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Unattended Remotely Operated Deep-Water Sediment Oxygen Demand Chambers

Drake Theodore Mailes

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of
Master of Science

Gustavious P. Williams, Chair
A. Woodruff Miller
E. James Nelson

Department of Civil and Environmental Engineering

Brigham Young University

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ABSTRACT

Unattended Remotely Operated Deep-Water Sediment Oxygen Demand Chambers

Drake Theodore Mailes
Department of Civil and Environmental Engineering, BYU
Master of Science

Dissolved oxygen (DO) depletion in a water body is governed by two primary mechanisms: biological oxygen demand (BOD) from the water column, and sediment oxygen demand (SOD) from sediments. SOD is the dominant oxygen sink in many water bodies; measurements show as much as 95% of oxygen consumption as attributable to SOD (Truax, Shindala, & Sartain, 1996). Measuring SOD in surface water impoundments is an essential component in evaluating and an important input for modeling the health of a water body.

Traditional SOD measurement methods are difficult in deeper waters, such as in reservoirs or lakes, because traditional SOD measurement chambers require direct placement. The goal of this research was to modify an existing SOD chamber design to support deployment and recovery in depths in excess of 5ft, typically from a boat or other floating platform. The design required accurate DO measurements, taken unattended and recorded for several hours to several days, for SOD calculations and other parameters such as cation releases under anaerobic conditions.

Using a previously designed chamber, I developed tools and methods to meet these requirements. DO data logger probes were purchased so that DO calculations could be taken without the need of surface support. To mount the chambers inside the previously designed chambers, a new mounting mechanism was designed and installed onto the chamber lids. Deployment and recovery methods and design were developed to ensure the chambers would be recoverable from a boat in deep waters. Previously, the unmodified chambers could not be deployed unattended because of the required power and data link with the surface.

Here I present an easily replicated chamber design that allows for remote chamber placement and measurement of SOD in deep waters without the need of SCUBA or other specialized equipment that is traditionally required. The chamber design allows water to circulate through the chambers until they are placed and closed on the sediment bed, at which time the measurements start, ensuring correct initial conditions. During deployment, the data logger will log DO concentrations at predetermined intervals for several hours or days at a time. To recover the chambers, the researcher must only find the buoy attached to the rope and hoist the units back to the surface.

Modifications and methods were tested and revised over the course of several months and dozens of tests. Experiments were conducted at various depths, ranging from 12–50ft, which showed the versatility of the chambers. Using this design, other researchers will be able to generate substantial amounts of SOD data at depths that will allow accurate SOD behavior to be included in models of water impoundments.

Keywords: sediment oxygen demand, dissolved oxygen, deep-water, independent, remote

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Without the support of Brent Hargis and Dillon Harker in the development and deployment of the chambers, this research would not have been possible. Brent was able to use his many talents to keep the boat afloat and running properly, as well as to come up with novel solutions to the many problems that we faced. Without him, the chambers would have been lost long ago in the depths of the reservoir. Dillon was a much-needed hand in helping to recover the chambers and to deploy them in less-than-ideal conditions.

I would be remiss if I did not thank Professor Williams, who trusted this project to a wayward engineer. Thank you for your support, confidence, and understanding.

TABLE OF CONTENTS

LIST OF TABLESvi

LIST OF FIGURESvii

1 INTRODUCTION..... 1

2 BACKGROUND 4

 2.1 Deer Creek Reservoir 4

 2.2 Sediment Oxygen Demand..... 4

3 SOD CHAMBERS 7

 3.1 SOD Measurements..... 7

 3.2 Design Considerations..... 8

 3.3 BYU SOD Chamber Design 10

4 TESTING METHOD..... 15

 4.1 Theory 15

 4.2 Method 17

 4.3 Probe Calibration..... 19

5 RESULTS AND DISCUSSION 21

 5.1 Introduction..... 21

 5.2 SOD Chamber Testing Schedule..... 21

6 EVOLUTION OF CHAMBER DESIGN AND DEPLOYMENT 23

 6.1 Preliminary Tests..... 23

 6.2 Shallow Trials 24

 6.3 Initial Deepwater Testing 25

6.4 Weighted Top	28
6.5 Mounting Straps and Acrylic Plates.....	28
6.6 Fine Sediment and Sinking Chambers	29
7 DCR SOD MEASUREMENTS	35
7.1 Number of Trials	35
7.2 DCR Temperature and Trial Length	36
7.3 SOD Measurements.....	36
8 CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORK.....	41
8.1 Conclusion.....	41
8.2 Recommendation for Future Work	42
REFERENCES.....	44
APPENDIX.....	46

LIST OF TABLES

Table 1: Statistics of Field and Bucket in Open and Closed Chamber Probe Comparison	20
Table 2: Testing Timetable	22
Table 3: SOD Measurements from DCR Deployments	38

LIST OF FIGURES

Figure 1: Map Showing DCR	6
Figure 2: SOD Rate versus Chamber Mixing Velocity Graph	9
Figure 3: Closed Chamber Submerged in Test Chamber	11
Figure 4: Mounting Mechanism with Probe Attached.....	12
Figure 5: Chamber Lid with Added Plated Attached as Indicated by Red Circle	13
Figure 6: Graph from 9 May Open chamber at Mid Inlet.....	16
Figure 7: Example Results Showing Properly Functioning Chambers	17
Figure 8: 1 May Duck Pond Open Chamber Graph	24
Figure 9: 1 May Duck Pond Closed Chamber Graph.....	24
Figure 10: Open and Closed Chamber 3hr Trial.....	25
Figure 11: May 16 Deep Open Chamber Trail Graph.....	26
Figure 12: Map of DCR with Diamonds showing Testing Locations	27
Figure 13: Details of Change Made to Mounting System Inside Open Bottom Chamber	30
Figure 14: Details of Changes Made to Mounting System Inside Closed Bottom Chamber	31
Figure 15: 21 Aug. Open and Closed Hite Trial Graph Showing Open Chamber Malfunction...	32
Figure 16: Probes Zip Tied to the Top of Chamber Lid	33
Figure 17: 21 Aug. Open and Closed chamber Ticaboo Trial After Modifications	34
Figure 18: 21 May Mid Open and Closed Trail Graph.....	37
Figure 19: 16 May Near Dam Open and Closed Trial Graph.....	38
Figure 20: Gap Marked with Red Circle Indicating Gap in O-Ring.....	39
Figure 21: 21 May Mid Inlet Open and Closed Trial Graph	40

1 INTRODUCTION

Dissolved oxygen (DO) depletion in a water body is governed by two primary mechanisms: biological oxygen demand (BOD) from the water column, and sediment oxygen demand (SOD) from sediments. SOD is the dominant oxygen sink in many water bodies; measurements show as much as 95% of oxygen consumption as attributable to SOD (Truax et al. 1996). The amount of DO depletion that is contributed by SOD is dependent on water depth and the trophic state of the water body (Nakamura and Stefan 1994; Truax et al. 1996). SOD results from a combination of factors, including organic materials that settle to the bottom, the respiration in the benthic ecosystem supported, decomposition of sediments derived from aquatic life, and decomposition of runoff detritus in the sediment (Truax et al. 1996). SOD, reported in $\frac{gm\ O_2}{m^2\ hr}$ or $\frac{gm\ O_2}{m^2\ day}$, is commonly measured by two techniques: in situ respirometry and laboratory respirometry, with in situ methods being more commonly used (Truax et al. 1996).

For in situ methods, a chamber is placed with the bottom open to the sediment, and the SOD rate is calculated using the volume of the chamber, the area of exposed sediments, and the rate of oxygen depletion (Murphy and Hicks 1986; Truax et al. 1996). A second chamber is typically deployed to collect data to correct for oxygen depletion from BOD in the water column (Murphy and Hicks 1986). The standard method for SOD measurement requires the placement of two standard chambers (one with an open bottom and one with a closed bottom) with a volume of 27.2L and an exposed area of $0.15m^2$ on the bottom of the water body, which measure DO

levels over time (Murphy and Hicks 1986). Initially both chambers are open, allowing non-oxygen-depleted water to flow through the chambers as they are lowered, equalizing conditions between the two chambers and more accurately representing in situ oxygen concentration and water conditions at the bottom. Once placed on the sediment, the chambers are closed and measurements are started (Murphy and Hicks 1986). The standard design requires the manual closing and opening of ports in the sides of the chambers in order to allow water to flow through prior to initiation of the measurement (EPA 2009). At any significant depths, this requires people to use SCUBA gear to place the chambers, which greatly adds to the complexity of measuring SOD and can prevent measurements for deeper water bodies. Furthermore, most chamber designs require oxygen concentration sensors that are tethered to a computer at the surface for power and data logging, which hinders long-term data collection and deep placement.

My design, which can be easily replicated by other researchers, allows for remote placement and operation of SOD chambers at depths up to 100m (limited by the DO probe). Furthermore, the newly designed mounting mechanism allows for a rapid turnaround in the redeployment of chambers, which maximizes data gathering. In addition, the mounting design permits other probes to be easily deployed inside the chamber. This design is easily deployed and recovered from the surface without the need of SCUBA gear and is able to gather data unattended by a surface support team. This provides several benefits: (1) the ability to easily measure SOD at greater depths allows for a more complete characterization of reservoir and lake processes; (2) unattended operation allows for more efficient data collection; and (3) the ability to support long-term operation allows anaerobic conditions to develop in the chamber, supporting measurements of cation such as phosphorus (a nutrient), which are released from the sediments because of changed redox conditions. This last item is important because releases of

phosphorus from sediments can significantly affect the ecosystem, and this source is not easily measured (Holdren and Armstrong 1980). Our chamber design includes ports that mechanically open or close depending on the posture of the chamber (suspended or in place on the sediment), and dissolved oxygen sensors with internal data loggers for unattended operation and measurements. Therefore, this design affords researchers flexibility in the type of data being measured, as well as increases the amount of data gathered per experimental trial.

The development of the chambers has been a multi-year process undertaken by several graduate students. My efforts add to and complete the development of BYU's SOD chambers into a functional scientific instrument. While the specifics will be discussed herein, I mention for the sake of clarity my specific contributions to the SOD chambers. Which were to find compatible DO data loggers and install a mounting platform for the loggers inside the chambers. To gather accurate data holes in the chamber lids were plugged to provide a watertight environment within the chambers. A buoy attached to 100ft of line were tied to mounting points on the chamber lids to allow launching and recovery of the chambers from boats on the water. Finally a method for using the chambers was developed.

This paper discusses the SOD chamber design, as well as the type and placement of the data loggers. We present results that demonstrate the ability to take measurements at deep depths and the ability to support long-term measurements (5 days). In addition to evaluating phosphorus release in anaerobic conditions, long-term measurements may be required at deep depths because of colder water temperatures, which significantly slow the kinetics of SOD and increase the time needed to make accurate measurements (Walker and Snodgrass 1986).

2 BACKGROUND

2.1 Deer Creek Reservoir

Completed in 1941 by the Bureau of Reclamation (USBOR), Deer Creek Reservoir (DCR), shown in Figure 1, serves populations throughout central Utah with agricultural, industrial, and residential water supplies. During the 1980s, DCR was classified as highly eutrophic due to low DO levels. As a result, schemes were undertaken to reduce the nutrient load delivered to the reservoir, such as the installation of a phosphate removal facility at the outlet of the Jordanelle Dam upstream of DCR. While DO concentrations and temperature levels remain outside compliance levels, overall reservoir health has improved to the point where DCR has been classified as mesotrophic (PSOMAS 2002). Possible causes of continuing DO depletion are resuspended sediments and geochemical dissolution, which introduce nutrients into the water column (Casbeer 2009).

2.2 Sediment Oxygen Demand

Oxygen consumption in a water body is governed by two primary mechanisms: biological oxygen demand, BOD from the water column and SOD from sediments. SOD is the dominant oxygen sink in many water bodies, with measurements showing as much as 60% (Jaffe & Park 1998) to 95% of oxygen consumption as attributed to SOD (Truax et al. 1996). As such,

measuring SOD is important to understanding and modeling the health of an aquatic system (Hatcher 1986).

Decomposition of plant and other organisms influence SOD predominantly as microorganisms consume DO. As DO levels decrease, metallic ions and other nutrients dissolve from the sediments, becoming available for use by microorganisms and plants (Casbeer 2009)—thereby further contributing to increased SOD and depressed DO because of increased biological activity.

If DO concentrations are less than $4.0 \frac{mg}{l}$, state regulators consider the water body to be impaired (PSOMAS 2002). Impaired water bodies not only affect the taste and odor of drinking water but also aquatic life as well. Low DO levels, termed anoxic conditions, can cause death in local fish and microbial populations. Because over 50% of the DCR water column is below the 4.0 mg/l, the reservoir is considered to be impaired (PSOMAS 2002).

As SOD is a major determining factor in DO consumption, measuring it in DCR is important in guiding efforts to remove DCR from Utah's list of impaired water bodies. One of the goals of this research was to develop the SOD chambers to measure DO levels throughout DCR. Gathered data will be used to assist in the creation of SOD models specific to DCR. DCR was used as a field laboratory to demonstrate and validate these methods, which will also be used at Lake Powell and Lake Mead to support USBOR requirements. This design and methods are applicable to measuring SOD in any water body at depths.



Figure 1: Map Showing DCR (Utah Automated Geographic Reference Center 2012)

3 SOD CHAMBERS

3.1 SOD Measurements

There are two methods for measuring SOD: in situ and within a laboratory setting. Laboratory testing lends itself to controlled conditions and duplication. However, such testing inherently disturbs the sediment, which can result in inflated SOD readings (Doyle and Rounds 2003).

Several research studies have shown that in situ testing is more accurate in measuring SOD (Utley et al. 2008; Whittemore 1968). In-site testing best represents actual environmental conditions. The Environmental Protection Agency and U.S. Geological Survey have both established in situ protocols for SOD testing.

As explained above, in situ testing requires the use of two SOD chambers, one with an open bottom, which when lowered creates a seal with the sedimentary floor, exposing the water contained in the chamber to SOD from the sediment exposed at the bottom of the chamber, and BOD from the water contained in the chamber. The second chamber has a closed bottom and only measures the contribution from water BOD. Using the data from the second chamber, the results from the first chamber can be corrected to separate the SOD contribution from the BOD

contribution. Data are taken over time, as both SOD and BOD are measured by using the kinetics (or rate) of DO depletion (Lounsbury 2011; Murphy and Hicks 1986; Truax et al. 1996).

Recent research into in situ testing has suggested that traditional chambers are not the only method for determining SOD. For example, a profile method uses three DO probes lowered at different heights with a single flow meter to measure flow velocity (Miskewitz et al. 2010). This method adjusts for effect of stream turbulence on SOD by measuring a concentration gradient in DO versus depth, multiplied by vertical eddy diffusivity. A comparison study of the two in situ methods showed considerable differences in SOD when stream velocity was higher, but relatively insignificant differences in other cases (Miskewitz et al. 2010). This approach, while valid in rivers or streams, has not been demonstrated in reservoirs or other water impoundments where water velocities are minimal.

3.2 Design Considerations

There are three primary design considerations with regard to SOD chambers: internal stream velocity, watertight integrity, and ease of deployment. The first two considerations are integral to gathering accurate data, while the third enhances usability.

Recently there has been considerable research conducted on the effect that circulation velocity within the chamber has upon SOD measurements. Some argue that SOD is linearly related to stream velocity, while others suggest that low velocities cause more change in SOD than higher velocities (Stefan 1994). The most recent study, conducted in 2003, proposes that low to medium velocities ($0.6\text{--}6.9\frac{\text{cm}}{\text{sec}}$) have little effect on SOD, but velocities higher than $7.5\frac{\text{cm}}{\text{sec}}$ show significant increases in SOD (Doyle and Rounds 2003).

Figure 2 shows the effects chamber circulation velocity may have on SOD rates. For this reason, many SOD chambers, including those used by the EPA, use some form of chamber mixing mechanism to ensure accurate readings (EPA 2009). These apparatuses commonly take two forms, either a pump that circulates water throughout or paddle mixers. Most chambers are used in streams or rivers, where there is a pronounced current. DCR, however, especially at depths in excess of 20ft, have very little if any current at the bottom. Because of this, we believe a circulation system for measurements in deep lakes or reservoirs is not required to obtain accurate measurements. DO diffusion in the chambers occurs over a very short distance (maximum of 20cm, the height of the chambers) and should have a minimal effect on the results. Based on this research, and to minimize design complexity, we did not include pumps or propellers to create water movement inside our chambers during measurements. These assumptions have not been verified.

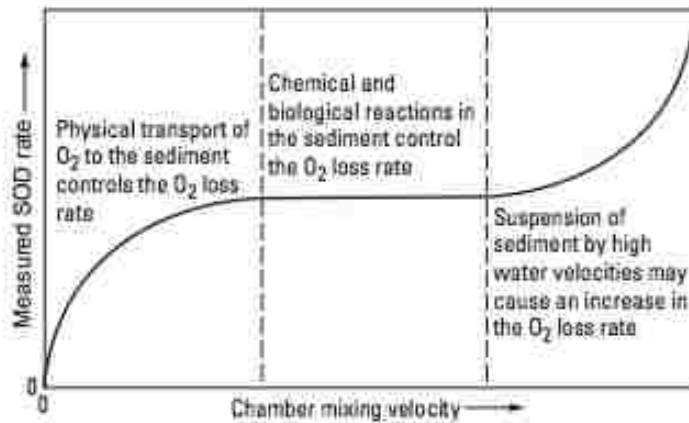


Figure 2: SOD Rate versus Chamber Mixing Velocity Graph (Doyle and Rounds 2003)

Accurate SOD measurements hinge upon the chambers' ability to isolate a given body of water from its surroundings. Isolation allows for the measurement of sediment oxygen demand

as the confined water DO concentration decreases with time. However, if new water were allowed to enter into the system, the DO levels would not reflect the DO usage rate, but rather some combination of DO use and replenishment, thereby nullifying the purpose of the chamber. The most challenging aspect to a remotely deployed chamber design is sealing the open bottom chamber against the sediment. In silt-rich sediment a seal is easily obtained. However, in rocky and coarse sand, sealing the bottom is much more difficult. In shallow situations, those placing the unit can stand on the unit or apply other pressure to the top of the chamber to obtain an adequate seal and to verify that a seal has been achieved. At deeper depths this type of manual placement would be difficult, if not impossible, without SCUBA or other gear to support deep-water manual placement. The closed chamber does not address this issue. The second design issue that affects both chambers is the requirement to have the chambers open to the in situ water prior to the measurement, and then isolated when the measurement begins. In chambers designed for shallow placement, this is typically accomplished by doors that can be slid shut to isolate the chamber.

Minimizing openings in the units not only ensures watertight integrity, but also makes the unit easier to maintain and handle in the field. Because SOD chambers are field instruments, straightforward and easy operation is an important aspect to their design. Key considerations we considered for design were manageable size and weight, construction out of durable material, easy placement and removal from operational sites, and the ability to take and store unattended measurements.

3.3 BYU SOD Chamber Design

In 2011 Derek Lounsbury constructed two SOD chambers, an open- and closed-bottom chamber (shown in Figure 3). These chambers were fabricated out of 6061 aluminum alloy and

had a volume and chamber area of 33.36L and 0.164m² respectively (Lounsbury 2011). Through several holes drilled through the top, DO and other probes were lowered into the chamber. For more specifics on the design of the chamber, please refer to Lounsbury (2011).

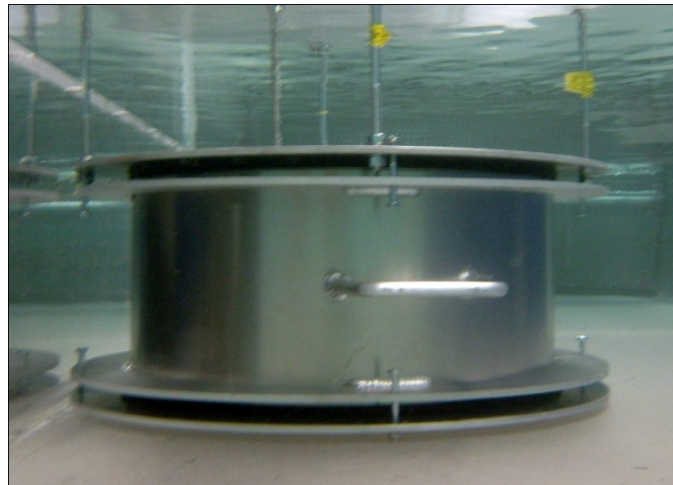


Figure 3: Closed Chamber Submerged in Test Chamber (Lounsbury 2011)

The Lounsbury chambers were designed to be used with DO probes that were attached to power and data relay cables that were connected to a power source and data logger (typically a laptop computer) on the surface. In the field this is acceptable for monitoring streams and shallow lakes, but it creates problems when deepwater monitoring or long-term measurement is desired. Our design goal was to monitor areas of DCR, where depths are in excess of 30ft, and Lake Powell, where depths are significantly more. Because of the required tether, unattended as well as deep operations were difficult if not impossible in Lake Powell or DCR. Therefore, a different type of DO probe was required, that had self-contained data loggers and power supplies were desired. The probes needed to be able to be mounted to the inside of the chamber and left for several hours, days, or longer. After searching we selected DO loggers from the Onset Computer Corp. (HOBO DO Logger Model U26-001), as they met the size requirements and

have the ability to measure and store data up to several weeks, depending on the recording interval. Furthermore, the Onset probes could be redeployed without the need of a computer terminal. Thereby allowing rapid turn around on site, permitting several runs to be conducted each day if desired.

Previous methods for attaching the loggers to the inside of the chambers proved to be problematic and caused erratic readings. Due to the importance of maintaining watertight integrity, drilling into the chambers was not desired. We used 2-ton waterproof epoxy, a 6x1in strap of nylon (similar to those found on backpacks) and two-side release plastic clips (placed 1/3 and 2/3 along the nylon strap) to create attachment points at top of the chamber. These points included adhesive, industrial-strength Velcro that was wrapped around the outside of the probes and a complimenting Velcro section wrapped through the webbing loops of the aforementioned clips, shown in Figure 4. This Velcro and clip system allows for easy installation and removal of the probes, as well as for simple integration of other probes types. A fail-safe system using a high-strength steel wire attached to a carabineer and a small climbing rope secures the probes to a bolt inside the chamber in case the Velcro attachment is loosened during use.



Figure 4: Mounting Mechanism with Probe Attached

The original chambers had several openings to accommodate probes and to take water samples from the chambers. To close these holes, ¼in-thick acrylic plates were attached the top of the chamber using 2-ton waterproof epoxy, as shown in Figure 5. By using epoxy instead of welding aluminum plates to the top, adjustments can easily be made to the chamber if necessary.



Figure 5: Chamber Lid with Added Plated Attached as Indicated by Red Circle

To take water samples, if desired, a 6in-piece of ¼in-thick plastic tubing was inserted through a hole drilled through one of the acrylic plates, and the area around the hole was reinforced with epoxy for watertight integrity. The tubing extends 3in inside and 3in outside the chamber, and a 60ml syringe can be attached to the tubing outside the chamber in order to extract a water sample from the chamber. The tubing inside the chamber can be seen in Figure 5.

The Lounsbury design exhibited a problem with the top lid occasionally not closing when the chamber reached the reservoir bed. To overcome this problem 10lbs of weight were added to the top lid. This weight does not prevent water from flowing through the top, as it is lowered as

the attachment points are on the lid, but this weight is sufficient to close and seal the lid once the chamber comes to rest on the bottom of the impoundment.

We deployed and recovered the SOD chambers at depth by attaching a 100ft buoyant line to the chambers' 4 anchor points located on the lid. This line was then tied to a buoy, which floated on the surface. For situations when the chambers are left over extended periods, the buoy can be submerged 6ft (to avoid collisions with boats) and a strobe beacon can be attached to assist in recovery operations.

4 TESTING METHOD

4.1 Theory

SOD is a measure of the oxygen demand of the sediment. Using data gathered from the DO probes, SOD rates can be calculated. To compute the SOD, measured DO concentrations are graphed with respect to time. However, placement of the open-bottom chamber disturbs the sediment, which mixes sediments with the water in the chamber. This results in irregular increases or decreases in DO concentrations within the first 30–45min, as shown in Figure 6; these measurements are ignored and the slope of the oxygen-depletion curve of the remaining data is obtained. In warmer waters, such as shallow surface streams, the entire measurement may only take 1–2 hours. However, kinetics are significantly slower in the colder water deep within reservoirs, and ignoring these first data still leave sufficient data to compute the SOD rates.

Using Equation 1, SOD was calculated:

$$SOD_T = 1.44 \frac{V}{A} (b_1 - b_2) \quad (1)$$

where V is volume of the chamber in liters, A is the area of bottom sediment covered by the chamber in m², and b is the slope of the oxygen-depletion curve in $\frac{mg}{l \text{ min}}$ of the open (b_1) and closed (b_2) chambers (Doyle and Rounds 2003).

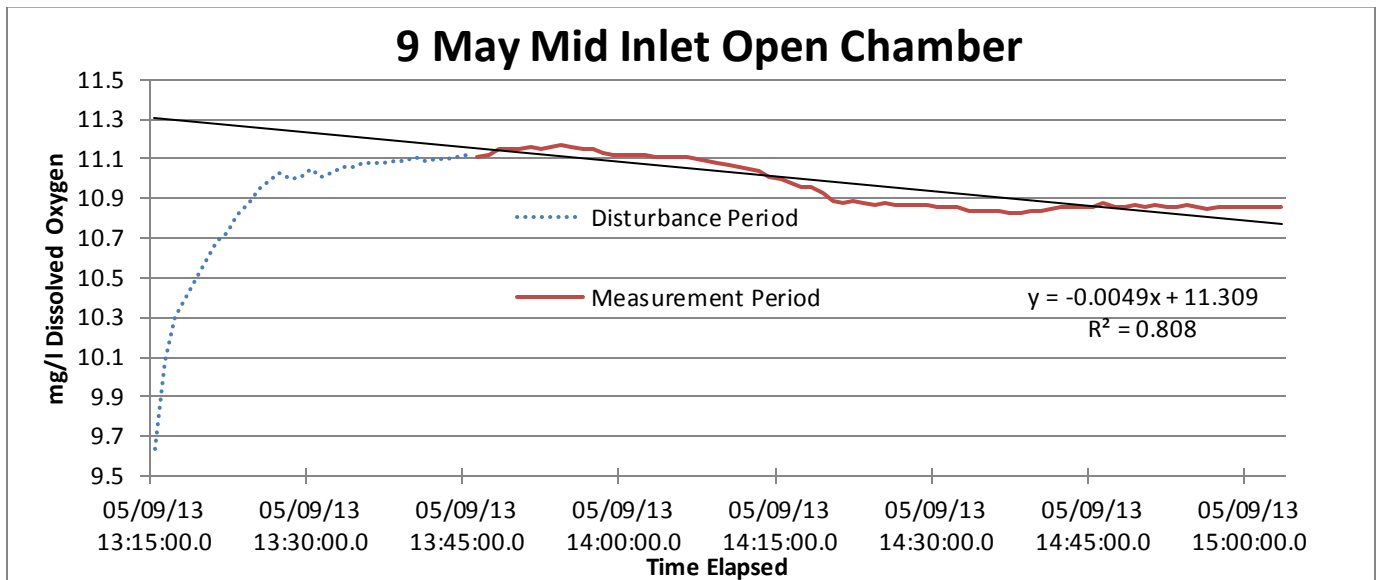


Figure 6: Graph from 9 May Open chamber at Mid Inlet

Typically the van't Hoff equation is used to correct the effect of temperature on SOD rates (Doyle and Rounds 2003), though it is only valid for temperatures greater than 10 °C. Because the average temperature of DCR during our testing was less than 10 °C, this was not used, and the rate calculated at the ambient temperature is the rate reported for validation and demonstration purposes.

DO data from the closed and open chambers will reveal whether or not the SOD chamber operated properly for a given measurement. A correctly operating SOD chamber will show a gradual decrease with time, as shown in Figure 7. In a correct measurement, the closed chamber should show little decrease or a decrease less than the open chamber, as it is only affected by BOD, while the open chamber is affected by both BOD and SOD. An example of the open chamber data is shown by the red curve in Figure 7, which indicates that the water at this reading exerted little BOD.

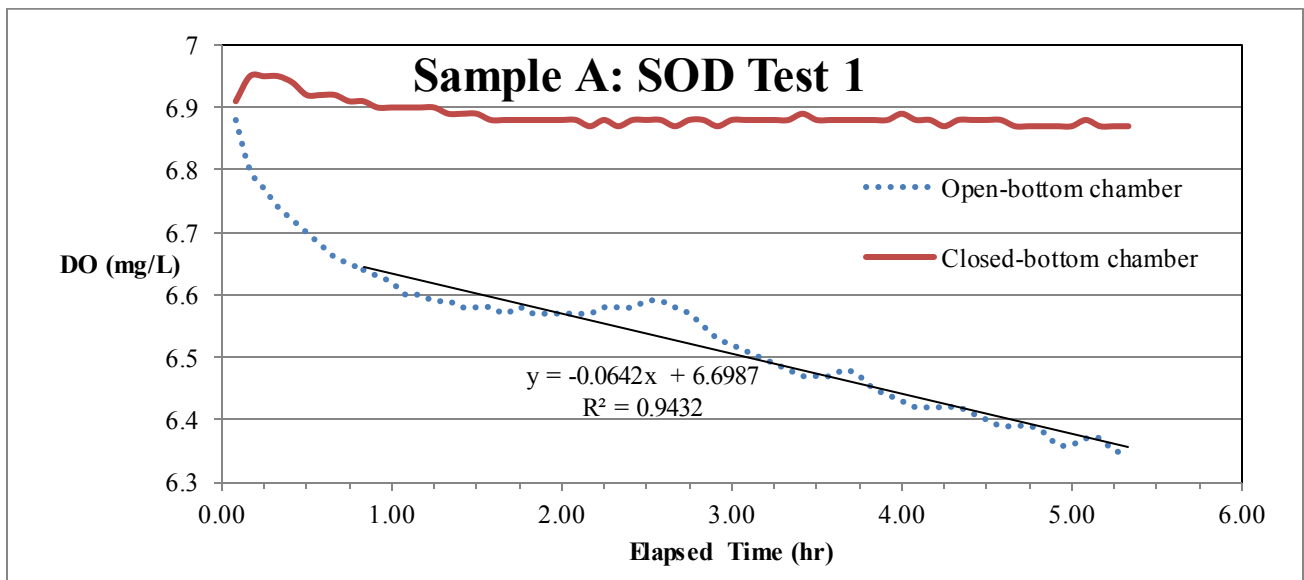


Figure 7: Example Results Showing Properly Functioning Chambers (Lounsbury 2011)

4.2 Method

Ideal sites for these SOD chambers have little or no slope to the bed, to prevent the unit from rolling. Coarse sand or rocky terrain does not create as good of a seal as sediment that is primarily composed of silt or mud. Therefore, site selection is important for proper operation. Measurements can be taken at difficult terrains (e.g., large slopes or granular sediments), but care

must be taken, and generally several measurements must be taken before a set of good data results.

Before a measurement, the probes are initialized by connecting the probes to a computer and running the HOBOWare program. This software allows the user to specify a specific time when the loggers will begin collecting DO concentrations and the measurement interval. Typically the loggers are set to become active 15min after they are disconnected from HOBOWare, which allows enough time to load the probes into chambers and to lower the chambers into position. The software allows the user to specify the logging interval, anywhere from once every minute to once every week. Given that EPA SOD testing protocols call for tests that last 1.5–2hrs, 1min interval logs were chosen. However, due to the cold water as noted above and seen in Figure 7, our readings typically lasted 4–7 hours.

Once the probes were mounted to the chambers, and the fail-safe mechanisms were secured to retain the probes if the Velcro became unattached, the chambers were taken to the back of the boat. Before lowering the chambers, a measurement probe was lowered to measure the depth, temperature, conductivity, and DO concentrations of the water column. Once these data were gathered, which took a couple of minutes, the chambers were lowered into place.

This lowering was done manually using a buoyant marine rope with a buoy attached to one end. The two chambers were placed within 10-15ft of each other to allow for an accurate comparison. Once the desired measurement period elapsed, the chambers were raised manually. Using the HOBOWaterproof Shuttle (Part: W-DTW-1), the data from the loggers were retrieved and analyzed using HOBOWare software.

Extended tests were conducted in a similar way over the course of several days. But the logging period was changed to 5min and the buoys attached in such a way that they were 6ft

below the surface when deployed. This way, the chambers would accurately reflect real differences in the water column and be protected against any curious individuals or passing boats but also were easily retrievable.

4.3 Probe Calibration

The probes were calibrated according to manufacturer specifications before operation. Calibration consisted of zeroing out the probe in an oxygen-deficient solution, as well as maxing out the sensor in a 100%-saturated environment. Hoboware suggested that the DO probes only needed to be calibrated when a new sensor cap was installed; because we only used one cap throughout the entire testing period, we only calibrated the probes at the beginning of the testing season.

To verify that the probes were calibrated to each other and that they provided consistent readings, we placed the probes side by side in a bucket of water in the lab and left them for 15min to 24hrs. We also lowered the probes side by side into DCR on three occasions for a field comparison of the DO profile. To compare the data taken by the two probes we computed the average and standard deviation of the difference. Table 1 shows that the deviations between the probes in the closed bucket tests were insignificant. Field tests showed a larger but still small difference between the two probes. The measurements taken in DCR are most likely accurate because even small variations in location can result in differences in DO concentrations. Therefore, we are confident that the two probes are both accurate and precise in their measurements. Specific average data on each test can viewed in Appendix A.

Table 1: Statistics of Field and Bucket in Open and Closed Chamber Probe Comparison

	Average	Standard Deviation
DCR Trials	0.203	0.386
Lab Bucket Trials	-0.003	0.031

5 RESULTS AND DISCUSSION

5.1 Introduction

Determining how to modify and deploy the chambers was a progressive process that took several months, with testing continuing throughout the development period. This chapter presents the progression the chambers and the deployment methods made from the base state in April 2013 to the current configuration. This section details problems and issues that occurred when deploying the chambers and what steps we took to address these issues. The subsequent sections present the results from our trials. Graphs of trials not shown in the bulk of the paper are provided in Appendix A.

5.2 SOD Chamber Testing Schedule

After the initial modification and probe placement we started to test the chambers and to develop the experimental method. We first demonstrated that the probes and chambers could operate in shallow water before they were deployed at deeper depths. After weeks of testing in DCR, the chambers showed that they were able to operate at depths in excess of 40ft and that we had developed a method that provided consistent results. The ultimate goal, however, was to demonstrate to the Bureau of Reclamation that the chambers could operate in Lake Powell, which we did on August 20–22, 2013. Table 2 shows the testing timeline.

Table 2: Testing Timetable

Chamber Deployment Timeline (2013)	
Duck Pond Testing	April 30 – May 3
Shallow DCR Testing	May 7 – May 14
Deep DCR Testing	May 14 – Sept 9
Lake Powell Testing	Aug 20 – 22

6 EVOLUTION OF CHAMBER DESIGN AND DEPLOYMENT

6.1 Preliminary Tests

Preliminary tests of the method and chambers were conducted in the BYU Duck Pond south of campus. The pond was chosen because of its shallow depths and the ample organic material that settles on the bottom from the ducks, which was expected to have high SOD values. These initial tests showed that the modified chambers performed as expected. Figure 8 shows the open-chamber DO concentrations. Figure 9 shows that small DO concentrations changed with time in the closed chambers, which is to be expected because the water column itself has a large oxygen demand (BOD). Nevertheless, the data are consistent with a successfully isolated unit—meaning that both the lid and the bottom were well sealed. Figure 8 shows a gradual decrease over time, demonstrating that the unit sealed properly against the sediments and was watertight.

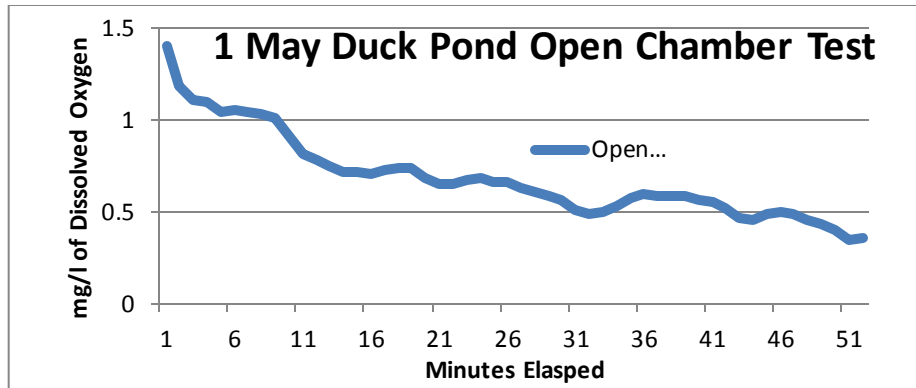


Figure 8: 1 May Duck Pond Open Chamber Graph

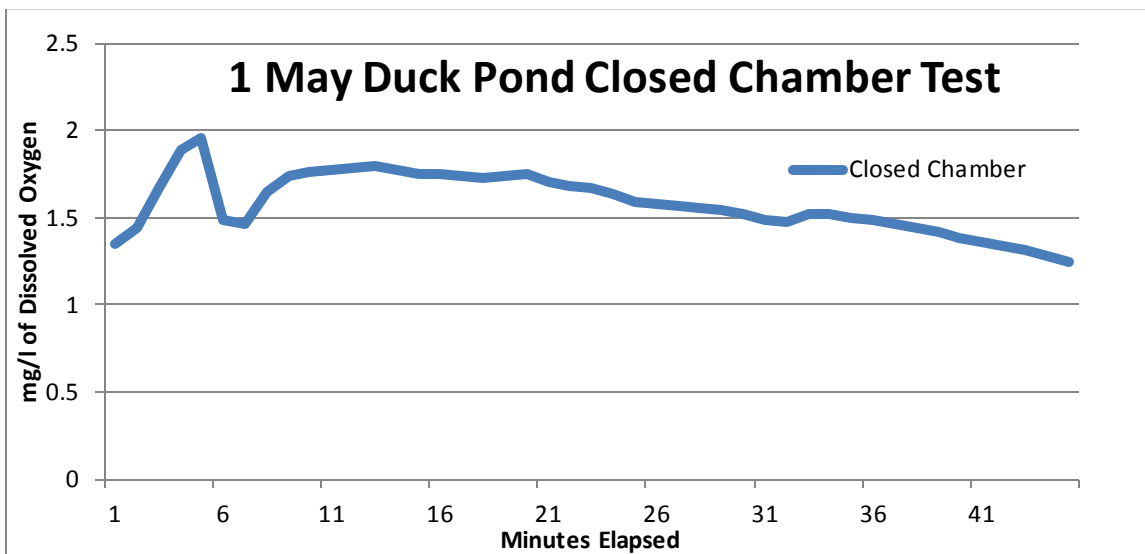


Figure 9: 1 May Duck Pond Closed Chamber Graph

6.2 Shallow Trials

Following successful trials on campus, the chambers were taken to the DCR for field testing. These initial tests were conducted in shallow water, where the chambers could be manually placed onto the sediment. Once the chambers were in place, we applied pressure to the lids to ensure that they were properly closed and sealed against the sediment. Figure 10 shows one of the data sets from these trials. The decreasing DO concentration with time for the open

chamber shows that the chamber functioned as expected. In situations where the closed chamber showed oxygen concentrations increasing, which was the case here, we assumed the slope to be zero. Because the open chamber behaved as expected we proceeded to deep-water trials. Increasing oxygen content could be due to temperature changes or to water plants continuing to off-gas, as the changes are very small.

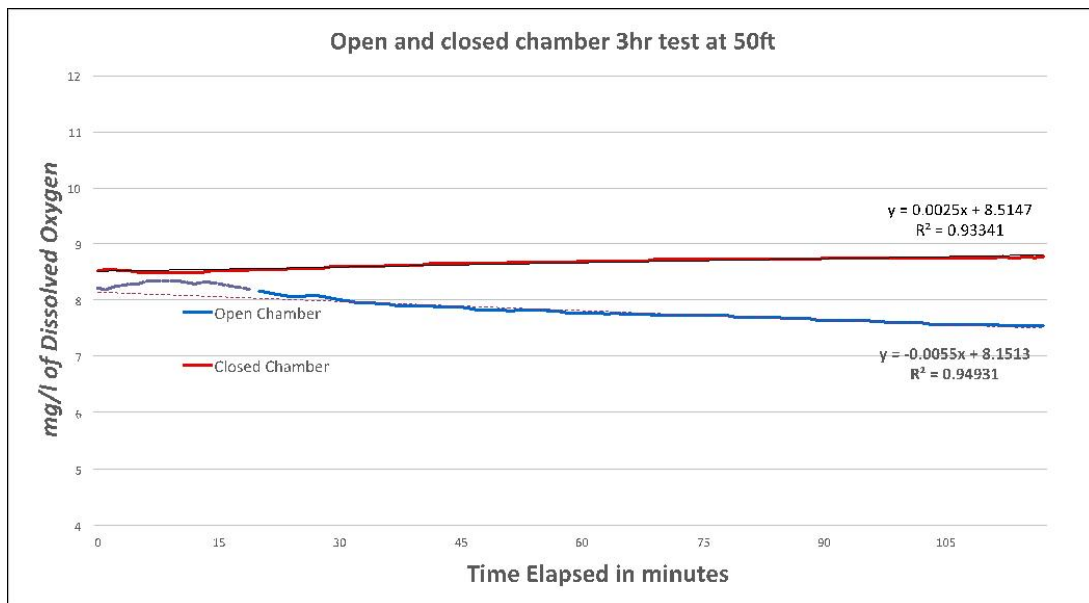


Figure 10: Open and Closed Chamber 3hr Trial

6.3 Initial Deepwater Testing

To support deepwater placement, 75ft of ½in marine cord with a buoy at the end was fastened to the 4 attachment points on the chamber lids. In our first trial we hoped to be able to deploy the chambers in 80ft of water. With 75ft of line, we thought that the buoy would be able to be seen from the surface, but that it would go unnoticed by other lake visitors and would pose no hazard to passing boats. We selected the inlet of Wallsburg Bay for the first test because of its depth, small area, and proximity to permanent landmarks for easy reference. Before dropping the

chambers, the depth was checked using a measurement probe. Upon confirming the depth of approximately 80ft, we dropped the chambers. We watched as the chambers' accompanying buoy dropped out of sight. Figure 11 shows the data from the open chamber that came from the resulting two-day test. As can be seen, the chambers did not seal properly against the sediment. Upon consultation with a topographical map, we concluded that the chambers tumbled and rolled once they landed on the steep reservoir bed. This would also explain why they fell out of sight once they were launched.

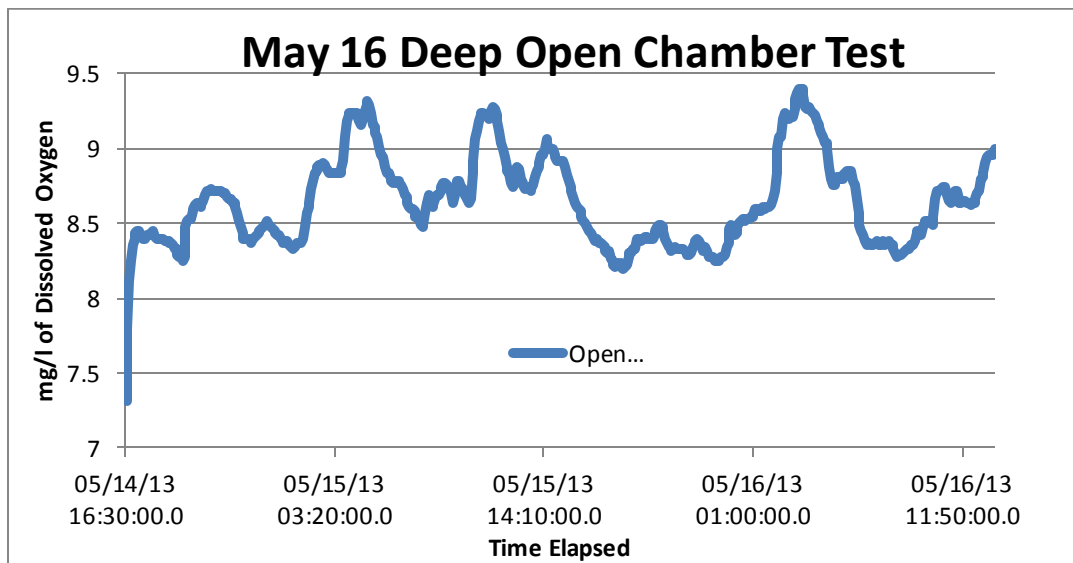


Figure 11: May 16 Deep Open Chamber Trail Graph

To ensure that this situation was never repeated, we selected sites that were 40–50ft in depth to guarantee that the buoys would rest on the surface and thereby be easily retrievable. To avoid interference from curious people we selected secluded, overnight sites, while 3-hr trial locations were unchanged. These measurement sites are marked in Figure 12 below and are all located on the western side of the reservoir.



Figure 12: Map of DCR with Diamonds showing Testing Locations
(Green: Near Dam, Red: Wallsburg, Orange: Mid inlet, Yellow: Upper Dam)

6.4 Weighted Top

Previous users of the chambers had reported problems with them not sealing properly. Because the initial tests had us manually placing the chambers and applying pressure to the top, this problem was not noticed. Once tests progressed to deeper depths, we tied about 10lb of ballast to the top of the open chamber (3ft x 6in aluminum plates) to meet the perceived requirement. Later in the summer these weights were removed because they hindered deployment and recovery of the chambers, and because there seemed to be no noticeable change in results: the weight of the chamber lid seemed sufficient to provide a good seal.

Addition of ballast should be considered on a case-by-case basis. When the chambers are deployed in areas where the sediment is particularly coarse or tough, additional weight is prudent to assist in ensuring that the teeth of the open chamber are properly embedded into the sediment. When the sediment is finer, the weight of the chambers themselves will be sufficient to ensure a proper seal. On the opposite end of the spectrum, especially fluffy sediment will not be able support the weight of the chambers, causing them to sink into the sediment. Such sinking was a problem we encountered during our trials in Lake Powell (details to be discussed later in this paper).

6.5 Mounting Straps and Acrylic Plates

About one month into testing, the straps adhered to the inside chamber lid started to separate from the lid. One of the acrylic plates that was glued to the chamber with epoxy also came off. We believe that the ¼-ton epoxy that was applied was not allowed to cure properly. During replacement the surfaces were sanded and the epoxy was reapplied and left for several

days to cure before trials continued. However, about a month later, the same issue arose again. Figures 13 and 14 shows the changes made to the chambers to address the bonding issues.

To fill the holes, 1/16in steel plating was cut to size and attached to the bottom side of the lid using a resin mixture of epoxy and superglue. Ensuring a watertight seal, silicone was used where the steel plate and the chamber met. A bolt fastened to the top of the chamber (using previously drilled holes) mounted a small PVC pipe to the bottom of the chamber lid. Through holes drilled in the pipe, a thick copper wire was strung, and loops at the end of the wire were made, as seen in Figure 13. The clips used to directly attach the probes were connected to these loops. The failsafe mechanism was similarly attached but at the opposite end of the PVC pipe.

In the following months, no additional problems were noted with the mounting system, nor with the covers made to seal the holes in the chamber lids. However, the Velcro around the probes has started to peel slightly, but this wear is slight and continues to be monitored.

6.6 Fine Sediment and Sinking Chambers

We validated that the chamber design and our method could take accurate and consistent readings in DCR at depths ranging from 20–50ft. At this point the chambers were taken to Lake Powell (LP) for further evaluation. Because the average depth of LP is 140ft, these chambers are ideally suited to studying SOD within the lake (Utah Department of Environmental Quality 1993). Between August 20 and 22, 2013, along with a team from the Bureau of Reclamation, the chambers were deployed at 2 locations in LP. These trials took place at Hite (where the Colorado River enters LP) and Ticaboo Canyon. There were two overnight trials, one at Hite and the other in Ticaboo, while three 3-hr trials were conducted at Hite.

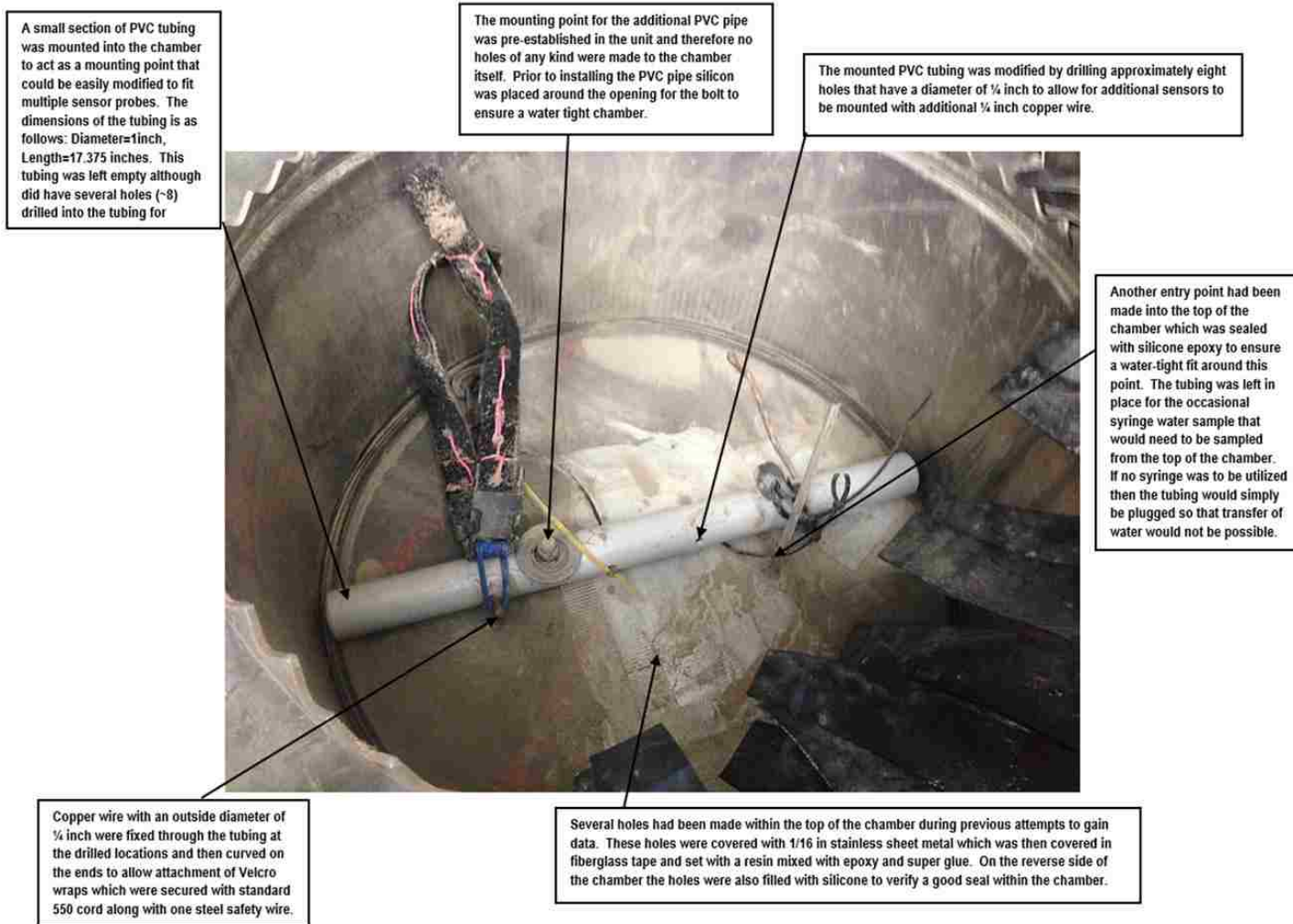


Figure 13: Details of Change Made to Mounting System Inside Open Bottom Chamber

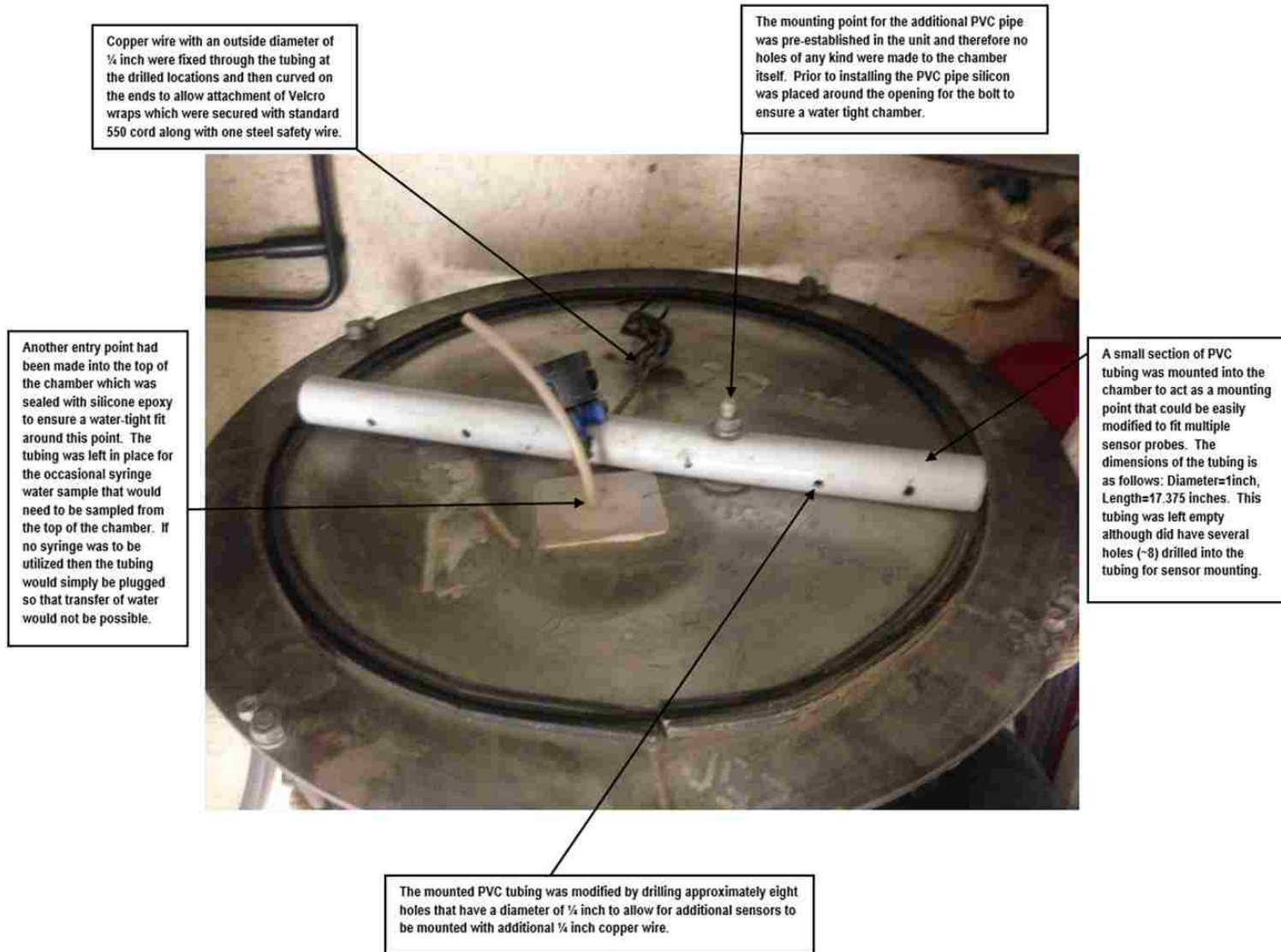


Figure 14: Details of Changes Made to Mounting System Inside Closed Bottom Chamber

Figure 15 shows data from the overnight deployment at Hite, during which the closed chamber operated as expected. However, the open chamber shows a drop in DO almost immediately to zero. Assuming an operator or equipment error, the chambers were deployed again for a 3hr test and had the same results. Further investigation led us to believe that the ultrafine sediment found at this location was not supporting the weight of the chambers, causing them to sink into sediment. This allowed sediment to fill the chamber to the point that the probes, which hung halfway down the chamber, came into contact with the sediment, causing the readings to drop to zero. Judging from residue within the chamber, the sediment did not completely fill the chamber. It was thought that if the probes were zip tied to the top of the chamber (Figure 16), they would function properly; Figure 17 shows the data taken after this modification.

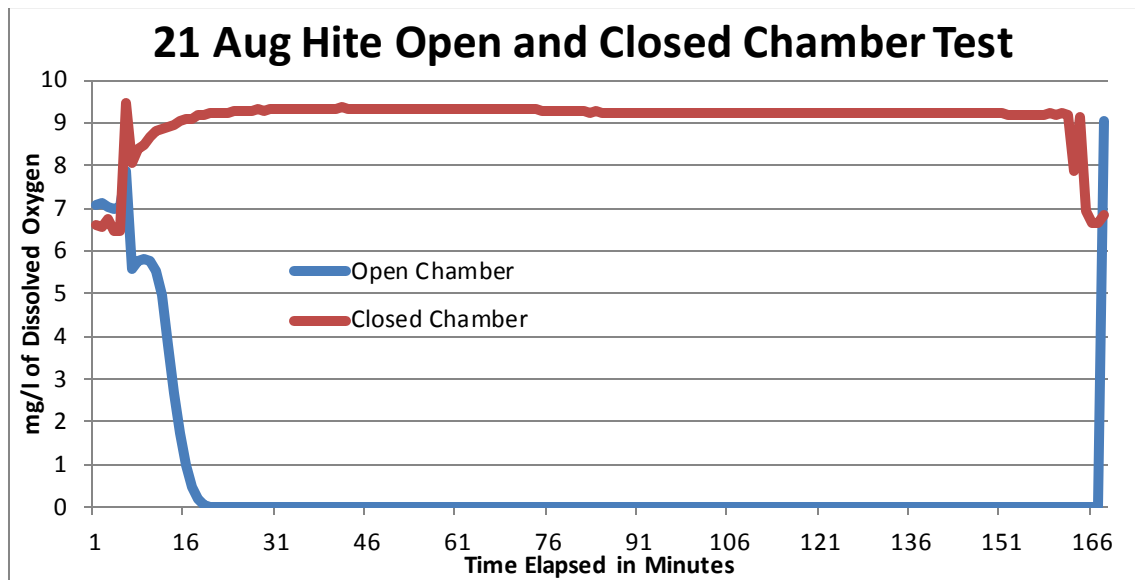


Figure 15: 21 Aug. Open and Closed Hite Trial Graph Showing Open Chamber Malfunction



Figure 16: Probes Zip Tied to the Top of Chamber Lid

After modifications to the open chamber were made, the pair was deployed overnight in Ticaboo Canyon. Figure 17 shows that the adjustment provided more useful results. The open chamber showed a steady decrease in DO concentrations as the night progressed, though the closed chamber DO behavior was abnormal. We attribute this deviation to local boaters who anchored their boat less than 5ft from the closed chamber deployment site and who may have interfered with testing. Without a closed chamber to compare results with, accurate SOD data cannot be calculated. Ignoring b_2 , the SOD for Ticaboo was estimated to be $65.03 \frac{mg}{m^2 hr}$, with an average temperature of 26.6 °C.

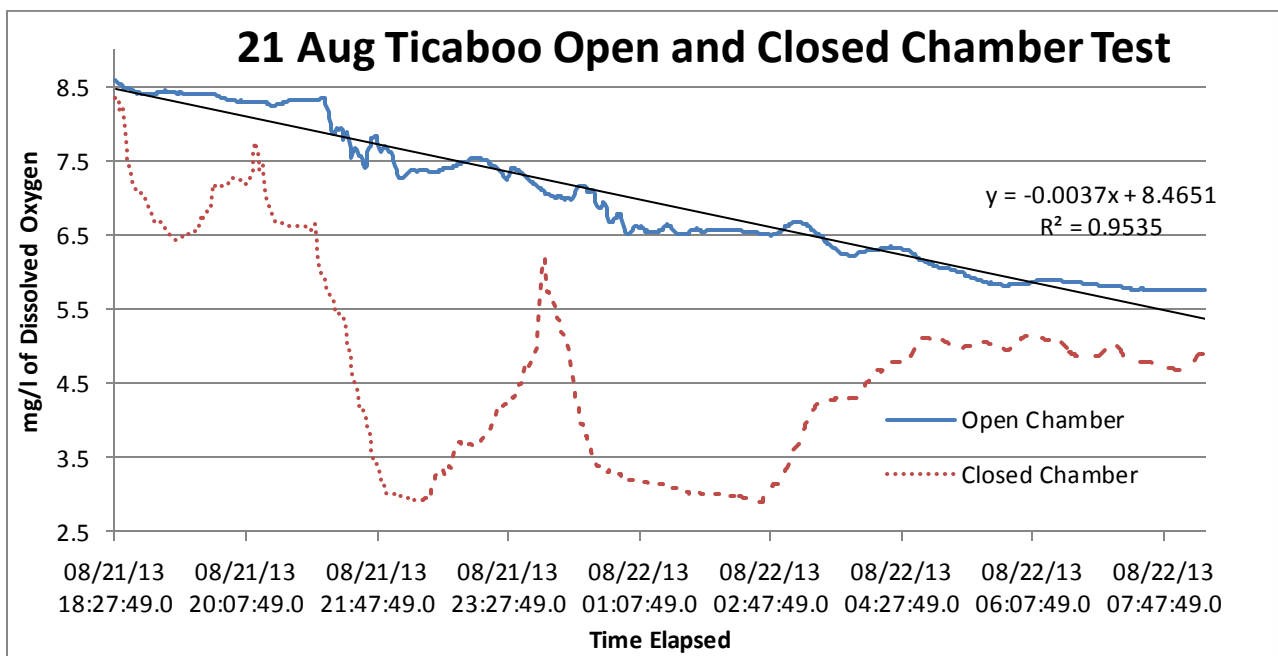


Figure 17: 21 Aug. Open and Closed chamber Ticaboo Trial After Modifications, Showing Open Chamber Operating Normally but with Closed Chamber Not Operating Properly

7 DCR SOD MEASUREMENTS

7.1 Number of Trials

Over 30 trials of various lengths (2–3hrs to several days) were conducted on DCR. To be considered a viable trial, both the open and closed chamber needed to return data indicating that the chambers were properly functioning. As discussed in the theory section and shown in Figure 7, this would entail a generally flat or shallow, sloped DO curve for the closed chamber and a decreasing curve for the open chamber. Without data from both chambers, and especially from the open chamber, an accurate SOD calculation cannot be made.

Best efforts were made to select locations that would minimize the potential for the chambers to land on any large rocks, land on their side, or roll (See “Initial Deepwater Testing” section for more details)—all of which would prevent the chambers from isolating a volume of water and operating properly. However, this could not be prevented every time and there were some instances where our experiments did not produce usable results. In addition, numerous datasets were not recoverable when the laptop storing them was destroyed because of a rogue wave that came across the boat.

7.2 DCR Temperature and Trial Length

DCR is fed by snow runoff, which, in combination with its high elevation (in excess of 5,400ft), causes the temperature of the reservoir to be low. Throughout May and June the bottom water temperature averaged 7 °C. Because the mechanisms involved with oxygen consumption are strongly correlated to temperature, the depletion of DO at low temperatures was expected to be slow. Tests lasting 3hr, such as those in Figure 18, show a modest change in DO concentrations. The open chamber decreased from $8.2\frac{mg}{l}$ to $7.55\frac{mg}{l}$, a decrease of 7.9%. Tests in excess of 12hrs show a significant drop DO in concentrations within the open chambers. For example, during the test in Figure 19, which was conducted in 45ft of water over the course of five days, the open chamber showed a decrease of $2.07\frac{mg}{l}$ (10.16 to $8.09\frac{mg}{l}$). In contrast, the closed-chamber DO decreased from $0.37\frac{mg}{l}$, from 9.65 to $9.28\frac{mg}{l}$: a 3.8% decrease over five days, while the open-bottom unit showed a 20.4% reduction. I am confident that had the chambers worked properly at LP (where lake temperatures were in excess of 26 °C), a significant drop in DO within the 2.5hr testing period recommended by the EPA would have been recorded (EPA 2009).

7.3 SOD Measurements

Using Equation 1, the SOD from selected trials were calculated and are shown in Table 3. While 21 May (2-day) shows an unusually low SOD demand, the other three test dates show reasonable values. Figure 18 shows results from the 21 May (2-day) test and displays the open- and closed-chamber DO curves as closely mirroring each other. Because of the small difference between the respective trend lines, the SOD demand was calculated to be quite small. Had the

trial lasted longer, a more significant deviation may have been observed. SOD rates are first order, so any difference would become increasing apparent with time.

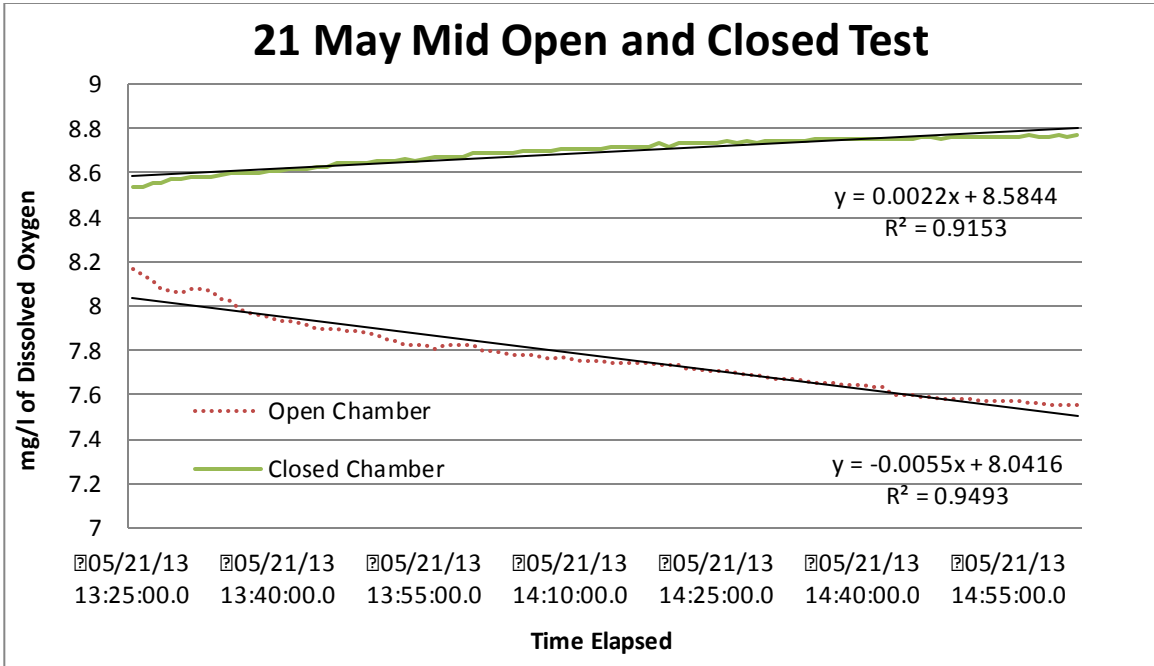


Figure 18: 21 May Mid Open and Closed Trail Graph

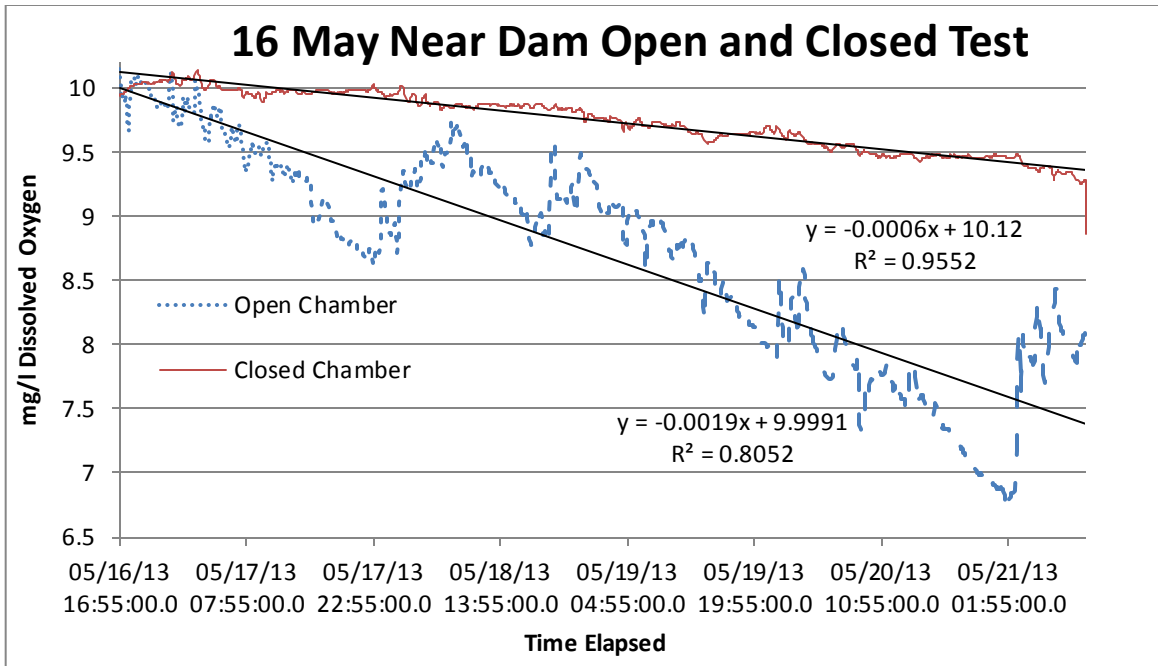


Figure 19: 16 May Near Dam Open and Closed Trial Graph

Table 3: SOD Measurements from DCR Deployments

Test Date	Closed Chamber DO Depletion Rate $\frac{mg}{hr}$	Open Chamber DO Depletion Rate $\frac{mg}{hr}$	SOD $\frac{mg}{m^2 hr}$
9 May	0.114	0.288	50.96
16 May	0.036	0.114	22.84
21 May (3hr)	0	0.0055	96.66
21 May (2-day)	0.078	0.096	5.27

In Figure 21, as well as in Figure 19, both the open and closed chambers show noticeable fluctuations. One reason may be that small leaks in the O-ring were used to seal the chamber lids. The O-rings are not molded into a ring, but are formed by one straight piece glued into circle. At the point where the two ends meet, there is a small gap, as shown in Figure 20.

Another reason could be the change in temperature of the water in the chamber, which would explain the peaks and troughs. Nevertheless, the decreasing trend in spite of the fluctuations shows that the chambers work as designed.



Figure 20: Gap Marked with Red Circle Indicating Gap in O-Ring

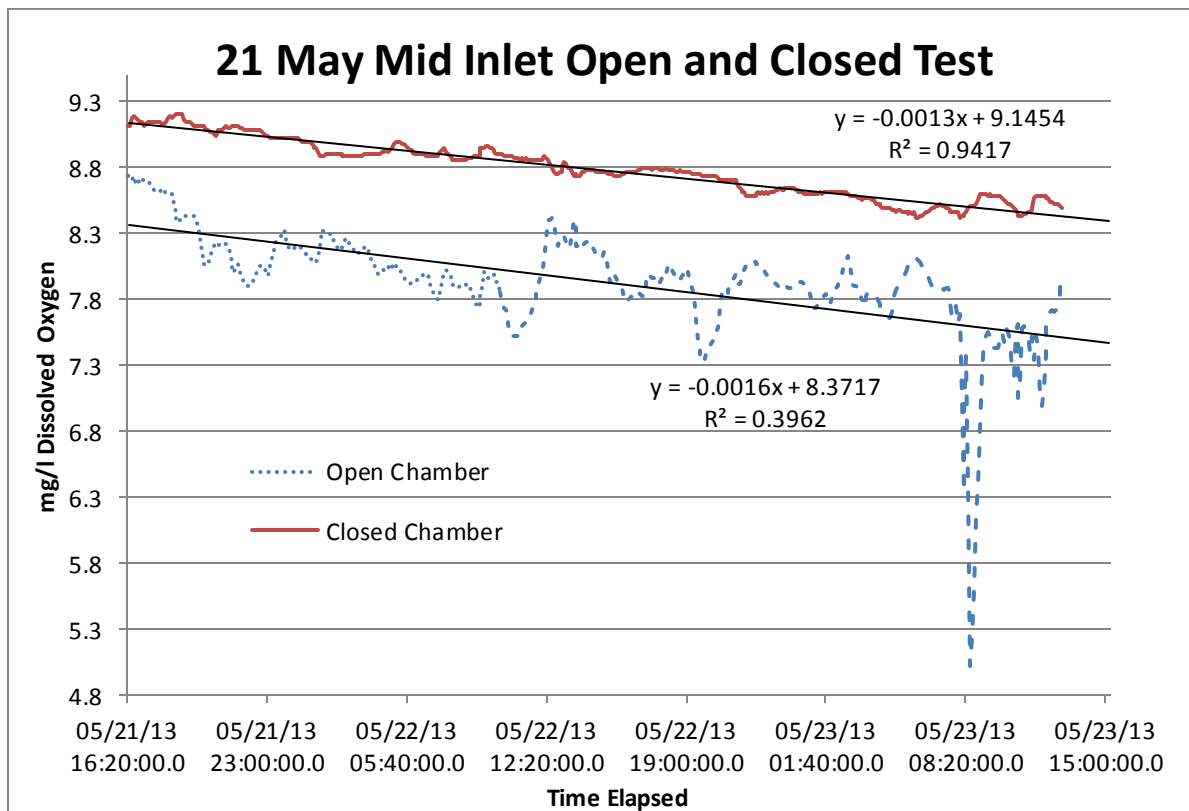


Figure 21: 21 May Mid Inlet Open and Closed Trial Graph

8 CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORK

As mentioned, the purpose of this research was not to exhaustively measure SOD spatial variation in DCR, but to develop a chamber that could be remotely placed and unattended in deep-water in order to measure SOD values. The development of these chambers has been the subject of several previous graduate projects. Previous attempts to deploy the chambers in DCR did not yield the results that could be used to calculate SOD. This study was successful and provides both the tools and the methods that will allow those who desire to gather SOD data in lakes and reservoirs a way to generate accurate SOD measurements.

8.1 Conclusion

The goal of this research was to modify the existing SOD chambers so that they could be deployed and recovered from a boat into any surface water and in depths in excess of 5ft by remote placement. Once deployed, the chambers needed to take accurate DO measurements independently for several hours to several days so that SOD calculations could be made. In order to achieve these goals, DO data logging probes were purchased and mounted inside of the chambers using off-the-shelf technology. Holes drilled into the chamber lid were covered and sealed so the chambers could isolate a column of water. To ensure the chambers would be recoverable from a boat in deep-waters, rope with a buoy at the end was attached to four anchor

points on the chambers. These modifications allowed the chambers to be deployed for several days and recovered from depths in excess of 45ft. DO data recovered from the loggers and that were used in Equation 1 allowed SOD calculations to be made.

Over the course of several months and dozens of tests, we showed that the chambers were able to take accurate and precise DO measurements that are critical in calculating SOD, which is the determining mechanism in oxygen consumption in surface waters (Jaffè and Park 1998). Using this proven design, other researchers will be able to generate substantial amounts of SOD data that will allow for accurate models of SOD behavior to be generated. Such models will allow researchers and regulators to gain a better understanding of the health of surface waters, with the hope of maximizing remediation efforts at minimal cost.

Modifications that allowed the mounting of the data loggers also permits other loggers to be installed easily, ensuring that the chamber can be used in other sediment-based experiments. This flexibility allows the chambers to be not just a single-use platform but also a versatile tool in our efforts to measure water quality in surface waters.

This work shows that the SOD measurements at significant depths in surface waters can be done remotely. Previously this could only be accomplished through expensive SCUBA dives, which in addition to being risky also limited measurements to depths less than 100ft. With this design, the chambers can be deployed in environments up to 300ft (with appropriate probes), which allows SOD measurements to be taken in a vast majority of surface waters around the world.

8.2 Recommendation for Future Work

While the chambers function properly, additional changes would improve functionality and versatility. As noted in the “Fine Sediment and Sinking Chambers” section, the chambers

would sink in areas where the sediment was especially fine or loose. To overcome this problem, removable snowshoe-like attachments may be considered. These add-ons would need to be located a couple inches above the bottom, to allow the chambers to sink enough to create a seal with the sediment as well as to stop the chambers from sinking so far as to disrupt DO probe measurements.

As previously mentioned, previous user of the chambers found was that the chambers were not sealing properly. We added weight to the top of the chamber to overcome this problem. However, the weights we attached were long and wide, making deployment and recovery of the chambers more difficult due to drag. I would recommend that plates similar to those used on dumbbells be mounted onto a short rod that rises vertically 3 to 4in from the center of the chamber lid and that is fastened with a bolt or other comparable mechanism. This way, the weight would be centered on chamber and prevent it being heavy on any one side. The design would also allow the weight to be easily adjusted depending on the circumstance.

Another point of concern was the O-ring used to seal the chamber. Instead of using a linear strip that is glued into a circular shape, buy a custom ring. This would ensure that leaks coming from the gap between the stripes would be eliminated. While the cost would be higher, it is more likely that the ring would not have to be replaced and that it would last throughout the lifetime of the chamber. This enhancement would improve the accuracy of SOD measurements.

Beyond being able to gather long-term SOD measurements, the chambers could be modified to take water samples of isolated waters after extended periods. Adding an automated pump that takes water samples towards the end of a trial could accomplish this. This would allow studies of phosphorus and the release other nutrients after the isolated column become anoxic. Such studies could enhance models used to understand surface water health.

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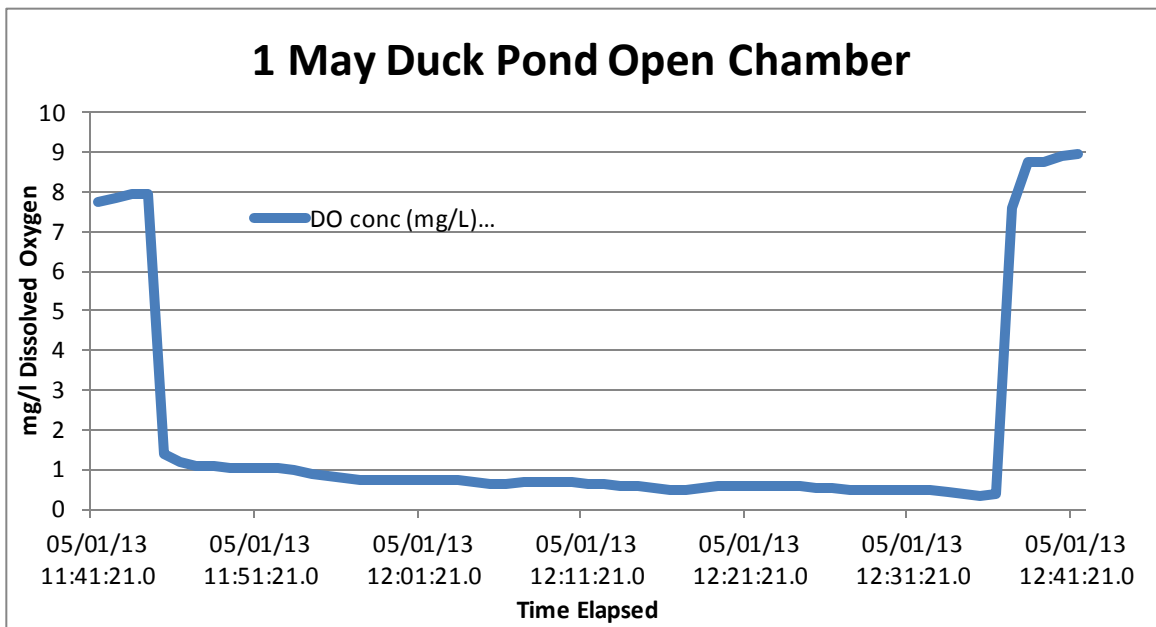
APPENDIX

A.1 DO Probe Field and Bucket Test

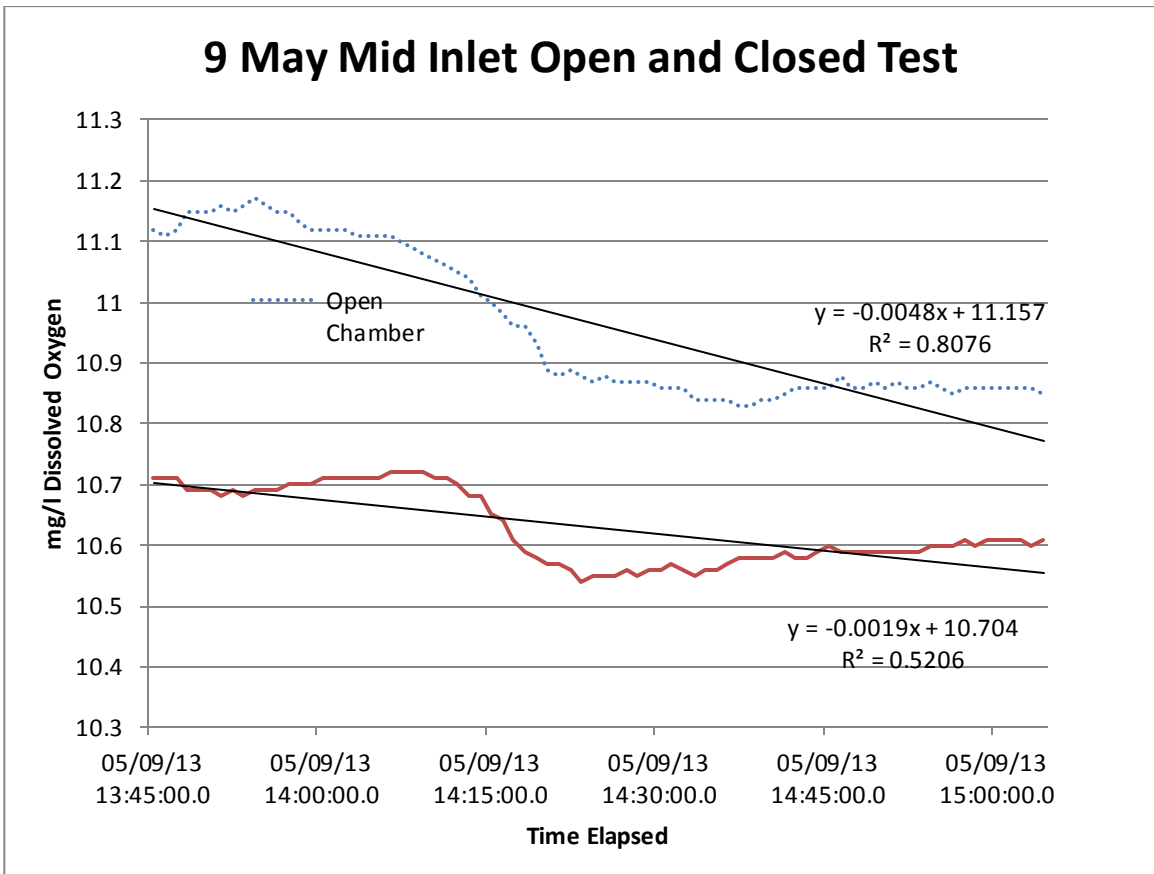
All tests were of various lengths, but in each instance DO points were logged every minute. Some of the tests lasted 15min while others were several hours to over a day in length.

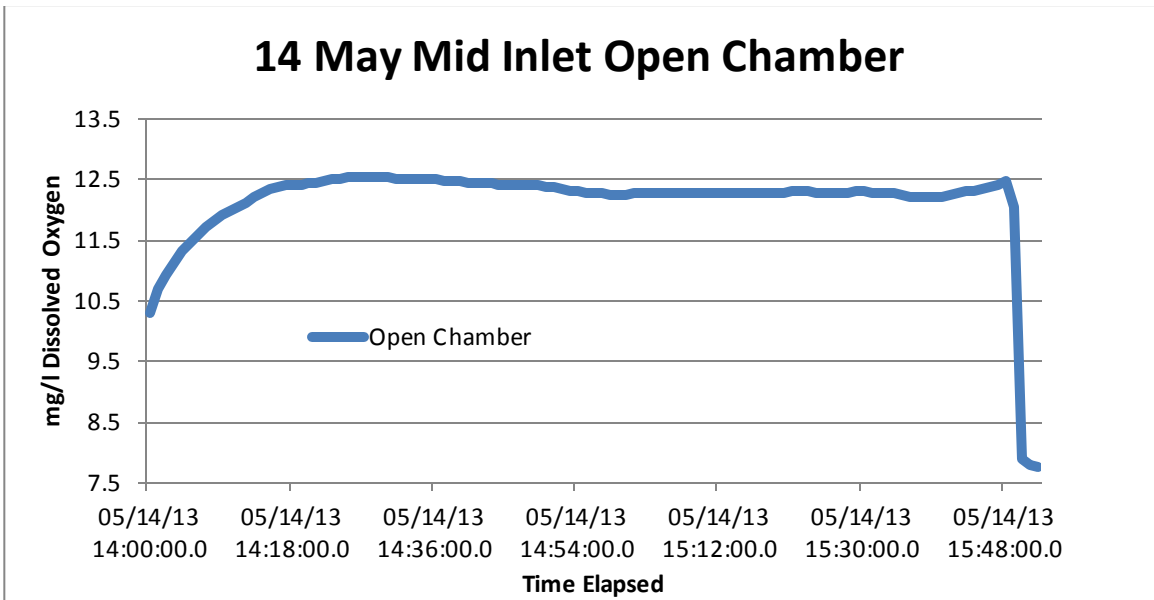
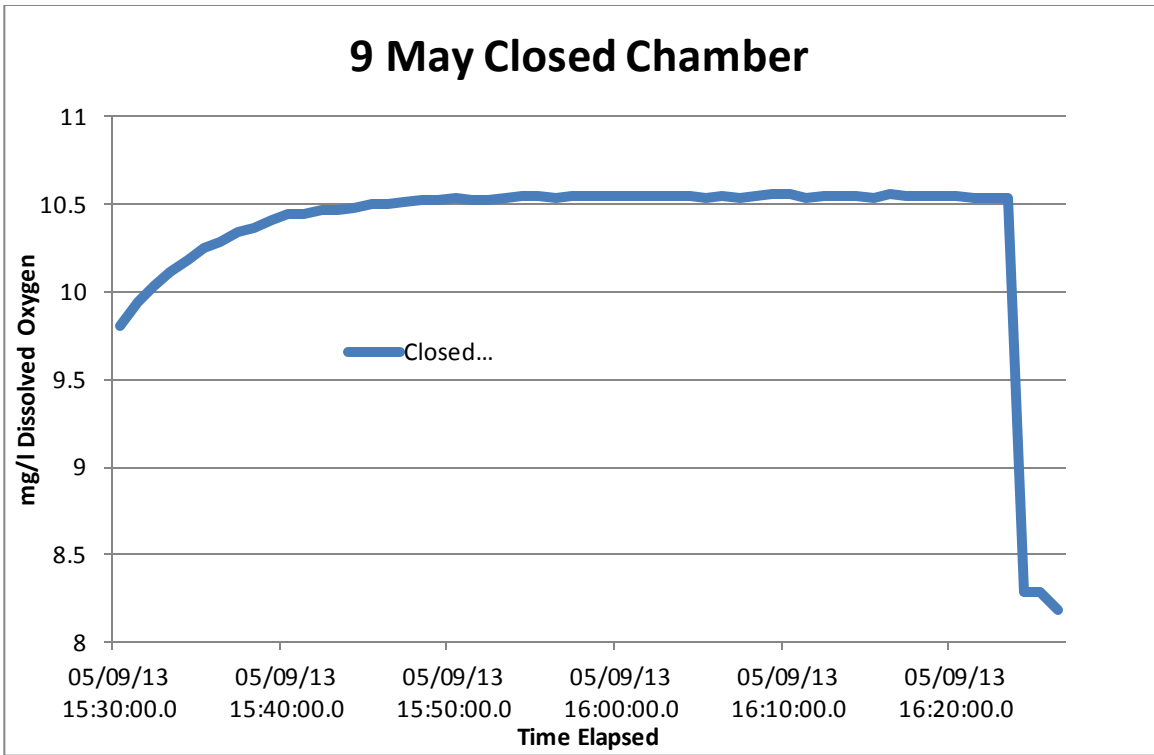
	Average Difference	Standard Deviation
Field Trials	0.203	0.205
Trial 1	0.190	0.499
Trial 2	0.070	0.983
Trial 3	0.390	0.601
Bucket Trials	-0.003	0.031
Trial 1	0.160	0.044
Trial 2	-0.070	0.118
Trial 3	0.060	0.033
Trial 4	0.030	0.049
Trial 5	0.003	0.039
Trial 6	-0.038	0.065
Trial 7	0	0.069
All Trials	0.079	0.250

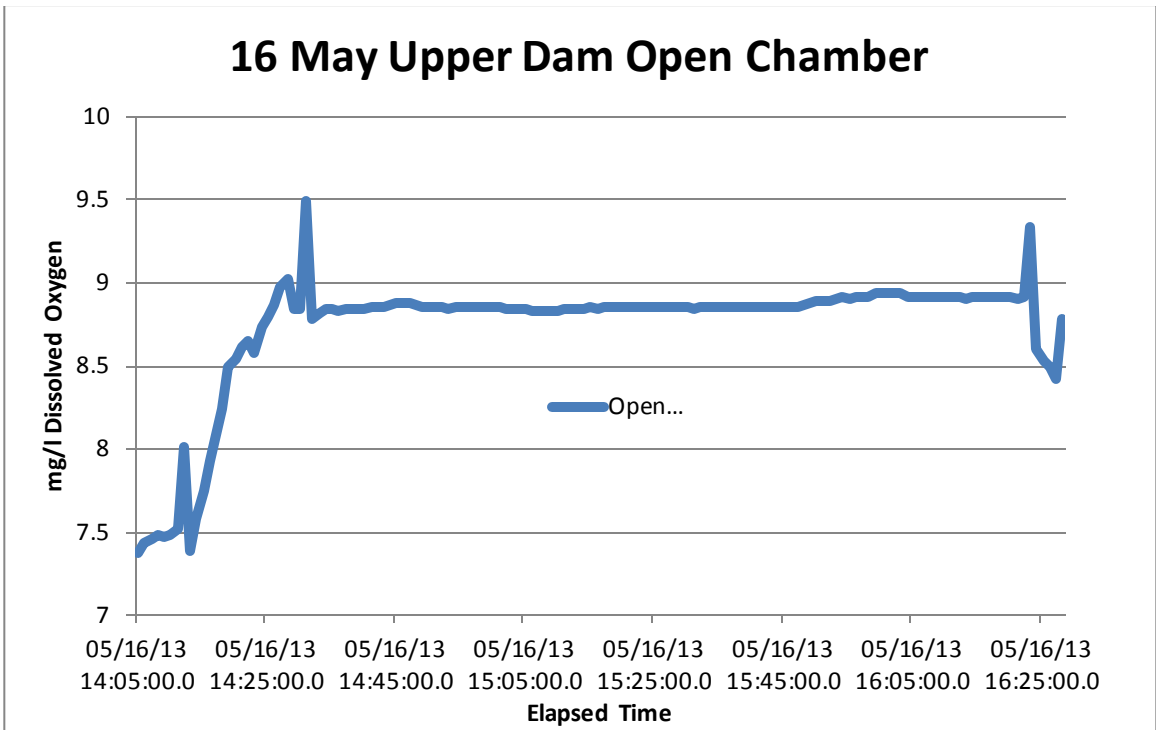
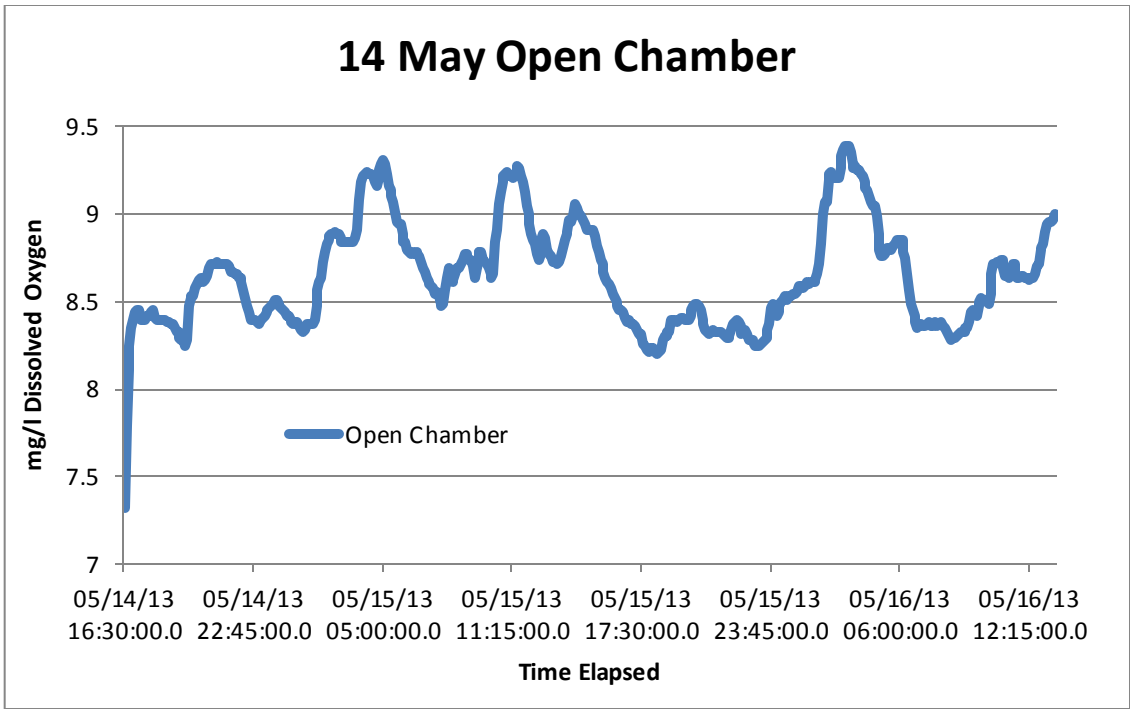
A.2 Duck Pond Trial Graph



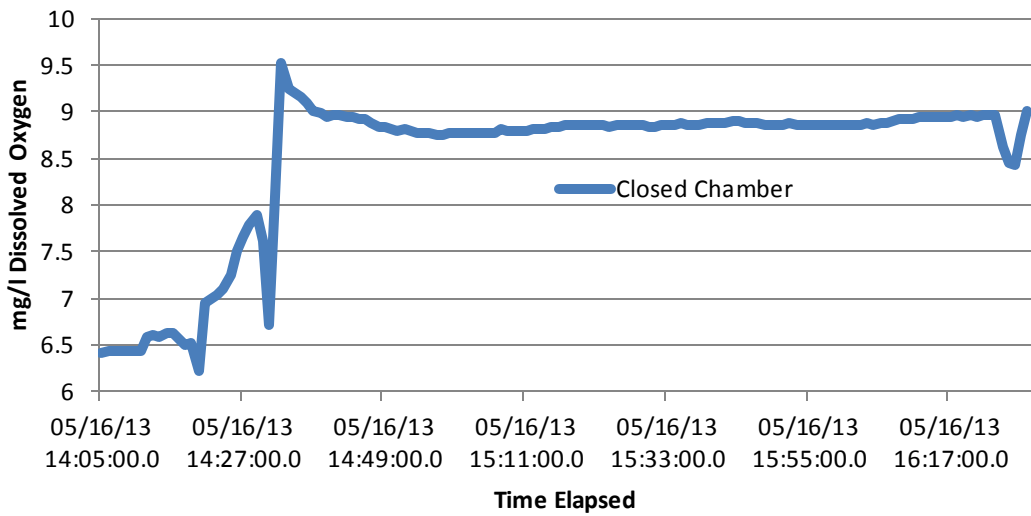
A.3 DCR Trial Graphs



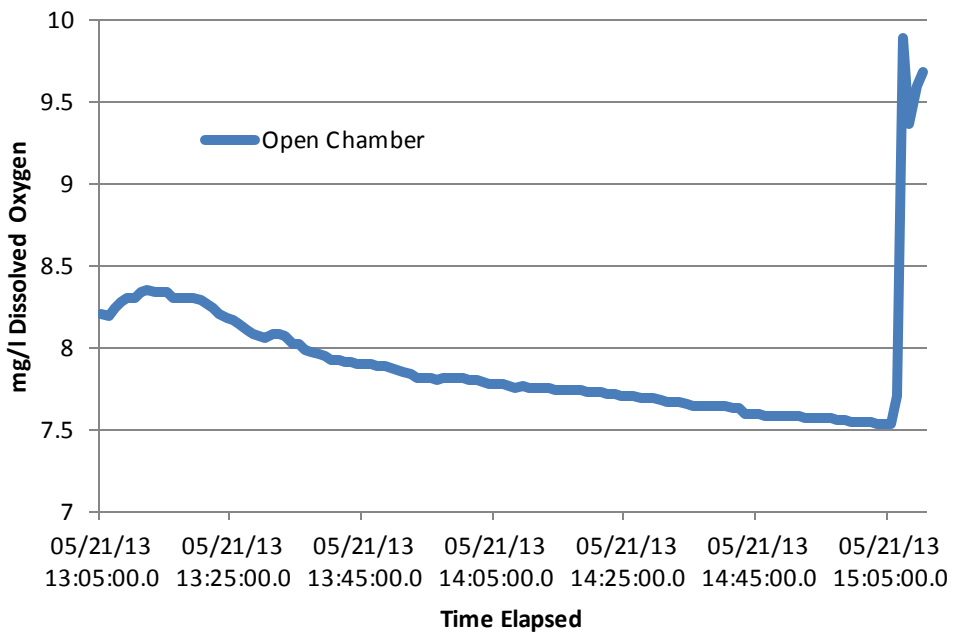




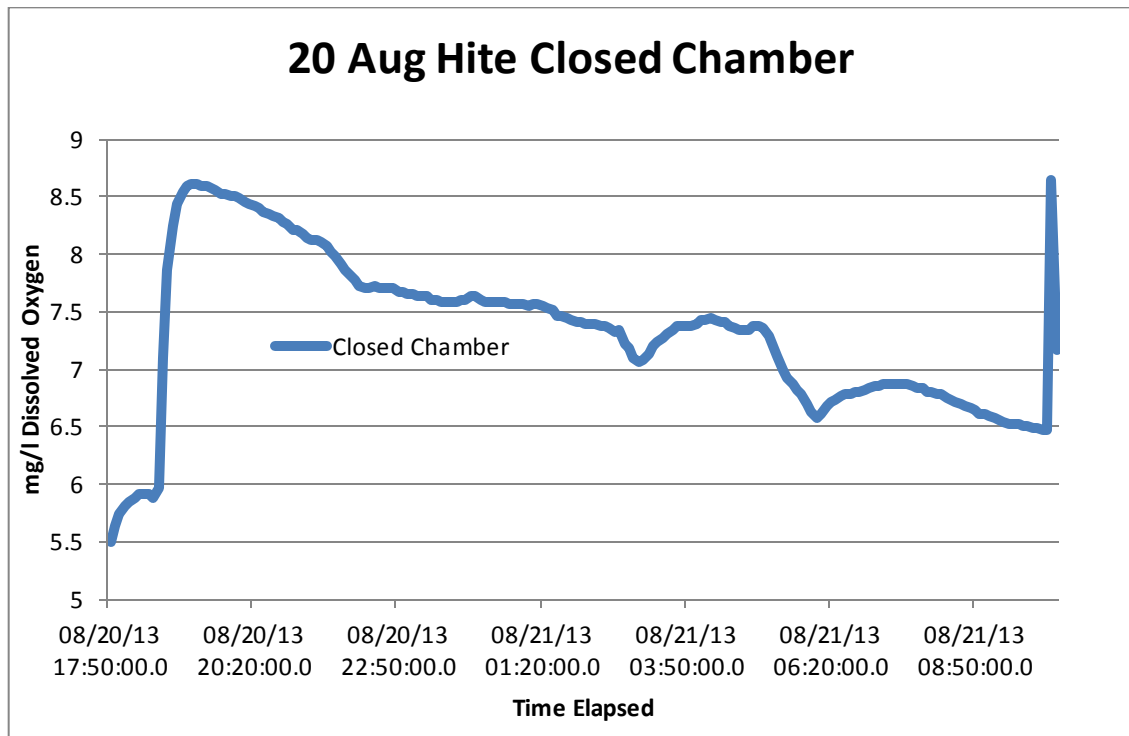
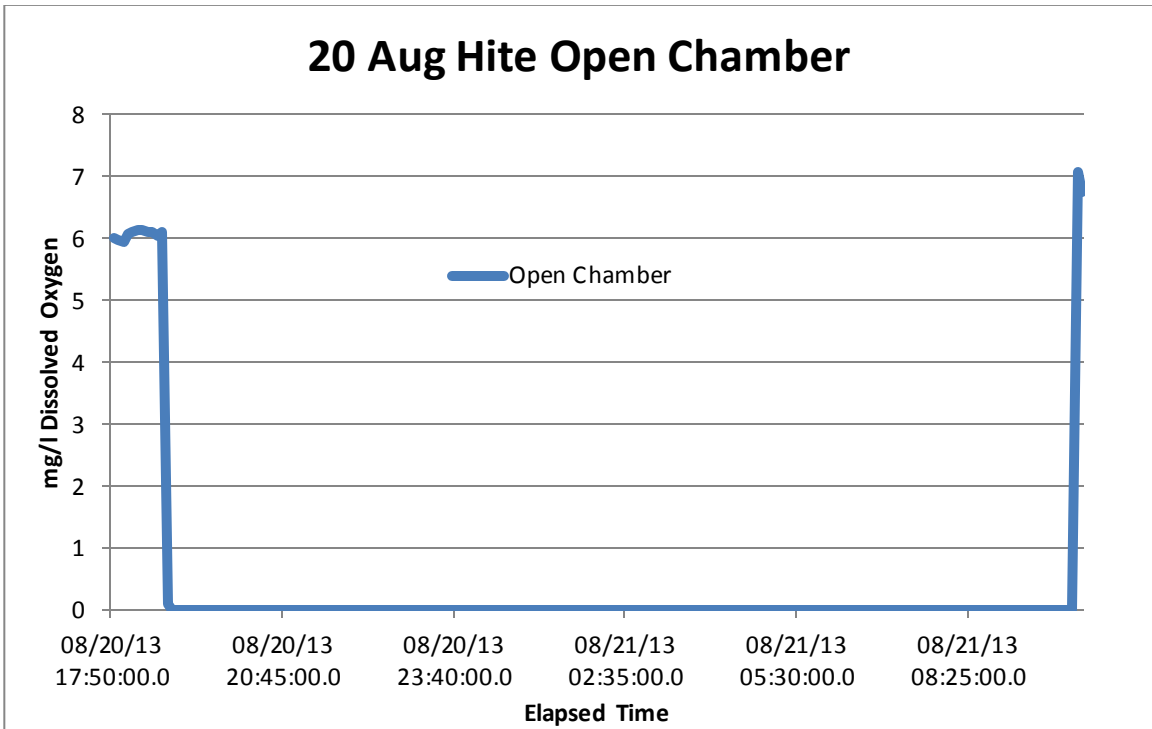
16 May Upper Dam Closed Chamber

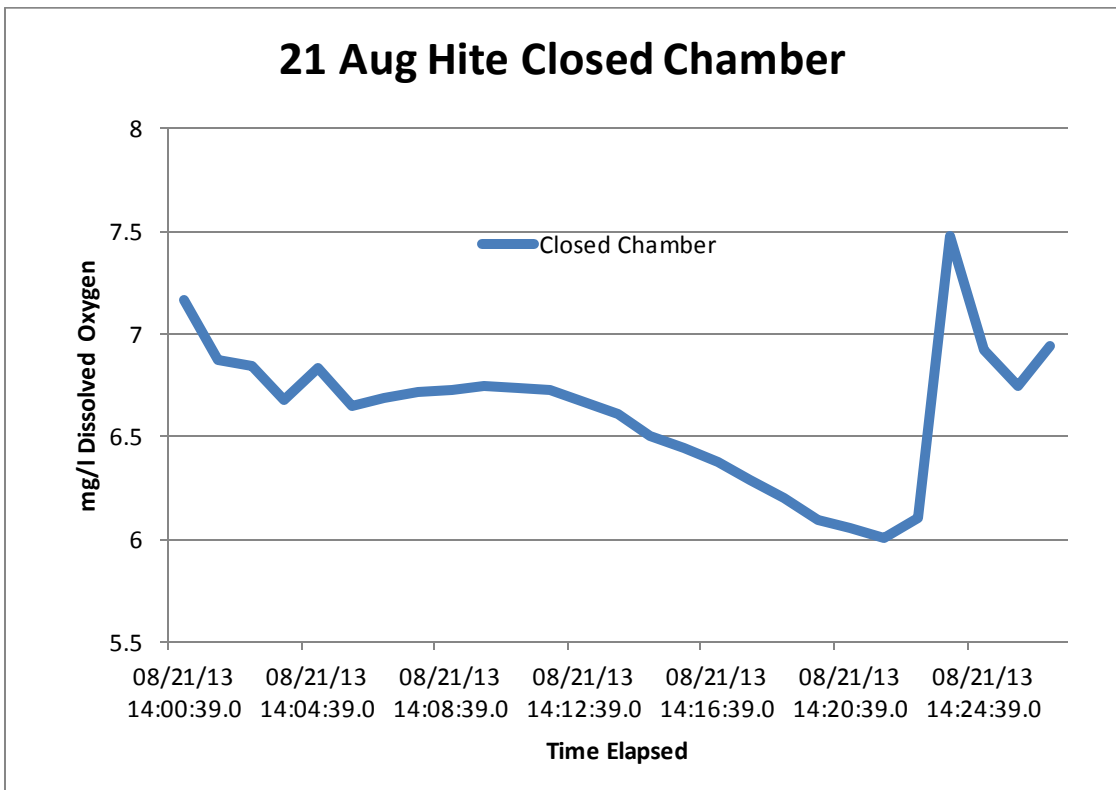
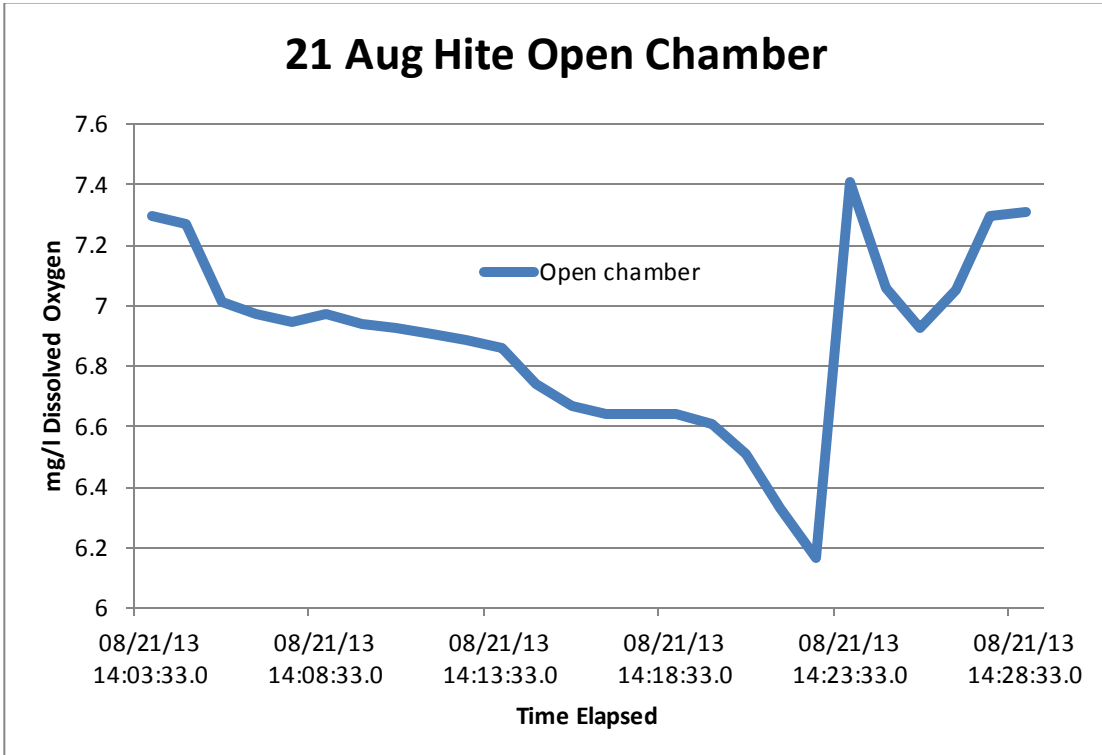


21 May Mid Dam Open Chamber

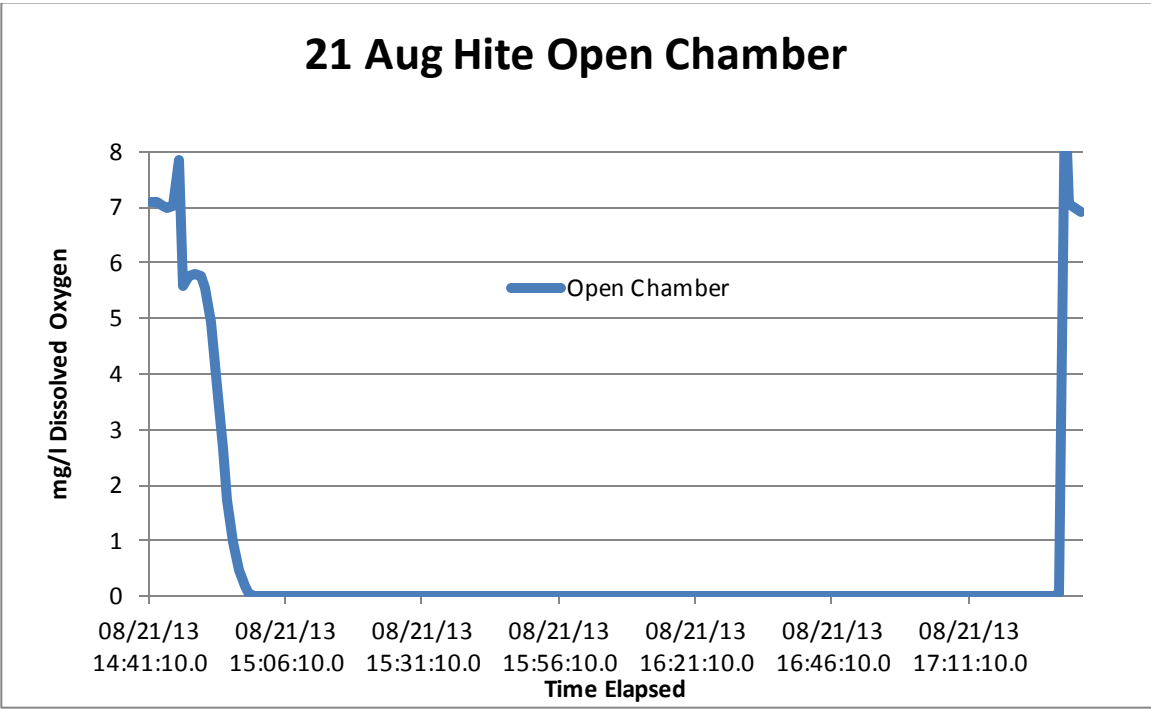


A.4 Lake Powell Trial Graphs

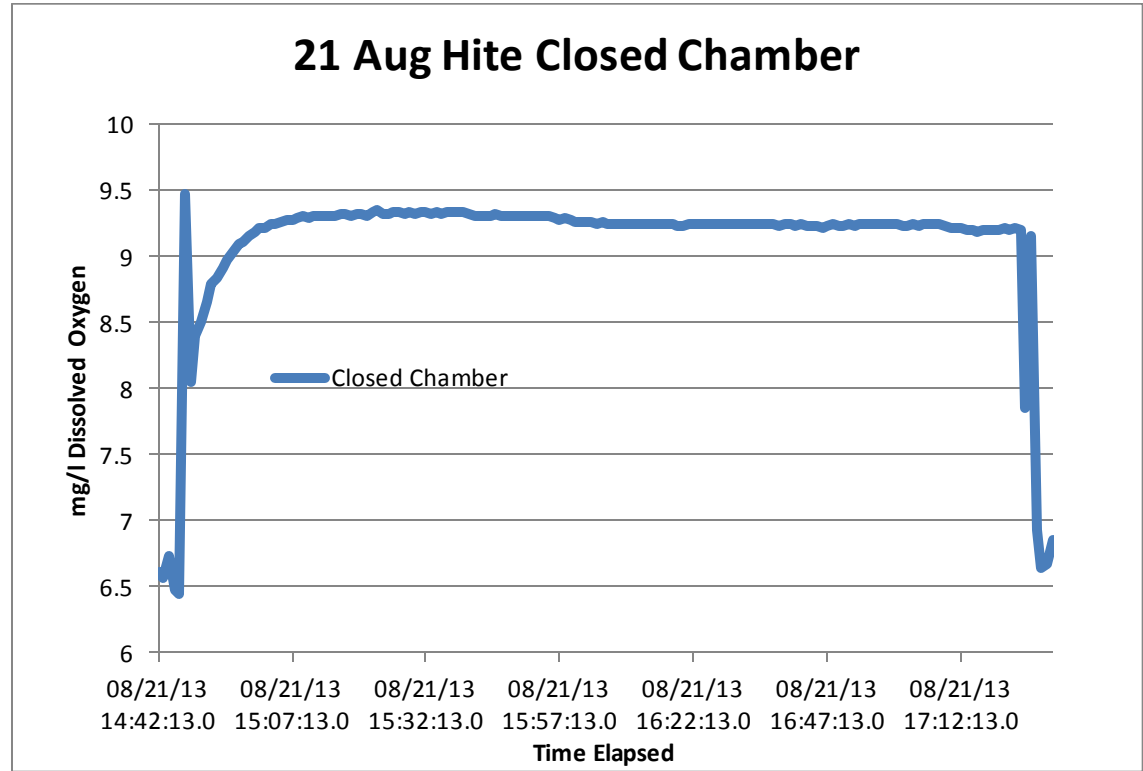




21 Aug Hite Open Chamber



21 Aug Hite Closed Chamber



A.5 Field Deployment Methods

Operating Procedures for SOD Chambers and Probes

You want to measure SOD, huh? Here is a short, and hopefully helpful, guide to help you do just that with BYU's SOD chambers and HOBOWare probes.

BYU has two SOD chambers, one with an open bottom and one with a closed bottom. The open-bottom chamber is designed to hold **one** dissolved oxygen probe and **one** conductivity probe, while the closed-bottom chamber will hold **one** dissolved oxygen probe.

Launching the Probes

The probes require HOBOWare software in order to be launched (i.e., in order to start measuring). Assuming that you have a PC/Mac with this software on it, you will need to do the following:

1. Attach the waterproof shuttle to the computer using the USB cord.
2. Attach the shuttle with the probe of choice, ensuring that you align the arrows or depressed lined with the probe with the arrow the says "align" on the shuttle.
3. Press the lever to start (it is black and extends out from the shuttle). The yellow light should blink and go to green. If it blinks red make sure that the probe and shuttle are properly aligned.
4. In the HOBOWare software, scroll over to the top-left icon. A box should come up telling you that this is "Launch Shuttle" icon. Click it.
5. A box will come up detailing the type of probe attached to the shuttle. You can ignore most of the information on it—the most important information is at the bottom. Here you can select whether you want to launch at a certain date and time or immediately. I usually

select a time 15min in the future to allow the probes time to be mounted to the chamber and lowered to the bottom.

6. To launch the shuttle, click “Launch”. **DO NOT** remove the probe from the shuttle until the percentage box shows that the launching shuttle is complete; this may take 1min.
7. To launch more shuttles, depress the lever again. It should blink yellow and turn off. Then repeat steps 2–6 to deploy another shuttle.

Open Chamber Deployment:

1. Ensure that all the straps, acrylic pieces, and failsafe wire are still firmly in place, attached, etc.
2. Attach the probes to the chamber, ensuring that the Velcro wraps completely around the probes. This is best done by removing the clips and wrapping them, and then clipping the probes onto the chamber.
3. Attach the carabineer to the loop on the probes (this is the failsafe mechanism in case the Velcro fails).
4. Ensure the syringe is connected and firmly clasped.
5. Double check the straps and failsafe.
6. Using the SONOD probe, collect data on conductivity and depth. This data should be saved as such: “Location Date SOD START.”
7. Double check depth of water and ensure that the attached buoy is on a long enough line.
8. Move to the back of boat and begin lowering the chamber, bottom first, into the water.
9. Hold the line only to ensure that it doesn’t bunch or knot. Finally, release and record location on the GPS.

Closed Chamber Deployment (this is very similar to Open Chamber Deployment):

1. Remove the nuts on the bottom the chamber to remove covering.
2. Install probes as mentioned above.
3. Close chamber by replacing screws and nuts.
4. Take to the back of boat and lower into the water. Check the line for length.
5. A second person will need to ensure that the top and bottom lids are open so that water can enter into the chamber. If you skip this step, the chamber will float.
6. Allow the chamber to sink, ensuring that the line doesn't become tangled.

Chamber Recovery

After a **minimum of 2hrs**, follow these steps to recover the chambers:

1. Approach one of the buoys head-on, and with one person laying down on the deck grab the buoy out of the water.
2. Immediately reverse the boat to ensure you don't run over the buoy and drag it. A second person grabs the line from the first person and begins hoisting it up, with the first person assisting.
3. After raising the chamber, move it to the back and recover the second chamber.
4. Remove the probes from both chambers, keeping them separate from each other.

Recovering Data from the Probes:

1. With the HOBO shuttle attached via USB cord to the laptop, align and attach the probes to the shuttle.
2. Depress the lever, ensuring that the light goes from yellow to green.

3. Now go to the computer, and using the HOBOWare software, select the icon next to the “Deploy Shuttle” icon. This icon should look like a paper with a green arrow pointing away from the paper. Click it.
4. A box titled “Plot Setup” will appear; then right click the icon titled “Plot”.
5. Go to the “File” menu and select “Save Project”. Save the project using the following process: “Location Date DO/Conductivity Open/Closed”. DO/conductivity and Open/Closed should be selected given the type of probe and chamber it was used in.
6. Once saved, remove the probe from the shuttle and turn it up by depressing the lever on the shuttle.

To redeploy the same probe again follow steps 4–6 from the “Launching the Probes” section. To recover data from more probes, repeat steps 2–6