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BENTHIC RESPIRATION OF ESTUARINE MUDS

A review of influencing factors

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ABSTRACT

Benthal oxygen demand can be a significant factor affecting the oxygen balance of an estuary. Many of the existing mathematical models of oxygen balance do not include benthal oxygen demand, those that do generally do so in a very simplistic manner. This report describes a literature review which was undertaken to acquire a greater understanding of the processes involved and to identify the controlling factors which would need to be included in an improved mathematical model.

Data collected from the Lagan estuary, Northern Ireland were analysed and the results used in a mathematical model to test hypotheses relating to the dependence of benthal oxygen demand to the oxygen levels in the overlying water.

It is concluded that further investigations are required under controlled conditions if the effects of several different factors on benthal respiration are to be adequately identified.

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1 INTRODUCTION

Past discharges of settleable and colloidal organic solids into natural waterways have resulted in appreciable accumulations of sludge, which may become one of the most important factors influencing the quality of natural water. (Fillos and Molof (15)). In certain locations, benthic deposits may be responsible for approximately 50% of the total oxygen depletion in a given section of a river. (Hanes and Irvine (18)).

The upper layers of the sediment in estuarine waters are subject to intense microbial activity and the subsequent changes affecting both the organic and inorganic chemistry of the sediments occur under both aerobic and anaerobic conditions. Such benthal decomposition processes can affect the overlying water in two basic ways:-

(a) dissolved oxygen is removed from the overlying water by bacterial respiration in the aerobic layer and by the immediate oxygen demand of the reduced substances diffusing upwards from the deeper anaerobic layers.

(b) benthal deposits can also release organic substances and various nutrients into the overlying water, thus causing additional oxygen removal. The release of such nutrients as ammonia and phosphates can cause large biotic growths that would adversely affect the quality of the natural waters. (Fillos and Molof (15)).

The influencing factors and processes governing such benthal oxygen demands need to be understood so that their contribution to the overall oxygen balance of an estuary may be incorporated within mathematical models with greater confidence than at present. Bowman and

Delfino (2) emphasised the requirement for realistic modelling of benthal oxygen demand with reference to Pollution Legislation levels in the USA :

> "Serious legal and economic consequences can follow from the enforcement of discharge limits based on computer models in which one of the most important parameters (sediment oxygen demand) contains significant analytical uncertainty"

In order to improve the simulation of benthal demand in present mathematical models, a literature survey was undertaken to highlight the main factors that should be considered. It soon became apparent that numerous studies had been undertaken whereby the Benthal oxygen demand had been measured, and thus numerous theories and viewpoints had been developed from laboratory and in-situ studies, and yet there still appeared to be no satisfactory understanding of the processes occurring. There appear to be five main factors influencing the benthal oxygen demand:

(a) Influence of the dissolved oxygen concentration in the water overlying the sediment. There are two main hypotheses:

  (i) the oxygen uptake by the sediment is proportional to the dissolved oxygen concentration in the overlying water column.

  (ii) there exists an oxygen demand independent of the dissolved oxygen concentration.

(b) Organic content of the sediment. Therefore a knowledge of the origin of the sediment would be advantageous so that allowance may be made for fast and slow carbonaceous demand.

(c) Physical structure, and thus density of the sediment influencing the diffusion of substances, both into and out of the sediment. The affect of turbulent motion in the overlying water on the density of the sediment also needs to be considered.

(d) Contribution of the benthic organisms, particularly in the surface layer, affecting not only the chemistry of the whole environment but also causing mechanical transport (bioturbation).

(e) Influence of temperature on the rate of oxygen uptake.

Table 1 summarises oxygen uptake rates from sediments in marine, river and lake studies. It is important to note that numerous different methods were employed for such measurements and that the locations varied considerably, but even so the variability highlights the need for a more detailed understanding of the factors influencing the oxygen demand in order to be able to provide realistic computational estimates.

2 INFLUENCE OF THE DISSOLVED OXYGEN CONCENTRATION IN WATER OVERLYING THE SEDIMENT

The relationship between the sediment oxygen uptake and the oxygen concentration of overlying water has caused a division among investigators. Some have found benthic oxygen demand to be independent of the dissolved oxygen concentration above approximately

1mg/l - 2mg/l, these include Baity (from 6), Fair, Moore and Thomas (14), Fillos and Molof (15), Dale (8), Martin and Bella (32), Mortimer (36). However, Edwards and Rolley (13), McDonnell and Hall (33), Edberg and Hofsten (12) and Chiaro and Burke (6) find the oxygen demand to be dependent on the oxygen concentration. An explanation for such differing viewpoints may be the varying sediment characteristics and the different measurement procedures employed by the investigators. Chiaro and Burke (6) suggested that the pre-dominance or not of certain sediment processes may influence the type of relationship, as follows:

Mechanisms dependent on oxygen concentration

- Oxygen diffusion to and into sediments
- chemical oxidation of reduced substances
- macro-organism respiration

Mechanisms independent of oxygen concentration

- micro-organism respiration and production, release and transport of reduced substances in and through sediments

Martin and Bella (32) quoted a study by Camp (1963) who reasoned that whether a dependency existed or not was influenced by whether the oxygen uptake was a result of the release of oxygen demanding substances to the water, or whether the oxygen uptake was caused by the diffusion of oxygen into bottom sediments. Hargrave (19) pointed out that whatever theory is favoured, the oxygen uptake rate depends on the biological system, since a chemical demand is created by substances from biological decomposition.

Edwards and Rolley (13) in a study of river muds in the United Kingdom, found that the oxygen consumption of the muds was dependent on the oxygen concentration in the overlying water up to about 8 mg/l. The relationship between the oxygen uptake and the dissolved oxygen concentration was described by the formula:

$$R = aC^b$$

where

R = oxygen uptake
C = oxygen concentration
a and b are empirical constants

Edberg and Hofsten (12) concluded from laboratory experiments that the oxygen uptake was dependent upon the oxygen concentration. Both types of relationship were observed Pamatmat (41) under different circumstances. Thus, whenever the rate of chemical oxidation was enhanced by the disturbance of the surface sediment and exposure to the anoxic layer or wherever chemical oxidation was a large proportion of the total oxygen uptake, the rate of this uptake was proportional to the oxygen concentration. However, where respiration was predominant, the oxygen consumption was independent of the oxygen concentration until a critical level (approximately 1 mg/l) was reached when the dependency became apparent. Chemical oxidation and biological demand was separated by the use of formaldehyde poison.

Fillos and Molof (15) used a continuous flow respirometer in which a flow of water was maintained over an area of bed isolated from the surrounding bottom deposits. Their findings indicated that the dissolved oxygen level affected both the oxygen uptake of benthal deposits and the release rate of organics and nutrients from the benthal deposits into the overlying water. The ability to maintain the bottom water dissolved oxygen above a certain level means that retardation of eutrophication may be accomplished. The release of nutrients, for example, phosphate and ammonia, increased with a fall in dissolved oxygen. It was also shown that the production of reduced substances by anaerobic decomposition were not hindered by the presence of aerobic conditions, therefore, suggesting that any relations between dissolved oxygen and oxygen uptake are largely caused by changes in aerobic bacterial activity rather than the affects of anaerobic decomposition within the sediment. A critical oxygen concentration existed at approximately 2mg/l below which the dissolved oxygen concentration became dependent on the oxygen uptake. A similar relationship was noted by Baity (from 6), also using a continuous benthal system, the relationship being independent of oxygen concentration between 2.19 - 5.11mg/l. When the dissolved oxygen was lowered to values below 2mg/l, the oxygen uptake rate decreased.

A study undertaken by Fisher et al (16) in three North Carolina estuaries, also exhibited the two forms of relationship. Diver-installed chambers were placed on the bed sediments and the oxygen consumption was predominantly continuous, consistent and usually linear over time. However, under a strongly stratified water column and low in-situ oxygen conditions, the oxygen consumption was dependent on the concentration at oxygen levels of less than 25% saturation, resulting in decreasing oxygen uptake rates over time.

Seasonal variations in oxygen levels were found by Dale (8), in a study of marine sediments, but no correlation between oxygen consumption and oxygen content was found. Edberg and Hofsten (12) reported on a study by Martin and Bella (32) in which mud cores were taken for laboratory study from the Yaquina estuary, near Newport, Oregon. Graphs were produced of the oxygen concentration (mg O_2/l) above three mud cores at 10°C, against time (days). The lines produced were subsequently described by the equation:

$$C = a + bt + ct^2 \qquad (1)$$

where

C = oxygen concentration
t = time
a, b and c are constants

If differentiated with respect to time, the oxygen uptake may be represented as:

$$R = \frac{dC}{dt} = b + 2ct \qquad (2)$$

where

R = oxygen uptake

The oxygen uptake was then calculated according to Equation (2) and plotted against the oxygen concentration calculated according to Equation (1). The resultant curve produced could not be described by the 'dependent' relationship stated by Edwards and Rolley (13) and McDonnell and Hall (33):

$$R = aC^b$$

It was concluded that the independent nature of the oxygen uptake to oxygen concentration in this study could primarily be attributed to the release of biodegradable substances from the bottom material into the overlying water.

Laboratory experiments with mud taken from the River Lagan, Belfast have been analysed by Downing (11). The rate of uptake of dissolved oxygen was measured and then remeasured after the dissolved oxygen had been raised again to the initial level. The remeasurements were very similar to the initial ones, thus offering no evidence that the exhaustion of a degradable substrate had caused the reduction in dissolved oxygen uptake rate. The rate of removal of dissolved oxygen was almost directly proportional to the dissolved oxygen, thus providing an indication that the oxygen uptake was diffusion controlled, depending on the kinetics of the reaction within the mud.

3 ORGANIC CONTENT OF THE SEDIMENT

The influence of the sediment depth on the oxygen consumption has been considered by numerous investigators. Early work by Fair et al (14) indicated that sludge depth influenced sediment oxygen demand. However, later investigators generally reported that sediment oxygen demand was independent of sludge depth, within certain limits. (Fillos and Molof (15); Edwards and Rolley (13); Hargrave (19); Knowles et al (31); Martin and Bella (32); Pamatmat (41); James (27); and Edberg and Hofsten (12)).

Certain types of organic matter are well known to have some considerable affect on the oxygen levels of overlying waters. However, it is questionable whether the total amount of organic carbon may be employed as an indicator.

The following investigators have found no correlation between oxygen consumption and organic carbon content: Anderson (from 2), Edwards and Rolley (13), James (27), Kalo (from 2). A study in Puget Sound by Pamatmat and Banse (40) found no correlation between total oxygen consumed and total organic matter. However, a possible correlation was noted with the 'available' organic content. The assumption behind this theory being that there exists a significant amount of 'buried organic matter' whose oxygen demand is not necessarily reflected at the mud-water interface. This theory could be the basis for the idea that diffusion of oxygen into the sediment controls the oxygen uptake.

Martin and Bella (32) pointed out that the unoxidised material in a natural system is a mixture of an undetermined number of substances, all of which may possess different reaction coefficients. Hence, a first order reaction would be an oversimplification. Edberg and Hofsten (12) emphasized from their laboratory studies that there is no simple correlation between oxygen uptake and the content of organic matter in the sediment. The nature and quality of the organic substance has a greater influence on the extent of oxygen uptake. The study by James (27) within the Tyne estuary provides an ideal example - the presence of coal dust providing a high total organic carbon content. However coal biodegrades slowly and so does not create an excessive oxygen demand.

Pamatmat and Banse (40) indicated a relationship between seasonal changes in supply of organic matter and changes in biological activity and hence seasonal changes in oxygen consumption. However, for such a relationship to be used as an indicator of oxygen consumption further information is required regarding the seasonal changes in the rate of deposition of particulate organic matter, the amount of assimiliable organic matter in the sediment and the partition of total oxygen consumption between respiration and inorganic chemical oxidation. Fenchal (from 8) suggested a different theory, in that the effect on benthal metabolism of temporal variations in detritus production may be lower than expected, due to the relatively low nutritive value of detritus which, compared to proteins, contains small amounts of phosphorus and nitrogen.

The usefulness of organic content as an indicator for potential oxygen consumption has been doubted both by Johnson and Brinkhurst (29) and Hargrave (from 2), who stated that it is not possible to conclude anything about the metabolic capacity of the sediment on the basis of its organic matter content.

The fate of organic matter entering a system has been described by Fischer et al (16) - with three possible pathways:

1. aerobic degradation at the surface
2. temporary burial followed by anaerobic decomposition
3. deeper permanent burial

It is important to know the relative importance of these three pathways, their variations possibly having significant implications for the dissolved oxygen content of the overlying water. The conclusion, by Nixon (from 16), that 25 - 50% of organic matter is oxidised, demonstrates that an oxygen demand is not created by the total carbon input to a system.

Organic matter from municipal and industrial outfalls represent a source of replenishment for the sediment oxygen demand. For example, Morris (35) considered that the particulate organic materials of both natural and anthropogenic origins, localised within the low salinity region - either in suspension or oscillating tidally between the suspended and deposited states, are responsible for the exertion of the predominant oxygen demand.

A preliminary survey of the Tyne estuary (as reported by James (27)) suggested there was little correlation between the organic content of the mud and the rate of oxygen uptake. Further study was carried out on mud samples and Downing (11) commented on the results. The uptake rates were slightly dependent on the organic content of the mud, rates in mud containing 26% organic matter being about 15% greater than those in muds containing 10%, these organic contents spanning the range observed. The average oxygen uptake value being 8g/m ^{2}/day.

The contribution of organic matter to a system, along with its subsequent decomposition by micro-organisms, has long been recognised as the dominant mode of oxygen uptake. However, although there appears to be no direct correlation between the organic matter content and the rate of oxygen uptake there is still a need to know of the origin of the organic matter and the amount of oxidisable material remaining at any one time so that any potential oxygen uptake may be predicted.

4 PHYSICAL STRUCTURE OF THE MUD

4.1 Disturbance of sediments

Having discussed the influence of oxygen concentration and organic content on the potential oxygen uptake of a sediment, the physical structure of the sediment also needs to be considered. The 'exposure' of the organic content to the oxygen within the water column, and thus the related oxygen uptake, will depend upon the diffusion of both oxygen into the sediment and reduced substances upwards to the sediment-water interface. Such diffusion will be significantly influenced or controlled by the physical structure of the sediment.

Edwards and Rolley (13) in an experimental study on river muds identified an increase in the oxygen consumption of the sediments upon erosion. An increased oxygen uptake from muds where the volume of interstitial water in exchange with the overlying water is large was noted. This is a point that must be considered when using respirometers as the oxygen consumption is calculated from the volume and change in oxygen content of the overlying water alone, thereby leading to possible underestimation. The effect of the stirring velocity, in an experimental situation, was also noted by Carey (5), a definite increase in the oxygen uptake being noted once a critical velocity had been reached. Callender and Hammond (4) also showed that the aerobic respiration and chemical oxygen demand were both positively affected by the stirring of the overlying waters.

Reporting on a study of the River Tyne, James (27) described the results obtained from an annular respirometer in which the velocity could be controlled. An exponential relationship was found (Fig 1) relating percentage increase in oxygen uptake rate to velocity. The oxygen uptake was shown to level off once the scouring velocity had been reached, approximately 0.2m/s. A tentative biochemical oxygen demand (BOD) budget was produced for the Tyne estuary by Brady (from 27) within which the benthal respiration had been adjusted for the velocities associated with Neap and Spring tides. The significant increase in velocities and the respiration during a Spring tide as compared to a Neap had been shown by numerous previous studies. Allen (from 27), in a previous hydraulic study of the River Tyne, had indicated the tidal amplitude as a dominant factor in determining the velocities near the bed.

The Tyne study concluded that the non-linear nature of the oxygen uptake to velocity relationship needs to be incorporated into a dissolved oxygen model in order to compute the benthal oxygen demand. The relationship between the water velocity and oxygen uptake obtained in the Tyne study may not be applicable to other estuaries where the erosion characteristics of the bed sediments are different. However the effect of sediment disturbance on oxygen uptake needs to be considered as a significant factor.

4.2 Sediment depth

The relative importance of respiration and chemical oxidation was related to the depth of oxidised sediment, by Hargrave (19), and therefore also to the rate of movement of reduced substances to the water surface. Pamatmat (41) queried the variation in the role of chemical oxidation as the rate did not appear to be related to the organic nitrogen content of the sediment alone. He stated that the rate should be related to the amount and possibly the kinds of reduced substances in the sediment along with the rate of diffusion governed by the compactness and porosity of the sediment. It was also found experimentally that if the chemical oxidation was enhanced by disturbance of the mud then the rate would decrease with decreasing oxygen concentration.

The composition of the mud was not considered to be uniform by Fillos and Molof (15). The aerobic layer may be only a few millimetres thick, with the anaerobic layer possibly exhibiting varying redox potentials (and thus reductivities) with depth. A critical depth of 75-100mm was identified above which the oxygen uptake rate may be independent of the sludge depth. The importance of this non-uniformity becomes evident when the influence of benthic organisms are considered. The potential oxygen uptake being influenced by the presence or absence of such maxima of reduced substances. Jahnke et al (25) highlighted the influence of micro-organism respiration along with the physical action of tides and waves as the ventilation of sediment, thus emphasising that there was no reason for uniform oxygen uptake rates from place to place.

4.3 Sediment compactness

The importance of the desorption of material concentrated in the sediments, and or the resuspension of the sediments themselves was considered by Shaw (from 2). Such processes are dependent upon the consolidation of the sediments as unconsolidated deposits which are resuspended frequently by strong tides may have a greater influence on the oxygen balance than those that are consolidated and thus less easily resuspended.

McMaster (34) in a study at Narragansett Bay, South Massachusetts, gave the view that the compactness variability of sediment follows a cycle beginning with relatively open packing for the grains of the surface sediment layers when the bottom layers are warmer than 8 to 10°C and so that biological and chemical processes are active. However, as the temperature falls below 3 to 5°C, the biological and chemical processes are retarded and the particles consequently assume a more closely packed condition, thus influencing the diffusion.

The physical structure of the sediment influences the diffusion into and out of the sediment. Water turbulence and consolidation obviously influence the structure but the presence of benthic organisms may also considerably alter the structure of the sediment.

5 EFFECT OF BENTHIC ORGANISMS

The processes of molecular diffusion govern the transport of oxygen into the sediments and also the upward migration of reduced, oxygen demanding substances into the overlying water where they exert a biological or chemical oxygen demand. However, large macro-invertebrate populations of borers and detritus feeders may hasten the release of nutrients and release of oxygen demanding matter into the overlying water, while simultaneously permitting increased oxygen transport into the sediments (Chiaro and Burke (6)).

Hargrave (19) observed that differences in oxygen consumption expected with different algae, bacteria and macro-invertebrates for example, appear of secondary importance to the temperature. However, exceptions do occur in organically polluted rivers containing large numbers of macro-invertebrates (Knowles et al (31)) where the oxygen uptake is correspondingly high.

To determine how far invertebrates affected the distribution of water into muds, the vertical distribution of Lithium (Li^+) was measured, by Edwards and Rolley (13), in mud cores which had been exposed to a solution of Lithium chloride for six hours. Variation in penetration may be associated with the degree of compaction and water content of the muds and the effect of larval distribution. It was shown that appreciable interchange occurred between the water above and within the muds, this increasing with the numbers of macro-invertebrates.

Pamatmat (41) quoted a study by Teal and Kanwisher (47) in which animal burrows were considered to make up 22% of the total area of the mud-water interface - thus providing an indication of the extent of the effect benthal organisms have on the processes within the mud. Revsbech et al (43) from studies at Randers Fjord estuary, Denmark, pointed out that macro-faunal activity, rather than molecular diffusion and water turbulence, was important for the occasional transport of oxygen into deeper layers and thus the provision of oxidised conditions (positive redox potentials) down to 5 to 10cm below the sediment surface.

A possible relationship between benthic nutrient regeneration and sediment metabolism was suggested by Flint and Kamykowski (17). Under experimental conditions a decrease in faunal activity within sediments was related to a decrease in flux of ammonia, implying the fauna's role as a regulator of nutrient regeneration. The vertical movement of materials and burrow irrigation by fauna exposes nutrient reservoirs to overlying waters that would not otherwise have been available.

Barrett et al (1972) reported on a study of the disposal of sludge in Liverpool Bay. Experimental results of measurements of the rate of oxygen uptake from deposited sludge particles of two densities (equivalent to 23 and 100g dry solids/m^2) were reported. The lighter density deposit oxidised more rapidly than the heavier deposit, a possible explanation for this being that the former may have formed a less coherent layer that could be more easily penetrated by mobile organisms responsible for its biological oxidation. A tentative conclusion was made that the rate of aerobic biological breakdown may be dependent on the thickness of deposit.

Having considered the fact that fauna may significantly effect the oxygen uptake of a sediment, it is necessary to appreciate factors that may subsequently effect the extent of activity of the fauna. Organic matter has previously been mentioned as a possible controlling factor over fauna numbers but temperature should also be considered.

6 EFFECT OF TEMPERATURE

The seasonal effect of oxygen uptake by sediments has been noted by numerous investigators {Edwards and Rolley (13), Pamatmat and Banse (40), Hargrave (19), Edberg and Hofsten (12)}, and may be considered to be indirectly related to the temperature. The river mud study by Edwards and Rolley (13) refers to this by claiming that the oxygen consumption increased during March and April, probably in association with the growth of an epi-benthic algae. Such a seasonal effect was also noted by Carey (5) with a maximum in the late summer.

Hargrave stated in 1969 that the widespread importance of temperature had not been recognised, in that both the temperature and oxygen concentration affected the rate of diffusion of oxygen and reducing compounds across the mud-water interface, and the respiration of organisms in the sediment. The differences in the oxygen consumption expected with different algae, bacteria and invertebrates were thus considered to be of secondary importance to the temperature.

Temperature was not considered to be the only factor contributing to the seasonal increase in oxygen consumption by Pamatmat and Banse (40), a changing supply of organic matter may be related to changes in biological activity and thus subsequent changes in the rates of oxygen consumption.

Sorensen et al (46) identified a clear correlation between benthic oxygen consumption and temperature. The study by Dale (8) in Lindaspollene, Norway, identified only small variations in the benthic oxygen consumption throughout the year, the small temperature range (1.6°C) experienced providing a possible explanation. Pamatmat et al (40) found a seasonal cycle in both total and chemical oxygen consumption, in Puget Sound. Such a seasonal cycle was considered to be only partially influenced by temperature with variations in the flux of organic matter or its oxidizability being the main factor. However, the main limiting factors for benthic metabolism vary between locations. Temperature may be the limiting factor at one location whilst at another level of nutrients or organic material may be limiting.

From the study of three North Carolina estuaries [Fisher et al (16)], it was indicated that the temperature was influencing the sediment metabolism and sediment-water column exchange, but that other processes were probably more important.

Hargraves and Philips (21), from a study in Eastern Passage, Nova Scotia, showed that rates of sediment oxygen uptake were not closely correlated with seasonal changes in temperature. This agrees with Hargrave (from 21), but not with other observations {Hargrave (19), Pamatmat and Banse (40), Davies (1975) and Howarth and Teal (1979) (from 2)}. The lack of a simple linear relation between seasonal changes in temperature and sulphate reduction implied that the supply of substrates for anaerobic respiration was not closely coupled to the temperature variations.

In a study of the carbon dioxide release and oxygen consumption by sediments, Hargrave (21) showed that changes in temperature accounted for a greater amount of variation in sediment oxygen uptake than carbon dioxide release. Even so this temperature effect was still considered to have only a 50% effect on oxygen uptake.

A seasonal exchange between sediment and water was noted by Nedwell (37), in that deoxygenation of the surface (0-50mm) layer of sediment during the summer could be attributed both to higher temperature and to a layer of organic planktonic detritus, deposited on the sediment.

A correlation between sediment-oxygen consumption and temperature was demonstrated by Hargrave (19), based on values reported in the literature. The regression equation he produced was:

$$\log_e y = 1.74 \log_e(x) - 0.41$$

where

y = oxygen consumption

x = temperature

The effect of temperature on the rate of absorption of oxygen by mud deposits, from the Thames estuary, was calculated from laboratory studies to be an increase of about 13% per °C [(Water Pollution Research (9)].

There does appear to be some kind of relationship between the temperature and the oxygen uptake by sediments, however, in situ studies showing different oxygen consumptions at different times of year cannot be explained solely on the grounds of different temperatures prevailing at the time of measurement. The composition of the bottom deposits and the activity of benthic organisms changing through the year seems a more likely explanation.

7 THE MEASUREMENT OF OXYGEN CONSUMPTION BY MUD DEPOSITS

Bowman and Delfino (2) undertook an extensive literature review on methods of measuring sediment oxygen demand as it was apparent that significant errors may arise by comparing oxygen demands evaluated by different methods. For example, Patterson et al (from 2) found up to a ten fold difference between laboratory and in-situ measurements, while Edberg and Hofsten (12) reported up to a five fold difference. Both sets of measurements were uncorrected for temperature (Tables 2 and 3). Bowman and Delfino aimed to develop a standardised technique, and in so doing they identified numerous advantages and disadvantages of both laboratory and in-situ techniques. They also identified three criteria that should be met for a sediment oxygen demand method to be considered acceptable: consistency, reproducability and efficiency.

7.1 In situ benthic respirometers

The in-situ benthic respirometer is typically open on the bottom with a vertical cutting edge and externally attached flanges. The chamber is dropped onto the sediment and allowed to penetrate into the sediment. This entraps a known volume of water over a known surface area of sediment. The water is generally circulated within the chamber, in order to prevent stratification, and the dissolved oxygen is monitored. The resulting dissolved oxygen decrease over time is used to calculate the sediment oxygen demand, which is usually expressed as oxygen demand per unit area of sediment.

Numerous investigators have used batch in-situ respirometers, being constructed in varying shapes : rectangular (James (26)); cylindrical (Fisher et al (16), Edberg and Hofsten (12), Wilson (personal communication), James (26)) and dome (Chiaro and Burke (6)).

The chambers are usually constructed of synthetic materials such as Plexiglass (Fisher et al (16)) or perspex (Edwards and Rolley (13)). Some have been constructed of metal (Wilson (1984)) and glass (Hargrave (19)).

7.1.1 Advantages and disadvantages

Although measurements in real conditions possess obvious advantages: ambient conditions and minimal disturbance of the bed sediment, there do exist numerous uncontrollable variables that may affect sediment oxygen demand : temperature, turbulence, light and current velocity. Thus, there are many factors which must be controlled during measurement in order to collect accurate and reproduceable sediment oxygen data - which are not easily accomplished in-situ. If there is no mechanism to control the dissolved oxygen concentration of the overlying water, the experiment length is limited to the finite amount of dissolved oxygen.

7.2 Laboratory techniques

Laboratory measurement of benthic respiration requires the collection of undisturbed sediment cores [for example, Edberg and Hofsten (12), Edwards and Rolley (13), Pomroy et al (42), Dye (10) and Knowles and Edwards (31)], or dredge samples [Bowman and Delfino (2)]. Again dissolved oxygen measurements are made - the length of the experiment being determined by the dissolved oxygen concentration.

7.2.1 Advantages and disadvantages

External variables may be controlled more easily than those for in-situ studies, therefore allowing improved precision among replicates [Bowman and Delfino (2)]. Disturbance of the bed is inevitable - the sedimental structure being affected in the course of removing samples [Edberg and Hofsten (12)] - thereby making it difficult to reproduce natural conditions in the laboratory. The sediment cores should not be stored as reproduction of bacteria, for example, may increase the sediment demand. James (27) showed that some compaction of mud occurred during core removal, causing up to a 15% reduction in depth of the mud. This affected the interstitial water and thus the concentration gradients within the mud, with an associated reduction in potential oxygen uptake.

Continuous flow systems, open-ended systems containing a known surface area of sediment and having a continuous regulated flow of well aerated water moving over the sediment, have also been used. The difference in the dissolved oxygen concentration measured in the influent and effluent water being used to calculate the sediment oxygen demand. Such experiments are usually performed under laboratory conditions, the continuous water, and hence dissolved oxygen flow, enabling long-term experiments. (Fillos and Molof (15) for example). James (26) devised a tunnel respirometer for in-situ use.

8 MATHEMATICAL MODELLING OF BENTHIC RESPIRATION

The lack of a clear interpretation of the role of various processes on benthic respiration means that the incorporation of benthic respiration in a predictive mathematical model is by no means straight forward. It was decided that hypotheses derived from the literature be tested in a mathematical model and compared with field data from the River Lagan which had been collected by the Department of Economic Development, Northern Ireland as part of an investigation of the effects of a proposed tidal weir.

8.1 Experimental data

The main body of available data specific to the River Lagan consisted of twenty in-situ and five laboratory measurements made during 1984 with a submersible respirometer, described in a report prepared by Industrial Science Division, Department of Economic Development, Northern Ireland. The results of the various measurements were analysed by Dr A L Downing.

The respirometer enclosed an area of mud of about $0.1m^2$, and a volume of some 25 litres of water above the mud. A pump circulated the enclosed water at a rate sufficient to maintain a uniform concentration of dissolved oxygen uniform but insufficient to cause appreciable erosion of mud. When the respirometer was in position dissolved oxygen (DO) was measured periodically using a membrane electrode and the results plotted as a function of time. In some cases DO fell almost linearly at a nearly constant rate during the test; in others the rate of reduction of DO decreased continuously throughout.

In Table 3 are listed the oberved rates of removal, determined by fitting tangents to the curves by eye, when concentrations of DO were 8, 6, 3 and 1mg/litre. Also included are the temperatures of the water and locations at which the measurements were made.

The data show the following features:

- In the case of the three intially highest rates of demand observed the rate decreased much more rapidly with decreasing concentration of DO during the test than at the lower rates (of less than 18g/m^2/day).

- In tests on different occasions at a given site but in which temperature differed, demands at the lower temperature were markedly below those at the higher temperature; if the differences were due to temperature, the effect is greater than the doubling occurring over an interval of 10°C, often considered characteristic of biochemical processes.

- In tests at similar temperatures and at the same DO, rates appear to be higher in the middle reaches around Blackstaff Culvert than at the upper and lower bounds of the study area but the distinction is not clear cut probably because of the blurring effects of various variables.

The fact that the reduction of high initial rates of respiration with time was proportionately greater than the reduction in DO suggests that some mechanism other than or additional to diffusion influences demand. The lack of influence of DO concentration in some other tests also suggests that, in these cases, there were other mechanisms at work.

The effect of DO in the tests in which uptake was initially relatively high were somewhat similar to those reported by Edwards and Rolley (13), who concluded that in their tests variation in rate with DO above 2mg/l could be described by an equation of the form:

$$R = aC^{b}$$

where the value of the exponent b was 0.45.

The large differences between observations at the same site but at different times of the year seem too large to be due solely to differences in temperature which one might expect to roughly double rates for each 10°C change. Other factors, correlated with temperature, might well have an influence such as growth and deposition of algae. Nevertheless with absence of clear evidence it seemed reasonable to postulate a dependence on temperature, which would cater for the observed differences in rates of uptake in the hope that by so doing the effects of other factors, especially seasonal ones, might thereby be engrossed.

To arrive at suitable rate to assume for modelling, all values in Table 3 were converted to estimates of those to be expected if DO had been 6mg/l, and temperature 17°C. This was done by mulitplying the values by $(C/6)(1.15)^{(T-17)}$ where C is DO (8, 6, 3 or

1) and T is water temperature (°C) at the time of the measurements. A DO of 6mg/l was chosen as the reference concentration because more estimates were available for this DO than any other. The spread of results was then examined and it appeared that they might reasonably be grouped into those between 0 and 1.5km from Stranmillis Weir, 1.5 and 3km, and 3 and 4.5km. The values within each group were then averaged and rounded to obtain estimates respectively of 10, 25 and 10g/m^2/day for the three locations at a DO of 6mg/litre and 17°C.

As a result of this analysis a relationship between oxygen uptake, temperature and dissolved oxygen was derived which best described the experimental data:

$$R = R_s(C/6)(1.15)^{T-17}$$

where:

R = rate of uptake of DO under any given conditions of DO, temperature and load

R_s = the 'standard' rate appropriate to the relevant reach of river

C = DO content (mg/l)

T = temperature in °C

With the present load, about 5t/day, appropriate values of R_s are:

DISTANCE FROM STRANMILLIS WEIR (km)	R_s (g/m^2/day)
0 - 1.5	10
1.5 - 3.0	25
3.0 - 4.5	10

8.2 Mathematical model application to River Lagan

A two-dimensional, in depth, mathematical model of oxygen balance was amended to incorporate benthic respiration using the formula above. The model was then applied to the River Lagan (Fig 2) to simulate conditions during July/August 1984 when the bulk of the observations had been made. All known loadings of BOD were included in the model.

Observations of dissolved oxygen levels upstream of McConnell weir had shown that the saline lower layer of water impounded upstream of the weir was anoxic. However using a benthal demand formulation in which the oxygen demand decreased with the oxygen level in the overlying water it was not possible to reproduce these anoxic conditions in the model.

The benthal demand formulation was then amended so that at dissolved oxygen levels below 1mg/l the benthal demand was kept at that for an oxygen level of 1mg/l. The results from this test are shown in Figures 3a, b and were little different from those with the original formulation.

It became apparent that, in the Lagan, the relatively large body of anoxic water could not be adequately simulated using a benthal demand which was strongly dependent on levels of dissolved oxygen in the overlying water. The model was thus amended to allow for a benthal demand which was independent of the oxygen level where this was below 6mg/l but was dependent on oxygen level when above 6mg/l. Thus at concentrations above 6mg/l the original formulation was used but for dissolved oxygen levels below 6mg/l the formula was amended to:

$$R = R_s(1.15)^{T-17}$$

Results from this simulation were encouraging with the extent of the anoxic conditions being reproduced reasonably accurately. A comparison of simulated and observed oxygen levels is shown in Figures 4a, b.

9 DISCUSSION AND CONCLUSIONS

There is at present no clear consensus regarding the processes governing benthic respiration.

A review by Bouldin (1) discussed six hypotheses based on diffusion kinetics, each envisaging that dissolved oxygen from the overlying water diffuses with a constant diffusion coefficient into a column of static mud. Downing (11) in an review of the hypotheses discussed by Bouldin, and an analysis of respirometer studies of the benthal oxygen uptake of the River Lagan, Belfast, suggested that it was reasonable to assume that the oxygen uptake rate will vary in proportion to the dissolved oxygen, if diffusion is considered as an important rate-limiting factor.

However a formulation of benthic demand based on this assumption was not found to be satisfactory when used in a mathematical model of oxygen balance in the Lagan estuary. It was apparent that, in this case, diffusion was not the main controlling factor. There are many factors which could influence the diffusion of oxygen into the mud.

- The effect of temperature. Its influence on metabolic activity will affect the rate of oxidation of organic matter and thus also the rate of oxygen uptake.

- The physical structure of the mud. The density may represent an indicator of several structural influences. For example, the extent of benthal organism activity may be related to the compactness of the sediment, thus effecting the diffusion paths into the sediment.

- Sediment compactness may also indicate any disturbance of the sediment due to excessive water currents near the mud-water interface.

- Erosion and deposition. Accumulation of sediment over time, should be considered, as the oxygen demand of organic matter is not necessarily exerted instantaneously, accumulated sediment possibly representing an increased demand with time. Officer et al (38) in a study of Chesapeake Bay confirmed that the residue from the previous summer and fall plankton blooms were essential for the description of the onset of anoxic conditions in the following spring. This demonstrated that benthic respiration effects from a given phytoplankton bloom may be felt over an extended period of seasonal time.

If reliable predictions of benthic respiration are to be made using mathematical models then further investigation of the above processes is required. The use of a mathematical model can facilitate such an investigation by testing the hypotheses which arise from experimental data.

In order to investigate the effect of each possible factor on benthic respiration it is necessary to undertake experiments in controlled conditions which simulate as nearly as possible conditions found in-situ. One method of achieving this would be to allow a bed to settle from a high concentration suspension of benthic material in a closed recirculatory flume. After settlement, water could then be circulated over the bed and a prescribed oxygen level maintained by oxygen injection. Measurement of dissolved oxygen levels immediately before and after formation of the artificial bed combined with the volume of oxygen injected could then be used to derive respiration rates. This approach has the advantage that the length of time the bed is allowed to consolidate and the velocity of the circulating water can be varied to produce different bed structures in the flume.

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11 REFERENCES

1. Bouldin, D R (1968). Model for describing the diffusion of oxygen and other mobile constituents across the mud-water interface. J. of Ecology, 56 p 77-87.

2. Bowman, G T and Delfino, J J (1980). Sediment oxygen demand techniques: A review and comparison of laboratory and in situ system. Water Research, Vol 14 pp 491-499.

3. Burton, J D and Liss, P S (1976). Chemistry Academic Press. London.

4. Callender E and Hammond D (1982). Nutrient exchange across the sediment - water interface in the Potomac River Estuary. Estuarine coastal and shelf science Vol 15, No 4.

5. Carey, G (1967). Energetics of the benthos of Long Island Sound. Oxygen utilisation of the sediment. Bulletin of the Bingham Oceanographic Collection. 19 pp 136-144.

6. Chiaro, P S and Burke, D A (1980). Sediment oxygen demand and nutrient release. J. of the Env. Eng. Div, Proceedings of ASCE, Vol 106, No EE1.

7. Clifford, C H, Eliason, A H, Walden, B, Rowe, G T and Teal, J M (1976). A free vehicle for measuring benthic community metabolism. Limnology and Oceanography, Vol 21, pp 164-170.

8. Dale, T (1978). Total, Chemical and Biological oxygen consumption of the sediments of Lindaspollene, W. Norway. Marine Biology, 49 pp 333-341.

9. Department of scientific and industrial research (1964). Effects of Polluting Discharges on the Thames Estuary. Water Pollution Research. Technical paper Note 1.

10. Dye, A H (1983). Oxygen consumption by sediments in a South African Mangrove swamp. Estuarine Coastal and Shelf Science. Vol 17 No 4.

11. Downing, A L (1985). Uptake of dissolved oxygen by mud in the River Lagan - working paper.

12. Edberg, N and Hofsten, B V (1973). Oxygen uptake of Bottom sediments studied in-situ and in the laboratory. Water Research, Vol 7 No 9 pp 1285-1294.

13. Edwards, R W and Rolley, H L J (1965). "Oxygen consumption of River Muds." J. of Ecology, Vol 53 No 1 pp 1-19.

14. Fair, G M, Moore, E W and Thomas, H A. The Natural Purification of River Muds and Pollutional Sediments.

15. Fillos, J and Molof A H (1972). Effect of Benthal Deposits on oxygen and nutrient economy of flowing waters. Water Pollution Control Federation Journal Vol 44, No 4 pp 644-662.

16. Fisher, T R, Carlson, P R and Barber, R T (1980). Sediment Nutrient regeneration in Three North Carolina Estuaries. Estuarine Coastal and Shelf Science, Vol 14 p 101-114.

17. Flint, W R and Kamykowski D (1984). Benthic Nutrient regeneration in South Texas Coastal Waters. Estuarine Coastal and Shelf Science, Vol 18, No 2, pp 221-230.

18. Hanes, N B and Irvine R L (1968). New Technique for measuring oxygen uptake rates of benthal systems. Water Pollution Control Federation Journal, Vol 40, No 2 pp 223-232.

19. Hargrave, B T (1969). Similarity of oxygen uptake by benthic communities. Limnology and Oceanography, 14 pp 801-805.

20. Hargrave and Connolly (1978). A device to collect supernatant water for measurement of flux of dissolved compounds across sediment surfaces. Limnology and Oceanography, 23 pp 1005-1010.

21. Hargrave, B T and Philips, G A (1981). Annual in-situ carbon dioxide and oxygen flux across a subtidal marine sediment. Estuarine Coastal and Shelf Science, Vol 12, No 6.

22. Hartwig, E O (1978). Factors effecting respiration and photosynthesis by the benthic community of a subtidal siliceous sediment. Marine Biology, 46, p 283-293.

23. Hayes, F R and Macaulay, M A (1979). Lake water and sediment. V Oxygen consumption in water over sediment cores. Limnology and Oceanography, 4, 291-299.

24. Hutchinson, G E (1957). A Treatise on Limnology Vol 1, New York. pp 572-652.

25. Jahnke, R A, Emerson, S R and Murray, J W (1982). A model of oxygen reduction, denitrification and organic matter mineralisation in marine sediments. Limnology and Oceanography, 27 (4), pp 610-623.

26. James, A (1974). The measurement of Benthal respiration. Water Research, Vol 8, No. 11 pp 955-959.

27. James, A (1982). Benthal respiration in the River Tyne Estuary. Northumbrian Water Authority, Bull. No. 44.

28. Jamson, B and Hagstöm A (1978). Sea bed respiration: core samples for oxygen consumption measurements. Proceedings of the 11th Conference of Baltic Oceanographers, Vol 2. Rostock, DDR. pp 806-820.

29. Johnston, M G and Brinkhurst, R O (1971). Benthic community metabolism in Bay of Quinte and Lake Ontario. J. Fish. Res. Bd Can. 28, pp 1715-1725.

30. Kemp, W M and Boynton, W R (1979). Influence of Biological and Physical Processes on Dissolved Oxygen Dynamics in an Estuarine System: Implications for measurement of Community Metabolism. Estuarine Coastal and Shelf Science.

31. Knowles, G and Edwards, R W 91962). Polarographic measurement of the rate of respiration of natural sediments. Limnology and Oceanography, Vol 7, pp 481-484.

32. Martin, D C and Bella, D A (1971). Effect of mixing on oxygen uptake rate of Estuarine Bottom deposits. Water Pollution Control Federation Journal, Vol 43 No. 9, pp 1865-1876.

33. McDonnell, A J and Hall, S D (1967). Effect of Environmental Factors on Benthal oxygen uptake. Proc. 22nd Industrial Waste Conference, Pardue University, Lalayette, Ind.

34. McMaster, R L. Compactness variability of Estuarine sediments: An in-situ study from Estuaries ed. Lauff G H.

35. Morris, A W (1984). Chemistry of the Severn Estuary and the Bristol Channel. Marine Pollution Bulletin, Vol 15, No 2.

36. Mortimer, C H. The exchange of dissolved substances between mud and water in lakes. Journal of Ecology, Vol 29, pp 280-329.

37. Nedwell, D B, Hall, S E and Andersson, A (1983). Seasonal changes in the distribution and exchange of inorganic nitrogen between sediment and water in the North Baltic. Estuarine Coastal and Shelf Science, Vol 17, No 2.

38. Officer, C B, Lynch, D R, Kemp, W M and Boynton, W R (1985). Estimation of Benthic respiration parameters from field data. Estuarine Coastal and Shelf Science, 21, pp 357-364.

39. Pamatmat, M M and Fenton, D (1968). An instrument for measuring subtidal benthic metabolism In situ. Limnology and Oceanography, Vol 13, No. 3 pp 537-540.

40. Pamatmat, M M and Banse K (1969). Oxygen consumption by the seabed. II. In situ measurements to a depth of 180m. Limnology and Oceanography, 14, pp 250-259.

41. Pamatmat, M M (1971). Oxygen consumption by the seabed, IV, Shipboard and laboratory experiments. Limnology and Oceanography, Vol 16, pp 536-550.

42. Pomroy, A J, Joint, E R and Clarke, K R (1983). Benthic nutrient flux in a shallow coastal environment. Oecologia (Berlin), 60 pp 306-312.

43. Revsbech, N P, Sorensen, J and Blackburn, T H (1980). Distribution of oxygen in marine sediments measured with micro-electrodes. Limnology and Oceangraphy, 25 (3) pp 403-411.

44. Rowe, G T and Nichols, J A (1973). Benthic community repiration near Woods Hole sewage outfall. Estuarine and Coastal Marine Science, 1 pp 65-70.

45. Sonzogni, W C, Larsen, D P, Malveg, K W and Schuldt, M D (1977). Use of large submerged chambers to measure sediment-water interactions. Water Research, Vol 11, pp 461-464.

46. Sorensen J, Jorgensen, B and Revsbech, N (1979). Comparison of oxygen, nitrate and respiration in coastal marine sediments. Microbial Ecology, 5, pp 105-115.

47. Teal, J M and Kanwisher, J (1961). Gas exchange in a Georgia salt marsh. Limnol and Ocean. 6, pp 388-993.

48. Umbreit, W W, Burris, R H and Stauffer, J F (1964). Manometric techniques, 4th ed. Burgess, Minneapolis.

49. Watson, P G, Frickers, P E and Goodchild, C M (1985). Spatial and seasonal variations in the chemistry of sediment interstitial waters in the Tamar estuary. Estuarine Coastal and Shelf Science, Vol 21, pp 105-119.

50. Wollast, R and Vanderborght, J P (1974). Model of mass transfer in a benthic boundary layer submitted to physical and biological perturbations. NATO Science Committee Conference. The Benthic Boundary Layer - working papers.

TABLES.

TABLE 1: **Oxygen uptake rates, marine, river and lake**

MARINE

RATE	COMMENT	LOCATION	REFERENCE
8.7mg/m ^{2}/hr 17.24mg/m ^{2}/hr	Min Jan-Feb (Cores incubated) Max Oct (to ambient temp)	Camarthen Bay	42
3.0g/m ^{2}/d 0.71g/m ^{2}/d	in-situ -13°C Lab mud cores -10°C	Baltic Sea	12
10.67ml/m ^{2}/hr (0.015g/m ^{2}/hr)	cores + water samples -7°C	Norway - Lindaposllene	8
0.029g/m ^{2}/hr	cores at ambient temp	Long Island Sound	5
0.037-0.05g/m ^{2}/hr	cores + DO probe	Massachusetts salt marsh	5
0.021g/m ^{2}/hr 0.008g/m ^{2}/hr	summer (10-15°C) winter (0°C)(marine sediment)	Massachusetts Woods hole	5
0.018g/m ^{2}/hr	range 0.0066-0.052	Long Island Sound	5
0.163g/m ^{2}/hr 0.052g/m ^{2}/hr	corrected to 20°C (mud cores)	Yaquina Estuary, nr Newport, Oregon	32
0.03g/m ^{2}/hr	30m depth	Spanish Sahara coast	7
257.22g/m ^{2}/yr 0.0064g/m ^{2}/hr 0.045g/m ^{2}/hr	annual exhange min Jan-Feb, max July (sediment cores)	Eastern Passage Nova Scotia	21
0.213g/m ^{2}/hr 0.127g/m ^{2}/hr	July 1982 (in-situ fibre) Jan 1982 (glass chamber)	NW Gulf of Mexico - S Texas Coast	17
0.008-> 0.014g /m ^{2}/hr 0.0073-> 0.0135g /m ^{2}/hr	Bell jars in-situ 22m depth 7°C sediment cores	Port Madison Puget Sound Washington	41
0.19g/m ^{2}/hr 0.31g/m ^{2}/hr 0.31g/m ^{2}/hr	1" (Continuous respirometer) 3" (with respect to flow) 5"	Simulated sludges with varying depths	15
0.004g/m ^{2}/hr ->0.053g/m ^{2}/hr	sediment cores	Mangrove swamp S Africa	10
0.0405g/m ^{2}/hr	mud samples tested in annular respirometer to allow for velocity effect	Tyne Estuary Newcastle	27

TABLE 1: Marine: Continued

RATE	COMMENT	LOCATION	REFERENCE
2.4g/m ^{2}/d 2.3g/m ^{2}/d 1.4g/m ^{2}/d 1.2g/m ^{2}/d	June (Benthic Chambers) July Sept Sept	Chesapeake Bay	30
2.35-45.0g/m ^{2}/d	Benthic respirometer	River Lagan N Ireland	11
	RIVER		
0.2g/m ^{2}/hr 1.2g/m ^{2}/hr	mud cores, 20°C - increase upon scouring	R Gade, UK	13
0.1gm/m ^{2}/d 5.3gm/m ^{2}/d	in-situ respirometer - corrected to 20°C	Saginaw river Michigan	6
1.4g/m ^{2}/d 0.42-0.63g/m ^{2}/d	in-situ respirometer - 2°C mud cores - 5°C	Norway stream Jaders Bruk	12
2.2g/m ^{2}/d	Polarographic measurement	Ivel river	31
	LAKE		
2.6g/m ^{2}/d 0.58-1.2g/m ^{2}/d	in-situ respirometer -18°C Lab - mud cores - 13°C	Norway - Lake Ekoln	12
0.016g/m ^{2}/hr	11 ± 1.5°C	Variety of lake sediments eutrophic lakes	23
0.3-0.5g/m ^{2}/d 0.12-0.22g/m ^{2}/d 0.005-0.0092g/m ^{2}/hr	in-situ chambers	Shagaura lake Minnesota	45

TABLE 2: Sediment oxygen demands (SOD) in Lower Green Bay: in-situ vs. Laboratory measurements (Patterson et al (1975) (from 2)

Sampling Locations	IN-SITU SOD $g/m^2/day$	IN-SITU TEMP °C	LABORATORY SOD $g/m^2/day$	LABORATORY TEMP °C
Mouth of the River	1.90	12	0.48	20
Near Red Bank	1.65	12	0.16	20

In situ vs laboratory sediment oxygen demand measurements Edberg & Hofsten (12)

Sampling Locations	IN-SITU SOD $g/m^2/day$	IN-SITU TEMP °C	LABORATORY SOD $g/m^2/day$	LABORATORY TEMP °C
Baltic Sea*				
Edeboviken 1	3.0	13	0.71	10
Edeboviken 2	0.92	15	0.40	10
Lakes				
Erken	0.43	4	0.32-0.36	10
Norruiken 1	1.8	5	1.1	10
Norruiken 2	2.4	7	1.5	10
Ramsen	2.3	17	0.21-1.08	10
Ekoln	2.6	18	0.58-1.2	13
Streams				
Venaviken	1.44	2	0.26-1.2	5
Jaders Bruk	1.4	2	0.42-0.63	5
Sjomosjon	0.31	0	0.31-0.61	10

* Sediments contained fibrous matter from sulphite and pulp mills
Eutrophic lake with newly deposited algae.

TABLE 3: Observed rates of uptake of oxygen by mud in River Lagan

LOCATION	km FROM STRANMILLIS WEIR	WATER TEMPERATURE °C	OXYGEN DEMAND ($g/m^2/day$) AT GIVEN DO (mg/l) IN WATER COLUMN 8	6	3	1
RBAI Boat Club	0.44	16.7		16.5	15.5	
		17.2	8.5			
		16.9		8.7		
		17.2		11.9	9.4	
		11.95	3.6			
		12			2.35E	
Downstream Governors Bridge	0.89	16.4	8.1	7.63		
		12.6			2.5E	
Upstream Kings Bridge	1.16	18.0		13.4		
Blackstaff Culvert/ Kings Bridge	1.5	12.3		2.7E		
Upstream Blackstaff Culvert	1.8	17.5		45.0	11.6	
		10.9		2.9		
Upstream Ormeau Bridge	2.14	17.2		18.2	7.4	
Upstream McConnell Weir	2.75	17.1	6.7			
Central Station	3.25	12.8		5.3		
Upstream Albert Bridge	3.50	14.3		6.7	4.9	
	3.50	10.9	7.2			
Upstream Railway Bridge	4.10	13		4.3		
Downstream Queens Bridge	4.60	13		7.0	6.2	

E = by extrapolation

FIGURES.

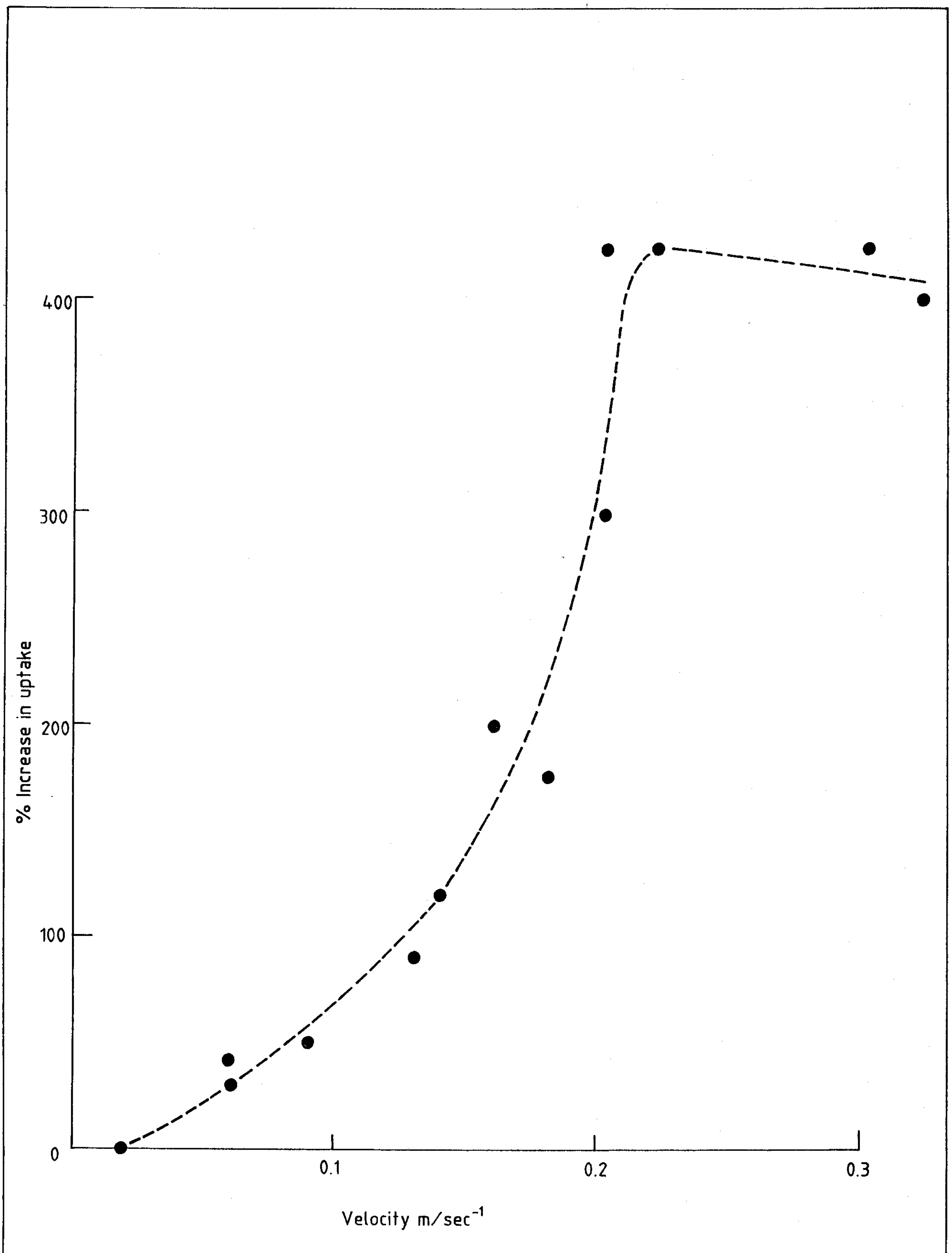

Fig 1 Relationship between oxygen uptake rate and velocity

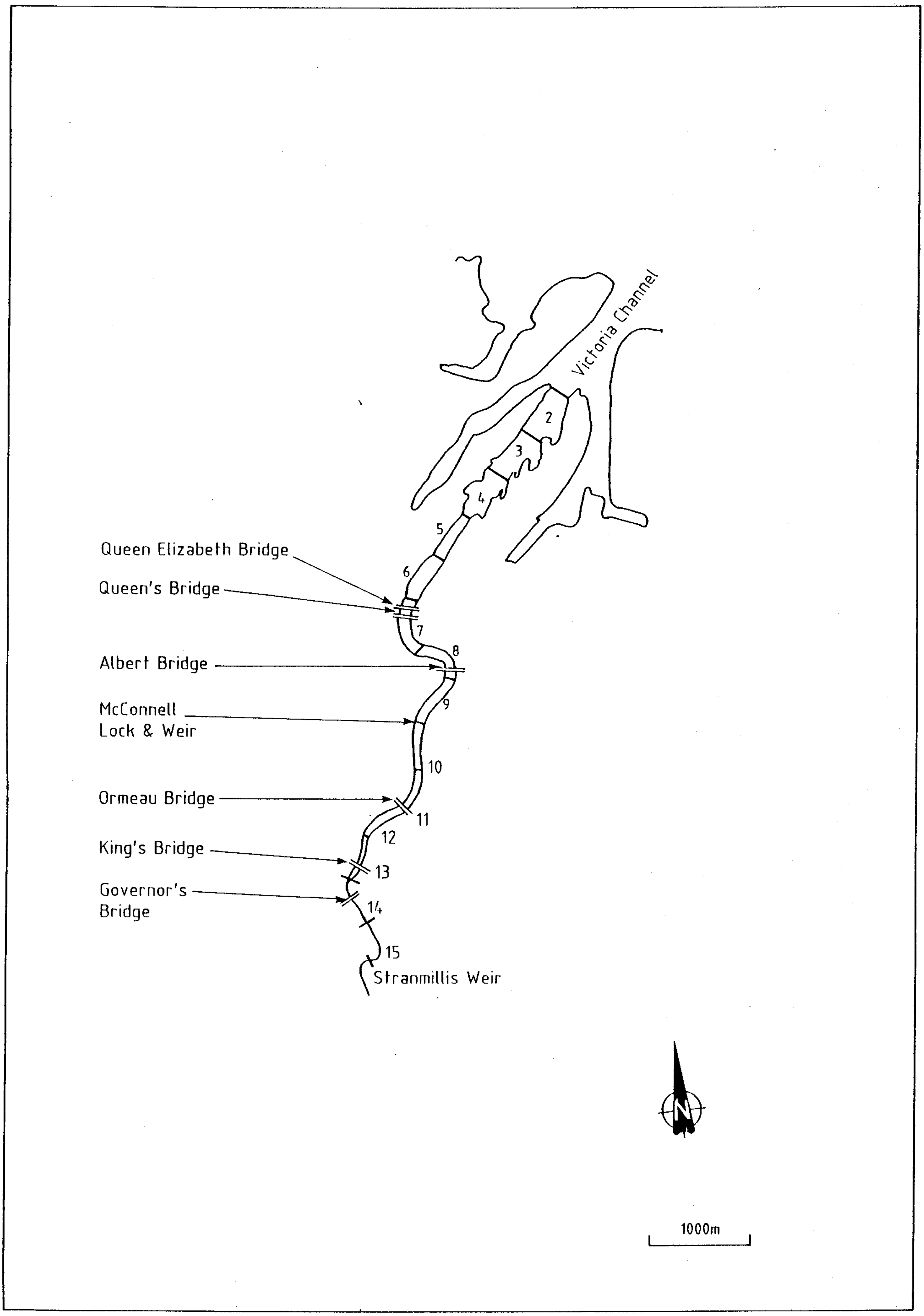

Fig 2 Lagan Estuary

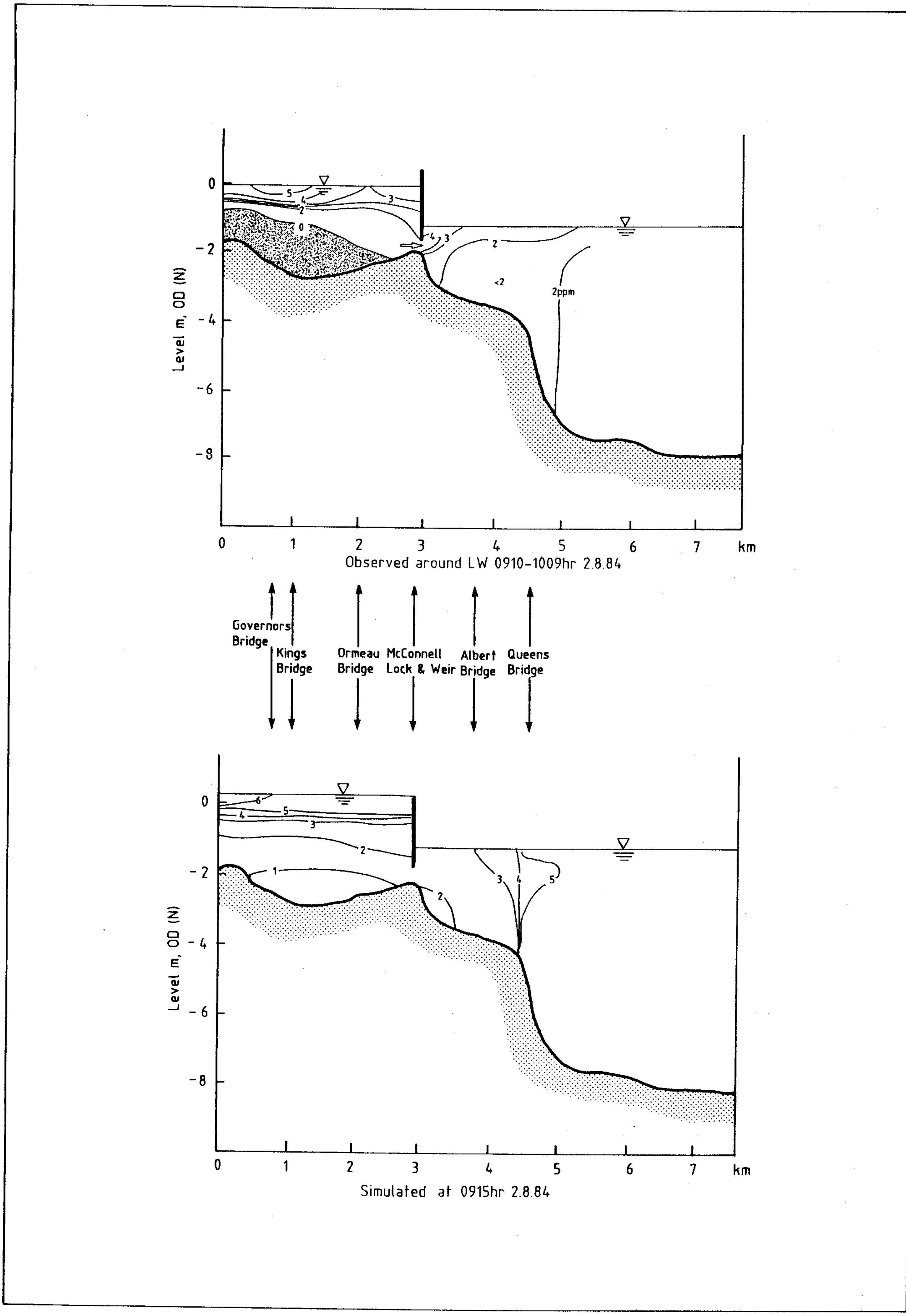

Fig 3a Comparison of simulated and observed dissolved oxygen LW 2.8.84 - benthal demand dependent on oxygen level

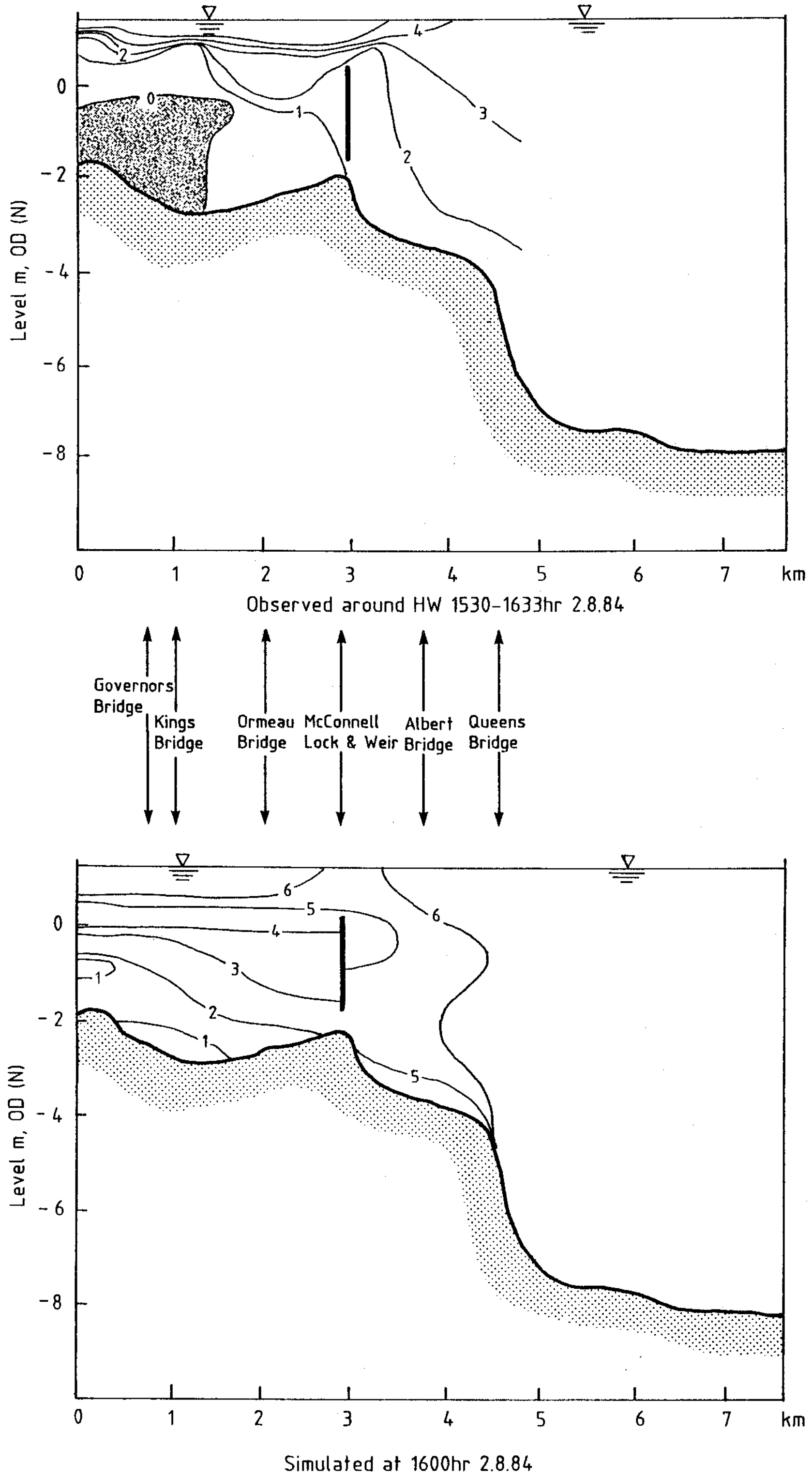

Fig 3b Comparison of simulated and observed dissolved oxygen HW 2.8.84 - benthal demand dependent on oxygen level

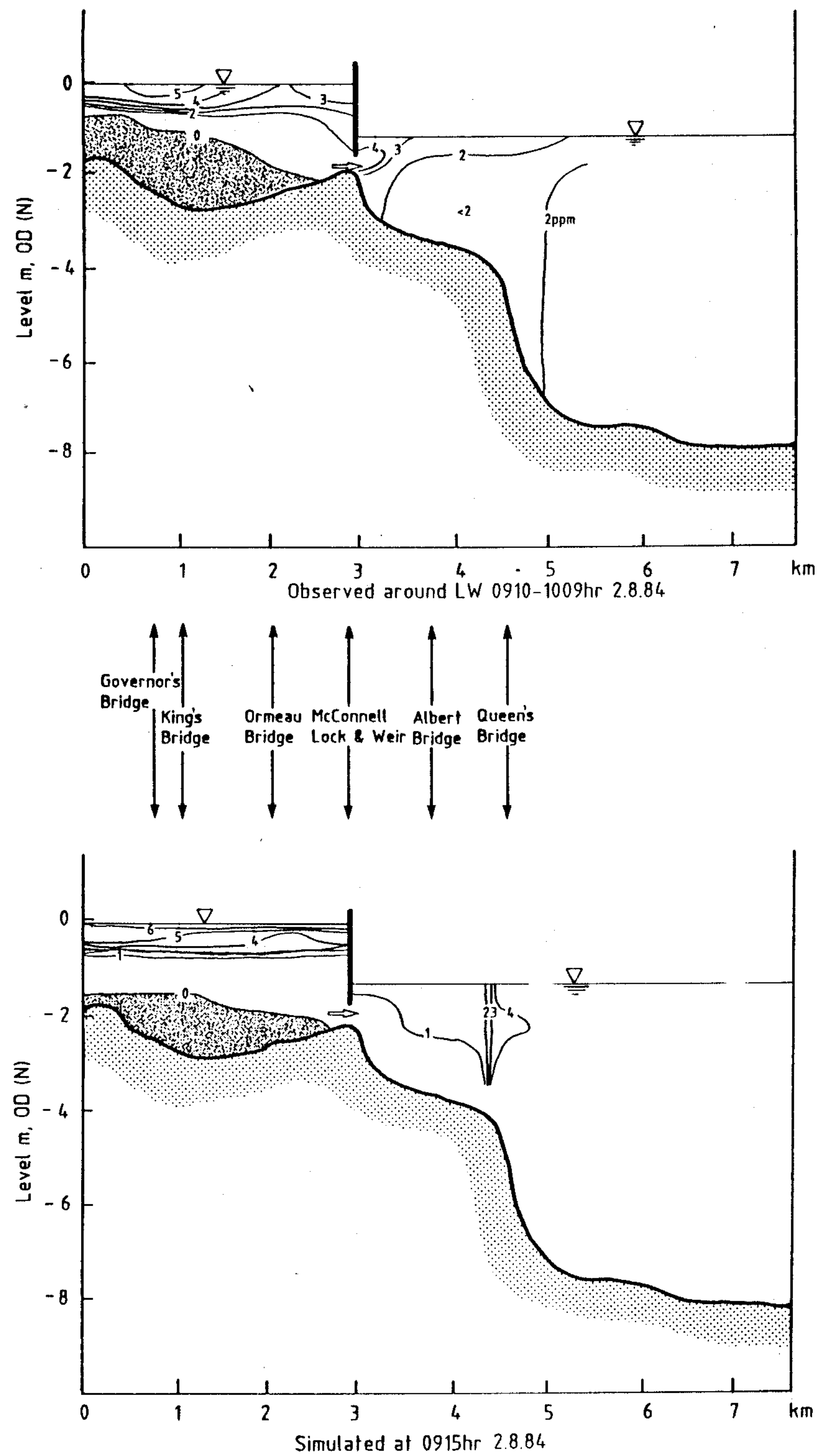

Fig 4a Comparison of simulated and observed dissolved oxygen LW 2.8.84 - benthal demand not dependent on oxygen level

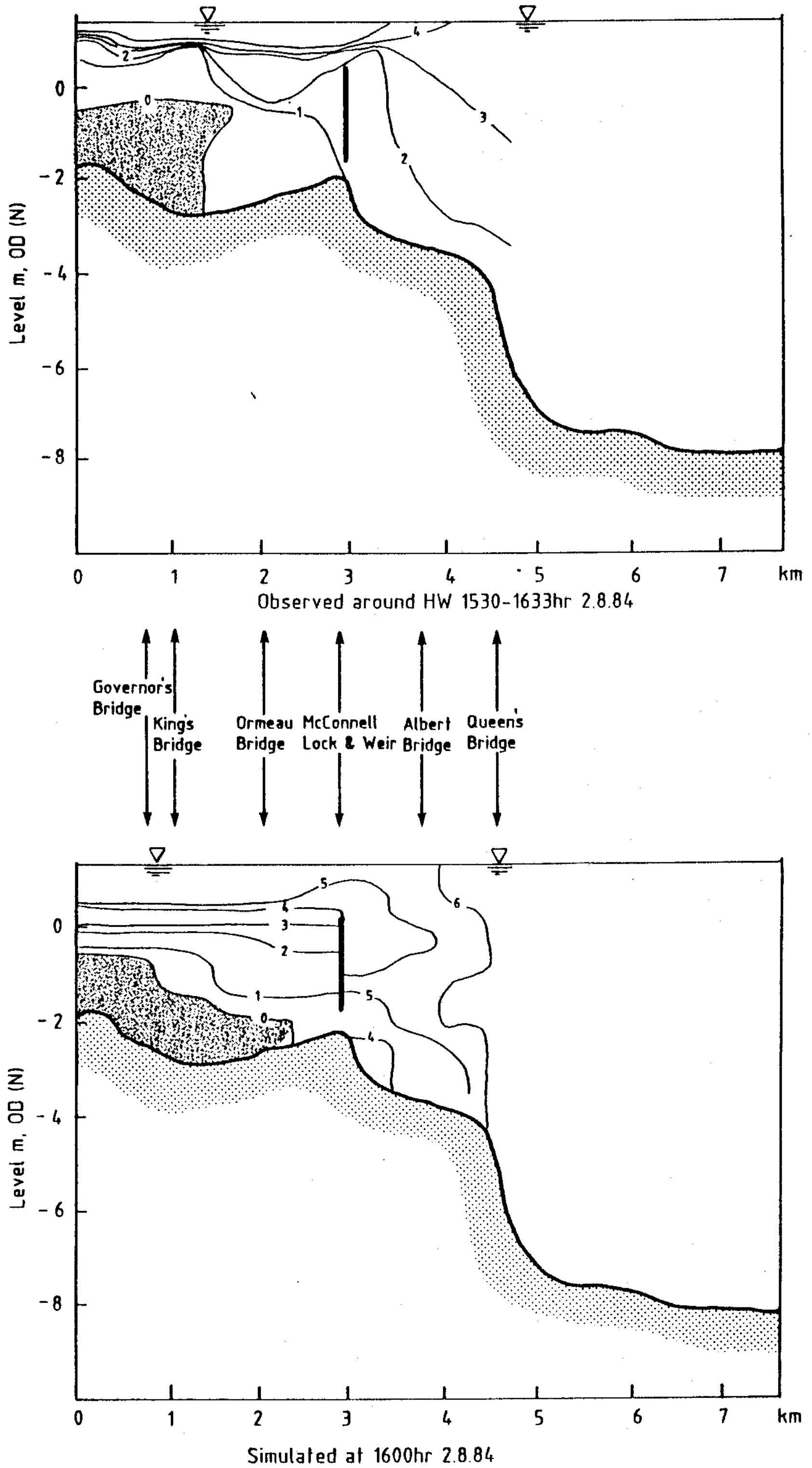

Fig 4b Comparison of simulated and observed dissolved oxygen HW 2.8.84 - benthal demand not dependent on oxygen level