in the main stream at the height of the flood, surface concentrations are soon reduced where the current slackens. Indeed Mr. Thorne reports that, in the Parrett estuary, the fish are to be seen swimming in the relatively clear surface layer. In one of the field surveys (October, 1977) 15 samples in all were taken at

West Quay and Dunball during the day; in freshly shaken samples, concentrations ranged up to 36900 mg l-1 , whilst in those settled beforehand for 1.5 h, they were up to only 191 mg l-1 . Thus, it is likely that, in the estuary, the maximum concentrations were not always experienced by the fish.

The effect of the suspended solids appears to be to increase the BOD of the water and thus lower the DO. The evidence points to minimum low DO being the dominant lethal factor, although exacerbated by high water temperature.

For five of the surveys when data on DO and fish mortality were available, the water temperature was also recorded; it ranged from 17 to 20.2°C and averaged 19°C. At these temperatures, values of DO that would be lethal to 50% of salmon under laboratory conditions (Alabaster et al., 1991) are estimated at 39-50% ASV. This is close to the value of 32.5% ASV estimated for the median lethal DO in the Parrett. Had another lethal factor, such as high SS, been operating to a significant extent then the DO associated with mortality in the field would be expected to have been higher than the 32.5% ASV that was observed.

On thirteen occasions between 1963 and 1992, when the waste discharge was not known to be shut-down, water temperature, as well as the minimum DO as percentage ASV, was measured at New Quay, enabling the lethality of the observed minimum DO to be assessed (because lethality increases with increase in temperature). The temperature averaged 18.4°C, from which the estimated lethal DO would average 44% ASV; the minimum observed DO, however, was much lower, averaging only 19% ASV, which was obviously well below the expected lethal value. The average of all (32) minimum values of DO available at West Quay, irrespective of

whether temperature was measured or not, was 26% ASV, which again would have been well below the lethal value, assuming that the temperature averaged 18.4°C or higher.

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Table I Average concentrations of dissolved oxygen in the Parrett estuary, 1963-1970

Station	Distance seawards of West Quay (km)	No. samples	DO (% air saturation)
Hoopers Lane	-8	130	66
Somerset Bridge	-2	233	46
West Quay	0	295	48
Dunball	4	271	40
Powlett	7	221	48
Combwich	12	157	57
Brunham-on-Sea	20	249	85

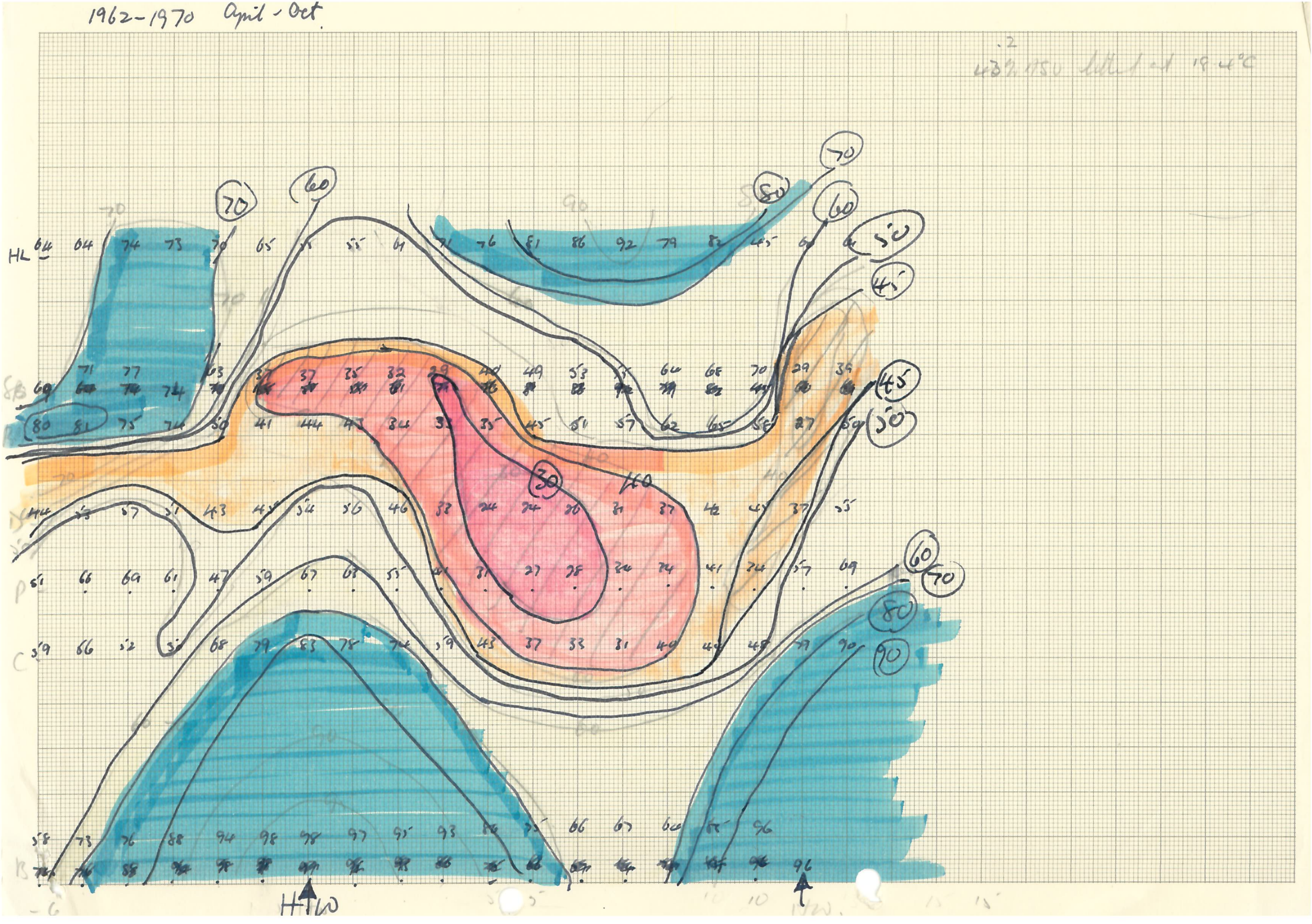
TABLE II. Concentrations of DO interpolated for different concentrations of suspended solids in the Parrett estuary at West Quay.

SS (mg l-1)	DO (% air saturation value)		
	13 October, 1977	14 August, 1978	27 July, 1992
100	110	117	84
1000	81	90	61
10000	58	63	38

TABLE III. Predicted maximum and range of concentrations of SS associated with salmon caught either dead or alive in the Parrett estuary

EFFECT OF SUSPENDED SOLIDS ON SALMON

Year	% dead	Median maximum SS concentration (mg l-1)	
		Dead	Alive
1967	79.6	4717 (1100-12111)	4996 (4511-12224)
1971	29.3	5929 (406-39436)	2941 (618-7079)
1972	28.6	3962 (180-12755)	6982 (5495-9020)
1974	59.1	4432 (859-10846)	7140 (4935-24597)


1962-1970 April - Oct.
HL
70
60
50
45
30
HTW