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RIBBLE SALMON
TRACKING PROJECT
REPORT
(ABERDEEN UNIV.)

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TRACKING MIGRATORY SALMONIDS

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INTRODUCTION

This is a preliminary report on a study of oxygen requirements of migratory Atlantic salmon (*Salmo salar* L.) and sea trout (*Salmo trutta* L.) in an estuary. Oxygen sensing transmitters, attached to fish were used to determine exposure of individuals to different dissolved oxygen concentrations as they moved in from the sea through the estuary of the R.Ribble. This estuary is subject to extreme variations in dissolved oxygen concentration.

The study has been undertaken jointly by the Water Research Centre (WRC Environment), the North West Water Authority (NWWA) and University of Aberdeen (AU). In the late 1970s the WRC were involved in an examination of the oxygen requirements of migratory salmonids which resulted in data compiled by Alabaster & Lloyd (1980) and Alabaster, Shurben & Mallet (1979). This work coincided with the development of a salinity sensing transmitter at the University of Aberdeen which enabled the salinities experienced by fish as they move through estuaries to be monitored directly (Priede 1982). The salinity transmitter used an electrochemical sensor and WRC commissioned a study by the University of Aberdeen to determine whether an oxygen sensing transmitter would be possible. The study concluded that a transmitter small enough for smolts was probably not feasible in the foreseeable future and recommended that work begin with tracking of returning adult fish. This led directly to the present project. The R. Ribble was chosen from a number of possible estuaries and the North West Water Authority became actively involved in the research.

The NWWA had already purchased acoustic fish tracking equipment and had experimented with tracking of salmon in the estuary of the Ribble using simple pinger (location only) transmitters. The first trials using oxygen sensing transmitters were attempted by a joint WRC,AU,NWWA team in 1981. Only a few short tracks were accomplished at that time but since then there has been a gradual elaboration of the tracking techniques; correct capture and handling of fish together with logistics being as important as technical development of the oxygen telemetry system. Work has been carried out during one or two week periods each summer when low dissolved oxygen concentrations are expected in June, July and August. In total 31 fish have been tracked:

1982	4 fish
1983	6 fish
1984	drought no tracking
1985	8 fish
1986	13 fish

Responsibility for the project has been apportioned approximately as follows:

WRC Overall strategy and provision of command tracking boat and personel.

NWWA Logistics, fishing equipment, tracking equipment, ground base, personel, tracking boat , safety boats, fish holding facilities.

AU. Design and manufacture of transmitters and equipment. Servicing of equipment, tracking personel, collation a preliminary analysis of data.

The three organisations have worked together in the field as an integrated team and these responsibilities do not represent rigid demarcations. Tracking of fish requires as many as 20 in a week, working in shifts round the clock, and it cannot be over-emphasised that the man-management accomplishment in sustaining this work is equal to any technical innovations which make the work possible.

Data is stored on audio tapes which are decoded and transcribed in Aberdeen. This report is based on the latest transcription and analysis of data completed in October 1986. A complete analysis will be undertaken during the next financial year with more man-hours allocated to that aspect as opposed to field data collection.

The aim of this report is to give an overview of the work done and conclusions which are apparent at this stage. Full transcripts of all data contained in a file for each fish have already been delivered to WRC in partial fulfillment of the current contract.

THE RIBBLE ESTUARY.

The chemical sensing transmitter attached to the fish measures directly the instantaneous DO levels experienced by an individual fish. Priede (1982) has already showed how an salinity sensing transmitter can be used to trace the salinities experienced by salmon migrating through an estuary. Estuaries are highly heterogeneous environments varying both in time and space. The water quality experienced by the fish greatly depends on its individual behaviour in terms of depth, direction and speed of swimming. The estuary chosen for this study with oxygen sensing transmitters suffers from low DO levels in the summer.

The River Ribble drains into the Irish sea on the West coast of England (53 45'N, 2 50 W). The estuary is approximately 20Km long, funnel shaped, tapering from a 100m width at Preston dock to 5Km at Lytham where it enters the sea.(Figure 1) In common with other West Coast estuaries this shape amplifies the effect of the tide with typical amplitudes of rise and fall of 8 metres or more. The tidal flow is asymetrical with a very fast flood filling the estuary in 4 hours followed by the ebb which lasts about 8 hours. The flood at Spring tides takes the form of a tidal wave or bore. At low water the river channel is often less than 50m wide and less than 0.5m deep, this means that despite the size of the estuary, navigation for tracking purposes is confined to use of small shallow-draft craft which can be manhandled over sandbanks in order to permit tracking at all states of the tide. The port of Preston is no longer used by ships but the navigation marks which are numbered in statute miles distance from the dock head remain and are a convenient reference scale for data collection. In figure 1 all distances are expressed in miles or kilometers upstream and downstream of the dock head in accordance with this nomenclature.

The graphs in figure 1 show DO levels measured in the estuary in a North West Water Authority survey on 14 July 1977 in conditions of low river discharge. The main source of deoxygenation is Biological Oxygen Demand (BOD) generated by sewage outfall from Clifton Marsh which only receives primary treatment. At low tide the oxygen sag extends to 10Km downstream of the treatment works. DO is lower at night than during the day and in the upper reaches of the estuary above Preston Dock during the day supersaturation occurs as a result of photosynthesis by algae. A fish progressing through the estuary could thus experience a change in oxygen partial pressure of 200mm Hg, a variation exceeding the total normal oxygen partial pressure of 152mm Hg. At high tide high DO sea water enters the estuary and the DO sag is diluted and pushed up to above the dock entrance. The DO profile thus shows considerable variations according to time of day, state of tide and river discharge.

The river contains populations of both Atlantic salmon (Salmo salar L) and sea trout (Salmo trutta L) which migrate through the estuary and form the basis of a small commercial net fishery working with drifting gill nets from small rowing boats between Lytham and the confluence with the R. Douglas. Fishing is only carried out on the last 4 hours of the ebb tide, the flood tide being too dangerous. Catches are low, usually less than 5 fish per boat per tide and the fishery no longer provides a viable wage for the fishermen.

Above Preston the River flows through open countryside with no serious pollution problems except for occasional agricultural seepages of silage and fertilizer run-off. The upper Ribble is considered by anglers to be a good sea trout and salmon fishery.

OXYGEN SENSING TRANSMITTER.

The transmitter is similar in concept to the salinity sensing transmitter developed by Priede (1982). It comprises four elements, a sensor, an amplifier, a voltage controlled oscillator and acoustic output pinger. (Figures 2 & 3).

The sensor used is a Clark type polarographic oxygen electrode machined from perspex made to a diameter of 15mm. A central 0.25 mm diameter platinum electrode is polarised to a voltage of 0.6 negative with reference to a silver electrode. The anode is a ring of silver wire in an annular groove on the face of the sensor (Fig 2(a). Saturated KCl solution acts as an electrolyte contained beneath a 10 micron thick teflon membrane covering the electrode. The membrane is held in place by an 'O' ring and is protected by a flexible PVC shroud placed over the sensor after filling (Fig 2 (b)). The sensor produces a current proportional to oxygen tension. Zero current flows in zero oxygen but in air saturated water typical currents are 50 nanoamps. The voltage generated by this current across a resistor is fed into a DC amplifier. Recent versions of the transmitter have included a temperature compensating thermistor which ensures the sensor network has a uniform output from 0 - 20 C (Figure 4).

Figure 3(a) shows the voltage output measured directly on a pen recorder from a sensor being transferred between water of 100% and 0% DO saturation. The response time is typical less than 30 seconds. The amplified DC signal is fed into a voltage controlled oscillator. In the Mk1 design the whole transmitter circuit is based on a single integrated circuit package with 4 operational amplifiers as used in the salinity sensing transmitter (Priede 1982). Two of these were used as amplifier stages, a third as a voltage sensitive multivibrator and the fourth as a buffer feeding the resulting pulses to the output stage. Typically a pulse rate variation between 2 and 1 Hz is used. At slower pulse rates the fish might be overlooked during a sweep search of the river but faster pulse rates would drain the transmitter battery too quickly. The tag is designed to pulse fastest in low dissolved oxygen so during normal use battery energy is conserved until the fish enters an interesting area of low dissolved oxygen.

The original Mk1 "single chip" design although economical in component count suffers from several disadvantages. The relationship between pulse rate and oxygen tension is non-linear and output pulse length and frequency were difficult to control. A Mk2 tag now uses 3 integrated circuits assembled using the surface mounting miniature printed circuit technology and is no bigger than the Mk1 model. This now has a linear calibration curve. Pulse length, frequency and sensitivity of the transmitter are all adjustable making manufacture much easier. Calibration curves of the two versions of the transmitter are shown in Figure 3(c).

The output stage uses a transformer to generate an output voltage of 120V to drive a ceramic ring transducer at its resonant frequency of 75KHz. Power is supplied from a 6V pack of lithium batteries to give a life of about 5 days. The pulse length is set at 5ms with an acoustic source level of 168dB re uPa at 1m.

Two versions of the transmitter, in terms of overall configuration have been built. A single cylindrical package weighs 22g in air is 16mm in diameter and 75 mm long (Figure 2a). A dual pack version with a separate battery pack on the opposite side of the fish (Figure 2b) enables batteries to be carried. The fish is well balanced with this configuration. The transmitter casings are polypropylene moulded tubes and are filled with silicone oil to protect the circuitry and provide acoustic coupling to the outside water.

During the course of the study there has been a continuous process of development of the transmitter which will be fully described elsewhere. For 1986 new low power amplifier modules were used which required less battery power and design reverted to a single cylindrical package for simplicity and reliability. The transmitter circuitry is also now implemented on a single double sided mini printed circuit board with miniature surface mounted components. (Fig 5). LIfe of the transmitters is now 10 days in contrast to the 3 day life of early designs using the same battery.

CAPTURE, TAGGING AND TRACKING OF FISH.

Fish are captured using the local commercial gill netting technique. Working from small boats about 3m long the net is set across the ebb tide. The net and boat are allowed to drift down with the tide and fish caughtduring such a passive drift typically from the 2.5mile mark to the 8 mile mark. We have evaluated all other methods of fishing, seine netting, fixed engines, angling etc. and now exclusively use the commercial drift netting technique. The research netting is often carried out during the weekly close season (with special dispensation) to avoid interference with the commercial fishery. Outboard motors are used which is not permitted on the commercial boats. This enables us to underake several sweeps of the estuary on an ebb tide whereas the commercial boats have to wait for the end of the ebb before thay can get back up the estuary. If the fish is removed from the net very quickly (often only caught by the teeth) survival is excellent. A large mesh is used which tends to grip fish by the girth rather than the gills. Any "gilled" fish are unlikely to survive but with the nets we now use this is very rare.

In the early stages of this work (1982,1983) it was thought that tagging a fish very quickly and then releasing it within minutes of capture was the best technique. This has now been rejected in favour of allowing fish to recover fully in a tank of oxygenated water. Fish were kept in a tank on board a boat for up to several days if not immediately required. For the 1986 season we introduced shore based holding tanks with an oxygen supply to hold fish to be used for tracking. The transmitter is calibrated in the field by immersion in water of known dissolved oxygen concentration and a zero reference solution. For the tagging procedure the fish is anaesthetised with benzocaine. The transmitter is attached by means of surgical nylon sutures in the region of the dorsal fin (Figure 2). At least one hour is allowed, following tagging to recover from the anaesthetic before release.

The fish is tracked using two boats each equipped with a conventional hydrophone and portable receiver (Stasko & Pincock 1977, Priede 1979) The signal from the tag is recorded on one track of a stereo cassette tape recorder and a commentary with times is recorded on the other track. The boats are able to communicate with one another and a shore base station using UHF portable radios or in more recent work the VHF marine band. Normally as the fish progresses up and down the estuary one boat stays ahead and the other behind the fish. One boat always records the transmitter signal whilst the other carries out any manoeuvring that may be necessary. Boats are equipped with oxygen, temperature and salinity probes so that water quality can be logged to check on variations in the estuary and also to provide occasional recalibration of the fish transmitter.

ACOUSTIC TELEMETRY

Transmitters attached to animals enabling them to be tracked are now widely used in field studies on animals. For fish either radio or acoustic transmitters can be used. Radio waves however will not propogate through seawater or brackish waters so in estuaries only acoustic transmitters can be used. (Priede 1979, Stasko & Pincock 1977, Solomon & Storeton-West 1983)

The signal from an acoustic transmitter is detected by a hydrophone immersed in the water. The signal level detected by the hydrophone is determined by the power output of the transmitter and transmission loss through the intervening water. The transmitter output power is usually measured in terms of acoustic pressure level at 1 meter from the transmitter expressed in decibels relative to a reference pressure, eg dB ref 1uPa at 1m. (Figure 6). For practical fish transmitters a maximum power output is about 1 watt or 170dB ref 1uPa at 1m. Expressing sound levels in decibels means that signal losses and gains can be calculated by simple arithmetic subtraction or addition. Different reference pressures are sometimes used so caution is required when comparing data from different sources. For work in the Ribble it has been necessary to use high poer tags with a source level of 168 dB re 1 uPa at 1m. Normally a pulse length of 5ms at 75KHz is used. Longer pulse lengths can be used at lower power levels (with narrower bandwidth) but probability of detection remains proportional to the acoustic energy transmitted.

In open sea water this sort of transmitter can be detected with a good quality receiver and directional hydrophone at a range of 1000 to 2000m. (In deep freshwater much longer ranges may be achieved). For convenient tracking it is normal to keep the fish well within the maximum range. A circle of radius 1000m is shown to scale in figure 1 to give an indication of the probability of detecting a fish in the estuary. To cover the whole estuary 10 to 15 listening stations would be necessary. Figure 7 shows how transmission loss increases with range from the transmitter. Spherical spreading predicts a loss of 20dB per decade increase in range. This is a useful rule of thumb but at longer ranges frequency dependent absorption losses become significant. Low frequencies(eg 10 Khz) suffer less loss but the transmitter would have to be 10cm diameter instead of the 12mm diameter emitting transducer resonant at 75 KHz used in this work.

An 80 dB transmission loss at extreme range is a reasonable practical limit for the system. In open water this gives a range of about 1000m but in the estuary with high turbidity and complex mixing layers of waters of different salinities transmission losses can be much higher. In extreme cases at a salinity interface there can be total reflection of the signal with no transmission to a receiver placed in the wrong mass of water.

Within the estuary the ability to detect the signal does not depend on receiver/hydrophone sensitivity; detection is limited by the ability to detect the signal above the ambient noise. Figure 8 shows the level of ambient noise in open seawater at different frequencies (Clay & Medwin 1977). Waves, currents, and tides produce noise mainly at low frequencies; the graph shows a general decrease with increase in frequency up to about 50 KHz when thermal noise becomes important. The 75 Khz chosen for the Ribble study is therefore a compromise between avoiding high absorption at high frequencies and high noise at low frequencies. Stormy conditions increase the noise level as indicated. Gale force winds generate sea noise 30dB above the base line level.

The high tidal velocities in the Ribble generate noise equivalent to stormy conditions at sea; particularly during a flood tide noise levels can be very high. Assuming a working 80dB transmission loss, 30db of noise will reduce the permitted transmission loss to 50dB. This, reading off the 75Khz line, in figure 7 gives a working range of only 200m in the Ribble when the tide is running. This accords well with our practical experience of this river. The 200m radius circle in figure 1 indicates how easy it may be to loose track of a fish under such conditions.

Any noise from the boat hull or the motors also serves to mask the signal and reduce range. Certain kinds of outboard motor are more noisy than others and careful attention to detail of mounting of hydrophones and layout of the boats can do more to enhance tracking performance than any breakthroughs in acoustic transmitter design. The boats and their equipment are an integral part of the telemetry system and deserve close attention.

DATA ANALYSIS.

All data is recorded on audio cassette tapes together with incidental notes in various records kept by individuals on different boats at different times. All tapes are transcribed, collated and tracks of the fish plotted out in terms of distance up and down the estuary.

All good sequences of transmitter pulses are then replayed through a system which logs the intervals between pulses. Suitable filtering is applied and pulse intervals loaded into a computer for further analysis. Calibration curves are prepared from the prerelease calibration recordings of the transmitter. Spot recalibrations are also carried out based on oxygen and temperature readings taken by the boat when close to the fish in well mixed conditions. The calibration of the tag may drift over a period of days and application of corrections may be necessary.

TABLE 1. Summary of Fish tracked

Year	Total No. of Fish	No. of Salmon	Salmon only. No going upstream	No going downstream	Direction not clear	
1982	4	4	1	2	1	
1983	6	3	-	2	1	
1985	8	5	1	2	2	
1986	8	5	1	6	2	*
Total	31	21	3	12	6	

* 1 fish was recovered dead.

RESULTS.

Tracking has been carried out in the summers of 1982, 1983, 1985 and 1986. In the drought of 1984 insufficient fish entered the estuary during the summer months to justify a field programme. Table 1 summarises the data obtained. The total of 31 fish represents 272 hours of data of fish behaviour in the estuary at various oxygen levels. Table 2 gives details of all the fish tracked.

Figure 9 gives a plot of all the oxygen readings taken from active fish both from the boat and from the transmitter. The extreme limits of the range were from 38% saturation to 157% saturation. The extreme values were observed high up the estuary towards Preston dock. The lower limit on fish activity seems to be between 40 and 50% saturation although the experimental work was limited by the fact that when DO concentrations are very low it was difficult to capture fish alive for the experiment. Fish when gill netted in the worst water conditions die very quickly, fishermen describing them as "chokers". There was little evidence that fish were able to avoid low DO conditions; once embarked upon up-river movement through the estuary the fish would be exposed to whatever happened to be the prevailing conditions.

Of the 31 fish tracked 21 were salmon and the rest were sea trout. The sea trout particularly, if released well up the estuary, showed a strong ability to escape up into freshwater even swimming against a strong ebb tide on occasions. This is well exemplified by fish 4(86) (Figure 10). The DO readings from the transmitter and the adjacent tracking boats are compared and show a close correspondance. The fish seemed to remain in higher DO values at around 6 miles by swimming close to the south bank whereas the boats were in the middle of the channel. This fish also showed reactions to inflow from a pipe at this point on the north bank and crossed over the river.

Figure 11 shows a Salmon Fish 6(86) escaping to sea from similar low DO concentrations. This fish was very interesting in that it was tracked into shallow water and was observed to have hauled partially out of the water and this was reflected by high DO readings from the transmitter although the prevailing DO in the main channel was some 30% lower. This behaviour might have been dismissed as aberrant if it were not for 2 other fish (without tags on) doing the same thing in the same area. This indicates the possibility of a behavioural mechanism for overcoming low DO levels.

Of the 21 salmon tracked only 3 went upstream into freshwater. 12 fish were definitely identified as going out to sea. Of these two were ultimately recaptured and tags returned from North Wales. This suggests that over 50 % of the fish in the estuary were non-Ribble fish.

Most of the fish showed a strong cyclical movement up and down the estuary tied to the tidal cycle. The fish would move up with the flood tide and down with the ebb. Figure 12 shows all the data for salmon giving distance from Preston dock normalised to the time frame of the tidal cycle with 0 and 360 degrees being high water. Figure 13 shows the mean fish position from all those curves showing a oscillation of about 10 Km in amplitude centred on the 5 mile mark. Fish which escape to sea show a mean track escaping from 4 miles to 13 miles within 4.5 hours corresponding to a mean velocity of 3.3Km/h. When the tracks of fish leaving the estuary are removed from the analysis of tidal movement a clearer sinusoid curve emerges describing the average movements of a fish within the estuary. Data was included if the fish was still in, or presumed to be still in, the estuary at the subsequent high water.

Figure 14 shows the tracks and DO readings for the salmon that were tracked and figure 15 the same data for all the sea trout. Table 2 gives brief details for all the fish that were tracked. All this data has been delivered to the WRC in the form of a archive of all raw data and observations together with preliminary graphical analysis.

DISCUSSION.

General pattern of movement

Dr. F.R. Harden-Jones author of the classic work "Fish Migration" once expressed the view that any study on fish migration requires about 10 years from conception to final completion. His team at the Fisheries Laboratory, Lowestoft studied the migration of plaice (*Pleuronectes platess*) in the North Sea using acoustic tracking and discovered that these fish alternate periods of active swimming near the surface with periods of rest on the sea bed. After some years of study it became apparent that these fish were using a system which they named Selective Tidal Stream Transport (STST) whereby the fish only leave the bottom to swim with favourable tides (Greer-Walker *et al* 1978). In the early stages of their work this simple model was obscured by the varia tions in individual behaviour.

Studies on tracking of returning adult salmon at sea show that salmon do not use STST. They swim at a uniform velocity in the chosen diection and any fluctuations in the tidal flow produce oscillations in the track as measured over the ground (Smith *et al* 1981). The fish swim at a speed of about 1.2 Body lengths per second and thus often move backwards with an adverse tide in contrast to the plaice which would rest on the bottom. The swimmming speed used corresponds to optimum speed as defined by Weihs (1973). When they reach the coast-line salmon follow the coast often in very shallow water less than a metre deep in the surf zone of the beaches where they are caught by coastal nets (Tesch 1980, Hawkins *et al* 1979). As they pass estuaries during this coastal following behaviour they are likely to enter non-natal estuaries before eventually finding the appropriate estuary. Malinin *et al* (1974) describe tracks of salmon encountering non-natal in-flows and found that they rapidly move on after a brief excursion into the mouth of the stream. Barbour (1985) using salinity sensing transmitters has shown that salmon require less than 30 seconds exposure to a freshwater inflow to reject it and move on to an appropriate home stream.

The Ribble is a very large estuary with a very strong flood tide. Fish swimming along the coast encountering the estuary are very likely to be carried in the flood tide well up the estuary before intercepting significant quantities of freshwater which may induce non-resident to fish to move off to another estuary. The estuary should be regarded as an inlet of the sea into which fish become entrained by the tide. The entrained fish will comprise a mixture of both Ribble and Non-Ribble fish. Our indications are that between 50 and 90% of fish are non-Ribble fish. It is not unusual for net fisheries in estuaries to catch a majority of fish not destined to enter the river concerned so the Ribble would not be exceptional in this respect, coastal searching being an important aspect of the salmon homing mechanism (1973).

Once entrained in the estuary the fish follow a very stereotyped oscillation with the tide as expressed by the curves in figure 15. Fish may spend one or more cycles in the estuary following this pattern before either escaping to sea or passing up into freshwater. This curve now enables us to predict with a high degree of certainty the location of fish at different states of the tide. Indeed the fishery within the estuary is based on this highly predictable behaviour of the fish with best catches being made at around the 8 mile mark on the last of the ebb tide when the fish are confined to a narrow residual channel at the last of ebb tide. There was no evidence that this cyclical pattern was disrupted by changes in DO. This opens up the possibility that if the location of fish is highly predictable then their exposure to discharges within the estuary will be highly predictable. It is planned to incorporate this into a model of exposure of fish to low DO the Ribble.

It should be emphasised that the movement of the fish is not passive drift; the rate of movement of the fish does not correspond simply to the rate of ebb and flood tidal flows. Legget and Trump (1977) and Trump & Legget (1980) discuss in detail the swimming strategies likley to be adopted by fish in tidal estuaries.

In an elegant series of experiments Westerberg (1984) has shown that salmon in fjords make vertical excursions in the water column to sample the vertically stratified layers and then swim within the layer which contains the appropriate home stream odour. The Ribble has strong currents and is well mixed so the fish rarely have the opportunity to make such subtle choices. It might have been reasonable to suppose that fish would seek out layers with higher DO levels. Our only indication of such behaviour was in fish 6(86) which was seen to move into very shallow, well oxygenated, water. In such shallow waters acoustic tracking is difficult since the signal can be blocked by sand banks and if the transmitter, on the back of the fish, emerges from the water no signal will be heard. In fact it was not unusual for us to lose track of fish in shallows where boats could not follow. Thus the "hauling out" behaviour to avoid low DOs may be more common than would be supposed from our results. Apart from this possibility it seems fish have little control over their exposure to low DOs in the estuary.

The movements of the sea trout have not yet been statistically analysed ~~statistically yet~~. It seems they show similarities with the salmon but we cannot be certain regarding their pattern of migration. Sea trout are likely to move in and out of the estuary both into freshwater and sea water and we do not know if in every case we are studying a fish that is attempting to migrate up an appropriate river from the sea (Nall 1930).

Oxygen requirements of fish

There are two aspects to this question.

(a) Do low DO conditions inhibit fish migration and if so at what threshold does this effect occur?

(b) If exposed to low DO conditions, is probability of mortality increased and at what threshold would that effect be significant?

The tracking data provides detailed information on exposure of fish to different DO levels. Fish were captured and replaced in the estuary . We therefore did not obtain information on whether fish were detered from entering the estuary; we simply studied the behaviour of those which which had entered. Setting aside that consideration there seems to be no inhibition of migration by DO levels down to 40-50 % saturation. This corresponds well with existing minimum levels as tentatively recommended by European Inland Fisheries Advisory Commission (EIFAC) .

EIFAC has reviewed the literature on the dissolved oxygen requirements of freshwater fish including migratory salmonids (Alabaster & Lloyd 1980). The information available is of two types; laboratory data and field observations. Slavonic literature reviewed by EIFAC gives lethal levels of DO for salmonids in the range 0.95-3.4 mg/l. Alabaster, Shurben & Mallet(1979) found that the median lethal threshold concentration for smolts of Atlantic salmon (Salmo salar) was 2.6 mg/l in water of 10 to 28 p.p.t. salinity typical of estuarine conditions. EIFAC reports that salmon were killed in the River Don, Scotland at DO levels of about 4 mg/l (at 18-23 C) and in the River Wye, England on a decrease in DO from 5 to 1 mg/l (temperatures up to 27.5 C) in both instances at high temperatures for Atlantic salmon. In a more recent review (Hugman, O'Donnel; & Mance 1984) it was found that fish kills attributable to low DO levels are associated with minimum DO levels in the range 0.6-3.6 mg/l. For adult migratory salmonids therefore EIFAC tentatively recommend that the 50 and 5 percentiles of DO in an estuary in summer at the worst location should be 5 and 2mg/l respectively (50 and 20% of saturation at 15 C). Extended zones of low DO or elevated temperatures, would require standards to be raised and higher standards would be needed to protect migratory smolts.

EIFAC considered that to allow juvenile and adult fish to survive for 24h the DO should not be less than 3 mg/l. The recommendations for migratory fish were very tentative.

When this study first began on the Ribble it seemed surprising that fish were active at all in the estuary in low DO conditions. Fishermen could still catch fish in low DOs and one working hypothesis at the time was that the fish could find pockets of high DO which enabled them to survive the otherwise adverse conditions. The tracking study has shown byond all doubt that fish are active in waters of DO concentrations down to 50% saturation. The only behaviour consistent with the high DO pocket hypothesis is the "hauling out" behaviour shown by some fish. Incidentally such behaviour would make fish more susceptable to predation. Birds were recorded as active in the "haul out" area such fish would be more readily caught by seals.

If there is little evidence that fish migration is inhibited by the DO sag in the Ribble, is there any evidence of adverse effects on the fish? It is self evident that a DO concentration of 50% saturation is not acutely lethal but salmonids show noticeable circulatory adjustments to hypoxia at DO values below 70%. Duthie (unpublished) has shown that as DO decreases the maximum sustainable swimming speed decreases as metabolic scope is reduced. Fish can be induced to swim at low DO concentrations in the laboratory but at the expense of large oxygen debts. The fish is forced to work at close to its metabolic limits. Priede (1977, 1984,1985) has shown how probability of mortality increases with metabolic rate as the maximum aerobic limit is reached. Applying that theory to Ribble fish it should be possible to model the expected increase in mortality rate associated with the exposure to low DO. Our sample of fish is too small to measure any mortality effect directly although mortalities were observed. It was difficult to separate these from the stress of tagging. There is little doubt that when in DO concentrations of less than 70% fish are progressively less able to withstand such stress. The effects of exposure to low DO are also likely to lead to a delayed death possibly after the fish leaves the estuary. Wood et al (1983) have investigated the post-exercise death syndrome in salmonids which occurs when fish are exercised to exhaustion. Apparently healthy fish can die for no apparent reason some time after exercise, during recovery in fully oxygenated water. Thus although fish may survive during the course of our tracking observations there may be a delayed mortality which we are unable to monitor.

The study has now placed us in a position where we can precisely predict the exposure to different DO concentrations in fish entering the estuary. This provides the basis for modelling the physiological effects and mortality probabilities resulting from that exposure.

CONCLUSIONS

1. There is no apparent inhibition of fish migration down to DO concentrations of 40-50% saturation.

2. There is no effect on the pattern of movement of the fish within the estuary over the range of DO values observed.

3. There is some evidence that fish may try to avoid low DO conditions by "hauling out" into very shallow waters but overall opportunities for choice and avoidance of low DO conditions are limited.

4. A majority of the fish (50-90%) active in the estuary are probably non-Ribble fish. If the estuary has adverse effects on fish these may manifest also themselves in populations other than the Ribble salmon and trout.

5. Fish adopt a stereotyped behaviour pattern in the estuary moving to and fro with the ebb and flow of the tide for one or more cycles before making a decision whether to move back out to sea or to move up into freshwater.

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TABLE 2 LIST OF ALL FISH TRACKED

The fish movement is given as the number of tidal cycles the fish takes to escape. A one cycle fish is one which leaves the estuary on the tidal cycle within which it was released counting from HW Liverpool. " Up" denotes movement into freshwater or the track was abandoned whilst the fish was moving upstream. "Down" denotes movement to sea or heading in a seaward direction when tracking was abandoned.

Fish No & Move.	Species	Date	Track Duration	Comments
1(82) Dead	salmon	10/7	11.65h	Released on ebb, abandoned after it had remained stationary for 8h 100m from release, presumed dead.
2(82) 1 cycle down	salmon	13/7	2.73h	Released by slip at Lytham. Lost going to sea at 12.75 mile mark.
3(82) 1 cycle down	salmon	15/7	2.18h	Released by slip at Lytham on ebb. Lost going to sea at 10.25 miles.
1(83) 3 cycle down	sea trout	16/7 – 17/7	27.2h	Released by 6 mile mark. Lost going to sea at 11.5 mile.
2(83) 3 cycle down	salmon	18/7 – 19/7	19.38h	Released at 4.5miles. lost to sea at 12 miles.
3(83) 2 cycle down	sea trout	20/7	12.46h	Released at 4.5 miles. Lost probably to sea at 12 miles.

TABLE 2 CONTINUED

4(83) 2 cycle down	salmon	21/7 – 22/7	9.03h	Released at 5.25 miles went to sea and recovered from N. Wales.
5(83) 2 cycle up	salmon	22/7	14.45h	Released at 1.5 miles. Tag fell off or fish died at 2.75miles. Track abandoned.
6(83)	?	23/7	3.3h	Released 100m below old Penwortham bridge. Recovered dead at release site.
1(85) 1 cycle up	sea trout	29/6	3.55h	Released at 1.25 miles. Lost above Dock head going upstream. Fish was found on 30/6/85 in a pool immediately upstream of A6 road bridge. Still there on 1/7/87.
2(85) 1 cycle down	sea trout	30/6	2.12h	Released at 2.25 miles. Lost going down stream at 5 miles.
3(85) 3cycle down	sea trout	1/7	22.0h	Released at 2 miles. Left going out to sea at 5 miles
4(85) 1 cycle down	salmon	26/7	3.77h	Released at 1.4 miles. Lost going downstream at 3 miles. High discharge "washed" fish downstream.

TABLE 2 CONTINUED

5(85) 1 cycle up?	salmon	29/7	7.07h	Released at 4.2 miles. Lost at 3.75 miles. (direction uncertain)
6(85) 1 cycle down	salmon	29/7	1.78h	Released at 4 miles. Fish caught at 5.75 miles going to sea.
7(85) 1 cycle down	salmon	31/7	1.53h	Released at 3 miles. Lost at 5 miles on the ebb.(fate uncertain)
8(85) 1 cycle up	salmon	1/8	0.75h	Released at -0.8 miles. Lost up into freshwater at -2.4 miles.
1(86) Dead	sea trout	28/6	4.50h	Dead fish recovered from release site. Suspect fish swam into outfall.
2(86) 1 cycle up	salmon	29/6	9.17h	Released at 7 miles. Lost going upstream at Penwortham power station. (-1.0 miles)
3(86) 1 cycle down	salmon	30/6	1.88h	Released at 6.25 miles. Abandoned at 7.5miles. Tag apparently fell off fish as it passed fishing nets.
4(86) 1 cycle up	sea trout	1/7	4.48h	Released at 2.5 miles. Lost going upstream at -0.9 miles.

TABLE 2 CONTINUED

5(86) Dead	salmon	19/7 - 20/7	11.8h	Released at 6.5 miles. Recovered dead at 7.75 miles.
6(86) 2 cycle down	salmon	21/7	9.31h	Released at 7 miles. Left going out to sea at 13 miles. Fish "hauled out" with several other fish.
7(86) 2 cycle down	salmon	22/7	11.3h	Released at 5.75 miles. Lost going seaward at 4.5 miles.
8(86) 1 cycle down	salmon	23/7	2.58h	Released at 2 miles. lost at 4.5miles, going seaward.
9(86) 1 cycle down	salmon	24/7	8.07h	Released at 5.5miles. Lost at 8.5 miles, going seaward.
10(86) 1 cycle down	sea trout	25/7	0.75h	Released at 5.5 miles. Lost at 6.5 miles. Tag recovered from N. Wales.
11(86) 2 cycle down	salmon	26/7	9.92h	Released at 3.5miles. Lost at 11.5 miles, going seaward.
12(86) 1 cycle down	salmon	27/7	3.58h	Released at 2.5 miles. Lost at 9.5 miles going seaward.

TABLE 2 CONTINUED

13(86) Dead	sea trout	28/7	2.48h	Released at 4 miles. Recovered dead at 4.5 miles.

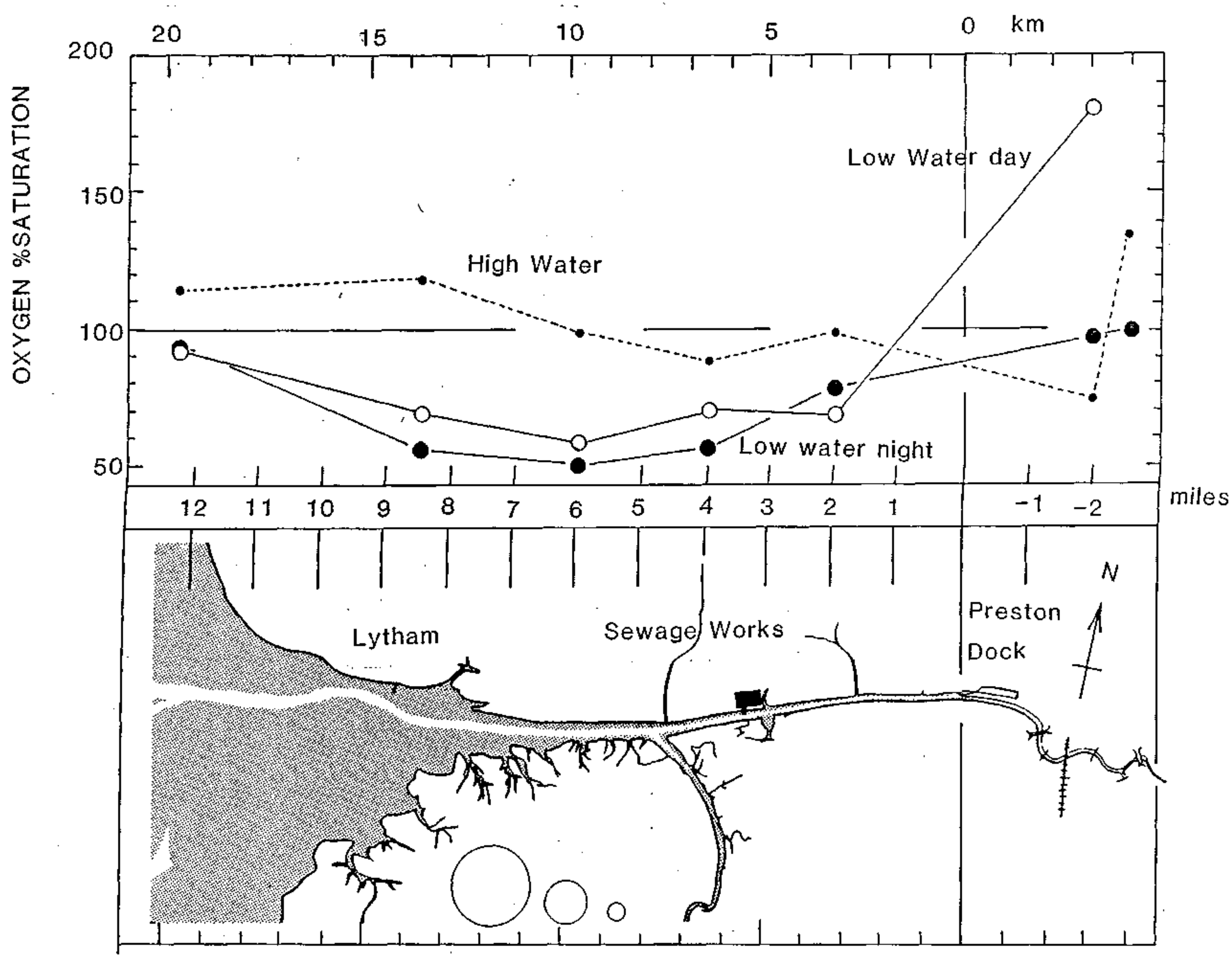
Notes.

1. Fish tracked each year are given a serial number followed by the year in brackets to give a unique identity code.

2. Dates are the day and month when the fish was released followed by day and month when tracking ceased ifthe track was spread over more than one day.

3. Track durations are given in hours and decimal fractions thereof. i.e. 2.5h is 2 hours and 30 minutes.

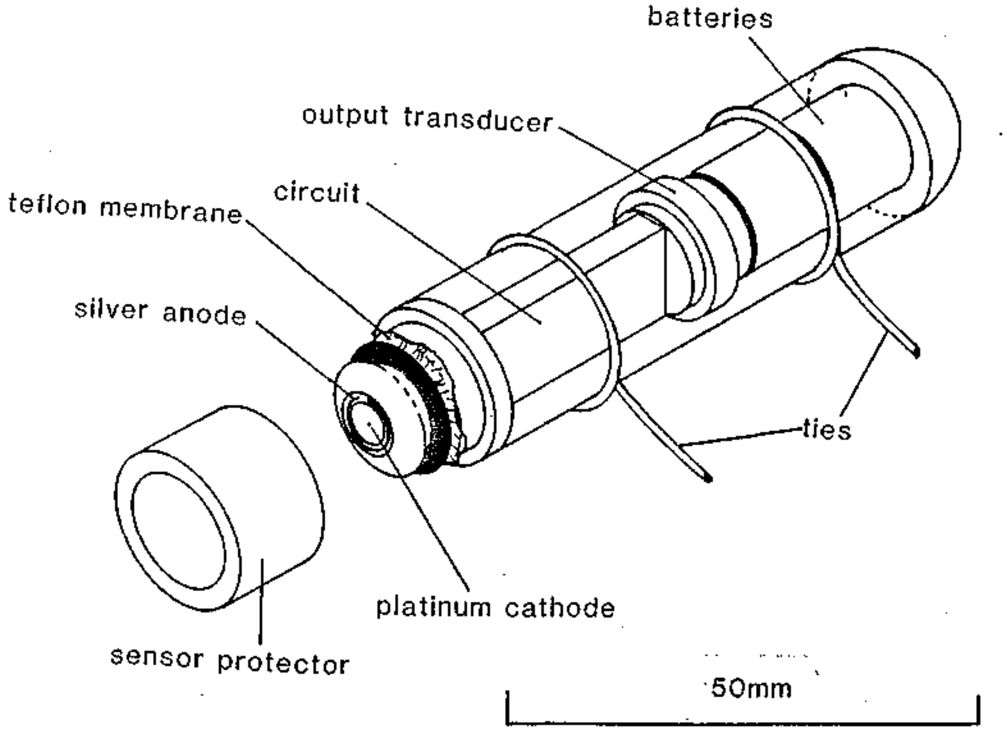
FIGURE 1. The River Ribble estuary. In the map the shaded areas indicate sand and mudflats exposed at low tide. The mile scale is in statute miles and corresponds to the nomenclature of navigation marks situated along the main channel. The circles of different radii indicate the working range of the acoustic transmitters under different conditions. The graph shows dissolved oxygen levels measured on 14 July 1977 at different states of the tide. Dotted line - High water at 11.05h, Solid circles - Low water at 07.00h. Open circles - Low water at 18.30h. Note the effect of photosynthesis compared with the early morning low water.



20
15
10
5
0
km
200
150
100
50
OXYGEN %SATURATION
Low Water day
High Water
Low water night
12
11
10
9
8
7
6
5
4
3
2
1
-1
-2
miles
N
Lytham
Sewage Works
Preston
Dock

FIGURE 2. The oxygen sensing transmitter. (a) Single package configuration. The protector fits over the sensor. (b) Dual pannier arrangement.

(a) DO transmitter single package



(b) DO transmitter dual package

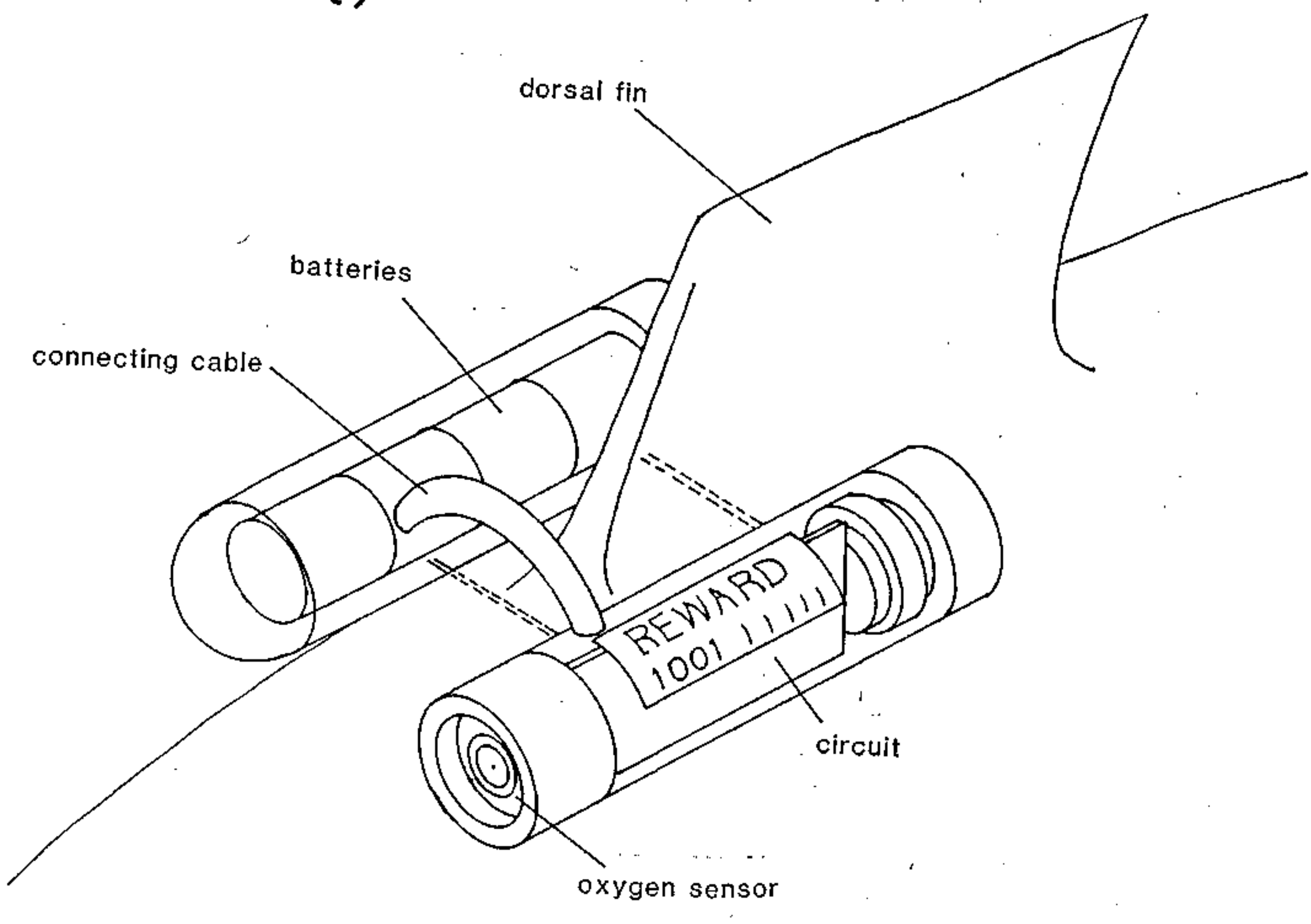


FIGURE 3. The oxygen sensing transmitter. (a) Block diagram of the transmitter. (b) Sensor output response time at 20 C. The voltage output (measured across a series resistor) from the sensor when transfered from 100% oxygen saturated water into 0% and then back again. (c) Transmitter calibration curves for the Mk I (logarithmic VCO) and Mk II (linear VCO) versions.

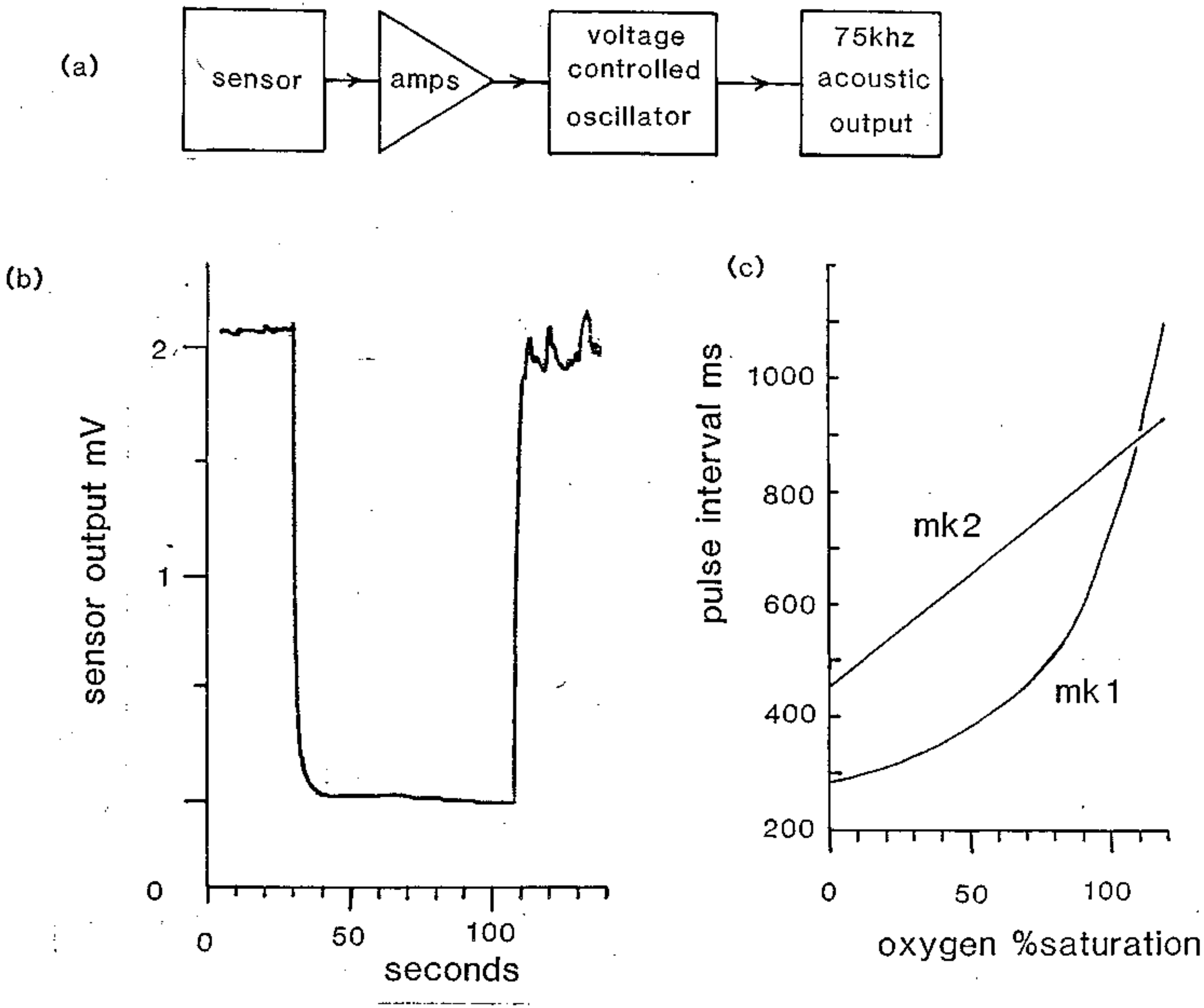

(a)
sensor
amps
voltage controlled oscillator
75khz acoustic output
(b)
sensor output mV
0
1
2
0
50
100
seconds
(c)
pulse interval ms
200
400
600
800
1000
mk2
mk1
0
50
100
oxygen %saturation

FIGURE 4. Variation in voltage output and response time of a batch of 10 sensors. This variation has to be allowed for in building transmitters

DO sensor Variation

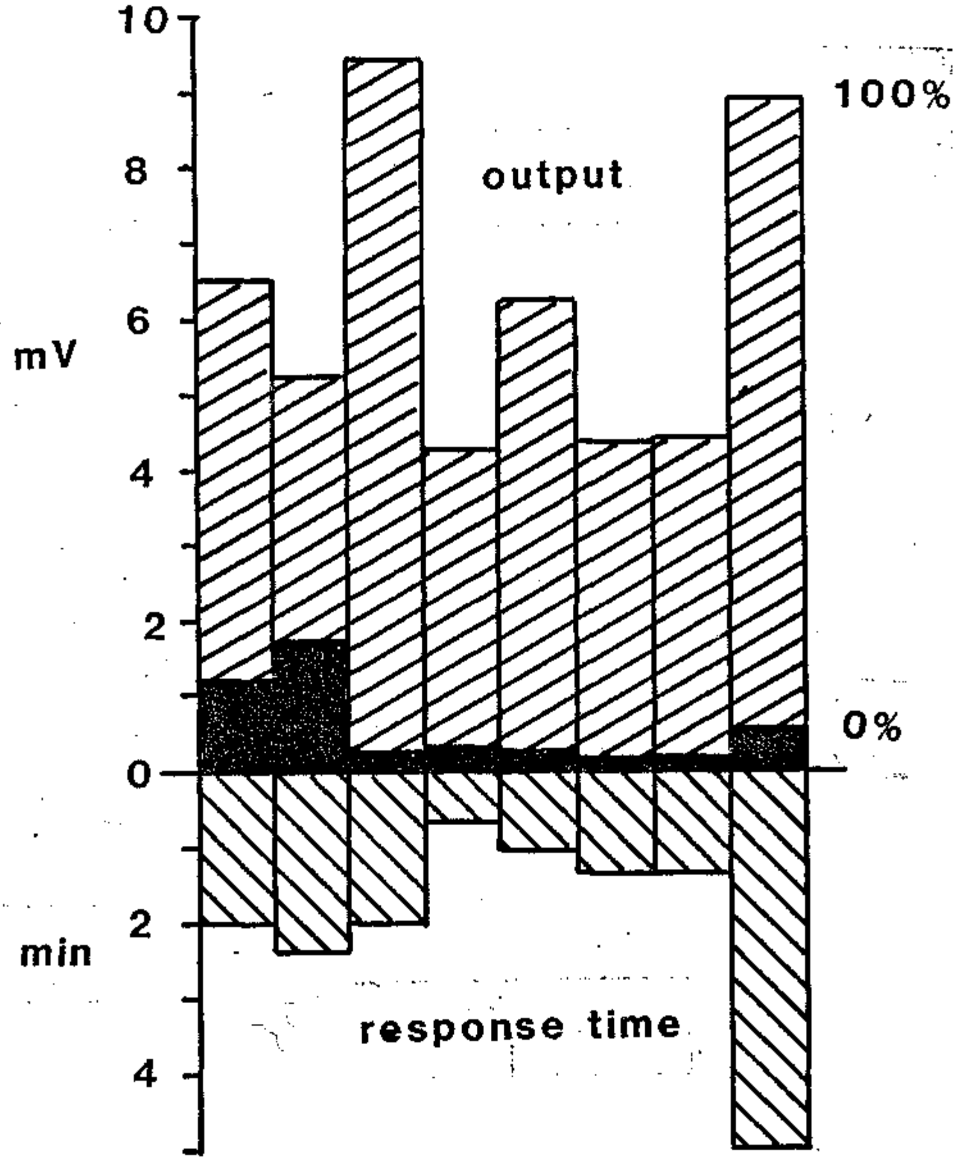
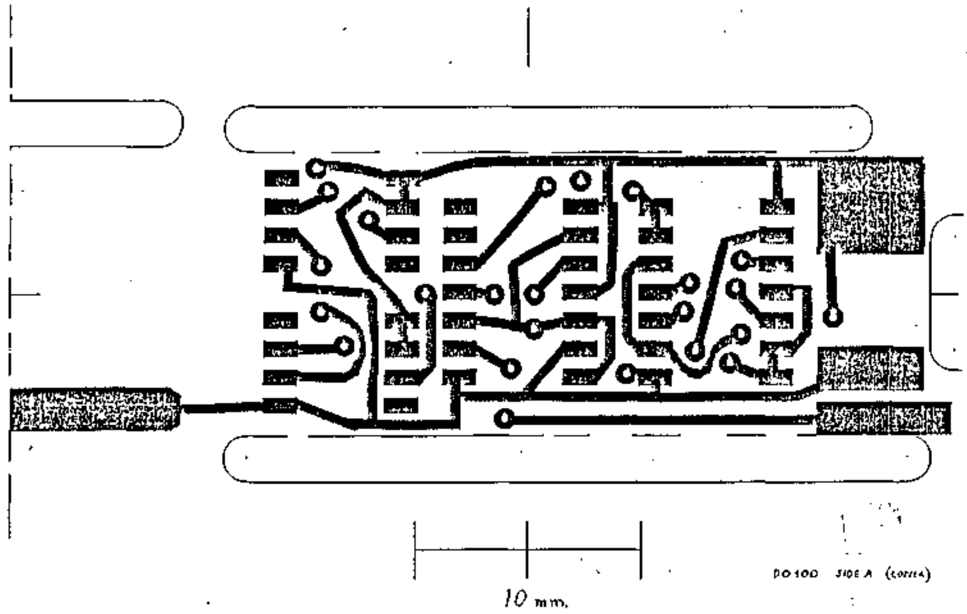
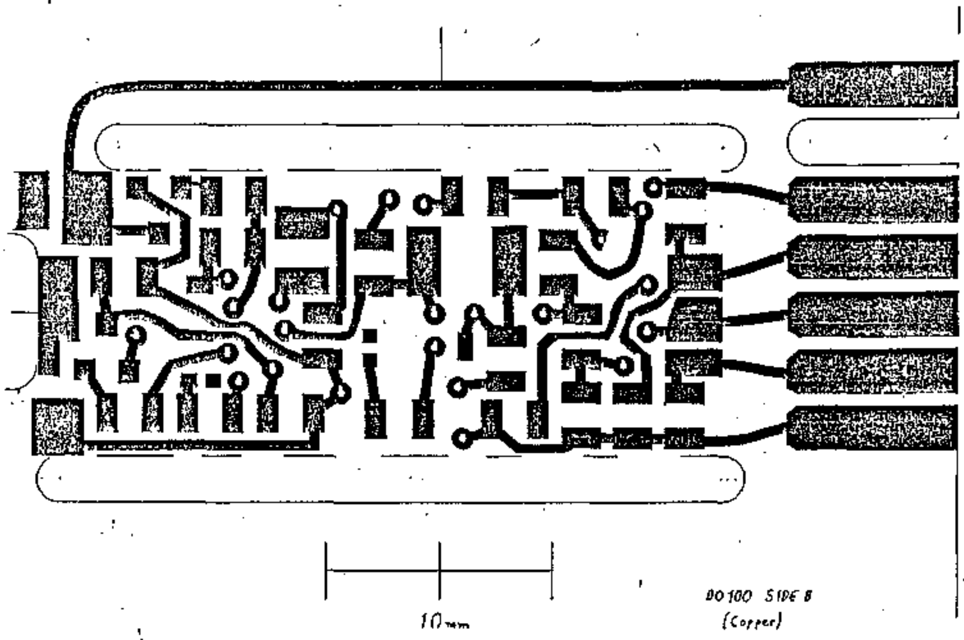


FIGURE 5. Layout of mini printed circuit boards for dissolved oxygen sensing transmitters. (a) layout of circuits on a strip. (b) Copper tracks on the two sides of the board. The edge connector pads allow testing of transmitters when the circuits are assembled on the stock board before separation and assembly into individual transmitters.

(a)


10 mm.
DO 100 SIDE A (COPPER)


10 mm
DO 100 SIDE B
(Copper)

(b)

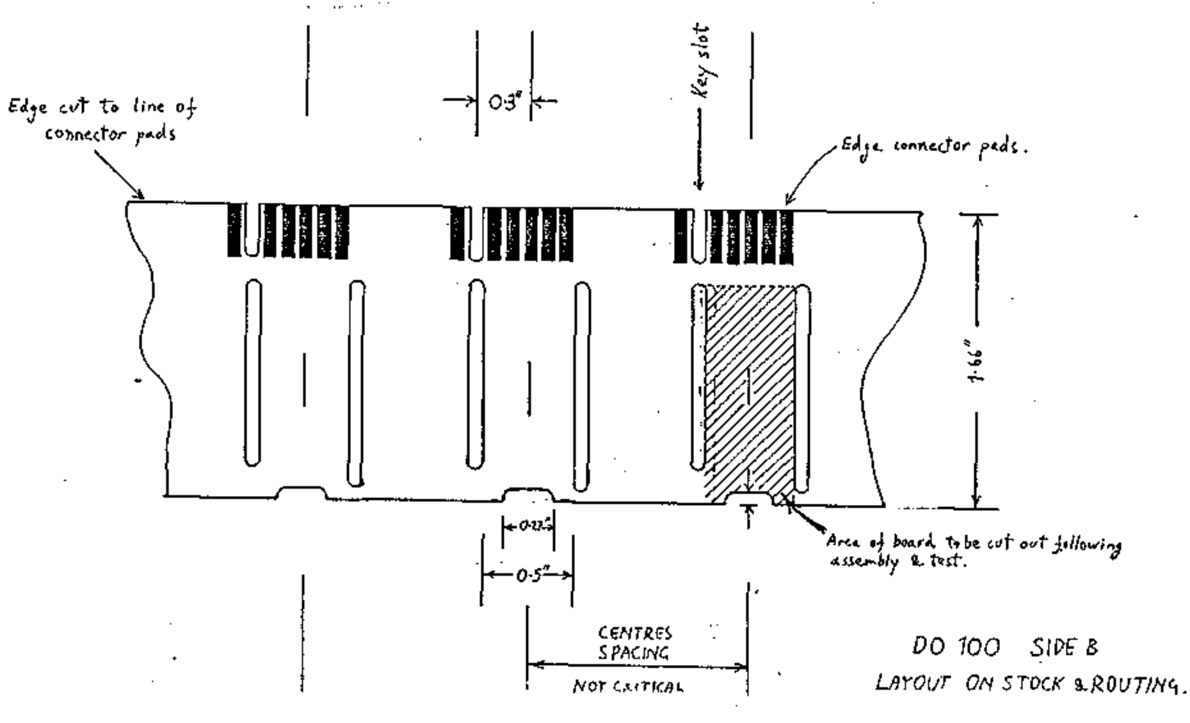

Edge cut to line of connector pads
0·3"
Key slot
Edge connector pads.
1·66"
0·22"
0·5"
Area of board to be cut out following assembly & test.
CENTRES SPACING
NOT CRITICAL
DO 100 SIDE B
LAYOUT ON STOCK & ROUTING.

FIGURE 6. Source levels of acoustic transmitters. Conversions between Decibels sound pressure and power (Watts). The level is conventionally measured at 1m from the source.

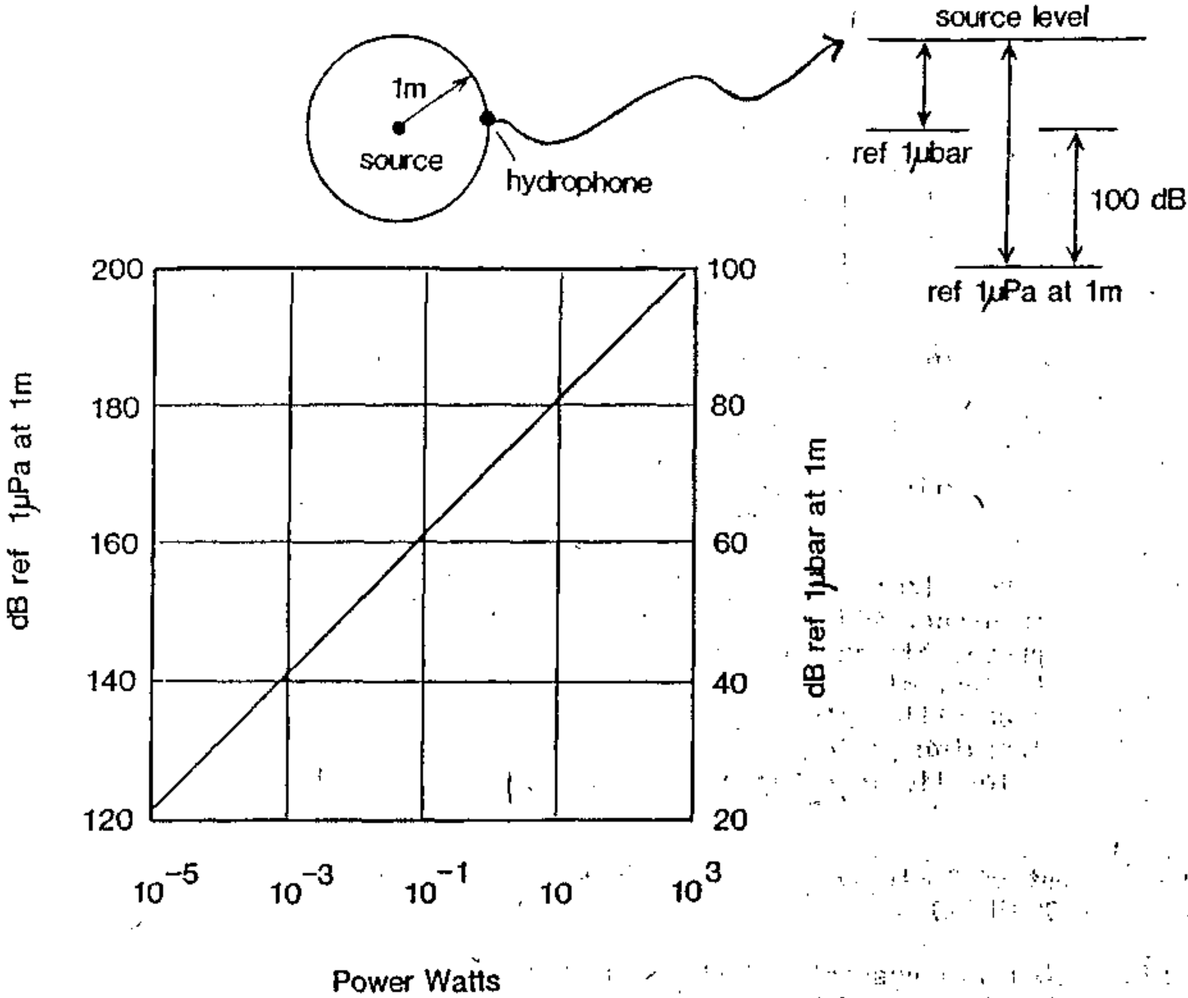
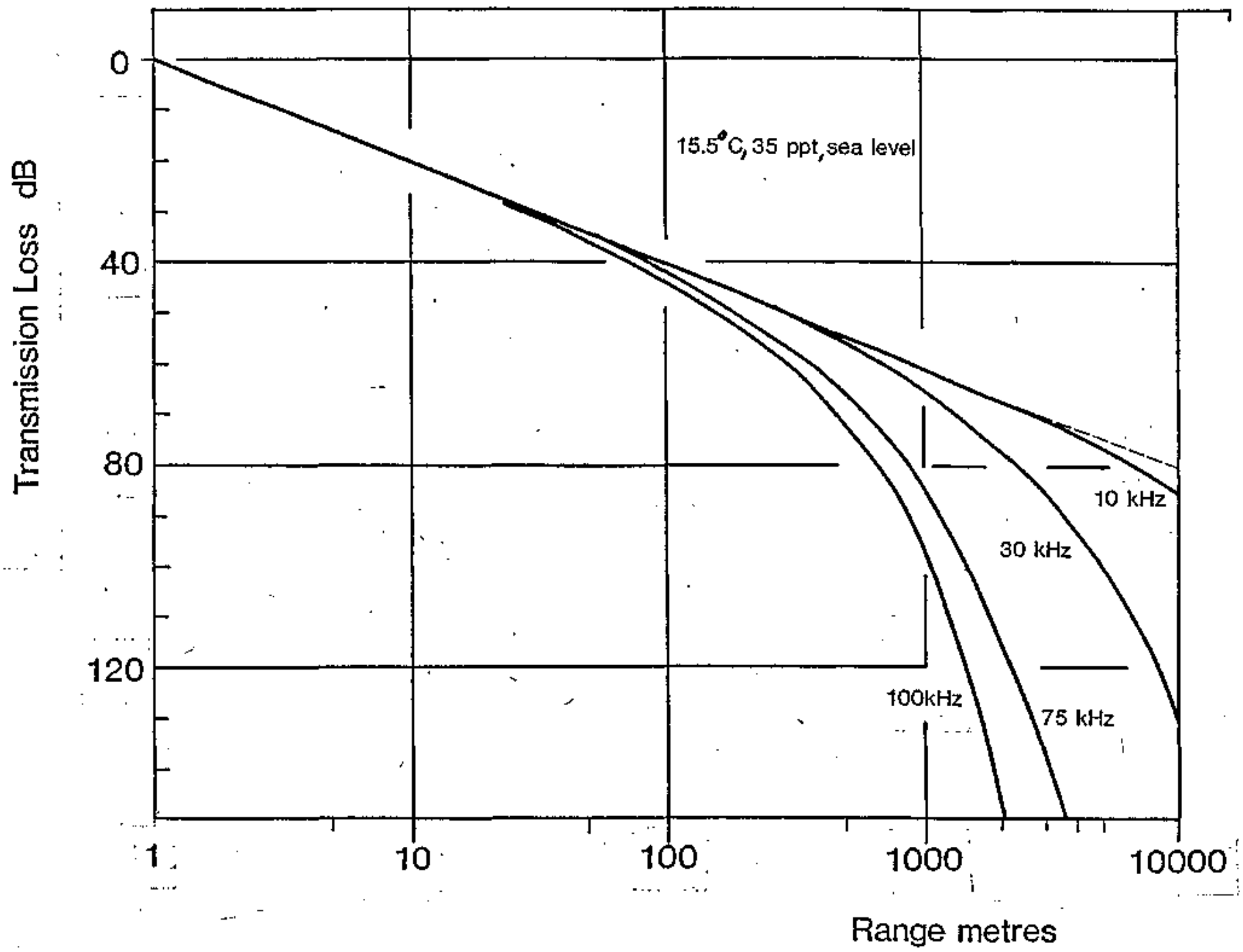
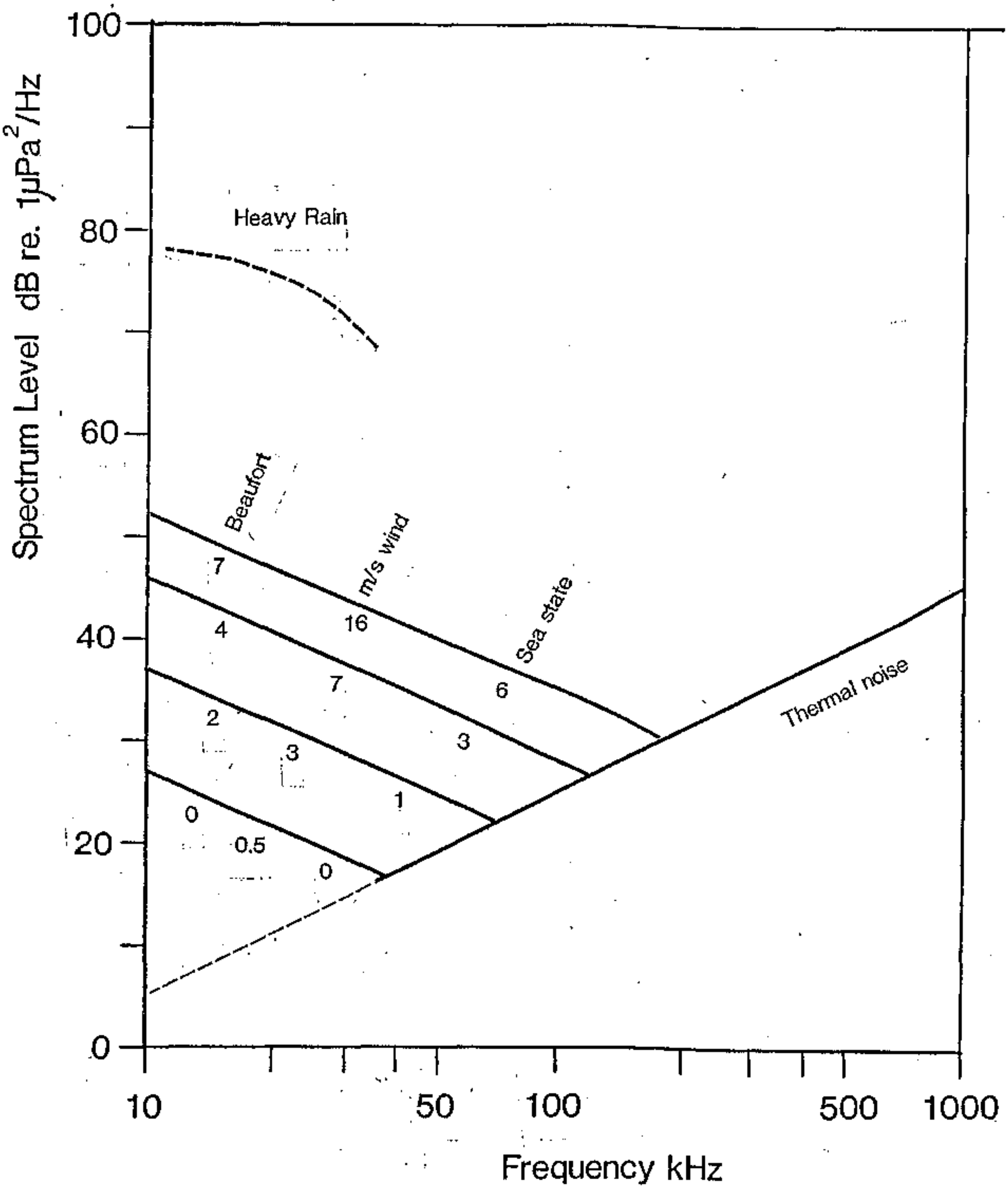

1m
source
hydrophone
source level
ref 1μbar
100 dB
ref 1μPa at 1m
dB ref 1μPa at 1m
dB ref 1μbar at 1m
200
180
160
140
120
100
80
60
40
20
10^{-5}
10^{-3}
10^{-1}
10
10^{3}
Power Watts

FIGURE 7. Transmission loss in sea water with range at different frequencies. 75Khz was chosen for work on the Ribble.



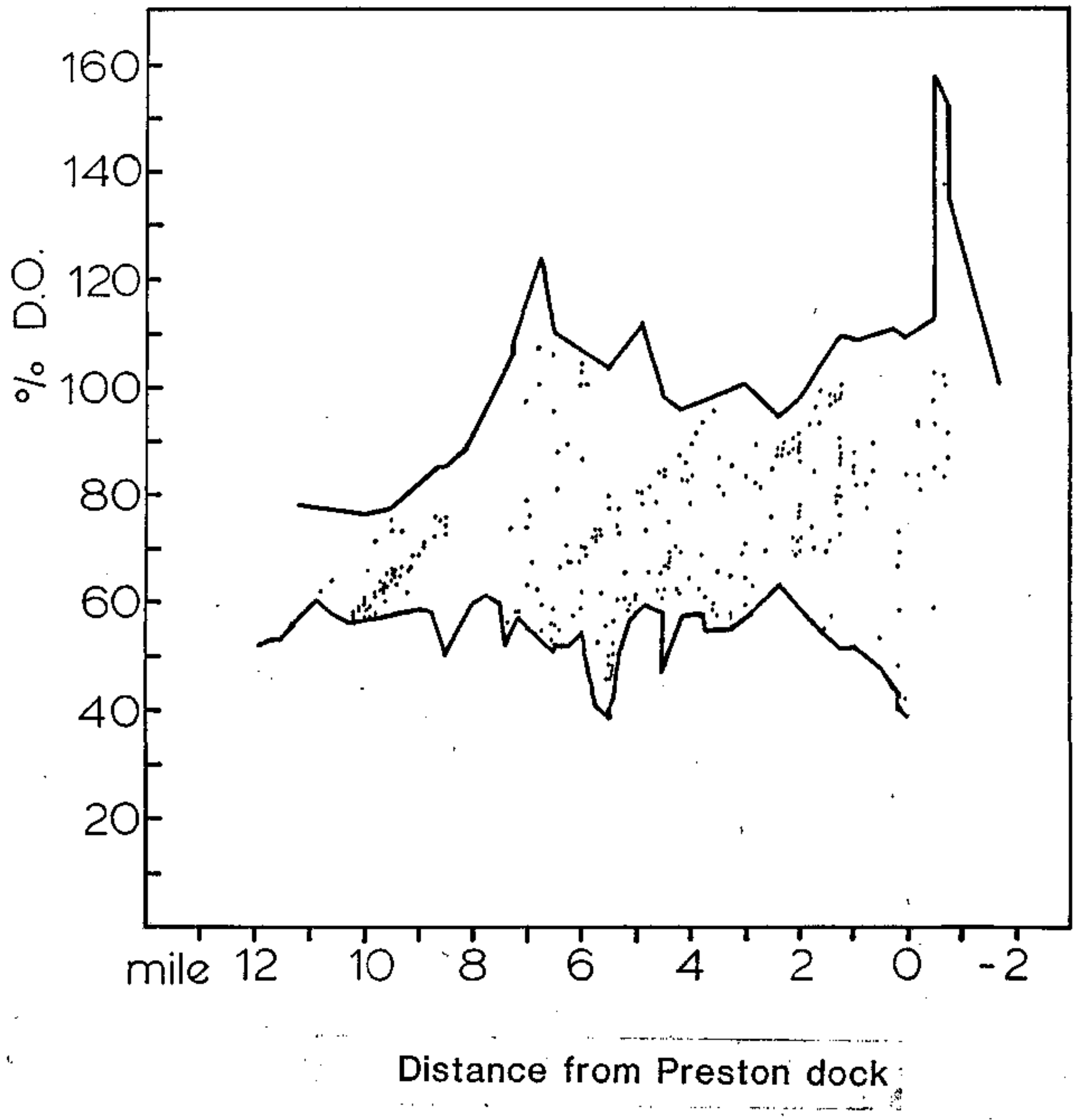
Transmission Loss dB
0
40
80
120
15.5°C, 35 ppt, sea level
10 kHz
30 kHz
100kHz
75 kHz
1
10
100
1000
10000
Range metres

FIGURE 8. Ambient noise spectra at sea. Noise levels are higher in coastal regions particularly in estuaries. Note that 75Khz coincides with minimum noise levels for moderate seas.



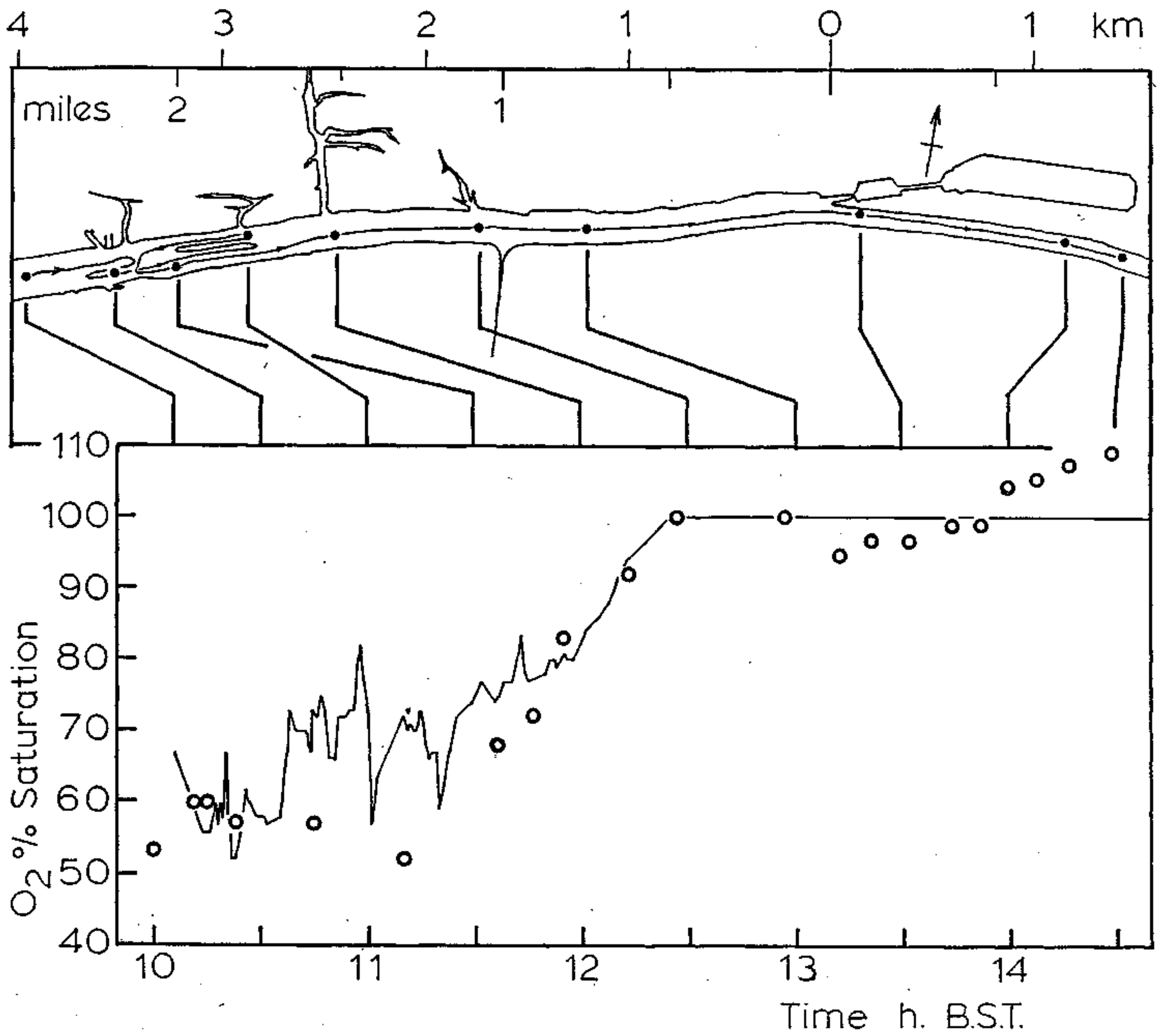
Spectrum Level dB re. 1μPa²/Hz
100
80
60
40
20
0
Heavy Rain
Beaufort
m/s wind
Sea state
7
16
6
4
7
3
2
3
1
0
0.5
0
Thermal noise
10
50
100
500
1000
Frequency kHz

FIGURE 9. Scatter diagram of all DO values measured for salmon and sea trout in the Ribble as a function distance from the dock head. The solid lines indicate the extremes encountred by fish in the estuary.



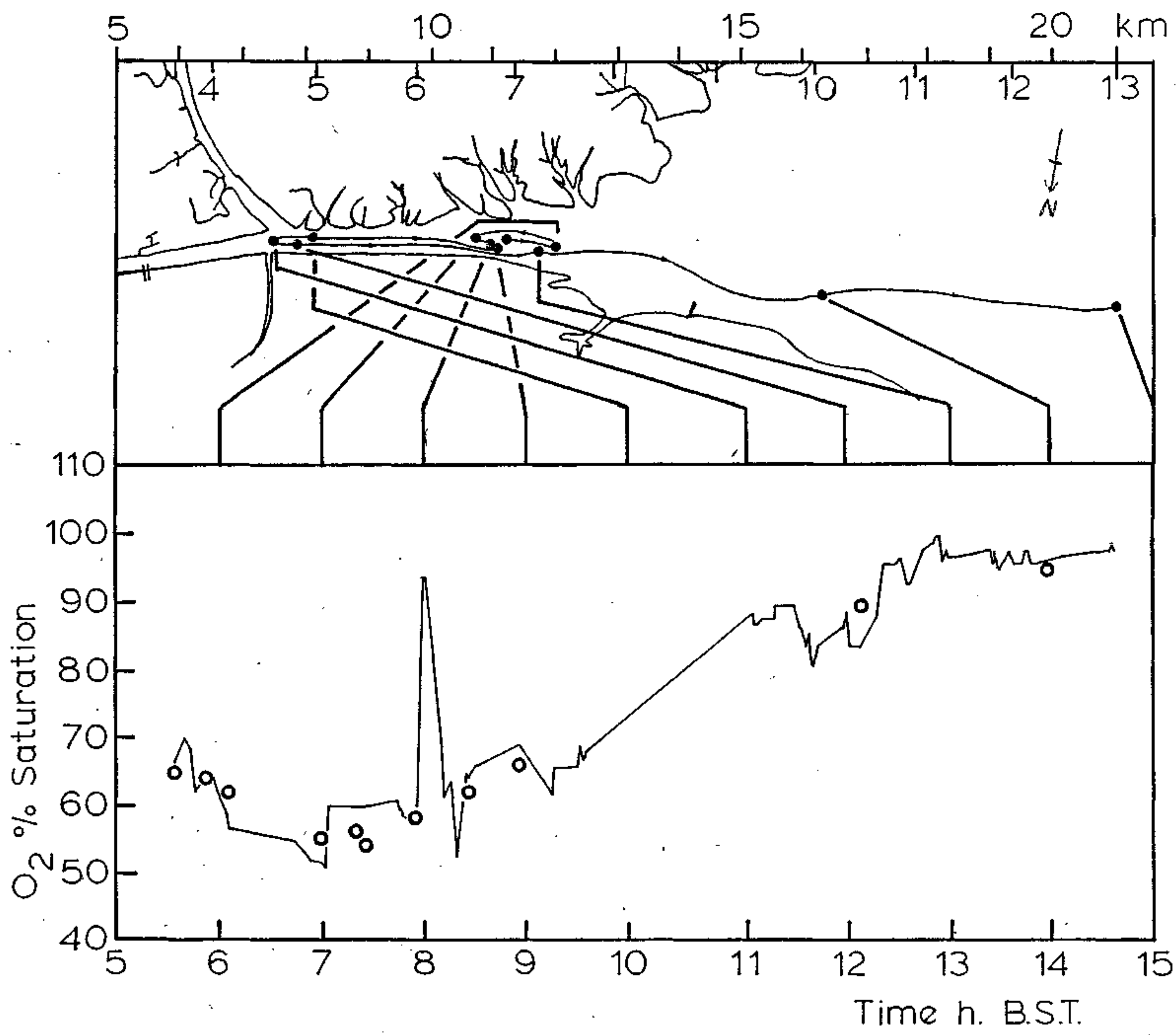
% D.O.
160
140
120
100
80
60
40
20
mile 12
10
8
6
4
2
0
-2
Distance from Preston dock

FIGURE 10. Track of sea trout , Fish 4(86). Comparison of boat readings of DO and readings from the transmitter. The maximum reading possible from the transmitter is 100% saturation; the reading therefore remains constant as the fish swims up into super-saturated conditions.



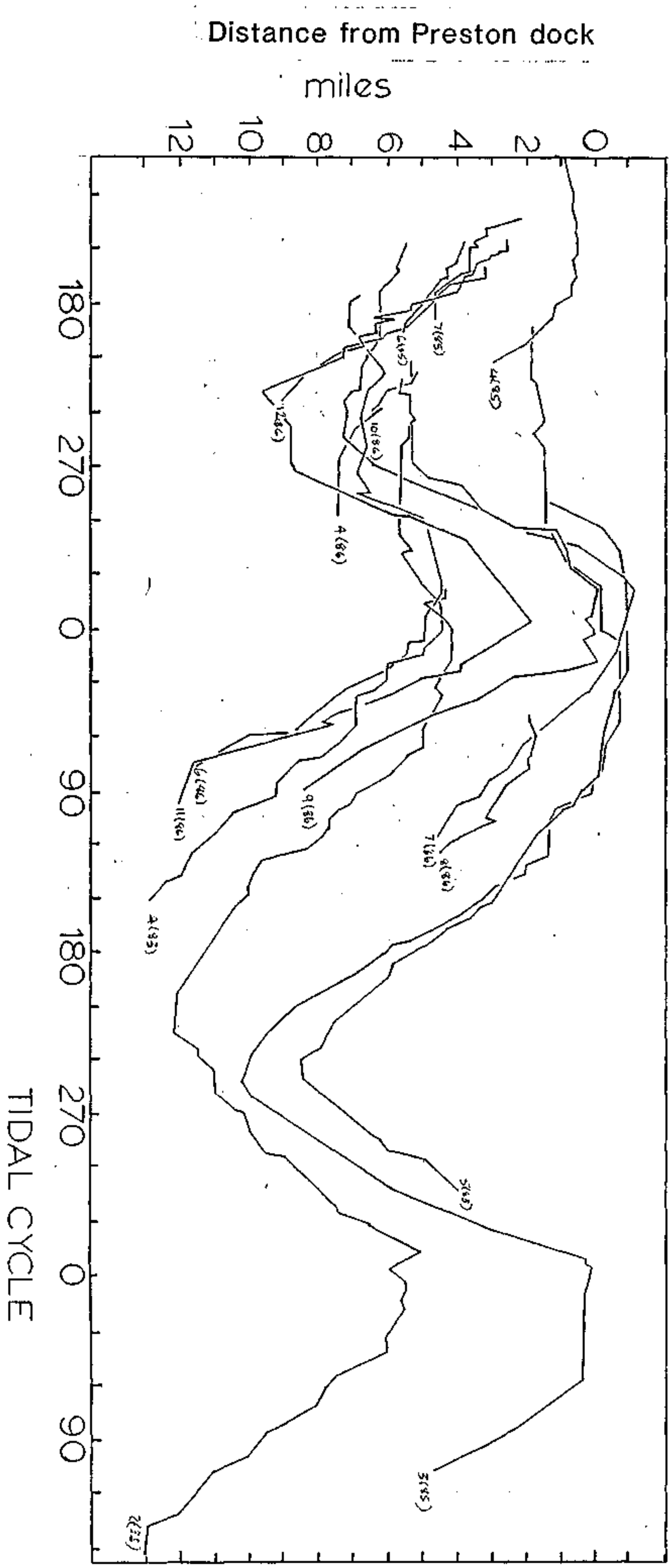
4
3
2
1
0
1
km
miles
2
1
110
100
90
80
70
60
50
40
O2 % Saturation
10
11
12
13
14
Time h. B.S.T.

FIGURE 11. Track of Salmon, Fish 6(86). This fish after oscillating to a fro rapidly moved out to sea on an ebb tide. The high DO readings at approximately 08.00h is where the fish moved out of the channel into very shallow water where it was observed to have "hauled out" in the company of other fish apparently to avoid low DO concentrations.



5
10
15
20
km
4
5
6
7
10
11
12
13
N
110
100
90
80
70
60
50
40
O_2 % Saturation
5
6
7
8
9
10
11
12
13
14
15
Time h. B.S.T.

FIGURE 12. A plot of all salmon tracks superimposed on a uniform scale related to the tidal cycle. ~~The crosses denote the times of high water and the 5 mile mark.~~ A distinct sinusoidal oscillation associated with the tide is immediately apparent.



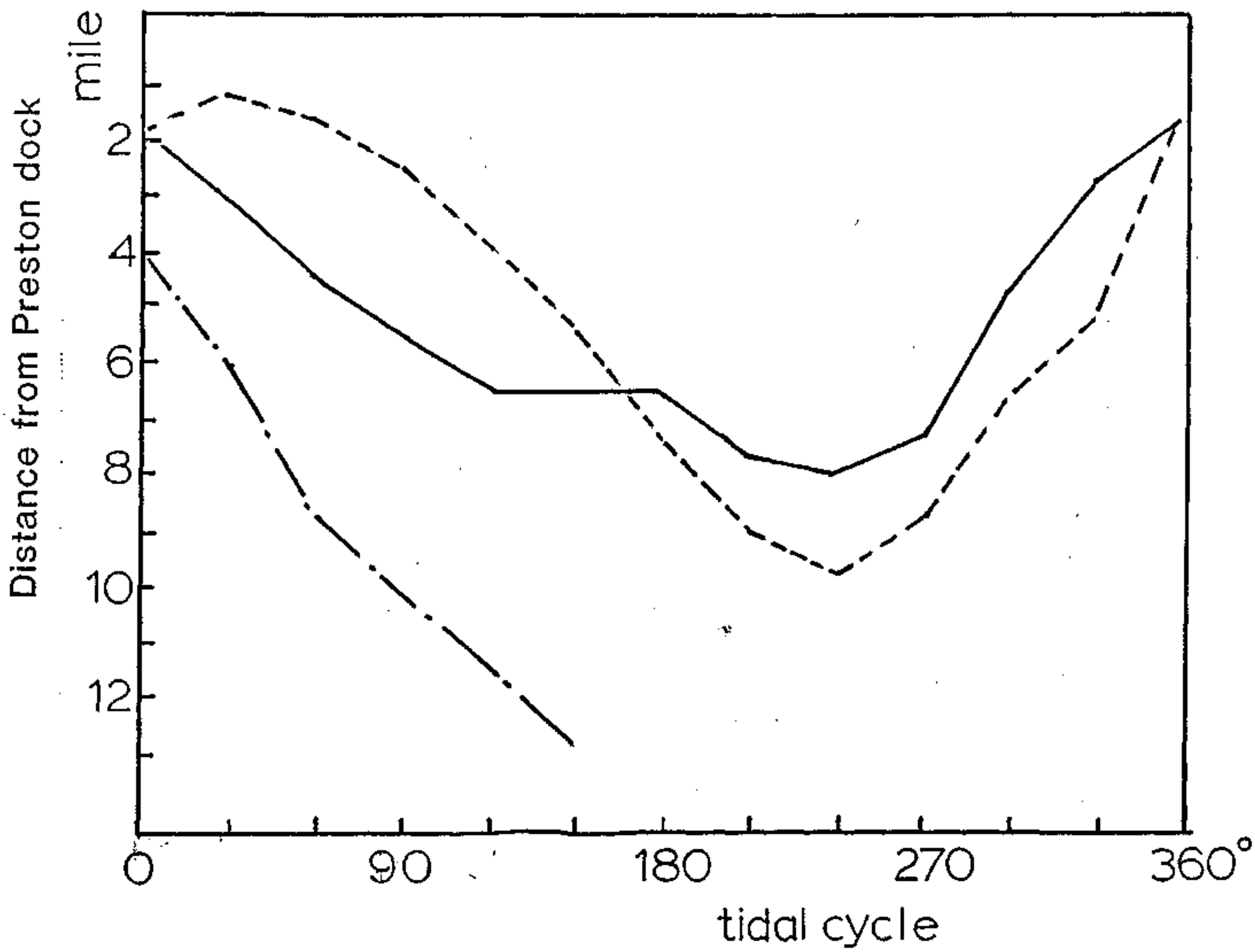
Distance from Preston dock
miles
0
2
4
6
8
10
12
TIDAL CYCLE
180
270
0
90
180
270
0
90

FIGURE 13. Analysis of salmon tracks. Plot of position of fish during the tidal cycle.

Solid line - mean of all data in Figure 11.

Dashed line - mean of all data of fish which remained within the estuary on the subsequent high water, ie all tracks of fish leaving the estuary were excluded from this. This can be taken to represent the normal pattern of movement of fish within the estuary.

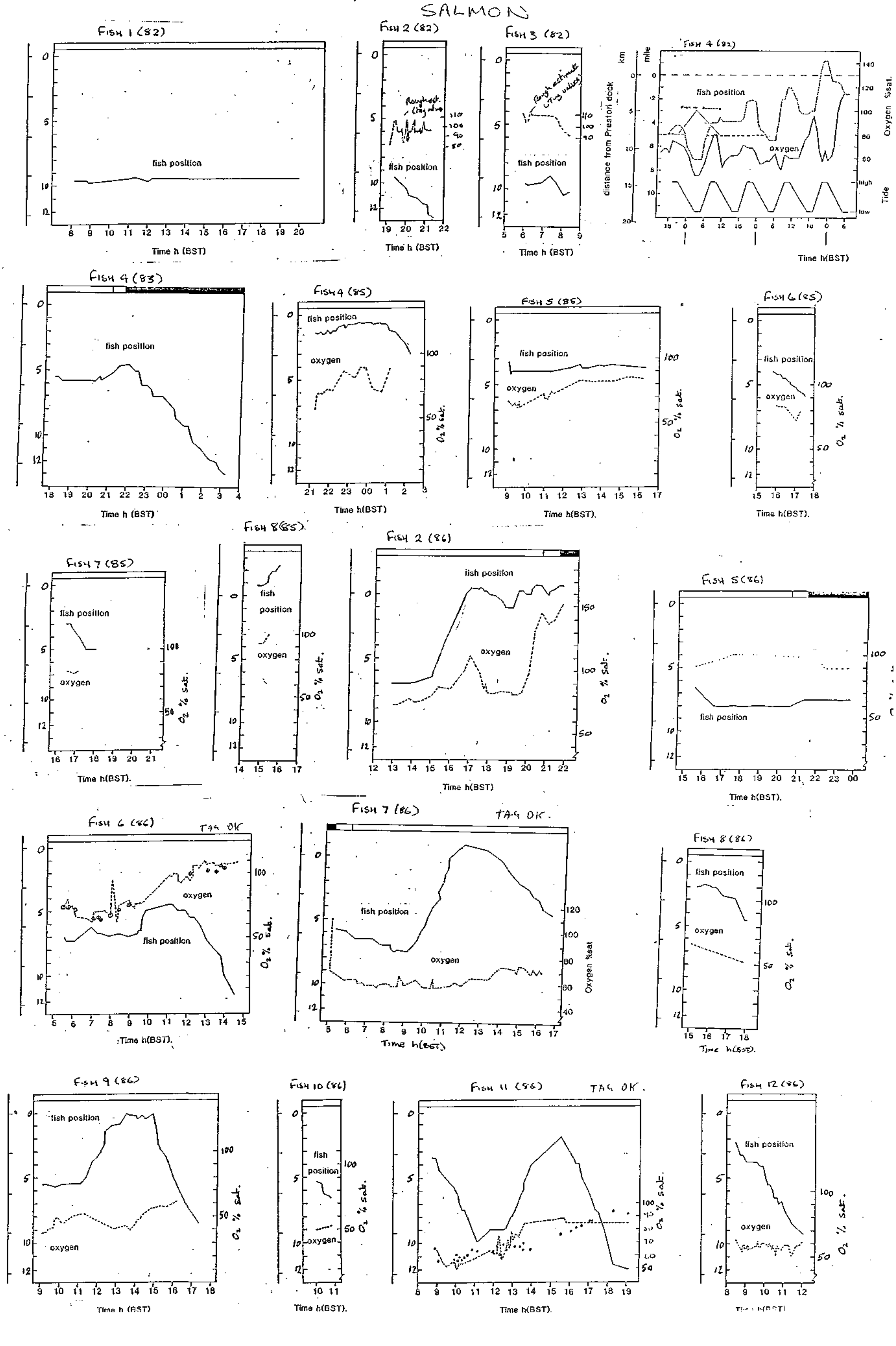
Dash & Dot line - mean of all fish leaving the estuary to go to sea. This shows that fish leave the estuary with the ebb flow.



mile
Distance from Preston dock
2
4
6
8
10
12
0
90
180
270
360°
tidal cycle

FIGURE 14. Tracks of all salmon together with DO readings.

SALMON

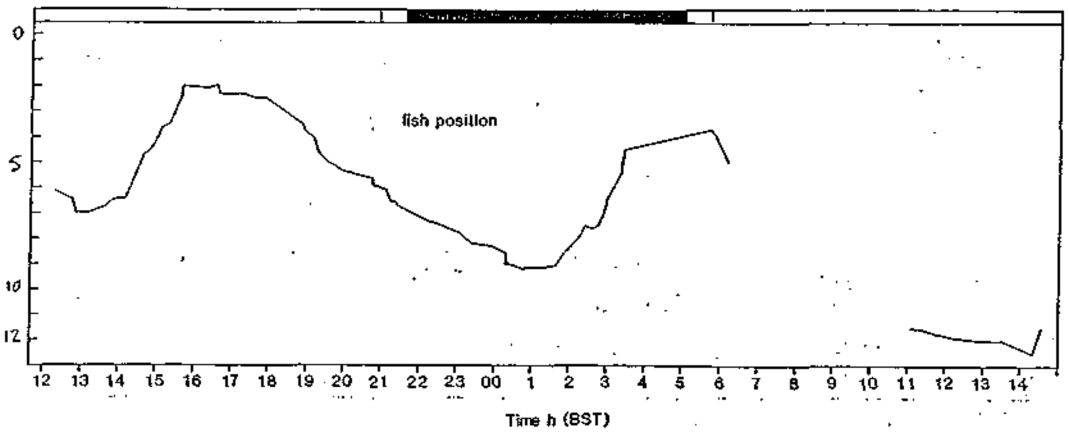


Fish 1 (82)
fish position
Time h (BST)
Fish 2 (82)
Roughest. (tag values)
fish position
Time h (BST)
Fish 3 (82)
Rough estimate (tag values)
fish position
Time h (BST)
Fish 4 (82)
km
mile
distance from Preston dock
fish position
oxygen
Oxygen %sat.
high
low
Tide
Time h(BST)
Fish 4 (83)
fish position
Time h (BST)
Fish 4 (85)
fish position
oxygen
O2 % sat.
Time h(BST)
Fish 5 (85)
fish position
oxygen
O2 % sat.
Time h(BST).
Fish 6 (85)
fish position
oxygen
O2 % sat.
Time h(BST).
Fish 7 (85)
fish position
oxygen
O2 % sat.
Time h(BST).
Fish 8 (85)
fish position
oxygen
O2 % sat.
Fish 2 (86)
fish position
oxygen
O2 % sat.
Time h(BST)
Fish 5 (86)
fish position
Time h(BST).
Fish 6 (86)
TAG OK
oxygen
fish position
O2 % sat.
Time h(BST).
Fish 7 (86)
TAG OK.
fish position
oxygen
Oxygen %sat
Time h(BST)
Fish 8 (86)
fish position
oxygen
O2 % sat.
Time h(BST).
Fish 9 (86)
fish position
oxygen
O2 % sat.
Time h (BST)
Fish 10 (86)
fish position
oxygen
O2 % sat.
Time h(BST).
Fish 11 (86)
TAG OK.
O2 % sat.
Time h(BST).
Fish 12 (86)
fish position
oxygen
O2 % sat.

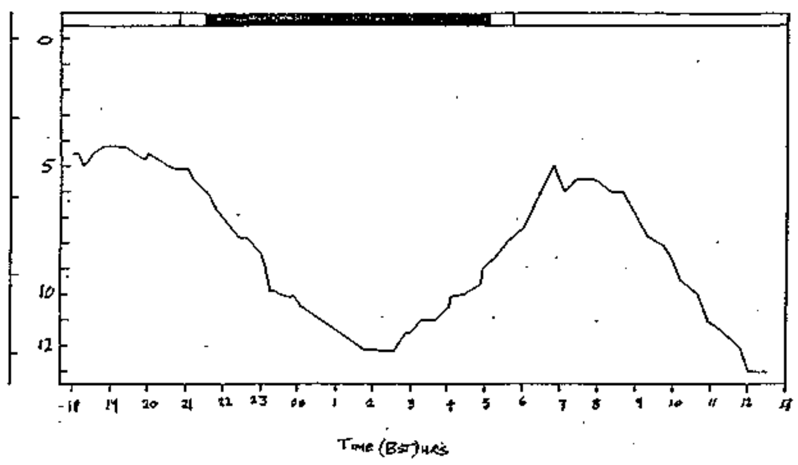
FIGURE 15. Tracks of all sea trout together with DO readings.

SEATROUT.

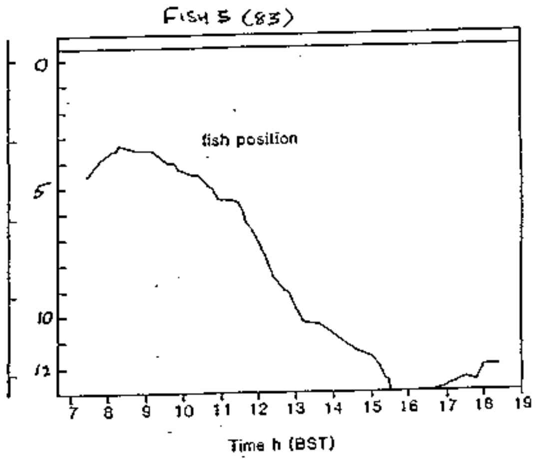
Fish 1 (83)



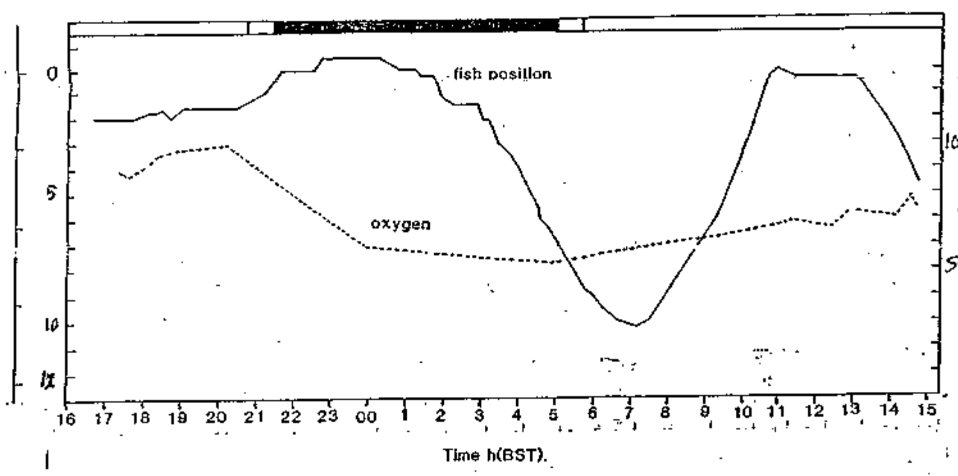
Fish 2 (83)



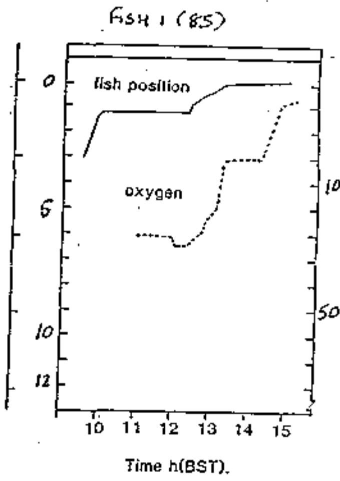
Fish 5 (83)



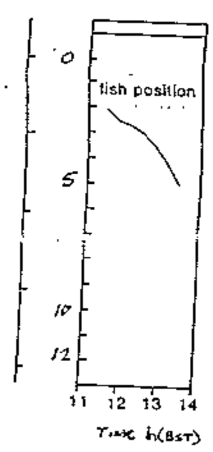
Fish 3 (85)



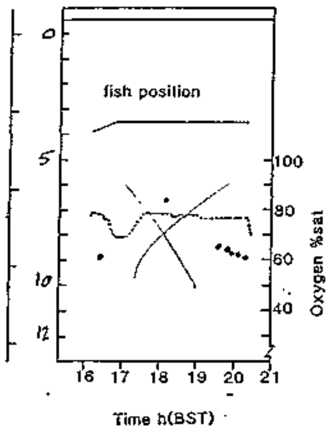
Fish 1 (85)



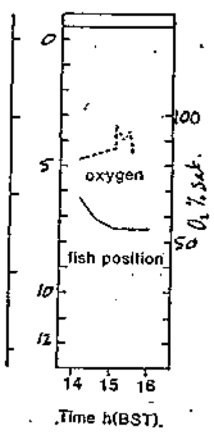
Fish 2 (85)



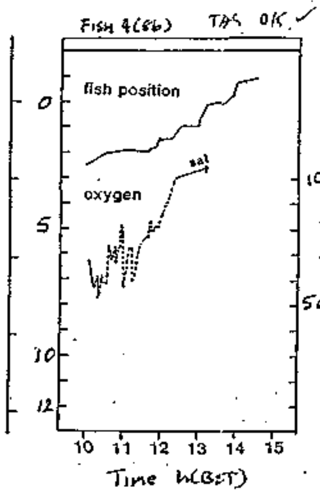
Fish 1 (86) TAG OK



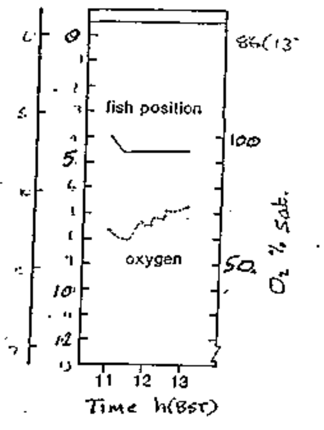
Fish 3 (86)



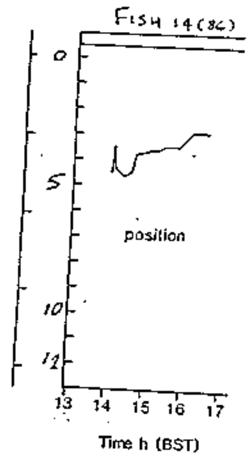
Fish 4 (86) TAG OK ✓



Fish 13 (86)



Fish 14 (86)



Fish 5 (83) – SPECIES UNKNOWN.