COMPARISON OF BENTHIC OXYGEN DEMAND MEASUREMENT TECHNIQUES

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Abstract: *Several common methods to measure benthic oxygen demand were compared using measured and literature data. An in situ respirometer technique, a laboratory core-uptake technique and a laboratory flow-through system technique were compared on sand and organic sediment in Lake Washington, Florida. In situ uptake rates were significantly higher than core-uptake rates, and this difference was greater for highly organic sediment than sand sediment. Measured and literature uptake values for in situ respirometer and core-uptake techniques with organic sediment were compared and resulted in a relationship* ($r = .99$; $P < .01$) *of the form: in situ uptake* ($g\ O_2/m^2$-hr) $= .036 + 1.16$ *core uptake* ($g\ O_2/m^2$-hr)*. In many cases both core-uptake and in situ respirometer techniques under estimate oxygen consumption, due to difficulties in obtaining correct water velocities over the sediment surface. In the flow-through system studies, sediment oxygen uptake varied considerably with flow rate and a significant logarithmic relationship* ($P < .01$) *was obtained with Lake Apopka, Florida organic sediment. Measurement techniques that simulate field flows are the most accurate, such as the flow-through system or the in situ tunnel respirometer technique.*

The principal oxygen sinks in aquatic systems are microbial and macrophyte metabolism in the water column and biological and chemical uptake by bottom sediments. Sediment oxygen uptake has received relatively little attention compared to oxygen demand in the water column, but sediment demand can represent a significant percentage of the total oxygen uptake in some aquatic systems. In some rivers and streams, sediment can act as a stationary oxygen sink and greatly affect the "oxygen sag" characteristics of the waterway. Hanes and Irvine (1968) indicated that oxygen uptake by sediments in certain rivers may account for as much as 50% of the total oxygen depletion from the water column.

Sediment uptake rates obtained from a variety of in situ and laboratory measurement techniques range over 3 orders of magnitude (Table 1). The rates range from 0.001 g $0_2/m^2$-hr for deep sea sediments (Smith and Teal, 1973) to 1.07 g O_2/m^2-hr for coral reef communities (Odum and Odum, 1955). The lack of an accepted or approved method for measuring benthic oxygen demand, however, may contribute to inaccuracies in the reported literature because different methods used to measure benthic oxygen demand may not be comparable. Common methods of measuring benthic oxygen demand have seldom been employed simultaneously in the same aquatic system for comparative purposes (Bradley and James, 1968; James, 1974; Edberg and Hofsten, 1973). In view of this, I wanted to: (1) statistically correlate several techniques using measured and literature data, and (2) discuss the feasibility of each method.

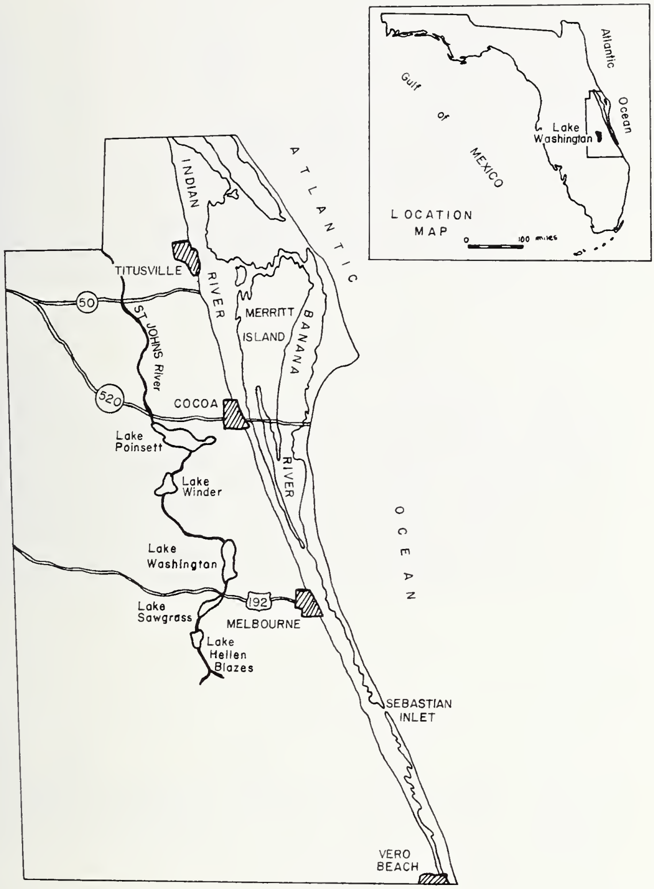

Fig. 1. Location of Lake Washington.

Sampling—Benthic oxygen demand measurements were made in August 1978 at sand (1.5% V.S.) and organic (20.5% V.S.) stations in Lake Washington, Florida. Lake Washington is the third uppermost of the naturally connected lakes of the northward-flowing St. Johns River and lies approximately 411 river Km south of Jacksonville, Florida (Fig. 1). An in situ respirometer technique, a laboratory core-uptake technique and a laboratory flow-through system technique were tested.

Core-uptake method—Several sand and organic sediment cores were taken at each station, placed in a styrofoam container, and transferred to a portable laboratory. Divers obtained the sediment cores (10 to 20 cm in depth) with 50.8 cm long plexiglas tubes (11.40 cm^2 openings). Care was taken to keep the sediment water interface in its natural state.

Table 1. Comparison of sediment oxygen uptake rates from several aquatic systems.

Systems	Uptake Rate (g 0_2/m^2-hr)	Method	Reference
Marine:			
Potomac Estuary	Avg - 0.10, Max - 0.36	*In Situ* Respirometer	O'Connell and Weeks, 1972
San Diego Trough Sediments	Avg - 0.003	*In Situ* Respirometer	Smith, 1974
Coral Reef Community	1.07	Diurnal Oxygen Method	Odum and Odum, 1955
Deep Sea Benthic Community at 1,850 m	0.001	*In Situ* Respirometer	Smith and Teal, 1973
Marine Sublittoral Community off Sapelo Island, Georgia	0.08 - 0.13	Lab Core Method	Smith, 1973
Unstressed Marine Sublittoral Communities (Long Island Sound, Woods Hole, Pudget Sound, etc.)	0.002 - 0.107	*In Situ* and Lab Methods	Riley, 1956; Carey, 1962, 1967; Kanwisher, 1962;
Eastern Tropical Pacific (off Peru)	0.002	Lab Core Method	Pamatmat, 1971
Northeastern Pacific	0.007	Lab Core Method	Pamatmat, 1971
Streams and Springs:			
Moose Burn (English Steam)	0.92	Lab Core Method	James, 1974
	1.13	*In Situ* Respirometer	
Cunsey Beck (English Stream)	0.15	Lab Core Method	James, 1974
	0.16	*In Situ* Respirometer	
	0.22	*In Situ* Respirometer	
Eutrophic Stream Muds—			
2 cm in Depth	0.14	Lab Reaction Chamber	McDonnell and Hall, 1969
25 cm in Depth	0.26	Lab Reaction Chamber	
Silver Springs, Florida	0.079	*In Situ* Bell Jar Method	Odum, 1957
Running Waters in Sweden	0.01 - 0.06 -	*In Situ* Respirometer	Edberg and Hofsten, 1973
Rivers:			
River Anker, England	0.04 - 0.10	Lab Core Method	Bradley and James, 1968
	0.22 - 1.09	Continuous Flow Tunnel	
	0.05 - 0.24	*In Situ* Respirometer	

River Anker, England	0.22	Lab Core Method	James, 1974
River Ivel, England	0.03 - 0.10	Lab Core Method	Edwards and Rolley, 1965
River Hiz, England	0.06 - 0.16	Lab Core Method	Edwards and Rolley, 1965
River Lark, England	0.95	Lab Core Method	Edwards and Rolley, 1965
River Coine, England	0.14 - 0.80	Lab Core Method	Edwards and Rolley, 1965
Selected English Rivers	0.006 - 0.41; Avg - 0.05	Lab Core and *In Situ* Resp.	Rolley and Owens, 1967
Lakes:			
Hypolimnion of Lake Travls, Texas	0.10 - 0.69	*In Situ* Respirometer	Steiner *et al.*, 1972
Swedish Lakes	0.02 - 0.11	*In Situ* Respirometer	
Lea Marston Lake, England	0.15	*In Situ* Respirometer	James, 1974
Esthwaite Water, England	0.39	Lab Core Method	James, 1974
	0.40	*In Situ* Respirometer	
Loch Leven, England	0.13	*In Situ* Respirometer	James, 1974
Lake Erie's Central Basin	0.01	*In Situ* Respirometer	Blanton and Winklhoffer, 1972
Lake Erie's Central Basin	0.0 - 0.10	*In Situ* Respirometer	Lucas and Thomas, 1972
Lake Esrom, Denmark	0.0 - 0.002	Lab Core Method	Hargrave, 1972
Middle St. Johns Lakes, Florida			
Lake Jessup	Avg - 0.10	*In Situ* Respirometer	Belanger, 1979
Lake Harney	Avg - 0.18	*In Situ* Respirometer	
Lake Monroe	Avg - 0.14	*In Situ* Respirometer	
Lake Apopka, Florida	Avg - 0.07	Lab Core Method	Belanger, 1979
	0.0 - 0.13	Continuous Flow-Through System (At Various $[0_2]$ and Flow Rates)	
Lake Washington, Florida			
Sand Sediment	Avg - 0.26	*In Situ* Respirometer	Belanger, 1979
	Avg - 0.20	Lab Core Method	
	0.16 - 0.27	Flow-Through System	
Peat-Muck Sediment	Avg - 0.27	*In Situ* Respirometer	
	Avg - 0.18	Lab Core Method	
	0.091 - 0.29	Flow-Through System	

In the lab, the sediment levels were adjusted to a 10 cm depth by discarding sediment from the bottom of the core. The overlying water was siphoned off and 375 mL of mid-depth lake water were added to each core. This water contained sufficient oxygen (> 5 mg/L) to conduct the uptake experiments. The water was siphoned carefully into the cores to minimize sediment disturbance. Next, the styrofoam container was filled with lake water to keep the cores at field temperature (30°C ± 2). At the same time, several empty cores were filled with lake water as control cores to estimate respiration in the water column.

Every core apparatus was filled entirely with water to insure the absence of air bubbles. After a 30 min incubation period, the dissolved oxygen in the water was measured with a YSI Model 51-A dissolved oxygen meter at 5-10 min intervals. The water in the core was closed to the atmosphere with a rubber stopper to eliminate the effects of atmospheric diffusion. The probe was positioned 10 cm below the upper edge of the tube. The purpose of the waiting period was to avoid the initial rapid uptake of oxygen by easily oxidized compounds that may have been exposed during the initial coring steps and refilling procedure. Dissolved oxygen was measured at 5-10 min intervals for approximately 2 hr. The average concentration at each time interval was plotted versus time and the rate of oxygen consumption was determined from the slope of the curve. The average control core rate was subtracted from the average sediment core-uptake rate to determine the sediment oxygen uptake rate.

To quantify the rates on an areal basis, the volume of water over the sediment in the cores (0.375 L) and the surface area of the core opening ($1.14 \times 10^{-3} m^2$) were taken into consideration:

Sediment uptake rate (mg O_2/m^2-hr) = O_2 uptake (mg/L-hr) x water volume x 1/sediment area

(1) = 329 x uptake rate (mg/L-hr).

IN SITU RESPIROMETER—A benthic respirometer described by Fruh and Davis, (1972) was constructed to measure in situ benthic oxygen demand (see Fig. 2). Dissolved oxygen was measured inside the uptake chamber with the YSI membrane electrode. A stirring apparatus attached to the electrode provided slight circulation within the chamber and aided in obtaining stable readings. The oxygen electrode was fixed in position, and the respirometer was submerged and inverted to allow air to escape, before placing it on the bottom. Once in place, the apparatus was allowed to sit undisturbed for 20 min before any readings were taken to allow settling to occur to eliminate the effects of bottom disturbance. Dissolved oxygen measurements were made at 5-10 min intervals for 80 to 100 min. To quantify the rates on an areal basis, the sediment area covered by the respirometer (0.26 m^2), the volume of water over the sediment (110.8 L), and the water column respiration were taken into account as follows:

Benthic O_2 demand (mg O_2 m^2-hr) = [O_2 uptake (mg/L-hr) - water respiration (mg/L-hr)] (water volume) x 1/respirometer area

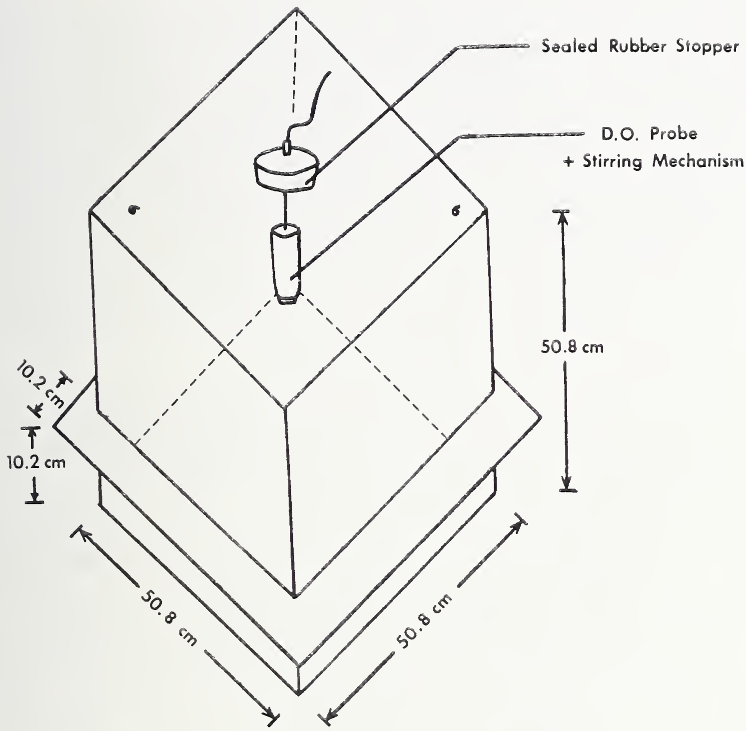

FIG. 2. In situ respirometer.

(2) $= 426\ [O_2 \text{ uptake (mg/L-hr)} - \text{water respiration (mg/L-hr)}]$

FLOW-THROUGH SYSTEM—The respirometer and core methods to measure benthic oxygen demand represent batch systems. The decrease in oxygen concentration in the overlying water was measured, and the results were used in calculating the oxygen uptake rates of the sediments. The following problems, however, are involved in using batch systems to measure benthic oxygen demand, and these problems may affect the results.

1. Batch systems do not approximate natural conditions because of the lack of water flow.
2. The length of each experimental run is limited to the length of time required to deplete the initial dissolved oxygen concentration in the overlying water.
3. Batch systems do not give the sediments sufficient time to acclimate

to experimental oxygen levels under consideration since the oxygen concentration of the overlying water continually decreases.

For these reasons a continuous (flow-through) system was constructed (Fig. 3) and used to measure sediment oxygen uptake rates for comparison with batch uptake rates. This flow-through system (1) better approximates natural flow conditions, an important factor in sediment oxygen uptake, and (2) permits the calculation of oxygen uptake rates along with uptake or release of other elements of interest under steady state conditions.

The flow-through apparatus consisted of 4 airtight chambers placed in series and connected by 0.95 cm inside-dia rubber hose and CPVC pipe, with appropriate fittings. Three of the chambers were constructed from Army surplus ammunition boxes which were painted on the inside with epoxy paint. One chamber was built using plexiglas so that turbidity of the water at different flow rates could be observed.

The total volume of the 4 chambers was 99.6 L, and the bottom surface area was 0.34 m^2. A submersible aquarium pump was placed in a closed plastic garbage bucket (water reservoir) and connected to the first tank with a rubber hose. Influent flow rates were varied by adjusting the position of pinch valves on the recycle line that was connected to the influent flow line (Fig. 3). A 1.27 cm inside diameter rubber return flow line entered the water reservoir so that the set-up was essentially a closed system. An air stone attached to plastic tubing was placed in the water reservoir so that the oxygen content of the influent water could be varied by bubbling in nitrogen or air. Sediment oxygen uptake studies using the flow-through system with Lake Apopka, Florida sediment generally indicated that benthic oxygen demand was independent of overlying dissolved oxygen at concentrations above approximately 2.5 mg/L, but below that level uptake rates were dependent on oxygen and decreased rapidly (Belanger, 1979). This relationship is shown in Fig. 4.

Observation of fluorescein dye in the clear plexiglas chamber at various flow rates indicated that mixing in the chambers was complete and no short circuiting between influent and effluent points occurred. Fluorescein dye was also used to simulate the range of water velocities (.05 - 1.0 ft/sec) obtained from measurements in Lake Washington and the upper St. Johns River, Florida and these velocities were then correlated to flow rates (L/hr) from the lab system. It was felt this range would encompass most in situ flow rates over the sediment-water interface. Water sample collection points were placed on the influent and return flow lines. Dissolved oxygen concentrations were determined in duplicate by Winkler titrations. Flocculent organic sediment was collected with a Ponar dredge, placed in sealed plastic buckets, and transported to the laboratory. Sand sediment was collected with box corers and carefully transferred to the flow-through chamber to keep the sediment-water interface intact. Sand and organic sediments were put in the flow-through chambers to a depth of 12.7 cm and covered with Lake Washington water that has been filtered through glass wool. Both sedi-

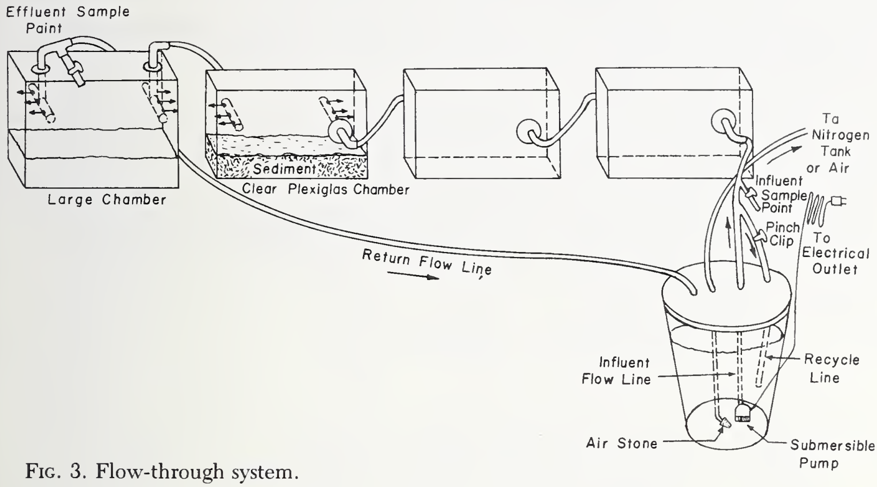

FIG. 3. Flow-through system.

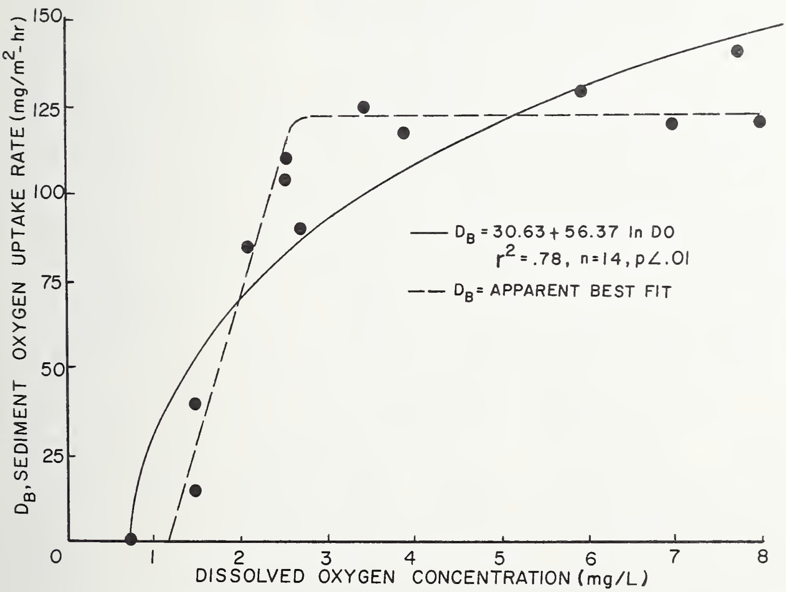

FIG. 4. Sediment oxygen uptake rate as function of overlying dissolved oxygen concentration for Lake Apopka station 2 sediment with flow rates varying from 138 to 240 L/hr.

ment types were allowed to equilibrate for approximately 7 da before the pump was turned on, and the pump was run at least one day before samples were taken. During this waiting period concentration gradients should be reestablished and in situ sediment conditions would be simulated in the organic sediment.

A simple equation was developed and used to calculate sediment oxygen uptake for the flow-through system. This equation can only be employed when the detention time at the particular flow rate in use has been equalled or surpassed. Usually a flow rate was selected and allowed to equilibrate for at least a day before samples were taken. The equation used was:

$$D_B = \left[\frac{DO_I - DO_F}{D.T.} - BOD_{D.T.}\right]\frac{V}{A}. \quad (6)$$

where D_B = net oxygen uptake rate (mg/hr-m^2),
DO_I = influent dissolved oxygen concentration (mg/L),
DO_F = effluent dissolved oxygen content (mg/L),
D.T. = detention time (hours),
$BOD_{D.T.}$ = BOD of overlying water for a particular D.T. (determined from regression equation of DO vs. time for five-day BOD),
V = volume of overlying water (liters), and
A = surface area of sediment (m^2).

Results and Discussion—Overlying water temperatures in each method were similar and kept at 30°C(±2°C). Core and in situ measurements were made on the same day for each sediment type so that direct comparisons could be made. Sediment for the flow-through system was collected on these days, also, but it was allowed to equilibrate for a week before measurements were made. The results from each method are in Table 2. A summary of the flow-through system uptake results is in Table 3.

Results from the comparative study indicate that in situ oxygen uptake rates are significantly higher than core uptake rates and that this difference is greater with organic sediment than with sand sediment. The higher uptake rates in flocculent organic sediments are probably related to sediment disturbance and resuspension. Core-uptake and in situ respirometer results from replicate measurements in Lake Washington indicated greater variability in uptake rates from organic than in those from sand sediments. In fact, uptake rates with sand sediment did not vary at all with these techniques (Table 2). Uptake rates in the flow-through system, however, varied considerably with flow rate but also varied to a greater extent in the organic sediment (Table 3). Highest uptake rates were obtained with organic sediment at high flow rates. Core uptake rates with sandy sediment were approximately the same as the flow-through uptake for the same sediment type at low flows (1 to 3 hr detention time). However, core uptake rates with

TABLE 2. Comparison of benthic oxygen demand measurement techniques on Lake Washington sediments.

Station	Date	Sediment Type	Method	Flow Rate (L/hr)	Oxygen Uptake Rate (mg 0_2/m^2-hr)	Average Uptake Rate (mg 0_2/m^2-hr)
1	8/4/78	Sand	Core-Uptake	—	198	198
					198	
					198	
			In Situ Respirometer	—	256	256
					256	
					256	
			Flow-Through System	25.7-210.3	162-270	
2	8/6/78	Organic	Core-Uptake	—	165	182
					198	
			In Situ Respirometer	—	277	267
			Flow-Through System	16.0-225.6	91-294	

TABLE 3. Summary of flow-through system uptake results from Lake Washington, Florida.

Station	Sediment Type	Flow Rate (L/hr)	Detention Time (hrs)	Overlying Water Dissolved Oxygen Conc. (mg/L)	Oxygen Uptake Rate (mg O_2/m^2-hr)	Average Uptake Rate (mg 0_2/m^2-hr)
1	Sand	25.7	3.00	7.6	169, 155	162
		85.7	0.90	7.4	222, 235	228
		210.3	0.36	7.4	252, 288	270
2	Organic	16.0	4.80	7.7	73, 90	81
		98.3	0.78	7.8	181, 216	198
		225.6	0.34	7.3	266,322	294

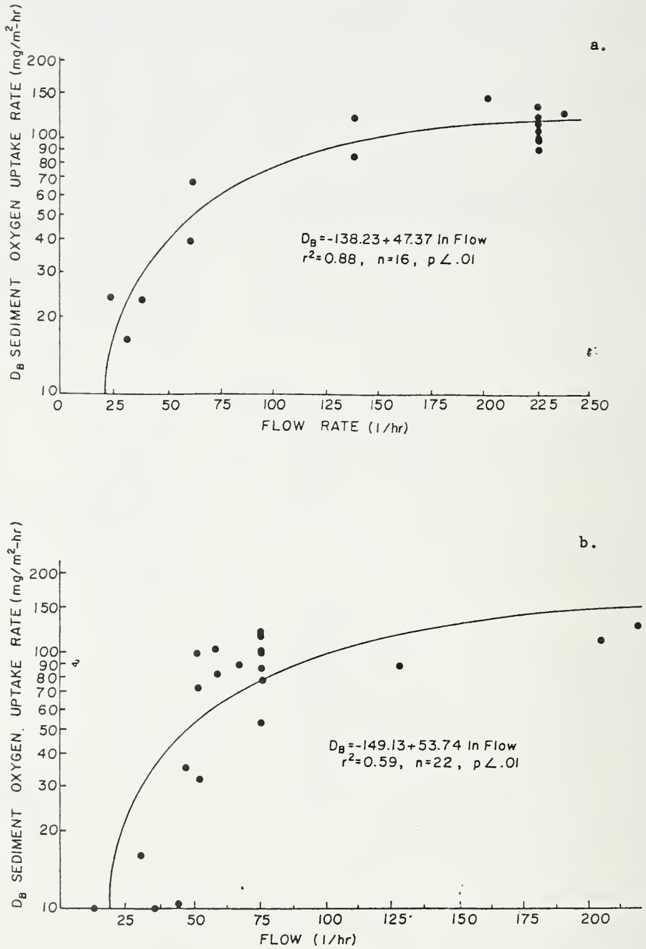

FIG. 5. Sediment oxygen uptake rate as a function of flow rate for (a) Lake Apopka north midlake and (b) south midlake sediment with overlying oxygen concentrations greater than 2.5 mg/L.

organic sediment approximated flow-through uptake at higher flows (0.75 to 1 hr detention time). In situ uptake by sand approximated flow-through uptake with a detention time of approximately 0.75 hr or less. In organic sediment, the in situ uptake approximated a flow-through uptake at a detention time of 0.50 hr or less.

In a comparison of the core-uptake, in situ respirometer, and in situ tunnel respirometer techniques in English streams, James (1974) showed that the core uptake technique and in situ respirometer method both underestimated oxygen consumption as determined by tunnel respirometers and mass balance calculations, with results from the laboratory core-uptake technique having the greatest percent deviation. Other workers have suggested that uptake rates from core methods are lower than those from in situ methods (Edberg and Hofsten, 1973; Rolley and Owens, 1967; Bradley and James, 1968). These results are consistent with findings in this study. In all cases the low values for core and in situ methods appear to be caused by a difficulty in obtaining the correct range of water velocities over the sediment surface. Results from using the laboratory flow-through system with Lake Apopka, Florida organic sediment (55 to 66% V.S.) indicated that sediment oxygen uptake rate (D_B) varied considerably with flow rate. A statistically significant ($r = .94, .75$; $p < .01$) logarithmic relationship of the form $D_B = -a + b \ln \text{Flow}$ was obtained with Lake Apopka sediment from 2 locations (Belanger, 1979). This relationship is shown in Fig. 5. In shallow streams, a large in situ tunnel respirometer as employed by James (1974) may eliminate the problem of simulating actual flows in the lab. The in situ tunnel respirometer, however, is not applicable in many aquatic systems, including lakes, deep canals, estuaries and deep rivers. In these situations a flow-through lab system such as shown in Fig. 3 may be the best method if the water velocities over the sediment can be approximated. Careful attention must be given to the flow rate in the flow through system, however, as unrealistically high rates can overestimate sediment oxygen uptake due to increased chemical oxygen demand from disturbed sediments.

TABLE 4. A comparison of sediment oxygen uptake measurement techniques (g O_2/m^2-hr).

Sediment	Study	Core	In Situ	Flow-Through Tunnel
English River Mud	Bradley and James, 1968	0.04 0.10	0.05 0.24	0.22 1.09
English River and Lake Mud	James, 1974	0.15 0.92 0.39 0.22 0.07 0.22	0.16 1.13 0.40 0.35 0.13 —	0.22 1.59 — — — 0.42
Eutrophic English Lake Mud with Newly Deposited Algae	Edberg and Hofsten, 1973	0.05 0.06	0.08 0.10	
Lake Washington, Florida	Belanger, 1979			
Organic		0.18	0.27	
Sand		0.20	0.24	

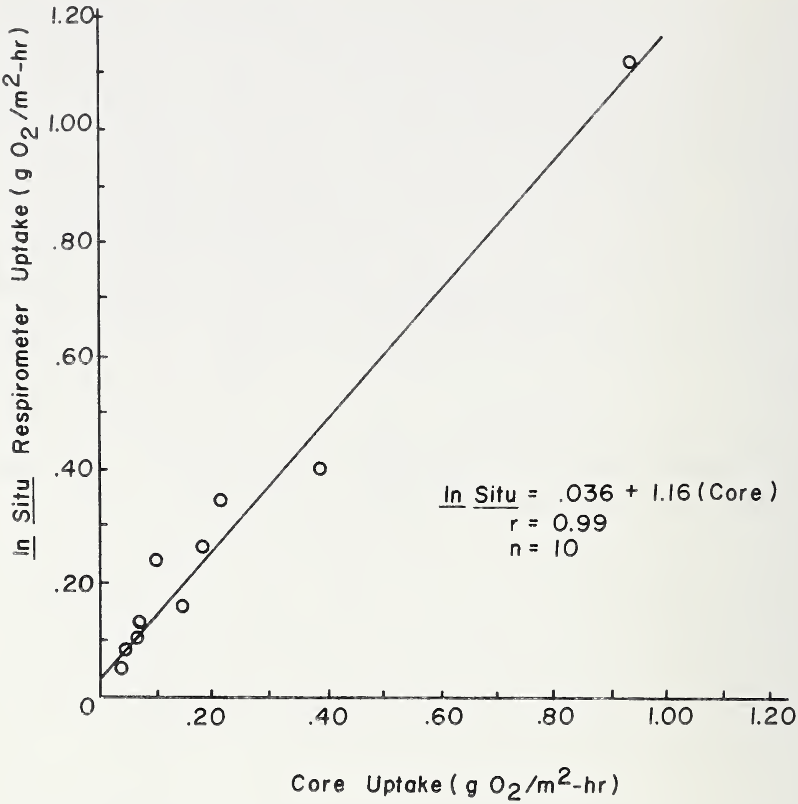

Fig. 6. Comparison of core-uptake and in situ respirometer measurement techniques.

A listing of sediment uptake rates from studies where several measurement techniques were employed is in Table 4. Uptake rates are presented primarily for organic sediment, as the lack of data for other sediment types prevented statistical comparisons. In situ respirometer and core-uptake techniques were significantly ($r = 0.99$; $P<0.05$) correlated (Fig. 6). Tunnel uptake results were compared with core-uptake rates from data collected from significantly flowing English rivers and lakes by James (1974) and a r value of 0.79 ($P<0.05$) was obtained (Fig. 7). Although a lack of data exists for the tunnel respirometer, probably due to the difficulty of constructing it, the in situ tunnel respirometer is expected to give the best results because it measures sediment oxygen uptake under in situ environmental conditions. Core-uptake results, then, significantly underestimate sediment oxygen uptake. The "best" approaches for flowing systems would be to simulate actual measured field flows in the lab or, if possible, use the tunnel respirometer technique in the field. For organic sediment systems that exhibit little flow or circulation, the in situ respirometer technique is recommended or the core

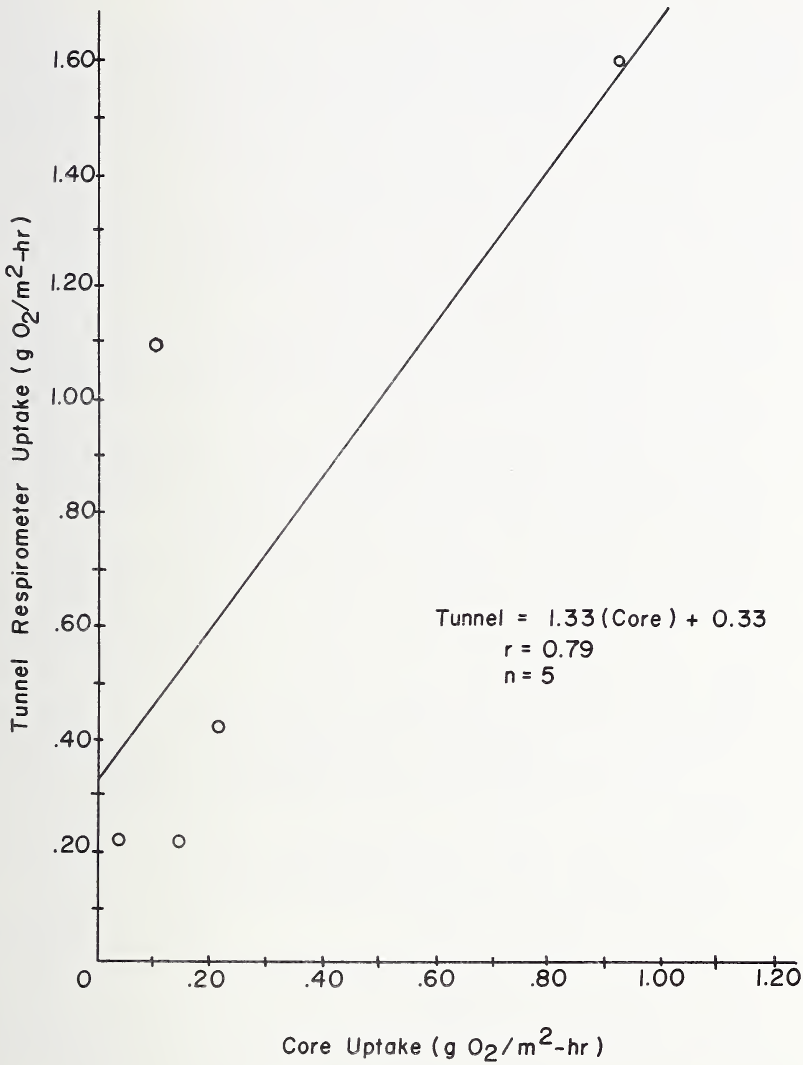

FIG. 7. Comparison of core-uptake and tunnel respirometer measurement techniques.

technique with the correction factor for conversion to in situ respirometer rates presented in Fig. 6. Although differences between the methods are generally less on sand sediments than organic sediments (Table 4), more comparative data should be collected on sand sediment to adequately establish this fact. Further data are also needed for comparisons with the tunnel respirometer, as only five data points were available in this study (Fig. 7).

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