Some influences of sediments in aerated lagoons and waste stabilization ponds

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Abstract Respirometric tests have been undertaken on sediments in aerated lagoons and waste stabilization ponds to quantify their oxygen demand and to determine the main factors governing the process. Factors such as seasonal variations, temperature, substrate, sediment layer thickness, density of macro-invertebrates and suspended sediments were investigated. The results showed that temperature and substrate concentration are the main factors that influence sediment oxygen demand; followed by spatial heterogeneity and resuspension of sediments, whereas the density of macro-invertebrates could have an effect in summer (hot season). Sediment layer thickness had no effect. A model of sediment oxygen demand is developed for the two main factors (temperature and substrate) with an r^2 of 0.98.

Keywords Modelling; ponds; sediment; sediment oxygen demand; substrate; temperature

Introduction

It is well known that aerated lagoons and waste stabilization ponds are not perfectly mixed systems as far as solids are concerned. Some portions of the suspended solids (including biomass) settle directly in the reactors. The gradual accumulation of these sediments on the pond base obviously affects performance by reducing the pond volume and shortening hydraulic residence times (Iwema *et al.*, 1987). However, the role played by these deposits is not restricted to such a physical effect. Far from being inert, sediments are an important oxygen sink that must be taken into account when designing aerator power and oxygen supply. Moreover, an effective model of pond purification kinetics should include an appropriate description of all the interactions, feedbacks and exchanges existing at the sediment-water interface (Bryant and Bauer, 1987).

These deposits have some positive effects on pond performance:

- They contribute to the pond removal rates for carbon, nitrogen and phosphorus compounds.
- Biomass production is easier to manage in such systems than in conventional (e.g. activated sludge) plants.

However, they have also some drawbacks:

- They exchange matter (C,N,P) with overlying waters.
- Even when they are removed from the pond base, sediments still pose environmental problems of sludge treatment, disposal and reuse. Deposits from aerated lagoons and stabilization ponds are likely to contain pathogenic microorganisms as well as organic and inorganic contaminants that may be hazardous or toxic to humans and could therefore limit their suitability for agricultural applications. For these reasons, the proper handling of these sludges is one of the most important components of the design and operation of these two wastewater treatment processes (Legeas *et al.*, 1992).

This paper intends to summarize some characteristics of sediments that we measured in a full-scale facility located in Belgium. We shall focus in particular on Sediment Oxygen Demand (SOD) and the influence of factors such as spatial and seasonal variations, temperature, substrate (COD) concentration, thickness of sediment layer, dissolved oxygen concentration in the overlying layer, and the presence of invertebrates on the oxygen consumption rate of those sediments. We shall also give information on the proportions of chemical oxidation and biological consumption in SOD. The huge influence of resuspension of deposits on oxygen consumption in the basins will also be demonstrated. Finally a model will be suggested to calculate SOD from the most important parameters.

Materials and method

Bertrix wastewater treatment plant

The data presented in this study were collected at the Bertrix wastewater plant presented in Namèche *et al.* (1999).

Methods

- *Sediment Oxygen Demand* – To compare the various analytical procedures described in the literature, sediment oxygen demand was measured by means of respirometric tests conducted on disrupted and undisrupted sludge samples. "Non-disruptive" measurements were carried out either in situ using a benthic chamber or in the laboratory using sediment cores. The laboratory measurements were performed with and without substrate addition, i.e., by replacing overlying water with oxygen-saturated dilution water with or without substrate. When the tests were conducted in the presence of substrate, an acclimatisation period of 12 hours proved necessary before any measurements could be performed. "Disruptive" measurements consisted of determining the rates of oxygen consumption of suspended sediments which were continuously stirred. To quantify the chemical component of these respirations, respirometric tests were also performed after the addition of $HgCl_2$, which, by acting as a metabolic inhibitor, stops all biological activity.
- The substrate employed for the tests was a mixture of glucose and glutamic acid in concentrations corresponding to a theoretical COD of 0, 100, 500, 1000, 1400 mg O_2/l.
- The temperatures tested were 5, 15, 25 and 35°C. Core samples were submitted to the four temperatures for 24 hours (one day per temperature).
- The influence of sediment layer thickness was studied by mixing the corresponding layers from various core samples and preparing new samples of various thickness from those slices.
- A micro-oxygen probe provided by Revsbech (1989) was also employed to quantify the thickness of the aerobic biofilm in the deposits. In this case the overlying water was kept at dissolved oxygen saturation to be sure that the oxygen gradient in the film was stationary.
- To date Sediment Oxygen Demand (SOD) in more than 420 cores has been studied.

Other characteristics of sediments of this plant were studied previously. They include accumulation rates, physicochemical and bacteriological characteristics, composition of interstitial waters, and exchange rates at the sediment-water interface. Details can be found in Namèche *et al.* (1997).

Sediment oxygen demand

It is important to note that Pond 3 was not in service during this study. Also, as the dissolved oxygen content in the liquid phase is high enough in this plant, conditions in the upper part of the sediments are aerobic most of the time.

Spatial and seasonal variations

The results are given in Figures 1 and 2. They may be summarized as follows. Mean SOD for the cold season (winter and autumn) is 1.81 (1.01g O_2 $m^{-2}d^{-1}$ and 2.75 for the warmer

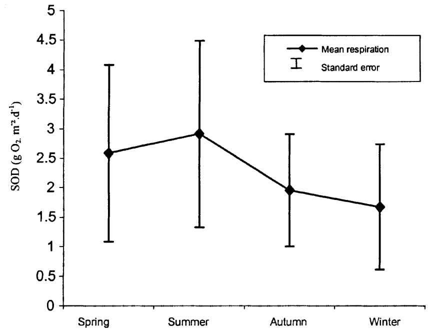

Figure 1 Seasonal variation in mean SOD for the complete plant

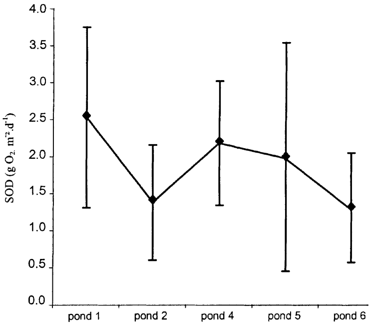

Figure 2 Spatial distribution of SOD (mean)

Table 1 ANOVA results on influence of temperature

Source	DF	Seq SS	Adj SS	Adj MS	F	P	
Temperature	3	848.90	848.90	282.97	43.27	0.000	***
Day	3	11.10	6.612	3.70	1.13	0.350	NS
Group	7	102.93	102.93	14.70	4.51	0.001	**
Error	18	117.716	117.716	6.540			
Residuals	36	117.433	117.433	3.262			
Total	67	1198.076					

NS = not significant ($P>0.05$); * = significant ($P\leq0.05$); ** = highly significant ($P\leq0.01$);
***= very highly significant (P(0.005); total effective (N)=95

season (spring and summer). Within the seasons the differences are not significant. Similar results were observed by Edwards and Rolley (1965), who could not determine whether the variations were due to temperature. For Edberg and Hofsten (1973), the variations were related to temperature.

Influence of temperature

To study the causes of the seasonal variations in the respiration rates of sediments at greater depth, we studied the influence of temperature on SOD separately. The sediment cores extracted from the ponds were placed in a thermostatic chamber at 5, 15, 25 and 35°C. The sediment layer thickness was 20 cm and the overlying water was free of substrate (COD≅ 0 mg/l). The assays ran for four days for each of the two series. Table 1 shows the results of ANOVA on the data.

ANOVA shows that the influence of temperature is very highly significant. The influence of the day of measurement is not significant, which means that the respiration rates do not vary rapidly and the measurements may be considered essentially constant throughout the test. The inter-group differences are highly significant, confirming the spatial heterogeneity of cores sampled in the same basin. Further analysis of the two series separately confirmed this fact, as the series proved to be statistically different.

The influence of temperature on SOD is highly significant and the day-to-day reproducibility of the measurements is good (at least for a 4-day period). The influence of temperature on mean SOD is given in Figure 3.

Fitting the following equation to the data.

$$R_T=R_{20}\theta^{T-20} \tag{1}$$

yields a θ value of 1.07 ± 0.01.

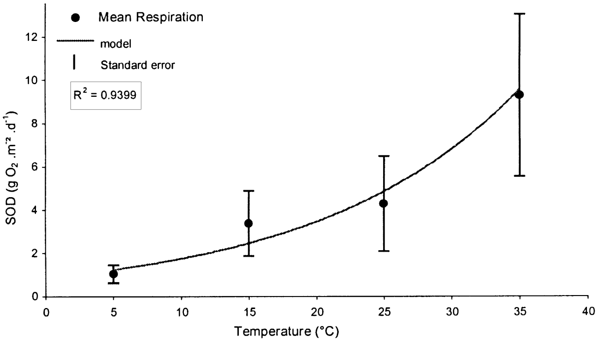

Figure 3 Influence of temperature on SOD

Table 2 Influence of substrate (100 mg/l) on SOD

SOD (g $O_2 \cdot m^{-2} \cdot d^{-1}$)	Pond 1	Pond 2	Pond 4	Pond 5
Mean	4.80	5.81	4.05	9.04
Standard error	1.50	2.53	1.62	2.39
Multiplication factor	2.4	4.6	2.3	9.7
Number of values	13	17	10	18

This is somewhat higher than the classical value of 1.047 suggested by Gotaas (1969), confirming that SOD is highly dependent on temperature.

Influence of substrate in the liquid phase

Comparison with and without substrate. So far the SOD has been measured without organic substrate in the overlying liquid. This means that the micro-organisms are using the substrate content of the sediment, including internal substrate, corresponding to an endogenous state. Some authors, e.g., Gunnison *et al.* (1983) and Rutherford *et al.* (1991), claim that SOD depends on the internal substrate as well as on the substrate content in the liquid phase. Gunnison *et al.* (1983) observed that SOD was increased by a factor of from 1 to 3 when a substrate such as glucose was added to the liquid. In the first part of the experiment we thus checked this assumption. So, SOD was measured using a synthetic wastewater with a BOD of 100 mg O_2/l and an acclimatisation period of 12 hours was maintained in the presence of substrate before the test. The results are presented in Table 2.

The multiplication factor is the ratio of SOD with substrate over SOD without substrate. Thus this multiplication factor is high. This is also confirmed in Figure 4.

Influence of substrate concentration. As the presence of substrate in the liquid obviously has a huge effect on SOD, we studied more deeply the effect of substrate concentration on SOD. Concentrations of 0, 100, 500, and 1000 mg COD/l were used. Every core was exposed to these concentrations for a whole day for each concentration. The influence of substrate is presented in Figure 5 (the data from all the cores are pooled).

The measured values reveal that a saturation level can be reached. We tested a Monod-like equation to model the shape of the response, to wit:

$$R = R_O + R_{max}\frac{S}{K_S + S} \qquad (2)$$

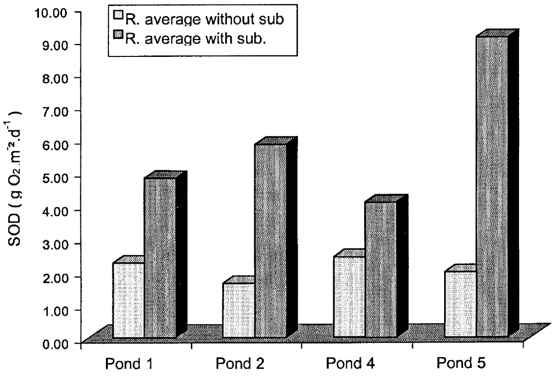

Figure 4 Mean SOD with and without substrate for the various ponds

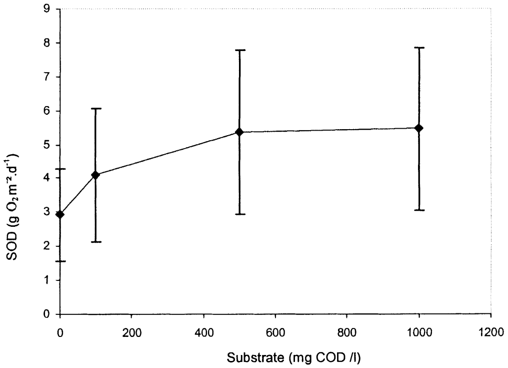

Figure 5 Influence of substrate on average SOD at 20°C (undisrupted cores)

Table 3 Adjusted values of equation (2) for every pond

Fitted parameter **Units**	R_0 ($g\ O_2\ m^{-2}d^{-1}$)	R_{max} ($g\ O_2\ m^{-2}d^{-1}$)	K_s ($mg\ COD \cdot l^{-1}$)	r^2
Pond 1 (aerated lagoon)	3.34	4.47	276.95	0.999
Pond 2 (aerated lagoon)	1.28	1.84	83.84	0.999
Pond 4 (natural pond)	2.28	2.45	91.99	0.999
Pond 5 (natural pond)	1.94	2.03	124.26	0.992
Pond 1 + Pond 2	2.49	3.63	221.87	0.991
Pond 4 + Pond 5	2.15	2.27	121.39	0.994
all the ponds	2.39	2.94	185.24	0.993

With

R	sediment respiration rate ($g\ O_2\ m^{-2}d^{-1}$)
R_O	endogenous respiration rate ($g\ O_2\ m^{-2}d^{-1}$)
R_{max}	maximum respiration rate related to substrate ($g\ O_2\ m^{-2}d^{-1}$)
S	substrate concentration ($mg\ COD\ l^{-1}$)
K_S	Michaelis constant (mg COD/l).

The same equation was fitted to the data obtained for the cores sampled in every pond. The results are given in Table 3.

The model fits very well with R_O and R_{max} in agreement with the spatial distribution of SOD (Figure 2). Notice that R_{max} is always greater than R_O, which means that the respiration rate related to the substrate will be higher than the endogenous respiration rate if the substrate concentration in the liquid phase is high enough. The K_S value varies from pond to pond. This could be an indication of the accessibility of the substrate to the sediment microorganisms trapped in the deposits.

Influence of the thickness of the sediment layer

The information gleaned from the literature on the influence of the thickness of the sediment layer is contradictory. Some authors [Davision and Hanes (1968); Ogunrombi and Dobbins, (1970)] observed an influence of the thickness on SOD. Others [Edwards and Rolley (1965)] suggest no influence or a limited one [Walker and Snodgrass (1986)].

Figure 6 presents our results (at 20°C with no substrate) for all the ponds, as the thickness of the sediment layer varies between 5 and more than 30 cm. The influence of thickness appears to be very poor but could be difficult to observe because of the spatial heterogeneity of SOD. This has been confirmed by mixing various slices of sediments as described above. ANOVA of the data indicates that the influence of thickness (in the range between 5 and 35 cm) is not significant.

An explanation can be suggested by using a microprobe to measure the dissolved oxygen in the sediments (Namèche *et al.*, 1997). For example, the aerobic layer of sediments (Pond 4) extends between 1000 and 2000 µm, with some spatial heterogeneity, in January but only from 35 to 200 µm in March.

Influence of macro-invertebrates on SOD

Macro-invertebrates were counted in some core samples in order to examine the influence of various types of macro-invertebrates. This is illustrated in Figure 7.

Again the influence of macro-invertebrates on SOD appears to be very poor but might be dampened by the influence of other factors, such as spatial heterogeneity, temperature, substrate, etc.

A separate experiment using Chironomidae mixed with 20 g of fresh deposits revealed a discernable influence of the macro-invertebrates on SOD. Since in our case the area density of macro-invertebrates is in the range 0 to 20,000 (Cheikhi, 1997), we can expect to find 0 to 5 individuals per 20 g of fresh matter in the 5 upper centimetres of deposits, which could represent up to 10% of SOD. Measurements are still being completed.

Measurements on suspended (perfectly mixed) sediments

Some authors (Rutherford *et al.*, 1991; Trevors, 1984; Roffes *et al.*, 1991) prefer measurements on suspended sediments to respirometric tests conducted both in situ and in the

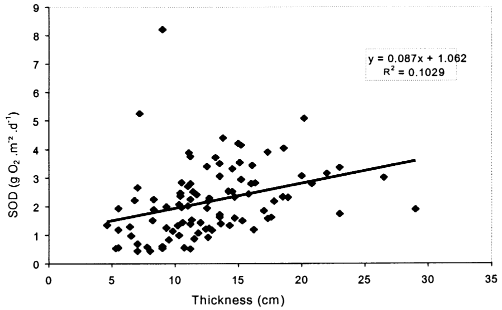

Figure 6 Influence of thickness of deposits on SOD (t°=20°C, no substrate)

laboratory on undisturbed samples. In this study both types of measurement were taken and compared. The findings are compared in Table 4.

The multiplication factor is the ratio between the total amount of oxygen consumed in the liquid phase when the sediments are completely mixed and when they are not.

Obviously, the respiration rates calculated for suspended sediments are several hundred times higher than those determined for undisrupted samples. On average, suspended sediments consume as much as 4.96 mg O_2 per day and per gram of fresh weight, that is to say, nine hundred times more than undisturbed sediments. Such large differences are definitely due to better oxygen availability, larger exchange surfaces and the sudden release of reduced inorganic compounds that normally diffuse much more slowly towards the sediment-water interface.

Another phenomenon related to resuspended sediments that was observed in aerated lagoons is the variation in measured respiration rates when aerators are running and switched off. The results of such an experiment are presented in Table 5.

One can see that the respiration rate increases progressively when the aerators are operating. Conversely, the oxygen consumption rate decreases slowly when aerators are switched off. As sedimentation progresses the respiration rate decreases and the respiration rate usually falls to a minimum again just before the aerators are restarted. ANOVA of the data confirms that the respiration rates are statistically different when aerators are on or off (for both ponds). However we detected no variations in the vertical distribution of oxygen consumption.

In many ways respiration rates calculated on suspended sediments appear to correspond to a potential oxygen demand. While they are usually restricted to particular situations such as pond desludging, they also coincide with periods of huge oxygen consumption. In fact,

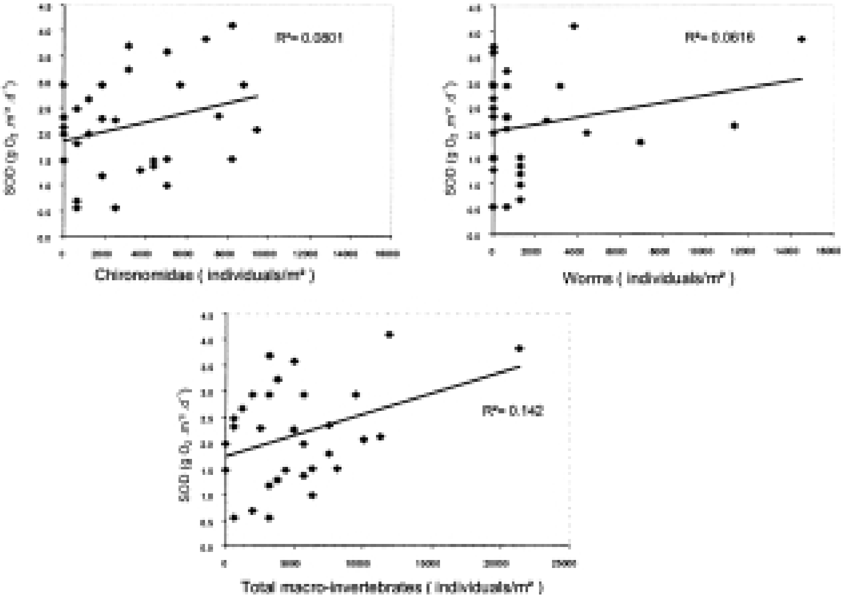

Figure 7 Influence of the density of macro-invertebrates on SOD (t°= 20°C no substrate)

Table 4 Oxygen consumption of suspended sediments (without $HgCl_2$)

SOD mg ($O_2 \cdot g\ SS^{-1} \cdot d^{-1}$)	Pond 1	Pond 4	Pond 5
Mean	3.92±3.59	6.56±6.91	5.55±2.10
Multiplication factor	1083	863	416
Number of values	23	12	8

Table 5 Variation of respiration rates with time and depth in aerated lagoons (mg $O_2 \cdot l^{-1} \cdot h^{-1}$)

After switching the aerators on											
First basin						**Second basin**					
Time (min)	**Surface**	**–50**	**–100**	**–150**	**–200**	**Time (min)**	**Surface**	**–50**	**–100**	**–150**	**–200**
0	1.12	1.50	1.52	2.03	1.85	0	0.66	0.53	0.49	0.58	0.66
30	2.50	2.13	2.19	2.30	2.37	30	0.90	0.74	0.89	0.87	0.8
60	2.67	2.33	2.19	2.26	2.32	60	1.05	0.96	0.85	0.91	0.98
120	2.61	2.33	2.45	2.46	2.49	120	1.39	1.13	1.2	1.26	1.48
After stopping the aerators											
First basin						**Second basin**					
Time (min)	**Surface**	**–50**	**–100**	**–150**	**–200**	**Time (min)**	**Surface**	**–50**	**–100**	**–150**	**–200**
0	1.65	1.71	1.61	1.66	1.67	0	1.78	1.51	1.96	1.73	2.10
30	0.94	1.05	0.98	1.11	1.08	30	1.75	1.58	1.60	1.68	1.68
60	0.68	0.93	0.96	1.05	1.31	60	1.58	1.54	1.59	1.58	1.96
120	0.80	1.05	1.29	1.37	1.39	120	1.73	1.79	1.75	1.80	2.27

such “resuspension” or “scouring” events are much more frequently encountered in aerated lagoons, since each time the aerators of the plant are switched on about 3 tons of fresh sediment are resuspended. The direct consequence is a surge in the overall respiration measured over the two aerated lagoons.

Share of chemical and biological oxidation in SOD

The measurement of dissolved oxygen consumption is called the respiration rate, but in fact chemical oxidation may also occur, especially when measurements are performed on resuspended sediments. In such a case reduced compounds present in the anaerobic layer of deposits can be liberated and oxidized by a chemical reaction. To quantify the proportion of this chemical SOD, which is governed exclusively by redox processes, respirometric tests were conducted on suspended sediments treated with mercury chloride ($HgCl_2$), which inhibits metabolic activity. According to the results presented in Table 6, chemical SOD appears to account for over one-third of overall respiration. This proportion is similar to those reported successively by Adams *et al.* (1982) and Walker and Snodgrass (1986).

Proposal of a new model for SOD

From the previous experiments we consider that the most important factors affecting SOD are substrate and temperature. We can combine Eqs. (1) and (2) to yield the following equation.

$$R_T = \left(R = R_O + R_{max} \frac{S}{K_S + S} \right) \theta^{T-20} \tag{3}$$

To verify the validity of the model we performed further assays on deposits from Pond 4 at various temperatures (5, 15, 25 and 35ºC) and for various substrate concentrations (0, 100, 500, and 1000 mg COD/l). The fit with the model is presented in Figure 8. The results are given in Table 7.

We see that the model fits very well and the consumption rate governed by external substrate is greater than the endogenous respiration rate. Again the K_S value is high, which means that the process probably is not controlled by enzymatic activities.

Table 6 Oxygen consumption of suspended sediments (with $HgCl_2$)

SOD (mg O_2 · g fresh W^{-1} · d^{-1})	Pond 1	Pond 4	Pond 5
Mean	1.08	1.97	1.31
% of total respiration	33	36	35
Number of values	11	10	1

Table 7 Values of parameters of the model

Test number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Substrate (g COD· l^{-1})	0	0	0	0	0	100	100	100	100	100	500	500	500	500	500	1000	1000	1000	1000	1000
Temperature (ºC)	5	15	20	25	35	5	15	20	25	35	5	15	20	25	35	5	15	20	25	35
SOD measured (g O_2· m^{-2} · d^{-1})	0.82	2.53	2.53	3.64	7.92	1.01	2.48	3.60	4.52	9.61	1.32	3.20	4.41	6.18	12.78	1.83	3.54	5.21	9.13	13.91
SOD calculated (g O_2· m^{-2} · d^{-1})	1.03	2.03	2.85	3.99	7.86	1.23	2.42	3.39	4.75	9.35	1.67	3.28	4.60	6.46	12.70	1.92	3.77	5.29	7.42	14.60

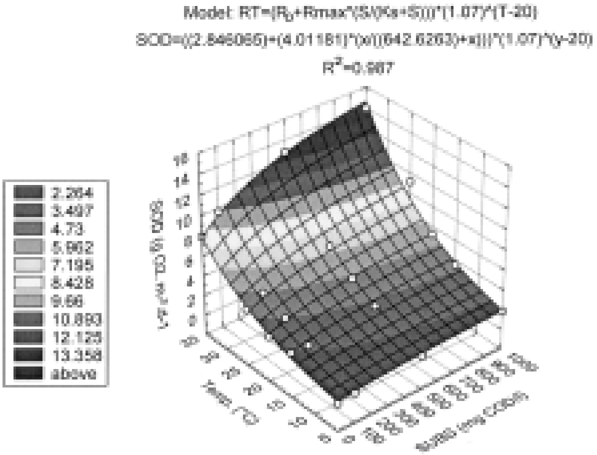

Figure 8 Combined influence of temperature and substrate on SOD (Pond 4)

Conclusions

The experiments demonstrate that temperature and substrate concentration in the liquid phase are the factors that affect the SOD most in plants where the upper part of deposits is aerobic. Other factors that can be very important are spatial heterogeneity and resuspension of sediments. The latter may not only be extremely important when mechanical aerators are used, but may also be induced by gas production, pumping or extraction of deposits, macrophyte harvesting or simply the in situ measurement system itself. To reduce the variability related to spatial heterogeneity we are now developing a new procedure for sampling and pooling samples divided into various fractions. Measurements are still being taken, but from the data available to date we believe that the influence of macro-invertebrates should not exceed around 20% of SOD.

The sediment layer thickness was not seen to influence SOD, but we must reiterate that in our case the upper part of sediments is aerobic.

We suggested a new model and fitted the model to the SOD of Pond 4. This should be confirmed for other ponds and other plants.

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