AN ABSTRACT OF THE THESIS OF

GENE RAY CROOK for the MASTER OF SCIENCE
(Name) (Degree)

in CIVIL ENGINEERING presented on [illegible]
(Major) (Date)

Title: IN SITU MEASUREMENT OF THE BENTHAL OXYGEN REQUIREMENTS OF TIDAL FLAT DEPOSITS

Abstract approved: Redacted for Privacy
Dr. David A. Bella

In situ light and dark planktonic and benthal respirometers were used to measure the oxygen requirements of Yaquina estuary water and benthal deposits. Respirometer devices were constructed so that actual conditions of mixing could be simulated and benthal deposit disturbance would be minimized.

A mathematical model of a benthal respirometer was developed and was used to make corrections for respirometer leakage and to conduct oxygen transfer parameter sensitivity studies. The effect of mixing on benthal oxygen uptake was studied by varying the simulated mixing velocities. Studies were made to determine the effects of scour of bottom material on the salinity of the respirometer water and on the benthal oxygen uptake rates. Plots of various parameters such as benthal oxygen uptake versus dissolved oxygen concentration and respirometer leakage versus time were made to attempt to evaluate relationships that may exist.

In Situ Measurement of the Benthal Oxygen Requirements of Tidal Flat Deposits

by

Gene Ray Crook

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

June 1970

APPROVED:

Redacted for Privacy

Assistant Professor of Civil Engineering
in charge of major

Redacted for Privacy

Head of Department of Civil Engineering

Redacted for Privacy

Dean of Graduate School

Redacted for Privacy

Date thesis is presented ____________

Typed by Donna L. Olson for Gene Ray Crook

ACKNOWLEDGEMENT

The writer gratefully acknowledges the financial assistance of the Federal Water Pollution Control Administration for the research support of grant number 16070 DGO and the traineeship, number 5T1-WP-187-01, which enabled the writer to pursue graduate study at Oregon State University.

Committee members, Professor Donald C. Phillips and Assistant Professor Bard Glenne, are thanked for their comments and help during the entire research project.

Special thanks are due Assistant Professor David A. Bella for his confidence and helpful assistance as major professor.

Grateful appreciation is expressed to my wife, Patricia, for her patience and inspiration during the year of study.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

IN SITU MEASUREMENT OF BENTHAL OXYGEN REQUIREMENTS OF TIDAL FLAT AREAS

INTRODUCTION

Purpose and Scope

The purposes of this research project were to design, construct, and make use of a device that would allow the measurement of oxygen uptake rates of biologically or chemically active tidal flat communities and to attempt to gain a better understanding of the mechanisms of benthal oxygen uptake. The primary goal was to measure oxygen uptake rates under environmental conditions that would simulate those which actually existed in nature. Although many types of benthal respirometers have been built by previous researchers, simulating actual conditions has been a difficult problem and a serious limitation.

The scope of this research required that benthal oxygen demands be differentiated from planktonic demands. Furthermore, the experiments were to be designed so that equipment could be placed in or on the benthal deposits at low water with minimum disturbance and that complete sample runs could be made during one low water-high water-low water tidal sequence.

The Need to Study Benthal Demands

Bottom deposits have been called "a vital self purification system" (24) without which our water ways would become choked with organic matter. Through physical adsorption and biochemical degradation of organic pollutants, benthal deposits remove organic matter from overlying waters (24). However, in removing and degrading organic material, benthal deposits exert a substantial oxygen demand (22, 24, 26, 37, 53). Many researchers have experimentally found values for benthal oxygen demand. In some water bodies, the benthal oxygen demand has been found to be as much as 40 percent of the total oxygen requirement (46).

Bottom deposits can also produce unsightly boils or gas emissions if allowed to build up in excess (53). Prevention of such conditions requires an understanding of the processes of removal or degradation of the deposits.

Another reason for understanding transfer rates between benthal deposits and overlying waters is that benthal deposits can act as sources of nutrients when overlying waters are nutrient deficient (11, 14, 35). Phosphorus and nitrogen can be recycled between bottom deposits and overlying waters (11, 37). Such recycling may be assisted by burrowing organisms (20), tidal-caused water surges, and diffusion of interstitial material. If overlying waters are not deficient in nutrients or oxygen, adsorption reactions and biological exchange can bring the reactants into the benthal deposits (41). In tidal flat areas, salts can be precipitated by evaporation directly on the mud surfaces at low water (36). These salts can later be liberated by physical, chemical, or bacterial reactions (36). As can be seen, knowing rates of transfer of reactants into or out of benthal deposits is desirable before any quantitative predictions of overall water-quality are made.

Tidal flat areas are considered in this study because they are very active biological areas (37) and may create future problems due to nutrient releases or oxygen requirements. It has also been observed that in some cases benthal metabolism contributes more than other factors to dissolved oxygen changes in estuarine environments (37). Such an observation further points out the importance of understanding benthal demands in estuarine areas. Since suspended material is known to settle out more readily in areas where salt water and fresh water meet and intermix, tidal flat and estuarine bottom areas should be areas of rapid sludge buildup (2). Tidal flats have the additional influence of tidal action which may produce flow of interstitial water which might assist some of the transfer mechanisms (52). Furthermore, tidal flat areas compose major portions of many estuarine systems. For example, in Yaquina Bay, 1590 acres of tidal flats are exposed at low water (50). At Coos Bay, Oregon, almost 7000 acres of exposed tidal flats exist at low water. Most studies or models of the marine environment have ignored not only the effects of tidal flat deposits but many of the more important physical factors of the intertidal environment. Tidal flat or estuarine bottom deposits represent an important, complex, and interesting problem that should be thoroughly understood so that wise usage of our marine waters for industrial and domestic purposes can proceed.

Factors and Mechanisms Controlling Benthal Oxygen Demands

The diffusion process is probably the major mechanism by which materials are transferred across mud-water interfaces (47). Some observers have concluded that diffusion of oxygen demanding material out of benthal deposits is of primary importance (2), while others have stated that diffusion of dissolved oxygen into the benthal deposits is of primary significance. Diffusive transport is dependent upon the concentration gradient of the material being transferred (5, 17). However, the diffusion process may be influenced by numerous factors.

It has been stated that changes in temperature on the order of several degrees over a time period of several hours does not affect the production or respiration of a balanced benthal community. But it is also known that temperature changes do have an effect upon diffusion rates (17). Since uptake of oxygen and other materials by benthal communities is a physical and biochemical process (24), temperature should affect the rate of uptake (17, 26, 27, 28).

Diffusive transport is also controlled indirectly by nutrient supply and population density (26) which may limit the formation of large gradients by limiting the biological activity of the populations. Population density is obviously an important controlling factor for without sufficient numbers of organisms, the demand for material is insufficient to create a large oxygen demand and deficit (38). Furthermore, the amount of organic matter and the degradability of the organic matter present in bottom deposits may also impose some control on overall uptake rates (38) by limiting biological activity so that a large transport gradient cannot be maintained.

Algal population is another controlling factor. Benthal algae produce quantities of oxygen under lighted conditions and respire under darkened conditions. Such phenomena have been noted and are said to cause a net oxygen uptake in most cases (33, 34). Therefore, large numbers of benthal algae should have a positive effect or, in other words, increase the overall benthal oxygen uptake.

Bacteria, both aerobic and anaerobic, either directly or indirectly cause increased oxygen uptake rates. Aerobic bacteria use oxygen in their respiration while anaerobic bacteria produce cellular waste products that may contribute to a chemical or biochemical oxygen demand as the waste products diffuse to the mud-water interface (13). In fact, gasses produced in anaerobic layers may be forced upward into overlying waters and exert further demands (13, 29).

Macroorganisms appear to contribute to the benthal oxygen demand directly due to their body respiration (12, 26) and indirectly by increasing the depth of the aerobic layer through their burrowing and sediment turnover processes (12). Burrowing may also assist the release of nutrients or oxygen requiring materials to surface waters. Macroorganisms in benthal deposits appear to cause a decrease of the benthal uptake rate when the oxygen concentration in the overlying water is low. This decrease is probably due to the inhibition of the aerobic life processes (26). However, oxygen concentration does not appear to affect the uptake rate if macroorganisms are not present (2, 13, 26).

Tidal effects may also influence benthal demands. Along with the hydrostatic pressure surges in the bottom deposits that may increase diffusion of oxygen demanding substances into overlying waters (52), tidal cycles will affect the factors regulating the transfer mechanisms. For example, tidal movements insure relatively strong mixing conditions on tidal flat areas. Mixing or high velocity increases diffusion rates and effectively increases uptake rates by assuring that a stratified layer of oxygen-depleted water does not form just above bottom muds (17, 28, 37, 48). If increased mixing produces scour of bottom deposits, even higher benthal demands may result (22, 29).

Review of Benthal Oxygen Demand Measurement Techniques

The concept of measuring the oxygen transfer or uptake rates of benthal deposits is not new. As early as 1931 and 1938 researchers were at least contemplating the possible problems caused by benthal deposits, benthal organisms, and benthal oxygen requirements (2, 30, 43).

Many early attempts at measuring the oxygen demand of benthal material were made in the field or laboratory using very simple devices and methods. In some cases, samples of bottom mud were simply placed into bottles of aerated water and shaken or mixed for a time period. By measuring the changes of dissolved oxygen concentration in the water, a very crude measure of benthal oxygen demand was observed (54). Such methods were inexpensive and easy to perform but definitely did not simulate actual conditions. In fact, most of the demand measured by such methods was due to the so-called "enzymatic" or chemical oxygen demand described by others (38, 47, 48).

More sophisticated methods of measuring benthal oxygen transfer rates or demands were developed. These methods resulted in the use of various laboratory and <u>in situ</u> benthal respirometers.

The simplest laboratory benthal respirometers were large carboys into which bottom deposits were placed by hand (2, 13, 43). In one case carboys were filled with water, and changes in BOD of the sludge and overlying waters were monitored. No mixing was used, and no attempt was made to control reaeration. Analysis of BOD changes corrected for assumed reaeration values gave an indication of the oxidative strength of the muds or sludges (43). Other carboy respirometers used sealed systems with inflowing water as the mixing mechanism. Water flowed into and out of the large carboy at a known rate. Changes in dissolved oxygen could be used to estimate benthal demands (2, 13). Results from these early devices were questionable considering the methods of mixing, of sample placement, and of control used.

More sophisticated benthal respirometers used in the laboratory consisted of reaction chambers into which samples of bottom material were placed. Mixing was usually supplied by a magnetic stirring device, and oxygen uptake rates were monitored using oxygen electrodes (15, 16, 29). Such respirometers gave complete mixing of overlying water, but the use of a greatly disturbed sample again severely limited the devices to studies of the relative effects of environmental changes.

Little difficulty was experienced in controlling or simulating conditions of light, temperature, constant salinity, and other environmental factors; but obtaining true undisturbed samples and reproducing actual mixing conditions was very difficult.

The next obvious step in respirometer evolution was to obtain samples with a minimum of disturbance. To do this, many observers used plastic tubes to obtain cores of bottom material with overlying water. These cores were brought back to the laboratory and tested in various ways to determine benthal uptake rates.

All investigators used a sealed system to exclude reaeration as a variable factor. Some used rubber stoppers or plastic lids (12, 19, 42, 48) while others used floating oil (33, 34) to seal their respirometer tubes from the atmosphere.

Mixing in these tubular laboratory benthal respirometers was provided by several methods. The methods ranged from no mixing at all (19) to plunger type stirring devices (9, 25). A magnetic stirring mechanism was frequently used (12, 15, 16, 29, 42, 48); several laboratory respirometers used water flow to achieve mixing (29, 31), and one investigator used a laboratory stirring paddle (26). In every instance, only limited control or simulation of actual mixing conditions was obtained.

Monitoring devices were also advanced along with the various in-lab benthal respirometers. Chemical and micro-chemical (25) oxygen determinations were used as were various polarographic determinations. Radioactive tracer methods were also developed to measure the transfer rates of trace elements between sediments and overlying water (11).

Even though relatively undisturbed samples could be tested in the laboratory with many controlled conditions and elaborate monitoring equipment, true actual conditions of mixing and other environmental factors such as tidal-caused pressure surges were difficult to reproduce.

Observers became aware of the problems of laboratory research and decided that *in situ* testing of benthic deposits was desirable if values of uptake rates were to be used in quantitative predictive models (45). Several types of *in situ* benthal respirometers resulted.

Most *in situ* benthal respirometers were of the bell jar variety. That is, they were simply inverted jar-like containers that were filled with water as they were placed into the mud deposit (37, 38, 39, 45). Dissolved oxygen values were measured over a time period, and uptake rates were developed.

These early respirometers had several serious draw-backs. First, since the respirometer was placed on or into the mud at the time of the test, some disturbance of the deposit was inevitable. Such a disturbance probably caused oxygen demanding material to escape into the water entrapped by the respirometer. Such disturbed material could give rise to great discrepancy in the initial results (38). Another problem with early jar-type respirometers was the fact that no controlled mixing was used. Simple stirring devices similar to in-lab respirometers were still used in most cases (37, 38, 39, 45). As has previously been stated, a lack of adequate mixing could allow the dissolved oxygen in the water to become depleted at the mud-water interface. If this occurred and the actual oxygen demand was greater than the oxygen diffusion rate through the depleted layer, any uptake rates measured would be deceptively low due to the lack of adequate mixing. Adequate mixing, however, was achieved in many respirometers. Some used pumps to recirculate the water (51) while others continued using impeller stirring devices to create artificial mixing. Even though the mixing devices were poorly controlled, researchers felt that better benthal oxygen uptake rates were being measured using in situ methods. Some stated that in situ measurements were even simpler and less expensive than complex attempts to simulate actual conditions in the laboratory (45).

Unfortunately, most jar-type respirometers used small benthal areas which limited the accuracy of most respirometer results. A representative area of bottom deposits could not be chosen for use in a 12-inch diameter bell-jar respirometer. A solution was developed using a very long and low tunnel-shaped respirometer that allowed a more random selection of bottom deposit area as well as more mud surface area for respirometer water volume (6). This in situ tunnel respirometer used natural currents flowing through it to simulate mixing conditions (6). By increasing the respirometer length to a point where incoming and outgoing waters had measurable dissolved oxygen differences, benthal oxygen uptakes were estimated (6). Such a tunnel respirometer approached a design that could better measure uptake or transfer rates since actual mixing conditions were well controlled. However, its usefulness was limited by the great length necessary to obtain measurable uptakes on a once through flow basis and by the difficulty of measuring actual flow-through times.

Using the past accounts of problems and successes in respirometer design and usage, a hybrid benthal respirometer system was developed during this research which seems to avoid many of the problems which have plagued past respirometer designs.

EXPERIMENTAL SITE LOCATIONS AND CHARACTERISTICS

General Location Information

This research was carried out in the Yaquina Bay-Estuary located on the central Oregon coast. A bay-estuary is defined as "a semi-enclosed body of water which has a free connection to the open sea and within which ocean water is measurably diluted with fresh water derived from land drainage" (50). The ecosystem that includes and affects the bottom deposits studied in this research consists of "surrounding landscapes with its plants and animals, towns and industrial complexes, and the associated ocean and atmosphere" (50).

Yaquina Bay-Estuary is basically a drowned river valley. It extends 23 miles inland to its fresh water head and covers 2700 acres at mean high water. At mean lower low water, the estuary consists of 1110 acres of water-covered area and over 1590 acres of tidal flat area (50).

At the mouth of the bay-estuary system, water temperatures range from 46.6^{o} F to 64.4^{o} F, and salinity values range between 8.6 and 34.7 parts per thousand (50). The waters of the system are well mixed during the June to October season (23). River flows during this period are very low. The average August fresh water flow is only 33.5 cfs (8) which is greatly overshadowed by tidal flows. A map of the Yaquina Bay-Estuary system showing the locations of the test areas is given in Figure 1. The test sites chosen for this research were selected so that the extremes of the estuarine environment might be covered. One test area was near the estuary mouth and was extensively influenced by ocean conditions. Another test area was more near the fresh water end of the estuary and was not as strongly influenced by the ocean environment. The test site in the upper portion of the estuary had been the site of earlier in-lab respirometer investigations. The desire to compare results with the in-lab measurements led to the final choice of the upper site.

Parker Slough Test Site

Two primary test locations were chosen. The first was located near river mile 4, 300 feet west of the Parker Sough tidal pool inlet. See Figures 1, 2, and 3. Sediments in the area were characterized by silty sand containing organic material in the upper layers. Mats of algal growths, probably Enteromorpha sp., covered most of the bottom muds for the entire test period. Algal growth of the same type were found free-floating in the overlying waters during high tidal periods. Several types of macroorganisms were prevalent in the tidal flat deposit at the Parker Slough test site. Mud shrimp and clams were prevalent.

Tidal depths at the Parker Slough test site during the test period ranged from 0 to 5 feet. Salinity varied from about 30 to 33

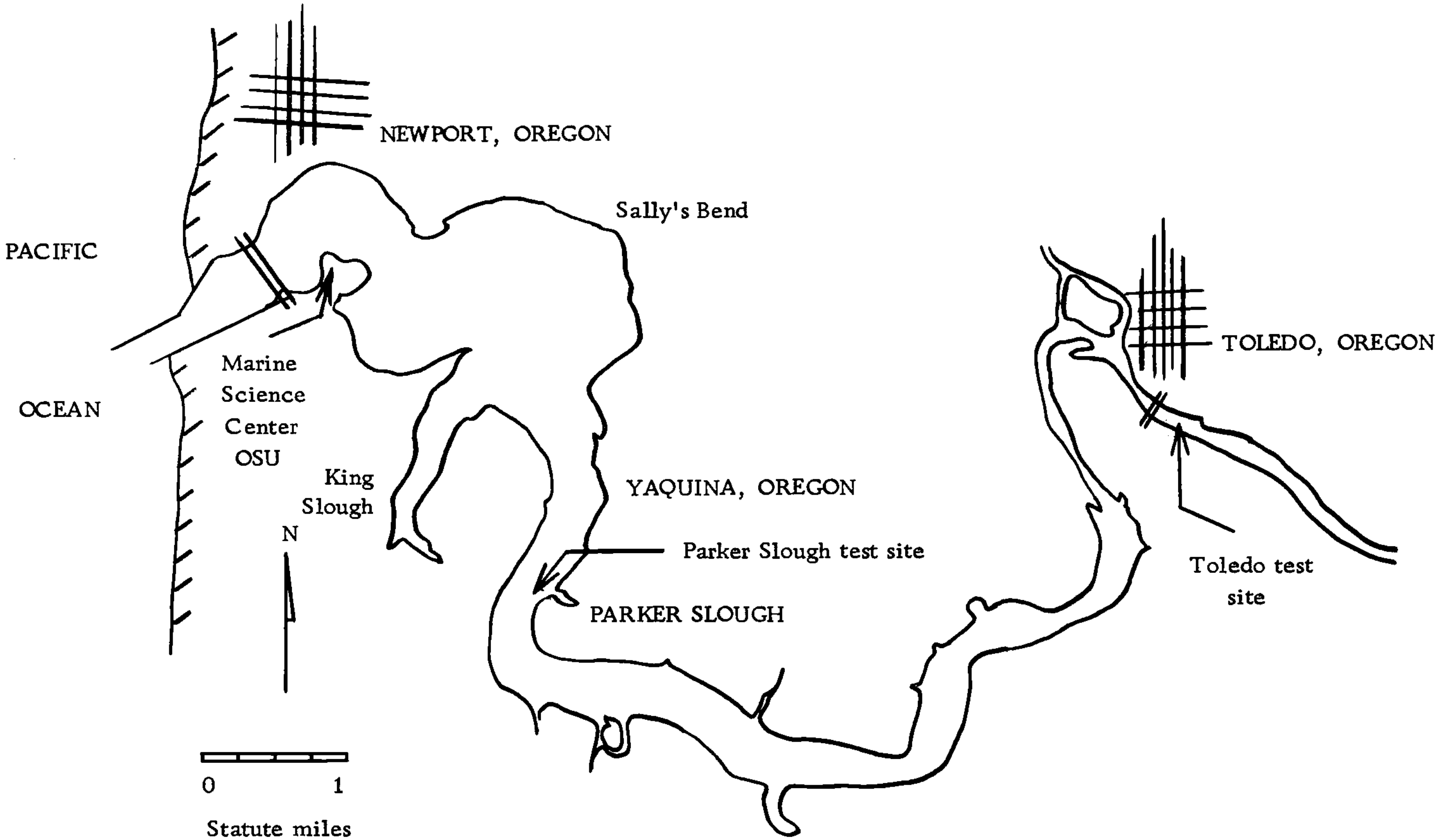


Figure 1. Map of Yaquina Estuary showing site locations.

Figure 2. Air photo of the Parker Slough test site and surrounding area.

Figure 3. Parker Slough test area showing algal growths and a portion of the access walkway.

parts per thousand. Temperature was also variable and ranged from about 11 to 19 degrees Centigrade. Dissolved oxygen values in the tidal water varied between 6.0 to 14.0 mg/l and were at times greatly supersaturated.

The Parker Slough test area was distant from any source of industrial pollution, log storage, or fish processing waste outfall. Any pollutional material was brought into the area by tidal current. No domestic contamination was evident.

During preliminary work, water velocity measurements were made in order to evaluate the needed respirometer simulation velocities. Using a Price current meter, maximum velocities of approximately 0.4 fps were measured at two to three inches from the bottom. See Figures 6, 7, and 8 for velocity comparisons. Other researchers have measured velocities in the main channels of the Yaquina Bay system. Tidal flat velocity measurements made during this research gave maximum velocities of less than half of those shown in the main channel regions (32).

Toledo Test Site

The second test area was located approximately 14 miles up river from the estuary mouth, 300 feet east of the Toledo, Oregon, Yaquina River bridge. See Figures 1, 4 and 5. This area was located within 20 feet of the sample gathering station used by an

Figure 4. Toledo test area showing the sampling floats and the general surroundings.

Figure 5. Partially installed light and dark benthal respirometers at the Toledo test site showing the benthal material tested.

earlier researcher on benthic oxygen demands. The previous study was performed one year prior to this research and used a laboratory benthal respirometer (25). Sediments in the Toledo area were a clayey silt. No macroorganisms of the type noted at Parker Slough were present at the Toledo test site. Furthermore, no large algal growths were present.

Tidal depths were from 0 to 8 feet during the test period. Salinity ranged from about 13 to 22 parts per thousand, and water temperature varied from about 18.5 to 23.5 degrees Centigrade. Dissolved oxygen values changed slightly with tidal fluctuations and usually cycled between 4.5 and 6.0 mg/l. Measurements were consistently below oxygen saturation values for the temperatures involved. Maximum bottom velocities were measured to be 0.6 fps. See Figures 6, 7, and 8 for velocity comparisons.

The Toledo test site was located near an industrialized area. A floating log storage area was located just up stream from the test area; several outfalls from a Kraft process paper mill were found just across the river channel, 300 feet from the test area; and saw mills were located both up- and down-river.

Bacterial Differences of Test Sites

To further differentiate the two test sites, a total bacterial count and a count of hydrogen sulfide (H_2S) producing bacteria were

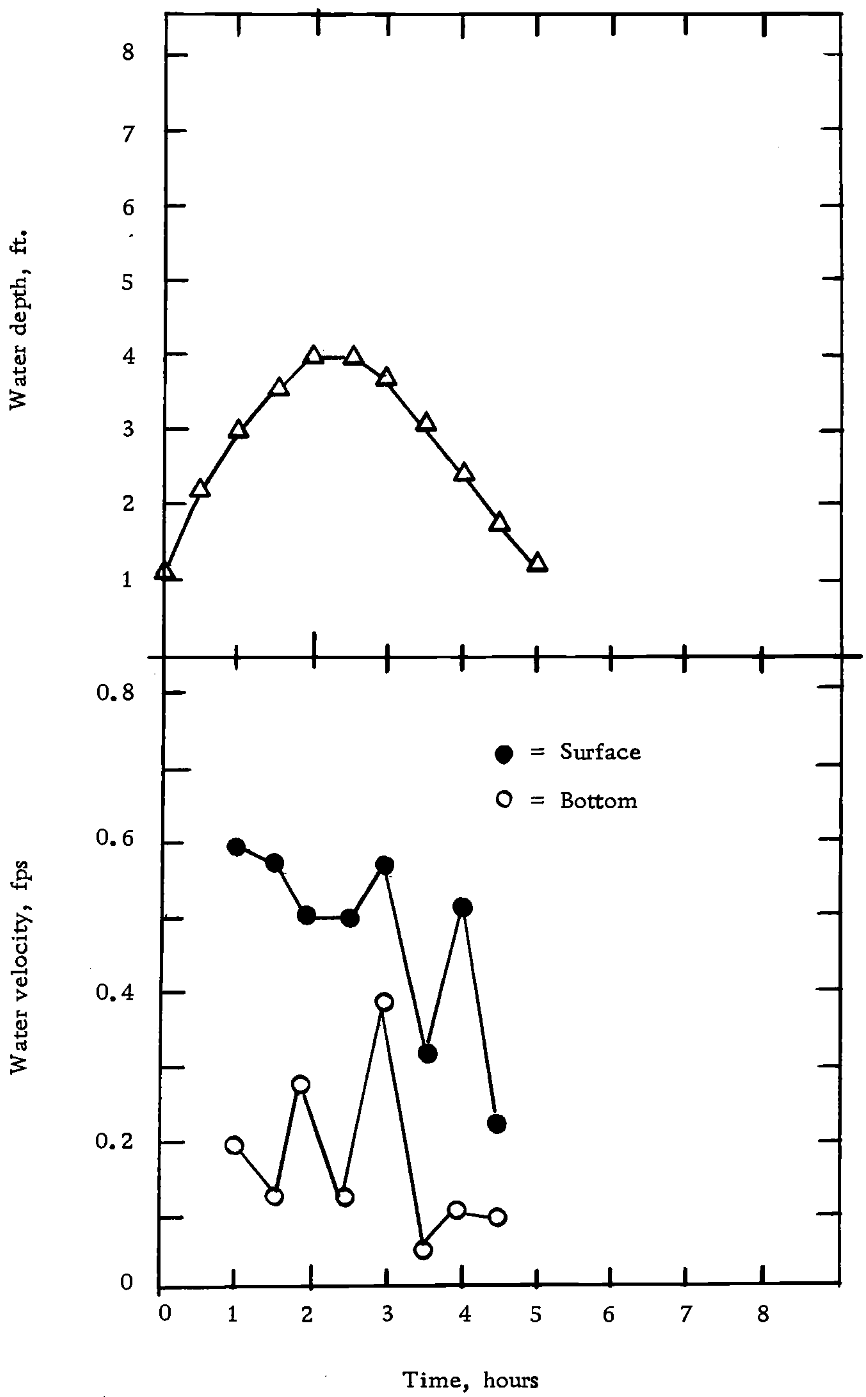


Figure 6. Water velocity measurements at the Parker Slough test site, 7-29-69.

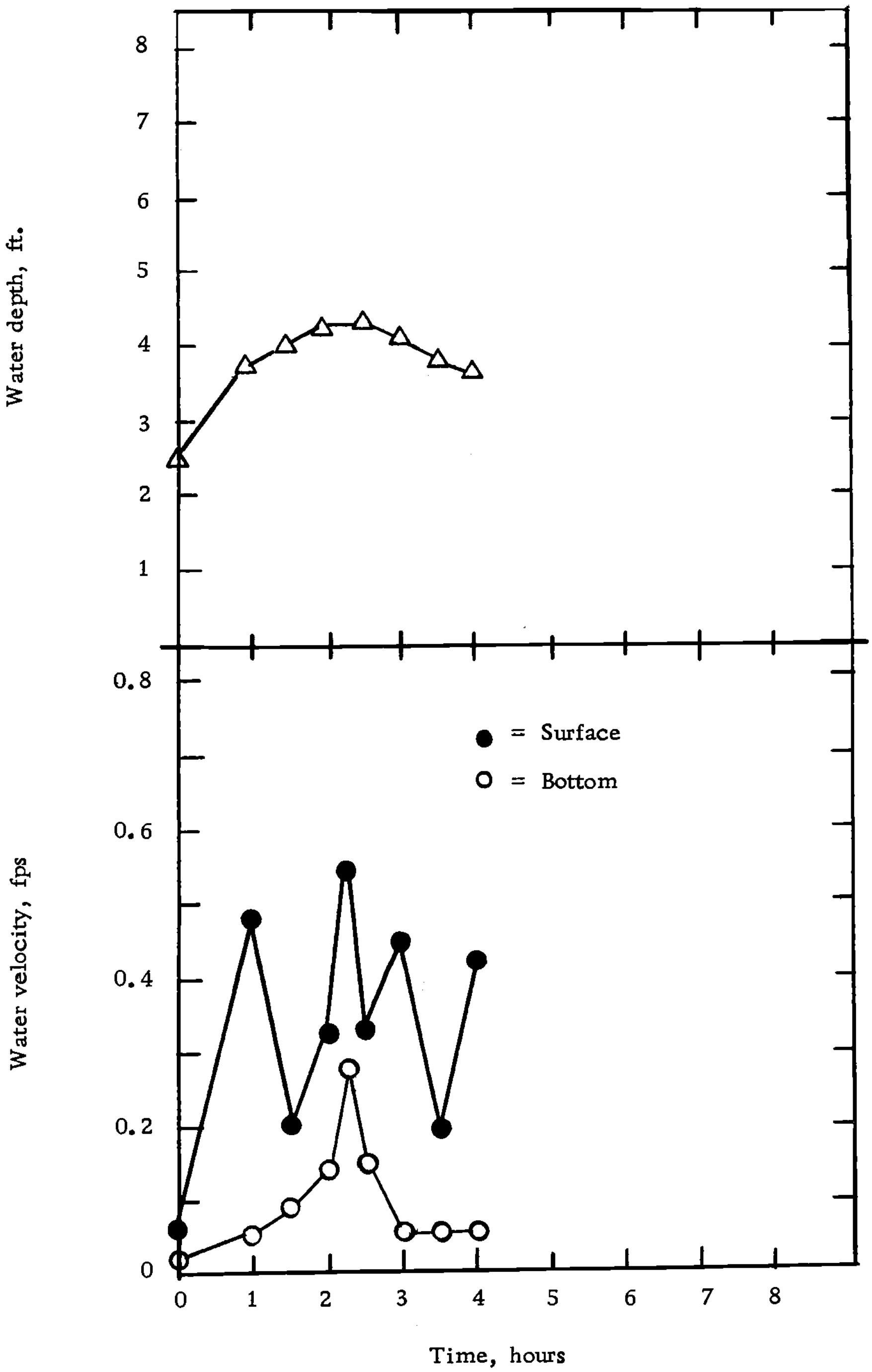


Figure 7. Water velocity measurements at the Parker Slough test site, 8-13-69.

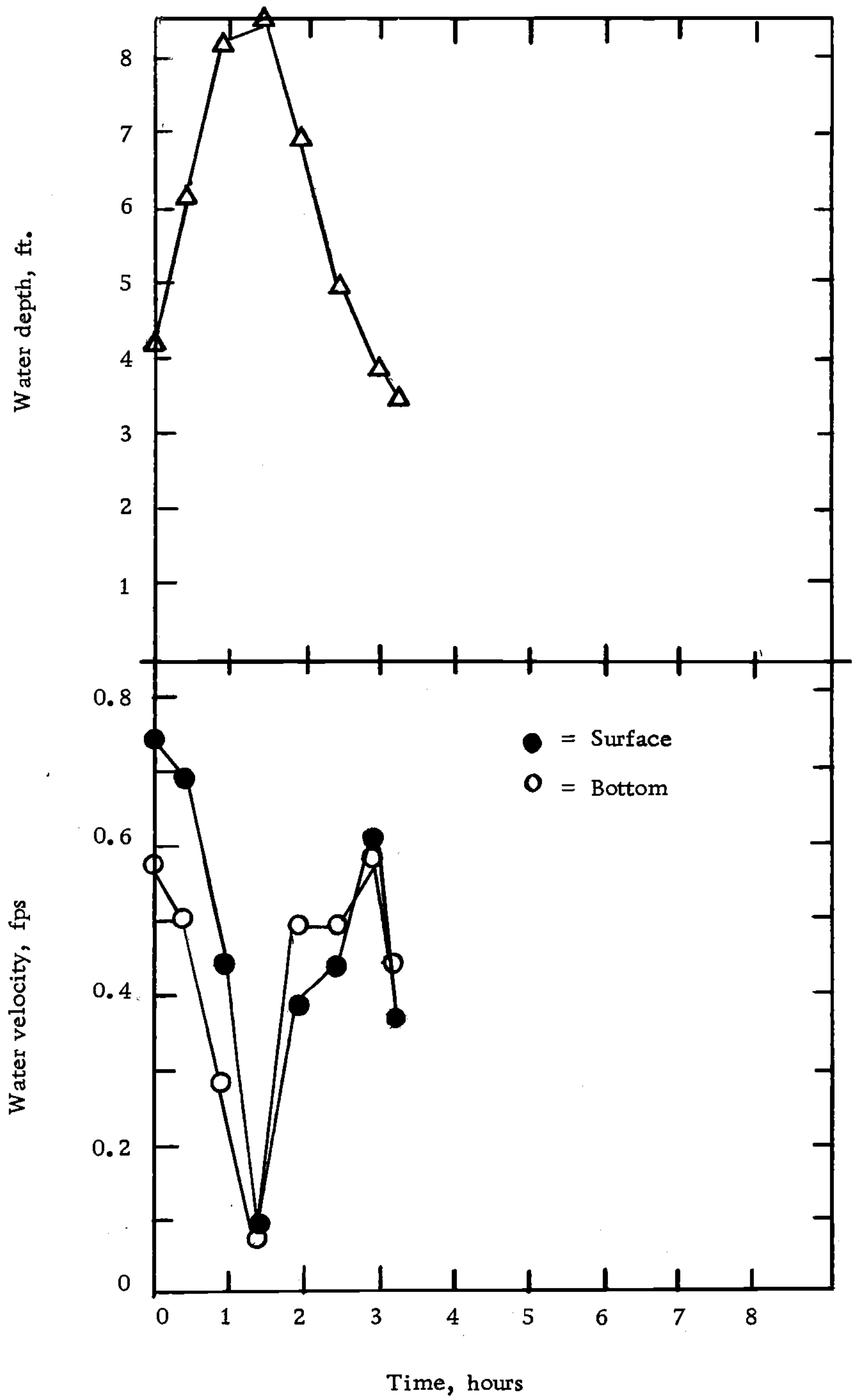


Figure 8. Water velocity measurements at the Toledo test site, 8-27-69.

made (40). SIM media was used to obtain counts of the H_2S producing bacteria while Marine Agar 2216 was employed for total viable plate counts. H_2S producing bacteria are anaerobes and are usually abundant in areas receiving pulp and paper wastes (44). Surface values and counts at various depths were measured. See Figures 9 and 10 and Table I. Although the results were quite variable, they indicated that the total bacterial counts were similar for both sites while the H_2S producers were more prevalent at the Toledo test site. This indicates that a higher level of anaerobic activity may exist at the Toledo mud flat, which may be expected considering the number of burrowing organisms aerating the Parker Slough deposit and the prevailing low dissolved oxygen concentration and paper mill effluent in the water at the Toledo site.

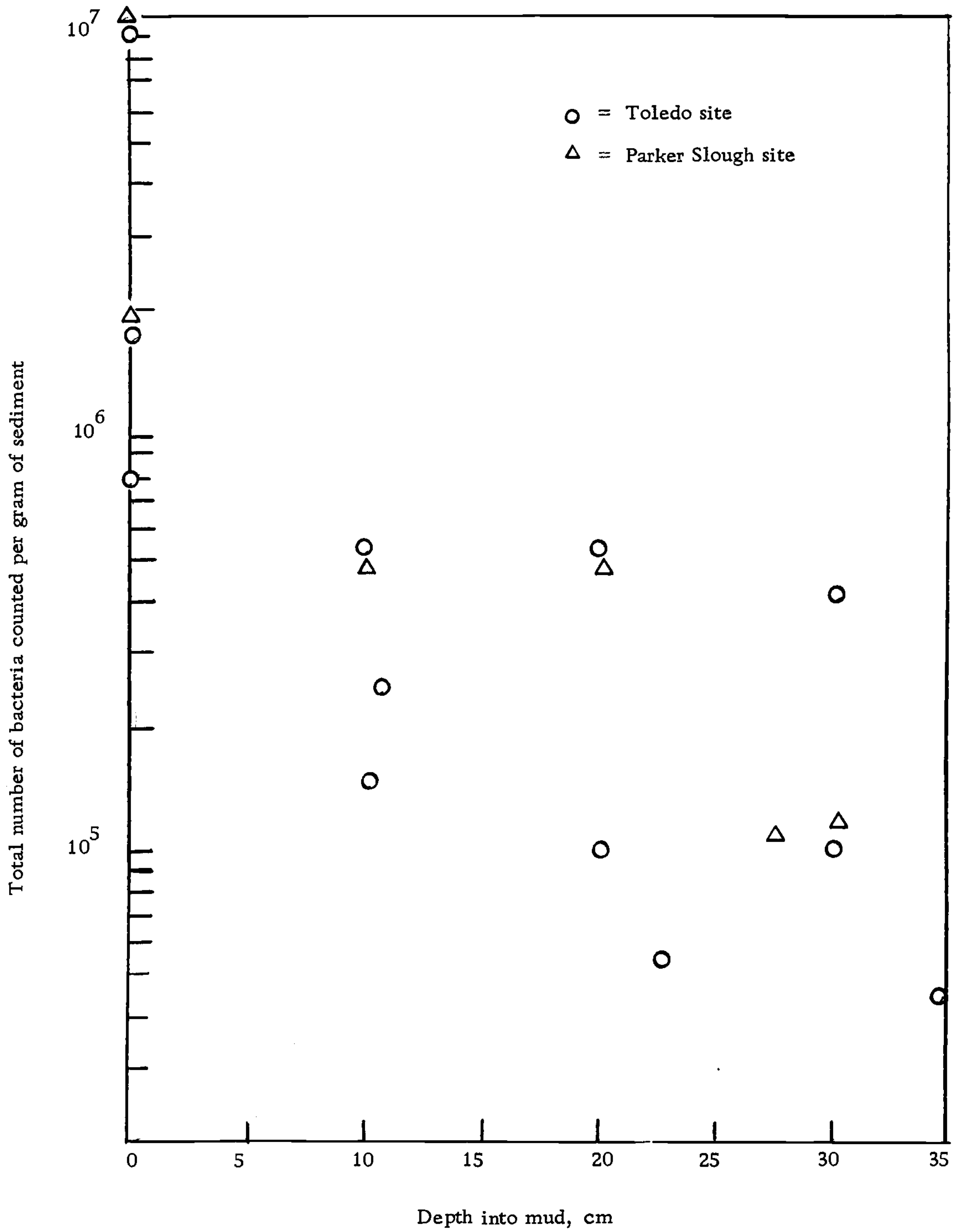


Figure 9. The total number of bacteria versus bottom deposit depth for the Parker Slough and Toledo test sites (40).

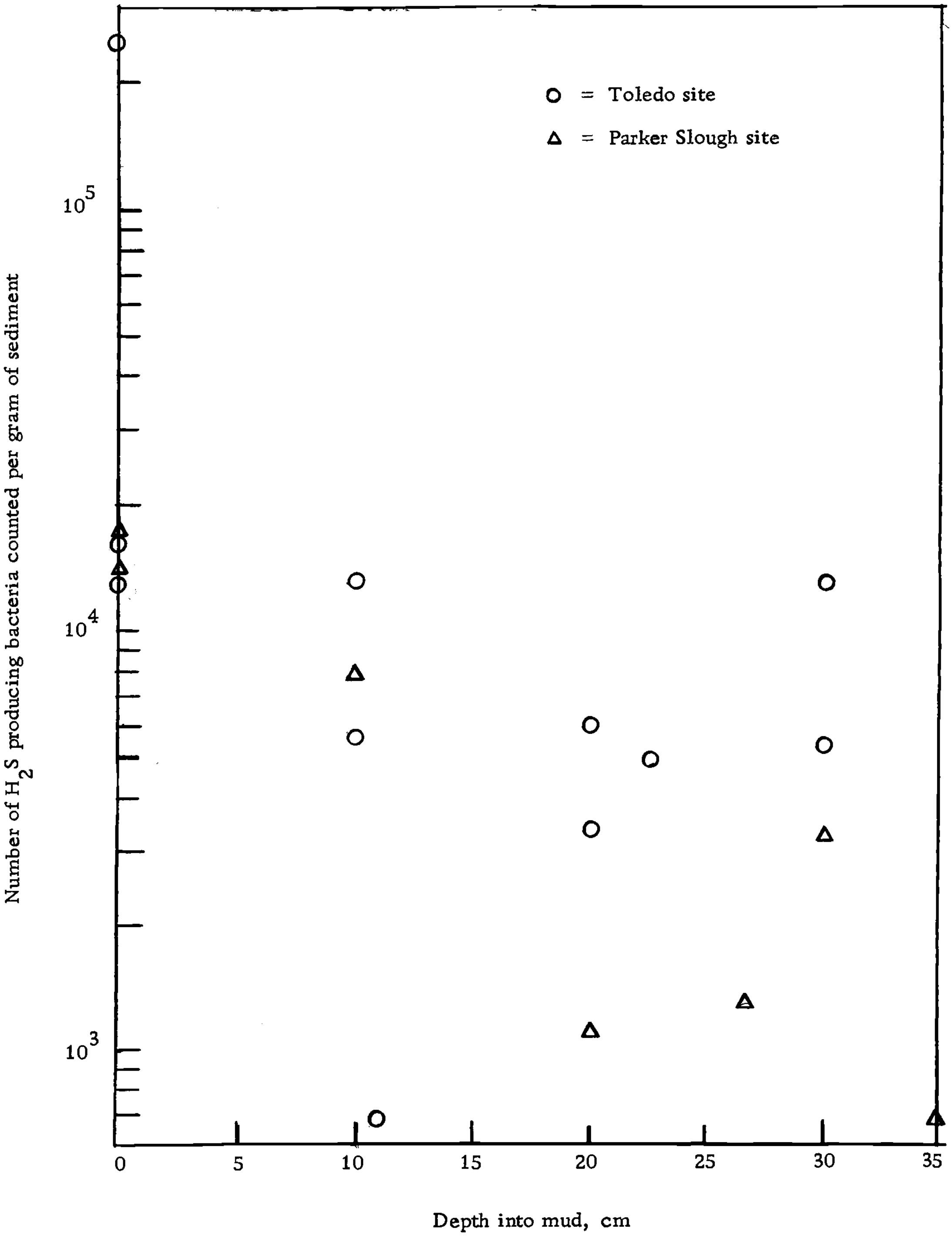


Figure 10. The number of H_2S producing bacteria versus bottom deposit depth for the Parker Slough and Toledo test sites (40).

Table I. Summary of results of bacterial plate count and H_2S producers from sediment (40). Bacteria per gram of sediment.

Location	Depth	Date	Total plate count (a)	H_2S producers (b)
Parker Slough	surface	9-19-69	1.9×10^6	1.4×10^4
	surface	10-25-69	1.0×10^7	1.7×10^4
	10 cm	10-25-69	4.8×10^5	7.9×10^3
	27 cm	9-19-69	1.1×10^5	1.3×10^3
	20 cm	10-25-69	4.8×10^5	1.1×10^3
	35 cm	9-19-69	4.4×10^4	7.8×10^2
	30 cm	10-25-69	1.2×10^5	3.3×10^3
	water	10-25-69	1.1×10^4	78
Toledo	surface	9-19-69	1.8×10^6	2.4×10^5
	surface	10-18-69	7.9×10^5	1.3×10^4
	surface	10-25-69	9.4×10^6	1.6×10^5
	10 cm	10-18-69	1.6×10^5	5.5×10^3
	10 cm	10-25-69	5.4×10^5	1.3×10^4
	11 cm	9-18-69	2.6×10^5	6.8×10^2
	20 cm	10-18-69	1.0×10^5	6.0×10^3
	20 cm	10-25-69	5.1×10^5	3.3×10^3
	23 cm	9-18-69	5.3×10^4	4.9×10^3
	30 cm	10-18-69	1.0×10^5	5.3×10^3
	30 cm	10-25-69	4.1×10^5	1.3×10^4
	water	10-18-69	2.3×10^4	61
	water	10-25-69	1.6×10^5	54

(a) As determined on Marine Agar 2216 medium

(b) As determined in SIM medium

EXPERIMENTAL DESIGN AND PROCEDURE

General

For this research, four different types of in situ devices were constructed to differentiate benthal respiration from planktonic respiration in the water and to differentiate benthal production from planktonic production in the water. All four respirometers attempted to simulate the actual environment factors present.

Benthal Respirometers

To measure oxygen requirements of bottom muds in tidal flat areas, benthal respirometers were constructed. See Figure 11. Both light and dark benthal respirometers were made to attempt to differentiate between benthal production and benthal demand. Six-inch inside-diameter plexiglas cylinders were cut in half longitudinally to form the benthal respirometer sections. Dark respirometer sections were coated with black epoxy paint until they were totally opaque. Flanges or cut-off walls to be embedded 4-1/2 inches into the bottom deposit were constructed of 1/8-inch thick sheet plexiglas. The half cylinder respirometer sections and the flanges were built so that they could be joined in the field using spring clips as shown in Figure 12. A soft rubber tube served as a seal between the respirometer sections and the embedded flanges. Flanges could be positioned in the bottom

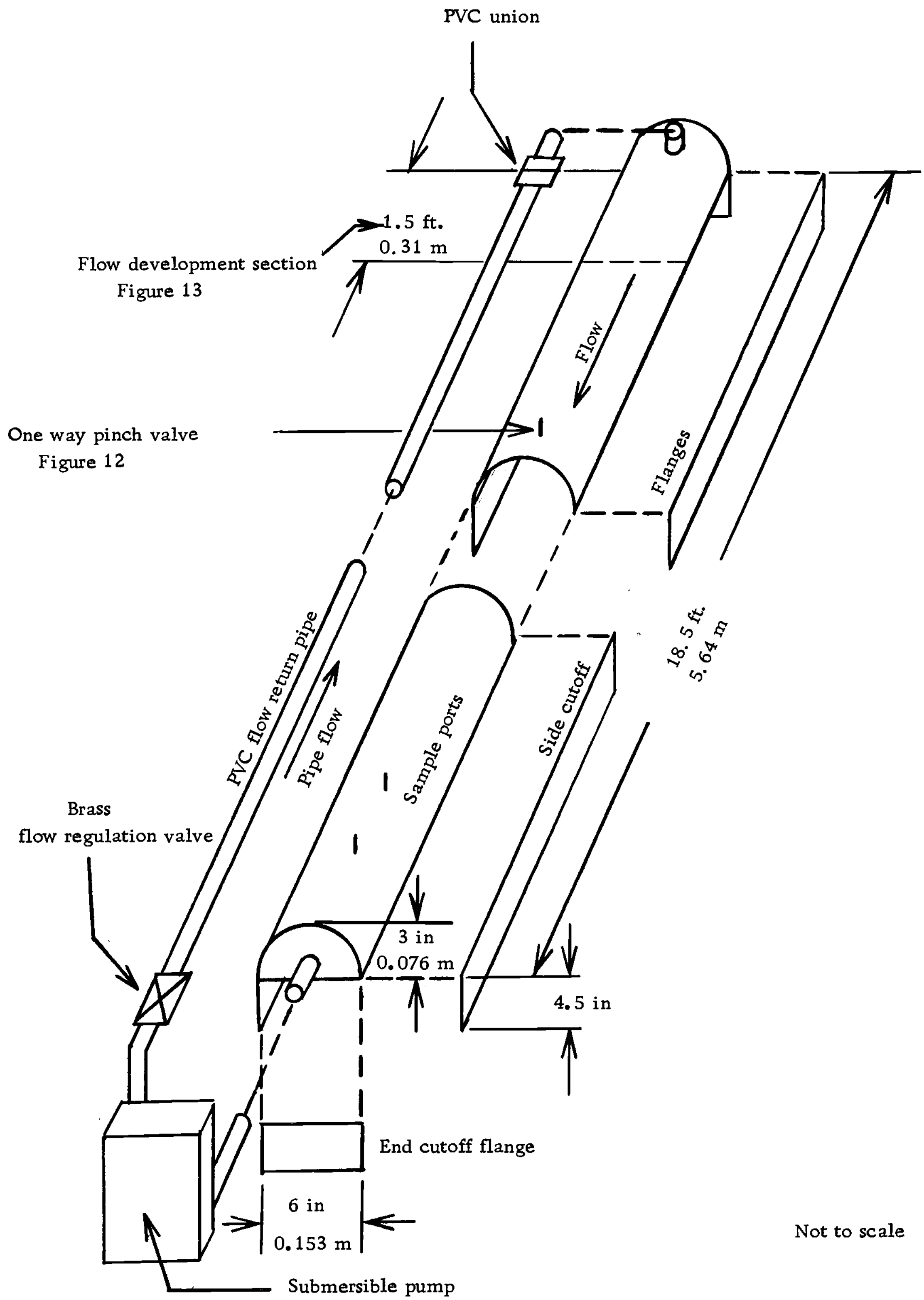


Figure 11. Schematic diagram of benthal respirometer layout.

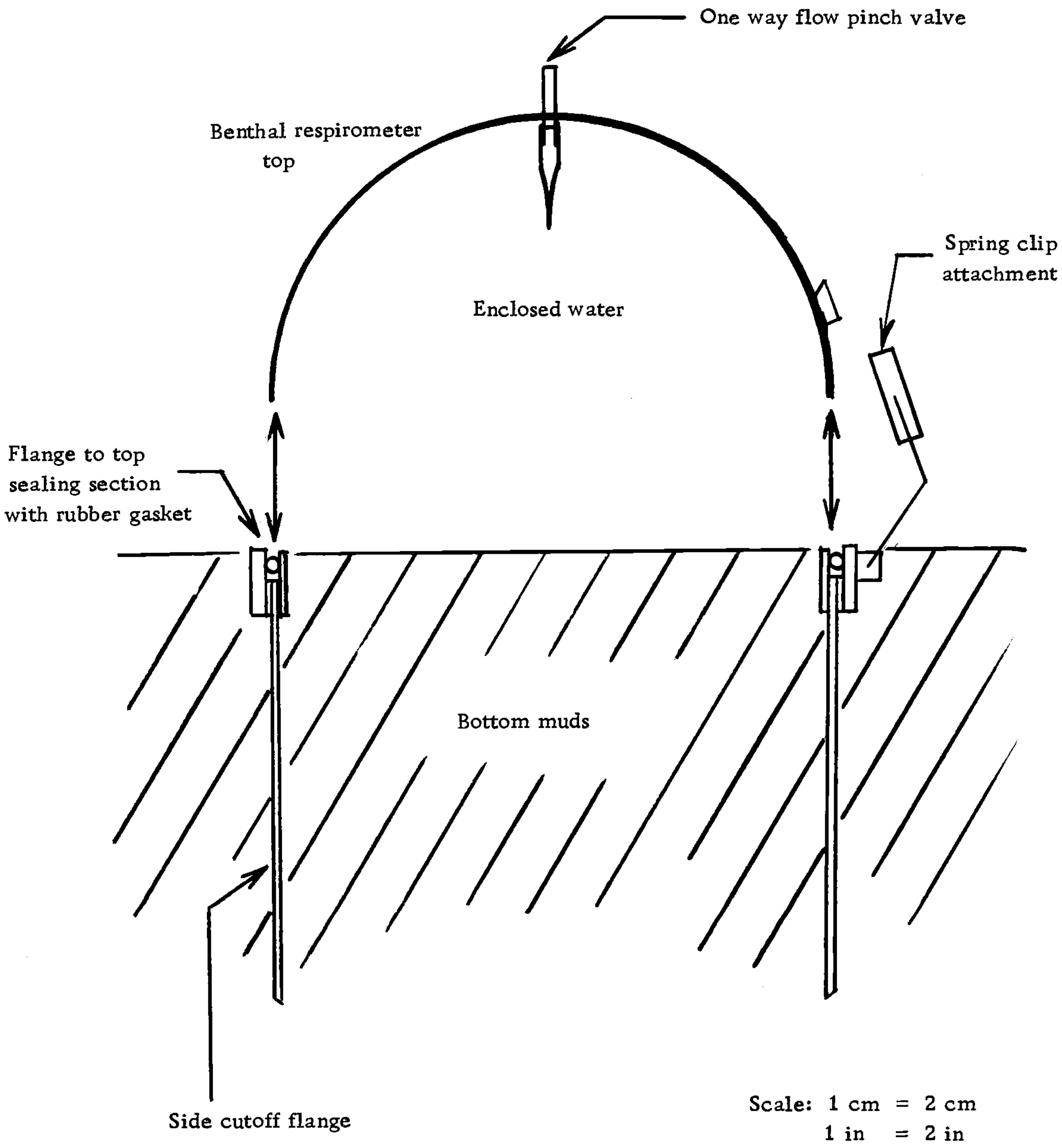


Figure 12. Benthal respirometer central cross-section.

muds days in advance of any testing so that the muds could return to a more undisturbed state. Furthermore, the respirometer sections could be placed on the flanges at low water just before the start of a test run. In this way, the area being tested for oxygen demand was disturbed a minimum amount and was covered by the respirometer only minutes before testing began.

Benthal respirometer ends were sealed with end flanges and end pieces glued onto the half cylinder sections forming a closed system of water and bottom deposit.

To provide mixing, a 1/4 hp submersible impeller pump was attached to the respirometer. Water was recycled in the benthal respirometer through the pump and a 1-1/4 inch polyvinyl chloride pipe. See Figure 11. Electric power was supplied using standard 110-volt house power or by a portable generator at the test site. Tests were run to determine if any change in dissolved oxygen concentration would result if near oxygen saturated water was passed through an impeller pump. No change was observed in any of the tests, and it was assumed that an impeller type of pump could be used to move the water in the respirometer systems without effect on dissolved oxygen concentrations.

To develop a well distributed flow in the benthal respirometer, a diffuser section was built at the inlet end. This section consisted of a sealed-off bottom floor, an inlet flow expansion chamber, and a flow development section with flow deflectors. See Figures 11 and 13. Dye dump tests indicated that a well-distributed flow did occur across the benthal respirometer cross-section.

Velocity control inside the respirometer was achieved by regulating the discharge of the pump. A 1-1/4 inch brass gate valve was used for this purpose. A rating curve showing velocity in the benthal respirometer versus turns of the gate valve is shown in Figure 14. The curve was constructed using visual observation and timings of dye flow through an inplace benthal respirometer. Velocities of 0 to slightly over 1 fps could be attained in the benthal respirometers. As stated, bottom velocities in the test areas did not exceed 0.6 fps during the test periods.

Benthal respirometer size was designed to give a water volume to mud surface area ratio so that a measurable oxygen uptake would be registered in one to five hours. From previous laboratory research done on some of the same bottom muds used for this project, a reasonable range of expected benthic uptake rates was available (25). Using these data, the required respirometer volume to mud surface area ratio was calculated. Furthermore, a long respirometer length was necessary to assure accurate velocity simulation as well as allowing a more representative selection of bottom deposit. The over-all size of deposit enclosed by the benthal respirometers was 5.33 by 0.152 meters or 0.812 m^2. The mud surface area was

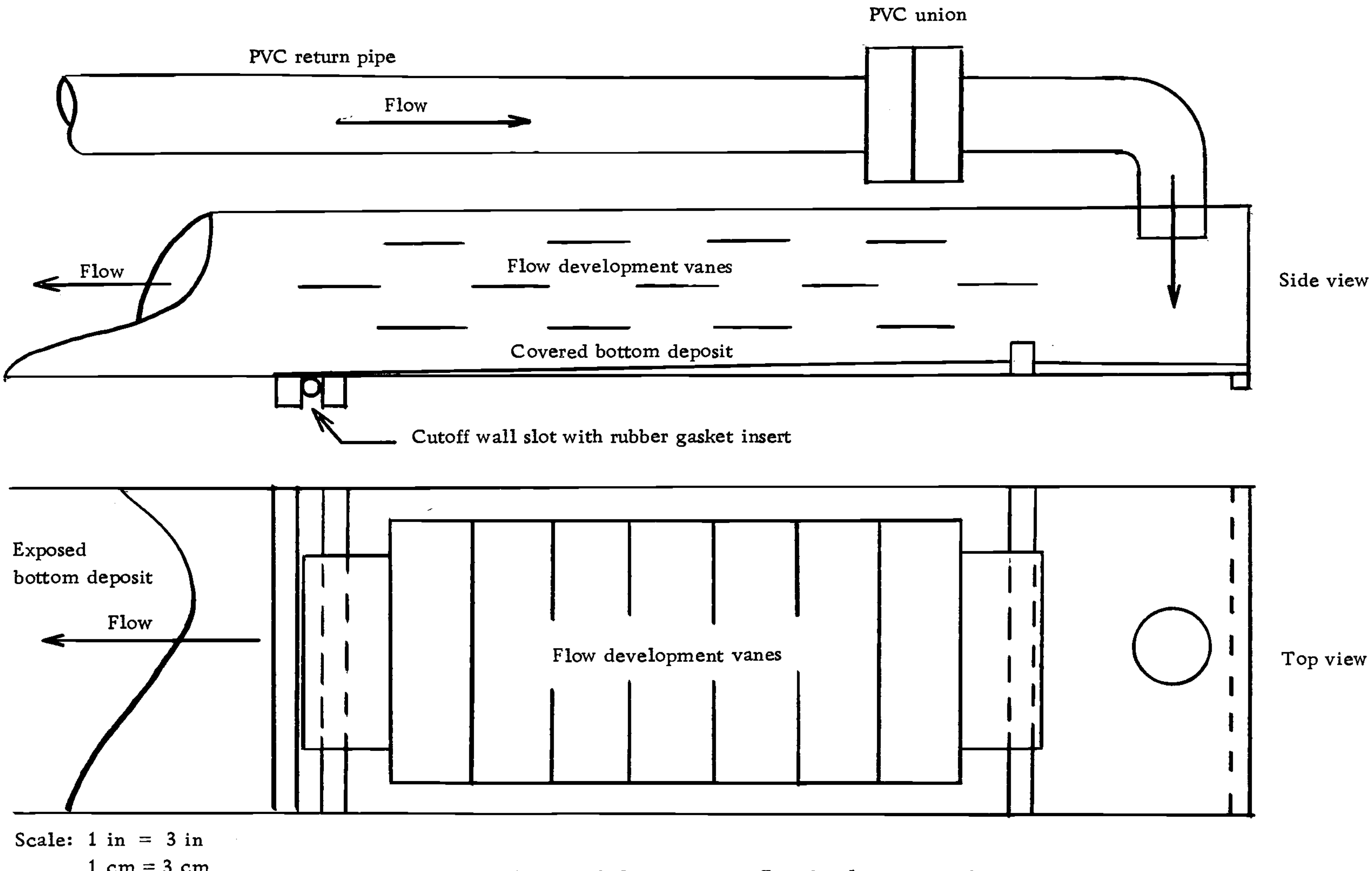


Figure 13. Benthal respirometer flow development section.

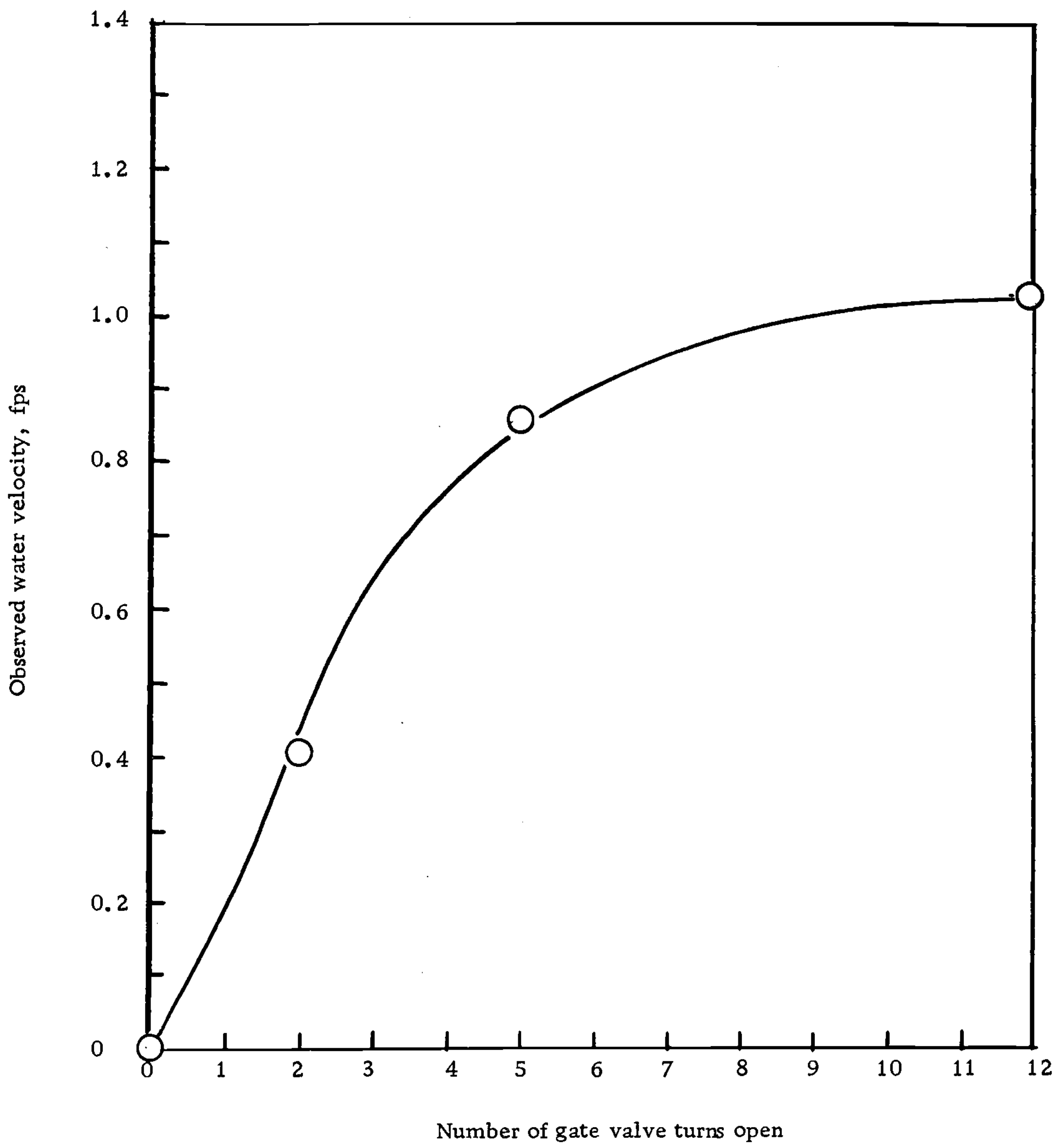


Figure 14. Number of turns that the benthal respirometer gate valve was opened versus the observed water velocity in the operating benthal respirometer.

covered by a water volume composed of the water in the six-inch diameter half-cylinder tunnel 5.64 meters long plus the water in the pump and return PVC pipe which resulted in a 60.4 liter volume. Note the 0.31 meter discrepancy between total respirometer length and bottom deposit length. This was due to the covered portion of bottom deposit in the diffuser section as stated before. See Figures 11 and 13.

Sampling procedure presented a major problem. If a dissolved oxygen meter was used, corrections for pressure and salinity would have to be made. A standard Winkler Dissolved Oxygen test was infeasible due to the large sample size required. However, by using a Micro-Winkler Dissolved Oxygen test, the total sample volume could be cut to only about two percent of the entire benthal respirometer volume during the longest test run expected. Therefore, the Micro-Winkler Dissolved Oxygen test as developed by another researcher was chosen (25). Since salinity samples were also taken, the total volume taken as a sample was about four percent of the total respirometer volume for the longest test run.

Samples were drawn to the surface from inside the benthal respirometer using a pinch valve hand pump. Lines were always cleared of any non-representative water by recirculating the water in the respirometer through the pump before sampling. Twenty-milliliter samples were drawn off by a hypodermic syringe through a serum cap on a "T" fitting in the pump line before passing through the pump itself. Changes in indicated dissolved oxygen caused by pressure changes from pumping the water to the surface for testing were found to be insignificant since the maximum depth of operation was about eight feet. Fixing chemicals were added directly to the sample in the syringe. Titration was carried out in the field using dilute (0.0025N) sodium thiosulfate as the titrant. As shown in previous work, the Micro-Winkler technique was reliable and accurate (25).

Water displaced by sampling was replaced inside the respirometer using a one-way valve allowing outside water to flow into the respirometer as the sample was withdrawn. The dissolved oxygen concentration of the incoming water was known, and the oxygen uptake rate was slightly corrected for this sample volume displacement using a mathematical model and computer simulation.

Before each test run was started, the benthal respirometers were flushed of the initial filling water. By disconnecting the PVC union on the return flow pipe while the submersible pump was in operation, fresh tidal water replaced the initial water that had accumulated in the benthal respirometers during the incoming tide. In this way, the effects of stagnant filling water or any possible effects caused by scoured material during respirometer start-up were minimized.

Several weeks before any field work began, in-lab tests were performed to evaluate the flow patterns in the respirometer, to check for any respirometer leaks, and to gain experience in setting up the benthal respirometer under simulated field conditions. For the in-lab tests a bottom deposit of fine silt was placed into a 12-foot diameter tank. The benthal respirometer diffuser section and exit end section were placed in the test tank in a similar manner as they would be in the field. The middle sections of the respirometer were not used during this in-lab test because of space limitations and because all types of joints and seams in the respirometer were present on the two sections tested.

Dye injections used for the in-lab tests indicated a well-developed flow that was evenly distributed over the benthal respirometer cross-section. No leaks from the benthal respirometer were visible throughout the in-lab tests. Under the ideal conditions of these in-lab tests no difficulties were encountered during installation of the respirometer. However, several minor changes in flange design were made before actual field testing.

Early benthal respirometer test runs were plagued with problems. Under ideal laboratory conditions, the first design of the benthal respirometer could be placed in the deposit and operated without leakage with little difficulty. However, during the first field attempts to place the respirometers, it was evident that other methods of placing the small end cutoff flanges were necessary. After several attempts and redesigns, as seen in the experimental summary Table III in the Results section, the final benthal respirometer working configuration as shown in Figure 11 evolved.

Planktonic Respirometers

In order to differentiate between benthal oxygen demand and oxygen demand due to plankton in the water over the tidal flats, light and dark planktonic respirometers were built. Similar devices had been built previously to study algal blooms (41) but had not been used in conjunction with benthal respirometer studies. The planktonic respirometers designed for this research were made so that velocity-caused mixing could be simulated.

The planktonic respirometers as shown in Figure 15 were made of three-inch inside-diameter plexiglas cylinders and were six feet in length. A small submersible pump was attached to one end while the other end was sealed except for an inlet pipe. Water was placed inside the plexiglas planktonic respirometer and recirculated through a smaller diameter plastic hose. Velocities of 0.2 fps were used in the planktonic respirometers.

The dark planktonic respirometer was made completely opaque by painting the plexiglas with black epoxy paint and using an opaque return hose.

The planktonic respirometers were designed to be filled with

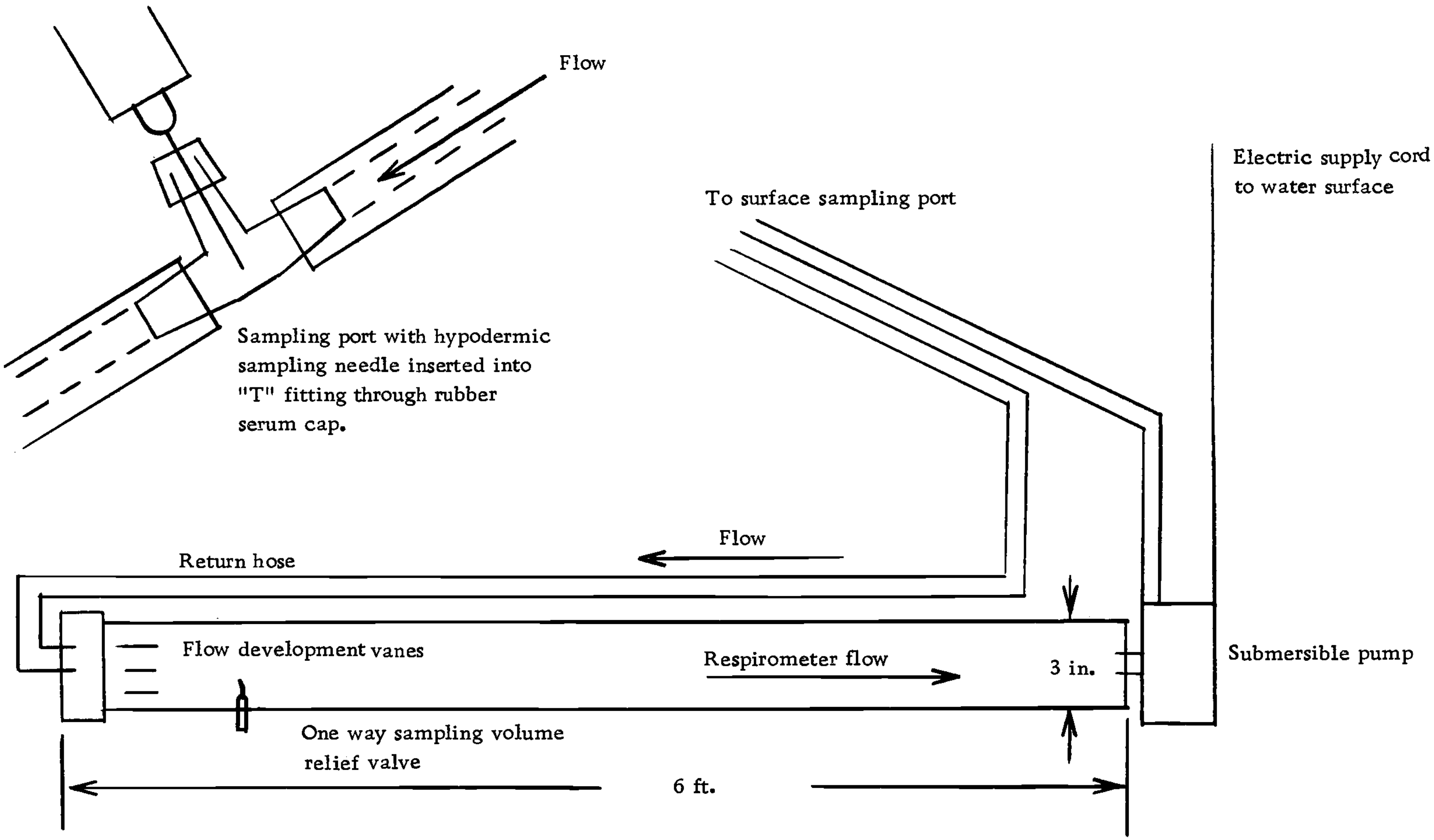


Figure 15. Planktonic respirometer and sampling ports.

estuarine water and to be placed on the tidal flat. Incoming water covered the planktonic respirometers simulating actual bottom light and temperature conditions.

The return hoses were long enough to be brought to the water's surface at high tide allowing sampling through serum caps in the return lines. Twenty-milliliter samples were taken for dissolved oxygen determination by the Micro-Winkler technique. Displaced water due to sample volume removal was replaced through one-way pinch valves. Less than three percent error was introduced because of the sampling technique requiring water to be displaced for every sample volume taken. See Figure 15 for further planktonic respirometer details.

Dissolved Oxygen Determination Equipment (Micro-Winkler)

As previously stated, a Micro-Winkler modification of the azide method was used to determine dissolved oxygen. Standard Winkler fixing chemicals were diluted to sufficient strengths to allow 20-milliliter samples to be taken instead of the usual 203-milliliter samples. A comparison with the standard Winkler method showed variations of less than 0.05 mg/l in dissolved oxygen values for the two methods (25). Possible errors that can occur in Winkler and Micro-Winkler determinations have been carefully examined by others

(7, 10). Necessary precautions were taken.

The apparatus used for dissolved oxygen sample fixing and titrating consisted of 30-milliliter hypodermic syringes, flasks of fixing chemicals, a burette, and glassware. The 30-milliliter hypodermic syringes were used to obtain samples from the various respirometers through serum caps. Fixing chemicals were drawn from inverted vacuum flasks through serum caps directly into the sample syringes. The vacuum flasks were constructed so that as fixing chemicals were removed, the displaced volume was replaced by air over the liquid. Therefore, no pressure or vacuum built up within the flask, and no possibility of sample aeration existed in the sample syringes. Samples with the two primary fixing chemicals were shaken and allowed to stand in the syringes for ten minutes before adding the final acid solution. At this point, the fixed sample was placed into a small erlenmeyer flask for titration. All samples were titrated in the field within minutes of the actual sampling.

Light Transmittance of Plexiglas

The results of an independent study were used to verify the assumption that little or no light energy was lost when light was passed through plexiglas. Tests on 1/8-inch plexiglas using a Beckman D.U.-2 spectrophotometer showed that over the visible light range, 390 millimicrons to 710 millimicrons, the percent of light transmittance varied from 92.2 to 93.1 percent respectively. See Table II. Therefore, only seven to eight percent of the visible light is obstructed when passing through 1/8-inch thick plexiglas.

Such a small interference should cause only very minor interferences with photosynthetic activity. It was concluded that the plexiglas used in constructing the respirometers would not greatly hinder any light reactions in the light respirometers.

Table II. Spectrum of 1/8-inch thick clear plexiglas run on a D.U.--2 Beckman spectrophotometer (3).

Light wave length	% observed light transmittance through 1/8-inch plexiglas
390	92.2%
410	92.2
430	92.5
450	92.5
470	92.7
490	92.7
530	92.7
550	92.7
570	92.9
590	92.9
610	92.9
630	93.1
650	93.1
670	93.1
690	93.3
710	93.1

Test Walkways and Platforms

During preliminary field testing, it was found to be difficult to walk and transport equipment through the mud to any test site. Furthermore, the test sites were to be relatively free of any gross disturbance. Therefore, a series of walkways and floats were built to gain access to the test sites. Such walkways and floats can be seen in Figures 3, 4, and 5 at the respective test sites.

Small two-inch by four-inch "pilings" were driven into the tidal flat mud. Using a series of two pilings and a cross member, a foundation was formed over which board walks could be placed at low water. These walkways proved to be very acceptable showing no visable effect upon surrounding mud during use. Areas near the actual test site with walkways were allowed to adjust to the small pilings for at least two weeks before any testing occurred. No changes in formations or even shrimp activity at the Parker Slough site were noticed during this period of adjustment. Bottom flanges for the benthal respirometers were in place during the two-week adjustment period also.

After the access problem to the test sites was solved, means of holding power plugs, sampling pumps, and thermistor connections was needed over the sampling sites. At the Parker Slough site, a large aluminum tripod was used. The three legs of the tripod were placed into the tidal flat area some distance from the respirometers so that no disturbance would occur. Power cords to the submersible electric pumps, cords from the temperature monitoring thermistors inside and outside the respirometers, and sampling tubes from the respirometers were attached to the tripod. The tripod also made an effective boat morage during sampling.

The Toledo test site was located near an existing floating log storage boom that was positioned by several pilings. A platform was built on this log float to accommodate equipment and personnel. Walkways similar to those used at Parker Slough were used to gain complete access to the respirometers. Power cords, thermistor wires, and sampling tubes were attached to a boom and plank attached to the log float. The cords and sampling tubes were thus positioned directly over their sites on the bottom.

BENTHAL RESPIROMETER SALINITY DISSOLVED OXYGEN, AND BOD BALANCE

General

To more thoroughly explain and analyze the results of the respirometer study, a mathematical model of the benthal respirometer system was developed. The model was formulated so that many of the possible variations that could occur during a respirometer run might be mathematically evaluated.

During initial benthal respirometer runs, excessive leakage was evident at the Parker Slough test site. The leakage was found to be caused by the extensive mud shrimp burrow activity. A mathematical simulation and leakage correction model became a necessity for evaluating leakage as well as helping to determine the importance of different mechanisms or processes of benthal uptake. The model was applied to all test runs where salinity data were taken, and corrected uptake rates were calculated where leakage existed. Salinity data were used to evaluate leakage rates.

Mathematical Model of the Benthal Respirometer System

Using mass balance techniques, mathematical models for variations of salinity, dissolved oxygen, and oxygen demand or BOD within the respirometer were developed. A schematic diagram of a benthal respirometer system is shown in Figure 16 with an explanation of terminology used for the equation formulation. The mass balance concept is shown by the follcwing expression.

$$\begin{bmatrix}\text{Rate change of sub-}\\\text{stance mass within the}\\\text{respirometer volume}\end{bmatrix} = \begin{bmatrix}\text{Rate of substance}\\\text{input into the}\\\text{volume}\end{bmatrix} - \begin{bmatrix}\text{Rate of substance}\\\text{output out of the}\\\text{volume}\end{bmatrix}$$

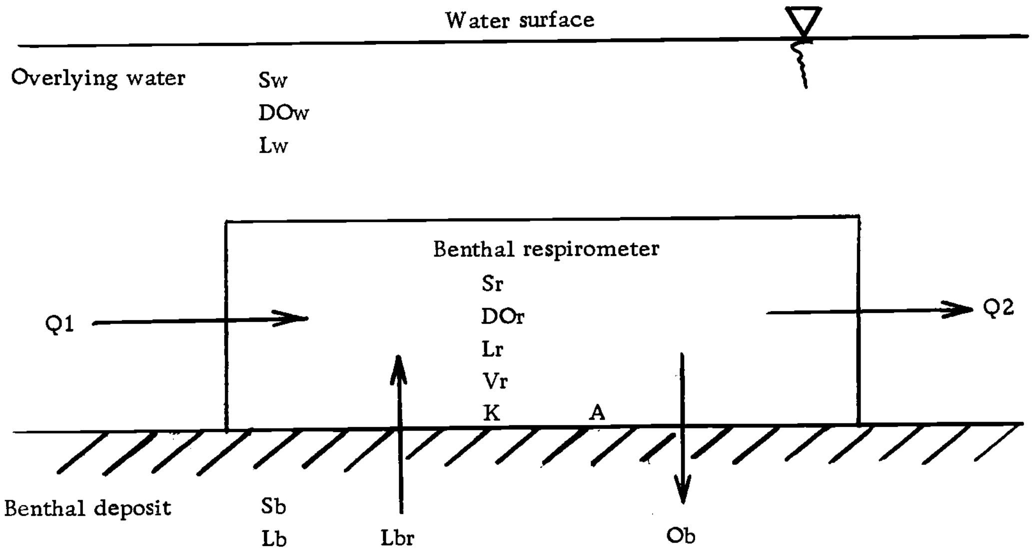
From Figure 16 and the mass balance relationship, the mass balance equation for changes in salinity was derived as shown in Equation 1.

Salinity Balance:

$$\frac{d(Sr)}{dt} = \frac{(Q_1)(Sw)}{Vr} - \frac{(Q_2)(Sr)}{Vr} \qquad (1)$$

It was assumed that the only mechanism of salinity change was by direct leakage into and out of the system. Some initial changes in salinity might be caused by bottom scour, but such changes cannot be evaluated at this time because of the minimal data available. Salinity changes that might arise from diffusion of material into or out of the bottom deposit were also considered to be small compared to leakage caused changes. Therefore, terms containing Sb do not appear in Equation 1. Volume of the respirometer was a constant.

A similar approach was used to model the changes in oxygen demand (BOD) and dissolved oxygen concentration (DOr). The following equations resulted.



Term	Units	Description
Q1	ml/min	Possible leakage into the system.
Q2	ml/min	Possible leakage out of the system, Q1 = Q2.
Sw	o/oo	Salinity in the overlying water.
DOw	mg/liter	Dissolved oxygen concentration in the overlying water.
Lw	mg/liter	Oxygen demand of the overlying water (BOD).
Sr	o/oo	Salinity in the respirometer.
DOr	mg/liter	Dissolved oxygen concentration in the respirometer.
DOri	mg/liter	Initial dissolved oxygen concentration in the respirometer.
Lr	mg/liter	Oxygen demand of the respirometer water (BOD).
Lri	mg/liter	Initial oxygen demand of the respirometer water.
Vr	liter	Volume of the respirometer.
K	1/min	Decay coefficient of the oxygen demand.
Sb	o/oo	Salinity of the bottom muds and interstitial water.
Lb	mg/liter	Oxygen demand of the interstitial water (BOD).
Lbr	mg/min	Rate of input of oxygen demanding material into the respirometer system from the covered mud area (A).
Ob	mg/min	Rate of oxygen diffusing into the covered bottom mud area (A).
A	m^2	Mud surface area covered by the respirometer.

Figure 16. Properties of the benthal respirometer system and its surroundings with the nomenclature used in the salinity and dissolved oxygen mass balance equations.

Oxygen Demand (BOD) Balance:

$$\frac{d(Lr)}{dt} = \frac{(Q)(Lw)}{Vr} - \frac{(Q)(Lr)}{Vr} - (K)(Lr) + \frac{Lbr}{Vr} \quad (2)$$

Dissolved Oxygen Balance:

$$\frac{d(DOr)}{dt} = \frac{(Q)(DOw)}{Vr} - \frac{(Q)(DOr)}{Vr} - (K)(Lr) - \frac{Ob}{Vr} \quad (3)$$

In deriving Equation 2, it was assumed that the rate of input of oxygen demanding material into the respirometer (Lbr) was independent of changes in respirometer BOD (Lr). No measurements were made to determine the effect of the interstitial BOD (Lb). The BOD in the overlying water (Lw) was considered to be zero. This was found to be the case during planktonic respirometer studies. By continuity of water, Q_1 was considered to equal Q_2. In Equation 3, the diffusion of oxygen into the bottom deposit (Ob) was assumed to be at a constant rate.

Calculation of Leakage

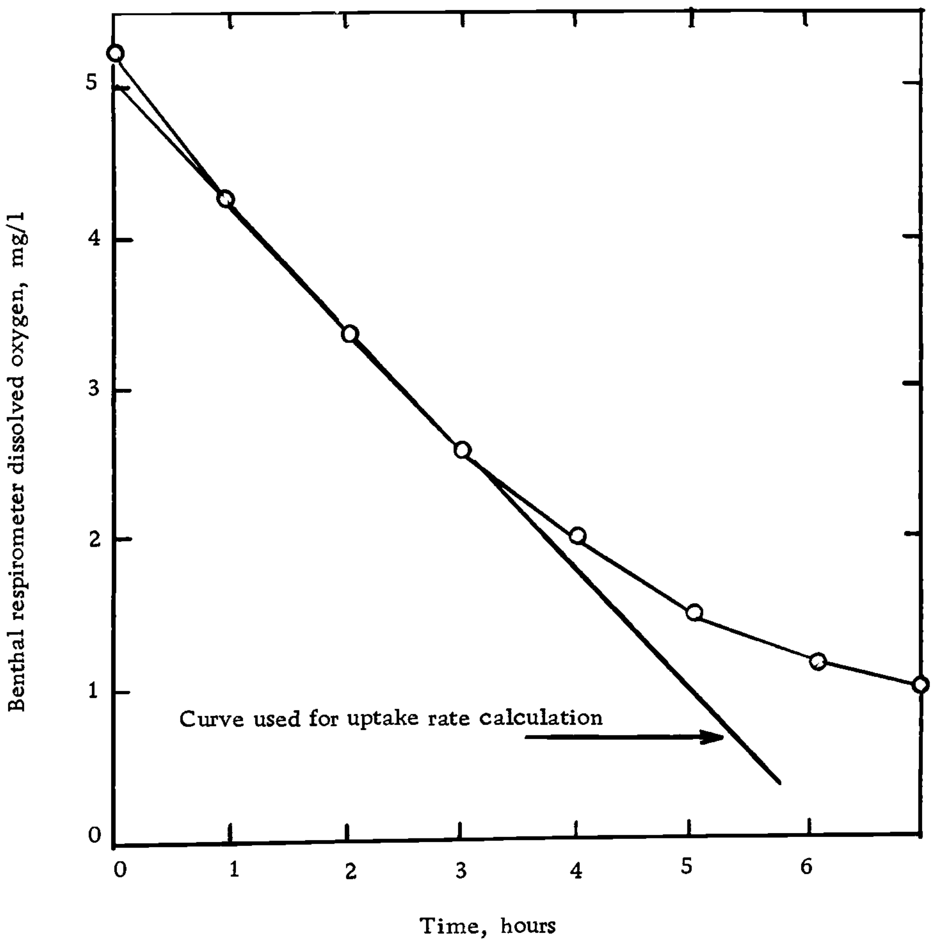
The availability of the benthal respirometer model made possible the calculation of leakage rates or total leakage of the respirometer system using only salinity data for water in the respirometer and overlying water. By multiple regression analysis, curves could be fitted to measured salinity data so that the $\frac{d(Sr)}{dt}$, Sw, and Sr could be evaluated at any time. Respirometer volume was a constant value of 60.4 liters and by continuity of water, Q_1 was assumed to equal Q_2. Therefore, all necessary values in the salinity mass balance equation were known, and estimates of leakage rates that occurred could be calculated using Equation 1.

DO Uptake Rate Calculations

Equations 1 and 3 were solved using the Runge-Kutta method for finite difference solutions. Fourth order solutions were obtained. Curve fits were used to input required measured quantities such as (DOr), (DOw), (Sr), and (Sw). By solving the salinity mass balance Equation 1 and the dissolved oxygen mass balance Equation 3 simultaneously, total oxygen uptake could be calculated by assuming (-K(Lr)-Ob/Vr) to be the unknown rate of benthal oxygen demand. Corrections could then be made for respirometer leakage. Therefore, even respirometer runs with high leakage rates could be corrected to obtain estimates of the true oxygen uptake rates. Of course, the basic assumption that the benthal uptake rate was not changed because of the leakage mechanism had to be made. For Parker Slough benthal respirometer runs where leakage was by way of mud shrimp burrows, only the evident uptake rates could be computed. No analysis of the uptake due to the benthos could be separated from that which may have been caused by water passing through the shrimp burrows.

During most benthal respirometer runs, slightly more rapid rates of oxygen demand were measured in the first hour of the run than for any succeeding time period. Furthermore, small increases in salinity usually occurred inside the benthal respirometers at start-up. It was hypothesized that some minor initial scour of bottom material occurred during respirometer start-up resulting in the slight increases in oxygen demand and salinity measured in the respirometers. Therefore, during benthal respirometer start-up, water in the respirometer was replaced by disconnecting the return flow pipe at the PVC union (see Figure 11) and allowing the pump to introduce fresh water into the respirometer. Even then, rapid initial oxygen uptake often occurred. Only DO measurements taken after the initial rapid uptake were utilized in calculating DO uptake rates.

Final uptake rates were lower than initial or intermediate rates in all cases. Reported representative benthal uptake rates as shown in Table IV were calculated using the intermediate portion of the corrected benthal uptake curve. A sample plot of oxygen concentration in a dark respirometer versus time of respirometer run with example uptake calculations is shown in Figure 17.



$$\text{Uptake rate} = \frac{(\Delta\, DOr)\,(Vr)\,(24\ hr)}{(\Delta T)\,(A)} \quad **$$

$$= \frac{(3.5\ mg/l)\,(60.4\ l)\,(24\ hr/day)}{(4.3\ hr)\,(0.813\ m^2)\,(1000\ mg/gm)}$$

$$= 1.45\ gm\ O_2/m^2 - day$$

**See Figure 15 for nomenclature

Figure 17. Sample calculation of benthal oxygen uptake rate for the 9-5-69 test run at the Toledo test site.

RESULTS

General

Benthal oxygen uptake rates of from 1.35 gm O_2/m^2 - day to 2.13 gm O_2/m^2 - day were measured at the Toledo test site. Slight benthal respirometer leakages occurred at the Toledo test site on about half of the test runs made, but corrections made using the computer simulation model changed the uptake rates only slightly. A difference was noted between light and dark benthal uptakes. However, due to the remote location of the test site and the difficulty in operating two respirometers simultaneously, only one sample run was made using both light and dark benthal respirometers. Planktonic respirometer tests showed no measurable oxygen demand was exerted by chemical or biological activity in the water at the Toledo site. All the demand measured in the benthal respirometers was due to the benthal deposits.

Excessive benthal respirometer leakage rates were evident at the Parker Slough test site. However, using the computer simulation model, corrected benthal uptake rates of from 4.8 gm O_2/m^2 - day to 8.5 gm O_2/m^2 - day were calculated. It was found that the benthal respirometer leakage at the Parker Slough site was by way of mud shrimp burrows which may have resulted in the large uptake rates. Oxygen demand of the estuary water was again found to be insignificant for the length of time of the sample runs. Supersaturated dissolved oxygen conditions were encountered at the Parker Slough site during the first part of the summer. These conditions were believed to be caused by large masses of free floating algal growths and the benthal algal communities.

Table III summarizes all of the experiments made during this research. Various notes concerning specific problems and findings can be found in the comments section of the table.

Figures 18 through 23 show plots of all data taken during planktonic respirometer test runs. The lack of any significant planktonic oxygen demand can be readily observed.

Figures 24 through 34 illustrate the results of all benthal respirometer runs where salinity data were taken. Corrected oxygen uptake curves are shown on runs where correction using the mathematical model was necessary. The broken correction curves in Figure 25 are the result of a multiple correction procedure. The left corrected curve was made for the portion of the uncorrected data that shows an apparent uptake. Starting with different initial conditions, the right corrected curve was made for the portion of the uncorrected oxygen curve that appears to be stabilized at a constant value.

Table III. Summary of test runs.

Date	Experiment	Location	Respirometer velocity (fps)	Comments
4-13-69	D.O. changes through pump	Lab		No changes in D.O. when pumped.
7-3	Light respirometer	Lab	0 to 1 fps	Six ft. section in a test tank. No leaks with dye run and well distributed velocity profile.
7-15	Light respirometer	Parker Slough	0.8	End section broken - a re-design.
7-18	Light respirometer		0.8	End flanges broken - re-design.
7-28	Light respirometer		0.8	Overcast 1/2 of run - when sun came out D.O. in respirometer increased - leakage probable.
7-29	Velocity monitoring	Parker Slough		Maximum bottom velocity = 0.4 fps.
8-13	Velocity monitoring	Parker Slough		Maximum bottom velocity = 0.3 fps.
	Light respirometer		0.8	Leakage probable.
	Dark respirometer		0.8	
	Light planktonic respirometer		0.2	
	Dark planktonic respirometer		0.2	
8-15	Light respirometer	Parker Slough	0.8	Leakage probable.
	Dark respirometer		0.8	
	Light planktonic respirometer		0.2	No BOD measured.
	Dark planktonic respirometer		0.2	
8-18	Light planktonic respirometer	OSU Dock	0.2	No BOD measured.
	Dark planktonic respirometer		0.2	Tidal height varied.
8-19	Light planktonic respirometer	OSU Dock	0.2	Planktonic respirometers kept at constant depth to test changes in uptake due to tidal fluctuations.
	Dark planktonic respirometer		0.2	

Table III Continued.

Date	Experiment	Location	Respirometer velocity (fps)	Comments
8-20	Light respirometer Dark respirometer Light planktonic respirometer Dark planktonic respirometer	Parker Slough	0.8 0.8 0.2 0.2	Run ended after dark. Uptake same as surrounding water, leaks apparent. However, no BOD measured (No large algae in light planktonic respirometers).
8-22	Light planktonic respirometer Dark planktonic respirometer	Toledo	0.2 0.2	No BOD in water for short term test (4 hrs.).
8-25	Velocity monitoring	Toledo	--	Meter failure.
8-26	Velocity monitoring		--	Meter failure.
8-27	Velocity monitoring			Maximum bottom velocity = 0.6 fps.
8-29	Light respirometer Dark respirometer	Toledo	0.8 0.8	Salinity samples taken so corrections for leakages can be made.
9-2	Dye check Dye check for velocity measurement Changes in salinity with scour	Parker Slough		Leaks around diffuser end (higher pressure). Velocities in the respirometers correlated to turns of valve. Measurable changes in salinity occur when bottom muds are scoured.
9-3	Dark respirometer	Toledo	0.8	Salinity data - small leakage.
9-5	Dark respirometer	Toledo	0.4	No leaks - salinity data O_2 uptake = 1.25 gm O_2/m^2-day.
9-8	Dark respirometer	Toledo	0.55	No leaks - salinity data.

Table III Continued.

Date	Experiment	Location	Respirometer velocities (fps)	Comments
9-9	Dark respirometer	Toledo	0.8	No leaks - salinity data (initial scour).
9-9	Dark respirometer	Toledo	0.8	No leaks - salinity data O_2 uptake = 2.05 gm O_2/m^2-day.
9-10	Dark respirometer	Parker Slough	0.4	Leaks - salinity data. Hypothesis - shrimp burrows are the cause of leaks.
9-11	Dark respirometer	Parker Slough	0.4	Leaks - dye run to try to find leaks - no leaks after 5 min. tide too low.
9-16	Dark respirometer	Parker Slough	0.4	Leaks - salinity data - dye showed shrimp burrows to be paths of leakage. First leak sighted from burrow 2 ft. from respirometer after 7 min.

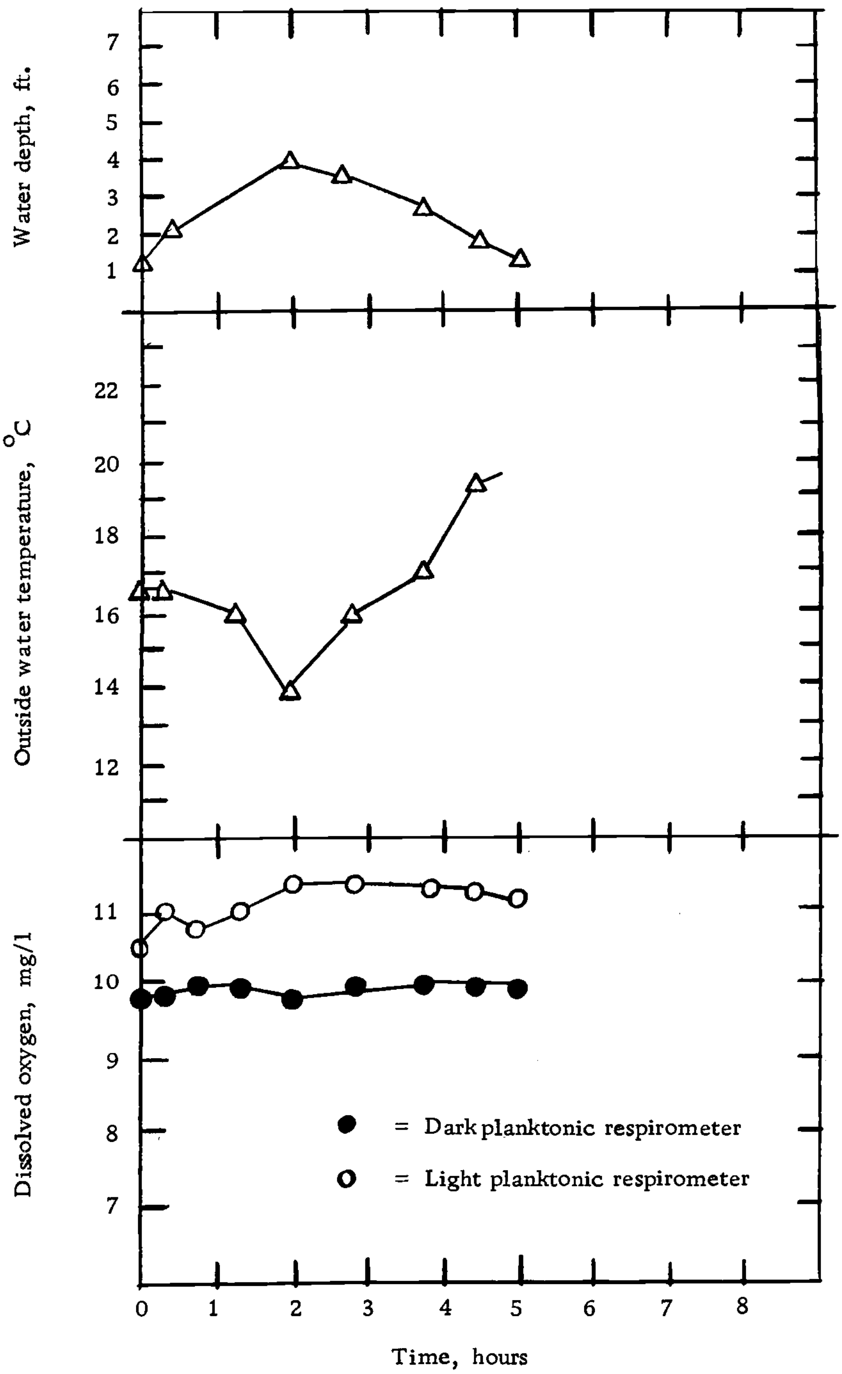


Figure 18. Light and dark planktonic respirometer measurements taken at the Parker Slough test site, 8-13-69.

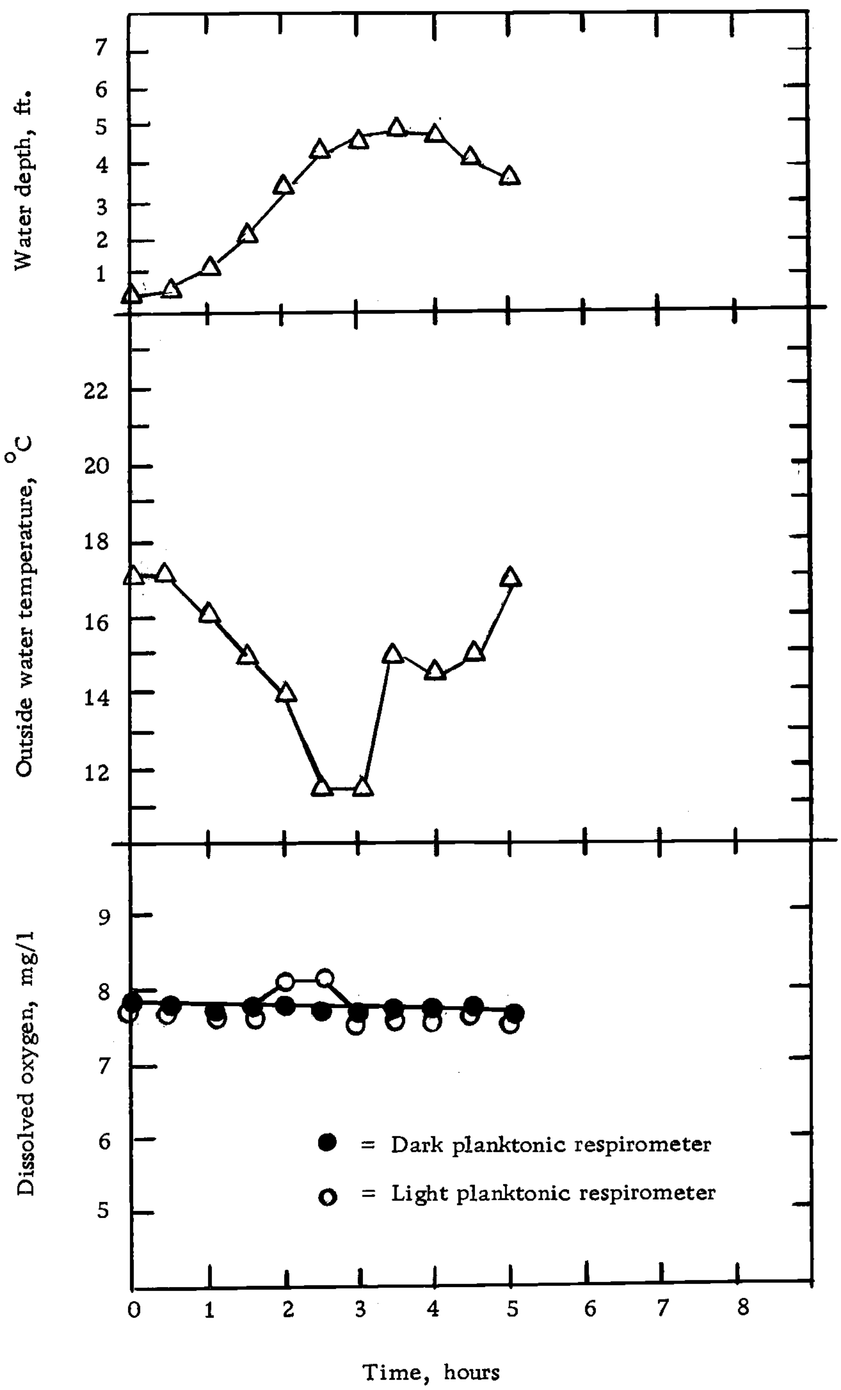


Figure 19. Light and dark planktonic respirometer measurements taken at the Parker Slough test site, 8-15-69.

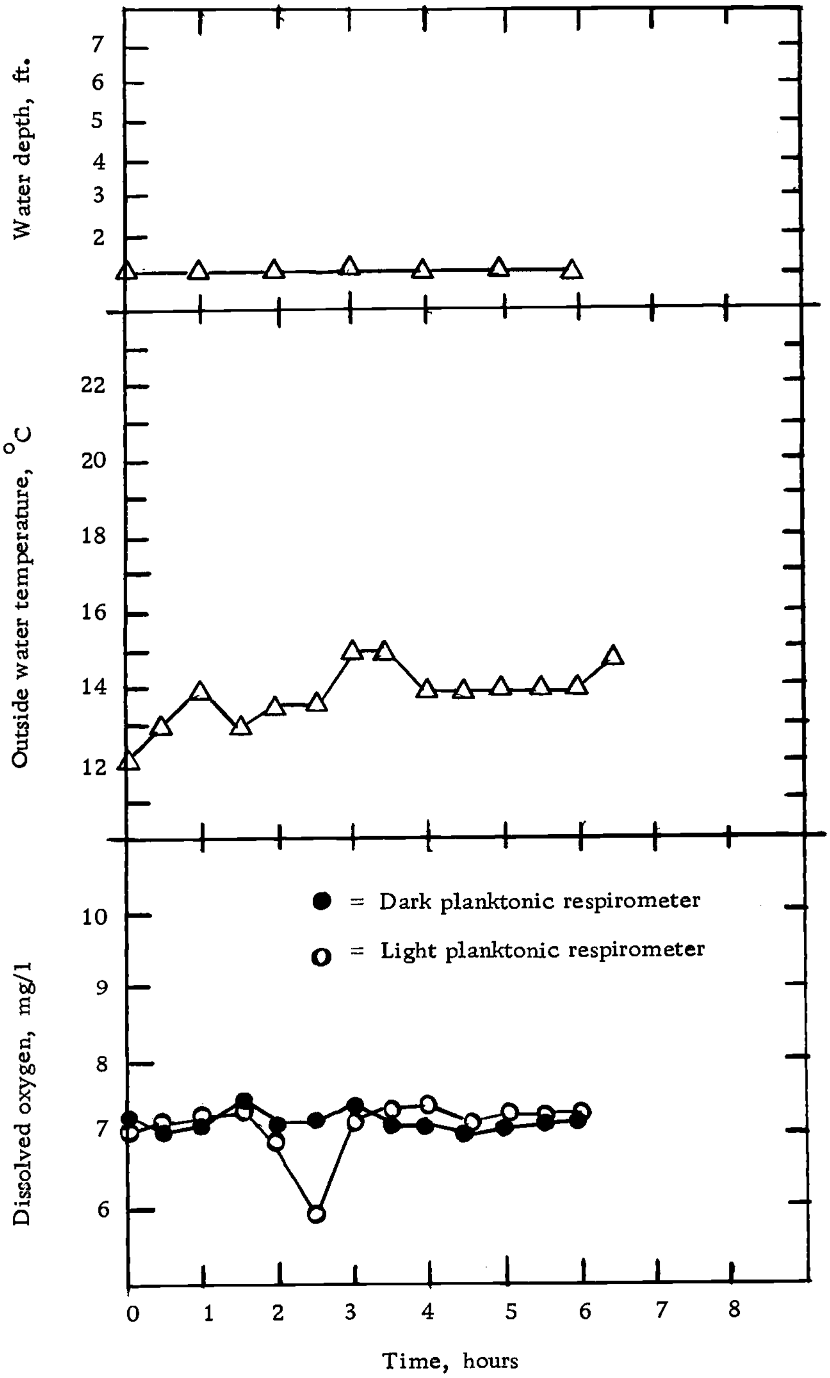


Figure 20. Light and dark planktonic respirometer measurements taken at the Oregon State University Marine Science Center dock at a constant depth, 8-19-69.

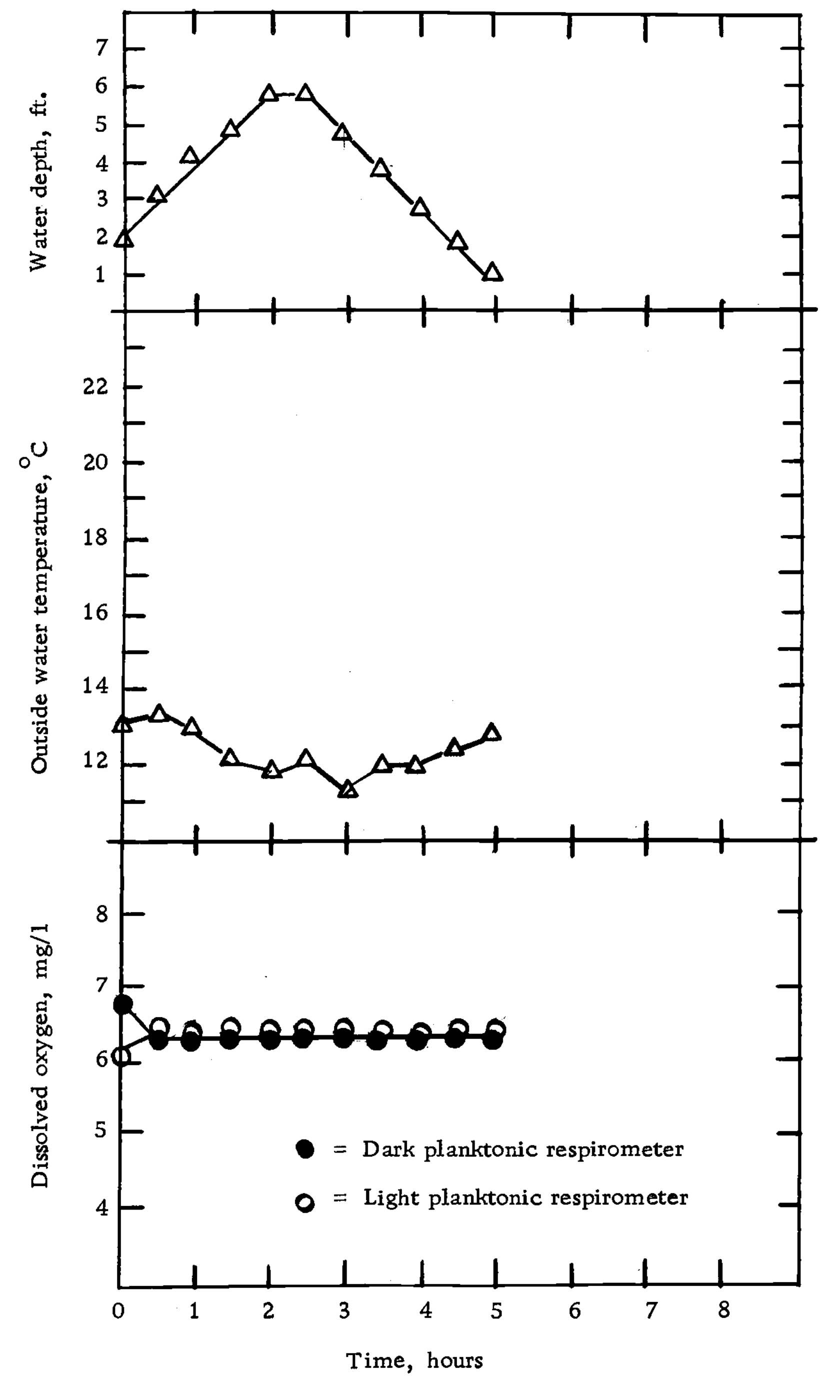


Figure 21. Light and dark planktonic respirometer measurements taken at the Oregon State University Marine Science Center dock, 8-18-69.

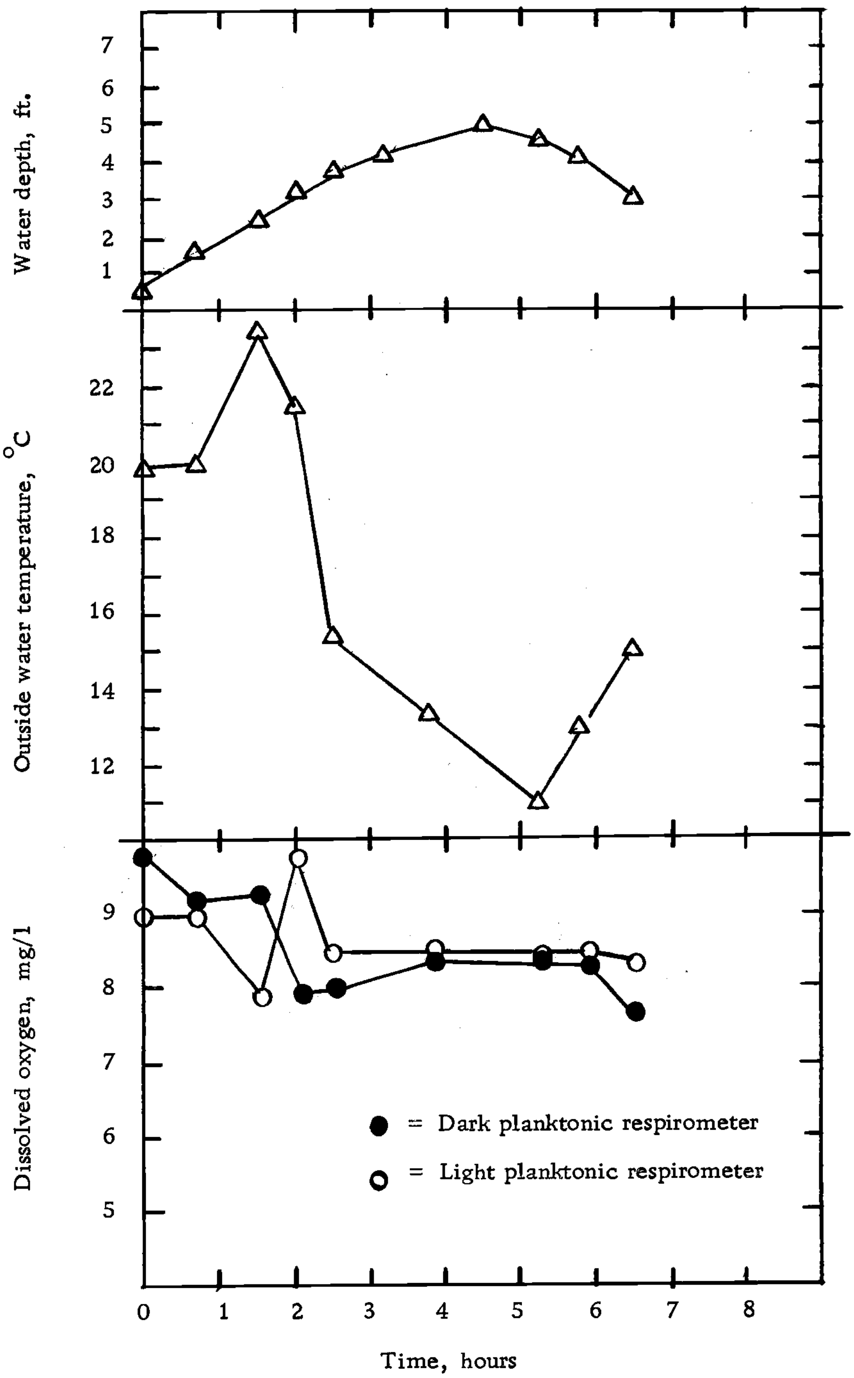


Figure 22. Light and dark planktonic respirometer measurement taken at the Parker Slough test site, 8-20-69.

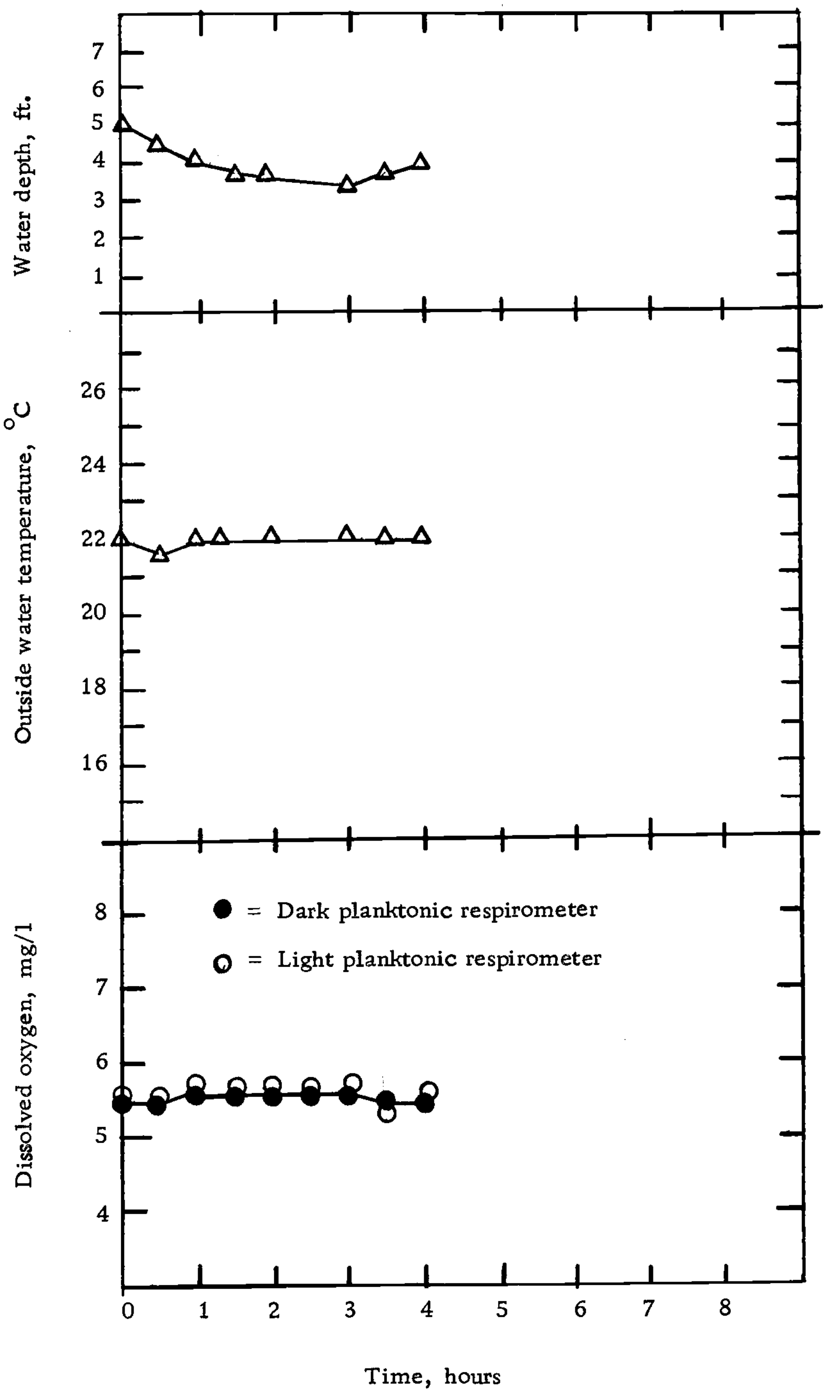


Figure 23. Light and dark planktonic respirometer measurement taken at the Toledo test site, 8-22-69.

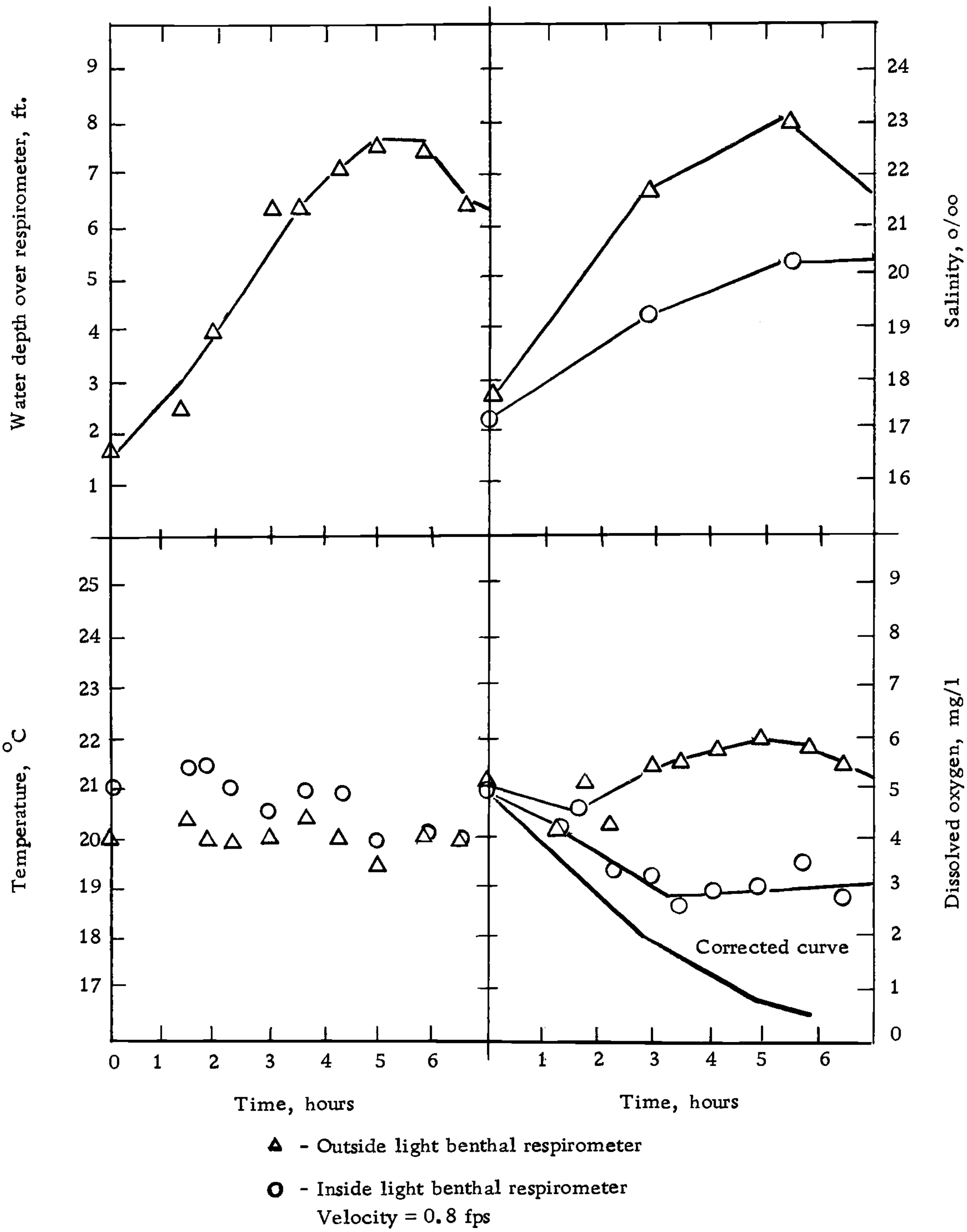


Figure 24. Summary of benthal respirometer data taken at the Toledo test site, 8-29-69, light respirometer.

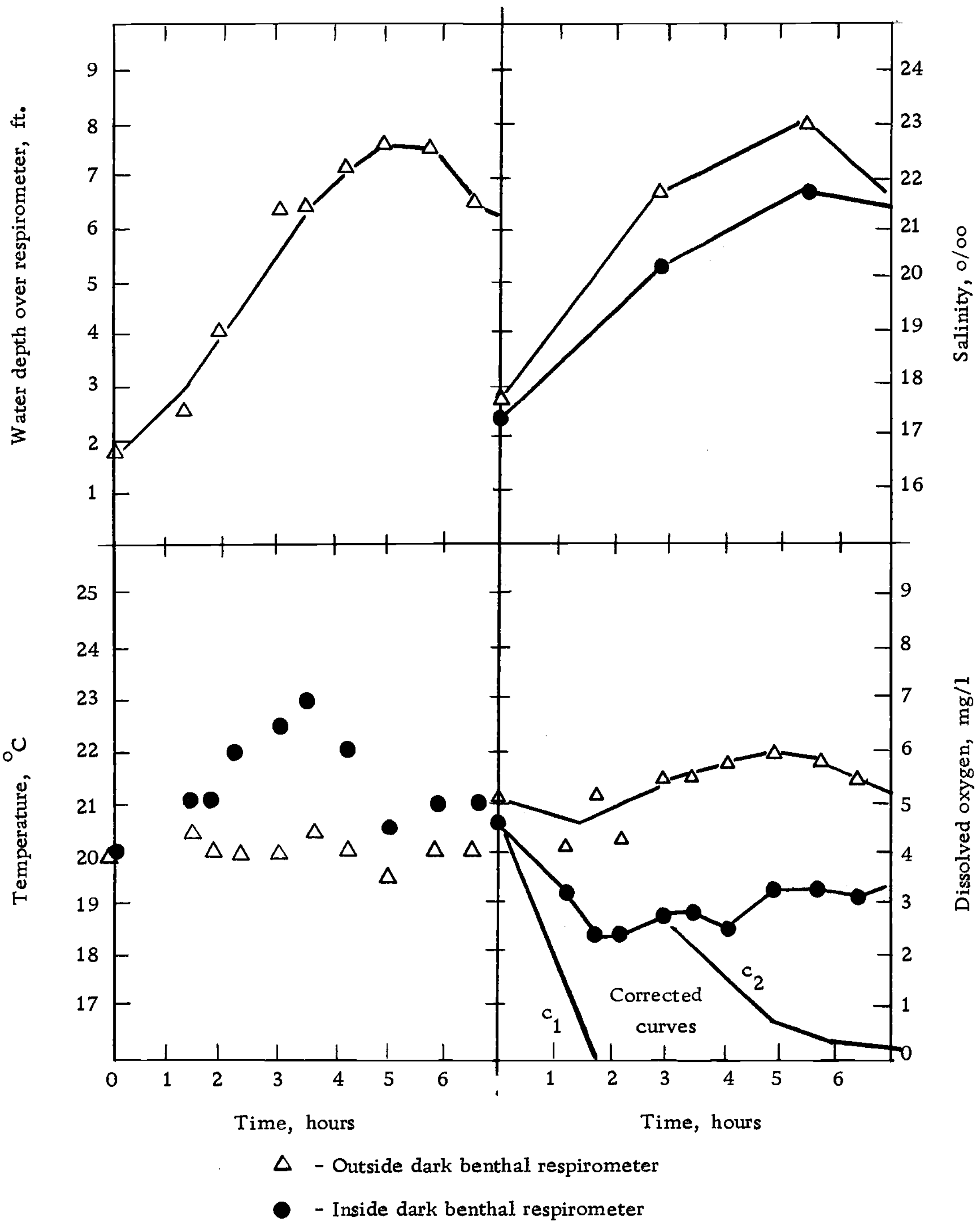


Figure 25. Summary of benthal respirometer data taken at the Toledo test site, 8-29-69, dark respirometer.

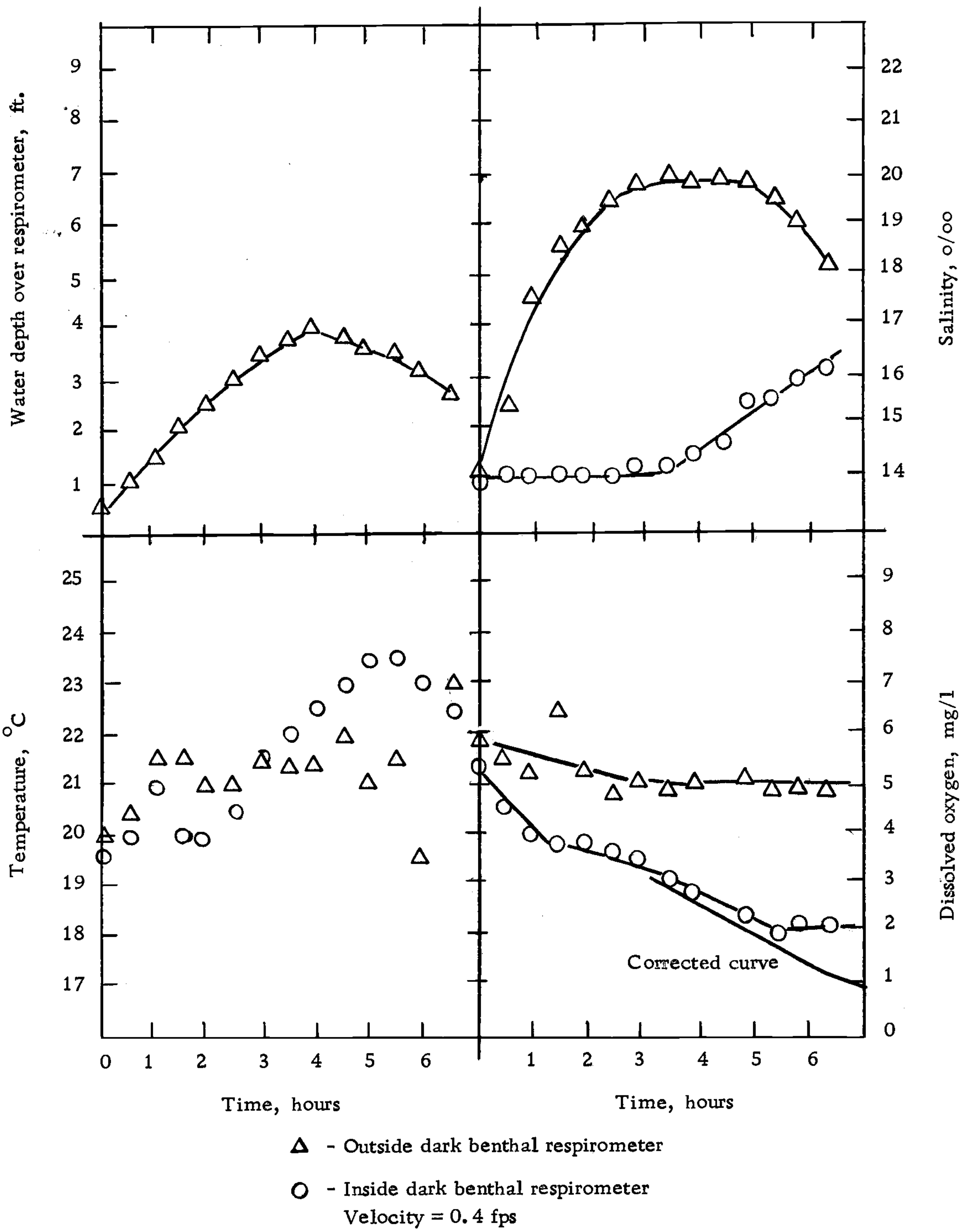


Figure 26. Summary of benthal respirometer data taken at the Toledo test site, 9-3-69.

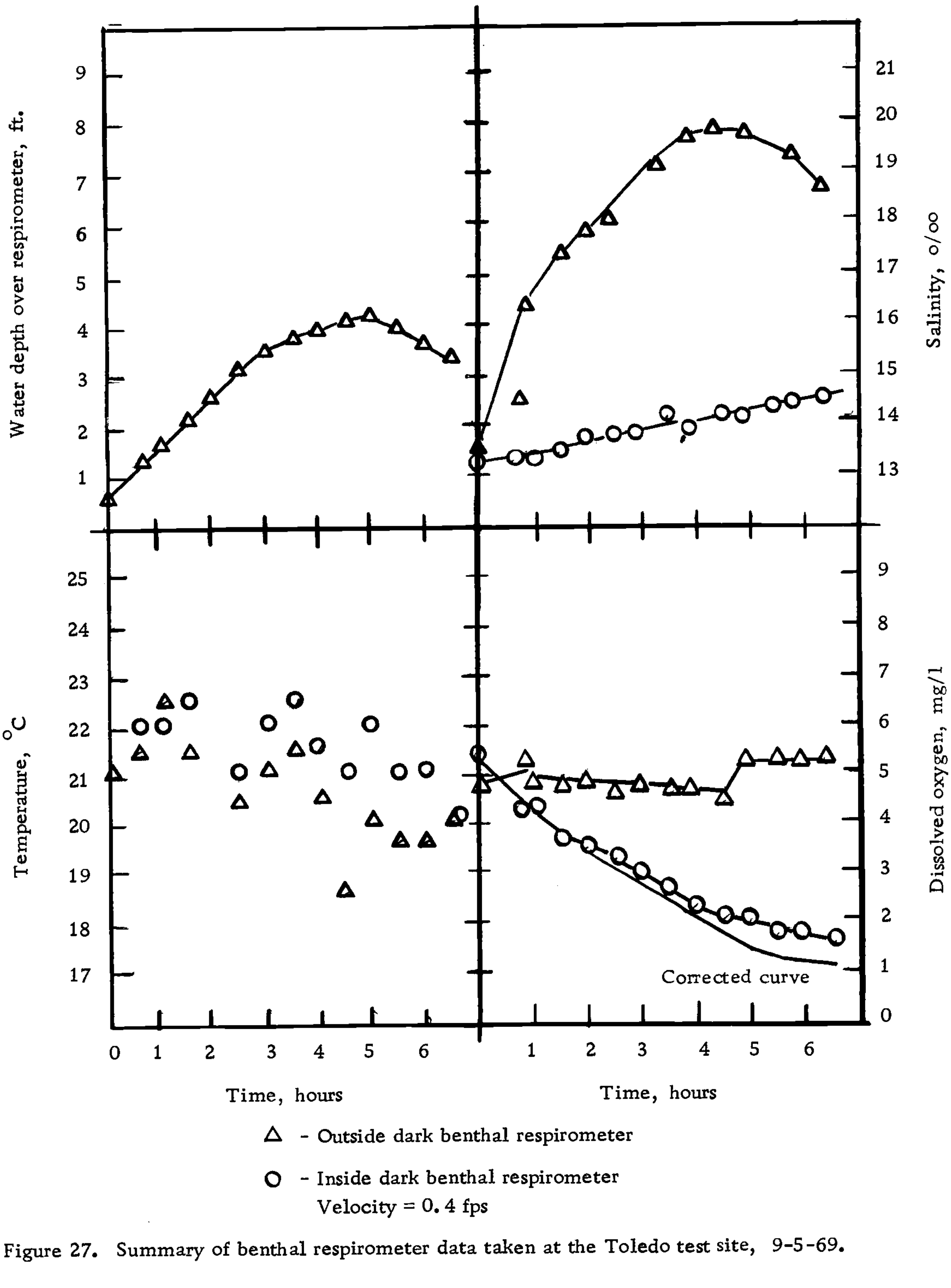


Figure 27. Summary of benthal respirometer data taken at the Toledo test site, 9-5-69.

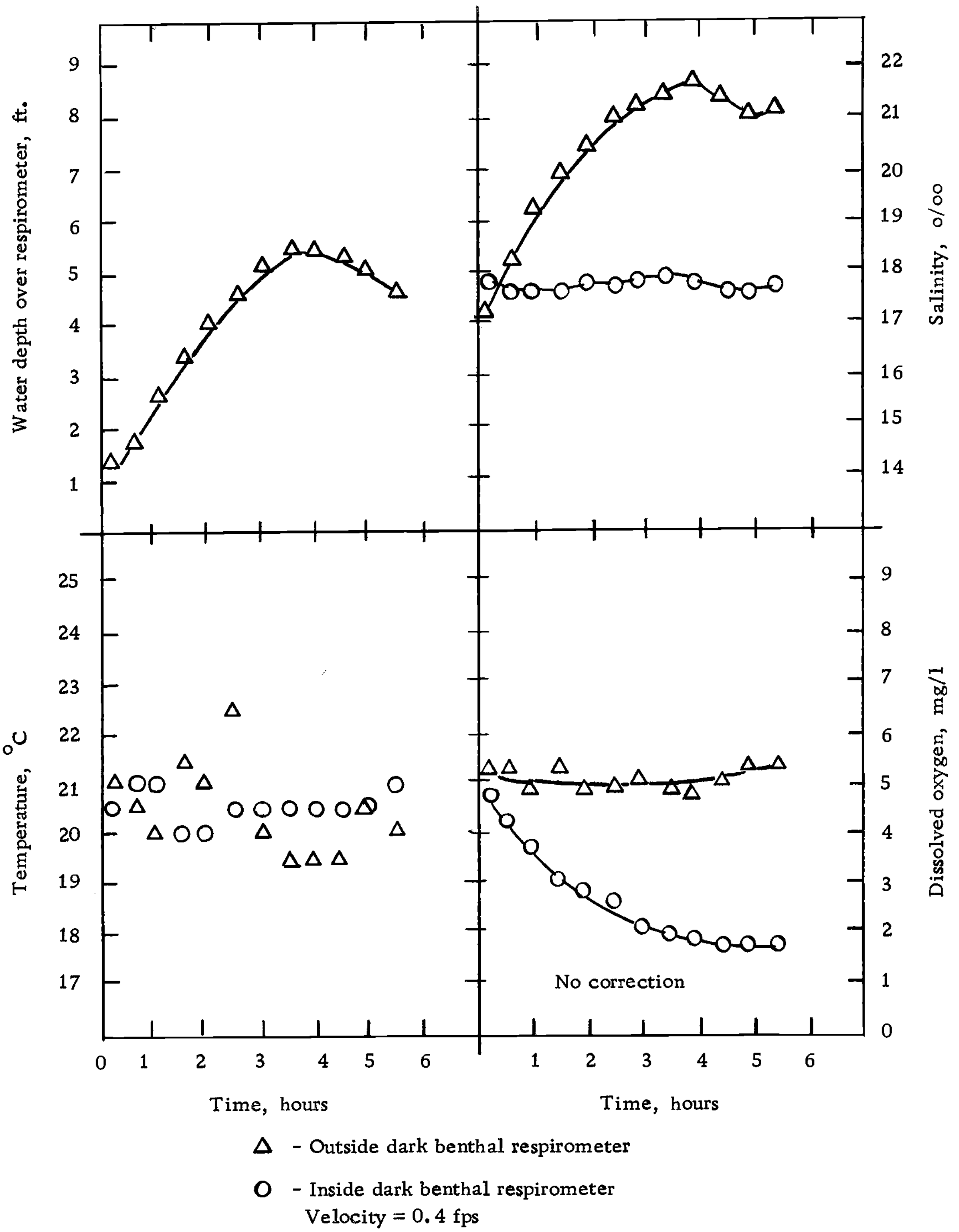


Figure 28. Summary of benthal respirometer data taken at the Toledo test site, 9-8-69.

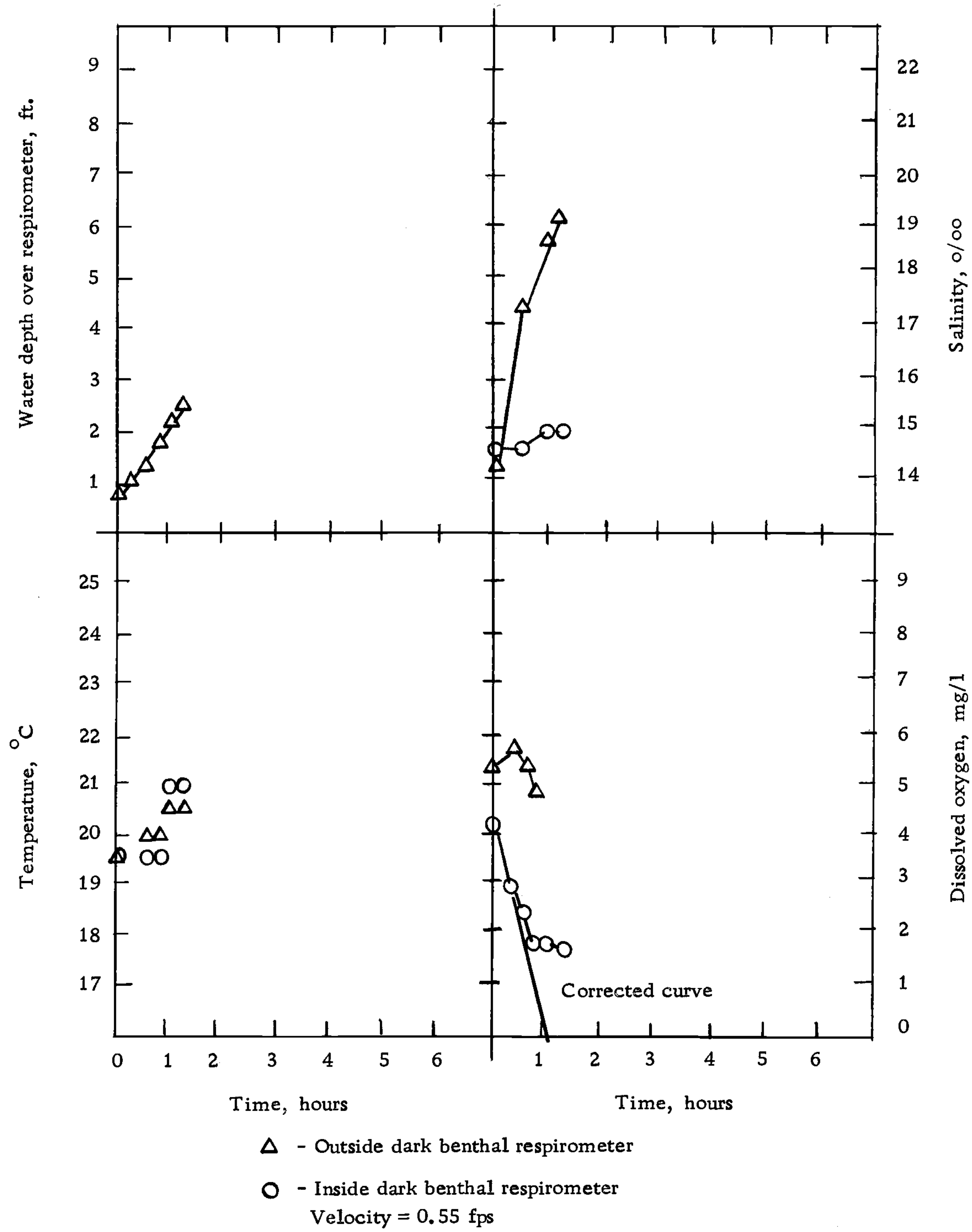


Figure 29. Summary of benthal respirometer data taken at the Toledo test site, 9-9-69, Run #1.

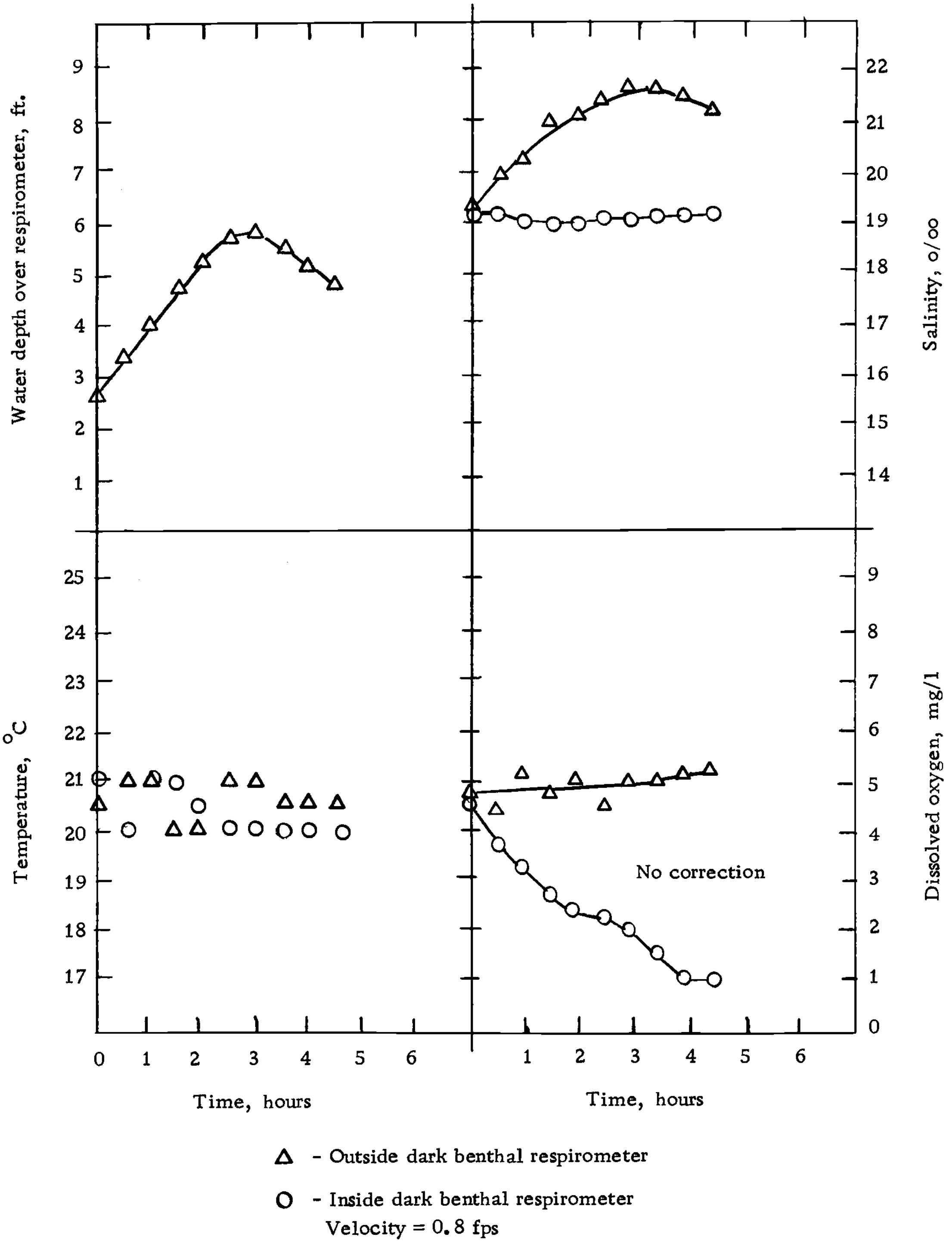


Figure 30. Summary of benthal respirometer data taken at the Toledo test site, 9-9-69, Run #2.

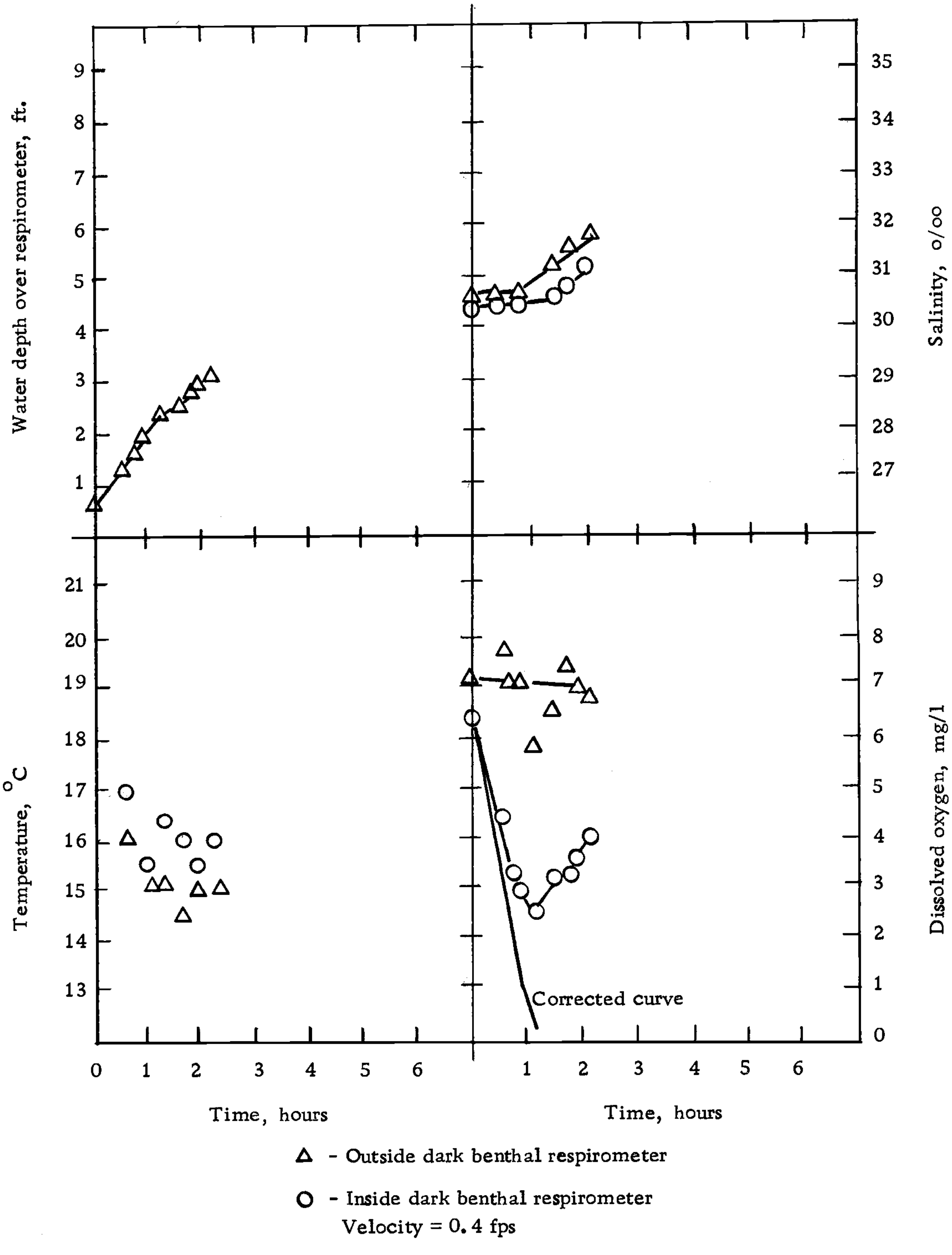


Figure 31. Summary of benthal respirometer data taken at the Parker Slough test site, 9-10-69, Run #1.

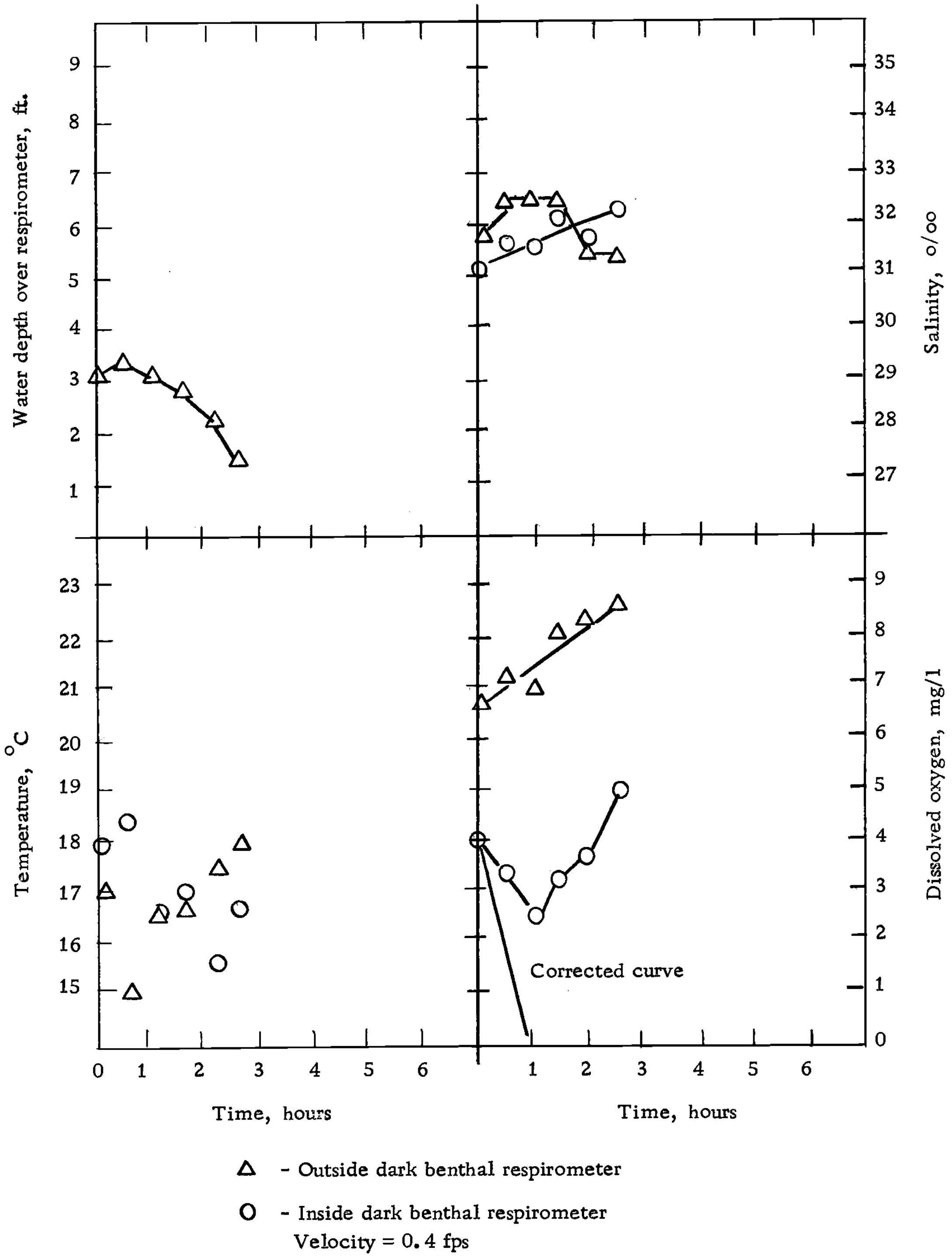


Figure 32. Summary of benthal respirometer data taken at the Parker Slough test site, 9-10-69, Run #2.

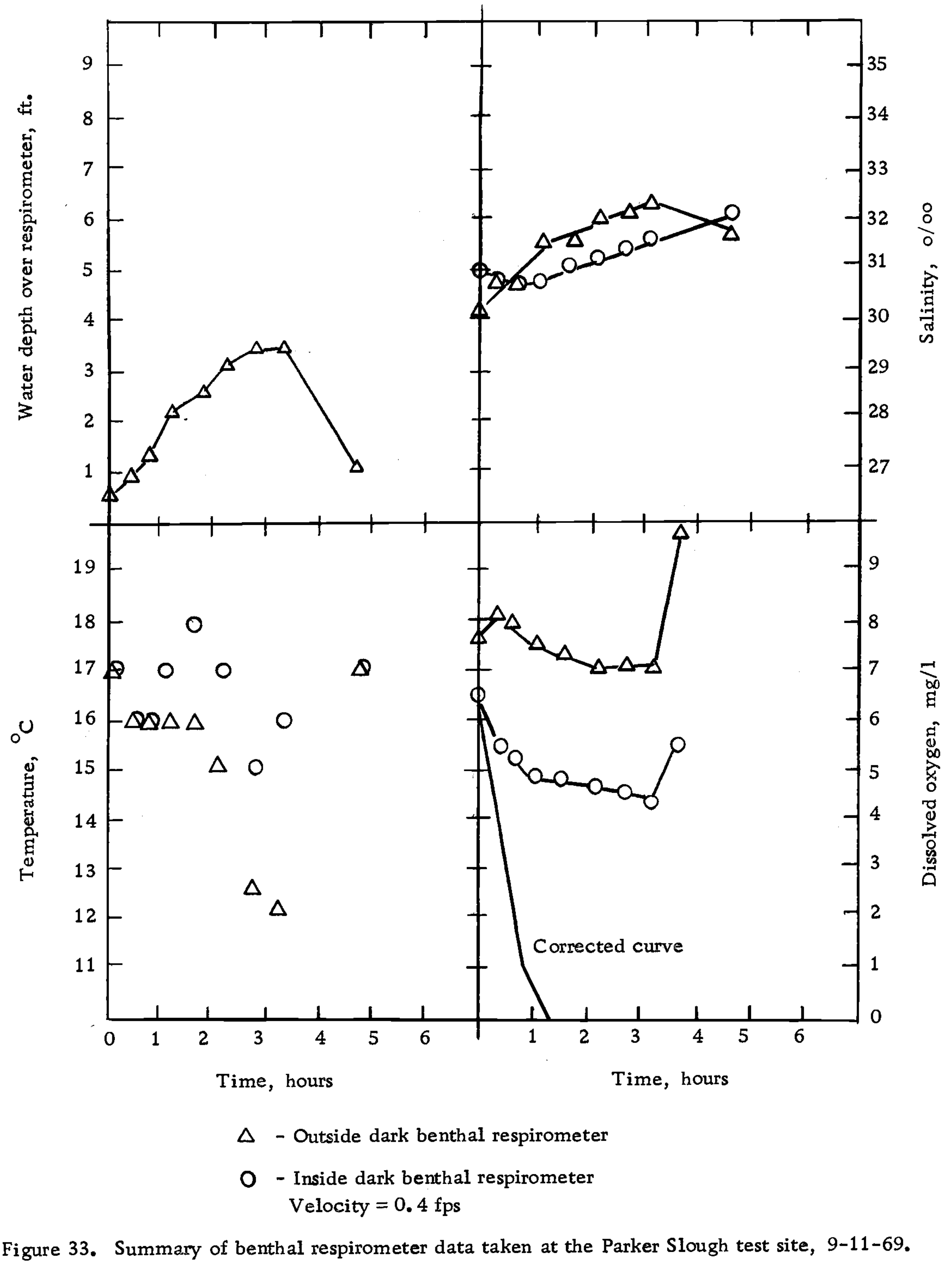


Figure 33. Summary of benthal respirometer data taken at the Parker Slough test site, 9-11-69.

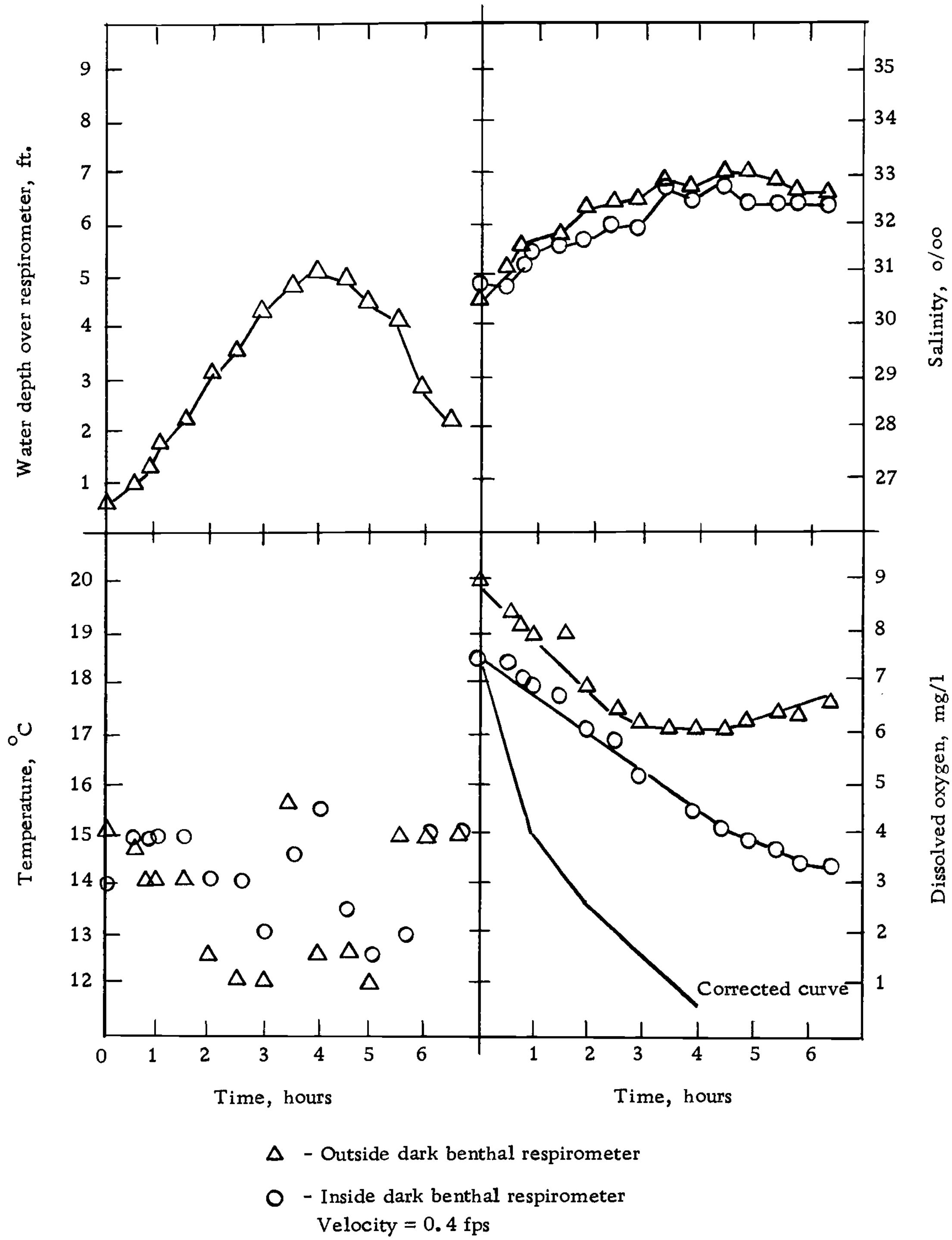


Figure 34. Summary of benthal respirometer data taken at the Parker Slough test site, 9-16-69.

DISCUSSION OF RESULTS

Planktonic Respirometer Studies

The attempt to measure the oxygen demand of the plankton in the bay water using planktonic respirometers gave consistent results. As previously described, the planktonic respirometers simulated a continuous mixing velocity of approximately 0.2 fps. Under in situ conditions located just to one side of the operating benthal respirometers, no observed planktonic oxygen demand was measurable in either the light or dark planktonic respirometers for the short sample runs involved in this respirometer study. Small deviations in readings did occur. However, such deviations were random and were probably due to the technique of dissolved oxygen measurement.

Sample tests of planktonic oxygen demand of water over the bottoms at the Parker Slough test site and at the Toledo test site are shown in Figures 18 through 23.

Several test runs were made at the Oregon State University Marine Science Center dock to determine the effect of tidal variation on the readings of the planktonic respirometers and to again establish the planktonic oxygen demand of the estuary water. During one run the planktonic respirometers were kept at a constant depth while during another run the respirometers were allowed to respond to the tidal height change. As shown in Figures 20 and 21, tidal variation appeared to produce no direct effect on the oxygen readings; and again no planktonic oxygen demand was measurable for the estuary water by either light or dark planktonic respirometers.

Since the large macrophytoplankton masses were excluded from the planktonic respirometers, the author cannot conclude that the plankton did not contribute to the overall oxygen demand of the bay-estuary system. However, it can be strongly implied that the micro-organisms found free floating in the bay-estuary water at the times of the planktonic respirometer tests did not exert a short-term oxygen demand that can be compared in magnitude to the benthal oxygen requirement that existed.

With this fact in mind, respirometer runs were then made using only benthal respirometers since for the period of the test run (four to eight hours), the planktonic oxygen demand was negligible.

Initial Dissolved Oxygen Uptake

It has been stated by others that benthal material can exert a rapid oxygen demand when mixed with water containing dissolved oxygen (38, 47, 48). Such rapid oxygen demand has been called an "enzymatic oxygen demand" (47). This author prefers the term initial oxygen uptake which does not presume that the mechanics of the initial oxygen demand are known, only that such a phenomenon does occur.

In an attempt to develop a technique to measure the relative oxidative strengths of different bottom muds, initial oxygen uptake values of the different bottom muds were measured. To measure the initial oxygen demand of a bottom mud, a core sample of known size was placed in a known volume of water with a known dissolved oxygen concentration. The coring device used was a two-inch diameter piston core. As the outer tube of the coring device was pushed into the mud deposit, a piston inside the coring device was kept stationary causing a partial vacuum over the mud core. The partial vacuum caused the mud core being taken to slide up inside the coring device with little or no compression or disturbance.

After obtaining the mud sample, a volume of water was obtained and placed into a jar that could be sealed. In this case, a liter volume of water appeared to give measurable uptakes for the amount of mud used. The initial dissolved oxygen concentration in the water volume was determined by Micro-Winkler technique. A small sample for salinity determination was also taken.

At this point, a known length of two-inch diameter mud core was placed directly from the coring device into the water volume. The top one to two inches of bottom mud was used. The water surface was covered with a square of plastic wrap to seal off any air, and the jar was capped. The water and mud was shaken ten times and allowed to stand for 7-1/2 minutes, then shaken three times and allowed to stand another 7-1/2 minutes. After the 15-minute period, the dissolved oxygen concentration and salinity of the water was again taken. A fairly standard test was thus developed that gave consistent results.

Analysis of initial oxygen uptakes for the two test sites showed that uptakes were about equal; the Toledo test site averaged only slightly higher. Average initial oxygen uptakes for the Parker Slough and Toledo sites were 47.5 and 54.8 mg O_2 uptake/l of wet mud sample respectively. Such results suggest that as little as 1 millimeter of scour of material below the aerobic layer could cause significant dissolved oxygen uptake in the benthal respirometer system. The benthal respirometers, as stated before, were flushed of initial start-up water before any dissolved oxygen readings were made to attempt to minimize any effect of scour.

Changes in Salinity with Scour

Three out of four samples tested for initial oxygen demand changed in salinity as well as dissolved oxygen when bottom mud was mixed with the water sample. The changes in salinity ranged as high as 0.11 parts per thousand and represented a 0.3 to 0.5 percent increase. The salinity tests were run on settled samples so that suspended particulate matter would not cause a discrepancy during testing in the laboratory salinometer. During respirometer runs, the initial salinities from inside the benthal respirometer were sometimes slightly higher than initial salinities outside the respirometers. These data, though not conclusive, all point to a direct increase in salinity of water over a bottom deposit when some scour of bottom material occurs.

Possibly during exposure of tidal flat areas to the atmosphere at low tide, some dissolved solids that can be measured as salinity are deposited by the evaporation process. When the tidal flats are covered with water and subjected to mixing or scour of the bottom muds, the deposited solids may go into solution and increase the salinity of overlying waters.

If such a process does occur, a buildup of salinity solids could result in tidal flat areas that are not subjected to much mixing or scouring. More research is needed in this area to reach any definite conclusions.

Water in the benthal respirometers at start-up was replaced with fresh tidal water before any actual oxygen or salinity samples were taken. Still, the short flush-out period apparently did not entirely rid the respirometer systems of all scoured material. Scour in the benthal respirometer system is probably not an instantaneous occurrence but is more likely an occurrence of exponential decrease. Therefore, some small amount of oxygen demanding or salinity increasing material scoured after the benthal respirometer system was flushed out could conceivably cause the slightly increased initial oxygen uptake rates or the small salinity increases noted during most benthal respirometer runs.

Benthal Respirometer Studies

Supersaturated Conditions

During the early tests at the Parker Slough site, incoming tidal flows were greatly supersaturated with dissolved oxygen. In some cases the dissolved oxygen levels were as much as 84 percent above saturation. This situation can be explained by the very great abundance of large phytoplankton masses free floating in the bay-estuary water at the Parker Slough location. Although oxygen production by this algal growth was not measured, small bubbles believed to be oxygen were seen being released into the water from the algal masses. Similar bubbles were observed being formed and released from benthal surfaces in shallow waters during bright light periods. Surface water flowing off an exposed tidal flat area where such bubbles were being produced was found to be supersaturated with oxygen by over a factor of two in one case. It is believed that production of the macrophytoplankton growths along with the benthal algal component produced sufficient dissolved oxygen to supersaturate the bay-estuary water around the Parker Slough site during the very sunny early summer period. Such oxygen releases from shallow water phytoplankton have been observed by other researchers (21). Severe interferences with respirometer operation resulted.

During initial operation with supersaturated water in the respirometers, large masses of bubbles formed. These bubbles were circulated through the entire respirometer systems and forced rejection of any results obtained during such runs. Apparently, oxygen from the supersaturated water was forced out of solution when passed through the impeller pumps of the respirometers. In an attempt to rectify the situation, bubble collection devices were placed along the benthal respirometer lengths. Samples of the bubbles were to be analyzed by gas chromatography to determine if the gas was primarily oxygen in content. Unfortunately, all subsequent test runs after installation of the gas collection devices were operated under subsaturated conditions. Apparently the season had changed sufficiently so that oxygen supersaturation was not encountered again for the remainder of the summer. Consequently, it was felt that meaningful data could then be taken.

Leakage

Early respirometer runs at Parker Slough still gave puzzling results. The dissolved oxygen levels in both light and dark benthal respirometers appeared to change directly with the dissolved oxygen levels in the surrounding waters as can be seen in the Parker Slough data of Figures 31 through 34. Respirometer leakage was the immediate thought. Initial and final salinity samples were then taken, and the leakage hypothesis was proven when the final salinity inside the benthal respirometer was about the same as the surrounding water while the initial salinity had been several parts per thousand lower. No amount of care in respirometer placement or tightening respirometer joints stopped the leakage. During all future runs, salinity was monitored along with dissolved oxygen so that if leakage resulted, corrections could possibly be made.

By observing salinity changes in the respirometers, it was determined that the benthal respirometers leaked water at the Parker Slough test site but not to any great extent at the Toledo test site. The only differences that could affect leakage between the Parker Slough site and the Toledo site were the slightly larger soil grain size distribution and the numerous mud shrimp burrows at the Parker Slough site. It is doubtful that the soil grain size differences could cause such a large difference in leakage rates. Therefore, mud shrimp burrows must have formed the avenues of leakage.

Dye tests were made to visually check for leakage through the shrimp burrows. Concentrated solutions of Rodamine-B dye were injected into an operating benthal respirometer. After five minutes of the first dye test, the tidal level was too low (+ 1.0 feet) to continue the test run. No leaks were observed after the five-minute test run. Several days later dye was again injected into an operating benthal respirometer at a higher tidal level (+2.5 feet). Seven minutes after the initial injection of Rodamine-B dye, a visible plume of dye-water solution was observed issuing from a shrimp hole two feet from the nearest respirometer section. See Figure 35 for the exact location of the initial shrimp burrow leak. Within ten minutes of dye injection, dye plumes were seen coming from seven to ten shrimp burrows surrounding the respirometer. It should be noted that before the first dye was sighted coming from the mud shrimp hole, no visable leakage from the respirometer sections or joints was observed.

Further indication of the extent of mud shrimp burrowing activity was noticed. On several occasions at low tide, water was observed flowing from shrimp holes on exposed mud flats. The water was flowing from the holes in a pulsating manner. Many of the holes emitting water were 20 to 50 feet upshore from the edge of the tidal water and at least two feet higher in elevation than the tidal height at the time. The pulsating flow from the mud shrimp burrows was of exactly the same period as small waves that were breaking against the exposed tidal flat many feet away from the shrimp holes. The waves were on the order of two to three inches in wave height. Such an observation suggests a network of adjoining shrimp burrows capable of transmitting hydrodynamic pressure surges throughout an exposed tidal flat area.

The above experiments and observations definitely indicated that

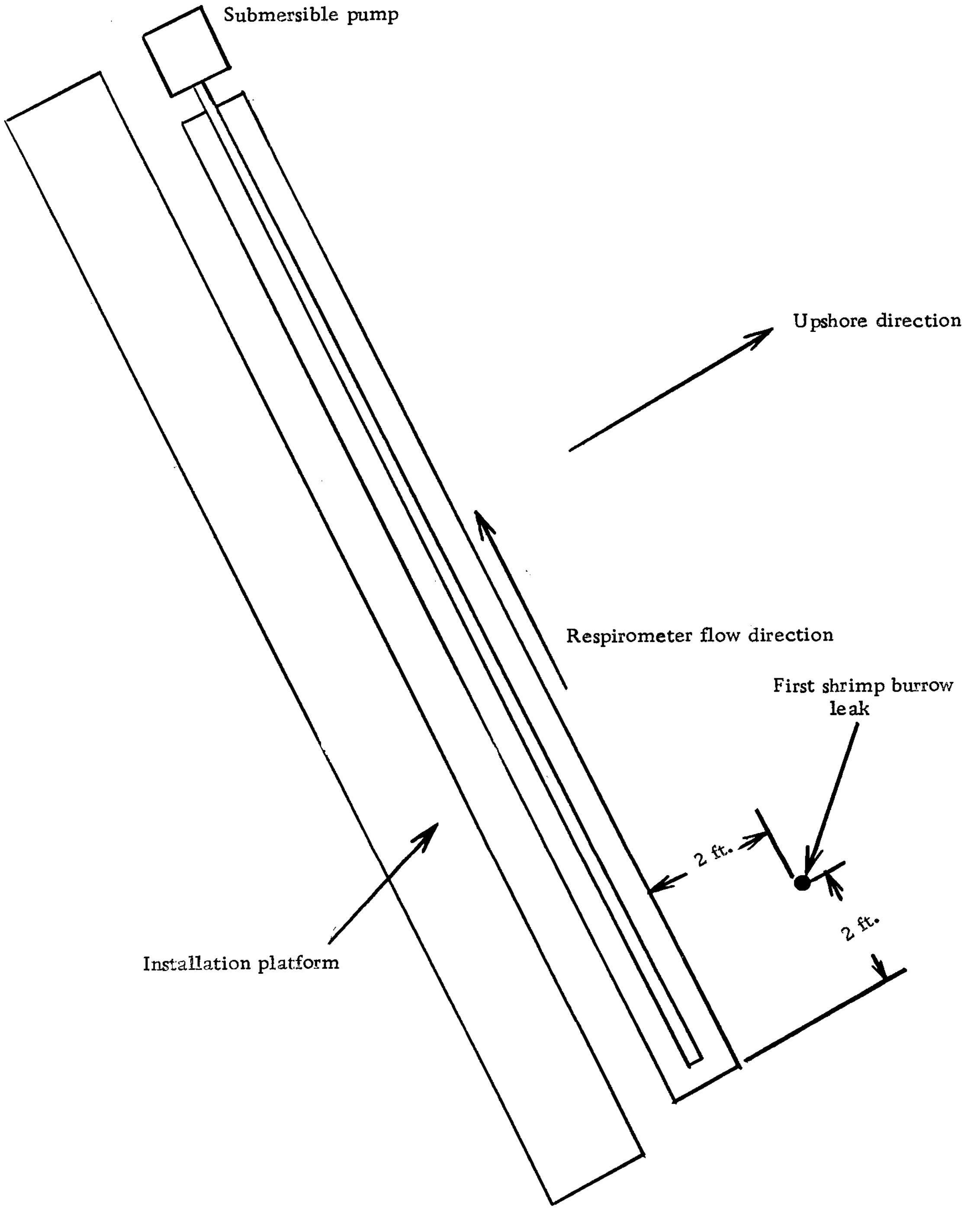


Figure 35. Benthal respirometer setup showing primary shrimp burrow leakage area.

mud shrimp burrows were the controlling factor in benthal respirometer leaks at the Parker Slough test site.

No shrimp burrows were present at the Toledo test site, and no great leakage of the benthal respirometer water occurred at that site. The Alsea estuary in the immediate vicinity of Newport on the Oregon coast was also examined to determine if mud shrimp burrows were present in areas with the same salinity range as that at Toledo. No shrimp burrows were found in this salinity range.

Since the leakage route at the Parker Slough test area was through mud shrimp burrows, even the corrected uptake rates for this area were of questionable validity. No means of evaluating the effect of the water passing through the shrimp burrows was available. The leakage or shrimp burrow circulation may be a naturally occurring process in tidal flat areas.

In any event, all test runs at Toledo as well as Parker Slough where salinity data was taken were corrected for leakage using the mathematical model previously described.

Corrected Parker Slough Uptake Rates

Using the corrected uptake for the Parker Slough area, curves such as those shown in Figure 36 were plotted. Much higher corrected rates of benthal demand occurred at the leaking Parker Slough site than at the Toledo site. See Figure 36. Corrected rates averaging

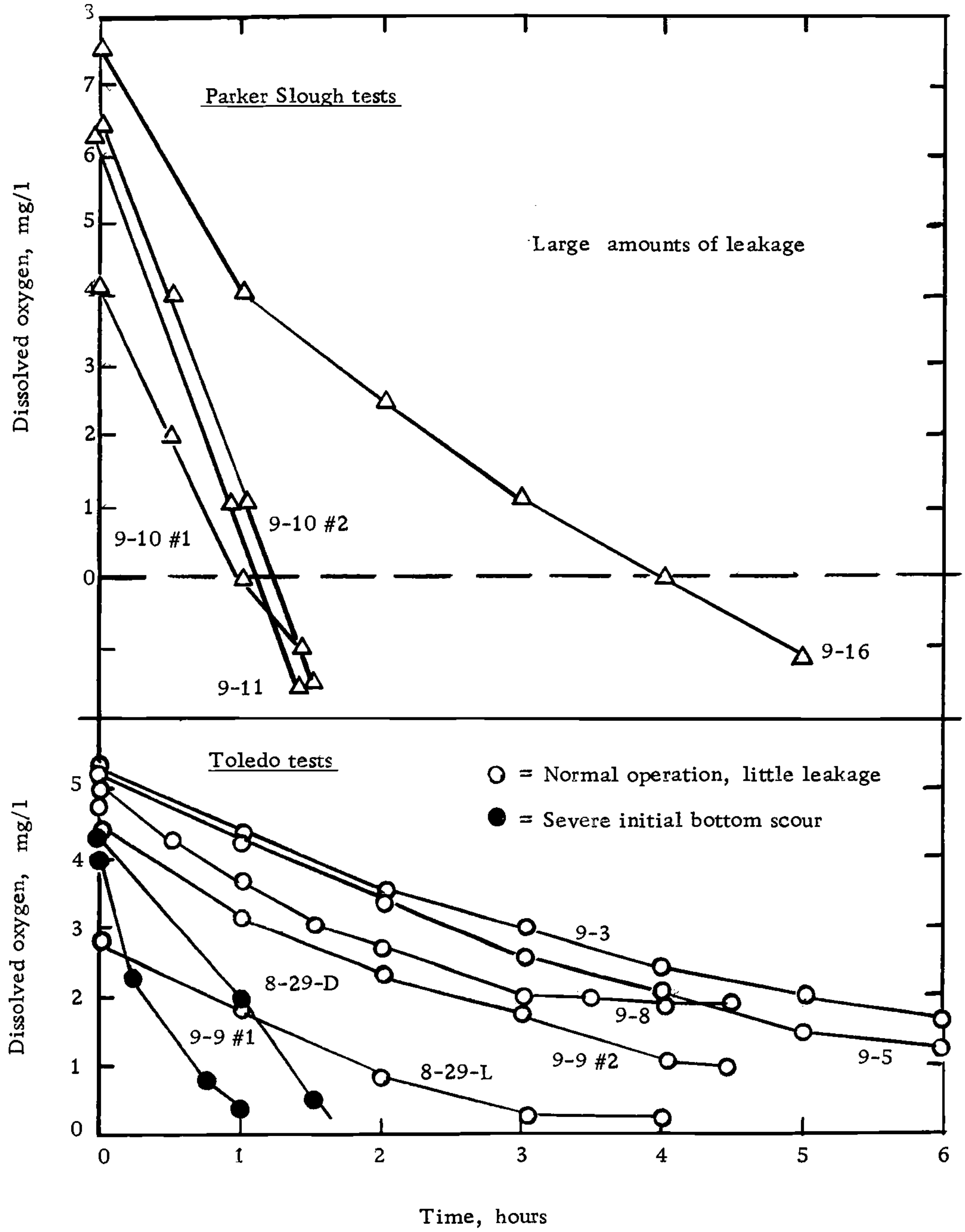


Figure 36. Summary of all corrected benthal oxygen uptake curves for the Parker Slough and Toledo test sites.

as high as 8.5 gm O_2/m^2 - day and ranging from 4.8 to 8.5 gm O_2/m^2 - day were observed if only the respirometer enclosed bottom mud surface area was considered when calculating uptake. But the leakage, as previously stated, took place through mud shrimp holes. Therefore, two explanations of the large oxygen demand were possible.

First, by passing the water through the mud shrimp holes, the water was exposed to a much greater mud surface area. The walls of the shrimp holes may have increased the quantity of bottom deposit exposed to the water manyfold. The mud shrimp burrow walls appeared to be in an aerobic state, much as the mud surfaces of tidal flat deposits. In examining the burrows, a 1/8-inch thick layer of light colored material lined the walls. All the surrounding mud was very dark and had a characteristic odor of sulfur compounds caused by anaerobic decomposition. Other investigators have stated that the burrow lining is an amorphous structure three to seven millimeters thick that appears only in the burrows of the mud shrimp (49). Furthermore, it has been stated that the dissolved oxygen concentration in the burrows, is very low but higher than that in the surrounding muds (49).

A large oxygen demand from burrow walls may exist. A much higher rate of oxygen demand may be calculated if only the projected area covered by the respirometer (0.813 m^2) is used to calculate the uptake rate instead of the total surface area including the burrow walls and the projected area.

A second possible explanation of the high uptake rate with shrimp hole leakage was that some oxygen requiring substances may have been leached or scoured from the shrimp burrows into the respirometer system thus causing an increased uptake.

Toledo Test Runs

The Toledo test area was the primary test area since previous in-lab benthal uptake rates had been observed (25). At the Toledo site, salinity samples and temperature readings inside and outside the respirometer were taken with all dissolved oxygen samples. No problems were experienced with supersaturation or algal growths, and again no planktonic respirometers were required as previous tests had shown.

Initial benthal respirometer runs showed small leaks when analyzed using the mathematical model but none to compare with those at the Parker Slough site. See Figure 37. With careful respirometer placement, essentially no leaks resulted. It was learned that to have time to properly place the benthal respirometers at this isolated location that was accessible only by boat, only one respirometer could be used effectively at one time. Therefore, on the final Toledo test runs, only the dark benthal respirometer was

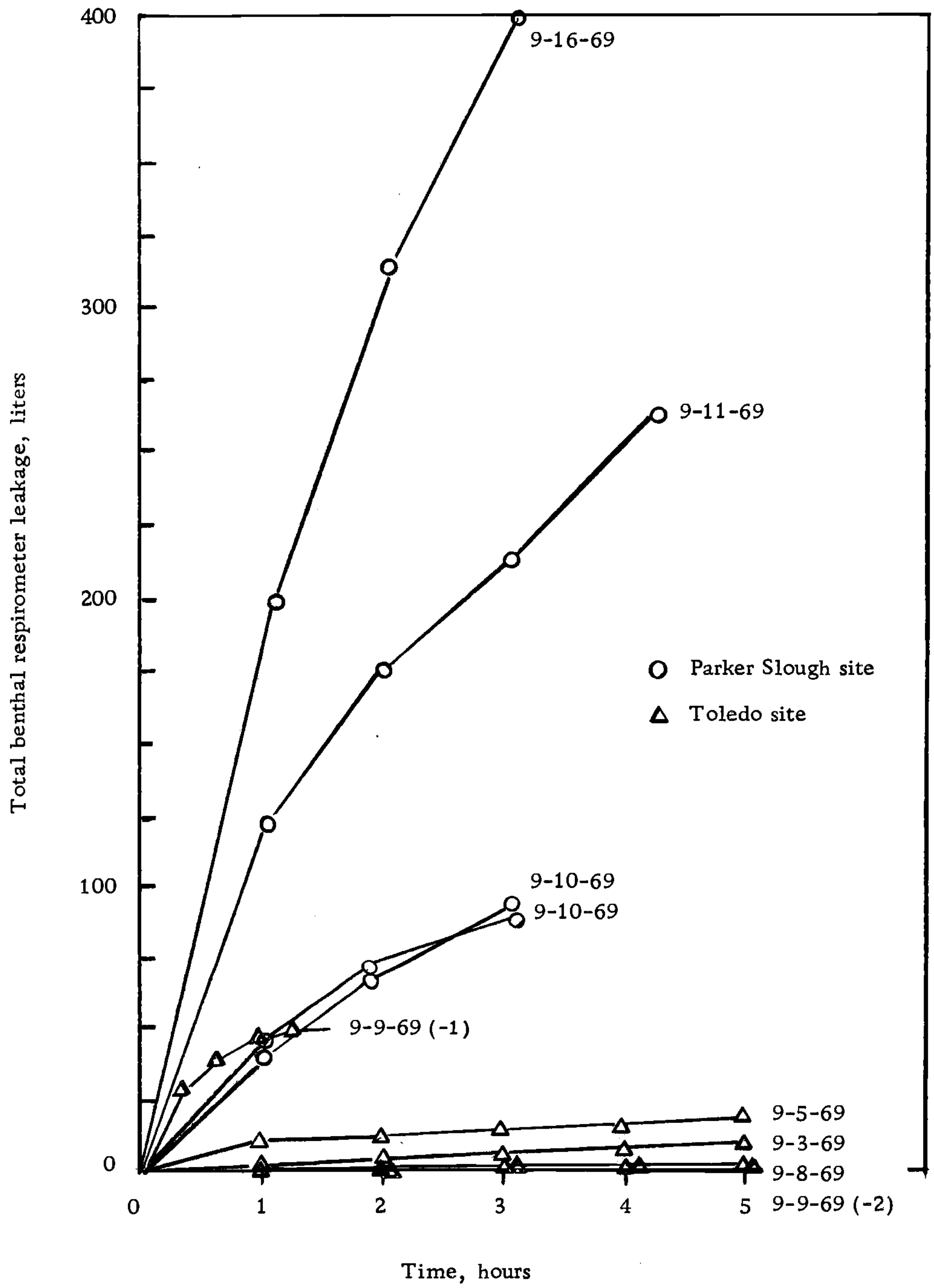


Figure 37. A comparison of the total benthal respirometer leakage at the Parker Slough test site with that at the Toledo test site for four runs at each site.

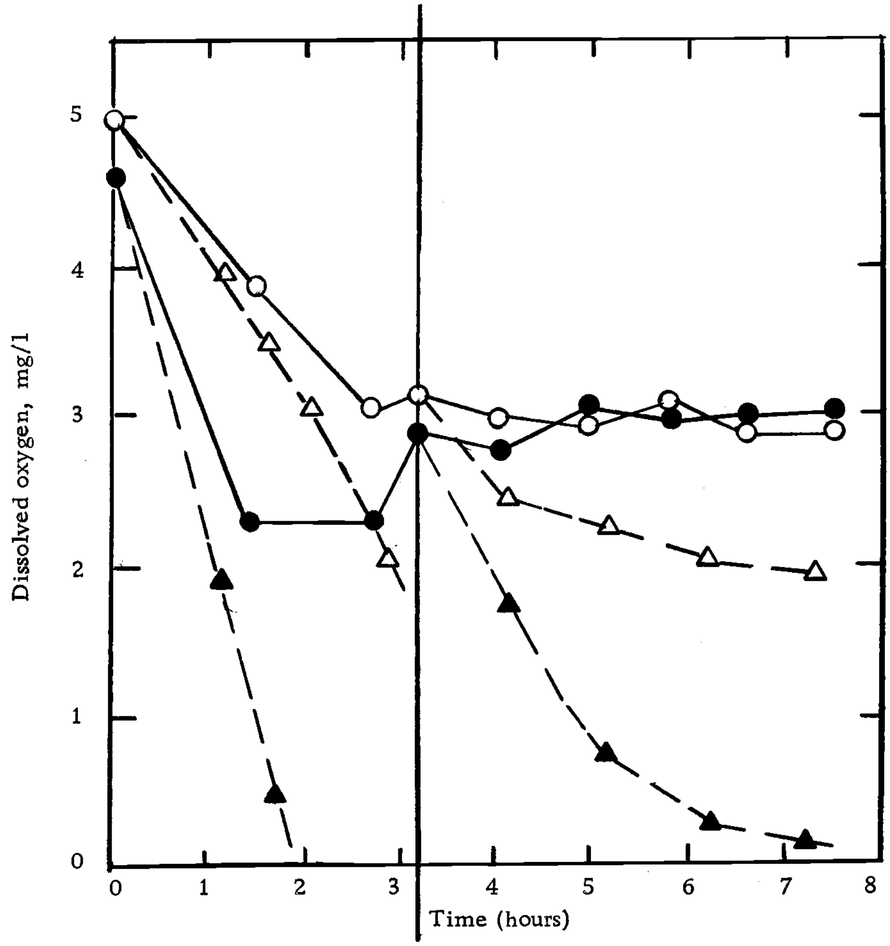
used.

Results from the initial light and dark Toledo respirometer run implied that some benthal algal productivity was present. Light benthal oxygen requirements were found to be 0.63 gm O_2/m^2 - day while dark benthal requirements were 1.97 gm O_2/m^2 - day as shown in Figure 38. The production appeared to be about 1.34 gm O_2/m^2 - day at Toledo for this one light and dark benthal respirometer run. Further study is indicated so that the true effect of benthal uptake can be evaluated considering production as well as respiration.

Velocity in the respirometer was varied in future dark benthal respirometer runs at Toledo with very interesting results. As was expected, benthal demand increased directly as the water velocity was increased. An average rate of 1.35 gm O_2/m^2 - day resulted with bottom velocity of 0.4 fps. At 0.8 fps, the average benthal uptake increased to over 2.13 gm O_2/m^2 - day. At a full velocity of over 1.0 fps, severe scour resulted which gave very large uptakes. Therefore, this research has again substantiated the rather intuitive fact that benthal uptake is related to the degree of mixing. Figure 36 summarizes the results of all benthal respirometer measurements at the Toledo test site during this research.

Result Comparisons

The uptake rates measured during this research are compared



● = Values measured from the dark respirometer.
○ = Values measured from the light respirometer.

▲ = Corrected dark respirometer values.
△ = Corrected light respirometer values.

Figure 38. Corrected light and dark benthal respirometer run made at the Toledo test site, 8-29-69.

in Table IV with those measured one year earlier in the laboratory (25) on samples from the same Toledo test site.

Table IV. Comparison of this research with results of previous in-lab respirometer uptakes from the Toledo test site.

	Average uptake rates gm O_2/m^2 - day	
Mixing conditions	Field measurements	Lab measurements (25)
Velocity = 0.4 fps	1.35	--
Velocity = 0.55 fps	1.67	--
Velocity = 0.8 fps	2.13	--
No mixing	--	1.94
Mixing	--	3.52

This table graphically indicates the importance of controlled mixing. The no-mixing condition of the laboratory tests tends toward a pure molecular diffusion mechanism of oxygen transport. Convective currents, vibrations, and sampling probably caused some small degree of mixing. The mixed condition is aided by turbulent diffusion and results in increased uptake rates. By varying mixing velocities in the _in situ_ benthal respirometer to more accurately simulate actual mixing conditions, the same type of mixing dependency was seen. However, at a mixing velocity slightly greater than that which occurs at the test area, lower values of benthal uptake resulted than were measured under a mixed condition one year earlier in the laboratory. This fact suggests that the benthal deposit composition and demand changed over the year, that mixing conditions used during the in-lab experiments were excessive, or that the samples used in the in-lab testing were greatly disturbed when extracted from the bottom deposit or when transported to the laboratory.

A comparison of the oxygen uptake results of this research with results of other researchers in different areas is shown in Table V. As can be seen, rates from 0.15 to 29 gm O_2/m^2 - day were obtained by other observers for various types of mud deposits and various methods of uptake measurement. Still, most measurements were in the range of about 1.0 to 5.0 gm O_2/m^2 - day for all deposits and methods of testing. This fact appears to point out that regardless of the method of measurement used, answers within that range usually result. The range is large, however, when considering that deviations of greater than 100 percent were not uncommon in past experiments on the same mud deposits. Consequently, it is difficult to examine results of this type and determine if the results are actually representative of the parameter being measured. The researcher must, therefore, consider the methods of measurement, the quality of control used, and the extent of actual environmental simulation built into the testing procedures before attempting to assess the true validity of a set of benthal respirometer experimental measurements. Statistical analysis of numerous test runs would also be a valuable contribution to the acceptibility of benthal uptake data. Since very few sample runs were made during this research and since different mixing

Table V. A comparison of the oxygen uptake rates measured during this research with the results of previous investigators.

Investigator	Uptake rates gm O_2/m^2-day	Comments
Author	4.7-8.5	*In situ*, Parker Slough, average corrected rates.
Author	1.35	*In situ*, Toledo,mixing velocity = 0.4 fps.
Author	1.67	*In situ*, Toledo, mixing velocity = 0.55 fps.
Author	2.13	*In situ*, Toledo, mixing velocity = 0.8 fps.
Bradley and James (6)	5.37-26.25	*In situ*, tunnel respirometer, water current mixed.
O'Connell and Weeks (51)	0.15-8.5	*In situ*, water current mixed.
Pamatmat and Banse (38)	0.6-1.2	*In situ*, bell jar respirometer, stirring prop.
Stein and Denison (45)	3.6	*In situ*, bell jar respirometer, stirring prop.
Edwards and Rolley (12)	2.8-4.8	In lab, magnetic stirring.
Edwards and Rolley (12)	29	In lab, magnetic stirring, bottom scour.
Hanes and Irving (15)	3.2	In lab, magnetic stirring.
Martin (25)	3.4	In lab, Plunger mixed, Toledo deposit.
Martin (25)	1.9	In lab, no mixing, Toledo deposit.
McKeown *et al*. (29)	2.7	In lab, water current mixing.
McKeown *et al*. (29)	0.8	In lab, no mixing.
Stein and Denison (45)	5.01-5.93	In lab, magnetic stirring, some scour.
Zobell (54)	0.2-4.8	In lab, dried mud mixed with water.

conditions were used for most sample runs, not enough data were available for statistical analysis. However, Figure 36 illustrates that most test runs gave similar and reproducible results.

Relationships of Factors Effecting Benthal Dissolved Oxygen Uptake

To further understand the processes or mechanisms of benthal oxygen uptake, several plots were constructed from data collected and from data calculated using the mathematical model. First, total leakage versus time was plotted to see if any relationship was indicated. Figure 37 shows that at both test sites, the initial leakage rate was usually largest and that the leakage rate decreased in most cases with time. Furthermore, the leakage at Parker Slough greatly overshadowed the leakage at the Toledo test site as seen in Figure 37 also.

One explanation for the leakage rate inhibition with time at the Toledo site is that suspended material in the benthal respirometer may have tended to plug any actual leaks in the respirometer. However, at Parker Slough where the leakage was the result of mud shrimp burrows, it seems unlikely that enough suspended material could be accumulated in the shrimp burrows to cause a lessening of the leakage rate. Possibly mud shrimp organisms controlled circulation in the burrows enough to have effected the leakage rates. However, a plot of oxygen concentration versus leakage rates showed no apparent correlation at the Parker Slough test site. Therefore, if the mud shrimp or some other living organisms were the controlling factor of leakage rates, apparently the concentration of dissolved oxygen was not the constituent that triggered such leakage.

In all instances, benthal oxygen uptake rates, dissolved oxygen concentrations in the benthal respirometers, and benthal respirometer leakage, when present, decreased with time. See Figures 24 through 34 and Figure 37. However, even the benthal respirometer runs that did not have leakage had decreasing oxygen uptake rates and decreasing dissolved oxygen concentrations. Tidal depth also changed with time but approximated a sine curve increasing and then decreasing as the other variables mentioned above steadily decreased.

At this time, the true relationships between the above factors cannot be formulated. Additional plots showing the relationships between the variables pointed out the false correlations that might be put forth. Figure 39 shows that both dissolved oxygen concentration and oxygen uptake rate vary with benthal respirometer leakage in a similar manner. Such a variation should be expected since the changes of all three variables with time is also similar. The possibility that some definite correlation exists should not be entirely discounted. However, it should be realized that several interrelationships could exist simultaneously in these cases.

Figure 40 shows that benthal oxygen uptake rate plotted against

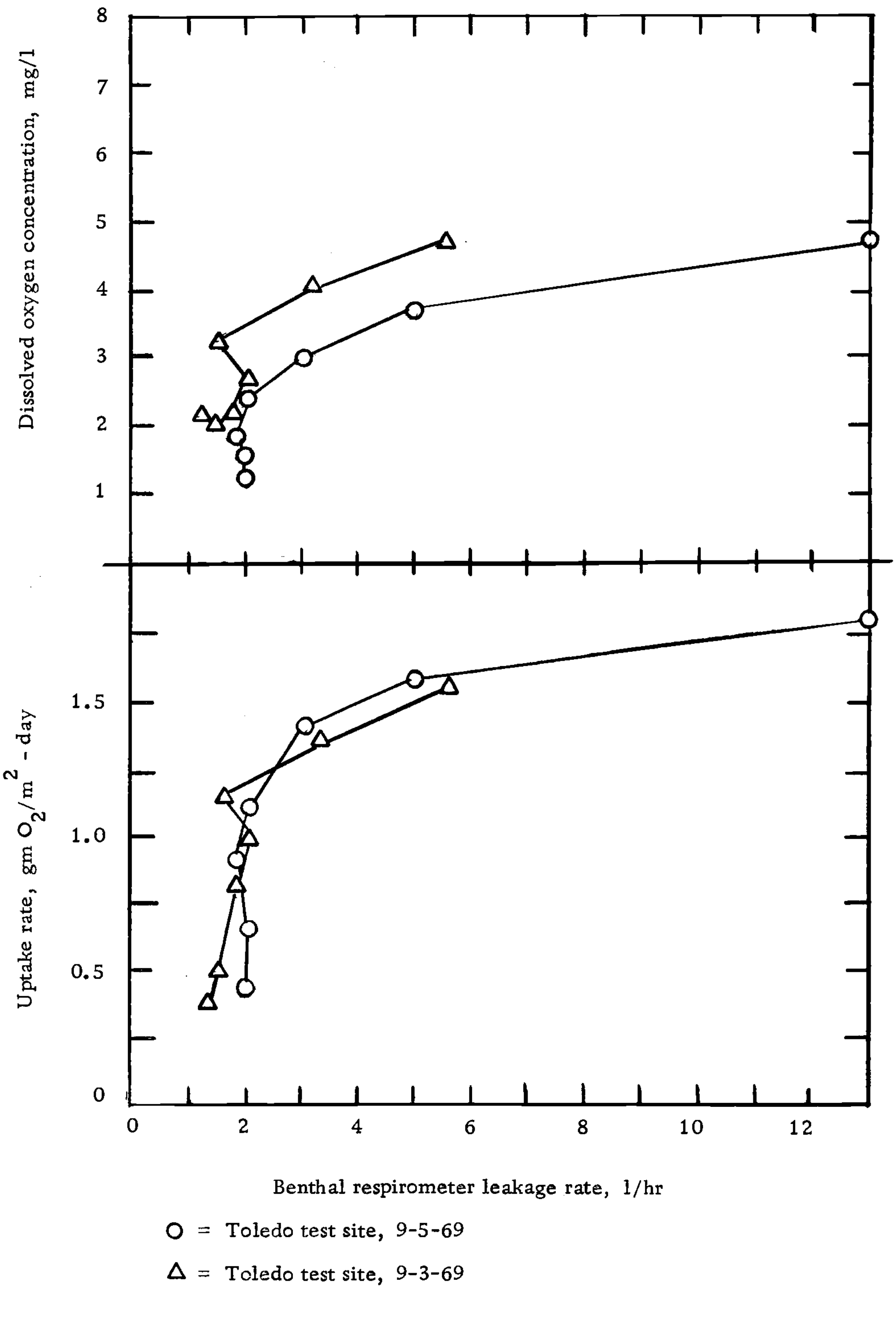


Figure 39. Benthal respirometer oxygen uptake rate and dissolved oxygen concentration versus benthal respirometer leakage rate for two Toledo test runs.

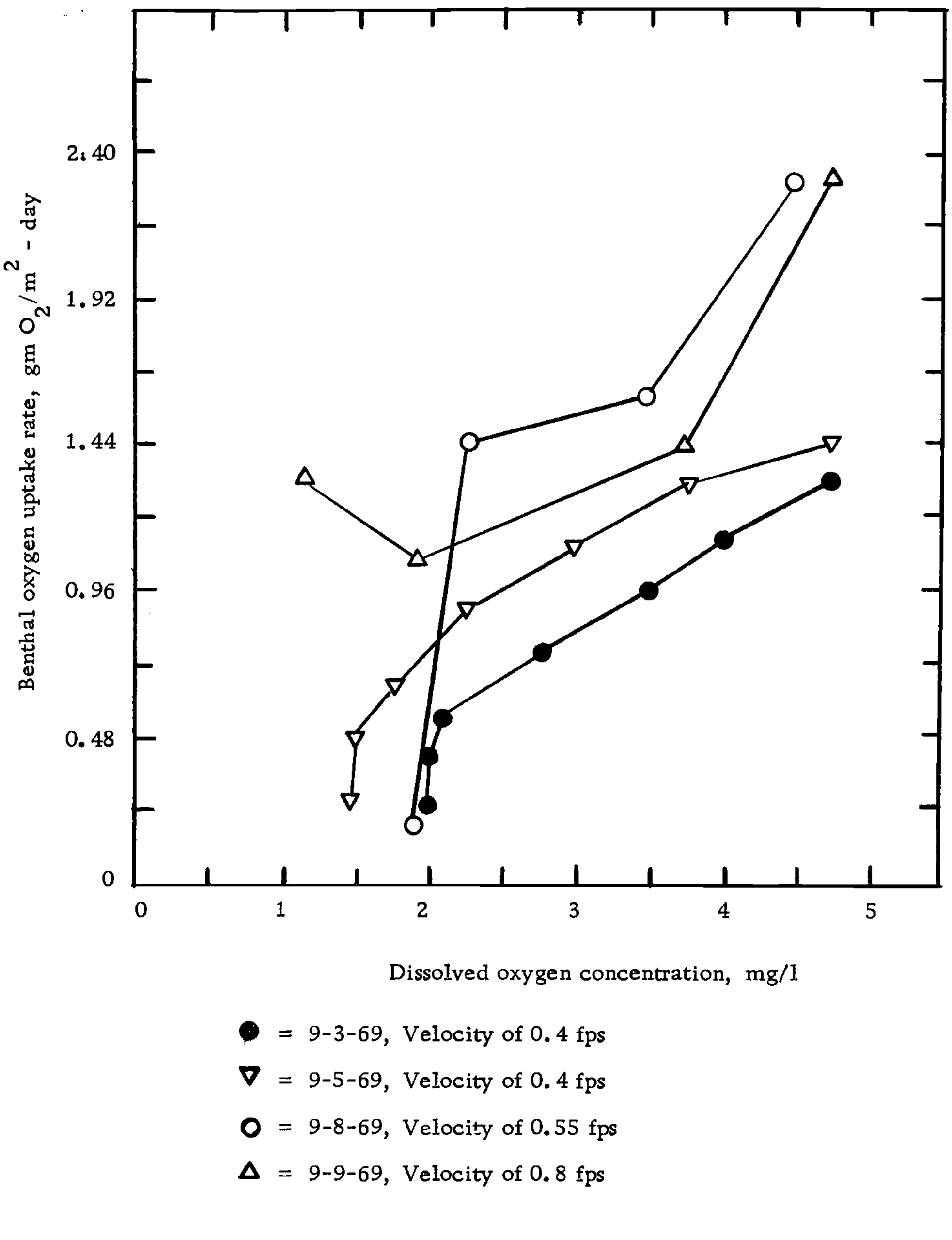


Figure 40. Benthal oxygen uptake rate versus oxygen concentration in the benthal respirometer, Toledo test site.

dissolved oxygen concentration forms another correlation similar to those shown in Figure 39. Again, both variables plotted in Figure 40 changed with time in a corresponding manner. Figure 40 also shows that changes in mixing velocity effect the relationship between the two variables. Since velocity was not a time function, Figure 40 does further indicate that the factors involved are influenced by mixing. Other researchers have noted an indicated dependency of benthal oxygen uptake upon dissolved oxygen concentration in the overlying water and have attributed the relationship to the inhibition of organisms in the benthal community.

Sensitivity Study

To further analyze the relative importance of the different mechanisms of oxygen uptake, a sensitivity study was performed using the mathematical model previously formulated. Computer techniques using fourth order Runge-Kutta finite difference solutions to the mathematical model equations allowed simulation of the benthal respirometer system. Three possible mechanisms of oxygen uptake were considered. Figure 16 gives an explanation of the nomenclature and respirometer system used in the simulation. The variables considered were diffusion of dissolved oxygen into the bottom deposit (Ob), diffusion or leakage of soluble oxygen demanding substances into the respirometer system from the benthal deposit (Lbr), and the decay rate of soluble oxygen demanding material in the benthal respirometer system (K). Leakage rates and other data from selected sample runs from each of the test sites were used for a portion of the computer runs while constant leakage rates and incoming dissolved oxygen values were assumed for several runs.

By solving Equations 2 and 3 simultaneously for the respirometer dissolved oxygen concentration (DOr) while substituting various values of the decay coefficient (K), soluble oxygen demanding material input (Lbr), and oxygen diffusion into the bottom (Ob), plots of oxygen concentration within the respirometer versus time were developed. To check the solutions obtained using the Runge-Kutta computer analysis, the analytical solutions of Equations 2 and 3 were developed with the assumption of constant values of Lbr and K while Ob was taken as zero. The analytical solutions for the special cases are shown as Equations 4 and 5.

BOD Equation:

$$\frac{d(Lr)}{dt} = \frac{(Q)(Lw)}{Vr} - \frac{(Q)(Lr)}{Vr} - (K)(Lr) + \frac{Lbr}{Vr} \qquad (2)$$

Analytical Solution:

$$Lr = \frac{Lbr/Vr}{Q/Vr+K} - \frac{(Lbr/Vr)e^{-(Q/Vr+K)T}}{Q/Vr+K} + (Lri)e^{-(Q/V+K)T} \qquad (4)$$

Dissolved Oxygen Equation:

$$\frac{d(DOr)}{dt} = \frac{Q(DOw)}{Vr} - \frac{Q(DOr)}{Vr} - K(Lr) \qquad (3)$$

Analytical Solution:

$$DOr = \left[DOw - \frac{(K)(Lbr)}{Q(Q/Vr+K)} \right] \left[1 - e^{-(Q/Vr)T} \right] - \left[\frac{Lbr}{Q+(K)Vr} - Lri \right] \left[e^{-(Q/Vr+K)T} - e^{-(Q/Vr)T} \right] + (DOri)\, e^{-(Q/Vr)T} \qquad (5)$$

Comparisons of the actual solutions with those obtained by the Runge-Kutta method were very favorable as shown in Table VI.

Table VI. A comparison of the analytical solutions to Equations 2 and 3 with the fourth order Runge-Kutta computer solutions.

	BOD solutions Lr, mg/l		Dissolved oxygen solutions DOr, mg/l	
Time	Analytical	Runge-Kutta	Analytical	Runge-Kutta
0	0.5000000	0.500000	5.000000	5.000000
30	0.7877005	0.787702	2.9709033	2.970900
60	0.8006698	0.800670	0.8861589	0.886159
90	0.8012545	0.801255	-1.0126036	-1.012600
120	0.8012808	0.801281	-2.7323162	-2.732320
150	0.8012820	0.801282	-4.2894300	-4.289430

The values obtained by both methods were essentially equal. Therefore, it was assumed that the Runge-Kutta approximations used to approximate the solutions to Equations 2 and 3 were sufficiently accurate and thus computer simulation and parameter sensitivity studies would give mathematically valid results. The use of seven significant figures in Table VI is for comparison only and is not meant to convey a false sense of precision.

After checking the accuracy of the computer simulation, attempts were made to mathematically obtain dissolved oxygen versus time curves similar to those measured during the selected benthal respirometer runs. In doing this, either Ob or Lbr was first assumed to be zero. If Ob was assumed to be zero, Lbr and K were varied to attempt to obtain calculated DO variations similar to measured DO variations. If Lbr was assumed to be zero, Ob was varied until some reasonable uptake curve was obtained. The initial value of oxygen demanding material (Lri) in the water was also considered as a variable parameter. Figure 41 shows examples of the results of such simulations. Table VII gives the corresponding parameters used. The characteristic shape of the curves obtained by varying each of the parameters singularly pointed to the parameter combinations which could produce the measured results.

Curves very close to those actually measured were generated using only Ob, oxygen diffusing into the bottom deposit. A value of 1.5 mg O_2/min (2.64 gm O_2/m^2 - day) for Ob gave characteristic curves with a leakage rate of 0.2 liters per minute. The values of

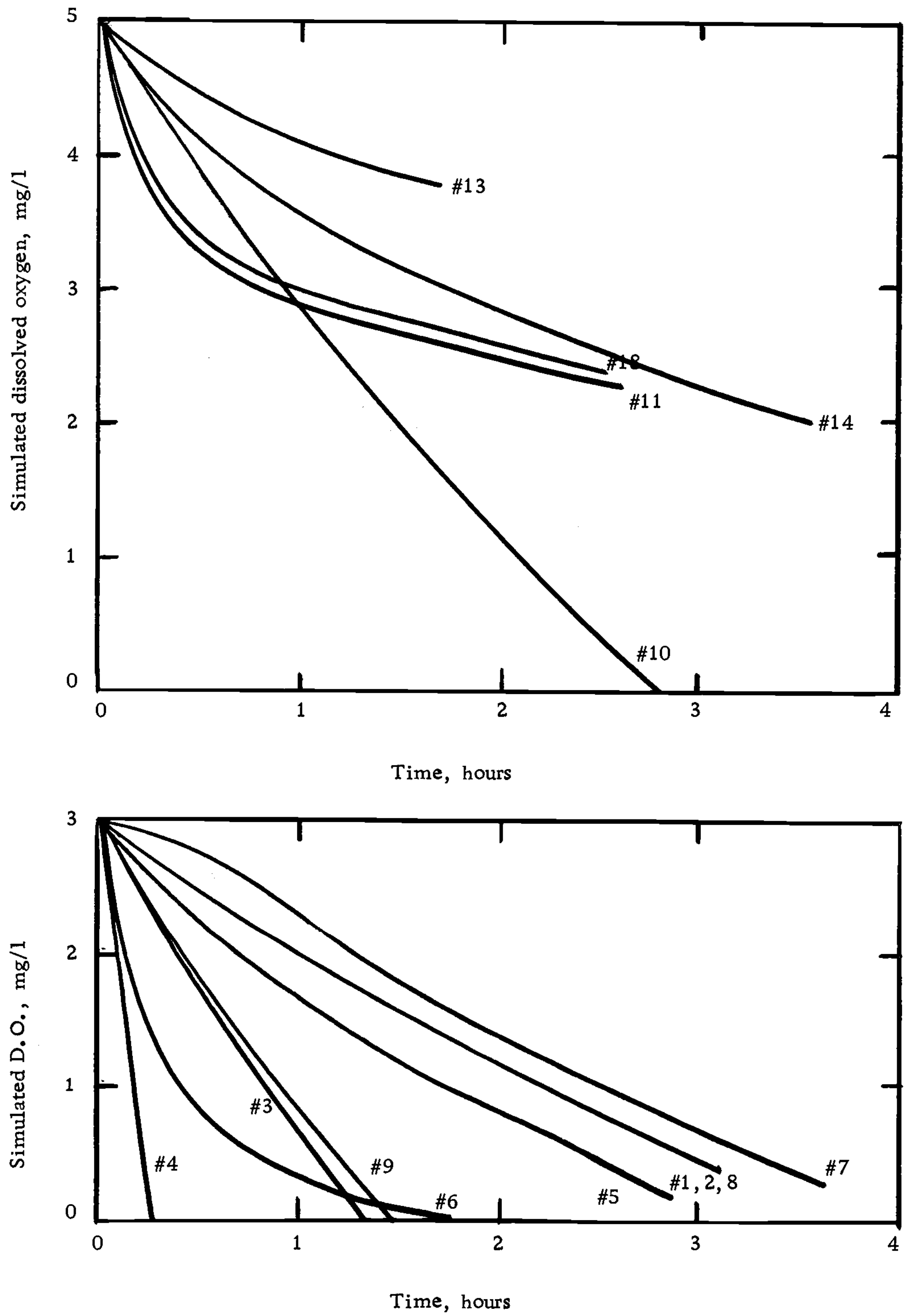


Figure 41. Summary of simulated benthal respirometer test runs. See Table VII for parameters used to calculate each curve.

oxygen uptake actually measured at the Toledo test site were in the range of 0.77 to 1.24 mg O_2/min (1.35 to 2.13 gm O_2/m^2 - day) and a leakage rate of 0.2 liters per minute occurred on one run. If a small amount of initial BOD (Lbi) with a very rapid decay rate was assumed to exist in the simulated respirometer system, curves more closely resembling measured results were generated. However, the decay rates required were on the order of 10 to 500/day when a normal decay coefficient for a polluted water or domestic sewage is usually about 0.2/day. It should be noted that Ob and Lbr are dependent upon the value of Q chosen.

Table VII. Parameters used for sensitivity simulation studies of benthal respirometer oxygen uptake as shown in graphical form in Figure 41.

Run #	Q 1/min	DOri mg/l	Lri mg/l	DOw mg/l	Ob mg/min	Lbr mg/min	K 1/min
1	0.2	3.0	0.0	5.0	1.5	0.0	0.0
2					↓		0.2
3			↓		3.0		0.0
4			4.0		↓		0.2
5			↓		1.5	↓	0.001
6			2.0				0.1
7			0.0			1.5	↓
8		↓				↓	1.0
9				↓		3.0	
10		5.0	↓	8.0	↓	↓	
11			1.5		1.5	0.0	↓
12							0.1
13							0.001
14	↓	↓	↓	↓	↓	↓	0.01

Similar high decay rates were necessary in order to obtain realistic uptake curves if the diffusion of oxygen into the bottom (Ob) was assumed to be zero while the diffusion of oxygen demanding material out of the enclosed bottom area (Lbr) was given a value corresponding to the measured uptake. Only if extremely high quantities of oxygen demanding material were to come out of the benthal deposit could the decay rate be effectively lowered. However, if such were the case, the water actually measured in the field should have a very high BOD which did not occur. Furthermore, tests for initial oxygen uptake, as discussed previously, did not indicate any particularly rapid or large oxygen demand in the upper portions of the mud deposit unless extreme scour occurred. This also tends to show that no large accumulation of oxygen demanding material was located in the upper portion of the mud deposit. Such a large concentration would probably be necessary if large quantities of oxygen demanding material were to be diffused continually across the mud water interface. The extremely low molecular diffusion rates of substances in mud deposits (21) would not allow an excessive continuous transfer unless very large gradients existed or unless burrowing organisms or tidal surges increased diffusion rates far above molecular diffusion rates.

A further indication that diffusion of oxygen into the bottom deposit is the controlling factor of benthal uptake is the following observation. If soluble oxygen demanding material coming out of the benthal deposit accounted for most of the oxygen demand noted in the benthal respirometer measurements, then respirometer runs with higher leakage rates should show lower benthal oxygen demands. The lower demands would result because more of the oxygen demanding material coming from the deposit would be flushed out of the respirometer system and replaced by water with little or no oxygen demand. However, in most cases during this research, benthal respirometers with the largest leakage rates also had the highest uptake rates. See Figures 36 and 37. The very existence of aerobic biological communities in the upper surfaces of benthal muds also indicates that at least some amount of oxygen does find its way to such communities. The data gathered is minimal but does support the premise that either the primary mechanism of benthal oxygen uptake is due to oxygen diffusion into the deposits or it is due to the release of very fast reacting materials from the mud. A combination of the two processes is also very likely. Further explanation of oxygen uptakes are not warranted at this time. However, the method presented in this research can be utilized to obtain further insight into the mechanics of benthal oxygen uptakes. The simulation models presented here can be used to design future experiments that might lead to a better understanding of benthal oxygen requirements and mechanisms.

SUMMARY AND CONCLUSIONS

In situ planktonic and benthal respirometers were built to differentiate the oxygen uptake caused by biological reactions in the water from the benthal oxygen uptake while simulating actual conditions of mixing and tidal action. The planktonic uptake was found to be negligible for all samples tested. Microphytoplankton and bacteria free-floating in the estuarine water tested during this research did not contribute to the oxygen demand during the short-term benthal respirometer sample runs. The primary sink for dissolved oxygen at the Toledo site and probably the Parker Slough site was the benthal deposits or benthal deposit caused oxygen demand.

Representative benthal oxygen uptake rates for the Toledo test site ranged from 1.35 gm O_2/m^2 - day to 2.13 gm O_2/m^2 - day depending on the degree of mixing. Large respirometer leakage rates occurred at the Parker Slough test site. Dye injected into an operating benthal respirometer showed that mud shrimp burrows formed the routes of the Parker Slough benthal respirometer leakage. By applying the mathematical model of the benthal respirometer system developed during this research, corrections for leakage were made and gave benthal uptake rates of from 4.8 gm O_2/m^2 - day to 8.5 gm O_2/m^2 - day at Parker Slough. The leakage through the shrimp burrows probably caused the higher oxygen uptake at Parker Slough by increasing the effective area covered by the respirometers or by scouring oxygen demanding material from the shrimp burrows. Great care must be taken if *in situ* benthal respirometer studies are to be made where burrowing organisms are prevalent. Any mixing may cause circulation through the burrows and might increase the uptake rates measured. Before the results are used, the effects should be analyzed to see if leakage or circulation is a natural occurring process in tidal flat areas.

Benthal oxygen uptake rates measured during this research were in the range of results published by other researchers as illustrated in Table V. Uptake rates for benthal deposits at the Toledo test site were less than in-lab results for the same site published one year earlier. The differences were probably due to the lack of controlled mixing or the disturbance of the samples during the in-lab tests.

Respirometer leakage, when present, appeared to decrease with time as did benthal oxygen uptake rates and respirometer oxygen concentrations. Some relationships between the above variables are indicated but cannot be fully evaluated at this time. However, benthal oxygen uptake may be related to the dissolved oxygen concentration in the overlying water and is dependent upon the degree of turbulence or mixing at the mud-water interface.

Sensitivity studies were made using the mathematical model and computer simulation techniques to help determine the relative importance of the various parameters that may effect benthal uptake. It was concluded that oxygen diffused into the benthal deposit, that oxygen demanding material with extremely high decay rates diffused from the deposits, or that a combination of the two processes occur to create the benthal oxygen demand.

Additional studies using core samples of bottom deposit and estuary water samples indicated that scour of benthal material might cause slight increases in the salinity of the water in the respirometers and that scour of anaerobic mud layers might cause increased oxygen uptake rates.

Water supersaturated with dissolved oxygen was encountered during early test runs at the Parker Slough test site. Such supersaturation was attributed to production by benthal algal growths and large macrophytoplankton masses found free-floating in the bay water during the early summer months.

BIBLIOGRAPHY

1. Anita, N. J. et al. Further measurements of primary production using a large-volume plastic sphere. Limnology and Oceanography 8(2):166-182. 1963.

2. Baity, H. G. Studies of sewage sludge. Sewage Works Journal 10:539-568. 1938.

3. Bentson, L., Marine Research Engineer. Plexiglas light transmittance data. FWPCA/PNW Water Lab., Marine Science Center, Newport, Oregon. 1968.

4. Beyers, Robert J. Relationship between temperature and the metabolism of experimental ecosystems. Science 136(3520): 980-982. June 15, 1962.

5. Bouldin, David R. Models for describing the diffusion of oxygen and other mobile constituents across the mud-water interface. Journal of Ecology 56:77-87. 1968.

6. Bradley, R. M. and A. James. A new method for the measurement of oxygen consumption in polluted rivers. Public Health Engineering Division, Dept. of Civil Engineering, University of Newcastle-upon-Tyne, Newcastle, England, 1967. 13p.

7. Bradfield, A. E. The oxygen content of interstitial water in sandy shores. Journal of Animal Ecology 33:97-116. 1964.

8. Byrne, J. V. and L. D. Kulm. Natural indicators of estuarine sediment movement. Journal of the Waterways and Harbors Division Proceedings of the American Society of Civil Engineers 93(WW2):181-194. May 1967.

9. Carey, Andrew G., Jr. Energetics of the benthos of Long Island Sound I. Oxygen utilization of sediment. In: Aspects of the oceanography of Long Island Sound. New Haven, Connecticut, 1967. p. 136-144. (Yale University. Peabody Museum of Natural History. Bingham Oceanographic Foundation. Bulletin of Bingham Oceanographic Collection. Vol. 19, Article 2)

10. Carpenter, James H. The accuracy of the Winkler Method for dissolved oxygen analysis. Limnology and Oceanography 10(1): 135-140. Jan. 1965.

11. Duke, Thomas W., James N. Willis and Douglas A. Wolfe. A technique for studying the exchange of trace elements between estuarine sediments and water. Limnology and Oceanography, Notes and Comments 13(3): 541-545. July 1968.

12. Edwards, R. W. and H. L. J. Rolley. Oxygen consumption of river muds. Journal of Ecology 53: 1-19. 1965.

13. Fair, G. M., E. W. Moore and H. A. Thomas. The natural purification of river muds and pollutional sediments. Sewage Works Journal 13:270-307, 756-779. 1941.

14. Frink, C. R. Nutrient budget: Rational analysis of eutrophication in a Connecticut lake. Environmental Science and Technology 1(5): 425-428. 1967.

15. Hanes, Bruce N. and Robert L. Irvine. Oxygen uptake rates of benthal systems by a new technique. In: Proceedings of the 21st Industrial Waste Conference, Lafayette, Indiana, 1966. p. 468-479. (Purdue University Engineering Bulletin, vol. 50, no. 2. Engineering Extension Series No. 121)

16. Hanes, Bruce N. and Thomas M. White. Effects of sea water concentration on oxygen uptake of a benthal system. In: Proceedings of the 22nd Industrial Waste Conference, Lafayette, Indiana, 1967. p. 67-77. (Engineering Extension Series No. 129)

17. Hargrave, Barry T. Similarity of oxygen uptake by benthic communities. Limnology and Oceanography, Notes and Comments 14(5): 801-805. Sept. 1969.

18. Hartman, L. Influence of turbulence on the activity of bacterial slimes. Journal of the Water Pollution Control Federation 39(6): 958-964. June 1967.

19. Hayes, F. R. and M. A. McAulay. Lake water and sediment V. Oxygen consumed over sediment cores. Limnology and Oceanography 3(3): 291-298. July 1959.

20. Holden, A. V. The removal of dissolved phosphates from lake waters by bottom deposits. International Association of Theoretical and Applied Limnology 14(1): 247-251. 1961.

21. Hutchinson, G. E. A treatise on limnology. 1st ed. New York, John Wiley and Sons, Inc., 1957. p. 1015.

22. Issaac, Peter C. G. The contribution of bottom muds to the depletion of oxygen in rivers, and suggested standards for suspended solids. U.S. Public Health Service Publication no. 999-WP-25, p. 346-354. 1962.

23. Kulm, L. D. and John V. Byrne. Sedimentary response to hydrography in an Oregon estuary. Marine Geology 4: 85-118. 1966.

24. Lenhard, G. Bottom deposits. A vital selfpurification system in the degradation of polluting material in natural waters and in biological treatment effluents. Hydrobiologia 25: 404-411. 1965.

25. Martin, Duane Collins. The effect of mixing on the oxygen uptake rate of estuarine bottom deposits. Masters thesis. Corvallis, Oregon State University, 1969. 50 numb. leaves.

26. McDonnell, Archie J. and S. Douglas Hall. Effect of environmental factors on benthal oxygen uptake. Journal of the Water Pollution Control Federation 41: R353-R363. 1969.

27. McIntire, David C. Physiological-ecological studies of algae in laboratory streams. Journal of the Water Pollution Control Federation 40 (11): 1940-1952. Nov. 1968.

28. McIntire, David C. Some factors affecting respiration of peridhyon communities in lotic environments. Ecology 47(6): 919-930. 1966.

29. McKeown, James J., Arthur H. Benedict and Gerald M. Locke. Studies on the behavior of benthal deposits of papermill origin. New York, National Council of the Paper Industry for Air and Stream Improvement, Sept. 1968. 28p. (Technical Bulletin no. 219)

30. Moore, H. B. The muds of the Clyde Sea area III. Chemical and physical conditions: Rate and nature of sedimentation; and fauna. Journal Marine Biological Association of the United Kingdom 17: 325-358.

31. National Council for Stream Improvement, Inc. The oxygen demand of strawboard sludge deposits. New York, New York. Oct. 1957. 28p. (Technical Bulletin no. 99)

32. Neal, Victor T. Tidal currents in Yaquina Bay. Northwest Science 40(2): 68-74. 1966.

33. O'Connell, Richard L. and Nelson A. Thomas. Effect of benthic algae on stream dissolved oxygen. Journal of the Sanitary Engineering Division Proceedings of the American Society of Civil Engineers 91(SA3): 1-16. June 1965.

34. Odum, Howard T. Analysis of diurnal oxygen curves for the essay of reaeration rates and metabolism in polluted marine bays. In: Waste Disposal in the Marine Environment, New York, New York, Pengamon Press, 1960. p. 547.

35. Odum, Howard T. and Ronald F. Wilson. Further studies on reaeration and metabolism of Texas Bays, 1958-1960. Port Aransas, 1962. 17p. (Texas Institute of Marine Science Publications, vol. 8)

36. Oppenheimer, C. H. and R. A. Ward. Release and capillary movement of phosphorous in exposed tidal sediments. In: Symposium on Marine Microbiology, Springfield, Illinois, Thomas, 1963. p. 664-673.

37. Pamatmat, Mario M. Ecology and metabolism of a benthic community. Internationale Revue der gesamten Hydrobiologie 53(2): 211-298. 1968.

38. Pamatmat, Mario M. and Karl Banse. Oxygen consumption by the seabed. II. In situ measurements to a depth of 180 m. Limnology and Oceanography 14(2): 250-259. March 1969.

39. Pamatmat, Mario M. and Douglas Fenton. An instrument for measuring subtidal benthic metabolism in situ. Limnology and Oceanography, Notes and Comments 13(3): 537-540. July 1968.

40. Peterson, Paul E., Graduate Assistant, Department of Microbiology. A summary of bacterial plate count and H_2S producers from sediment of Yaquina Bay. Corvallis, Oregon State University, 1968. (unpublished)

41. Pomeroy, L. R., E. E. Smith and Carol M. Grant. The exchange of phosphate between estuarine water and sediments. Limnology and Oceanography 10(2): 167-172. April 1965.

42. Rolley, H. L. J. and M. Owens. Oxygen consumption rates and some chemical properties of river muds. Water Research 1: 759-766. Nov.-Dec. 1967.

43. Rudolfs, William. Stabilization of sewage sludge banks. Industrial Engineering Chemistry 30: 337-340. 1938.

44. Starkey, Robert L. Sulfate reducing bacteria, their production of sulfide and the economic importance. Tappi 44(7): 493-496. 1961.

45. Stein, Jerome E. and John G. Denison. _In situ_ benthal oxygen demand of celluosic fibers. In: Advances in Water Pollution Research: Proceedings of the 3rd International Conference on Water Pollution Research, Munich, Germany, 1966. vol. 3. Washington, D. C., Water Pollution Control Federation, 1967. p. 181-197.

46. Streeter, H. W. Effects of sewage discharge on streams. Sewage Works Journal 3: 713-723. 1931.

47. Streeter, H. W. Measures of natural oxidation in polluted streams. I. The oxygen demand factor. Sewage Works Journal 7(2): 251-279. 1935.

48. Teal, John M. and John Kanwisher. Gas exchange in a Georgia salt marsh. Limnology and Oceanography 6(4): 388-399. Oct. 1961.

49. Thompson, Rogene Kasparek and Austin W. Pritchard. Respiratory adaptations of two burrowing crustaceans, _Callinassa californiensis_ and _Upogebia pugettenis_ (Decapoad, Thalassinidea). The Biological Bulletin 136(2): 274-287. April 1969.

50. U. S. Department of the Interior. Fish and Wildlife Service. Preliminary survey of fish and wildlife in relation to the ecological and biological aspects of Yaquina Bay, Oregon. Portland, Oregon, Nov. 1968. 35p.

51. U. S. Federal Water Pollution Control Administration. Middle Atlantic Region. An _in situ_ benthic respirometer. 1968? 9p. (CB-SREP Technical Paper no. 6) (Mimeographed)

52. U. S. Public Health Service, Division of Water Supply and Pollution Control, Region IX. Oceanography and related esturial pollution problems of the Northwest. In: Proceedings of the 6th Symposium on Water Pollution Research, Portland, Oregon, Nov. 1959. 53p.

53. Velz, C. J. Significance of organic sludge deposits. In: Oxygen relationships in streams. Proceedings of a seminar sponsored by the Water Supply and Water Pollution Program of the Sanitary Engineering Center, Cincinnati, 1957. Cincinnati, 1958. p. 47-61. (U. S. Robert A. Taft Sanitary Engineering Center. Technical Report no. W 58-2)

54. Zobell, C. E. and D. Q. Anderson. Vertical distribution of bacteria in marine sediments. Bulletin American Association of Petroleum Geologists 20(3):258-269. March 1936.