US Army Corps of Engineers
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Technical Report W-94-1
March 1994

Water Quality Research Program

Sediment Oxygen Demand and Its Effects on Dissolved Oxygen Concentrations and Nutrient Release; Initial Laboratory Studies

by Cynthia B. Price, Carl Cerco, Douglas Gunnison

WES

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U.S. Army Corps of Engineers
Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

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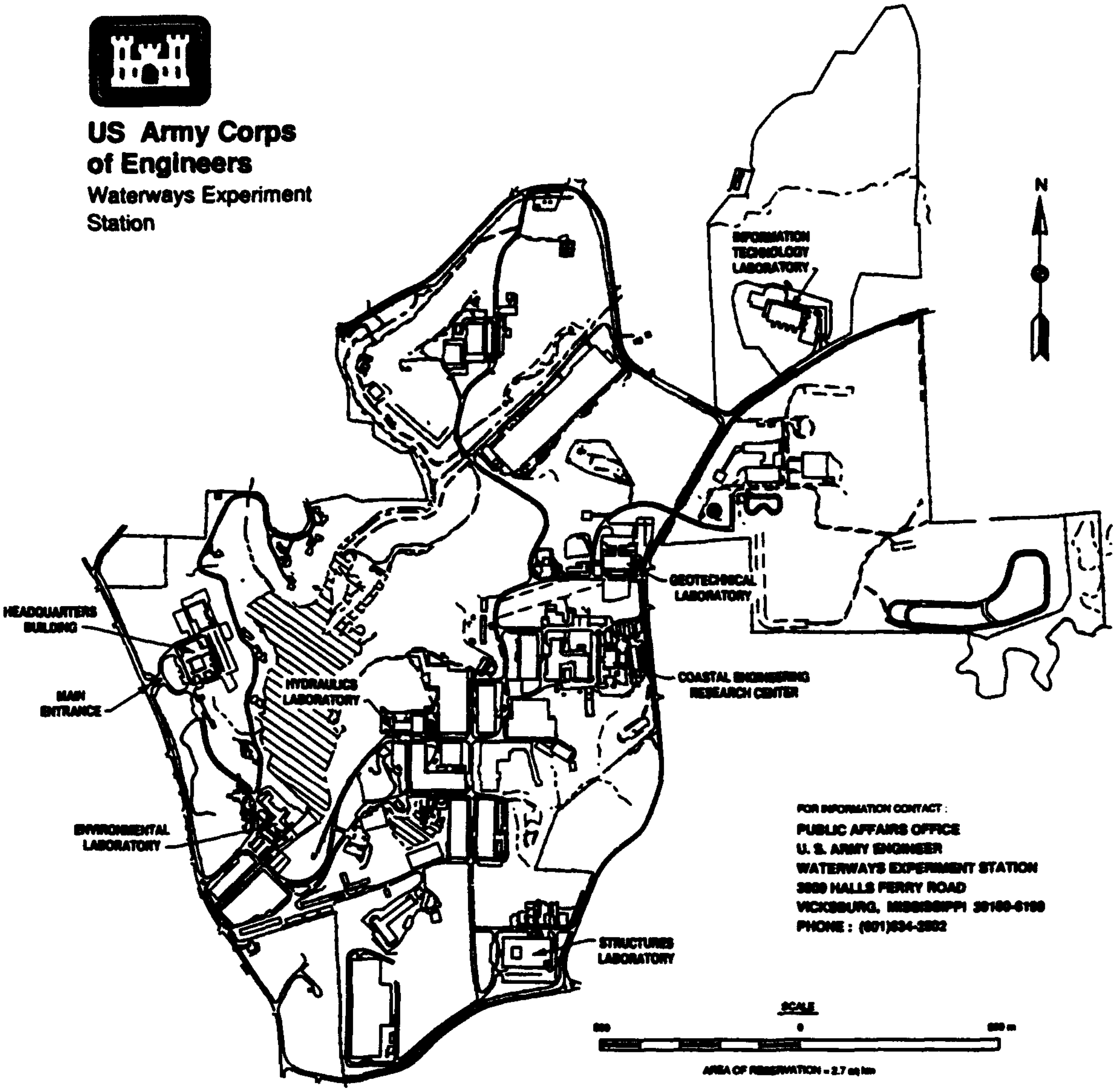

FOR INFORMATION CONTACT:
PUBLIC AFFAIRS OFFICE
U. S. ARMY ENGINEER
WATERWAYS EXPERIMENT STATION
3909 HALLS FERRY ROAD
VICKSBURG, MISSISSIPPI 39180-6199
PHONE: (601)634-2502

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Contents

Preface

The work reported herein was conducted as part of the Water Quality Research Program (WQRP), Work Unit 32694. The WQRP is sponsored by the Headquarters, U.S. Army Corps of Engineers (HQUSACE), and is assigned to the U.S. Army Engineer Waterways Experiment Station (WES) under the purview of the Environmental Laboratory (EL). Funding was provided under Department of the Army Appropriation No. 96X3121, General Investigation. The WQRP is managed under the Environmental Resources Research and Assistance Programs (ERRAP), Mr. J. L. Decell, Manager. Mr. Robert C. Gunkel was Assistant Manager, ERRAP, for the WQRP. Technical Monitors during this study were Mr. Frederick B. Juhle, Mr. Rixie Hardy, and Dr. John Bushman, HQUSACE.

The study was conducted by Ms. Cynthia B. Price of the Ecosystem Processes and Effects Branch (EPEB), EL, WES. Laboratory support in conducting this investigation was provided by Mr. Scott P. Towne of the EPEB. Dr. Carl Cerco of the Water Quality and Contaminant Modeling Branch (WQCMB) and Dr. Douglas Gunnison of the EPEB, EL, assisted with technical review of the study and preparation of the report.

The study was conducted under the direct supervision of Dr. Richard E. Price, Acting Chief, EPEB, and under the general supervision of Mr. Donald L. Robey, Chief, Environmental Processes and Effects Division, EL, and Dr. John Harrison, Director, EL. The report was reviewed by Dr. James Brannon and Dr. Craig Smith, EPEB.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

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1 Introduction

Background

Dissolved oxygen (DO) in the water column of rivers, lakes, and estuaries is an important determinant of water quality. Sediment oxygen demand (SOD) is a key contributor to undesirable low DO levels (Giga and Uchrin 1990). SOD is the rate of oxygen removal from the overlying water column due to the decomposition of settled organic matter. SOD encompasses oxygen consumption through biological activity in sediments and through the chemical oxidation of reduced species, including Fe^{2+}, Mn^{2+}, and S^{2-} (Wang 1981). In addition to DO depletion, degradation of organic matter in the sediment results in the release of nutrients and metals, such as ammonium, phosphorus, nitrogen, iron, and manganese, into the water column. DO depletion may also cause release of toxic substances. Anoxic conditions combined with release of toxic substances can lead to severe water quality problems (Gunnison, Chen, and Brannon 1983).

Understanding SOD and its related processes is necessary to assess the impacts of sediment-water interactions on U.S. Army Corps of Engineers (CE) water resource projects, including reservoirs, navigation projects, and water-control structures. Predicting the effects of CE projects on water quality has been difficult due to the lack of standard methods to accurately measure, quantify, and predict SOD.

Several different measurement techniques for determining SOD are currently being used by various agencies. These include in situ techniques in which an enclosed chamber is installed at the sediment surface and techniques in which sediments are removed to the laboratory for analysis. Both methods have advantages and disadvantages. In situ measurements minimize sediment disturbance. The major disadvantage of this type of system is that the DO level in the water trapped under the chamber declines during measurement making it necessary to periodically aerate the chamber in order to continue to obtain reliable SOD fluxes. Ensuring a good seal to the sediment surface is another difficulty. Laboratory measurements allow for closer control of system variables, such as temperature, water velocity, and light. However, a key disadvantage in laboratory SOD measurements is the necessity for field verification.

Objectives

One objective of this project is to develop a measurement technique for SOD that is easily applicable and requires a minimum of equipment. This has necessitated the development of an integrated, universally applicable CE-wide method to analyze SOD in both freshwater and estuarine systems.

The U.S. Army Engineer Waterways Experiment Station (WES) is currently developing laboratory techniques interactively with model development to measure, evaluate, and predict SOD for CE water resource projects. Initial investigations by the WES consisted of conducting a literature review and hosting a workshop to determine the state of the art of SOD research (Cerco, Gunnison, and Price 1991 and Price 1991). The panel discussion conducted during the workshop focussed on process- and modeling-related issues, interactive laboratory and model development, and the relative significance of SOD processes and optimum representation of such processes in models.

These initial laboratory experiments were conducted to provide a method for measurement of SOD and to evaluate major sources of SOD in a defined system. The studies have also provided a database for investigating an available mechanistic model of SOD and nutrient release. The existing sediment model has been extensively employed in only one system, Chesapeake Bay. Its applicability for a wide range of systems needs to be tested. Comparison of model and laboratory experiments will indicate pathways for improving and modifying both the model and existing laboratory techniques.

2 Materials and Methods

Test tubes and 20-ℓ columns were used to simulate bedded sediments with an overlying water column. The systems were allowed to develop anaerobic conditions naturally. Nutrient release and DO depletion were followed over time. Analytical methods for DO, ammonium-nitrogen, orthophosphate-phosphorus, nitrate-nitrogen, total organic carbon, and total inorganic carbon are presented in Table 1. Initial studies employed test tubes to allow for faster formation of anaerobic conditions due to the small DO capacity of the overlying water column. The replacement of water removed through sampling was also avoided because the test tubes were used as sacrificial samples. The second tube study was initiated to compare the SOD rates of sediments containing different concentrations of organic matter. Tubes were again used to avoid water replacement and to allow for a greater number of samples. Large-scale (20 ℓ) column testing was conducted to allow for lengthy experiments with DO manipulation of the overlying water column. The large water volume of the columns allowed water lost through sampling to be replaced without creating major changes in the water column chemical composition through dilution with makeup water.

Sample Collection

Sediments used in the laboratory studies included Brown's Lake, WES, Vicksburg, MS; Rathbun Lake, Wayne County, IO; Chesapeake Bay, upper bay Station R-64, MD; Eau Galle Reservoir, WI; and the north branch of the Chicago River, IL. Sediments were collected using a ponar grab dredge and were refrigerated in sealed containers at 4°C prior to use. The first sediment investigated, Brown's Lake, was selected because of its availability, known physical characteristics, and use in past studies. The remaining sediments were selected due to their variability in origin and physical characteristics (Table 2).

Table 1
Analytical Methods for Dissolved Oxygen and Nutrient Analysis

Parameter	Method[1]	Instrument
Ammonium-Nitrogen	Phenate Method 4500-NH3 D	Shimadzu UV-160A Spectrophotometer
Orthophosphate-Phosphorus	Ascorbic Acid Method 4500-P E	Shimadzu UV-160A Spectrophotometer
Nitrate-Nitrogen	Cadmium Reduction Method 4500-NO3-	Shimadzu UV-160A Spectrophotometer
Total Organic Carbon	Manufacturer's Suggested Procedure	Shimadzu 5050 TOC Analyzer
Total Inorganic Carbon	Manufacturer's Suggested Procedure	Shimadzu 5050 TOC Analyzer
Dissolved Oxygen	Manufacturer's Suggested Procedure	Orion 880 DO/BOD Meter

[1] Methods were obtained from *Standard Method for the Examination of Water and Wastewater*, 17th ed., 1989.

Table 2
Sediments Used in Test Tube and Column Studies

Sediment	Location	Fraction Solids	%OM[1]	Particle Size		
				%Sand	%Silt	%Clay
Brown's Lake	Mississippi	0.4513	1.82	5	70	25
Rathbun Lake	Iowa	0.6505	2.09	88	8	4
Chesapeake Bay	Maryland	0.7496	2.85	52	38	10
Eau Galle Reservoir	Wisconsin	0.3627	6.62	52.5	40	7.5
Chicago River	Illinois	0.303	6.96	25	17.5	7.5

[1] %OM = Percent Organic Matter.

Test-Tube Studies

Study I

Initial laboratory studies consisted of test tubes simulating a bedded sediment with an overlying water column. Fifty-milliliter glass test tubes were loaded with 10 g of Brown's Lake sediment amended with 1-percent organic matter. Freeze-dried Hydrilla, an available and easilydegradable plant material, was used for all organic matter amendments. The sediment was covered with 40-ml distilled-deionized water, and the tubes were sealed with rubber stoppers. All tubes were incubated at room temperature (23°C). Dissolved oxygen consumption and nutrient release were determined over a 36-day period. Sampling for DO, ammonium-nitrogen, and orthophosphate-phosphorus was conducted on days 0, 1, 3, 7, 11, 31, and 36 of the incubation period. Three separate tubes were sacrificed at each sampling time.

Study II

Tests in Study II were identical to Study I, except samples were also taken for nitrate-nitrogen and total organic carbon (TOC). Additional sets of test tubes containing sediment amended with 1-, 5-, and 10-percent organic matter were used for this study. Sample times also varied; samples were taken on days 0, 1, 2, 6, 11, 16, 23, and 36.

Column Studies

Twenty-liter Plexiglas columns were used to determine SOD and the release of nutrients from bedded sediments to the overlying water. All measures were run in triplicate. Columns were loaded with approximately 15 cm of sediment (3,600 g wet wt.) and overlaid with 102-cm distilled water (15.7 ℓ). The columns were incubated at 25°C in a walk-in environmental chamber. Dissolved oxygen, ammonium-nitrogen, orthophosphate-phosphorus, nitrate-nitrogen, total organic carbon, and total inorganic carbon were measured according to the following schedule. Four samples (60 ml each) were taken the first week, on days 0, 1, 5, and 8. All other samples were collected at 7-day intervals starting on day 8. Duration of experiments varied. In some instances, in order to distinguish aerobic from anaerobic sediment-water exchanges, columns were reaerated during the experiments. Duration of experiments and occurrence of reaeration intervals are summarized in Table 3. Analytical methods were identical to those in the test tube studies.

Table 3
Duration of Column Studies

Sediment Source	Duration, Days	Aerated at Days
Brown's Lake	67	107
Chesapeake Bay	178	49, 132
Chicago River	118	93
Eau Galle Reservoir	118	93
Rathbun Lake	132	42, 99

Two methods were employed to seal the sediment-water systems from the atmosphere. For the Brown's Lake sediments, a 2-cm layer of mineral oil was applied to the water surface to seal the system from atmospheric contact (Figure 1). A plunger was lowered into the water column of each unit and left in place. The plungers were used to thoroughly mix the water columns daily. For the remaining experiments, sealing from atmospheric contact was accomplished using Plexiglas lids (Figure 2). These lids provided an improved seal from the atmosphere. The sealed Plexiglas column covers required a fixed volume of water overlying the sediments. Therefore, water removed during sampling was replaced with nitrogen-sparged distilled water. The overlying water was continuously mixed by means of micro-circulating pumps at a speed of 210 ml/min.

In order to isolate sediment-water exchanges from processes occurring in the water column alone, water samples were collected at each sample interval nd incubated in 60-ml biochemical oxygen demand (BOD) bottles. Samples were incubated for 7-day periods before analysis was conducted for DO, nutrients, and carbon.

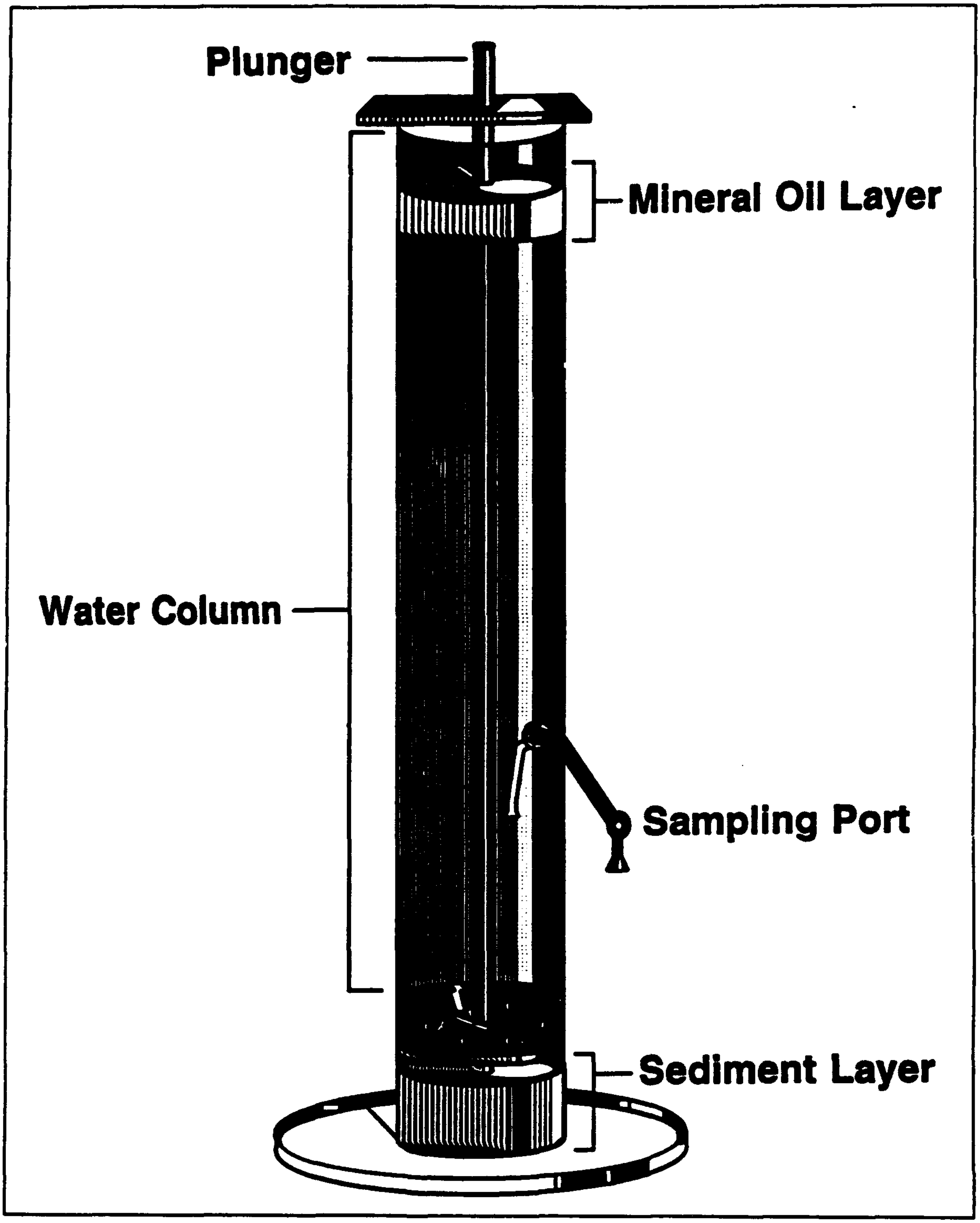

Figure 1. Plexiglas column used to determine SOD and nutrient release from Brown's Lake sediment

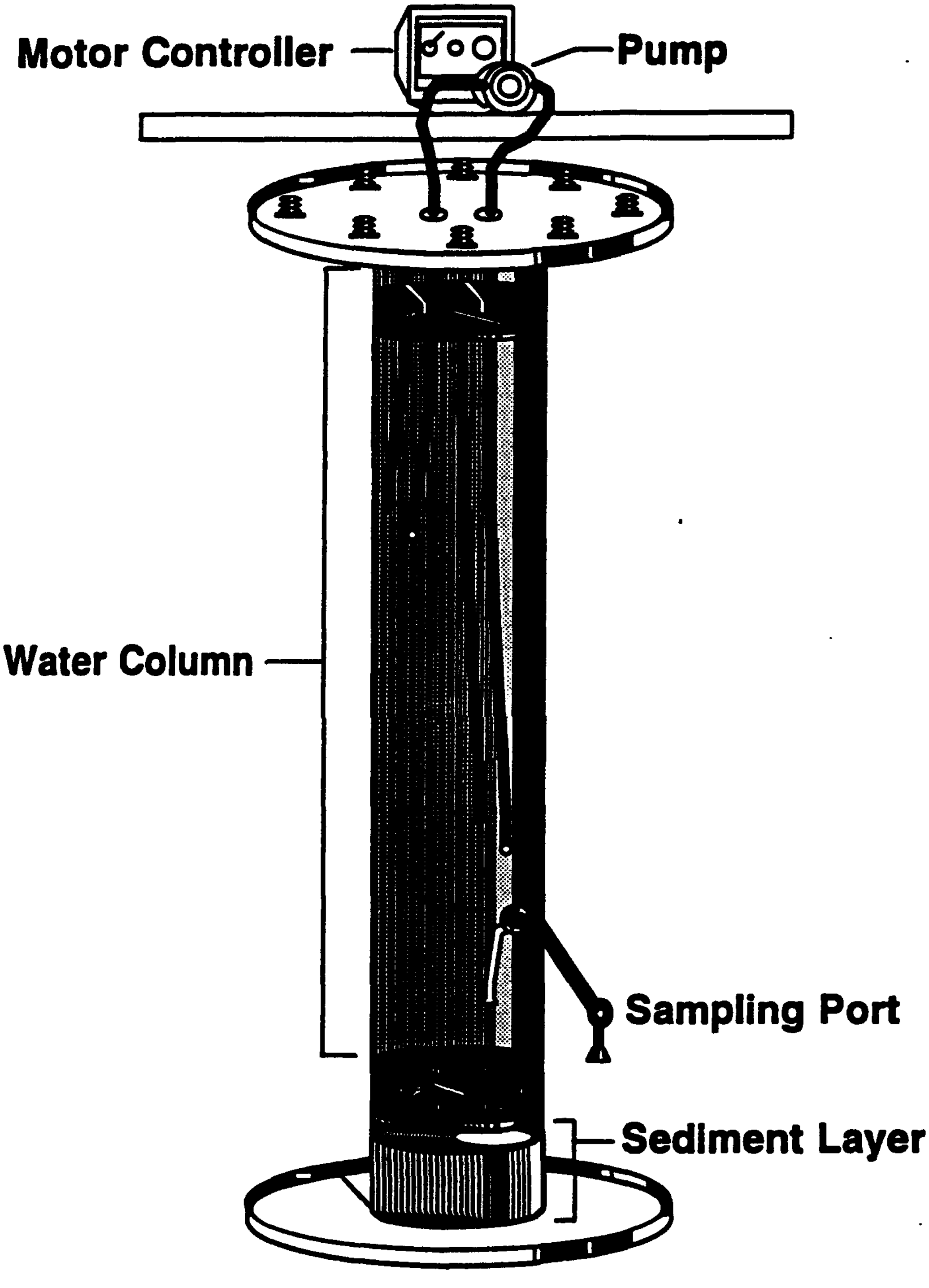

Figure 2. Revised Plexiglas column including sealing lid and pump

Reaeration rate studies were conducted to determine if the columns exchanged DO with the atmosphere. These studies were conducted on columns containing 20 ℓ of distilled water only. The water was sparged with nitrogen to force DO below saturation concentration. Dissolved oxygen was monitored over time. An increase in DO indicated exchange with the atmosphere.

3 Computation of Sediment-Water Fluxes

Test-Tube Measures

Sediment-water exchanges can be measured in numerous fashions. One method, adopted here, is to enclose a fixed volume of sediment and overlying water. Sediment-water exchanges are inferred from concentration changes in the water column. A concentration increase means material moved from sediments to water. A concentration decrease means material moved from water to sediments. An equation based on this principle was employed to quantify sediment-water fluxes in the test-tube studies:

$$Fsw = \frac{V}{A}(C_f - C_i)\Delta t \qquad (1)$$

Fsw = sediment-water flux ($M\ L^2\ T^{-1}$)

V = volume of overlying water (l^3)

A = area of sediment-water interface (L^2)

C_f = concentration in water at end of incubation ($M\ L^{-3}$)

C_i = concentration in water at beginning of incubation ($M\ L^{-3}$)

Δt = length of incubation (T)

Nutrient and Carbon Fluxes in Columns

Flux computation via Equation 1 can be confounded by substance transformations in the water column. For example, nitrification of ammonium to nitrate would influence the computation of sediment-water fluxes of both these nitrogen fractions. In order to correctly compute sediment-water exchange, a "blank" or "control" incubation of water alone must be conducted. Transformations in the water alone are subtracted from transformations in the sediment-water column to isolate sediment-water exchanges. The previously described BOD bottle incubations served as "controls" in these experiments.

The computation of sediment-water fluxes is based on a mass-balance equation that describes the water column:

$$\Delta C_T = \frac{Fsw\,\Delta t}{H} + Tw\,\Delta t \qquad (2)$$

ΔC_T = concentration change in water column ($M\ L^{-3}\ T^{-1}$)

H= depth of water column (L)

Tw= transformation in water column ($M\ L^{-3}\ T^{-1}$)

Equation 2 states that total concentration change in the water is the sum of sediment-water fluxes and water column transformations. Flux from sediment to water is defined as positive. Concentration change and water-column transformations can be expressed in terms of quantities measured in the experiments:

$$C_f - C_i = \frac{F\,\Delta t}{H} + (BOD_f - BOD_i)\,\Delta t \qquad (3)$$

BOD_f = concentration in BOD bottle at end of incubation (g^{-3})

BOD_i = concentration in BOD bottle at beginning of incubation (g^{-3})

In the experiments, initial concentration in the water and BOD bottle were equal. Substituting this equivalence into Equation 3 and solving for flux yields:

$$F = \frac{H}{\Delta t}(C_f - BOD_f) \qquad (4)$$

Sediment Oxygen Demand in Columns

During the incubations, no exchange of nutrients or carbon with the external environment takes place. Some exchange of DO oxygen with the atmosphere is inevitable, however, during lengthy incubations. These exchanges occur when samples are collected or else through leakage. Small exchanges of oxygen are no problem but must be accounted for in the computation of sediment oxygen demand.

Table 4
Reaeration in Oil-Sealed Columns

Day	Dissolved Oxygen, mg/ℓ
0	2.22
1	3.03
2	3.23
3	3.23
6	3.23
7	3.23
9	3.51
14	4.31

Several experiments were conducted to examine and quantify atmospheric oxygen exchange. For the oil-sealed columns, no definitive increase in oxygen occurred when samples were collected (Table 4). Dissolved oxygen did increase over a 14-day incubation, however, indicating diffusion through the oil film or leakage in the apparatus. The oxygen exchange was treated as a reaeration process. The reaeration rate was determined by fitting the data to the equation:

$$D(t) = D_0 e^{-\frac{Kt}{H}} \qquad (5)$$

$D(t)$ = DO deficit at time t (g m^{-3})

D_0 = initial DO deficit (g m^{-3})

K = reaeration rate (m day^{-1})

The reaeration rate for the oil-sealed columns was 0.021 m day^{-1} ($R^2 = 0.82$). The mass-balance equation (Equation 2) was modified to reflect reaeration:

$$C_f - C_i = \frac{F\Delta t}{H} + (BOD_f - BOD_i)\Delta t + \frac{K}{H}(C_{sat} - C_m) \qquad (6)$$

C_{sat} = saturation DO concentration (g m^{-3})

C_m = mean DO during incubation interval (g m^{-3})

Noting the equivalence of initial concentrations in the water column and BOD bottles and solving for flux yields:

$$SOD = \frac{H}{\Delta t}(C_f - BOD_f) - K(C_{sat} - C_m) \tag{7}$$

By convention in this report, negative sediment oxygen demand is transfer of oxygen from water to sediments.

Following the initial set of sediment-water flux measurements, the oil-seal on top of the columns was replaced with a fixed seal. An experiment indicated no atmospheric oxygen seeped into the redesigned columns (Table 5).

Table 5
Reaeration in Completely Sealed Columns

Day	Dissolved Oxygen No Sample Replacement, mg/ℓ	Dissolved Oxygen Sample Replacement, mg/ℓ
0	4.00	3.99
1	4.00	4.13
3	3.98	4.34
7	3.99	4.49

Some oxygen (≈ 0.15 g m^{-3}) was introduced by sample replacement, however. The mass-balance equation was modified to account for the dissolved oxygen introduced by sample replacement:

$$C_f - C_i = \frac{F\Delta t}{H} + (BOD_f - BOD_i)\Delta t + \Delta C_s \tag{8}$$

ΔC_s = dissolved oxygen introduced by sample replacement (g m^{-3})

Noting the equivalence of initial concentrations in the water column and BOD bottles and solving for flux yields:

$$SOD = \frac{H}{\Delta t}(C_f - BOD_f - \Delta C_s) \tag{9}$$

4 Results

Test Tube Study I

Results for these measures are presented in Figure 3 and Table 6. Dissolved oxygen concentrations dropped from 9.0 to 0.20 mg/ℓ in 36 days. Initially, DO declined rapidly and reached a steady state within the first week. The SOD flux ranged from -300 to -3.0 mg/m^2/day. Positive numbers represent DO release from the sediment.

Ammonium-nitrogen levels measured in the overlying water increased over time reaching a peak of 0.048 mg/ℓ at 30 days and leveling off to 0.042 mg/ℓ. Orthophosphate-phosphorus concentrations also increased, measuring 0.165 mg/ℓ in 36 days. A sharp increase in concentration occurred between sample days 31 and 36.

Test Tube Study II

Data for this study are presented in Table 7. Dissolved oxygen concentrations decreased from 8.80 mg/ℓ to 0.29 mg/ℓ during the 36-day test interval (Figure 4). DO depletion levels of the three organic matter treatments did not differ significantly at any time. Sediment oxygen demand ranged from -525 mg/m^2/day at time 0 to -2.0 mg/m^2/day on day 36 (Figure 4). Overlying water nutrient concentrations are presented in Figure 5. Ammonium-nitrogen concentrations increased in all three amendments over time. Initial concentrations in the water measured 0.002 mg/ℓ with final concentrations averaging 0.068 mg/ℓ on day 36. Ammonium concentration data revealed no significant difference between the three treatments. Orthophosphate-phosphorus concentrations increased to 0.140 mg/ℓ on sample day 6 and decreased to an average of 0.066 mg/ℓ by day 36. The different amendments showed no significant effect on phosphorus concentrations. Concentrations of nitrate-nitrogen initially increased to an average of 0.118 mg/ℓ on sample day 6 and decreased to an average of 0.066 mg/ℓ by day 36. The three sample treatments showed no significant difference. Total organic carbon concentrations increased from 0 mg/ℓ to an average of 32.8 mg/ℓ by day 6. Following this, TOC levels began decreasing to an average final concentration of 12.8 mg/ℓ.

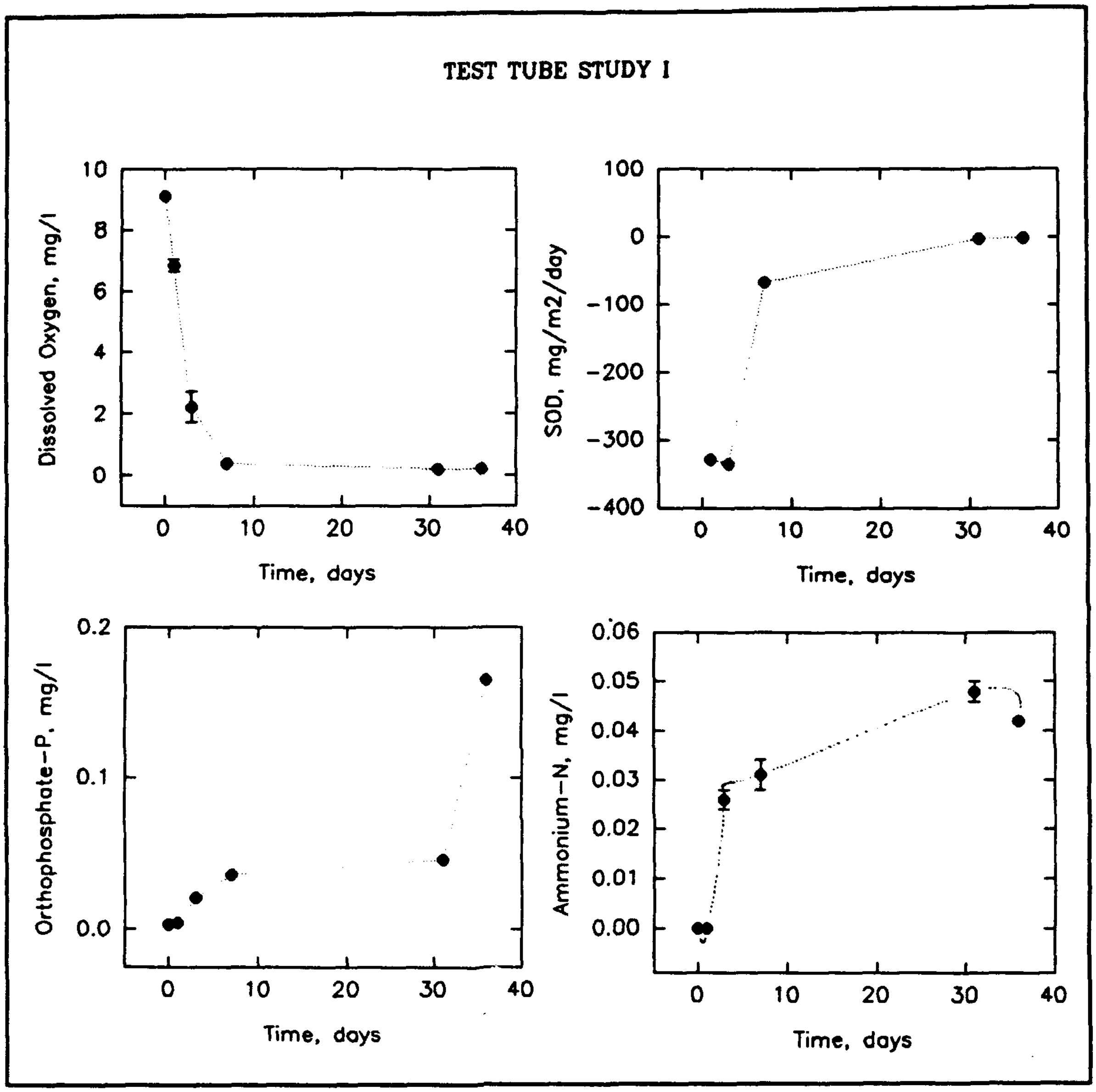

Figure 3. **Dissolved oxygen and nutrient concentrations measured in the overlying water of Brown's Lake sediment**

with the 10-percent organic matter-amended tubes maintaining the highest TOC of 14.5 mg/ℓ on sample day 36.

Brown's Lake Column Study

Dissolved oxygen, nutrient, and carbon concentrations and fluxes are presented in Figures 6 and 7. Sediment-water fluxes are summarized in Table 8. Results are presented separately for DO greater than 2 g m^{-3} and less

Table 6
Dissolved Oxygen and Nutrient Concentrations[1] Measured in the Overlying Water of Test Tube Study I

Sample Date	DO	DO Flux	Ammonium Nitrogen	Ammonium Nitrogen Flux	Orthophosphate Phosphorus	Orthophosphate Phosphorus Flux
0	9.12		0.001		0.003	
1	6.85	-328.52	0.0003	-0.096	0.004	0.096
3	2.22	-334.54	0.026	1.85	0.021	1.27
7	0.37	-66.84	0.031	0.169	0.036	0.53
11	0.46	3.25	0.023	-0.289	0.012	-0.867
31	0.21	-1.78	0.048	0.185	0.046	0.246
36	0.2	-0.29	0.042	-0.193	0.036	-0.289
50	0.63	4.44	0.026	-0.158	0.165	1.33

[1] All concentrations are in mg/ℓ

than 2 g m^{-3}. The separation allows for the influence that DO exerts on sediment-water fluxes. Concentrations and fluxes are listed completely in Appendix A. Dissolved oxygen concentrations decreased from initial levels of 9.15 mg/ℓ to 0.60 mg/ℓ in 50 days. An initial rapid decrease in DO occurred up to day 7; this was followed by a slower decline over the duration of the study. Ammonium-nitrogen concentrations increased from 0.002 at time 0 to 0.024 mg/ℓ by day 7, then fell back to <0.01 mg/ℓ. Orthophosphate-phosphorus increased to 0.45 mg/ℓ on day 19 and began to decline, reaching 0.029 mg/ℓ by day 50. Nitrate-nitrogen rose to 0.228 mg/ℓ on day 12, then decreased to 0.007 mg/ℓ, and remained relatively stable for the remainder of the study period. Total organic carbon measurements fluctuated, reaching a peak of 11.7 mg/ℓ by day 19 decreasing to 1.77 mg/ℓ by sample day 50. Total organic carbon levels fluctuated around a level of 8 mg/ℓ for the first 35 days of incubation, then fell off after time.

Rathbun Lake Column Study

Dissolved oxygen, nutrient, and carbon concentrations and fluxes are presented in Figures 8 and 9. Sediment-water fluxes are summarized in Table 9. Results are presented separately for DO greater than 2 g m^{-3} and less than 2 g m^{-3}. Concentrations and fluxes are listed completely in Appendix A. During three successive aerobic/anaerobic cycles, DO concentrations consistently exhibited initial rapid declines in the first 7 days after aeration. All DO levels fell to an average of 0.50 mg/ℓ at the end of each cycle. Ammonium-nitrogen levels increased over the course of each cycle and peaked

Table 7
Dissolved Oxygen and Nutrient Concentrations[1] Measured in the Overlying Water of Test Tube Study II

Sample Day	Organic Matter Amendment	DO	DO Flux	Ammonium Nitrogen	Ammonium Nitrogen Flux	Orthophosphate Phosphorus	Orthophosphate Phosphorus Flux	Nitrate Nitrogen	Nitrate Nitrogen Flux	TOC	TOC Flux
0	1%	8.81		0.002		0.002		0.005		0	
	5%	8.75		0.002		0.002		0.006		0	
	10%	8.79		0.002		0.002		0.005		0	
1	1%	7.06	-252	0.04	5.49	0.099	13.9	0.044	2.75	1.082	156.4
	5%	6.76	-296	0.034	4.67	0.093	13.1	0.042	2.41	1.14	164.7
	10%	6.75	-298	0.004	0.38	0.069	9.68	0.039	2.02	1.81	261.1
2	1%	3.51	-513	0.048	1.25	0.056	- 6.17	0.101	8.19	4.71	524.4
	5%	3.95	-406	0.05	2.36	0.066	- 3.85	0.131	13	11.81	1541.9
	10%	3.93	-407	0.043	5.64	0.141	10.4	0.121	11.9	11.45	1393.5
6	1%	1.78	- 62.7	0.029	-0.71	0.146	3.25	0.016	- 3.06	28.6	862.9
	5%	1.88	- 75	0.021	-1.06	0.132	2.38	0.04	- 3.31	36.85	904.5
	10%	1.62	- 83.6	0.042	-0.05	0.143	0.06	0.053	- 2.48	33.11	782.6

(Continued)

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[1] All concentrations are in mg/ℓ.

Table 7 (Concluded)

Sample Day	Organic Matter Amendment	DO	DO Flux	Ammonium Nitrogen	Ammonium Nitrogen Flux	Orthophosphate Phosphorus	Orthophosphate Phosphorus Flux	Nitrate Nitrogen	Nitrate Nitrogen Flux	TOC	TOC Flux
11	1%	1.12	-19	0.029	0	0.023	-3.56	0.025	0.25	17.45	-322.1
	5%	1.18	- 20.2	0.031	0.29	0.02	-3.24	0.023	-0.47	17.79	-550.8
	10%	1.02	- 17.2	0.024	-0.52	0.024	-3.42	0.019	-0.97	23.21	-286.1
16	1%	0.72	- 11.7	0.049	0.6	0.041	0.53	0.046	0.61	10.66	- 196.2
	5%	0.71	- 13.7	0.053	0.63	0.049	0.85	0.046	0.66	13.19	- 132.9
	10%	0.57	- 13.2	0.054	0.88	0.058	0.97	0.047	0.8	14.46	- 253
23	1%	0.55	- 3.37	0.061	0.25	0.051	0.21	0.037	- 0.18	--[1]	--
	5%	0.65	- 1.1	0.056	0.07	0.055	0.12	0.046	- 0.007	--	--
	10%	0.47	- 1.93	0.052	-0.05	0.053	- 0.1	0.045	- 0.028	--	--
36	1%	0.34	- 2.33	0.061	0.004	0.054	0.03	0.034	- 0.026	--	--
	5%	0.33	- 3.52	0.073	0.19	0.065	0.11	0.041	- 0.048	--	--
	10%	0.18	- 3.19	0.071	0.21	0.078	0.27	0.049	0.041	--	--

[1] No data were obtained on these days.

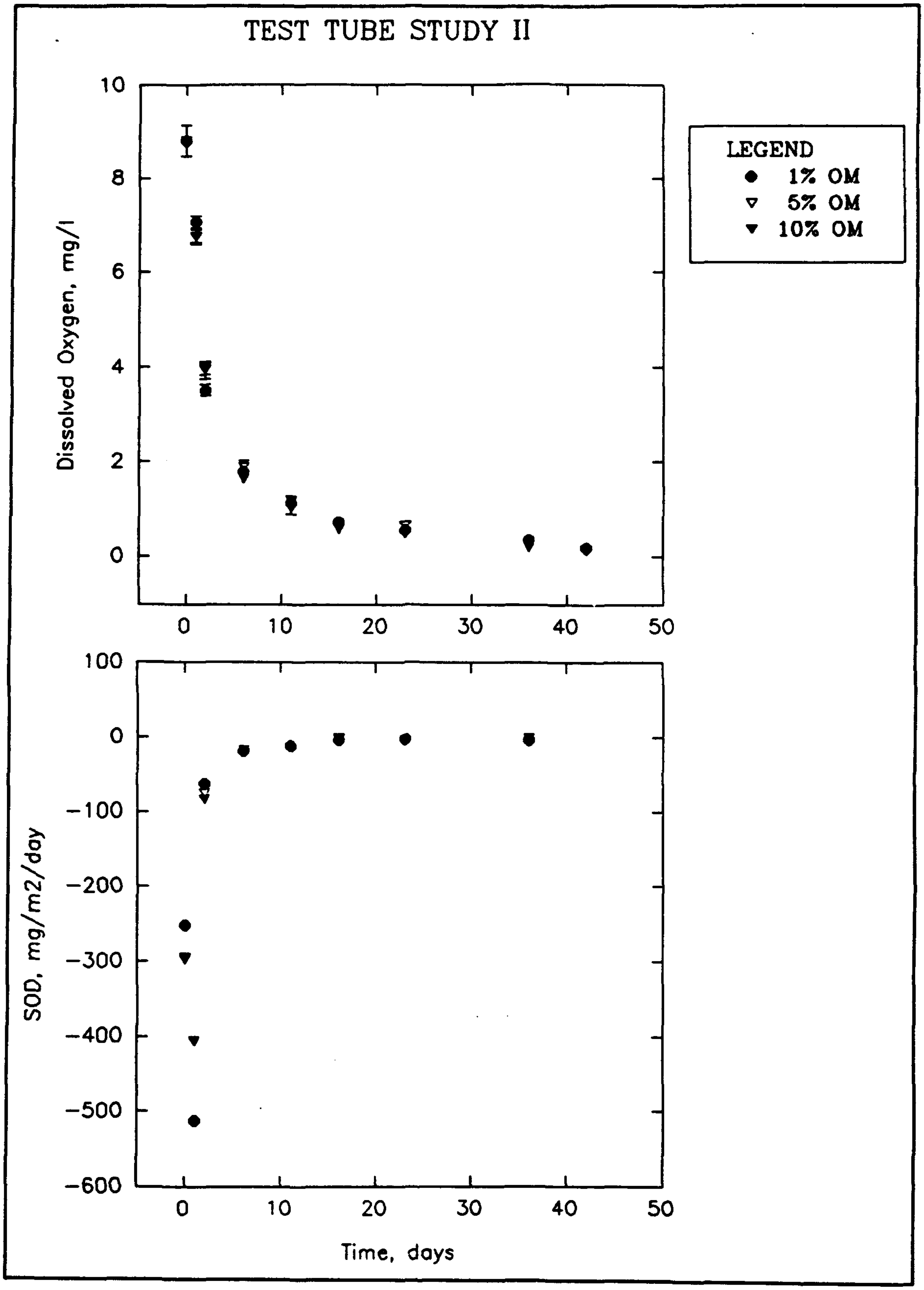

Figure 4. Dissolved oxygen concentrations and SOD calculated for Brown's Lake sediment

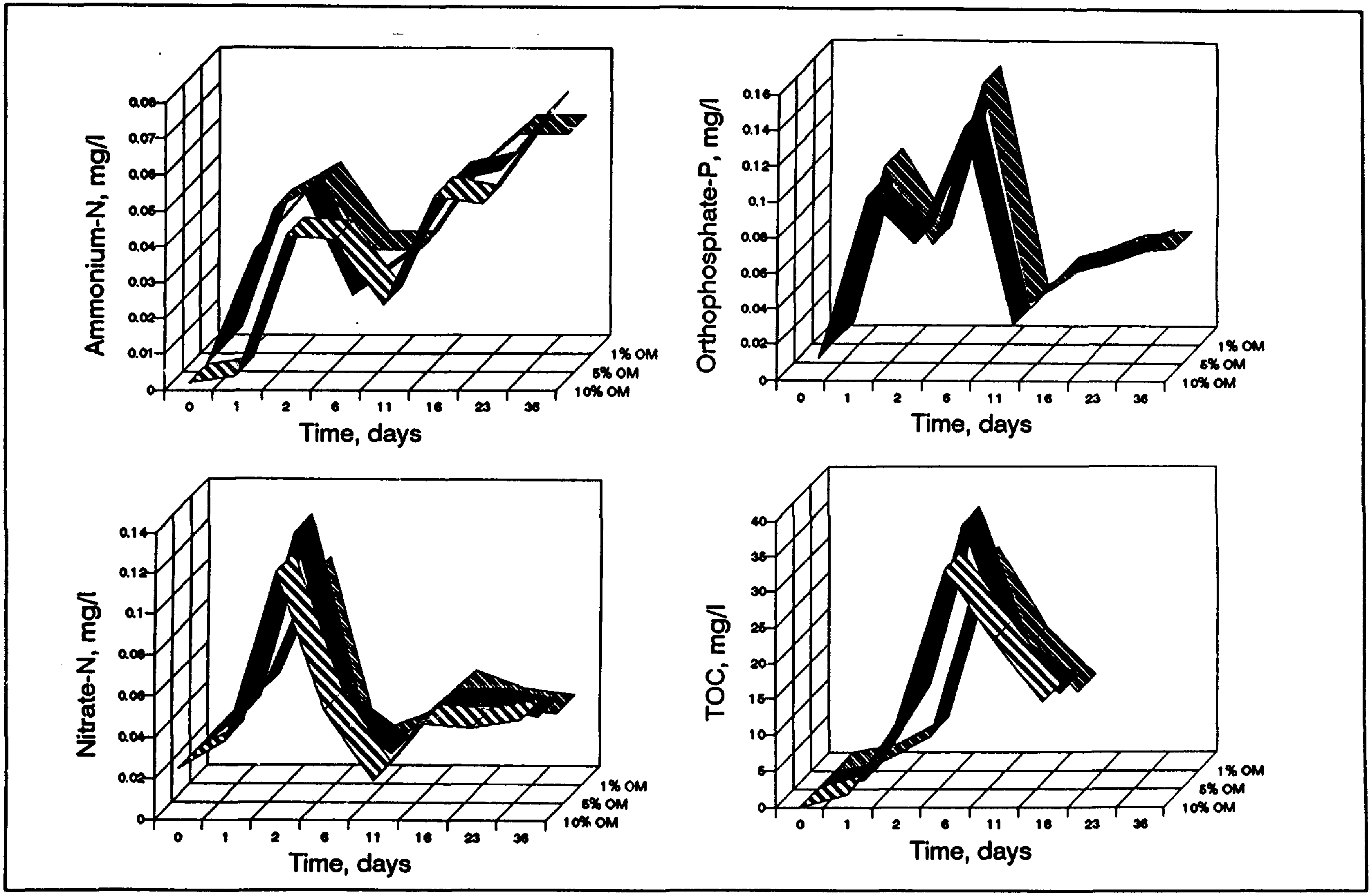

Figure 5. Nutrient and TOC concentrations measured in the water of the Brown's Lake test tube study with organic matter amendments

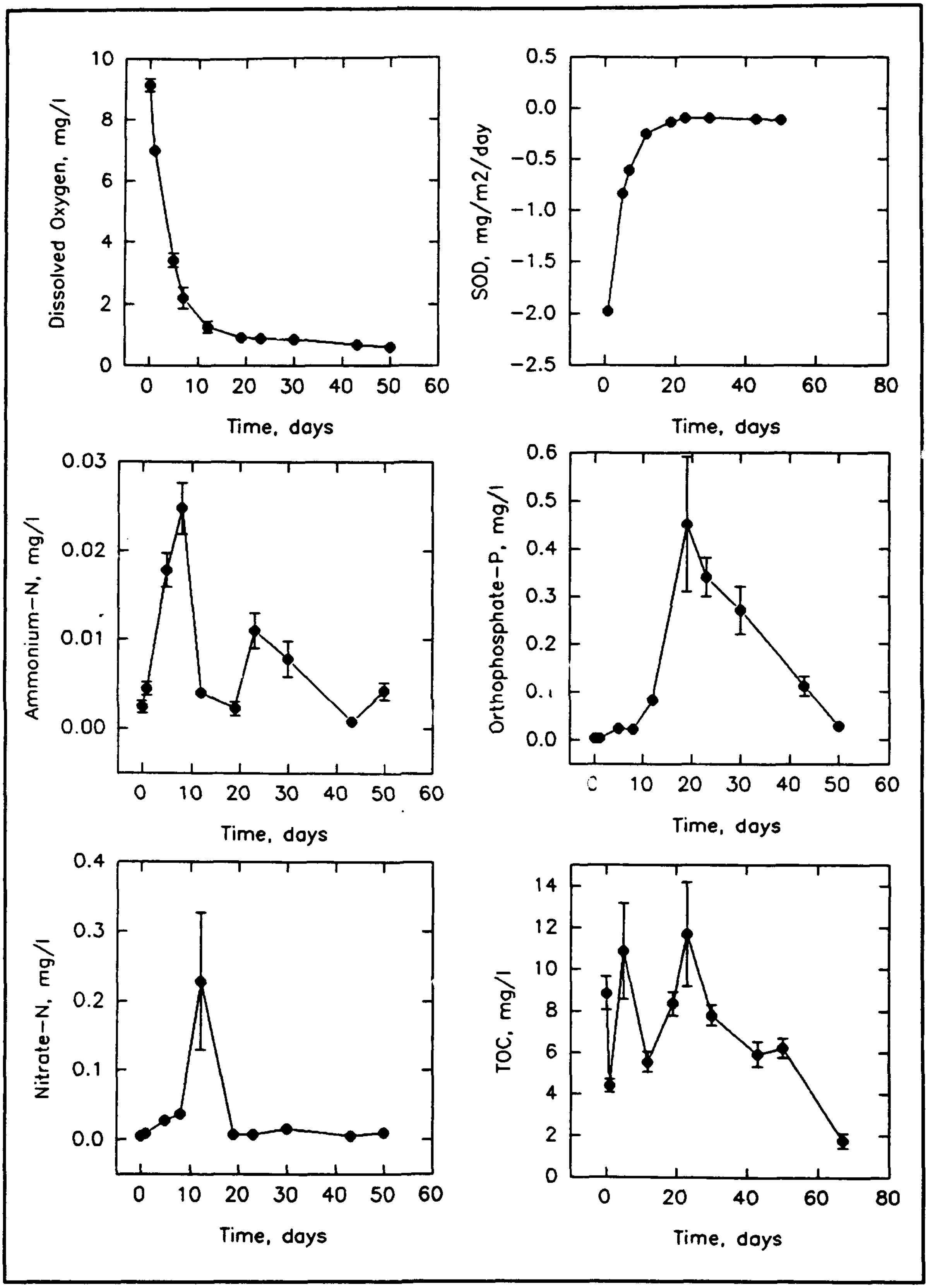

Figure 6. Dissolved Oxygen measured and SOD flux calculated in Brown's Lake anaerobic column study

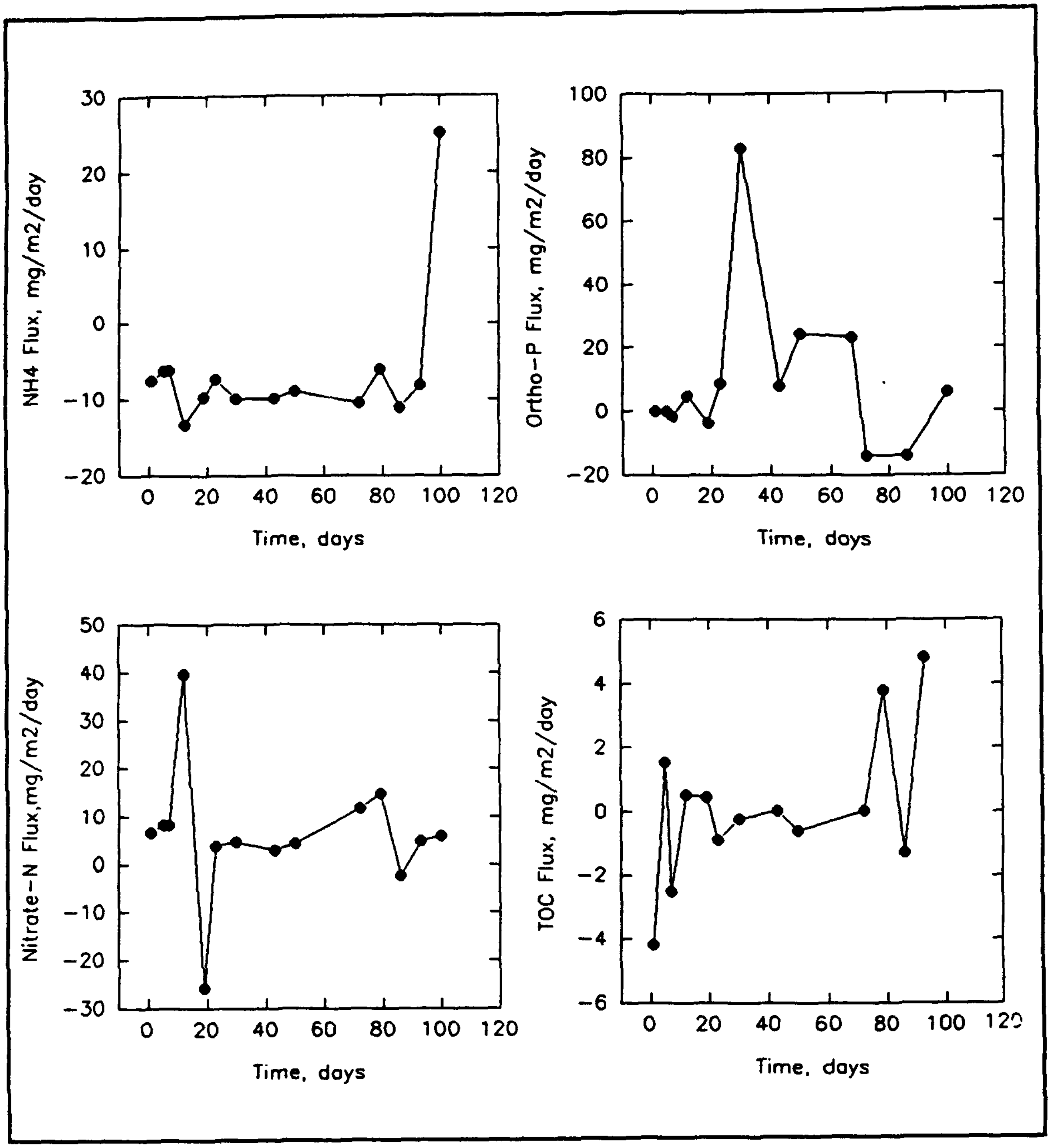

Figure 7. Nutrient fluxes calculated in Brown's Lake anaerobic column

approximately 30 days after reaeration. Concentrations reached peaks of 0.040, 0.066, and 0.047 mg/ℓ in each cycle, respectively. Orthophosphate-phosphorus concentrations increased in each cycle and reached steady state after approximately 30 days into each run. Peak concentrations were 0.040, 0.066, and 0.041 mg/ℓ in cycles I through III, respectively. Concentrations of nitrate-nitrogen initially increased after loading and reaeration, followed by rapid declines in the first and second cycles. No data were obtained for nitrate during the third cycle. Total organic carbon levels exhibited an initial rapid

Table 8
Brown's Lake Sediment-Water Fluxes[1]

Substance	DO mg/ℓ	Number of Measures	Flux mg/m^2/day	Standard Error mg/m^2/day
Sediment Oxygen Demand	≥ 2	4	-1120	299
	< 2	11	- 329	205
Ammonium	≥ 2	4	-7.57	1.00
	< 2	11	7.34	3.49
Nitrate	≥ 2	4	8.71	1.10
	< 2	11	4.77	4.61
Phosphate	≥ 2	4	-4.39	3.43
	< 2	11	21.3	11.3
Total Organic Carbon	≥ 2	4	-1284	1275
	< 2	9	725	707
Total Inorganic Carbon	≥ 2	2	1405	1208
	< 2	0		

[1] Positive fluxes are from sediment to water.

increase followed by a sharp decrease in the first cycle after loading. Concentrations averaged 9.06 mg/ℓ at day 1 and fell to 0.998 mg/ℓ by day 40. Total organic carbon levels remained low for the remainder of the study. Total inorganic carbon level followed the same trends as the TOC except for a rapid high peak in the first few days of cycle II.

Chesapeake Bay Column Study

Dissolved oxygen, nutrient, and carbon concentrations and fluxes are presented in Figures 10 and 11. Sediment-water fluxes are summarized in Table 10. Results are presented separately for DO greater than 2 g m^{-3} and less than 2 g m^{-3}. Concentrations and fluxes are listed completely in Appendix A. Dissolved oxygen levels followed the same trends as in the previous tube and column studies. Concentrations decreased from 7.84 mg/ℓ to an average of 0.01 mg/ℓ over a 42-day period. Ammonium-nitrogen levels initially increased followed by a decline to steady state in approximately 30 days as in the previous column studies. Ammonium levels reached a peak of 0.055 mg/ℓ. Orthophosphate-phosphorus levels exhibited the same trend, reaching a peak 0.053 mg/ℓ at day 14. Concentrations of nitrate-nitrogen rapidly increased and began to sharply decline within 2 weeks after initiation of testing. Total organic and inorganic carbon concentrations exhibited

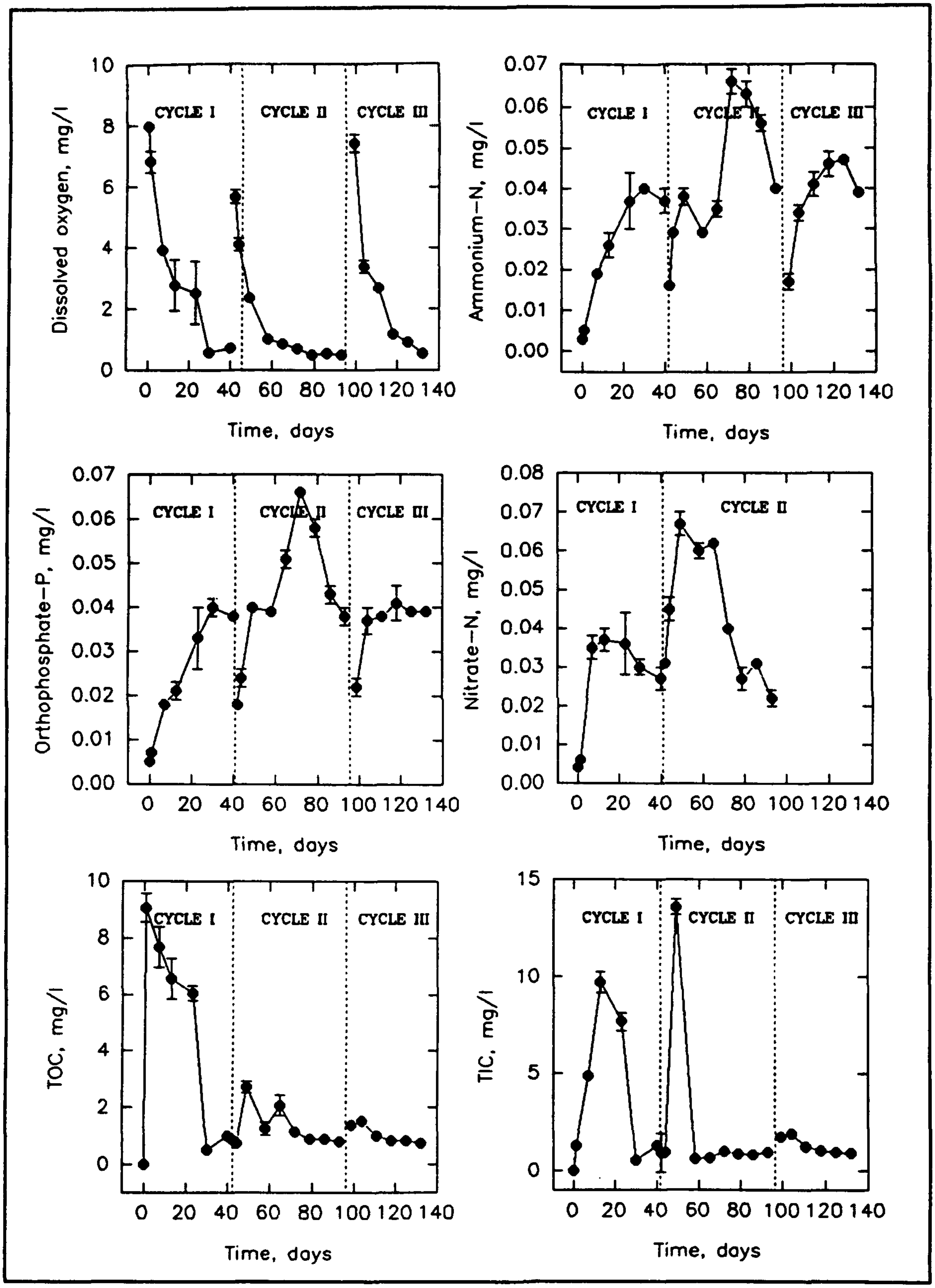

Figure 8. Dissolved oxygen and nutrient concentrations measured in the overlying water of the Rathbun Lake aerobic/anaerobic column study

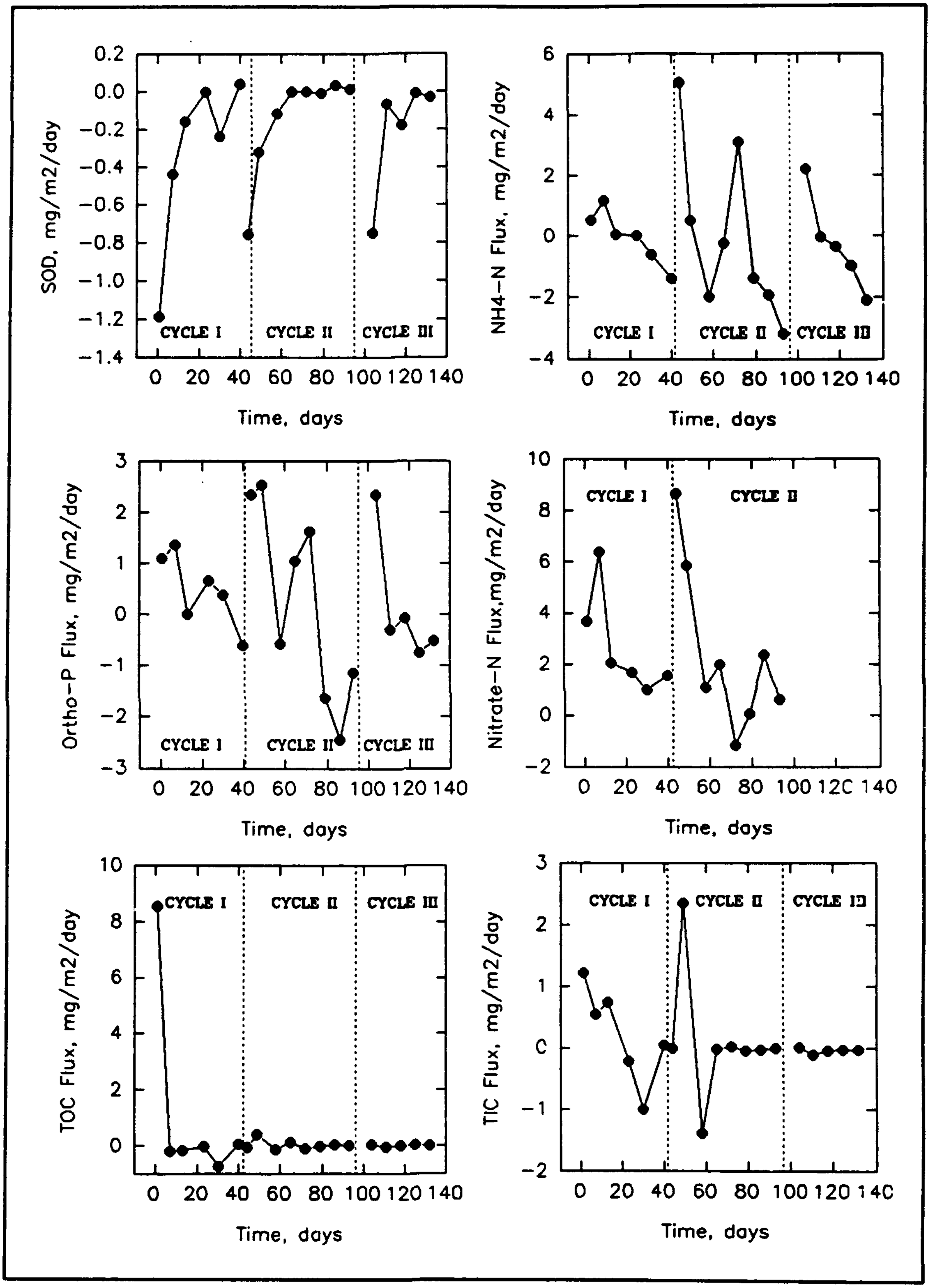

Figure 9. Sediment oxygen demand and nutrient fluxes calculated in Rathbun Lake aerobic/anaerobic column study

Table 9
Rathbun Lake Sediment-Water Fluxes[1]

Substance	DO mg/ℓ	Number of Measurements	Flux (mg/m^2/day)	Standard Error (mg/m^2/day)
Sediment Oxygen Demand	≥ 2	8	-460	145
	< 2	11	- 46	28
Ammonium	≥ 2	8	1.2	0.62
	< 2	11	- 1.0	0.49
Nitrate	≥ 2	8	4.36	0.86
	< 2	11	1.36	0.36
Phosphate	≥ 2	8	1.26	0.39
	< 2	11	- 0.42	0.35
Total Organic Carbon	≥ 2	8	1060	1070
	< 2	11	- 69	69
Total Inorganic Carbon	≥ 2	8	564	309
	< 2	11	-227	145

[1] Positive fluxes are from sediment to water.

identical trends with initial rapid increases followed by slower decreases in concentration.

Eau Galle Reservoir Column Study

Dissolved oxygen, nutrient, and carbon concentrations and fluxes are presented in Figures 12 and 13. Sediment-water fluxes are summarized in Table 11. Results are presented separately for DO greater than 2 g m^{-3} and less than 2 g m^{-3}. Concentrations and fluxes are listed completely in Appendix A. Dissolved oxygen concentrations decreased from 8.00 to 0.03 mg/ℓ over an 86-day period. Ammonium-nitrogen levels exhibited similar trends to the previous sediments. Concentrations reached a steady state of 0.050 mg/ℓ in 2 months, then declined after day 80. Phosphate concentrations also remained at high levels for 60 days and then began to decline. Total organic carbon levels initially increased and then dropped, fluctuating around 0.050 mg/ℓ after 30 days. Total inorganic carbon concentrations rapidly increased after day 0, and then began a slow decline to 2.45 mg/ℓ by the end of the study.

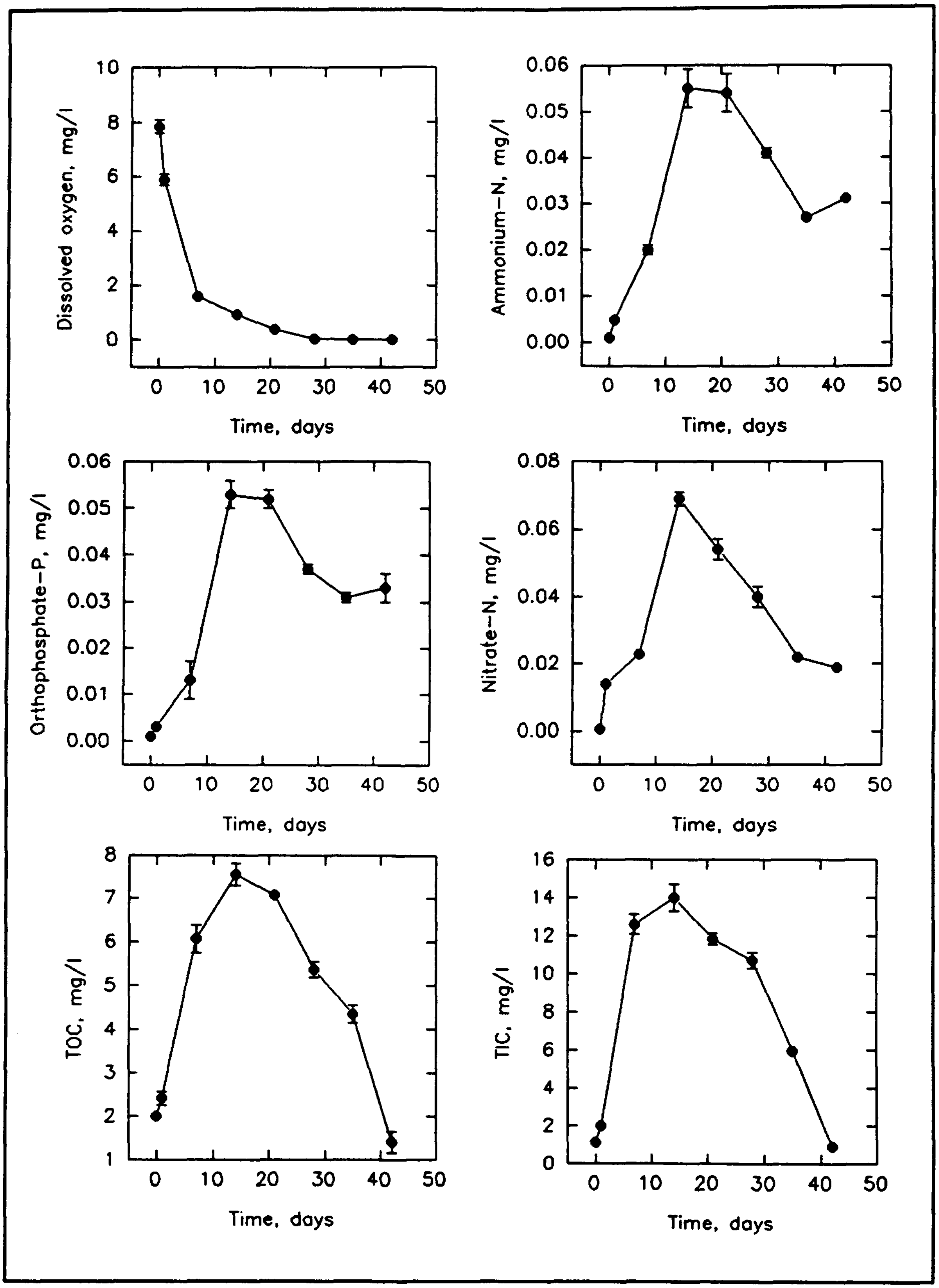

Figure 10. Dissolved oxygen and nutrient concentrations obtained in the overlying water of the Chesapeake Bay column study

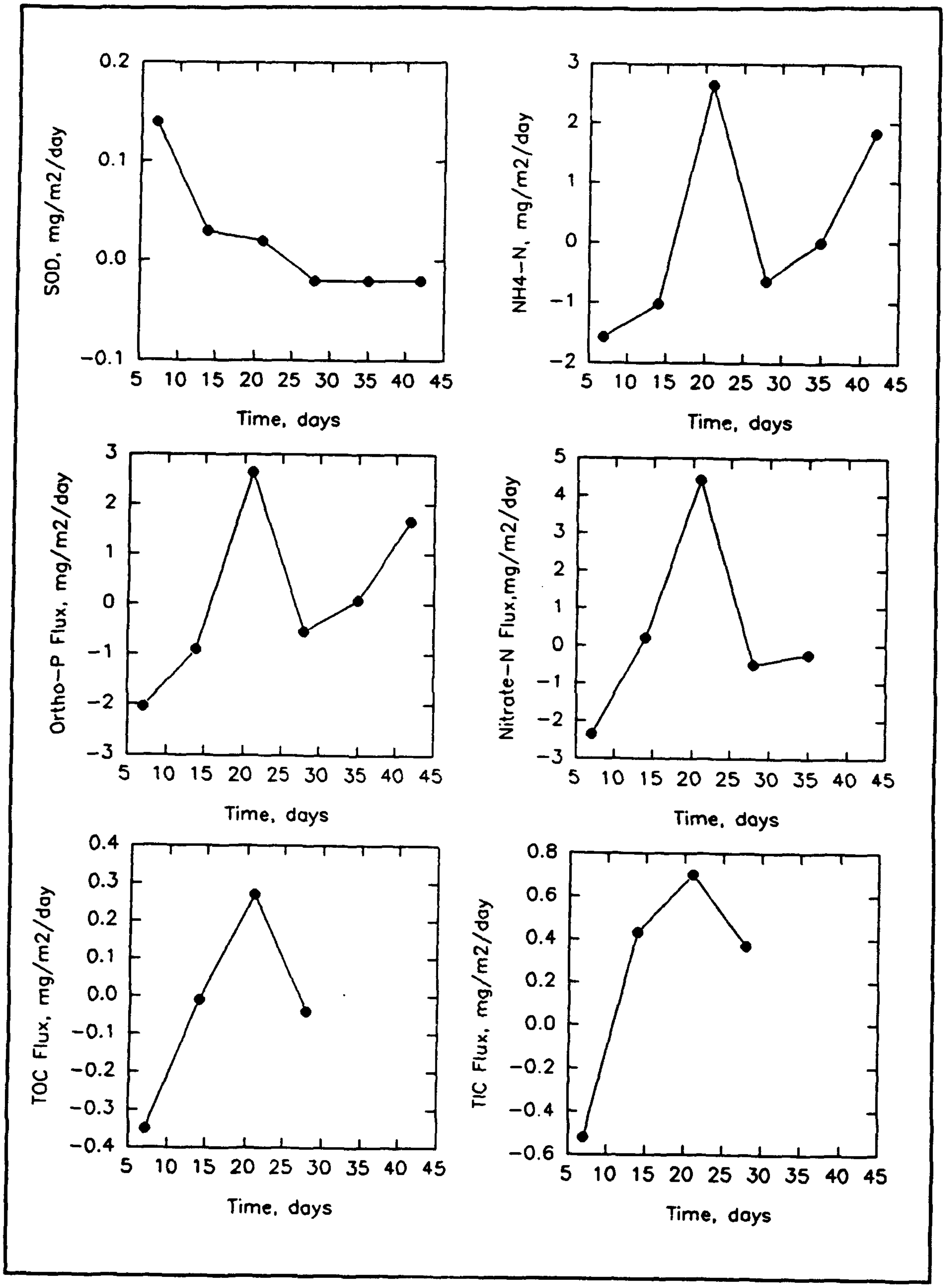

Figure 11. Sediment oxygen demand and nutrient fluxes calculated for the Chesapeake Bay column study

Table 10
Chesapeake Bay Sediment-Water Fluxes[1]

Substance	DO mg/ℓ	Number of Measures	Flux mg/m²/day	Standard Error mg/m²/day
Sediment Oxygen Demand	≥ 2	4	275	182
	< 2	14	-9	16
Ammonium	≥ 2	4	-0.34	1.18
	< 2	14	0.16	0.31
Nitrate	≥ 2	0		
	< 2	5	0.32	1.12
Phosphate	≥ 2	4	-0.55	0.94
	< 2	14	-0.09	0.30
Total Organic Carbon	≥ 2	4	30	35
	< 2	11	-32	49
Total Inorganic Carbon	≥ 2	4	101	295
	< 2	11	77	96

[1] Positive fluxes are from sediment to water.

Chicago River Column Study

Dissolved oxygen, nutrient, and carbon concentrations and fluxes are presented in Figures 14 and 15. Sediment-water fluxes are summarized in Table 12. Results are presented separately for DO greater than 2 g m^{-3} and less than 2 g m^{-3}. Concentrations and fluxes are listed completely in Appendix A. Chicago DO and nutrient concentrations exhibited very similar behavior to those of the Eau Galle study. Dissolved oxygen levels decreased to an average of 0.04 mg/ℓ in 86 days. Ammonium-nitrogen concentrations reached a steady state of 0.057 mg/ℓ in 40 days, then declined after 80 days. Orthophosphate increased over 80 days and then declined. Total organic carbon concentrations initially increased and declined to an average of 0.060 mg/ℓ in approximately 30 days. Total inorganic carbon levels increased to 6.37 mg/ℓ and then slowly declined to 3.2 at the end of the study.

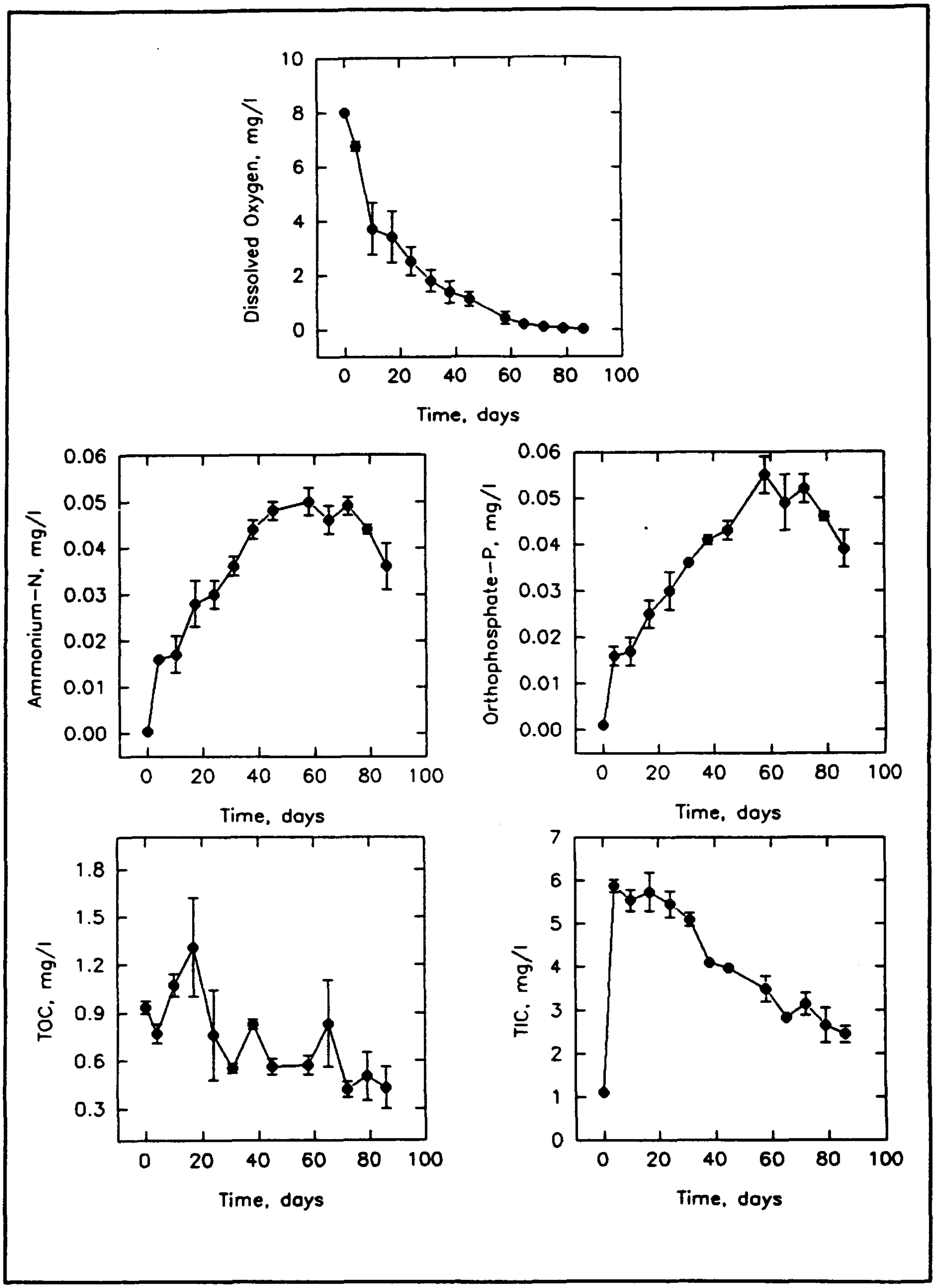

Figure 12. Dissolved oxygen and nutrient concentrations measured in the overlying water of the Eau Galle Reservoir column study

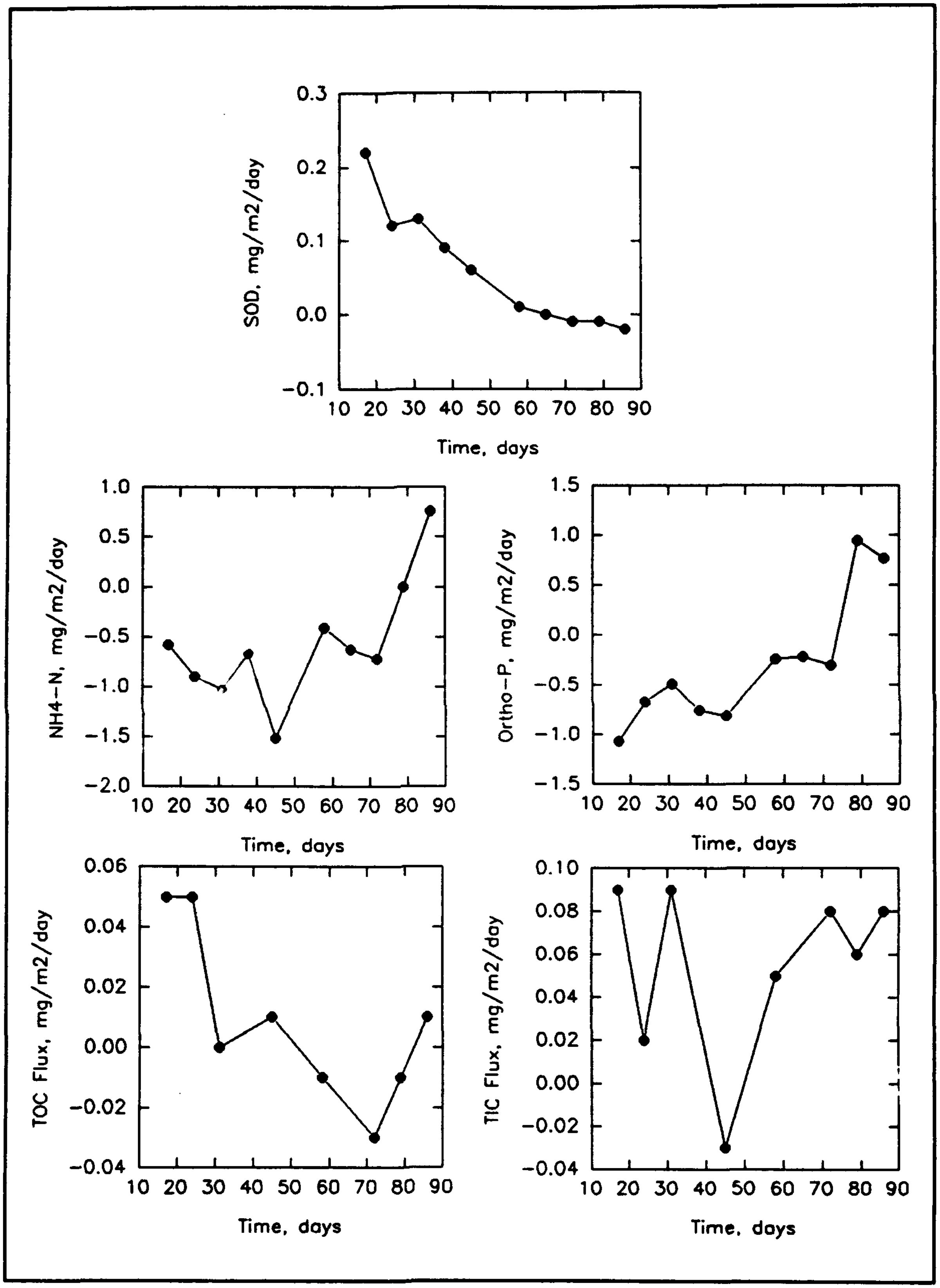

Figure 13. Sediment oxygen demand and nutrient fluxes calculated for the Eau Galle Reservoir column study

Table 11
Eau Galle Reservoir Sediment-Water Fluxes[1]

Substance	DO mg/ℓ	Number of Measures	Flux $mg/m^2/day$	Standard Error $mg/m^2/day$
Sediment Oxygen Demand	≥ 2	2	169	53
	< 2	8	32	19
Ammonium	≥ 2	2	-0.74	0.16
	< 2	8	-0.53	0.24
Nitrate	≥ 2	0		
	< 2	0		
Phosphate	≥ 2	2	-0.87	0.20
	< 2	8	-0.14	0.23
Total Organic Carbon	≥ 2	2	52	2
	< 2	6	6	7
Total Inorganic Carbon	≥ 2	2	59	35
	< 2	6	53	18

[1] Positive fluxes are from sediment to water.

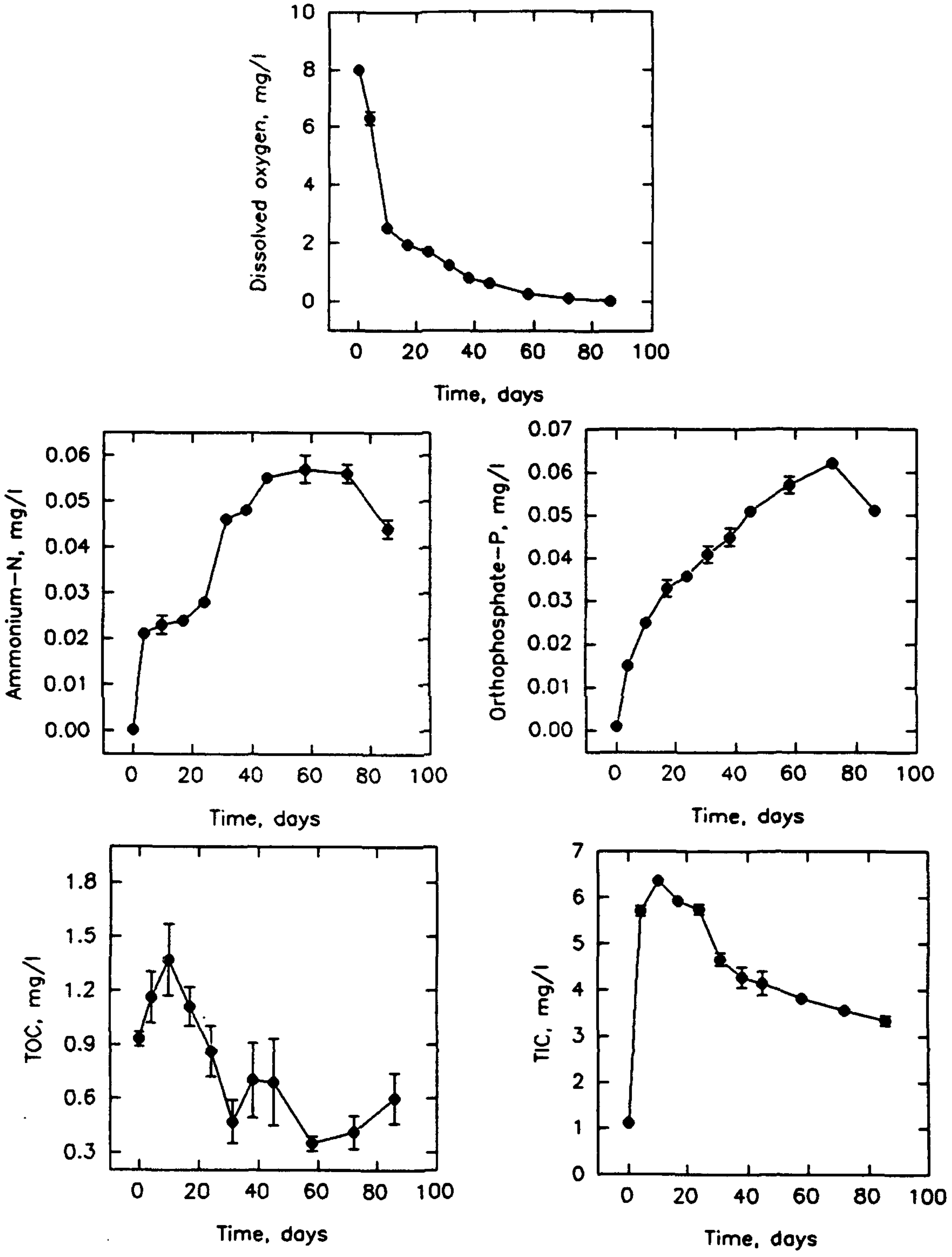

Figure 14. **Dissolved oxygen and nutrient concentrations measured in the overlying water of the Chicago River column study**

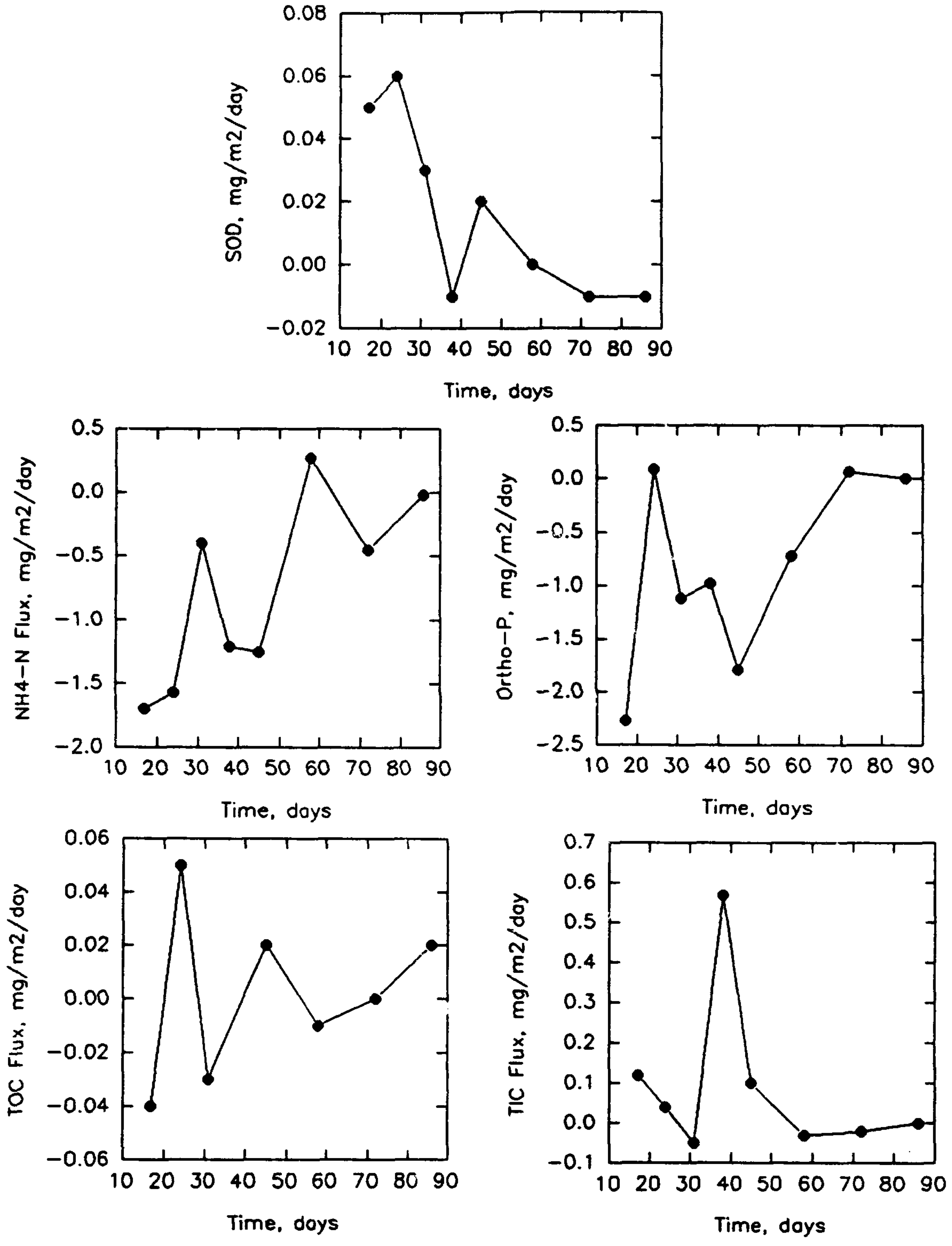

Figure 15. **Sediment oxygen demand and nutrient fluxes calculated for the Chicago River column study**

Table 12
Chicago River Sediment-Water Fluxes[1]

Substance	DO mg/ℓ	Number of Measures	Flux mg/m^2/day	Standard Error mg/m^2/day
Sediment Oxygen Demand	≥ 2	0		
	< 2	8	17	10
Ammonium	≥ 2	0		
	< 2	8	- 0.79	0.26
Nitrate	≥ 2	0		
	< 2	0		
Phosphate	≥ 2	0		
	< 2	8	- 0.84	0.31
Total Organic Carbon	≥ 2	0		
	< 2	7	0	12
Total Inorganic Carbon	≥ 2	0		
	< 2	8	91	72

[1] Positive fluxes are from sediment to water.

5 Discussion

Test Tube Study I

Dissolved oxygen concentrations in this study showed a decrease in the rate of DO depletion once oxygen levels fell below 2 mg/ℓ. Similar findings were reported by Wang (1981), who observed sharp initial decreases of residual oxygen, followed by a tendency to taper off after levels fell below 2 mg/ℓ.

Ammonium will diffuse to the surface of a sediment, and if oxygen is present, will be nitrified to nitrate. Ammonium-nitrogen levels in the test increased over time and leveled off after day 15. If a system is anaerobic, nitrification does not occur and ammonium accumulates in the water column (Klapwijk and Snodgrass 1986). Ammonium releases to the water column may have leveled off due to limitations in the organic nitrogen levels in the sediment. In anaerobic systems, microbial activity may result in direct mobilization of inorganic phosphorus through the degradation of organic matter or through dissolution of phosphate-adsorbing iron oxyhydroxides (Ryding 1985). The sharp increase in orthophosphate concentrations by day 36 of the sample interval may have resulted from these processes. At this time, DO levels in the water column were essentially 0.

Test Tube Study II

No significant differences were observed in DO depletion or nutrient release among the three organic matter treatment levels. These results suggest that the rate of oxygen supply to the sediment limited the utilization of these substrates. Dissolved oxygen depletion rates exhibited the same behavior as in Study I. The SOD rate mirrored the dissolved oxygen depletion rate. Dissolved oxygen concentrations in water overlying sediments can be considered a factor affecting SOD rates; as the DO concentration decreases, so does the SOD rate (Hicks 1990).

Ammonium-nitrogen levels increased in all amendments, but did not level off as in Study I. This may be a result of the addition of a source of organic matter which allowed for a prolonged period of mineralization of organic-nitrogen to ammonium. Differences among treatments were not significant.

Phosphorus release can be promoted in anaerobic bottom waters due to the microbially mediated reduction of Fe^{3+} to Fe^{2+}, and dissolution of the phosphate-adsorbing ferric oxyhydroxide (Ryding 1985). Orthophosphate-phosphorus concentrations initially increased and then decreased in all three amendments. The decline in phosphorus concentrations may be a result of phosphate interacting with Al^{3+} or Ca^{2+} to form insoluble precipitates. Alternatively, phosphate may be sorbed to colloidal oxides, hydroxides, and carbonates (Ryding 1985).

Nitrate-nitrogen concentrations increased as initial releases of ammonium were nitrified. Nitrate levels decreased markedly when DO concentrations reached approximately 1 mg/ℓ. Nitrate did not completely disappear from the system, indicating the presence of some oxygen in the overlying water. Nitrate will move downward by diffusion and undergo denitrification in the sediment (Ponnamperuma 1972). However, very little denitrification takes place until all oxygen has been depleted (Gunnison, Engler, and Patrick 1985).

Total organic carbon levels in the overlying water began to decrease when DO levels fell below 1 mg/ℓ. Gunnison, Chen, and Brannon (1983) reported that a decrease in concentration of soluble TOC in the water column was strongly correlated with a decrease in DO depletion rate. Dissolved oxygen depletion rates decreased by day 11 of sampling, corresponding to a decrease in TOC in the same period.

Column Studies

Much of the activity observed in the sediment-water columns took place in the water. Often, transformations in the BOD bottles equaled or exceeded activity in the columns. Mean sediment-water fluxes, corrected for activity in the water alone, were small relative to fluxes reported for sediments similar to those in the WES studies. Many of the mean fluxes that were measured cannot be differed significantly from zero. Several hypotheses can be advanced to explain the inert nature of the sediments. No single hypothesis explains all the experiments. Several are likely to have influenced the WES results. Sediments may be inert for the following reasons:

a. *System characteristics.* Substantial SOD and nutrient release occur only from sediments that receive substantial loads of organic particles. One or more of the WES sediments may have come from a system which received minimal organic loading.

b. *Sample collection time.* Deposition to sediments varies throughout the year. For example, deposition is usually large following an algal bloom in surface waters. One or more of the WES sediment samples may have been collected at a time in which deposition was minimal.

c. *Sample holding time.* The WES samples were held in a cold room for 1 to 7 months following collection. Although the cold storage should have restricted activity in the sediments, the holding time may still have been too long.

d. *Sample collection method.* Sediment activity decreases as a function of depth below the sediment-water interface. Deeper sediments are older and contain little or no remaining reactive organic matter. The dredge was intended to sample only active, surficial sediments, but a large fraction of deeper, inert sediments may have been collected as well.

6 Conclusions and Plans for Future Activities

The WES team has developed apparatus and protocol suitable for laboratory investigations of sediment-water exchange processes. The apparatus may also be suitable for laboratory measurement of actual environmental sediment-water oxygen and nutrient fluxes.

One purpose of these experiments was creation of a database for testing predictive SOD and nutrient flux model. Observations collected in the experiments are presently being examined within the model framework. Initial model simulations of the WES experiments have been conducted. This work will be the subject of an upcoming report.

In June, a field trip is planned for observation of in situ sediment flux measurement in Chesapeake Bay. One purpose of this trip is to evaluate the suitability of the device for use by the Corps. Sediments will be collected at the same time the in situ measures are conducted. These sediments will be returned to WES and immediately set up in the WES measurement device. These measures will be compared with the in situ measures collected in the Bay. The comparison will provide the first indication whether the WES device is suitable for measuring fluxes in the environment. The comparison will also provide insight into the effects of sample collection and holding time on the WES measurements.

As part of the modeling activity, prediction of sediment iron and manganese release is being added to the sediment model. The initial formulation of the model is complete. Comparison to existing Corps observations of iron and manganese release is next. Collection of additional observations to validate the model may be necessary. In that case, WES investigators will add iron and manganese to the suite of variables observed in the laboratory experiments.

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Appendix A
Data for Column Studies

Table A1
Data[1] Obtained in the Anaerobic Column Study Using Brown's Lake Sediment

Sample Day	Dissolved Oxygen	SOD	Ammonium Nitrogen	Ammonium Flux	Orthophosphate Phosphorus	Orthophosphate Flux	Nitrate Nitrogen	Nitrate Flux	TOC[2]	TOC Flux	TIC[3]	TIC Flux
0	9.146		0.0024		0.003		0.006		8.850		6.71	
1	6.978	-1.977	0.0044	- 7.520	0.005	- 1.504	0.009	6.580	4.400	-4.183	9.490	2.613
5	3.402	-0.840	0.0178	- 6.251	0.024	1.739	0.028	8.272	10.874	1.521	10.326	0.196
7	2.202	-0.614	0.0248	- 6.110	0.022	- 3.666	0.037	8.178	5.538	-2.508		
12	1.264	-0.248	0.004	-13.310	0.084	8.798	0.228	39.630	8.362	0.531		
19	0.91	-0.133	0.0022	- 9.642	0.451	83.096	0.007	-25.863	11.666	0.444		
23	0.886	-0.095	0.011	- 7.332	0.341	7.943	0.008	3.854	7.786	-0.912		
30	0.864	-0.093	0.0078	- 9.830	0.271	24.440	0.015	4.781	5.928	-0.249		
43	0.696	-0.104	0.0008	- 9.906	0.112	22.372	0.005	3.022	6.216	0.021		
50	0.6	-0.108	0.0042	- 8.943	0.029	-13.993	0.010	4.431	1.772	-0.597		
67	9.76		0.0076		0.098		0.065		4.546			
72	3.978	-1.051	0.0022	-10.415	0.038	-14.138	0.108	11.806	4.716	0.032		
76	9.1		0.0032		0.045		0.036		5.531			
79	1.526	-2.370	0.014	- 6.016	0.073	6.204	0.071	14.852	17.596	3.780		
86	1.684	-0.054	0.0016	-11.065	0.472	87.393	0.026	- 2.283	7.988	-1.293		
93	0.744	-0.209	0.0108	- 8.165	0.283	8.460	0.034	4.834	43.728	4.802		
100	0.498	-0.129	0.1214	25.192	0.310	37.493	0.050	5.935				

[1] *Dissolved oxygen and nutrient concentrations are expressed in mg/ℓ; fluxes are expressed as mg/m2/day.*

[2] TOC = Total organic carbon.

[3] TIC = Total inorganic carbon.

Table A2
Data[1] Obtained in the Anaerobic Column Study Using Rathbun Lake Sediment

Sample Day	Dissolved Oxygen	SOD	Ammonium Nitrogen	Ammonium Flux	Orthophosphate Phosphorus	Orthophosphate Flux	Nitrate Nitrogen	Nitrate Flux	TOC[2]	TOC Flux	TIC[3]	TIC Flux
0	7.99		0.00		0.01		0.00		0.00		0.00	
1	6.63	-1.19	0.00	0.53	0.01	1.10	0.01	3.67	9.08	8.53	1.32	1.22
7	3.92	-0.44	0.02	1.16	0.02	1.38	0.04	6.38	7.67	-0.20	4.89	0.54
13	2.79	-0.16	0.03	0.08	0.02	-0.00	0.04	2.05	6.58	-0.16	9.71	0.73
23	2.53	0.00	0.04	0.03	0.03	0.66	0.04	1.69	6.05	-0.03	7.69	-0.21
30	0.58	-0.24	0.04	-0.59	0.04	0.38	0.03	0.98	0.52	-0.73	0.53	-0.98
40	0.73	0.04	0.04	-1.38	0.04	-0.60	0.03	1.54	1.00	0.08	1.29	0.06
42	5.68		0.02		0.02		0.03		0.90		0.93	
44	4.12	-0.76	0.03	5.08	0.02	2.35	0.05	8.66	0.73	-0.08	0.98	0.00
49	2.38	-0.32	0.04	0.53	0.04	2.54	0.07	5.86	2.72	0.39	13.80	2.35
58	1.00	-0.12	0.03	-1.97	0.04	-0.57	0.08	1.09	1.28	-0.14	0.63	-1.38
66	0.86	0.00	0.03	-0.23	0.05	1.06	0.08	1.97	2.07	0.13	0.69	-0.02

(Continued)

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[1] Dissolved oxygen and nutrient concentrations are expressed in mg/ℓ; fluxes are expressed as mg/m2/day.
[2] TOC = Total organic carbon.
[3] TIC = Total inorganic carbon.

Table A2 (Concluded)

Sample Day	Dissolved Oxygen	SOD	Ammonium Nitrogen	Ammonium Flux	Orthophosphate Phosphorus	Orthophosphate Flux	Nitrate Nitrogen	Nitrate Flux	TOC^2	TOC Flux	TIC^3	TIC Flux
72	0.71	0.00	0.07	3.13	0.07	1.63	0.04	-1.17	1.15	-0.11	1.00	0.02
79	0.51	-0.01	0.06	-1.39	0.06	-1.63	0.03	0.04	0.88	-0.02	0.89	-0.04
86	0.55	0.03	0.06	-1.93	0.04	-2.44	0.03	2.37	0.90	0.02	0.84	-0.03
93	0.60	0.01	0.04	-3.18	0.04	-1.14	0.02	0.82	0.79	0.00	0.96	-0.01
99	7.44		0.02		0.02		0.03		1.37		1.74	
104	3.38	-0.75	0.03	2.22	0.04	2.36	0.04	4.04	1.82	0.04	1.91	0.01
111	2.69	-0.07	0.04	-0.05	0.04	-0.29	0.05	2.55	0.99	-0.06	1.25	-0.11
118	1.17	-0.18	0.05	-0.36	0.04	-0.07	0.05	2.82	0.84	-0.00	1.06	-0.06
125	0.92	-0.01	0.05	-0.99	0.04	-0.74	0.06	2.28	0.83	0.02	0.98	-0.03
132	0.54	-0.03	0.04	-2.11	0.04	-0.51	0.06	2.41	0.73	0.00	0.94	-0.03

Table A3
Data[1] Obtained in the Anaerobic Column Study Using Chesapeake Bay Sediment

Sample Day	Dissolved Oxygen	SOD	Ammonium Nitrogen	Ammonium Flux	Orthophosphate Phosphorus	Orthophosphate Flux	Nitrate Nitrogen	Nitrate Flux	TOC[2]	TOC Flux	TIC[3]	TIC Flux
0	7.84		0.00		0.00		0.00		1.99		1.11	
1	5.89		0.01		0.00		0.01		2.41		2.01	
7	1.58	0.14	0.02	-1.57	0.01	-2.04	0.02	-2.35	6.07	-0.35	12.58	-0.52
14	0.94	0.03	0.06	-1.03	0.05	-0.90	0.07	0.22	7.58	-0.01	13.98	0.43
21	0.37	0.02	0.05	2.84	0.05	2.64	0.05	4.43	7.08	0.27	11.84	0.70
28	0.03	-0.02	0.04	-0.63	0.04	-0.54	0.04	-0.49	5.37	-0.04	10.71	0.37
35	0.02	-0.02	0.03	0.00	0.03	0.09	0.02	-0.22	4.35		5.97	
42	0.01	-0.02	0.03	1.84	0.03	1.66			0.47		0.94	
49	5.82		0.02		0.02				0.99		5.84	
56	2.09	-0.23	0.04	2.69	0.04	1.61			1.42	0.10	1.72	-0.78
63	2.82	0.25	0.02	-3.09	0.02	-2.82			0.74	-0.06	3.92	0.38
70	0.16	-0.15	0.02	0.27	0.02	-0.72			-0.74	-0.27	5.28	-0.02

(Continued)

[1] Dissolved oxygen and nutrient concentrations are expressed in mg/ℓ; fluxes are expressed as mg/m2/day.
[2] TOC = Total organic carbon.
[3] TIC = Total inorganic carbon.

Table A3 (Concluded)

Sample Day	Dissolved Oxygen	SOD	Ammonium Nitrogen	Ammonium Flux	Orthophosphate Phosphorus	Orthophosphate Flux	Nitrate Nitrogen	Nitrate Flux	TOC^3	TOC Flux	TIC^3	TIC Flux
77	0.16	-0.01	0.03	0.54	0.02	-0.22			1.33	0.01	2.82	0.06
84	0.07	-0.02	0.03	0.22	0.03	0.13			0.59	-0.04	3.46	-0.04
91	0.06	-0.02	0.03	-1.12	0.03	0.22			0.73	0.01	3.30	-0.04
98	0.07	-0.02	0.04	1.21	0.03	-0.63			0.67	0.02	3.08	-0.09
105	0.07	-0.02	0.02	0.18	0.02	-0.72			0.56	0.02	2.86	-0.01
118	0.02	-0.01	0.04	-0.06	0.05	0.17			0.88	0.03	2.31	0.01
125	0.02	-0.02	0.04	-0.27	0.06	-0.36			1.02		2.00	
132	7.37		0.01		0.01				1.28		5.29	
139	5.82		0.02	-0.67	0.02	-1.34			0.84	0.03	5.63	
146	4.83	0.69	0.03	-0.54	0.03	-1.07			0.74	0.08	4.82	0.46
153	3.86	0.49	0.05	-0.40	0.04	0.09			0.82	0.01	4.23	0.38
178	2.99	0.11	0.03	1.04	0.03				0.91		2.65	

Table A4
Data[1] Obtained in the Anaerobic Column Study Using Eau Galle Reservoir Sediment

Sample Day	Dissolved Oxygen	SOD	Ammonium Nitrogen	Ammonium Flux	Orthophosphate Phosphorus	Orthophosphate Flux	TOC[2]	TOC Flux	TIC[3]	TIC Flux
0	8.00		0.00		0.00		0.93		1.11	
4	6.78		0.02		0.02		0.77		5.88	
10	3.73		0.02		0.02		1.07		5.54	
17	3.44	0.22	0.03	-0.58	0.03	-1.07	1.31	0.05	5.74	0.09
24	2.52	0.12	0.03	-0.90	0.03	-0.67	0.75	0.05	5.45	0.02
31	1.79	0.13	0.04	-1.03	0.04	-0.49	0.55	-0.00	5.10	0.09
38	1.37	0.09	0.04	-0.67	0.04	-0.76	0.83		4.10	
45	1.11	0.06	0.05	-1.52	0.04	-0.81	0.56	0.01	3.96	-0.03
58	0.42	0.01	0.05	-0.41	0.06	-0.24	0.57	0.01	3.49	0.05
65	0.19	0.00	0.05	-0.63	0.05	-0.22	0.83		2.83	
72	0.11	-0.01	0.05	-0.72	0.05	-0.31	0.42	-0.03	3.14	0.08
79	0.05	-0.01	0.04	0.00	0.05	0.94	0.50	-0.01	2.65	0.06
86	0.03	-0.02	0.04	0.76	0.04	0.76	0.43	0.01	2.45	0.08
93	7.83		0.03		0.02		0.50		5.16	
118	4.77		0.03		0.02		0.99		2.49	

[1] Dissolved oxygen and nutrient concentrations are expressed in mg/ℓ; fluxes are expressed as mg/m2/day.
[2] TOC = Total organic carbon.
[3] TIC = Total inorganic carbon.

Table A5
Data[1] Obtained in the Anaerobic Column Study Using Chicago River Sediment

Sample Day	Dissolved Oxygen	SOD	Ammonium Nitrogen	Ammonium Flux	Orthophosphate Phosphorus	Orthophosphate Flux	TOC[2]	TOC Flux	TIC[3]	TIC Flux
0	8.00		0.00		0.00		0.93		1.11	
4	6.29		0.02		0.01		1.16		5.70	
10	2.52		0.02		0.03		1.37		6.27	
17	1.94	0.05	0.02	-1.70	0.03	-2.28	1.11	-0.04	5.92	0.12
24	1.69	0.06	0.03	-1.57	0.04	0.09	0.86	0.05	5.75	0.04
31	1.22	0.03	0.05	-0.40	0.04	-1.12	0.47	-0.03	4.66	-0.05
38	0.80	-0.01	0.05	-1.21	0.05	-0.98	0.70		4.27	0.57
45	0.64	0.02	0.05	-1.25	0.05	-1.79	0.69	0.02	4.14	0.10
58	0.25	0.00	0.06	0.27	0.06	-0.72	0.35	-0.01	3.81	-0.03
72	0.13	-0.01	0.06	-0.45	0.06	0.07	0.41	-0.00	3.56	-0.02
86	0.04	-0.01	0.04	-0.02	0.05	0.00	0.60	0.02	3.34	-0.00
93	8.20		0.02		0.02		0.65		5.23	
118	3.45		0.01		0.02		0.47		3.92	

[1] Dissolved oxygen and nutrient concentrations are expressed in mg/ℓ; fluxes are expressed as mg/m2/day.
[2] TOC = Total organic carbon.
[3] TIC = Total inorganic carbon.

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Three different approaches for examining sediment oxygen demand (SOD) are discussed. These include the use of freshwater sediment amended with organic matter as a source of energy to drive SOD processes, the use of successive aerobic/anaerobic cycles to determine the flux of organic and reduced inorganic chemical species released from the sediment to the water column as a result of SOD, and the evaluation of interactions occurring between the sediment and water column in relation to SOD-driven processes occurring within the sediment. Results are summarized and discussed in terms of measurement and analytical techniques used to describe SOD interaction in fresh and saltwater sediments.

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