WRC WATER RESEARCH CENTRE

A SURVEY OF ESTUARINE OXYGEN CONCENTRATIONS IN RELATION TO THE PASSAGE OF MIGRATORY SALMONIDS

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SUMMARY

This report presents the first attempt at a national assessment of an Environmental Quality Standard (EQS) for dissolved oxygen (DO) in estuaries with the objective of allowing the passage of migratory salmonids.

Under the Control of Pollution Act, Water Authorities and River Purification Boards have powers to control discharges to estuaries and need to define an EQS for the calculation of consent conditions. The object of any such standards is to permit the existence of good quality salmonid fisheries with only very occasional restrictions to the passage of fish.

The report gives brief summaries of the DO regime in estuaries, the oxygen requirements of salmonids, and of tentative standards proposed by various authorities. These standards are then compared with DO and fishery data from UK estuaries, provided by the appropriate regulatory authorities. It concludes that a minimum annual lower 95-percentile of 5.0 mg/l will meet the objective in most estuaries, and that a lower value of 3.0 mg/l will permit the establishment of a more restricted fishery. However, more stringent standards may be needed in estuaries containing high concentrations of toxic pollutants.

CONTENTS

1. INTRODUCTION

Under the Control of Pollution Act 1974 (Part II), the Water Authorities (WAs) in England and Wales and River Purification Boards (RPBs) in Scotland will have their powers extended to encompass control of discharges to all estuaries and coastal waters within their respective areas.

Calculation of consent conditions for discharges depends on a definition of Environmental Quality Objectives (EQOs) of the receiving waters. The EQO approach then involves the setting of Environmental Quality Standards (EQSs) for the critical water-quality parameters in a particular water body so that it fulfils the defined objective(s). A commonly applied EQO for estuaries is that recommended in the Third Report of the Royal Commission on Environmental Pollution (1972)(1), namely "the ability to allow the passage of migratory fish at all states of the tide". In respect of this objective the most common limiting constraint on the water quality of estuaries is the level of dissolved oxygen (DO) in the water. In the UK it is the migration of the salmonid species (Atlantic salmon (*Salmo salar*) and sea trout (*Salmo trutta*)) that is most susceptible to disruption by low estuarine DO.

The initial selection of an EQS usually entails consideration of toxicity data and actual concentrations found in the environment. The resulting tentative proposals are then re-evaluated in the light of experience. It is difficult to define an easily applied single value EQS for dissolved oxygen for all estuaries because of the complexity of the DO distributions found and because of the difficulty in obtaining realistic experimental data. Nevertheless some values have already been proposed.

This report first gives a brief background summary of the DO regime of estuaries and of salmonid oxygen requirements, as well as of some proposed standards. These standards are then compared with field data provided by the regulatory authorities. The report highlights some of the problems in defining an EQS to protect migrating salmonids in estuaries and provides a wider database for re-evaluation of existing proposed standards than would normally be available to individual Water Authorities and River Purification Boards.

2. DISSOLVED OXYGEN IN ESTUARIES

Large variation in DO throughout an estuary can be seen on a temporal and spatial basis. Concentrations can range from zero to over 15 mg/l. In industrialised estuaries receiving effluents with high biochemical oxygen demand, such as sewage, the variation is even more complex.

In such estuaries, the highest DO concentrations occur at the seaward and freswater limits of the estuary (providing of course that the inflowing river is oxygenated). When the DO level at a point is plotted against its position along the axis of the estuary, the distribution produced is known as an "oxygen-sag" curve. Such curves give a profile of the DO concentration along the estuary at a given time.

Due to tidal movement, the DO at any one point is seldom constant over a tidal cycle. Sag curves plotted at low and high water will show the same general distribution, but the position of the curve will be displaced by the distance of the tidal excursion. This in turn is dependent on the amplitude of the tide, being generally greater for spring tides than for neaps.

Superimposed on this variation are the effects of freshwater flow and temperature. At low flows, flushing is reduced and consequently the concentration of pollutants in the estuary increases and the DO concentration falls. The minimum concentration will also occur nearer the head of the estuary. Temperature affects DO in two ways. At higher temperatures the solubility of oxygen is reduced, and biological activity (especially bacterial and phytoplankton growth) increases. These two effects normally result in a lower DO concentration. Minimum DO concentrations, usually occur when temperatures are highest and flows lowest - between late spring and early autumn.

In addition, DO may vary both laterally and vertically in a cross-section. Some estuaries are stratified and in these situations oxygenated water may overlay an anaerobic layer, or vice versa. An example from the Clyde estuary is shown in Figure 1.

A further complication in the measurement of DO is the variation in the solubility of oxygen with salinity (see Appendix A). Oxygen is about 20% less soluble in sea-water than in fresh-water, and therefore units such as "percentage air saturation" (% ASV sat) can imply very different absolute concentrations (measured in mg/l) and must be used with care.

3. DISSOLVED OXYGEN REQUIREMENTS OF MIGRATORY SALMONIDS

Salmon breed in fresh-water streams and rivers(2). After hatching the fry remain in fresh-water for between 2 and 4 years before developing into smolts which migrate down river through the estuary to the sea, where they mature.

Although some adult fish return in their first year (known as grilse), most only return after a further 2 to 4 years. After breeding many adults die, but some repeat the migratory cycle (spent fish being called kelts).

The seaward smolt migration usually occurs between April and June and, although adults can be found returning throughout the year, most rivers have specific periods of intense fish runs. Sea trout have a similar life-cycle but, unlike salmon, adult fish normally stay in coastal waters.

To maintain a salmon fishery in a river, its estuary must be capable of permitting the passage of salmonids at least during the critical periods of migration. The oxygen requirements of fish in fresh-water have been extensively reviewed in a report by European Inland Fisheries Advisory Commission (EIFAC)[3], who also considered salmonid requirements in estuaries. Most of the information in the following sections is derived from their report.

3.1. LABORATORY STUDIES

The EIFAC review of salmonid DO requirements in freshwater showed that DO consumption varied from species to species, between life-stages and with the activity that the fish were engaged in, such as swimming, feeding etc. It suggests that concentrations below 0.95-3.4 mg/l are lethal for salmonids and that the young are most sensitive. Active avoidance of low DO was noted in an experiment with chinook salmon.

There are very few equivalent data available on the oxygen requirements of salmonids in estuaries. However, Alabaster et al. 1979(4) did carry out a study on the effect of low DO concentrations on smolts in freshwater, and in 50% and 80% sea-water. The 3-day LC50 values for DO under these conditions were found to be 3.0 mg/l in fresh-water and 2.5 mg/l in 50% and 80% sea-water. It was also shown that fish kept at relatively low concentrations of DO prior to the test were able to acclimatise to these conditions resulting in lower LC50 values.

Further work(5) showed that at low DO levels other pollutants, namely ammonia, could become more toxic to salmonids than at normal levels of DO. When the DO was close to 100% saturation the 24-hr LC50 values of unionised ammonia to salmon smolts in freshwater and 30% sea-water were 0.15 and 0.30 mg/l respectively. However, when the DO under these conditions were reduced to 3.5 and 3.1 mg/l, the 24-hr LC50 values for unionised ammonia were 0.09 and 0.12 mg/l respectively. Evidence was also presented showing that these values increased if smolts were acclimated to high ammonia concentrations before testing.

Since avoidance and acclimation to low oxygen concentrations reduce the detrimental effects experienced by fish, the availability of alternative routes and their speed of migration through an estuary could affect the viability of a fishery.

3.2. FIELD STUDIES

Due to the difficulties experienced in determining precise requirements for estuarine DO in migrant salmonids in the laboratory and the problems of applying results to field conditions, some workers have attempted more direct field investigations.

EIFAC report that migration of chinook salmon through a fish pass was inhibited at DO concentrations below 5 mg/l, though some migration did occur even at 3 mg/l. Similarly, a study of catch data from the Tyne estuary (provided by the Northumbrian Water Authority) showed that salmon passed upstream when the DO was between 4.5 and 6.8 mg/l. However, in this case no minimum value could be determined.

Recently, experiments have attempted to track the movement of salmon and sea trout in relation to DO concentration in an estuary. This method involves the use of sonic-tagging techniques(6). So far, however, insufficient data are available from these experiments for use in determining an EQS for dissolved oxygen. Despite this a useful insight into the behaviour of migratory salmonids upon encountering poor quality estuarine water has been obtained.

3.3. EXISTING STANDARDS

DO standards or guidelines currently prepared and in use for UK estuaries are summarised in Table 1. All five authorities, whose proposals are given, recognise the importance of defining the minimum concentration in terms of a lower percentile, thus permitting occasional extreme values. Only North West Water Authority (NWWA) have proposed an absolute minimum (3 mg/l).

None of the standards appears to include a clear definition of the origin of the samples to be included in the calculation, or of the time period to be considered. Presumably, the four Water Authority bodies have considered the lower percentiles to be calculated from data collected throughout a year at a particular sampling site and at all states of the tide. The EIFAC standards are somewhat more explicit and require that the samples be taken during the "summer low-flow period in the zone of minimum dissolved oxygen". However, even this is a rather vague definition. No requirements are specified for depth or frequency of sampling.

The four annual lower 95-percentile standards are all in reasonable agreement (at 5-6 mg/l), except that the 40% saturation value proposed for the Humber could be as low as 2.9 mg/l if applied to sea-water at 20°C (an extreme possibility). Furthermore, they are in broad agreement with the EIFAC proposal which relates to a more restricted sampling period during the time of lowest DO.

Only two proposals were made for a mean concentration, which (if the variance of the DO distribution is constant) is not strictly necessary. The EIFAC proposal (5 mg/l) is in reasonable agreement with the annual mean of 7 mg/l proposed by NWWA.

In addition to the value given in Table 1, Welsh Water Authority (WWA) proposes a 95-percentile standard of 7.5 mg/l to be applied when ammonia concentrations are high, and a special standard of 6.5 mg/l for the Usk Estuary which has an unusual natural oxygen regime due to the resuspension of sediment.

4. DESCRIPTION OF THE SURVEY

Individual Water Authorities, such as WWA, have used their own experience and archived data to establish and re-evaluate oxygen standards for application to estuaries under their control. Until now, however, no attempt has been made to collate the information on a national basis.

To collect such information, WRC contacted all WAs and RPBs during 1982. That preliminary survey was followed up by further requests for specific information from selected sources. Table 2 gives a list of the 64 rivers for which data were provided and indicates their status as migratory fisheries.

The DO data received include detailed results of regular longitudinal surveys, statistical summaries of routine sampling at specific points, estimates of mean concentrations and spot measurements at times of specific incidents such as sightings of live fish or fish kills. Most DO concentrations were quoted in units of mg/l, but some were in percent saturation. As only a few of the latter included corresponding values of salinity and temperature no attempt has been made to convert them to absolute units.

Some authorities also provided information on the timing of the main smolt and fish runs.

5. RESULTS

5.1. REPORTED OXYGEN CONCENTRATIONS

In this Section, the DO data are summarised by type, the most useful being those from specific stations which can be reduced to mean and lower 95-percentile values. The resulting statistics are shown in Table 3a and graphically in Figure 2. Where data from several sites along an estuary were available, the values given are for the site with lowest DO concentration. When considering these figures it is important to note that, although some represent samples collected during one year only, most are derived from much longer sampling periods. The range of values is easiest to see in Figure 2, where the lower values indicated by the horizontal bars (L) represent the lower 95-percentiles and the higher values (M) represent the means. Excluding for the moment the Clyde estuary which is considered in more detail in Section 5.3, the figure shows that all estuaries which maintain regular fisheries (and for which no deleterious effects were reported) have minimum mean oxygen concentrations greater than 8.2 mg/l and that the minimum lower 95-percentile is 4.4 mg/l.

Similarly, the estuaries to which salmon are beginning to return (Trent and Thames) and where occasional oxygen restrictions occur (Usk and Ribble) have mean concentrations above 6.4 mg/l and 95-percentile values above 3 mg/l. The Tyne is stratified, and although the depth-averaged 95-percentile value is only 0.6 mg/l, it is possible that fish are able to select the depth containing the highest DO. If this were the case then the relevant 95-percentile value would be 2.5 mg/l. Yorkshire Water Authority (YWA) report that occasional smolt runs occur in the Ouse system, which has a lower DO than this, but that these do not seem to be very regular.

No self-sustaining fisheries were reported from the rivers Douglas, Mersey, Wampool or Waver. However, migrating salmonids do make runs into the estuaries of the Douglas and Mersey, but salmonid mortalities, associated with poor water quality, have also been reported. The absence of salmonid fisheries from the Wampool and Waver systems may be due to the physical unsuitability of their tributaries.

For some estuaries only mean values or extreme values have been reported, see Table 3b. These figures do not conflict with those in Table 3a. In addition, four authorities reported specific short term observations when fish were migrating (see Table 3c). The values are given here for completeness, but will not be considered further as they are not intercomparable. In this table the DO concentrations given for observations of live fish in the Clyde RPB area are the lowest measured in the vertical profile, whereas those for negative effects are the highest DO observed over the depth. Data for the Forth and Thames estuaries have been averaged over all sampling stations.

5.2. TIMING OF MIGRATORY RUNS

Most authorities also provided information on the timing of the main migratory runs;this is summarised in Table 4. Many also indicated that salmon often return throughout the year.

To maintain a viable fishery, the main migration periods are obviously the most critical times of year. However, for most estuaries these runs coincide with the minimum fresh-water flow and highest temperatures and therefore with the lowest oxygen concentrations. This situation is discussed in relation to the Clyde estuary.

5.3. CLYDE ESTUARY

The Clyde Estuary (Fig. 3) is particularly interesting because, although the River Clyde itself does not support a migratory fishery, the most seaward tributary to the estuary (the River Leven) has excellent salmonid runs. Salmon are also returning to another tributary, the River Gryfe.

The Leven joins the main estuary 23.4 km below the tidal weir in Glasgow, and the Gryfe is a tributary of the River Cart which joins the Clyde 11.4 km below the weir. In the main estuary the lowest depth-averaged oxygen concentration occurs at or slightly upstream of the R. Cart confluence.

Clyde RPB (CRPB) has provided regular survey data from along the central channel of the main estuary for 1980 and 1981. These have been analysed in an attempt to identify the conditions which permit the existence of these two fisheries. Interpretation of the data is complex because:

(a) Surveys were made at low water only and allowance has to be made for the tidal excursion (of between 6.5 and 9.5 km);
(b) The estuary is stratified and the oxygen concentration is not constant over the depth. Deoxygenated water often lies over water containing a reasonable concentration of oxygen, and vice versa;
(c) There is a complex of channels in the lower estuary and measurements in the central channel may not be representative of the whole cross-section.

Nevertheless, some conclusions can be drawn from the data, and the complexity of the analysis emphasises the difficulty of applying simple water quality standards to estuaries.

5.3.1. Leven fishery

CRPB state that there have been no observed fish kills either in the Leven or in the main estuary downstream of its confluence and that this zone meets the Royal Commission recommendations.

An initial simplistic analysis of the survey data gives the values quoted in Table 3 and Figure 1. These are the annual means and lower 95-percentiles of the depth-averaged concentrations observed at the confluence on the routine low-water surveys for 1980 and 1981. The values are clearly much lower than those observed in other estuaries supporting salmonid fisheries.

Two possible reasons for the free passage of salmonids under these conditions are the physical characteristics of the estuary and the seasonal variation in oxygen concentration. Data from 1980, the year in which lowest oxygen concentrations occurred, is used to illustrate these processes.

Firstly, fish may pass between the Leven estuary and the main channel at any phase of the tide. The oxygen concentrations to consider are therefore all those between high and low water at the confluence. Due to tidal excursion, these are equivalent to all those observed in the main channel between 23.4 and (at most) 32.9 km seaward of the tidal weir in Glasgow during the low-water surveys. The annual mean and 95-percentile values for this reach were 6.8 mg/l and 2.9 mg/l respectively, somewhat higher than those for samples taken at the confluence only. These values demonstrate that better quality water is available for passage of fish when considering all tidal states.

However, even over the entire reach the 95-percentile is low and indicates that low oxygen concentrations occur during a significant proportion of the year. It is therefore important to consider the concentrations during the critical periods of the main fish runs.

In the Leven (Table 4) the main smolt run occurs between April and June and adult salmon migrate upstream between February and May. During the period of the smolt run in 1980, the mean and 95-percentile values of the reach between 23.4 km and 32.9 km were 6.5 mg/l and 2.8 mg/l, respectively. For the period of salmon migration the equivalent figures are 7.2 mg/l and 4.3 mg/l. Only one survey was conducted during the sea-trout run in June so the relevant statistics cannot be calculated.

Water quality during the period of salmon migration is obviously better than that for the smolt run. This in turn gives an indication of the lower concentrations at which a healthy fishery can be maintained.

Nevertheless, it is important to note that two factors have not been taken into account in the above analysis. There may have been better quality water in the side channels of the main Clyde estuary and, due to stratification, water containing at least 3.7 mg/l of dissolved oxygen was always present throughout the reach at some depth within the vertical profile. Fish may therefore have been able to select migration routes which avoided the lowest oxygen concentrations. If this were the case and if smolts always chose the depth at which maximum DO occurred, then they would have encountered water with a mean DO of 7.3 mg/l and a 95-percentile of 4.6 mg/l.

5.3.2. Gryfe fishery

Similar arguments and methods of data analysis to those described for the Leven apply to the Gryfe. For this tributary the water in the main estuary which passes the confluence during a tidal cycle can be approximately equated with that between 13.8 km and 23.4 km downstream of the tidal weir at low-water.

The depth averaged mean and lower 95-percentile values during 1980 for this body of water were 5.5 mg/l and 0.03 mg/l, respectively. For the salmon migration period they were 5.6 mg/l and 0.9 mg/l; and during the smolt run they were 3.6 mg/l and 0.0 mg/l. At all times during the smolt migration there was water with at least 1.5 mg/l of oxygen at some depth in all parts of the reach. If the smolt were able to select their route through the reach, always choosing water with the highest oxygen concentration, then in fact they would have encountered water with a mean concentra- tion of 5.1 mg/l and 95-percentile of 1.0 mg/l.

These concentrations are all extremely low, yet a new fishery with regular runs is becoming established.

6. DISCUSSION

In this section the observed minimum DO concentrations in estuaries permitting the migration of salmon are compared with previous studies and with the proposed regional standards. The results from the Clyde are not included in the discussion because of the difficulty in interpretation of the data. However, the data from the Clyde suggest that salmon and smolt are capable of actively avoiding water in which low DO concentrations do occur if alternative, better quality, water is available. This is supported by preliminary tagging work on the Ribble estuary[6].

6.1. COMPARISON WITH PREVIOUS DATA

The concentrations at which negative effects have been observed to occur, in laboratory or restricted field studies, are not strictly comparable to the continuously varying concentrations normally found in the environment. However, it is reasonable to compare such values with the minimum lower

95-percentiles of the observed concentrations in estuaries with fisheries.

The two field studies quoted in Section 3.2 indicate that DO concentrations of at least 4.5-5.0 mg/l permit the free passage of migratory salmonids. This value is comparable with the minimum lower annual 95-percentile concentration of 4.4 mg/l observed in UK estuaries supporting regular fisheries.

Presumably at lower concentrations the ability of salmon to negotiate an estuary is reduced but is not prevented, provided of course that the lethal limit is not reached. On the basis of laboratory studies (Section 3.1) this lower limit is about 2.5 mg/l. This, in turn, is in reasonable agreement with the minimum 95-percentile of 3.0 mg/l for estuaries where fisheries are beginning to recover or experience occasional deleterious effects.

6.2. COMPARISON WITH PROPOSED ENVIRONMENTAL QUALITY STANDARDS

Standard concentrations of dissolved oxygen have been proposed by some regulatory agencies (see Table 1) to maintain regular migratory salmonid fisheries in UK estuaries. These standards range between 5 and 6 mg/l as minimum annual 95-percentiles and correlate with observed dissolved oxygen levels in most UK estuaries supporting salmonid fisheries. Only one estuary has a lower observed 95-percentile dissolved oxygen concentration that is the Tawe estuary in Wales; where the lower 95-percentile concentration is 4.4 mg/l. Despite this a standard of 5 mg/l as a lower 95-percentile concentration of dissolved oxygen is suggested as a guideline standard to protect migratory salmonid fisheries given the variation in physical and chemical conditions between individual estuaries.

At lower concentrations a reduced migration or occasional fish kills may occur. However, the minimum 95-percentile required to permit the limited migration of salmonids is approximately 3.0 mg/l, which equals the absolute minimum suggested by NWWA indicating that the latter value may be somewhat high. Data for the Clyde, Tyne and Ouse suggest that a lower value may be acceptable in stratified estuaries, which offer potential alternative migratory pathways at higher DO concentrations.

As seen from the discussion of the DO regime in the Clyde estuary, these standards must be applied with care. Furthermore, it is likely that, as in the case of the Usk, local exceptions will occasionally be required. Similarly, the presence of other pollutants may require higher DO concentrations if salmonid migrations are to be maintained.

In addition, even with a 95-percentile value of 5 or 6 mg/l it is still possible that the DO concentration will occasionally be insufficient to permit the passage of salmonids. Such a standard will therefore not meet the recommendation of the Royal Commission which is "to allow passage ... at all states of the tide". However, the standard should meet the implied recommendation that an estuary ought to be of sufficient quality to maintain a healthy migratory salmonid fishery.

7. RECOMMENDATIONS

1. In respect of salmonid migrations, the EQO applied in practice to an estuary may be defined as the ability to maintain a good quality migratory salmonid fishery.
2. The EQS for most estuaries should be that 95% of samples should have DO concentrations in excess of 5 mg/l at the sampling station recording the minimum annual 95-percentile concentration.
3. A lower EQS of 3.0 mg/l DO as a minimum 95-percentile concentration should enable the establishment of a more limited fishery, with restricted migration.
4. Where abnormally low oxygen conditions occur naturally, or where other toxic pollutants are present, a more stringent standard may be necessary.
5. In estuaries where several alternative migration routes are available to the fish, selection of sampling positions and depth may be critical in assessing both compliance with a local EQS and the viability of the salmonid migration.

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Table 1 Proposed standards for dissolved oxygen concentration in estuaries for the protection of migratory salmonid fisheries.

ORIGIN	MINIMUM PERCENTILE OXYGEN CONCENTRATION			COMMENTS
	100%	95%	50%	
EIFAC	-	2	5	Samples taken during summer low-flow period in zone of minimum dissolved oxygen. If the zone is longer than 2 km higher percentile-concentrations may be necessary.
Humber Technical Committee	-	40%	-	Samples taken throughout the whole year.
Severn Estuary Technical Working Party	-	6	-	Samples taken throughout the whole year.
North West Water Authority	3	5	7	Samples taken throughout the year.
Welsh Water Authority	-	5	-	Samples taken throughout the year.

Table 2. Rivers for which data have been received

Source of data	River	Comments
SCOTLAND		
Clyde RPB	Clyde(1)	Regular salmonid runs from the mouth to 23.4 km (confluence of the R Leven). A recovering salmonid run from 23.4 to 11.4 km (confluence of the R Cart). No run upstream of 11.4 km (R Kelvin to R Clyde)
	Gryfe	Regular fishery
	Leven	Salmon and sea trout fishery
	Kelvin	No salmonid run
	Cart	A recovering salmonid run
Forth RPB	Forth	Salmonid fishery
	Almond	Salmon and sea trout in estuary only, river has low DO
	Avon	Poor for salmonids, the river is polluted
	Black Devon	Poor for salmonids, due to low river flows
	Carron	No salmonids, polluted river
	Devon	Good migration, but restricted due to low DO in river during August and September
	Esk	Reasonable fishery in S Esk, but the N Esk is polluted
	Grangeburn	Poor for salmonids, the river is polluted
	Leith	Poor for salmon due to physical obstruction
	Leven	Very good for sea trout, with occasional DO problems
Highland RPB	Cromarty Firth	Good runs of salmon and sea trout

Table 2 (cont'd)

Source of data	River	Comments
	Inverness Firth	Good runs of salmon and sea trout
Nith Fishings Improvment Association	Nith	Excellent runs of salmon and sea trout
Tay RPB	Earn	Sea trout fishery
	South Esk	Excellent runs of migratory salmonids
	North Esk	Salmon fishery
	Tay	Excellent runs of migratory salmonids
Tweed RPB	Eye	-
	Tweed	Salmon fishery
WALES		
Welsh WA	Clwyd	Sea trout and some salmon
	Dee	Major salmon fishery
	Conwy	Salmon and sea trout fishery
	Glaslyn	Sea trout fishery
	Dwyryd	Sea trout fishery
	Tawe	Sea trout fishery
	Loughor	Sea trout fishery
	Tywi	Major salmon and sea trout fishery
	Taff	Small sea trout fishery improving
	Rhymney	Sea trout fishery
	Usk	Important salmon fishery, occasional problems
	Wye	Excellent salmon fishery

Table 2 (cont'd)

Source of data	River	Comments
ENGLAND		
Northumbrian WA	Tyne	Salmon fishery
North West WA	Derwent	Salmon fishery
	Douglas	No fishery, occasional fish mortalities
Duddon	Salmon fishery	
	Ehen	Salmon fishery
	Kent	Salmon fishery
	Leven	Salmon fishery
	Lune	Salmon fishery
	Mersey	No fishery (Very occasionally dead fish in estuary)
Ribble	Salmon fishery	
	Solway Firth	Salmon fishery
	Wampool	No fishery
	Waver	No fishery
	Wyre	Salmon fishery
Severn Trent WA	Trent	Increasing numbers of salmon found
Southern WA	Adur	Small/fair migratory fish run
	Arun	Good migratory fish run
	Great Stour	Small/fair migratory fish run
	Itchen	Good migratory fish run
	Medway	No migratory fish run known

Table 2 (cont'd)

Source of data	River	Comments
	Ouse	Good migratory fish run
	Rother	Small/fair migratory fish run
	Rotter	Sea trout fishery
	Stow	Salmonid fishery
	Test	Good migratory fish run
South West WA	Camel	Run of migratory salmonids
	Fal	Run of migratory salmonids
	Fowey	Run of migratory salmonids
	Tamar	Run of migratory salmonids
	Taw-Torridge	Salmon fishery
Thames WA	Thames	First good return of salmon in 1982
Yorkshire WA	Esk	Good salmonid runs
	Ouse tributaries:	
	Aire	No fishery
	Derwent	Occasional spawning
	Don	No fishery
	Ure	Occasional spawning
	Wharfe	Occasional spawning

NOTES: (1) Distances are from the tidal weir in Glasgow

Table 3. Reported oxygen concentrations and effects
a). Means and lower 95-percentiles

SOURCE OF DATA	ESTUARY	DATE	SAMPLE SITE	SAMPLE DEPTH (M)(1)	MINIMUM DISSOLVED OXYGEN (MG/L) (2) FISHERY $\bar{x}$	FISHERY min	NEGATIVE EFFECTS $\bar{x}$	NEGATIVE EFFECTS min	SALINITY (G/KG)	TEMP. (DEG C)	COMMENTS
SCOTLAND											
Clyde RPB	Clyde	1980	23.4 kms (3)	S-B	5.8	1.0E	-	-	-	-	Regular run
		1980	13.8 kms	S-B	5.2	0.0F	-	-	-	-	Recovering run
		1980	10.6 kms	S-B	-	-	5.4	0.0E	-	-	No run
		1981	23.4 km	S-B	6.8	2.1E	-	-	-	-	Regular run
		1981	13.8 kms	S-B	5.7	0.0E	-	-	-	-	Recovering run
		1981	10.6 kms	S-B	-	-	5.6	0.0E	-	-	No run
WALES											
WELSH WA	Clwyd	1980-3	Rhyll Slipway	S	11.3	8.9E	-	-	-	-	Sea Trout and some Salmon
	Dee	1980-3	Hawarden Br.	S	10.5	7.3E	-	-	-	-	Major Salmon Fishery
	Conwy	1982-3	2 km from estuary mouth	S	9.7	6.9E	-	-	-	-	Salmon and Sea Trout Fishery
	Glaslyn	1982-3	Porthmadog Br.	S	9.34	8.0E	-	-	-	-	Sea trout Fishery
	Dwyryd	1982-3	Pont Briwet Br.	S	9.7	8.0*	-	-	-	-	Sea Trout Fishery
	Tawe	1980-3	West Pier	S	8.0	4.4E	-	-	-	-	Minor Sea Trout Fishery
	Loughor	1981-3	Camarthen Bay	S	8.1	5.2F	-	-	-	-	Minor Sea Trout Fishery
	Tywi	1980-3	Llangain	S	10.4	8.1F	-	-	-	-	Major Salmon and Sea Trout Fishery
	Taff	1980-3	Castle St, Cardiff	S	10.2	7.5E	-	-	-	-	Small Sea Trout Fishery improving
	Rhymney	1980-3	Newport Road	S	10.1	7.0E	-	-	-	-	Sea Trout Fishery
	Usk	1980-3	Newport Rd Br.	S	7.8	3.8E	-	-	-	-	Important Salmon Fishery Occasional Problems
	Wye	1981-3	M4 Br. Chepstow	S	9.1	5.8E	-	-	-	-	Excellent Salmon Fishery
ENGLAND											
Northumbrian WA	Tyne	4.81-3.82	Above R.Derwent	S-B	7.1	0.6F	-	-	-	-	Fishery, occasional problems
North West WA	Derwent	1980-83	Workington Dock	-	9.2	7.4F	-	-	0.9	13.7	Existing fishery

Table 3a continued

SOURCE OF DATA	ESTUARY	DATE	SAMPLE SITE	SAMPLE DEPTH (M)(1)	MINIMUM DISSOLVED OXYGEN (MG/L) (2) FISHERY $\bar{x}$	FISHERY min	NEGATIVE EFFECTS $\bar{x}$	NEGATIVE EFFECTS min	SALINITY (G/KG)	TEMP. (DEG C)	COMMENTS
ENGLAND Northumbrian WA	Tyne	4.81-3.82	Above R.Derwent	S-B	7.1	0.6E	-	-	-	-	Fishery, occasional problems
North West WA	Derwent	1980-83	Workington Dock	-	9.2	7.4E	-	-	0.9	13.7	Existing fishery
	Douglas	1980-83	Tarleton Bridge	-	-	-	7.8	4.7E	0.2	12.5	No fishery
	Duddon	1980-83	Hodbarrow Point	-	10.4	7.2E	-	-	26.0	16.5	Salmon fishery
	Ehen	1980-83	d/s BNF Ltd	-	12.4	9.0E	-	-	0.2	10.3	Salmon fishery
	Kent	1980-83	-	-	9.4	6.9E	-	-	10.5	16.2	Salmon fishery
	Leven	1980-83	-	-	8.5	6.4E	-	-	26.0	16.6	Salmon fishery
	Lune	1980-83	Greyhound Bridge	-	10.0	7.6E	-	-	1.7	14.9	Salmon fishery
	Mersey	1980-83	Princes Pier	-	-	-	4.4	1.8E	14.0	17.2	No fishery
	Ribble	1980-83	Freckleton Pool	-	7.2	3.7E	-	-	0.2	12.5	Salmon fishery occasional problems
	Solway Firth	1980-83	Powfoot	-	10.2	9.0E	-	-	23.0	17.1	Fishery
	Wampool	1980-83	Solway House	-	-	-	8.2	-	14.0	14.9	No fishery
	Waver	1980-83	Rary Cote	-	-	-	7.2	4.6E	7.3	13.1	No fishery
	Wyre	1980-83	Shard Bridge	-	9.3	6.1E	-	-	9.6	11.2	Salmon fishery return

Table 3a. continued

SOURCE OF DATA	ESTUARY	DATE	SAMPLE SITE	SAMPLE DEPTH (M)(1)	MINIMUM DISSOLVED OXYGEN (MG/L) (2) FISHERY $\bar{x}$	FISHERY min	NEGATIVE EFFECTS $\bar{x}$	NEGATIVE EFFECTS min	SALINITY (G/KG)	TEMP. (DEG C)	COMMENTS
ENGLAND											
Severn Trent WA	Trent	1980	Keadby	S	8.2	3.0£	-	-	-	-	Salmon starting to
Southern WA	Adur	1977-82	Beading Bridge	-	9.0	6.6£	-	-	1.6	11.7	Small/fair migratory fishery
	Arun	1977-82	Houghton Bridge	-	10.1	7.2£	-	-	0.3	11.9	Good migratory fishery
	Great Stour	1977-82	Sandwich Toll Bridge	-	9.7	7.9£	-	-	0.6	13.9	Small/fair migratory fishery
	Itchen	1978-82	Kemps Boatyard	-	8.3	6.2£	-	-	16.9	11.4	Good migratory fishery
	Ouse	1977-82	Pells Footbridge	-	113.0%	67.8%£	-	-	1.4	14.5	Good migratory fishery
	Rother	1976-82	Hyde Road Bridge	-	9.8	6.9£	-	-	9.2	11.7	Small/fair migratory fishery
	Test	1978-82	Royal Pier	-	8.2	6.5£	-	-	27.5	11.7	Good migratory fishery
South West WA	Taw	1972-73	Ashford	-	11.7	5.3£	-	-	-	-	Salmonid fishery
	Torridge	1972-73	The Cleave	-	9.3	7.1£	-	-	-	-	Salmonid fishery
Thames WA	Thames	1979-82	19 kms below London Bridge	-	6.4	2.9£	-	-	-	-	Recovering salmon fishery
Yorkshire WA	Ouse tributaries: Aire, Derwent, Don, Ure, Wharfe	1980	Blacktoft	S	-	-	6.4	0.0£	-	-	No regular fishery

Table 3. continued
b). Means and extreme values

SOURCE OF DATA	ESTUARY	DATE	SAMPLE SITE	SAMPLE DEPTH (M)(1)	MINIMUM DISSOLVED OXYGEN (MG/L) (2) FISHERY $\bar{x}$	FISHERY min	NEGATIVE EFFECTS $\bar{x}$	NEGATIVE EFFECTS min	SALINITY (G/KG)	TEMP. (DEG C)	COMMENTS
SCOTLAND											
Highland RPB	Cromarty Firth	-	Whole estuary	-	95.0%	85.0%*	-	-	-	-	No kills reported
	Inverness Firth	-	Whole estuary	-	95.0%	85.0%*	-	-	-	-	No kills reported
Solway RPB	Nith	1974-81	Airds Point	M	-	7.5*	-	-	-	-	No kills reported
Tay RPB	Tay	1980-82	-	-	77.4%	6.7*	-	-	-	-	No kills reported
Tweed RPB	Eye	1975-82	Harbour Mouth	-	-	10.0*	-	-	-	-	No kills reported
	Tweed	1975-82	Pier Head	-	-	8.8*	-	-	-	-	No kills reported
ENGLAND											
Severn Trent WA	Trent	11-12. 1983	Burton Stather	-	30.0%	20.0%*	-	-			Salmon starting to return
Southern WA	Medway	-	-	-	-	-	-	-	-	-	No known fishery
	Rother	-	-	-	-	-	-	-	-	-	Sea trout fishery
	Stow	-	-	-	-	-	-	-	-	-	Salmon and sea trout fishery
South West WA	Camel	1975-82	-	-	116.0%	94.0%*	-	-	-	-	Run of migratory salmonids
	Fal	1975-82	-	-	97.0%	56.0%*	-	-	-	-	Run of migratory salmonids
	Fowey	1975-82	-	-	94.0%	81.0%*	-	-	-	-	Run of migratory salmonids
	Tamar	1975-82	-	-	99.8%	87.0%*	-	-	-	-	Run of migratory salmonids
Yorkshire WA	Esk	-	-	-	High DO		-	-	-	-	Good fishery

Table 3. continued
c). Reported incidents

SOURCE OF DATA	ESTUARY	DATE	SAMPLE SITE	SAMPLE DEPTH (M)(1)	MINIMUM DISSOLVED OXYGEN (MG/L) (2) FISHERY $\bar{x}$	FISHERY min	NEGATIVE EFFECTS $\bar{x}$	NEGATIVE EFFECTS min	SALINITY (G/KG)	TEMP. (DEG C)	COMMENTS
SCOTLAND											
Clyde RPB		1.1978	9.6 kms	S-B	-	8.2*	-	-	1.0-12.8	3.2- 4.7	Live seatrout
		1.1978	9.6 kms	S-B	-	11.2*	-	-	1.1- 2.5	2.1- 4.2	Live salmon
		8.1978	9.6 kms	S-B	-	-	-	3.6*	1.5- 4.0	14.9-14.8	Moribund salmon
		8.1978	9.6 kms	S-B	-	-	-	2.5*	6.6-14.5	14.5-13.9	Dead salmon
		9.1978	16.0 kms	S-B	-	-	-	1.7*	9.7-17.3	14.5-13.7	Dead salmon
		9.1978	6.4 kms	S-B	-	-	-	3.1*	4.6-12.1	14.5-14.0	Dead salmon
		1.1982	9.6 kms	S-B	-	9.4*	-	-	0.1- 3.2	6.6- 6.1	Live salmon
	Gryfe	4.1981	Dargavel	-	NA	-	-	-	0.2	NA	Live smolts
	Leven	4,5,6. 1980-82	Mouth	S-B	-	1.0*	-	-	5.6-26.5	8.1-15.1	Live smolts
		2-5. 1980-82	Mouth	S-B	-	1.2*	-	-	0.1-27.9	4.2-13.0	Live salmon
		6.1980-82	Mouth	S-B	-	0.9*	-	-	5.6-23.9	12.1-15.1	Live sea trout
	White Cart	6.1979	Mouth	-	-	-	-	-	-	-	Moribund salmon
		5.1980	Mouth	S-B	-	1.1*	-	-	12.3-20.0	12.9-13.8	Live salmon
Forth RPB	Forth	5.1979	Whole estuary	S-B	-	-	6.6	1.3*	0.1-32.1	8.4-13.4	Dead smolts
		7.1982	Whole estuary	S-B	-	-	4.8	0.6*	0.1-32.6	15.2-23.2	Dead grilse
		8.1982	Whole estuary	S-B	-	-	4.3	0.1*	0.1-32.7	17.2-21.6	Dead grilse
ENGLAND											
South West WA	Fowey	9-11.1982	2 km from mouth	S	83.0%	18.0%*	-	-	-	-	Sea trout moving
Thames WA	Thames	4.1982	Whole estuary	M	8.3	4.2£	-	-	-	-	Smolt run
		7-9.1982	Whole estuary	M	5.2	1.9£	-	-	-	-	Grilse/salmon run

NOTES ON TABLE 3:

1) S = Surface
M = Mid depth
B = Bottom

2) See text for an explanation of these values.
* = Extreme value
£ = Lower 95 percentile
% = Values in per cent saturation.

3) Distance from tidal weir in Glasgow

Table 4 Reported timing of major fish runs

SOURCE OF DATA	RIVER	SMOLT	KELTS	GRILSE	ADULT SALMON	SEA TROUT
ENGLAND						
Northumbrian WA	Tyne	April - June		Sept - October	Feb - May, Aug - Oct	Aug - Nov
Severn Trent WA	Trent				Oct - Dec	
Southern WA	Adur					June - Dec
	Arun					June - Dec
	Itchen	April	Jan - Feb	Aug - Sept	March - Sept	May - Oct
	Ouse					June - Dec
	Rother	April - May				May - July Oct - Feb
	Stow	April - May			May - July Oct - Feb	May - July Oct - Feb
	Test	April	Jan - Feb	Aug - Sept	March - Sept	May - Oct
South West WA	Taw-Torridge				December	
Thames WA	Thames	April		July - Sept	July - Sept	
Yorkshire WA	Ure	May - June			Spring and autumn	
	Wharfe	May - June			Spring and autumn	
SCOTLAND						
Clyde RPB	Clyde				June - July	
	Leven	April-June			Feb - May	June
Forth RPB	Forth	April - May		June - July	Aug - Nov	
	Devon				Oct - Nov	
Nith Fishings Improvement Association	Nith	April - May		June - Sept	Aug - Nov	Feb - Aug
Tay RPB	Earn					Jan - May
	North Esk	April - June September			June - Nov	
	Tay	May - June		May - Aug	Aug - Nov	
Tweed RPB	Tweed				March - May Oct - Dec	

Table 4 (cont.) Reported timing of major fish runs

SOURCE OF DATA	RIVER	SMOLT	KELTS	GRILSE	ADULT SALMON	SEA TROUT
WALES						
Welsh WA	Glaslyn					Apr - Aug
	Dwyryd					Apr - Aug
	Tywi (Camerthen)				Dec - Apr June -July Sep - Oct	March May - July
	Tawe (Swansea)	Apr - Jun				Mar - Oct
	Loughor	Apr - Jun				Mar - Oct
	Taff					Oct - Dec
	Rhymney					Oct - Dec
	Usk			July	Mar - Oct	
	Wye	May - June			June - Aug	

Figure 1. Vertical profiles of dissolved oxygen concentration (per cent saturation) in the Clyde Estuary, observed during routine LW surveys at the confluence of the R. Leven, 1981. (Provided by CRPB).

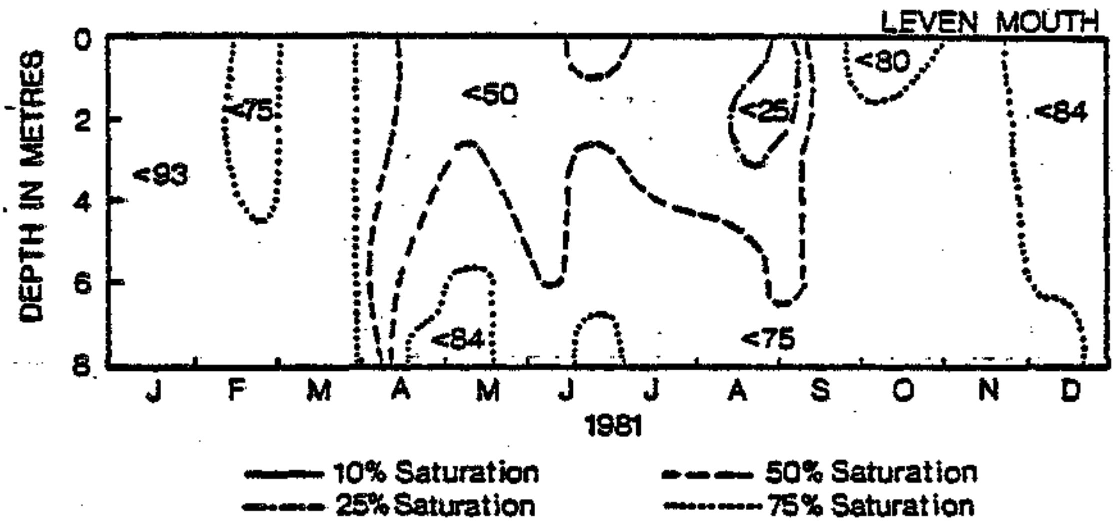


Figure 2.   Reported minimum oxygen concentrations, showing annual means (M) and lower 95-percentiles (L).

ESTUARIES WITH REGULAR SALMONID FISHERIES AND NO REPORTED OXYGEN RESTRICTIONS

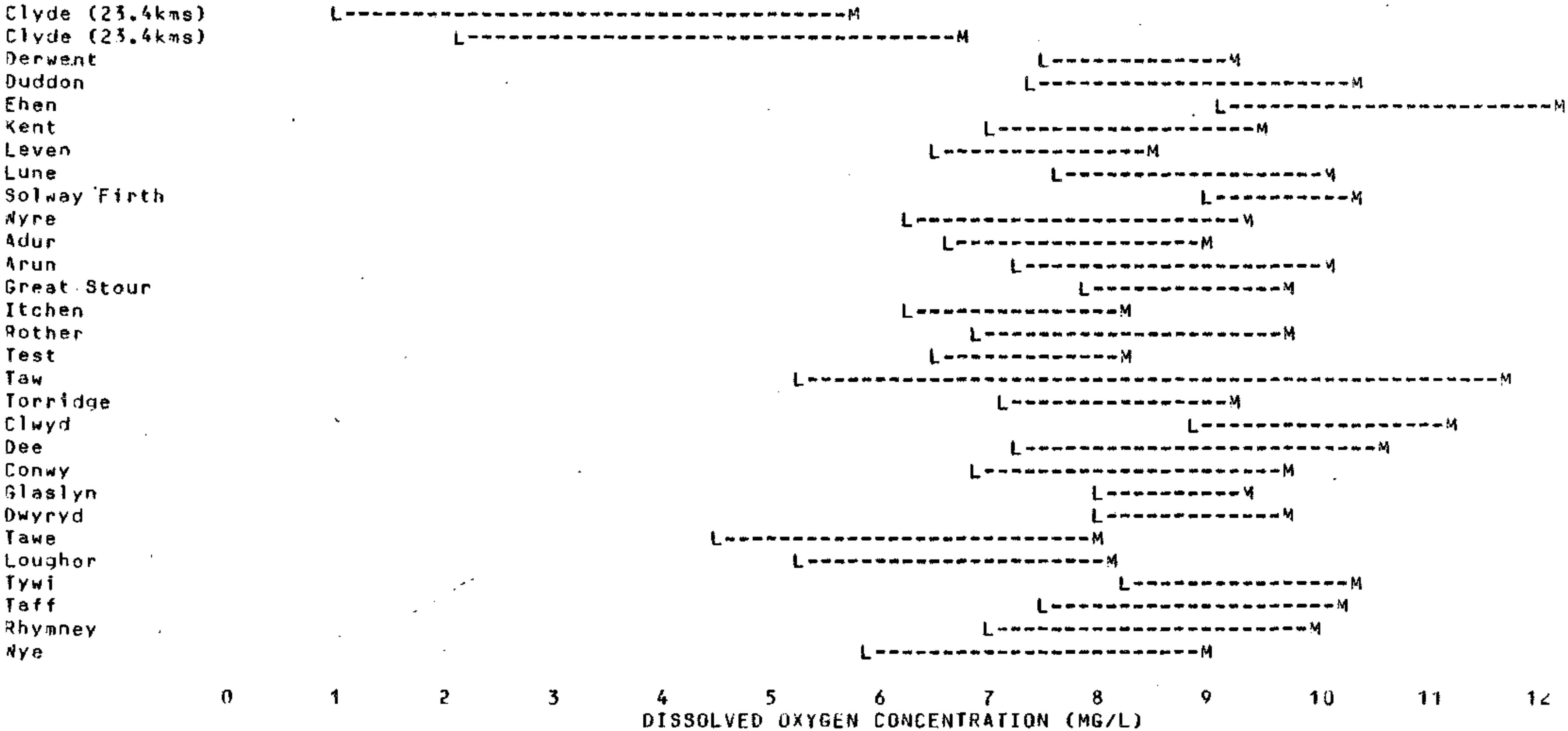


Figure 2.(cont.) Reported minimum oxygen concentrations, showing annual means (M) and lower 95-percentiles (L).

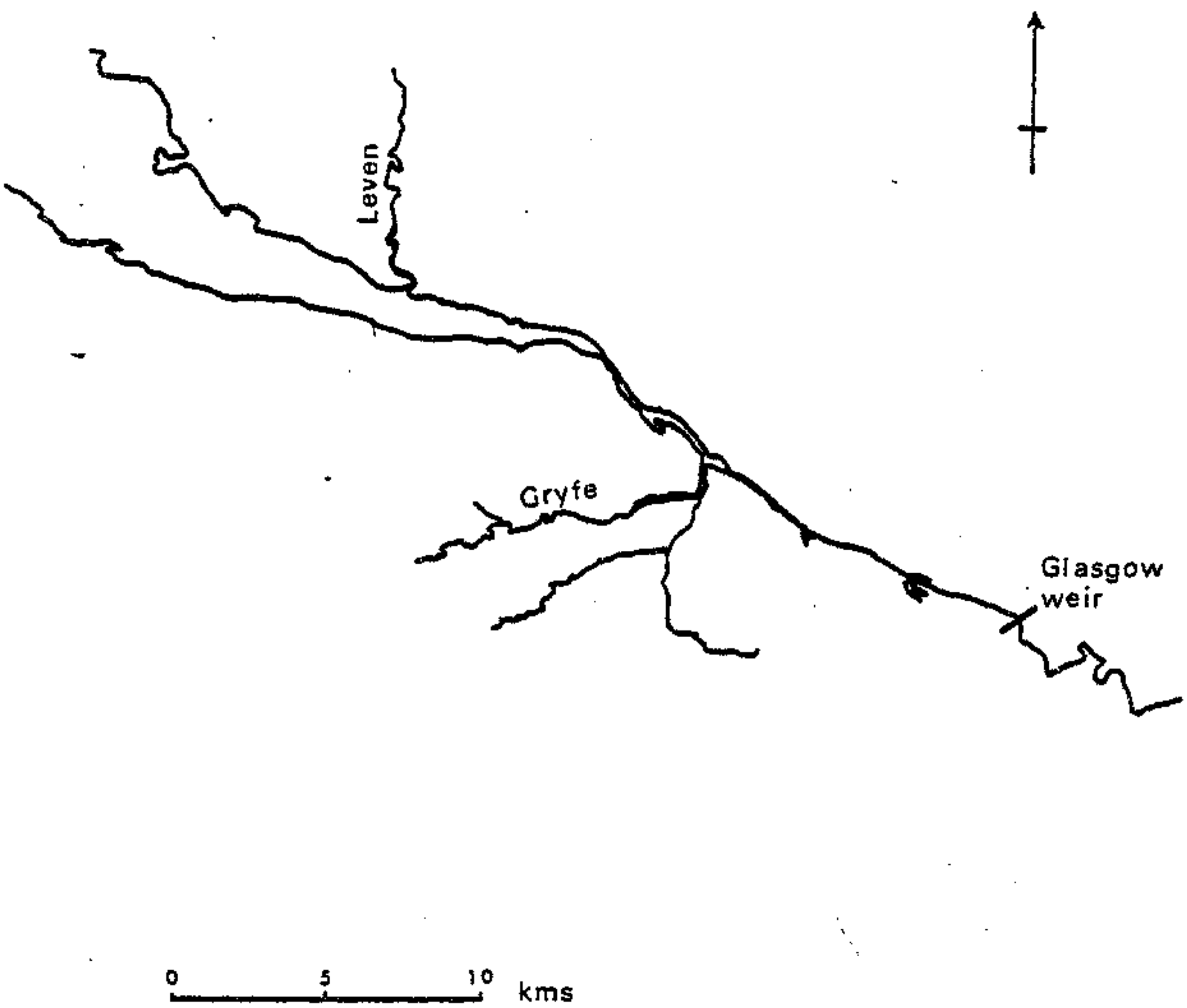
ESTUARIES WITH RECOVERING FISHERIES OR FISHERIES WITH OCCASIONAL OXYGEN RESTRICTIONS

```
Clyde (13.8kms) L--------------------------------------M
Clyde (13.8kms) L------------------------------------------M
Ouse            L----------------------------------------------M
Ribble                                     L-------------------------M
Tyne                 L----------------------------------------------M
Trent                                 L---------------------------------------M
Thames                               L-------------------------M
Usk                                          L----------------------------M

                0      1       2      3       4      5       6      7      8       9      10      11     12
                                                DISSOLVED OXYGEN CONCENTRATION (MG/L)
```

ESTUARIES WITH NO FISHERIES

```
Clyde (10.6kms) L---------------------------------------M
Clyde (10.6kms) L-----------------------------------------M
Douglas                                            L------------------------------M
Mersey                       L-------------------M
Wampool                                                               - - - -  M
Naver                                             L-------------------M

                0      1       2      3       4      5       6      7      8       9      10      11     12
                                                DISSOLVED OXYGEN CONCENTRATION (MG/L)
```

Figure 3. Map of the Clyde Estuary
(showing the positions of the R. Leven and R. Gryfe in relation to the tidal weir in Glasgow)



APPENDIX A - CONVERSION TABLES FOR THE SOLUBILITY OF OXYGEN IN WATER AT VARIOUS SALINITIES

PREPARED BY J GARDINER, WRC

Table 1.1. Solubility of oxygen in water at various salinities and at normal temperatures from air saturated with water vapour at a pressure of 1 atmosphere.

OXYGEN SOLUBILITY (mg/l or mg/dm^3)

TEMP °C	SALINITY (g/kg) 0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0
4.0	13.09	13.01	12.92	12.84	12.75	12.67	12.58	12.50	12.42	12.33
4.5	12.92	12.84	12.75	12.67	12.59	12.50	12.42	12.34	12.26	12.18
5.0	12.76	12.67	12.59	12.51	12.43	12.34	12.26	12.18	12.10	12.02
5.5	12.59	12.51	12.43	12.35	12.27	12.19	12.11	12.03	11.95	11.87
6.0	12.44	12.35	12.27	12.19	12.11	12.04	11.96	11.88	11.80	11.72
6.5	12.28	12.20	12.12	12.04	11.96	11.89	11.81	11.73	11.66	11.58
7.0	12.13	12.05	11.97	11.89	11.82	11.74	11.66	11.59	11.51	11.44
7.5	11.98	11.90	11.82	11.75	11.67	11.60	11.52	11.45	11.37	11.30
8.0	11.83	11.76	11.68	11.61	11.53	11.46	11.38	11.31	11.24	11.17
8.5	11.69	11.61	11.54	11.47	11.39	11.32	11.25	11.18	11.10	11.03
9.0	11.55	11.48	11.40	11.33	11.26	11.19	11.11	11.04	10.97	10.90
9.5	11.41	11.34	11.27	11.20	11.12	11.05	10.98	10.91	10.84	10.78
10.0	11.28	11.21	11.13	11.06	10.99	10.92	10.86	10.79	10.72	10.65
10.5	11.15	11.08	11.01	10.94	10.87	10.80	10.73	10.66	10.60	10.53
11.0	11.02	10.95	10.88	10.81	10.74	10.67	10.61	10.54	10.47	10.41
11.5	10.89	10.82	10.75	10.69	10.62	10.55	10.49	10.42	10.36	10.29
12.0	10.77	10.70	10.63	10.57	10.50	10.43	10.37	10.30	10.24	10.18
12.5	10.64	10.58	10.51	10.45	10.38	10.32	10.25	10.19	10.13	10.06
13.0	10.53	10.46	10.40	10.33	10.27	10.20	10.14	10.08	10.02	9.95
13.5	10.41	10.34	10.28	10.22	10.15	10.09	10.03	9.97	9.91	9.84
14.0	10.29	10.23	10.17	10.11	10.04	9.98	9.92	9.86	9.80	9.74
14.5	10.18	10.12	10.06	10.00	9.93	9.87	9.81	9.75	9.69	9.63
15.0	10.07	10.01	9.95	9.89	9.83	9.77	9.71	9.65	9.59	9.53
15.5	9.96	9.90	9.84	9.78	9.72	9.66	9.61	9.55	9.49	9.43
16.0	9.86	9.80	9.74	9.68	9.62	9.56	9.50	9.45	9.39	9.33
16.5	9.75	9.69	9.64	9.58	9.52	9.46	9.41	9.35	9.29	9.24
17.0	9.65	9.59	9.54	9.48	9.42	9.36	9.31	9.25	9.20	9.14
17.5	9.55	9.49	9.44	9.38	9.32	9.27	9.21	9.16	9.10	9.05
18.0	9.45	9.40	9.34	9.28	9.23	9.17	9.12	9.06	9.01	8.96
18.5	9.36	9.30	9.25	9.19	9.14	9.08	9.03	8.97	8.92	8.87
19.0	9.26	9.21	9.15	9.10	9.04	8.99	8.94	8.88	8.83	8.78
19.5	9.17	9.11	9.06	9.01	8.95	8.90	8.85	8.80	8.74	8.69
20.0	9.08	9.02	8.97	8.92	8.86	8.81	8.76	8.71	8.66	8.61
20.5	8.99	8.93	8.88	8.83	8.78	8.73	8.67	8.62	8.57	8.52
21.0	8.90	8.85	8.79	8.74	8.69	8.64	8.59	8.54	8.49	8.44
21.5	8.81	8.76	8.71	8.66	8.61	8.56	8.51	8.46	8.41	8.36

Table 1.1. (continued) OXYGEN SOLUBILITY (mg/l or mg/dm^3)

TEMP °C	SALINITY (g/kg) 10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	18.0	19.0
4.0	12.25	12.17	12.09	12.01	11.93	11.85	11.78	11.70	11.62	11.54
4.5	12.10	12.02	11.94	11.86	11.78	11.70	11.63	11.55	11.47	11.40
5.0	11.94	11.87	11.79	11.71	11.63	11.56	11.48	11.41	11.33	11.26
5.5	11.79	11.72	11.64	11.56	11.49	11.41	11.34	11.27	11.19	11.12
6.0	11.65	11.57	11.50	11.42	11.35	11.27	11.20	11.13	11.05	10.98
6.5	11.51	11.43	11.36	11.28	11.21	11.14	11.06	10.99	10.92	10.85
7.0	11.37	11.29	11.22	11.15	11.07	11.00	10.93	10.86	10.79	10.72
7.5	11.23	11.16	11.08	11.01	10.94	10.87	10.80	10.73	10.66	10.59
8.0	11.09	11.02	10.95	10.88	10.81	10.74	10.67	10.60	10.54	10.47
8.5	10.96	10.89	10.82	10.75	10.68	10.62	10.55	10.48	10.41	10.35
9.0	10.83	10.76	10.70	10.63	10.56	10.49	10.43	10.36	10.29	10.23
9.5	10.71	10.64	10.57	10.50	10.44	10.37	10.31	10.24	10.17	10.11
10.0	10.58	10.52	10.45	10.38	10.32	10.25	10.19	10.12	10.06	10.00
10.5	10.46	10.40	10.33	10.27	10.20	10.14	10.07	10.01	9.95	9.88
11.0	10.34	10.28	10.21	10.15	10.09	10.02	9.96	9.90	9.83	9.77
11.5	10.23	10.16	10.10	10.04	9.97	9.91	9.85	9.79	9.73	9.66
12.0	10.11	10.05	9.99	9.92	9.86	9.80	9.74	9.68	9.62	9.56
12.5	10.00	9.94	9.88	9.82	9.75	9.69	9.63	9.57	9.51	9.46
13.0	9.89	9.83	9.77	9.71	9.65	9.59	9.53	9.47	9.41	9.35
13.5	9.78	9.72	9.66	9.60	9.54	9.49	9.43	9.37	9.31	9.25
14.0	9.68	9.62	9.56	9.50	9.44	9.38	9.33	9.27	9.21	9.16
14.5	9.57	9.52	9.46	9.40	9.34	9.29	9.23	9.17	9.12	9.06
15.0	9.47	9.42	9.36	9.30	9.24	9.19	9.13	9.08	9.02	8.97
15.5	9.37	9.32	9.26	9.20	9.15	9.09	9.04	8.98	8.93	8.87
16.0	9.28	9.22	9.16	9.11	9.05	9.00	8.94	8.89	8.84	8.78
16.5	9.18	9.12	9.07	9.01	8.96	8.91	8.85	8.80	8.75	8.69
17.0	9.09	9.03	8.98	8.92	8.87	8.82	8.76	8.71	8.66	8.61
17.5	8.99	8.94	8.89	8.83	8.78	8.73	8.68	8.62	8.57	8.52
18.0	8.90	8.85	8.80	8.74	8.69	8.64	8.59	8.54	8.49	8.44
18.5	8.81	8.76	8.71	8.66	8.61	8.55	8.50	8.45	8.40	8.35
19.0	8.73	8.67	8.62	8.57	8.52	8.47	8.42	8.37	8.32	8.27
19.5	8.64	8.59	8.54	8.49	8.44	8.39	8.34	8.29	8.24	8.19
20.0	8.56	8.51	8.46	8.41	8.36	8.31	8.26	8.21	8.16	8.11
20.5	8.47	8.42	8.37	8.32	8.28	8.23	8.18	8.13	8.08	8.04
21.0	8.39	8.34	8.29	8.25	8.20	8.15	8.10	8.05	8.01	7.96
21.5	8.31	8.26	8.22	8.17	8.12	8.07	8.03	7.98	7.93	7.89

Table 1.1. (continued) OXYGEN SOLUBILITY (mg/l or mg/dm^3)

SALINITY (g/kg)

TEMP °C	20.0	21.0	22.0	23.0	24.0	25.0	26.0	27.0	28.0	29.0
4.0	11.47	11.39	11.32	11.24	11.17	11.09	11.02	10.95	10.87	10.80
4.5	11.32	11.25	11.17	11.10	11.03	10.95	10.88	10.81	10.74	10.67
5.0	11.18	11.11	11.04	10.96	10.89	10.82	10.75	10.68	10.61	10.54
5.5	11.05	10.97	10.90	10.83	10.76	10.69	10.62	10.55	10.48	10.41
6.0	10.91	10.84	10.77	10.70	10.63	10.56	10.49	10.42	10.35	10.29
6.5	10.78	10.71	10.64	10.57	10.50	10.43	10.37	10.30	10.23	10.17
7.0	10.65	10.58	10.51	10.45	10.38	10.31	10.24	10.18	10.11	10.05
7.5	10.52	10.46	10.39	10.32	10.26	10.19	10.12	10.06	9.99	9.93
8.0	10.40	10.33	10.27	10.20	10.14	10.07	10.01	9.94	9.88	9.82
8.5	10.28	10.21	10.15	10.08	10.02	9.96	9.89	9.83	9.77	9.70
9.0	10.16	10.10	10.03	9.97	9.90	9.84	9.78	9.72	9.65	9.59
9.5	10.05	9.98	9.92	9.86	9.79	9.73	9.67	9.61	9.55	9.49
10.0	9.93	9.87	9.81	9.74	9.68	9.62	9.56	9.50	9.44	9.38
10.5	9.82	9.76	9.70	9.64	9.58	9.51	9.45	9.39	9.34	9.28
11.0	9.71	9.65	9.59	9.53	9.47	9.41	9.35	9.29	9.23	9.18
11.5	9.60	9.54	9.48	9.42	9.37	9.31	9.25	9.19	9.13	9.08
12.0	9.50	9.44	9.38	9.32	9.26	9.21	9.15	9.09	9.04	8.98
12.5	9.40	9.34	9.28	9.22	9.16	9.11	9.05	8.99	8.94	8.88
13.0	9.30	9.24	9.18	9.12	9.07	9.01	8.96	8.90	8.84	8.79
13.5	9.20	9.14	9.08	9.03	8.97	8.92	8.86	8.81	8.75	8.70
14.0	9.10	9.04	8.99	8.93	8.88	8.82	8.77	8.71	8.66	8.61
14.5	9.00	8.95	8.89	8.84	8.79	8.73	8.68	8.62	8.57	8.52
15.0	8.91	8.86	8.80	8.75	8.70	8.64	8.59	8.54	8.48	8.43
15.5	8.82	8.77	8.71	8.66	8.61	8.55	8.50	8.45	8.40	8.35
16.0	8.73	8.68	8.62	8.57	8.52	8.47	8.42	8.37	8.31	8.26
16.5	8.64	8.59	8.54	8.49	8.43	8.38	8.33	8.28	8.23	8.18
17.0	8.55	8.50	8.45	8.40	8.35	8.30	8.25	8.20	8.15	8.10
17.5	8.47	8.42	8.37	8.32	8.27	8.22	8.17	8.12	8.07	8.02
18.0	8.39	8.34	8.29	8.24	8.19	8.14	8.09	8.04	7.99	7.95
18.5	8.30	8.25	8.20	8.16	8.11	8.06	8.01	7.96	7.92	7.87
19.0	8.22	8.17	8.13	8.08	8.03	7.98	7.93	7.89	7.84	7.79
19.5	8.14	8.10	8.05	8.00	7.95	7.91	7.86	7.81	7.77	7.72
20.0	8.07	8.02	7.97	7.92	7.88	7.83	7.78	7.74	7.69	7.65
20.5	7.99	7.94	7.90	7.85	7.80	7.76	7.71	7.67	7.62	7.58
21.0	7.91	7.87	7.82	7.78	7.73	7.69	7.64	7.60	7.55	7.51
21.5	7.84	7.79	7.75	7.70	7.66	7.61	7.57	7.53	7.48	7.44

Table 1.1. (continued)   OXYGEN SOLUBILITY (mg/l or mg/dm³)

SALINITY (g/kg)

TEMP °C	30.0	31.0	32.0	33.0	34.0	35.0	36.0	37.0	38.0	39.0
4.0	10.73	10.66	10.59	10.52	10.45	10.38	10.31	10.24	10.18	10.11
4.5	10.60	10.53	10.46	10.39	10.32	10.25	10.19	10.12	10.05	9.99
5.0	10.47	10.40	10.33	10.27	10.20	10.13	10.06	10.00	9.93	9.87
5.5	10.34	10.28	10.21	10.14	10.08	10.01	9.94	9.88	9.81	9.75
6.0	10.22	10.15	10.09	10.02	9.96	9.89	9.83	9.76	9.70	9.64
6.5	10.10	10.03	9.97	9.90	9.84	9.78	9.71	9.65	9.59	9.52
7.0	9.98	9.92	9.85	9.79	9.73	9.66	9.60	9.54	9.48	9.41
7.5	9.87	9.80	9.74	9.68	9.61	9.55	9.49	9.43	9.37	9.31
8.0	9.75	9.69	9.63	9.57	9.50	9.44	9.38	9.32	9.26	9.20
8.5	9.64	9.58	9.52	9.46	9.40	9.34	9.28	9.22	9.16	9.10
9.0	9.53	9.47	9.41	9.35	9.29	9.23	9.17	9.11	9.06	9.00
9.5	9.43	9.37	9.31	9.25	9.19	9.13	9.07	9.01	8.96	8.90
10.0	9.32	9.26	9.20	9.14	9.09	9.03	8.97	8.92	8.86	8.80
10.5	9.22	9.16	9.10	9.04	8.99	8.93	8.87	8.82	8.76	8.71
11.0	9.12	9.06	9.00	8.95	8.89	8.83	8.78	8.72	8.67	8.61
11.5	9.02	8.96	8.91	8.85	8.80	8.74	8.69	8.63	8.58	8.52
12.0	8.92	8.87	8.81	8.76	8.70	8.65	8.59	8.54	8.49	8.43
12.5	8.83	8.77	8.72	8.66	8.61	8.56	8.50	8.45	8.40	8.35
13.0	8.74	8.68	8.63	8.57	8.52	8.47	8.42	8.36	8.31	8.26
13.5	8.64	8.59	8.54	8.49	8.43	8.38	8.33	8.28	8.23	8.18
14.0	8.56	8.50	8.45	8.40	8.35	8.30	8.24	8.19	8.14	8.09
14.5	8.47	8.42	8.36	8.31	8.26	8.21	8.16	8.11	8.06	8.01
15.0	8.38	8.33	8.28	8.23	8.18	8.13	8.08	8.03	7.98	7.93
15.5	8.30	8.25	8.20	8.15	8.10	8.05	8.00	7.95	7.90	7.85
16.0	8.21	8.16	8.11	8.07	8.02	7.97	7.92	7.87	7.82	7.78
16.5	8.13	8.08	8.03	7.99	7.94	7.89	7.84	7.80	7.75	7.70
17.0	8.05	8.00	7.96	7.91	7.86	7.81	7.77	7.72	7.67	7.63
17.5	7.97	7.93	7.88	7.83	7.79	7.74	7.69	7.65	7.60	7.55
18.0	7.90	7.85	7.80	7.76	7.71	7.66	7.62	7.57	7.53	7.48
18.5	7.82	7.78	7.73	7.68	7.64	7.59	7.55	7.50	7.46	7.41
19.0	7.75	7.70	7.66	7.61	7.57	7.52	7.48	7.43	7.39	7.34
19.5	7.67	7.63	7.58	7.54	7.49	7.45	7.41	7.36	7.32	7.28
20.0	7.60	7.56	7.51	7.47	7.43	7.38	7.34	7.30	7.25	7.21
20.5	7.53	7.49	7.44	7.40	7.36	7.31	7.27	7.23	7.19	7.14
21.0	7.46	7.42	7.38	7.33	7.29	7.25	7.21	7.16	7.12	7.08
21.5	7.40	7.35	7.31	7.27	7.22	7.18	7.14	7.10	7.06	7.02

Table 1.2. Solubility of oxygen in water at various salinities and at extreme temperatures from air saturated with water vapour at a pressure of 1 atmosphere

OXYGEN SOLUBILITY (mg/l or mg/dm^3)

SALINITY (g/kg)

TEMP °C	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0
0.0	14.60	14.50	14.40	14.31	14.21	14.11	14.02	13.92	13.83	13.73
0.5	14.40	14.30	14.20	14.11	14.01	13.92	13.82	13.73	13.63	13.54
1.0	14.20	14.10	14.01	13.91	13.82	13.73	13.63	13.54	13.45	13.36
1.5	14.00	13.91	13.82	13.72	13.63	13.54	13.45	13.36	13.27	13.18
2.0	13.81	13.72	13.63	13.54	13.45	13.36	13.27	13.18	13.09	13.00
2.5	13.63	13.54	13.45	13.36	13.27	13.18	13.09	13.00	12.92	12.83
3.0	13.45	13.36	13.27	13.18	13.09	13.00	12.92	12.83	12.75	12.66
3.5	13.27	13.18	13.09	13.01	12.92	12.83	12.75	12.66	12.58	12.50
4.0	13.09	13.01	12.92	12.84	12.75	12.67	12.58	12.50	12.42	12.33
4.5	12.92	12.84	12.75	12.67	12.59	12.50	12.42	12.34	12.26	12.18
5.0	12.76	12.67	12.59	12.51	12.43	12.34	12.26	12.18	12.10	12.02
5.5	12.59	12.51	12.43	12.35	12.27	12.19	12.11	12.03	11.95	11.87
20.0	9.08	9.02	8.97	8.92	8.86	8.81	8.76	8.71	8.66	8.61
20.5	8.99	8.93	8.88	8.83	8.78	8.73	8.67	8.62	8.57	8.52
21.0	8.90	8.85	8.79	8.74	8.69	8.64	8.59	8.54	8.49	8.44
21.5	8.81	8.76	8.71	8.66	8.61	8.56	8.51	8.46	8.41	8.36
22.0	8.73	8.68	8.63	8.58	8.53	8.48	8.43	8.38	8.33	8.28
22.5	8.64	8.59	8.54	8.49	8.44	8.40	8.35	8.30	8.25	8.20
23.0	8.56	8.51	8.46	8.41	8.36	8.32	8.27	8.22	8.17	8.13
23.5	8.48	8.43	8.38	8.33	8.29	8.24	8.19	8.14	8.10	8.05
24.0	8.40	8.35	8.30	8.26	8.21	8.16	8.12	8.07	8.02	7.98
24.5	8.32	8.27	8.23	8.18	8.13	8.09	8.04	7.99	7.95	7.90
25.0	8.24	8.20	8.15	8.10	8.06	8.01	7.97	7.92	7.88	7.83
25.5	8.17	8.12	8.08	8.03	7.99	7.94	7.90	7.85	7.81	7.76
26.0	8.09	8.05	8.00	7.96	7.91	7.87	7.82	7.78	7.74	7.69
26.5	8.02	7.98	7.93	7.89	7.84	7.80	7.75	7.71	7.67	7.62
27.0	7.95	7.90	7.86	7.82	7.77	7.73	7.69	7.64	7.60	7.56
27.5	7.88	7.83	7.79	7.75	7.70	7.66	7.62	7.58	7.53	7.49
28.0	7.81	7.76	7.72	7.68	7.64	7.59	7.55	7.51	7.47	7.43
28.5	7.74	7.70	7.65	7.61	7.57	7.53	7.49	7.44	7.40	7.36
29.0	7.67	7.63	7.59	7.55	7.50	7.46	7.42	7.38	7.34	7.30
29.5	7.60	7.56	7.52	7.48	7.44	7.40	7.36	7.32	7.28	7.24

Table 1.2. (continued) OXYGEN SOLUBILITY (mg/l or mg/dm^3)

SALINITY (g/kg)

TEMP °C	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	18.0	19.0
0.0	13.60	13.54	13.45	13.36	13.27	13.18	13.09	13.00	12.91	12.82
0.5	13.45	13.36	13.27	13.18	13.09	13.00	12.91	12.82	12.74	12.65
1.0	13.27	13.18	13.09	13.00	12.91	12.83	12.74	12.65	12.57	12.48
1.5	13.09	13.00	12.91	12.83	12.74	12.65	12.57	12.48	12.40	12.32
2.0	12.91	12.83	12.74	12.66	12.57	12.49	12.40	12.32	12.24	12.15
2.5	12.74	12.66	12.57	12.49	12.41	12.32	12.24	12.16	12.08	12.00
3.0	12.58	12.49	12.41	12.33	12.24	12.16	12.08	12.00	11.92	11.84
3.5	12.41	12.33	12.25	12.17	12.09	12.01	11.93	11.85	11.77	11.69
4.0	12.25	12.17	12.09	12.01	11.93	11.85	11.78	11.70	11.62	11.54
4.5	12.10	12.02	11.94	11.86	11.78	11.70	11.63	11.55	11.47	11.40
5.0	11.94	11.87	11.79	11.71	11.63	11.56	11.48	11.41	11.33	11.26
5.5	11.79	11.72	11.64	11.56	11.49	11.41	11.34	11.27	11.19	11.12
20.0	8.56	8.51	8.46	8.41	8.36	8.31	8.26	8.21	8.16	8.11
20.5	8.47	8.42	8.37	8.32	8.28	8.23	8.18	8.13	8.08	8.04
21.0	8.39	8.34	8.29	8.25	8.20	8.15	8.10	8.05	8.01	7.96
21.5	8.31	8.26	8.22	8.17	8.12	8.07	8.03	7.98	7.93	7.89
22.0	8.23	8.19	8.14	8.09	8.04	8.00	7.95	7.90	7.86	7.81
22.5	8.16	8.11	8.06	8.01	7.97	7.92	7.88	7.83	7.79	7.74
23.0	8.08	8.03	7.99	7.94	7.89	7.85	7.80	7.76	7.71	7.67
23.5	8.00	7.96	7.91	7.87	7.82	7.78	7.73	7.69	7.64	7.60
24.0	7.93	7.89	7.84	7.80	7.75	7.71	7.66	7.62	7.58	7.53
24.5	7.86	7.81	7.77	7.73	7.68	7.64	7.59	7.55	7.51	7.46
25.0	7.79	7.74	7.70	7.66	7.61	7.57	7.53	7.48	7.44	7.40
25.5	7.72	7.67	7.63	7.59	7.54	7.50	7.46	7.42	7.38	7.33
26.0	7.65	7.61	7.56	7.52	7.48	7.44	7.39	7.35	7.31	7.27
26.5	7.58	7.54	7.50	7.45	7.41	7.37	7.33	7.29	7.25	7.21
27.0	7.51	7.47	7.43	7.39	7.35	7.31	7.27	7.23	7.18	7.14
27.5	7.45	7.41	7.37	7.33	7.28	7.24	7.20	7.16	7.12	7.08
28.0	7.38	7.34	7.30	7.26	7.22	7.18	7.14	7.10	7.06	7.02
28.5	7.32	7.28	7.24	7.20	7.16	7.12	7.08	7.04	7.00	6.96
29.0	7.26	7.22	7.18	7.14	7.10	7.06	7.02	6.98	6.94	6.91
29.5	7.20	7.16	7.12	7.08	7.04	7.00	6.96	6.92	6.89	6.85

Table 1.2. (continued) OXYGEN SOLUBILITY (mg/1 or mg/dm^3)

SALINITY (g/kg)

TEMP °C	20.0	21.0	22.0	23.0	24.0	25.0	26.0	27.0	28.0	29.0
0.0	12.74	12.65	12.56	12.48	12.39	12.31	12.23	12.14	12.06	11.98
0.5	12.57	12.48	12.40	12.31	12.23	12.14	12.06	11.98	11.90	11.82
1.0	12.40	12.31	12.23	12.15	12.07	11.98	11.90	11.82	11.74	11.66
1.5	12.23	12.15	12.07	11.99	11.91	11.83	11.75	11.67	11.59	11.51
2.0	12.07	11.99	11.91	11.83	11.75	11.67	11.60	11.52	11.44	11.36
2.5	11.92	11.84	11.76	11.68	11.60	11.52	11.45	11.37	11.29	11.22
3.0	11.76	11.68	11.61	11.53	11.45	11.38	11.30	11.23	11.15	11.08
3.5	11.61	11.54	11.46	11.38	11.31	11.23	11.16	11.08	11.01	10.94
4.0	11.47	11.39	11.32	11.24	11.17	11.09	11.02	10.95	10.87	10.80
4.5	11.32	11.25	11.17	11.10	11.03	10.95	10.88	10.81	10.74	10.67
5.0	11.18	11.11	11.04	10.96	10.89	10.82	10.75	10.68	10.61	10.54
5.5	11.05	10.97	10.90	10.83	10.76	10.69	10.62	10.55	10.48	10.41
20.0	8.07	8.02	7.97	7.92	7.88	7.83	7.78	7.74	7.69	7.65
20.5	7.99	7.94	7.90	7.85	7.80	7.76	7.71	7.67	7.62	7.58
21.0	7.91	7.87	7.82	7.78	7.73	7.69	7.64	7.60	7.55	7.51
21.5	7.84	7.79	7.75	7.70	7.66	7.61	7.57	7.53	7.48	7.44
22.0	7.77	7.72	7.68	7.63	7.59	7.54	7.50	7.46	7.41	7.37
22.5	7.70	7.65	7.61	7.56	7.52	7.48	7.43	7.39	7.35	7.30
23.0	7.63	7.58	7.54	7.49	7.45	7.41	7.37	7.32	7.28	7.24
23.5	7.56	7.51	7.47	7.43	7.38	7.34	7.30	7.26	7.22	7.18
24.0	7.49	7.45	7.40	7.36	7.32	7.28	7.24	7.19	7.15	7.11
24.5	7.42	7.38	7.34	7.30	7.25	7.21	7.17	7.13	7.09	7.05
25.0	7.36	7.32	7.27	7.23	7.19	7.15	7.11	7.07	7.03	6.99
25.5	7.29	7.25	7.21	7.17	7.13	7.09	7.05	7.01	6.97	6.93
26.0	7.23	7.19	7.15	7.11	7.07	7.03	6.99	6.95	6.91	6.87
26.5	7.17	7.13	7.09	7.05	7.01	6.97	6.93	6.89	6.85	6.81
27.0	7.10	7.06	7.03	6.99	6.95	6.91	6.87	6.83	6.79	6.75
27.5	7.04	7.00	6.97	6.93	6.89	6.85	6.81	6.77	6.74	6.70
28.0	6.98	6.95	6.91	6.87	6.83	6.79	6.75	6.72	6.68	6.64
28.5	6.93	6.89	6.85	6.81	6.77	6.74	6.70	6.66	6.62	6.59
29.0	6.87	6.83	6.79	6.75	6.72	6.68	6.64	6.61	6.57	6.53
29.5	6.81	6.77	6.74	6.70	6.66	6.63	6.59	6.55	6.52	6.48

Table 1.2. (continued) OXYGEN SOLUBILITY (mg/l or mg/dm^3)

TEMP °C	SALINITY (g/kg) 30.0	31.0	32.0	33.0	34.0	35.0	36.0	37.0	38.0	39.0
0.0	11.90	11.82	11.73	11.65	11.58	11.50	11.42	11.34	11.26	11.19
0.5	11.74	11.66	11.58	11.50	11.42	11.35	11.27	11.19	11.12	11.04
1.0	11.58	11.51	11.43	11.35	11.27	11.20	11.12	11.05	10.97	10.90
1.5	11.43	11.36	11.28	11.20	11.13	11.05	10.98	10.91	10.83	10.76
2.0	11.29	11.21	11.14	11.06	10.99	10.91	10.84	10.77	10.70	10.62
2.5	11.14	11.07	10.99	10.92	10.85	10.78	10.70	10.63	10.56	10.49
3.0	11.00	10.93	10.86	10.78	10.71	10.64	10.57	10.50	10.43	10.36
3.5	10.87	10.79	10.72	10.65	10.58	10.51	10.44	10.37	10.30	10.23
4.0	10.73	10.66	10.59	10.52	10.45	10.38	10.31	10.24	10.18	10.11
4.5	10.60	10.53	10.46	10.39	10.32	10.25	10.19	10.12	10.05	9.99
5.0	10.47	10.40	10.33	10.27	10.20	10.13	10.06	10.00	9.93	9.87
5.5	10.34	10.28	10.21	10.14	10.08	10.01	9.94	9.88	9.81	9.75
20.0	7.60	7.56	7.51	7.47	7.43	7.38	7.34	7.30	7.25	7.21
20.5	7.53	7.49	7.44	7.40	7.36	7.31	7.27	7.23	7.19	7.14
21.0	7.46	7.42	7.38	7.33	7.29	7.25	7.21	7.16	7.12	7.08
21.5	7.40	7.35	7.31	7.27	7.22	7.18	7.14	7.10	7.06	7.02
22.0	7.33	7.29	7.24	7.20	7.16	7.12	7.08	7.04	6.99	6.95
22.5	7.26	7.22	7.18	7.14	7.10	7.05	7.01	6.97	6.93	6.89
23.0	7.20	7.16	7.12	7.07	7.03	6.99	6.95	6.91	6.87	6.83
23.5	7.13	7.09	7.05	7.01	6.97	6.93	6.89	6.85	6.81	6.77
24.0	7.07	7.03	6.99	6.95	6.91	6.87	6.83	6.79	6.75	6.72
24.5	7.01	6.97	6.93	6.89	6.85	6.81	6.77	6.74	6.70	6.66
25.0	6.95	6.91	6.87	6.83	6.79	6.75	6.72	6.68	6.64	6.60
25.5	6.89	6.85	6.81	6.77	6.74	6.70	6.66	6.62	6.58	6.55
26.0	6.83	6.79	6.75	6.72	6.68	6.64	6.60	6.57	6.53	6.49
26.5	6.77	6.74	6.70	6.66	6.62	6.59	6.55	6.51	6.48	6.44
27.0	6.72	6.68	6.64	6.60	6.57	6.53	6.49	6.46	6.42	6.39
27.5	6.66	6.62	6.59	6.55	6.51	6.48	6.44	6.41	6.37	6.33
28.0	6.61	6.57	6.53	6.50	6.46	6.42	6.39	6.35	6.32	6.28
28.5	6.55	6.52	6.48	6.44	6.41	6.37	6.34	6.30	6.27	6.23
29.0	6.50	6.46	6.43	6.39	6.36	6.32	6.29	6.25	6.22	6.18
29.5	6.45	6.41	6.37	6.34	6.31	6.27	6.24	6.20	6.17	6.13

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