

Oxygen uptake kinetics
at the sediment-sea
water interface in the
Puck Bay*

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Oxygen
Sediments
Chamber experiments
Puck Bay

JERZY BOLALEK

Institute of Oceanography,
Gdańsk University,
Gdynia

ANDREY VERSHININ

Institute of Oceanology,
USSR Academy of Sciences,
Moscow

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Abstract

The paper presents the parameters of oxygen exchange at the sea water-sediment interface in Puck Bay. The calculations were based on data on oxygen concentration changes in water, obtained at two stations in chamber experiments in June 1989. Oxygen consumption in the processes of respiration and mineralization of organic matter was determined on the basis of oxygen concentration changes, data on the plankton biomass in water, and data on the biomass of macro- and meiobenthos in the sediment.

The following parameters of oxygen exchange at the water-sediment interface were calculated using the quasi-stationary model of oxygen uptake: oxygen consumption in the benthic water A_w , oxygen uptake by the sediment at the beginning of the experiment J_0 , oxygen penetration depth into the sediment x_1 , diffusive sublayer height h , oxygen concentration in the diffusive sublayer C_{wo} , oxygen concentration at the bottom of the diffusive sublayer at the initial moment.

The parameters obtained agreed very well with the character of the sediments, as well as the number of meiobenthic organisms and their biomass in the sediment, and plankton biomass in water.

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1. Introduction

Exchange of chemical substances through the water-bottom interface is a component of element circulation between the hydrosphere and the lithosphere. As a result investigations into various processes taking place at the water-bottom interface are important. Investigation of oxygen uptake by sediments is significant with respect to meiobenthos existence and the diagenetic reactions which occur (Hargrave, 1969, 1972; Hopkinson and Wetzel, 1982; Pamatmat, 1971; Smith, 1974).

The most frequently used technique to measure oxygen uptake by sediments are based on incubation of a certain amount of water and sediment and subsequent monitoring of oxygen concentration changes in water above the sediment as a function of time (Bågander, 1977; Hall, 1984; Rozanov *et al.*, 1988; Rutgers van der Loeff *et al.*, 1984). Oxygen uptake by the sediments can also be estimated from the oxygen profiles in sediments measured with microelectrodes (Reimers *et al.*, 1984; Reimers and Smith, 1986; Revsbech *et al.*, 1980a,b). Numerous experiments have revealed that oxygen uptake by the sediment depends on temperature (Duff and Teal, 1965; Hall, 1984), meiobenthos biological activity (Edwards and Rolley, 1965), turbulence and currents in the water above the sediment (Boynton *et al.*, 1981). The effect of the initial oxygen concentration on its uptake by the sediment is not entirely recognized. For instance, Pamatmat and Banse (1969) found that these two parameters are independent, while Knowles *et al.* (1962), as well as Edberg and Hofsten (1973) established that the oxygen uptake by the sediment is lower at lower initial oxygen concentrations. Another group of researchers thinks that oxygen concentration in water does not influence its uptake by the sediment until its concentration falls below a certain level. According to Martin and Bella (1971) this concentration is of the order of $60-90 \mu\text{mole} \cdot \text{dm}^{-3}$.

This paper aims at presenting a method of calculation of the parameters of oxygen exchange processes at the water-bottom interface, as well as discussion of the parameters of this exchange in Puck Bay, and attempts to determine oxygen uptake in the benthic water and sediment (respiration of organisms and mineralization of organic matter).

2. Materials and methods

2.1. Field and laboratory works

Employees of the Institute of Oceanography of Gdańsk University and of the Institute of Oceanology of the USSR Academy of Sciences (Moscow) took part in the experiments carried out in Puck Bay between 7th and 21st June, 1989, within the 'Mirovoy Okean' COMECON project. The exper-

iment was carried out at two stations of different bottom sediment characteristics and different depth. Station location description of the chambers and their parameters, the manner of settling at the bottom, sampling procedure, as well as methods of sea water and sediment analysis, have been described previously (Bolalek *et al.*, 1991). Oxygen in sea water was determined by the Winkler method. Organic matter content in the sediments was determined as the loss on roasting.

The phyto- and zooplankton composition was determined at each station in the near-bottom water sampled by scuba divers, using methods recommended by BMB¹ (Edler, 1979). The number of specimens has been recalculated to biomass.

Samples of bottom sediments were drawn at the end of the experiment from below the chambers and from the adjacent area. The samples were divided into 1 cm segments, in which the meiobenthos classification units were determined (Elmgren and Radziejowska, 1989).

2.2. Calculation methods

The results obtained during the experiment were elaborated on the basis of the quasi-stationary model described by Yegorov and Vershinin (1990). The model is based on the following four equations (Berner, 1971; Hall, 1984 *et al.*, 1989; Lerman, 1979; Revsbech *et al.*, 1980b):

1. Sediment diagenesis equation:

$$D_s \frac{\partial^2 C}{\partial x^2} = K_s C_s^n \quad x > 0;$$

2. Equation describing the change of the concentration in the chamber as a function of time:

$$\frac{\partial C_w}{\partial t} = -\frac{J}{H} - K_w C_w^m \quad -H < x < -h;$$

3. Equation describing the flux of the substances through the sediment surface (first Fick's law):

$$J = -D_s \circlearrowleft \frac{\partial C_s}{\partial x} \quad x = 0;$$

4. Equation describing the diffusion through the diffusive sublayer:

$$J = D \frac{C_w - C_0}{h} \quad -h < x < 0;$$

where:

- x - vertical coordinate (with positive sense into the sediment $x > 0$; at the sediment surface $x = 0$),

¹Baltic Marine Biologists.

- t – time,
 D, D_s – molecular diffusion coefficients of a substance dissolved in water and in the sediment, respectively,
 n, m – order of reaction of utilization or excretion of the dissolved substance in the sediment and in water, respectively,
 K_s, K_w – equilibrium constants of reactions of utilization or excretion of the dissolved substance in the sediment and in water, respectively,
 C_s – concentration of the dissolved substance in the interstitial water,
 C_w – concentration of the dissolved substance in the chamber (in the turbulent mixing zone),
 h – diffusive sublayer thickness, equal to 1–2 mm (Boudreaw and Guinasso, 1982; Hall *et al.*, 1989). In this sublayer the molecular diffusion prevails over the turbulent mixing,
 C_o – concentration of the dissolved substance at the bottom of the diffusive sublayer (or at the sediment surface),
 H – range of turbulent mixing, equal to the height of the chamber,
 J – dissolved substance flux through the water-sediment interface.

Similar equations or a part of these equations were considered in the papers by Bågander (1977), Hall *et al.* (1989), Jones and Murray (1985), Rutgers van der Loeff *et al.* (1984), Ullmann and Aller (1982). Only zero order reactions ($n = 0$) were considered in papers taking into account equation (2), (Bågander, 1977; Hall, 1984; Hall *et al.*, 1989; Holm, 1978; Rutgers van der Loeff *et al.*, 1984). Moreover, oxygen uptake by the near-bottom water layer has not been taken into account in the second equation – there was no $K_w C_w^m$ term. This resulted from the fact that the authors of these papers did not use the reference chamber, allowing for the changes occurring in the near-bottom water.

The system of equations presented above describes a quasi-stationary process of a change in concentration of a chosen substance dissolved in the chamber, in which water contacted the sediment. Solving this equation system using the experimentally determined concentration changes in time $C_w(t)$ allows not only the magnitude of the flux across the water-sediment interface, but also the reaction constants K_w and K_s to be determined, as well as the vertical distribution of a given substance in the sediment. It additionally enables the selection of the reaction order m and n , and the evaluation of the size of the diffusive sublayer, penetration depth of a substance into the sediment (x_1), total uptake (or excretion) intensity of the soluble form of a substance in the sediment at the initial moment of locating the chambers ($A_{s_0} = K_s C_s^n$). Apart from the previously mentioned parameters of exchange the model allows the following concentrations to be evaluated:

- C_{wo} - initial concentration in the diffusive sublayer,
- C'_o - initial concentration of the dissolved substance (oxygen in this case) at the bottom of the diffusive sublayer,
- $C' = C_{wo} - C'_o$ - initial concentration difference in the diffusive sublayer.

A method of data analysis obtained in chamber experiments was developed on the basis of the above equations (Vershinin *et al.*, 1990). The calculations were carried out in the USSR Academy of Sciences (Moscow) using an EC 1061 computer (program written in Fortran language).

The experimental C_w as a function of time dependences obtained in the No. 2 chamber, isolated from the bottom, have been utilized in the first stage of calculations. The values of K_w ($K_w \neq 0$) have been determined from the present values of m ($m = 0, 1, 2, 3, 4$). The K_w and m values obtained are the kinetic parameters of oxygen uptake in the near-bottom water layer. Oxygen uptake is equal $K_w C_w^m$. This is the amount of oxygen consumed by 1 m³ of water in 1 s. This value has been used in further calculations.

A curve reflecting the continuous process of the reduction of oxygen concentration in water contained in the chambers was drawn in the second stage. The following were the input parameters: $d, D_s, H, \phi, K_w, C_{wi}, t_i, m, \alpha = 0.5(n + 1)$, and h - where C_{wi} and t_i are the experimental data obtained in the No. 1 chamber. The h parameter was changed in the calculations. It has been assumed in the final calculations that the real process corresponded to this value of h , at which the magnitude of the minimum risk function (SM) was the smallest (Taylor, 1985). The D and D_s parameters are interrelated by the $D_s = D/\kappa$ dependence (Lerman, 1978). The values of the κ parameter (1.4) and the ϕ parameter (0.9) were adopted on the basis of literature data (Manheim and Waterman, 1979; Yegorov and Bolshakov, 1988). The J_o, h, n and K_s parameters were the output values obtained at this stage of the calculations. The flux obtained represents the initial total oxygen uptake for the mineralization of the organic matter in the sediment and the respiration of the organisms at the beginning of the measurements.

3. Results and discussion

Changes of dissolved oxygen concentration in chambers, in which water directly contacted the sediment (chamber No. 1), were very rapid (Tabl. 1). In general, oxygen contained in the water was used up during the second week of the observations. At ST I, where the sediments were a few times richer in organic matter compared to ST II, a complete exhaustion of

Table 1. Changes in oxygen concentration ($\text{ml} \cdot \text{dm}^{-3}$) in the Puck Bay during the chamber experiments performed in June, 1989

Data	Station I - ST I			Station II - ST II		
	1	2	3	1	2	3
7	7.12	7.33	7.92	7.74	7.70	7.73
8	3.45	7.25	6.23	6.45	7.47	7.66
9	2.55	5.93	7.62	5.15	7.35	7.04
12	1.05	4.30	8.64	1.55	6.67	4.50
13		3.80	7.97	1.43		5.41
14	0.39	3.27	7.03		6.45	7.65
15			6.83		6.28	6.31
16	0.26		7.88	0.63	6.19	7.32
19	0.08	3.02	7.75	0.56	5.81	6.65
21	0.00	2.39	7.09	0.33	5.57	6.97

1 - chamber No. 1,

2 - chamber No. 2,

3 - chamber surroundings.

oxygen was observed after 12 days. No complete exhaustion of oxygen was observed until the end of the measurements, *i.e.* within 15 days, at ST II.

Table 2. Selection of the h and n parameters on the example of ST II

h [cm]	$n = 0$ ($\alpha = 0.5$)		$n = 1$ ($\alpha = 1$)		$n = 2$ ($\alpha = 1.5$)	
	SM	$J_0 \cdot 10^{-4}$	SM	$J_0 \cdot 10^{-4}$	SM	$J_0 \cdot 10^{-4}$
0.01	480.5	6.646	87.50	9.828	47.92	22.02
0.0125	456.5	6.695			38.55	19.21
0.025	409.7	6.549			32.64	16.77
0.0375	347.5	6.617			33.26	15.00
0.05	290.5	6.928	88.81	9.613	36.83	13.86
0.075	184.6	7.706			52.10	11.14

J_0 expressed in $\text{ml} \cdot \text{dm}^{-3} \cdot \text{cm} \cdot \text{s}^{-1}$.

Determined for the following data:

$H = 0.47$ m,

$D = 1.45 \cdot 10^{-5}$ $\text{cm} \cdot \text{s}^{-2}$,

C_{wi} - oxygen concentration in the No. 1 chamber in time i ,

$\phi = 0.9$,

$K_w = 0.6219 \cdot 10^{-8}$ $\text{ml}^{-2} \cdot \text{dm}^{-6} \cdot \text{s}^{-1}$.

A slow reduction of oxygen concentration was observed in water isolated from the bottom (chamber No. 2). The changes ranged from 0.08 to 1.32 $\text{ml} \cdot \text{dm}^{-3} \cdot \text{day}^{-1}$. Concentration of oxygen dissolved in water at ST I decreased within 15 days from 7.46 to 2.39 $\text{ml} \cdot \text{dm}^{-3}$, while at ST II - from 7.73 to 5.57 $\text{ml} \cdot \text{dm}^{-3}$.

Table 3. Results of calculations of the oxygen exchange parameters at the water-sediment interface in the Puck Bay in June 1989

Parameter	Dimension	Station I	Station II
M		1	3
n		2	2
α		1.5	1.5
K_w	$(\text{ml} \cdot \text{dm}^{-3})^{1-m} \cdot \text{s}^{-1}$	$1.379 \cdot 10^{-6}$	$0.6219 \cdot 10^{-8}$
A_w	$10^{-6} \text{ mmole} \cdot \text{m}^{-3} \cdot \text{s}^{-1}$	439	143
h	nm	0.50	0.25
D	$10^{-5} \text{ cm}^2 \cdot \text{s}^{-1}$	1.65	1.45
J_o	$\text{mmole} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$	55.31	64.91
B	$10^{-4} (\text{ml} \cdot \text{dm}^{-3})^{-0.5} \cdot \text{cm} \cdot \text{s}^{-1}$	3.09	1.445
K_s	$\text{m}^3 \cdot \text{mmole}^{-1} \cdot \text{day}^{-1}$	28.93	7.21
C'_o	$\text{mmole} \cdot \text{dm}^{-3}$	124	230
C_{wo}	$\text{mmole} \cdot \text{dm}^{-3}$	318	359
C	$\text{mmole} \cdot \text{dm}^{-3}$	194	129
A_{so}	$\text{mmole} \cdot \text{m}^{-3} \cdot \text{day}^{-1}$	444823	381409
x_1	nm	2.63	5.14

where:

$$C'_o = (J_o \cdot B^{-1})^{-\alpha},$$

$$C_{wo} = (J_o \cdot B^{-1})^{-\alpha} + h \cdot J_o \cdot D^{-1},$$

$$C = C_{wo} = C'_o,$$

$$K_s = B^2 \cdot \alpha \cdot \kappa \cdot D^{-1} \cdot \varnothing^{-2},$$

$$A_w = K_w \cdot C_w^m,$$

$$x_1 = \frac{\frac{1}{\sqrt{C(x_1)}} - \frac{1}{\sqrt{C'_o}}}{0.5 \sqrt{\frac{2K_s}{3D}}},$$

$C(x_1) = 0.05 \text{ ml} \cdot \text{dm}^{-3}$ - the lowest oxygen concentration determinable by the Winkler's method (Vershinin *et al.*, 1990).

Table 2 illustrates an example of the choice of the values of the h and m parameters at ST II, based on the equation system presented. From the various preliminary adopted values of h and m those for which the magnitude of the minimum risk function was the lowest were chosen. The results presented in Tables 1 and 2 can also be illustrated graphically. Figures 1a and 2a present the results of determination of oxygen concentration in water from the chambers. The solid lines depicted in Figures 1a and 2a correspond to theoretical curves obtained on the basis of the model. Figures 1b and 2b illustrate an example of selection of the optimal value of the diffusive sublayer h , expressed in cm.

All the calculated parameters of oxygen exchange between the near-bottom water and the sediment at both the stations are listed in Table 3. In general, all the parameters more or less in agreement with the literature data.

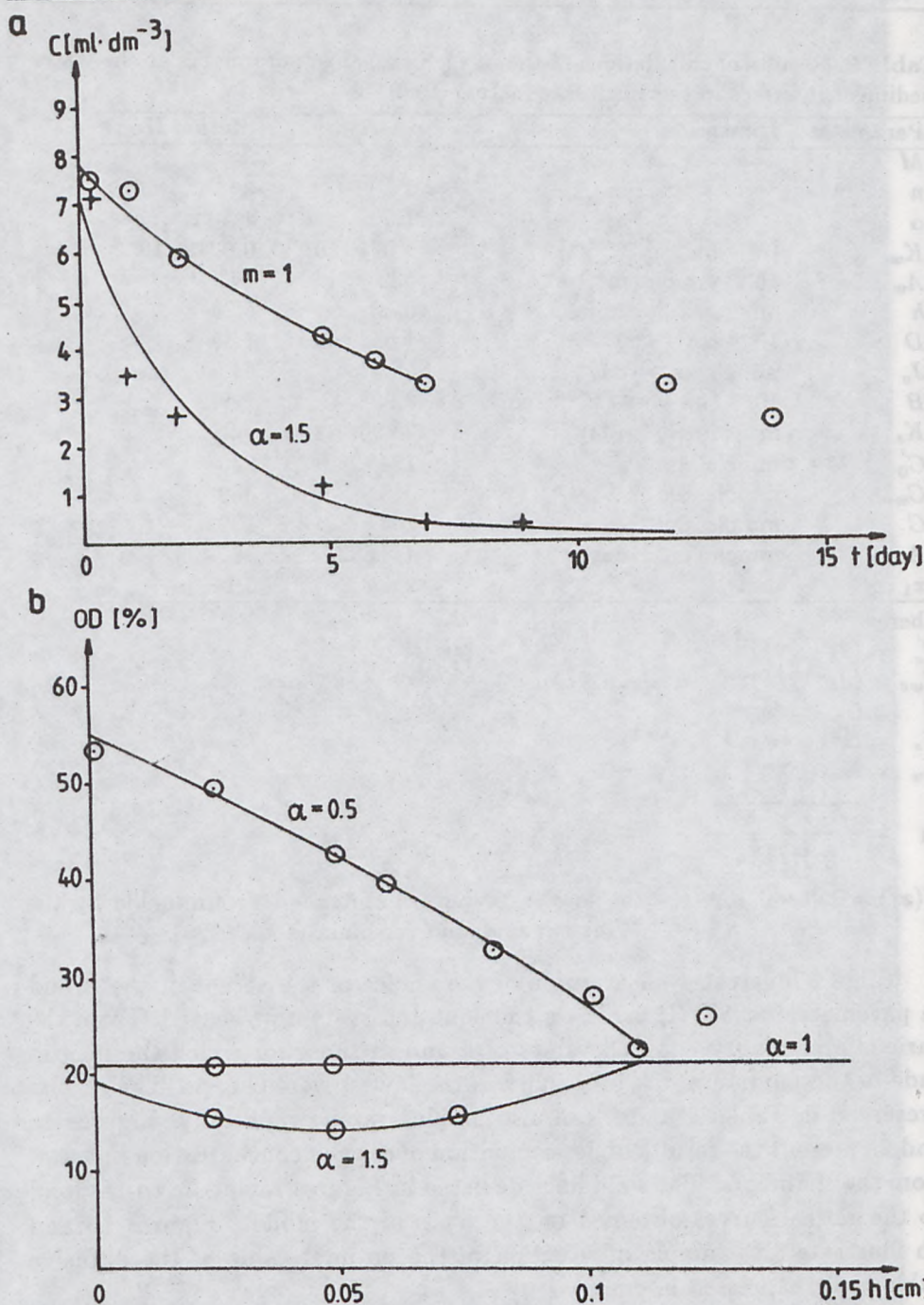


Fig. 1. a - empirical data and theoretical approximation of oxygen distribution in the chambers at ST I, b - graphical illustration of the selection of the h and n parameters at ST I; + experimental data from chamber No. 1, \odot experimental data from chamber No. 2

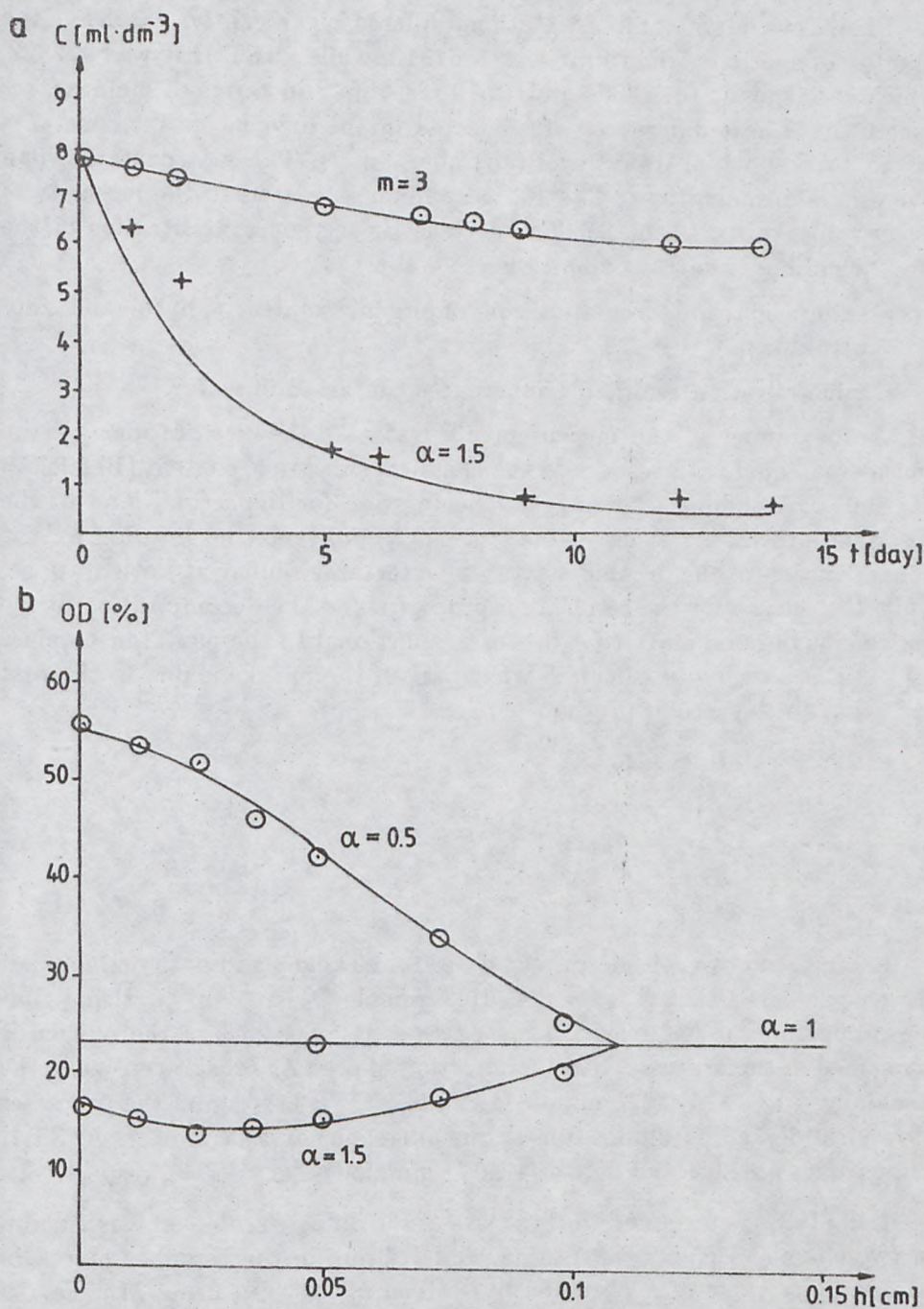


Fig. 2. a - empirical data and theoretical approximation of oxygen distribution in the chambers at ST II, b - graphical illustration of the selection of the h and n parameters at ST II. Denotations as in Figure 1

Plankton content at both stations differed significantly. At ST I the number of specimens in 1 dm³ was 1967313, while at ST II it was 922822, which corresponds to 16.804 and 1.519 mg · dm⁻³ in terms of biomass, respectively. These differences are reflected in the oxygen uptake constants in the near-bottom water layer (chamber No. 2). The K_w constants span two orders of magnitude. The K_w parameter is related to the intensity of oxygen uptake A_w (Tabl. 3). The decrease in oxygen concentration in the No. 2 chamber is due to two processes:

- respiration and decomposition of organic matter (phyto- and zooplankton),
- mineralization of organic substances contained in water.

At the beginning of the measurements water at the two stations can be considered equal with respect to the chemical substance content (Bolalek *et al.*, 1991). Assuming that oxygen consumption for the second kind of the described processes (let us denote it as A_{wos} – oxygen consumption for the mineralization of the organic matter in water) was similar at both stations, while the uptake for the respiration processes and the decomposition of the indigenous organic matter (A_{wR} was proportional to the plankton biomass (BP)), it is possible to calculate what part of the uptake is due to the first and what to the second process:

$$\begin{aligned} A_{wI} &= A_{wosI} + A_{wRI}, \\ A_{wII} &= A_{wosII} + A_{wRII}, \\ A_{wosI} &= A_{wosII} = A_{wos}, \\ \frac{A_{wRI}}{A_{wRII}} &= \frac{BP_I}{BP_{II}}. \end{aligned}$$

Using the above considerations, data from Table 3 and data on biomass, it was calculated that $A_{wos} = 114 \cdot 10^{-6}$ mmole O₂ · m⁻³ · s⁻¹). Using simple proportions it has been calculated that at ST I 26% of the oxygen is consumed in the processes of mineralization of organic substances, while the remaining 74% ($325 \cdot 10^{-6}$ mmole O₂ · m⁻³ · s⁻¹) is used up in the processes of respiration and decomposition of the indigenous organic matter. At ST II these values are 80% and 20% ($29 \cdot 10^{-6}$ mmole O₂ · m⁻³ · s⁻¹), respectively.

Hall (1984) determined that the size of the diffusive sublayer was 1.0 mm in two chambers placed in autumn, and 1.7 mm in the chamber placed in winter. The value of h obtained by Hall *et al.* (1989), using Mn, Fe, Zn and Hg isotopes as indicators, ranged from 0.7 to 1.9 mm. In our case the thickness of the diffusive sublayer was slightly smaller (Tabl. 3), measuring 0.5 mm at ST I and 0.25 at ST II. Most probably the value of this parameter is related to bioturbation processes, which depend among other

things on the amount and number of meiofauna, and its migrations. These will be discussed later on.

Rutgers van der Loeff *et al.* (1984) revealed that oxygen penetration depth into the sediment (x_1) is a few mm and depends on the season of a year. Hall *et al.* (1989) determined that at the beginning of the experiment x_1 was 0.6 mm in autumn and 2.7 mm in winter. They found that this was due to a greater oxygen uptake by the sediment in autumn. Slightly higher values of the depth of oxygen penetration depths into the sediment were obtained using microelectrodes - ca. 2 mm (Jørgensen and Revsbech, 1985). Revsbech *et al.* (1980b), examining oxygen concentration in the sediments with the use of microelectrodes, obtained differentiated values of the x_1 parameter depending on water temperature (3°C - 10 mm, 0°C - 7 mm, 18°C - 5.5 mm). Helder and Bakker (1985) obtained a value of 10 mm with the use of micro- and millielectrodes. The depths of oxygen penetration into the sediment in Puck Bay are close to the literature data. At ST I x_1 was 2.63 mm, while at ST II it was 5.14 mm. The differences in the obtained values of x_1 should be related to the different character of the bottom and to the bioturbation processes. At ST I the meiobenthic organisms occurred in the sediment to the depth of 5 cm, while at ST II - to 7 cm. The conditions of oxygen penetration into the sediment are better for sandy sediments (ST II), due to greater porosity and interstitial spaces.

At the beginning of the investigations the oxygen concentration in the diffusive sublayer (C_{wo}) slightly exceeded 300 $\mu\text{mole} \cdot \text{dm}^{-3}$. The ($C_{wo} - C'_o$) difference in this sublayer was larger at ST I (194 $\mu\text{mole} \cdot \text{dm}^{-3}$). This could be due to the different character of the bottom, and to the greater number of meiobenthos, requiring oxygen. At ST I the organic matter content in the 0-5 cm layer was 2.48%, while at ST II 0.69% (Bołalek *et al.*, 1991). The meiofauna biomass was approximately equal to 21.7 and 6.4 $\text{g} \cdot \text{m}^{-2}$, respectively.

Measurements of oxygen concentration microgradients, diffusive sublayer thickness and oxygen penetration depth into the sediment are extremely difficult to analyse because of the instability and spatial non-uniformity of these parameters. The problem is additionally complicated by the activity of macro- and microfauna, which loosens the sediment and pumps water inside the 'burrows'. Bioturbation by benthic animals plays an important role in the distribution and exchange of substances dissolved in the sediment, particularly of oxygen (Aller, 1982). Jørgensen and Revsbech (1985) presented three vertical oxygen profiles within the sediment-water interface (Fig. 3). Oxygen concentration in the upper part of the diffusive sublayer was of the order of 250 $\mu\text{mole} \cdot \text{dm}^{-3}$, while in the lower part it was 50-80 $\mu\text{mole} \cdot \text{dm}^{-3}$. Oxygen penetration depth slightly exceeded 1 mm.

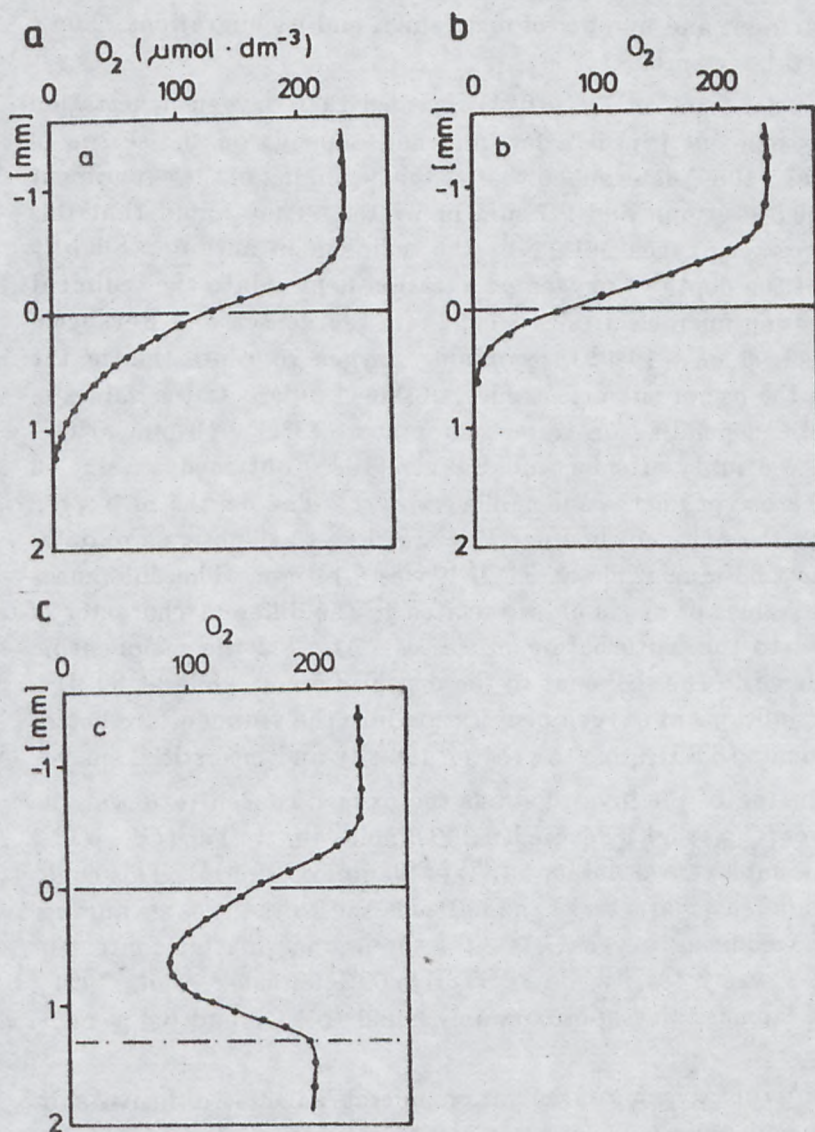


Fig. 3. An example of the vertical oxygen distribution in the sediment (Jørgensen and Revsbech, 1985)

A non-typical oxygen distribution at the water-sediment interface is illustrated in Figure 3c. Such a distribution occurred when the sediment was cut with oblique channels drilled by meiobenthos. Within the channels the concentration continuously changed according to the 'pumping' rhythm of the organisms.

Table 4. The number of meiobenthic organisms in the Puck Bay sediments in the 2.25 cm² section

Organisms	ST	Layer																		Total					
		0-1 cm			1-2 cm			2-3 cm			3-4 cm			4-5 cm			5-6 cm			6-7 cm			1	2	3
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3						
<i>Foraminifera</i>	I			1																					
	II			1																					
<i>Turbellaria</i>	I	1					1																		
	II			6			8						1												
<i>Gastrotricha</i>	I																								
	II	1		2			1			2															
<i>Nematoda</i>	I	90	17	61	82	8	52	5	151	2	15	2	2												
	II	31	37	133	50	12	320	18	70	12	3	46	8	2	3	1	4	2	179	25	119	57	576		
<i>Polychaeta</i>	I			1																					
	II			3																					
<i>Oligochaeta</i>	I	3		99			1	5																	
	II			16																					
<i>Bivalvia</i>	I			9			1																		
	II			9			4																		
<i>Ostracoda</i>	I			5																					
	II			15			2																		
<i>Harpacticoda</i>	I			27																					
	II	1		14			1			1															
<i>Isopoda</i>	I																								
	II			1																					
<i>Tardierada</i>	I																								
	II																								
Total	I	94	17	204	82	8	55	10	151	2	15	2	2												
	II	33	37	197	50	12	336	18	73	12	3	50	8	2	4	1	4	2	188	25	121	57	664		

1 - below the No. 1 chamber,

2 - below the No. 2 chamber,

3 - in the chamber surroundings.

On the other hand, oxygen penetration depth is important for small animals, which require oxygen for respiration. These organisms are adapted to migration in the direction of water more abundant in oxygen and food. For example, Jørgensen and Revsbech (1985) found out, using microelectrodes, that *Polycheta elegans* forms channels protruding a few millimeters above the sediment and assuring more oxygenized water for respiration.

A shift from aerobic to anaerobic or almost anaerobic conditions at the end of the measurements within the sediment under the No. 1 chamber (Tabl. 1) caused drastic changes in the classification units and number of meiobenthos (Tabl. 4). At the beginning of the experiment the most numerous groups in the 0–1 cm sediment layer at ST I were *Oligocheta* (48.5%), *Nematoda* (29.9%) and *Harpacicoidea* (13.2%). In the deeper layers practically the only group was *Nematoda*. At ST II *Nematoda* prevailed in all the layers, although other groups also occurred. Such a distribution of meiofauna is probably determined by the character of the sediment and the related possibilities of oxygen penetration and migration of organisms. A decrease in water aeration was accompanied by a complete disappearance of aerobic organisms. Such a tendency manifested itself at both the stations. Distinct migrations of *Nematoda* from the deeper layers upwards are noticeable in the example of ST I, where 113 specimens were found in the upper 2 cm of the sediment at the beginning of the experiment, the number increasing to 172 at the end. It is possible that the organisms living initially in the upper layer of the sediment died and were replaced by the organisms from the deeper layers, accustomed to anaerobic or almost anaerobic conditions.

In Puck Bay oxygen uptake by the sediment was equal to 53.31 mmole · m⁻² · day⁻¹ (ST I) and 64.91 mmole · m⁻² · day⁻¹ (ST II). These values are higher than those obtained by Hall (1984) for the Baltic on the Swedish coast (from 6.1 to 16.2 mmole · m⁻² · day⁻¹). The Swedes obtained their results for a bottom of a different character and in the autumn–winter season, when the rhythm of biological life was slower, hence oxygen was consumed mainly in the processes of mineralization of the organic matter contained in the sediment.

The entire oxygen uptake can be divided, with good approximation, into the part used up for the mineralization of the organic matter in the sediment (J_{os}), the part used for the respiration of macrobenthic organisms (J_{RB}) and meiobenthic organisms (J_{RMB}):

$$J_I = J_{soI} + J_{RBI} + J_{RMBI},$$

$$J_{II} = J_{soII} + J_{RBII} + J_{RMBII}.$$

It has been assumed that:

$$\begin{aligned}
 J_R &= J_{RB} + J_{RMB}, \\
 \frac{J_{RBI}}{J_{RBII}} &= \frac{BB_I}{BB_{II}}, \\
 \frac{J_{RI}}{J_{RII}} &= \frac{BB_I + BMB_I}{BB_{II} + BMB_{II}}, \\
 \frac{J_{RMBI}}{J_{RMBII}} &= \frac{BMB_I}{BMB_{II}}, \\
 \frac{J_{soI}}{J_{soII}} &= \frac{C_{orgI}}{C_{orgII}},
 \end{aligned}$$

where:

BB - macrobenthos biomass,

BMB - meiobenthos biomass,

C_{org} - organic matter content in the sediment,

I, II - ST I, ST II.

Unfortunately the macrobenthos biomass in the region of the measuring stations was not determined during the experiment. It follows from the literature (Legeżyńska and Wiktor, 1981) that the macrobenthos biomass in the ST I region is of the order of $150 \text{ g} \cdot \text{m}^{-2}$, while in the ST II region it is $550 \text{ g} \cdot \text{m}^{-2}$. The approximate values of the total benthos biomass were obtained by summing the macro- and meiobenthos biomass. After solving the above system of equations it has been calculated that $J_{soI} = 38.62$, $J_{soII} = 10.73$, $J_{RBI} = 14.45$, $J_{RBII} = 53.52$, $J_{RMBI} = 2.24$ and $J_{RMBII} = 0.66 \text{ mmole} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$. The obtained values of oxygen uptake by the sediment equate to 38.62 and 10.73 $\text{mmole} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$ and are close to the literature data.

4. Conclusions

The results of calculation of the parameters of oxygen exchange at the water-sediment interface in Puck Bay, obtained on the basis of the quasi-stationary model, remained in close agreement with the literature data for the Baltic. On the basis of the results of oxygen concentration changes during the chamber experiment, as well as the data on plankton biomass in water and benthos biomass in the sediment it was possible to divide the total oxygen uptake into those parts used up for the respiration processes and those used for organic matter mineralization. The oxygen demand in water (A_w) was $439 \cdot 10^{-6}$ (ST I) and $143 \cdot 10^{-6}$ (ST II). These numbers agreed with the phyto- and zooplankton biomass (16.8 and $1.5 \text{ mg} \cdot \text{dm}^{-3}$, respectively). This agreement allowed us to determine that at ST I 74% of the oxygen was consumed in the processes related to plankton respiration,

while the remaining 26% was used up for the mineralization of the organic matter contained in water (at ST II these numbers were 20 and 80%, respectively). After recalculating it has been found that 1 g of plankton uses 69 μmole oxygen per hour for respiration processes. Laboratory determined oxygen consumption by the plankton (Donnelly and Torres, 1987; Gorsky *et al.*, 1987; Hirche, 1987) ranged from 4.5 to 2450 $\mu\text{mole} \cdot \text{g}^{-1} \cdot \text{h}^{-1}$ and depended on the plankton type.

The discussed parameters of oxygen exchange at the water-sediment interface remained in good agreement with the character of the sediment and the magnitude of bioturbation, as well as the number and biomass of the meiobenthic organisms.

Oxygen uptake by the sediment was equal to 55.3 $\text{mmole} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$ at ST I and 64.9 $\text{mmole} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$ at ST II. This data is consistent with the total macro- and meiobenthos biomass (ST I - 172 $\text{g} \cdot \text{m}^{-2}$, ST II - 55 $\text{g} \cdot \text{m}^{-2}$) and the organic matter content in the sediment (ST I - 2.48%, ST II - 0.69%). This consistency allowed us to divide oxygen consumption at the water-sediment interface into part used for mineralization of the organic matter in the sediment (J_{os}), that part used for macrobenthos respiration (J_{RB}), and the part used for meiobenthos respiration (J_{RMB}). The following values of the particular components of oxygen uptake were obtained at ST I: $J_{os} = 38.6$, $J_{RB} = 14.5$, $J_{RMB} = 2.2$ $\text{mmole} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$; at ST II these values were $J_{os} = 10.7$, $J_{RB} = 53.5$ and $J_{RMB} = 0.7$ $\text{mmole} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$. It has been determined that the amount of oxygen consumed by the benthos is 104 $\mu\text{mole} \cdot \text{g}^{-1} \cdot \text{h}^{-1}$. For instance, *Policheta Nereis virens* uses 155 $\mu\text{mole} \cdot \text{g}^{-1} \cdot \text{day}^{-1}$ (Kirstensen, 1989).

The high level of agreement between the values of oxygen uptake for the respiration of plankton and benthos obtained in this work, and in the literature data, allowed us to establish that the method of chamber experiments can be applied for the approximate *in situ* determination of the values of oxygen uptake by particular organisms, provided that the number of the measuring stations and of the biological determinations is increased.

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