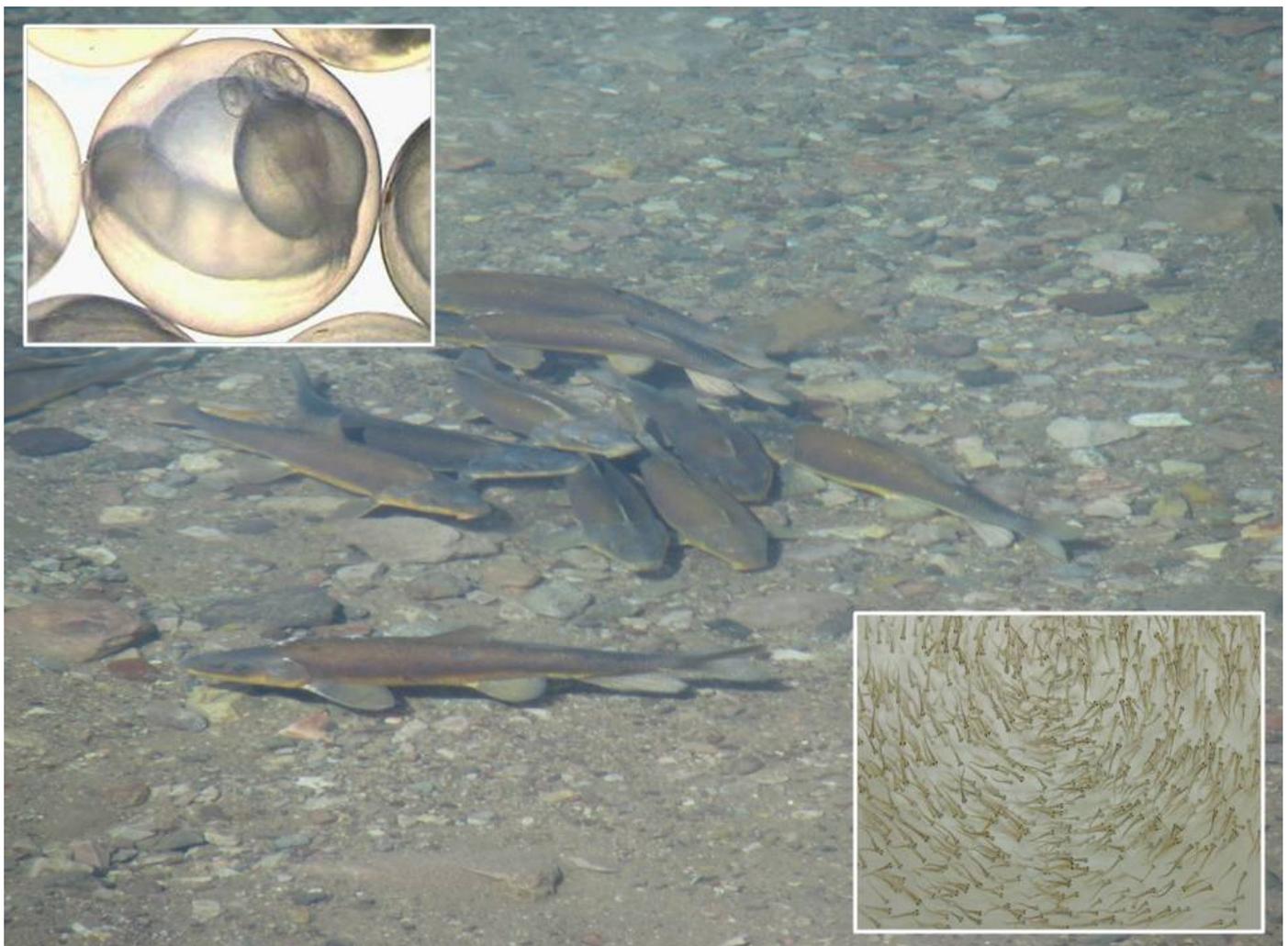




# Lower Colorado River Multi-Species Conservation Program

*Balancing Resource Use and Conservation*

## Dissolved Oxygen Tolerances for Egg and Larval Stages of Razorback Sucker



November 2009

# Lower Colorado River Multi-Species Conservation Program Steering Committee Members

## **Federal Participant Group**

Bureau of Reclamation  
U.S. Fish and Wildlife Service  
National Park Service  
Bureau of Land Management  
Bureau of Indian Affairs  
Western Area Power Administration

## **Arizona Participant Group**

Arizona Department of Water Resources  
Arizona Electric Power Cooperative, Inc.  
Arizona Game and Fish Department  
Arizona Power Authority  
Central Arizona Water Conservation District  
Cibola Valley Irrigation and Drainage District  
City of Bullhead City  
City of Lake Havasu City  
City of Mesa  
City of Somerton  
City of Yuma  
Electrical District No. 3, Pinal County, Arizona  
Golden Shores Water Conservation District  
Mohave County Water Authority  
Mohave Valley Irrigation and Drainage District  
Mohave Water Conservation District  
North Gila Valley Irrigation and Drainage District  
Town of Fredonia  
Town of Thatcher  
Town of Wickenburg  
Salt River Project Agricultural Improvement and Power District  
Unit "B" Irrigation and Drainage District  
Wellton-Mohawk Irrigation and Drainage District  
Yuma County Water Users' Association  
Yuma Irrigation District  
Yuma Mesa Irrigation and Drainage District

## **Other Interested Parties Participant Group**

QuadState County Government Coalition  
Desert Wildlife Unlimited

## **California Participant Group**

California Department of Fish and Game  
City of Needles  
Coachella Valley Water District  
Colorado River Board of California  
Bard Water District  
Imperial Irrigation District  
Los Angeles Department of Water and Power  
Palo Verde Irrigation District  
San Diego County Water Authority  
Southern California Edison Company  
Southern California Public Power Authority  
The Metropolitan Water District of Southern California

## **Nevada Participant Group**

Colorado River Commission of Nevada  
Nevada Department of Wildlife  
Southern Nevada Water Authority  
Colorado River Commission Power Users  
Basic Water Company

## **Native American Participant Group**

Hualapai Tribe  
Colorado River Indian Tribes  
Chemehuevi Indian Tribe

## **Conservation Participant Group**

Ducks Unlimited  
Lower Colorado River RC&D Area, Inc.  
The Nature Conservancy



# **Lower Colorado River Multi-Species Conservation Program**

## **Dissolved Oxygen Tolerances for Egg and Larval Stages of Razorback Sucker**

*Prepared by:*

Jim Stolberg, Fisheries

Lower Colorado River  
Multi-Species Conservation Program  
Bureau of Reclamation  
Lower Colorado Region  
Boulder City, Nevada  
<http://www.lcrmscp.gov>

**November 2012**

## ACRONYMS AND ABBREVIATIONS

DO	dissolved oxygen
km	kilometer(s)
L	liter(s)
LCR	lower Colorado River
LCR MSCP	Lower Colorado River Multi-Species Conservation Program
m	meter(s)
mg/L	milligrams per liter
mi	mile(s)
mm	millimeter(s)
SE	standard error
TL	total length
$\mu\text{S/cm}$	microsiemens per centimeter

### **Symbols (if any)**

$^{\circ}\text{C}$	degrees Celsius
%	percent

# CONTENTS

	Page
Abstract.....	vii
Introduction.....	1
Study Area .....	2
Methods.....	2
Egg Dissolved Oxygen Tolerance .....	4
Larval Dissolved Oxygen Tolerance .....	4
Comparative Larval Growth .....	5
Results.....	5
Egg Dissolved Oxygen Tolerance .....	5
Larval Dissolved Oxygen Tolerance .....	6
Comparative Larval Growth .....	8
Discussion.....	9
Literature Cited .....	47

## Tables

Table		Page
1	Mean DO and percent hatch of razorback sucker eggs.....	6
2	Mean DO and percent mortality for 72-hour larval trials.....	7
3	Mean DO and percent mortality for 20-day larval trials.....	8
4	Summary of effects of different DO concentrations on growth of 20-day-old larvae.....	8

## Figures

Figure		Page
1	Mean daily DO, mean daily temperature, and daily ranges (line projections) for 1-mg/L egg trial replicate (tank 1).....	13
2	Mean daily DO, mean daily temperature, and daily ranges (line projections) for 1-mg/L egg trial replicate (tank 2).....	13
3	Mean daily DO, mean daily temperature, and daily ranges (line projections) for 1-mg/L egg trial replicate (tank 3).....	14
4	Mean daily DO, mean daily temperature, and daily ranges (line projections) for 2-mg/L egg trial replicate (tank 4).....	14

**Figures** (continued)

Figure	Page
5	Mean daily DO, mean daily temperature, and daily ranges (line projections) for 2-mg/L egg trial replicate (tank 5)..... 15
6	Mean daily DO, mean daily temperature, and daily ranges (line projections) for 2-mg/L egg trial replicate (tank 6)..... 15
7	Mean daily DO, mean daily temperature, and daily ranges (line projections) for 3-mg/L egg trial replicate (tank 7)..... 16
8	Mean daily DO, mean daily temperature, and daily ranges (line projections) for 3-mg/L egg trial replicate (tnak 8)..... 16
9	Mean daily DO, mean daily temperature, and daily ranges (line projections) for 3-mg/L egg trial replicate (tank 9)..... 17
10	Mean daily DO, mean daily temperature, and daily ranges (line projections) for 4-mg/L egg trial replicate (tank 10)..... 17
11	Mean daily DO, mean daily temperature, and daily ranges (line projections) for 4-mg/L egg trial replicate (tank 11)..... 18
12	Mean daily DO, mean daily temperature, and daily ranges (line projections) for 4-mg/L egg trial replicate (tank 12)..... 18
13	Mean daily DO, mean daily temperature, and daily ranges (line projections) for 5-mg/L egg trial replicate (tank 13)..... 19
14	Mean daily DO, mean daily temperature, and daily ranges (line projections) for 5-mg/L egg trial replicate (tank 14)..... 19
15	Mean daily DO, mean daily temperature, and daily ranges (line projections) for 5-mg/L egg trial replicate (tank 15)..... 20
16	Mean daily DO, mean daily temperature, and daily ranges (line projections) for 6-mg/L egg trial replicate (tank 16)..... 20
17	Mean daily DO, mean daily temperature, and daily ranges (line projections) for 6-mg/L egg trial replicate (tank 17)..... 21
18	Mean daily DO, mean daily temperature, and daily ranges (line projections) for 6-mg/L egg trial replicate (tank 18)..... 21
19	Mean daily DO, mean daily temperature, and daily ranges (line projections) for air-saturated (8-mg/L) egg trial replicate (tank 19). ..... 22
20	Mean daily DO, mean daily temperature, and daily ranges (line projections) for air -saturated (8-mg/L) egg trial replicate (tank 20). ..... 22
21	Mean daily DO, mean daily temperature, and daily ranges (line projections) for air-saturated (8-mg/L) egg trial replicate (tank 21). ..... 23
22	Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 1)..... 23
23	Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 2)..... 24

**Figures (continued)**

Figure	Page
24	Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 3). . . . . 24
25	Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 4). . . . . 25
26	Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 5). . . . . 25
27	Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 6). . . . . 26
28	Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 7). . . . . 26
29	Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 8). . . . . 27
30	Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 9). . . . . 27
31	Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 10). . . . . 28
32	Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 11). . . . . 28
33	Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 12). . . . . 29
34	Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 13). . . . . 29
35	Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 14). . . . . 30
36	Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 15). . . . . 30
37	Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 16). . . . . 31
38	Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 17). . . . . 31
39	Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 18). . . . . 32
40	Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 21). . . . . 32
41	Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 22). . . . . 33
42	Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 23). . . . . 33
43	Mean daily DO and observed mortality for 20-day (chronic) larval trials. Line projections represent daily DO ranges (tank 4). . . . . 34

## Figures (continued)

Figure	Page
44	Mean daily DO and observed mortality for 20-day (chronic) larval trials. Line projections represent daily DO ranges (tank 5)..... 34
45	Mean daily DO and observed mortality for 20-day (chronic) larval trials. Line projections represent daily DO ranges (tank 6)..... 35
46	Mean daily DO and observed mortality for 20-day (chronic) larval trials. Line projections represent daily DO ranges (tank 7)..... 35
47	Mean daily DO and observed mortality for 20-day (chronic) larval trials. Line projections represent daily DO ranges (tank 8)..... 36
48	Mean daily DO and observed mortality for 20-day (chronic) larval trials. Line projections represent daily DO ranges (tank 9)..... 36
49	Mean daily DO and observed mortality for 20-day (chronic) larval trials. Line projections represent daily DO ranges (tank 10)..... 37
50	Mean daily DO and observed mortality for 20-day (chronic) larval trials. Line projections represent daily DO ranges (tank 11)..... 37
51	Mean daily DO and observed mortality for 20-day (chronic) larval trials. Line projections represent daily DO ranges (tank 12)..... 38
52	Mean daily DO and observed mortality for 20-day (chronic) larval trials. Line projections represent daily DO ranges (tank 13)..... 38
53	Mean daily DO and observed mortality for 20-day (chronic) larval trials. Line projections represent daily DO ranges (tank 14)..... 39
54	Mean daily DO and observed mortality for 20-day (chronic) larval trials. Line projections represent daily DO ranges (tank 15)..... 39
55	Mean daily DO and observed mortality for 20-day (chronic) larval trials. Line projections represent daily DO ranges (tank 16)..... 40
56	Mean daily DO and observed mortality for 20-day (chronic) larval trials. Line projections represent daily DO ranges (tank 17)..... 40
57	Mean daily DO and observed mortality for 20-day (chronic) larval trials. Line projections represent daily DO ranges (tank 18)..... 41

## Figures (continued)

Figure		Page
58	Mean daily DO and observed mortality for 20-day (chronic) larval trials. Line projections represent daily DO ranges (tank 21).....	41
59	Mean daily DO and observed mortality for 20-day (chronic) larval trials. Line projections represent daily DO ranges (tank 22).....	42
60	Mean daily DO and observed mortality for 20-day (chronic) larval trials. Line projections represent daily DO ranges (tank 23).....	42
61	Growth of razorback sucker larvae exposed to DO concentrations of 3 mg/L for 20 days. Mean TL for day 0 and for day 20 were calculated using 10% (n = 30) of the treatment group from each tank. Line projections represent the range of TL measurements. ....	43
62	Growth of razorback sucker larvae exposed to DO concentrations of 4 mg/L for 20 days. Mean TL for day 0 and for day 20 were calculated using 10% (n = 30) of the treatment group from each tank. Line projections represent the range of TL measurements. ....	43
63	Growth of razorback sucker larvae exposed to DO concentrations of 5 mg/L for 20 days. Mean TL for day 0 and for day 20 were calculated using 10% (n = 30) of the treatment group from each tank. Line projections represent the range of TL measurements. ....	44
64	Growth of razorback sucker larvae exposed to DO concentrations of 6 mg/L for 20 days. Mean TL for day 0 and for day 20 were calculated using 10% (n = 30) of the treatment group from each tank. Line projections represent the range of TL measurements. ....	44
65	Growth of razorback sucker larvae reared in air-saturated tanks for 20 days. Mean TL for day 0 and for day 20 were calculated using 10% (n = 30) of the treatment group from each tank. Line projections represent the range of TL measurements.....	45
66	Comparative growth of razorback sucker larvae reared in all experimental DO concentrations for 20 days. Day 0 and day 20 mean TL were calculated using 10% (n = 30) of the treatment group from each tank. Line projections represent the range of TL measurements.....	45

## ABSTRACT

Laboratory experiments were conducted to compare hatching success, survival, and growth of razorback sucker (*Xyrauchen texanus*) eggs and larvae exposed to dissolved oxygen (DO) concentrations of 1–8 milligrams per liter (mg/L) at a nominal temperature of 20 degrees Celsius. Total mortality of eggs occurred in 72 hours at 1 mg/L ( $0.78 \pm 0.06$ ) and in 120 hours at 2 mg/L ( $2.12 \pm 0.01$ ). Hatch success for the remaining treatments ranged from 27.6–61.3 percent (%). Larval response was evaluated in 72-hour tests and resulted in near total mortality at 1 mg/L ( $1.39 \pm 0.03$ ) and mortalities of 43.6% and 5.33% at 2 mg/L ( $2.14 \pm 0.01$ ) and 3 mg/L ( $2.92 \pm 0.01$ ), respectively. Less than 1% mortality was observed for larval fish exposed to DO concentrations equal to or greater than 4 mg/L ( $3.95 \pm 0.02$ ). Larval mortality and comparative growth were also evaluated for 20-day-old fish exposed to DO concentrations of 2–8 mg/L for 20 days. Mortality ranged from 0.67–100% during this test, and no difference in mean growth measured as total length was observed for larval fish surviving the full trial period.

# INTRODUCTION

The Lower Colorado River Multi-Species Conservation Program (LCR MSCP) is developing 360 acres of backwater habitat for razorback sucker (*Xyrauchen texanus*) and bonytail (*Gila elegans*), two endangered native fish of the Colorado River Basin. Development of suitable habitats for these species is being carried out through modifications to existing backwaters as well as the creation of new backwaters through excavation of undeveloped land. Most of these backwater habitats will be flood plain ponds and sloughs isolated from the main river channel. Once completed, these habitats will be managed and maintained as native fish refugia.

Dissolved oxygen (DO) is one of the most important indicators of the ability of a body of water to support aquatic life. There are numerous factors that affect DO concentrations, including climate, season, temperature, volume, velocity, aquatic organisms, vegetation, dissolved solids, salinity, and organic wastes. DO concentrations found in backwater habitats along the lower Colorado River (LCR) are typically favorable in the fall, winter, and early spring months and tend to decrease towards less favorable levels in late spring and summer. The combined effects of the biotic and abiotic factors listed above drive these changes throughout the year.

During warmer months, elevated water temperatures and higher salinities are common in isolated backwaters along the LCR. Increases in one or both of these parameters are known to reduce the oxygen concentration of saturated waters (Fry 1971). Temperature, however, seems to have a greater overall effect on the DO concentration in these habitats, as increases in salinity are relatively moderate in managed ponds. Wetzel (1983) describes the nonlinear relationship between temperature and DO, stating that colder water has a greater capacity for oxygen storage. Therefore, as water temperatures increase in these various habitats, less oxygen is available for biological processes. This can be problematic, as metabolic rates, and therefore the oxygen consumption of fish, increase with higher temperatures. The correlation between warm water and low oxygen environments may lead to decreased survival of fish. Temperature and salinity may also act to stratify ponds by creating layers of water with different density. Stratification can lead to sustained, low levels of DO because mixing occurs more readily within layers than between them (Kramer 1987). Large zones of low DO can be stressful or even fatal to fish if allowed to persist.

DO is made available to aquatic organisms through both atmospheric diffusion and the photosynthetic productivity of phytoplankton and green plants. As the duration and intensity of solar radiation increases during the spring and summer months, aquatic communities see a marked increase in this productivity. Boyd (1985) observed DO concentrations throughout a single growing season, finding that although high phytoplankton productivity generated substantial quantities of DO, respiration by these organisms depleted the majority of the oxygen produced.

## **Dissolved Oxygen Tolerances for Egg and Larval Stages of Razorback Sucker**

In addition, stagnant, densely vegetated ponds can have large diel fluctuations with very high and very low DO concentrations during the day and night, respectively (Maitland 1978). Atmospheric diffusion can, to some degree, help offset these low concentrations and deficits. Wave action induced by wind can prevent stagnation and improve DO diffusion and concentrations within many of these habitats. Circulation of water through wave action can also reduce stratification and preclude prolonged low oxygen conditions (Stanley and Nixon 1992).

With these factors in mind, the present study was designed as part of the continuing effort to establish guidelines for the development and maintenance of high quality backwater habitats for native fish. Findings will help identify conditions that may be less favorable or possibly harmful to the early life stages of these fish. These less favorable conditions may require site managers to take active steps towards improving DO levels during some portion of the year.

## **STUDY AREA**

Field work associated with this study took place in the LCR MSCP's river Reach 2, Lake Mohave, Arizona-Nevada. Lake Mohave was created in 1953 following the construction and closure of Davis Dam. The reservoir is 108 kilometers (km) [67 miles (mi)] long, less than 6.4 km (4 mi) wide at its widest point, and has a storage capacity of more than 2.2 billion cubic meters (1.82 million acre-feet). Sampling for adult razorback sucker was conducted along a noncontinuous 10-km stretch of the Nevada shoreline. All laboratory work associated with this study took place at the LCR MSCP's Fisheries Laboratory, Boulder City, Nevada.

## **METHODS**

The LCR MSCP Fisheries Group, with the assistance of the National Park Service and the Nevada Department of Wildlife, collected adult razorback suckers by trammel net from shoreline areas of Lake Mohave, Nevada, in March 2009. A total of 15 female and 12 male razorbacks were collected from two distinct spawning groups at Halfway Wash and Tequila Cove. Fish were separated by sex and held in separate 1.2 meter (m) x 1.2 m floating live cages for 24 to 48 hours prior to being manually spawned on March 19. Of the captured razorbacks, eggs and sperm were obtained from 8 females and 10 males. Razorbacks were spawned in three groups of 2–3 females and 3–4 males. A single female was used in two of the groups due to a relatively high number of eggs being released.

## Dissolved Oxygen Tolerances for Egg and Larval Stages of Razorback Sucker

Gametes from individuals of each group were captured and mixed in 9.5-liter (L) containers partially filled with lake water. Lake water quality was recorded at the time fish were spawned using an In-Situ Inc., TROLL<sup>®</sup> 9500 multiparameter water quality unit. To prevent eggs from clumping together or from adhering to the sides of the containers, calcium bentonite was added after gametes had been mixed. Eggs were then transferred to floating Nitex<sup>®</sup> cloth hatching trays where they were allowed to water harden for 4 hours. Eggs were removed from hatching trays via a small dip net, placed in 3.78-L plastic bags partially filled with lake water, and arranged in a small cooler for transport to the Bureau of Reclamation LCR MSCP Fisheries Laboratory.

Laboratory tests were run from March 19 through May 5, 2009. Egg and larval DO tolerances were tested through exposure to static bath DO concentrations of 1–6 milligrams per liter (mg/L) and at a nominal 20 degrees Celsius (°C). A target temperature of 20 °C was set based on previous observations that determined this temperature to be near optimal for hatching success of razorback sucker embryos in a laboratory setting (Marsh 1985; Bozek et al. 1990; Haines 1995). Control groups of both life stages were also maintained concurrently with each test in water near oxygen saturation (7–8 mg/L). Egg exposure lasted for 8 days, or through last hatch, and separate groups of larvae were exposed to experimental concentrations for periods of 72 hours and 20 days.

Three replicate 37.8-L tanks were used for each DO concentration during both egg and larval tests. Oxygen concentrations were maintained by diffusing a predetermined ratio of nitrogen and air through a single air stone in each tank. A Hach HQ40d<sup>®</sup> DO probe was used to record temperature and oxygen concentrations for each tank three times a day. Multiple readings were taken from different locations within each tank during initial testing of the apparatus, and periodically throughout the tests, to verify sufficient mixing of the gases. Specific conductivity and pH were also periodically recorded using an In-Situ TROLL<sup>®</sup> 9500 multiparameter water quality unit.

To reduce gas transfer between tanks and the atmosphere, Plexiglas<sup>®</sup> covers were placed on each tank, and gas lines were passed through sealed bulkheads. Even though tanks were sealed, tank volumes were maintained at 25 L to remain below the height of the bulkhead and to prevent any possible leakage. Covers were kept in place and gently seated to each tank using hook and loop straps. Tank covers remained in place except during DO measurements, larval feedings, water exchanges, and periodic cleaning of the tanks. During these events, covers were not removed, but slid back only enough to facilitate these tasks.

For the duration of testing, a 12-hour light, 12-hour dark photoperiod was maintained to mimic vernal conditions. Daytime hours were sustained using both natural and overhead artificial light. Because static bath treatments were used to

## **Dissolved Oxygen Tolerances for Egg and Larval Stages of Razorback Sucker**

maintain the desired DO concentrations, water exchanges were performed on test tanks as needed to preserve water quality. Reserve tanks for each DO treatment were sustained separately to supply appropriate water for these exchanges.

### **Egg Dissolved Oxygen Tolerance**

Razorback sucker eggs were fertilized in three groups at our field campsite using oxygen-saturated lake water (10.1 mg/L at 17.5 °C). To improve the likelihood of evaluating eggs of mixed parentage in each of the experimental DO concentrations, eggs from all three spawning groups were pooled together upon returning to the laboratory. Eggs were counted by taking several subsamples and calculating the average number of eggs per unit of volume. Eggs were then distributed equally between hatching trays in the six experimental DO concentrations, the saturated control tanks, and several surplus tanks that also contained oxygen-saturated water.

From March 19 to March 26, eggs were exposed to the full experimental range of DO concentrations. During the incubation period, eggs were routinely examined to document development and to look for signs of damage or fungus. When damage, fungus, or dead (white/opaque) eggs were observed, eggs were removed from the hatching tray, counted, examined, and discarded. Dudley and Eipper (1975) observed near total mortality for largemouth bass (*Micropterus salmoides*) embryos that were moved during incubation as part of their study, and for that reason, damaged, fungused, or dead eggs were removed carefully, and water exchanges were performed sparingly during these tests in an effort to disturb the eggs as little as possible. When exchanges were necessary, water was slowly siphoned out of and into the bottom of the tank using a 0.5-centimeter- diameter tube. As hatching was completed and larval fish began swimming, hatching trays were removed from each tank. Larvae remained in their hatch tanks for up to 5 days to evaluate any immediate or delayed mortality. Following this period, larvae were counted individually and used to calculate percent hatch for each treatment.

### **Larval Dissolved Oxygen Tolerance**

Twenty-day-old larvae hatched in oxygen-saturated tanks were exposed to the full experimental range of DO concentrations following egg trials. Exposure times included 72-hour acute mortality trials and 20-day chronic mortality trials. Each tank contained 300 larvae for both trial durations. Mortalities were recorded and removed from tanks as they occurred.

## Comparative Larval Growth

In addition to defining lethal limits of DO, comparative growth rates of larvae exposed to DO concentrations of 2 mg/L to air saturation were also examined as part of the 20-day chronic trial. A subsample (n = 30) of the 300 larvae going into each tank was measured for total length (TL) in millimeters (mm) at the beginning of the 20-day trial period. Larvae were fed equal amounts of brine shrimp twice a day for the trial duration. Following the trial period, another subsample of larvae (n = 30) was taken from each tank and measured for TL.

## RESULTS

### Egg Dissolved Oxygen Tolerance

Four to seven days were required for complete hatch at all successful DO concentrations. Eggs incubated at 1 mg/L appeared to cease development within 24 hours of exposure and had 100 percent (%) mortality at 72 hours. It should be noted that DO concentrations for this treatment did fall below the targeted 1 mg/L due to difficulties controlling the nitrogen regulator. DO concentrations were recorded as low as 0.26 mg/L within the first 3 days of exposure (figures 1–3). These extremely low levels of DO likely contributed to the disruption of egg development.

Eggs exposed to the 2-mg/L treatment fared slightly better, with at least a low level of development occurring. Protol larvae emerged earliest in this concentration, and despite DO concentrations being slightly above the targeted 2 mg/L (figures 4–6), all were underdeveloped and survived for only a short period post-emergence. Oseid and Smith (1971a, 1971b) made similar observations of reduced size at hatch for both white sucker (*Catostomus commersoni*) and walleye (*Sander vitreus*), but also observed longer incubation periods and relatively higher survival at lower oxygen levels. Due to the lack of development observed for emergent protol larvae in the current study, this treatment was considered to have an unsuccessful hatch. Total mortality for this treatment was recorded at approximately 120 hours.

Eggs incubated in oxygen concentrations of 3–8 mg/L developed normally, and larvae began swimming within 36 hours of hatching. Hatch success was, however, variable among the treatments with a successful brood (table 1). The average temperature for all individual treatments ranged from 21.4 to 22.7 °C, and DO was maintained within 0.5 mg/L of the targeted value (figures 7–21). All three 6-mg/L tanks did, however, experience a spike in temperature due to heating from a nearby 1/8-horsepower blower. Temperatures only exceeded 25 °C for a short time (figures 16–18), but this may be the cause of the reduced hatch observed for this treatment. Marsh (1985) had very similar results for

## Dissolved Oxygen Tolerances for Egg and Larval Stages of Razorback Sucker

Table 1.—Mean DO and percent hatch of razorback sucker eggs (Mean DO  $\pm$  standard error (SE), number of eggs, larvae from eggs, and percent hatch represent combined totals from three replicate treatments)

Target DO (mg/L)	Mean DO (mg/L) $\pm$ SE	Number of eggs <sup>1</sup>	Larvae from eggs	Percent hatch
1.00	0.78 $\pm$ 0.06	6,150	0	0
2.00	2.12 $\pm$ 0.01	6,150	0	0
3.00	2.71 $\pm$ 0.02	6,150	2,677	43.5
4.00	3.98 $\pm$ 0.03	6,150	3,769	61.3
5.00	4.80 $\pm$ 0.03	6,150	3,636	59.1
6.00	6.08 $\pm$ 0.03	6,150	1,698	27.6
Saturation	7.57 $\pm$ 0.01	6,300	3,841	60.9

<sup>1</sup> Number of eggs estimated based on 51 eggs/mL measurement.

razorback embryos incubated at 25 °C in air-saturated water with approximately 29% hatch for six replicate treatments. Specific conductivity and pH ranged from 1,004 to 1,095 microsiemens per centimeter ( $\mu$ S/cm) and from 7.74 to 8.17 respectively, during egg trials.

## Larval Dissolved Oxygen Tolerance

Larvae exposed to the 1-mg/L treatment during 72-hour acute mortality trials displayed near total mortality between all replicates within the first 48 hours (figures 22–24). All larvae in this treatment were observed to move toward the water's surface within a few minutes of exposure and remained there skimming the air-water interface during all subsequent observations. Dean and Richardson (1999) made similar observations for multiple species that were exposed to this concentration during their study as well. Of the 900 larvae exposed to this treatment, only 10 survived for the full 72-hour period. It should be noted that during this trial, DO concentrations remained above the targeted 1 mg/L, ranging from 1.09 to 1.53 mg/L. Mean dissolved oxygen and percent mortality have been summarized for all 72-hour trials in table 2. These values represent the combined totals from the three replicate treatments.

Larvae exposed to the 2-mg/L treatment also displayed relatively high mortality during the 72-hour trial period. While the majority of mortalities were observed within the first 48 hours (figures 25–27), mortality remained below 50% for the full trial period. Behavioral responses similar to those observed during the 1-mg/L treatment were also noted during this treatment. Larvae seemed to be maximizing their available oxygen by skimming the surface of the water. This behavior would also be expected in a natural setting where higher levels of DO

## Dissolved Oxygen Tolerances for Egg and Larval Stages of Razorback Sucker

Table 2.—Mean DO and percent mortality for 72-hour larval trials (Mean DO  $\pm$  SE, mean temperature  $\pm$  SE, mortalities, and percent mortality represent combined totals from three replicate treatments)

Target DO (mg/L)	Mean DO (mg/L) $\pm$ SE	Mean temperature ( $^{\circ}$ C) $\pm$ SE	Mortalities	Percent mortality
1.00	1.39 $\pm$ 0.03	21.4 $\pm$ 0.44	890	98.9
2.00	2.14 $\pm$ 0.01	21.2 $\pm$ 0.43	392	43.6
3.00	2.92 $\pm$ 0.01	21.2 $\pm$ 0.77	48	5.33
4.00	3.95 $\pm$ 0.02	21.4 $\pm$ 0.75	4	0.44
5.00	5.14 $\pm$ 0.02	20.5 $\pm$ 1.00	7	0.78
6.00	6.12 $\pm$ 0.15	20.8 $\pm$ 1.09	5	0.56
Saturation	8.11 $\pm$ 0.16	19.2 $\pm$ 0.49	4	0.67

are maintained at the surface through diffusion (Kramer 1987). It appears that even with the use of Plexiglas<sup>®</sup> covers, some additional oxygen may have been available within the headspace of the tank.

Larval mortality was greatly reduced for 72-hour trials run at DO concentrations equal to or greater than 3 mg/L (table 2; figures 28–42). Mortality for the 3-mg/L treatment varied between tanks, but totaled only 5.33% for the trial period. The majority of mortalities for this treatment (4%) occurred in a single tank. Mortality for the remaining treatments was further reduced over the 72-hour trial period and ranged from 0.44 to 0.78%. Specific conductivity ranged from 1,028 to 1,109  $\mu$ S/cm and pH from 7.55 to 7.98 during the 72-hour trials.

Following the 72-hour acute mortality trials, 20-day-old larval razorback suckers were exposed to DO concentrations of 2 mg/L to air saturation for a 20-day period. Larval fish were observed for this extended period of time to evaluate any chronic effects these treatments had on mortality that would not be apparent during shorter periods of exposure. For fish exposed to the 2-mg/L treatment, mortality reached 100% within 6 days (figures 43–45). Behavioral responses to this treatment were similar to those observed during the 72-hour trial, and mortality occurred at a similar rate, with approximately 50% occurring between the combined replicates within 72 hours.

With the exception of the 2-mg/L treatment, larval mortality was low during the extended period of exposure (figures 46–60). Fish exposed to DO concentrations of 3 mg/L to saturation exhibited 20-day mortality ranging from 0.67 to 1.33%. These observations were similar to those recorded during the 72-hour trials, with a notable decline in mortality for the 3-mg/L treatment. Mean DO and percent mortality for each treatment are summarized in table 3. These values again represent the combined totals for the three replicate treatments. Specific conductivity ranged from 1,011 to 1,132  $\mu$ S/cm, and pH ranged from 7.55 to 8.21 over the 20-day trial period.

## Dissolved Oxygen Tolerances for Egg and Larval Stages of Razorback Sucker

Table 3.—Mean DO and percent mortality for 20-day larval trials (Mean DO  $\pm$  SE, mean temperature  $\pm$  SE, mortalities, and percent mortality represent combined totals from three replicate treatments)

Target DO (mg/L)	Mean DO (mg/L) $\pm$ SE	Mean temperature ( $^{\circ}$ C) $\pm$ SE	Mortalities	Percent mortality
2.00*	2.06 $\pm$ 0.01	20.7 $\pm$ 0.15	900	100
3.00	3.06 $\pm$ 0.01	21.4 $\pm$ 0.05	11	1.22
4.00	3.98 $\pm$ 0.01	21.5 $\pm$ 0.05	6	0.67
5.00	5.07 $\pm$ 0.01	21.5 $\pm$ 0.06	12	1.33
6.00	6.01 $\pm$ 0.02	21.4 $\pm$ 0.05	12	1.33
Saturation	7.86 $\pm$ 0.01	19.3 $\pm$ 0.08	11	1.22

\* Total mortality for this treatment was observed within 6 days of exposure.

## Comparative Larval Growth

The mean TL for larval subsamples ( $n = 30$ ) taken from 15 individual trial tanks ranged from 10.8 to 11.5 mm at the beginning of the 20-day trial. Initially, growth was to be compared between a total of 18 tanks, but the 2-mg/L replicate treatments were removed from growth observations after 100% mortality was observed within the first week of exposure. Larval growth as measured by TL did not appear to be influenced by DO levels, and very little difference in growth was observed within or between DO treatments (figures 61–65). Temperature (table 3) and food ration also varied only slightly during the trial period. Twenty-day growth averaged 7.92 mm (0.40 mm/day) between all treatments. Bestgen (2008) observed the same mean growth rate per day for 37-day post-hatch razorback sucker larvae reared in flow through containers at 19.5  $^{\circ}$ C. Mean TL was considerably higher during his study; however, larval densities were only 20% that of the current study. Following the 20-day trial, mean TL for the individual tanks ranged from 18.4 to 19.2 mm (table 4; figure 66). Detailed comparative larval growth data have been summarized in table 4.

Table 4.—Summary of effects of different DO concentrations on growth of 20-day-old larvae (Five DO concentrations with three replicate treatments are presented. Mean TL was calculated from a subsample [ $n = 30$ ] of larvae from each tank)

DO	3 mg/L			4 mg/L			5 mg/L			6 mg/L			Air saturated		
Tank	7	8	9	10	11	12	13	14	15	16	17	18	21	22	23
	Mean TL (mm)														
Day0	10.9	11	10.8	10.8	10.9	11	11.3	11	10.9	11	10.8	11.5	10.8	11.2	11.3
Day20	18.9	18.8	18.8	18.8	18.9	18.6	19.2	19.2	18.7	18.9	19.2	19.6	18.4	19.3	18.9

## DISCUSSION

Although efforts were made to normalize variables other than DO and temperature, factors including effectiveness of fertilization, fungus on eggs, health and condition of spawned adults, and handling and manipulation of adult fish, juveniles, and eggs may have influenced trial results. These factors could of course have an underlying influence on percent hatch and survival of larval fish and may attribute to the differences observed during multiple studies on early life stage razorback sucker. When comparing results between studies, these and other potential factors should be considered.

Based on the results of this study, the lower lethal DO limit for successful development of razorback sucker embryos appears to be between 2 and 3 mg/L under these experimental conditions. During incubation, the lowest mean DO concentration producing viable larvae was 2.71 (2.27–2.91) mg/L. This value is the mean DO concentration of the 3-mg/L treatment replicates and resulted in 43.5% hatch. At a mean DO concentration of 2.12 (2.01–2.19) mg/L, the 2-mg/L treatment produced no viable larvae. No overlap was observed for the range of these means during the trial period, which may indicate that the true DO limit preventing a successful hatch is in the low 2-mg/L range. In order to determine a more accurate lower limit, a closer order study could be performed.

Hatching success for treatments producing viable larvae during this study was similar to those previously reported (Bozek et al. 1990; Haines 1995). The majority of these studies looked at hatching success as a function of water temperature, but with the exception of Bozek et al. (1990) who reported viable hatch as high as 71%, laboratory hatch in the 60% range seems to be common for razorback sucker. The results from this and previous studies indicate that successful hatch may be more dependent on the temperature at time of incubation rather than on other factors. Stolberg (2012) reported the upper salinity tolerance for razorback sucker eggs to be near 12,000  $\mu\text{S}/\text{cm}$  in air-saturated water at a mean temperature of 19 °C. This value represents a 3- to 12-time increase over salinities found in lakes Mead and Mohave where adult populations of razorback sucker successfully spawn larval fish (Stolberg 2012; Bureau of Reclamation 2010). Although that study only evaluated salinity tolerance at a single nominal temperature of 20 °C, it and the current study both indicate that some level of hatch can occur when extreme conditions exist and the temperature is favorable. Future work concerning the development and successful hatch of razorback sucker embryos should look to incorporate a wider thermal range to evaluate additional interactions between multiple water quality parameters.

Observations of larval razorback DO tolerance were similar to those observed for razorback eggs. Short-term exposure to a mean DO concentration of 2.14 (2.02–2.25) mg/L resulted in mortality of 43.6% of fish. However, mortality increased to 100% when exposure to a mean DO concentration of

## **Dissolved Oxygen Tolerances for Egg and Larval Stages of Razorback Sucker**

2.06 (1.86–2.26) mg/L was extended to 6 days. Mortality decreased significantly in the 3-mg/L treatment, with short-term mortality of 5.33% at a mean DO concentration of 2.92 (2.78–2.99) mg/L. Observed mortality decreased further during the 3-mg/L 20-day exposure to 1.22% at a mean DO of 3.06 (2.87–3.23) mg/L. These results indicate that under these experimental conditions, the lower DO limit for larval survival is between 2 and 3 mg/L.

Larval growth was not affected by the different DO treatments during this study. Despite the wide range of DO concentrations evaluated, results were similar across 5 treatments and 15 individual tanks. In fact, mean daily growth rates observed during this study were consistent with at least one other study in which larvae were reared in air-saturated waters (Bestgen 2008). It appears that either growth is unaffected by DO concentrations greater than or approximately equal to 3 mg/L, or that this study did not observe larvae for a long enough period to observe any differences.

The lasting effects of the DO concentrations evaluated during this study remain unknown. Incubation or prolonged larval exposure to DO concentrations near the lower lethal limit for this species may have an effect on either future growth or survival. Intensively cultured razorback suckers often display physical abnormalities in the form of spinal and fin deformities that generally present themselves at the larval or juvenile stages. Some have attributed the presence of these deformities to dietary deficiencies at the larval stage, while others have concluded that some deformity can be attributed to handling stress (Martinez 1996). Stolberg (2012) also alluded to larval deformity as a result of handling, noting a high incidence of larvae with crooked backs. Regardless of the cause, be it dietary, handling, or environmental stressors such as low DO, the onset of deformities seems to occur during early or critical stages of development. This should be taken into account when considering the results of this study. Even though egg development and larval survival occurred in the 3 mg/L DO range, it is unknown how stressful this condition is for early life stage razorback sucker. In order to determine if the duration of exposure during this study, or if similar prolonged environmental conditions have an effect on development and survival, a longer term study would need to be performed.

The overriding purpose of this study was to provide additional information that would assist in the management of disconnected and off-channel habitats where native fish are expected to complete their life cycle. DO concentrations such as those evaluated during this study would not likely occur for any extended period during the time of year when these early life stages are present. Early stage juvenile fish could, however, be exposed to similar DO concentrations at even higher temperatures during summer months. For this reason, the information herein is still important for establishing water quality standards that will provide a suitable environment for this species. While adult and juvenile fish are generally less affected by environmental conditions, using the lower lethal limit of a more sensitive life stage as a guideline for acceptable water quality standards could be a

## **Dissolved Oxygen Tolerances for Egg and Larval Stages of Razorback Sucker**

useful tool for management. By developing a plan that manages above minimal water quality standards, the well-being of the species can be protected while allowing for the implementation of any management actions should they be needed.

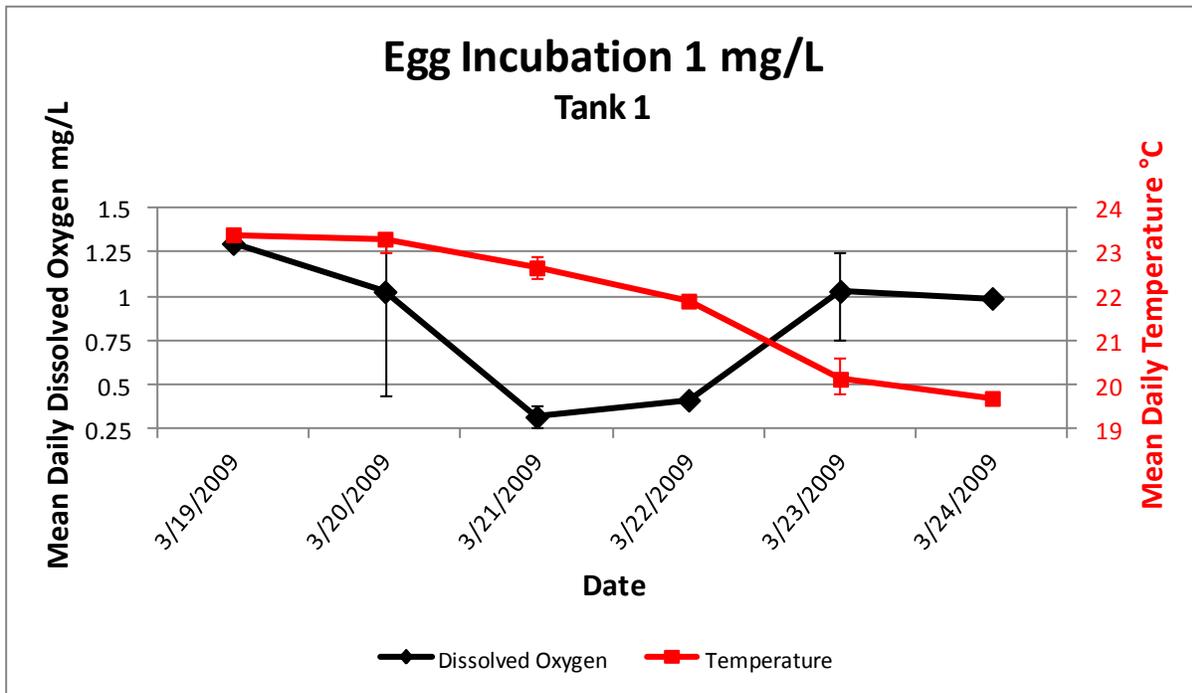


Figure 1.—Mean daily DO, mean daily temperature, and daily ranges (line projections) for 1-mg/L egg trial replicate (tank 1).

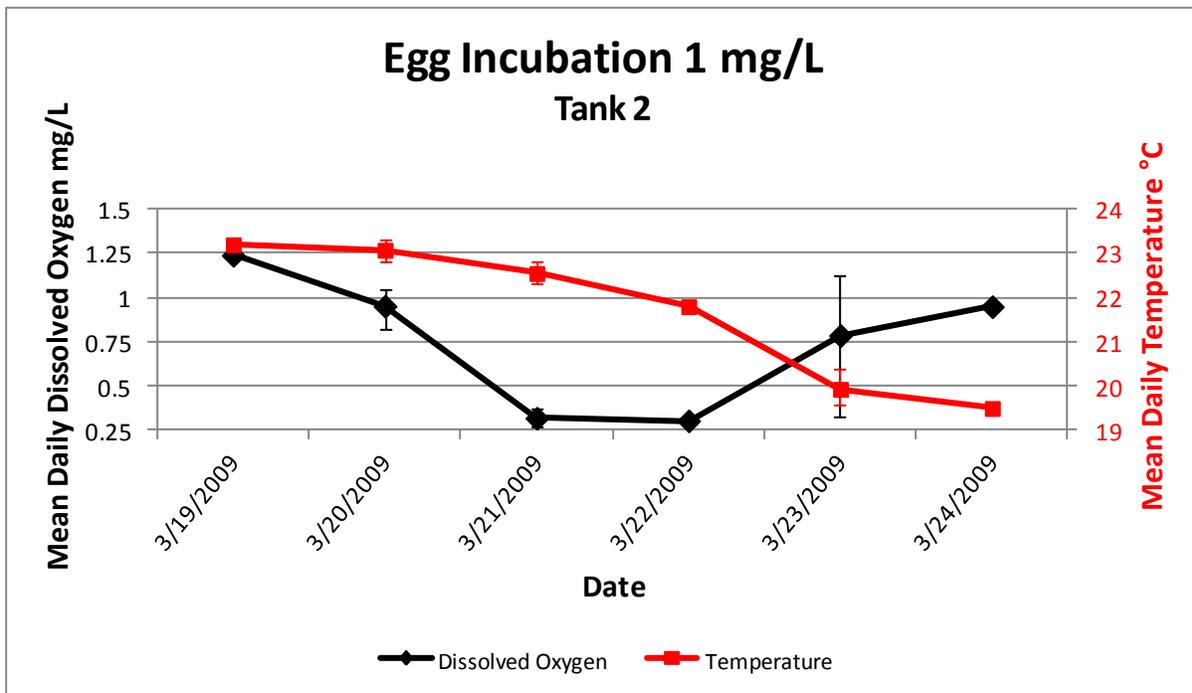


Figure 2.—Mean daily DO, mean daily temperature, and daily ranges (line projections) for 1-mg/L egg trial replicate (tank 2).

Dissolved Oxygen Tolerances for Egg and Larval Stages of Razorback Sucker

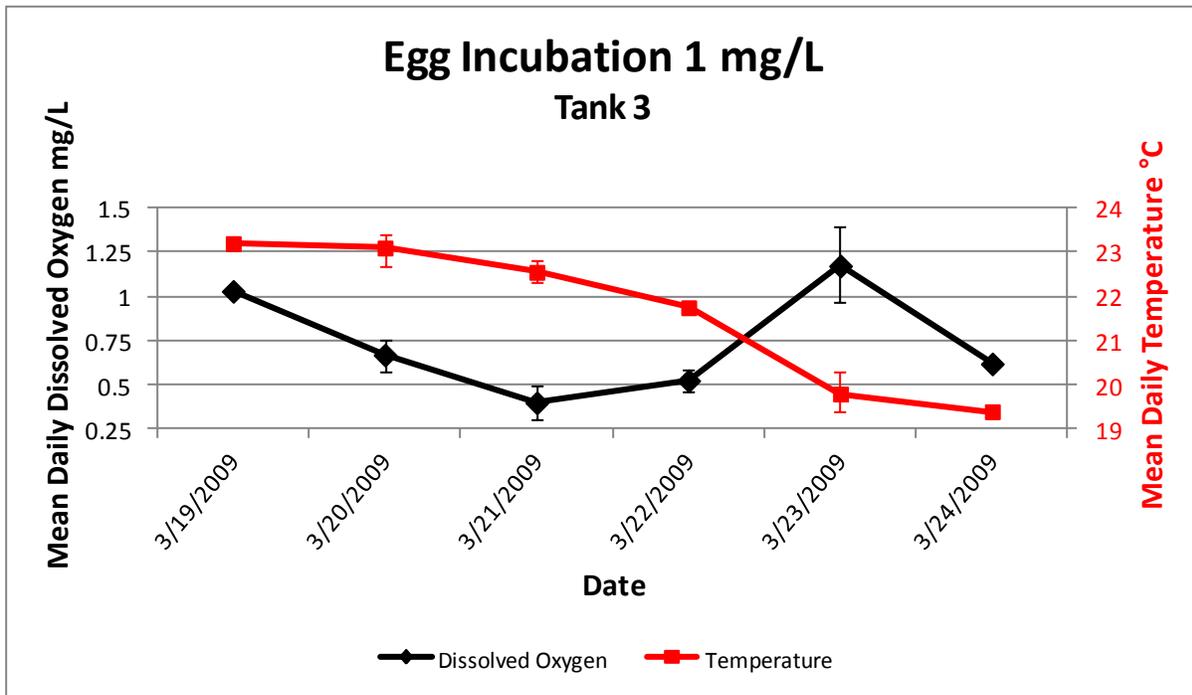


Figure 3.—Mean daily DO, mean daily temperature, and daily ranges (line projections) for 1-mg/L egg trial replicate (tank 3).

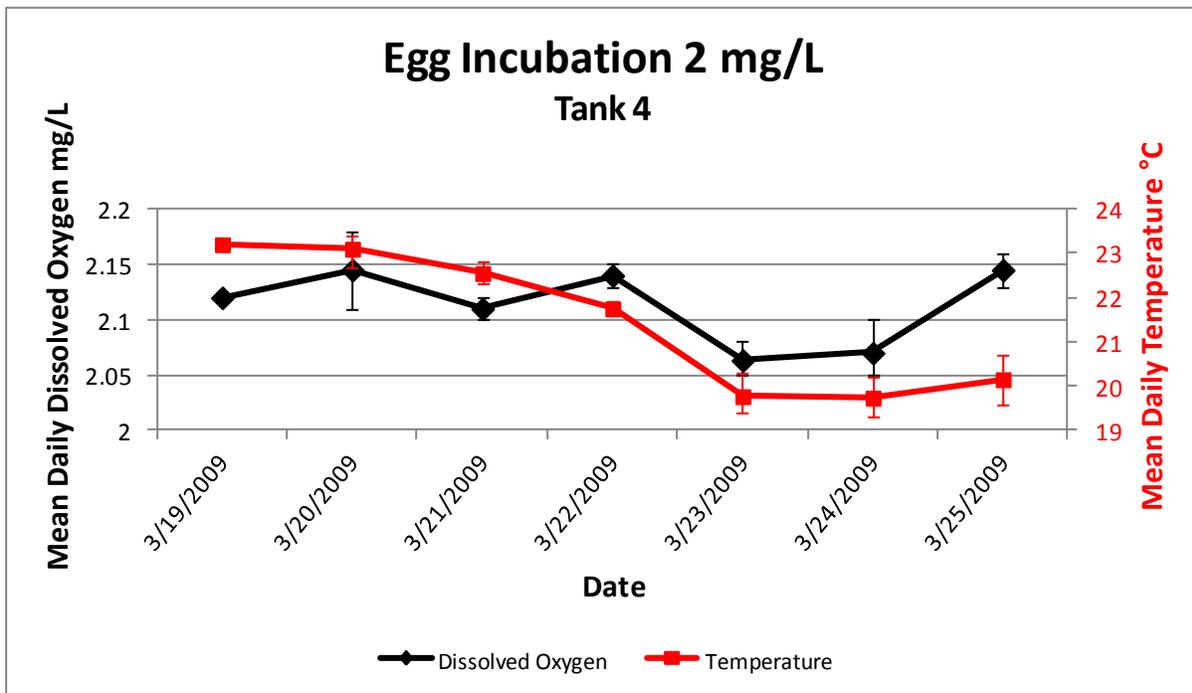


Figure 4.—Mean daily DO, mean daily temperature, and daily ranges (line projections) for 2-mg/L egg trial replicate (tank 4).

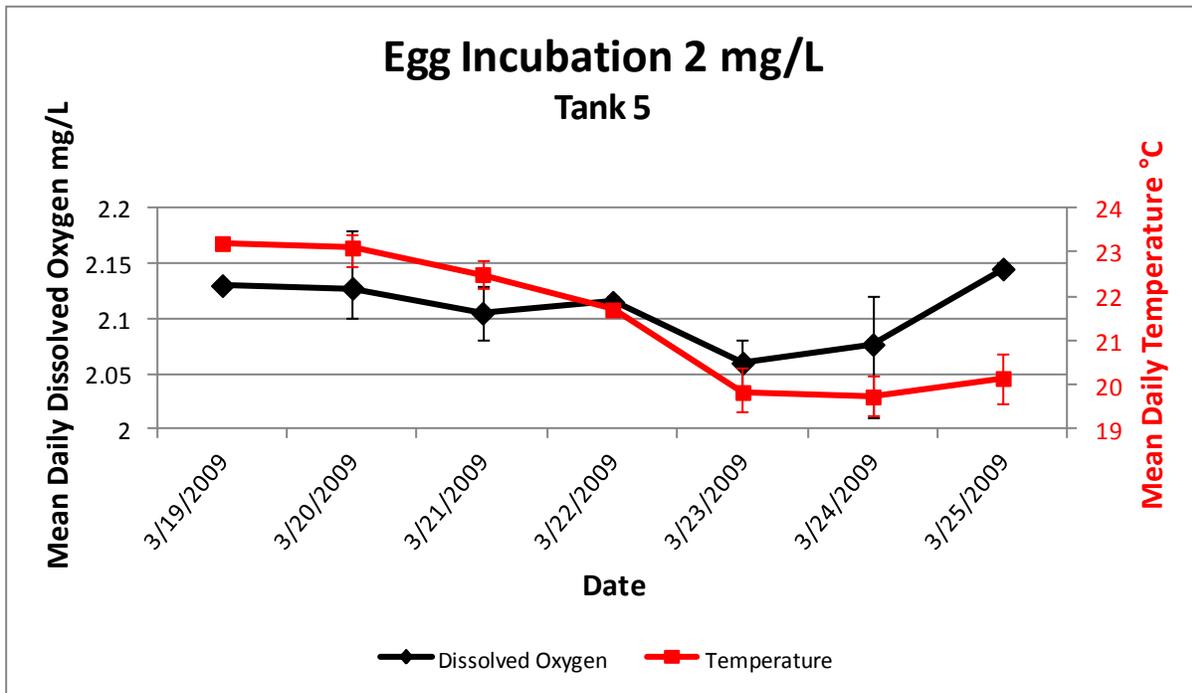


Figure 5.—Mean daily DO, mean daily temperature, and daily ranges (line projections) for 2-mg/L egg trial replicate (tank 5).

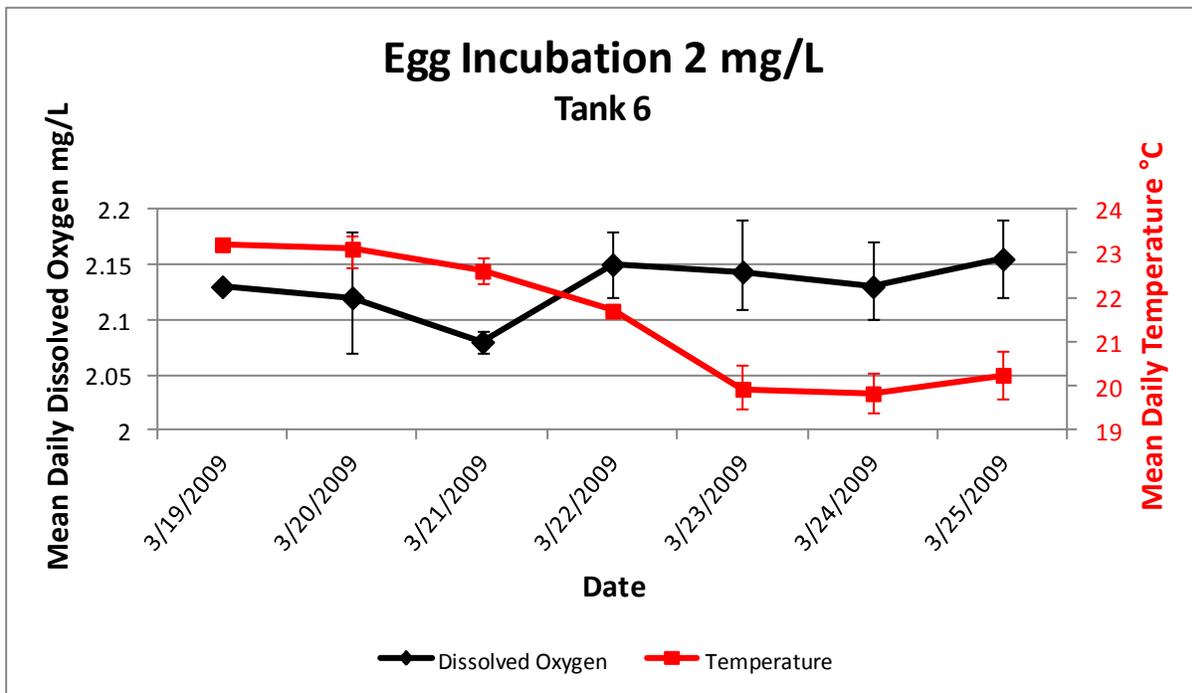


Figure 6.—Mean daily DO, mean daily temperature, and daily ranges (line projections) for 2-mg/L egg trial replicate (tank 6).

Dissolved Oxygen Tolerances for Egg and Larval Stages of Razorback Sucker

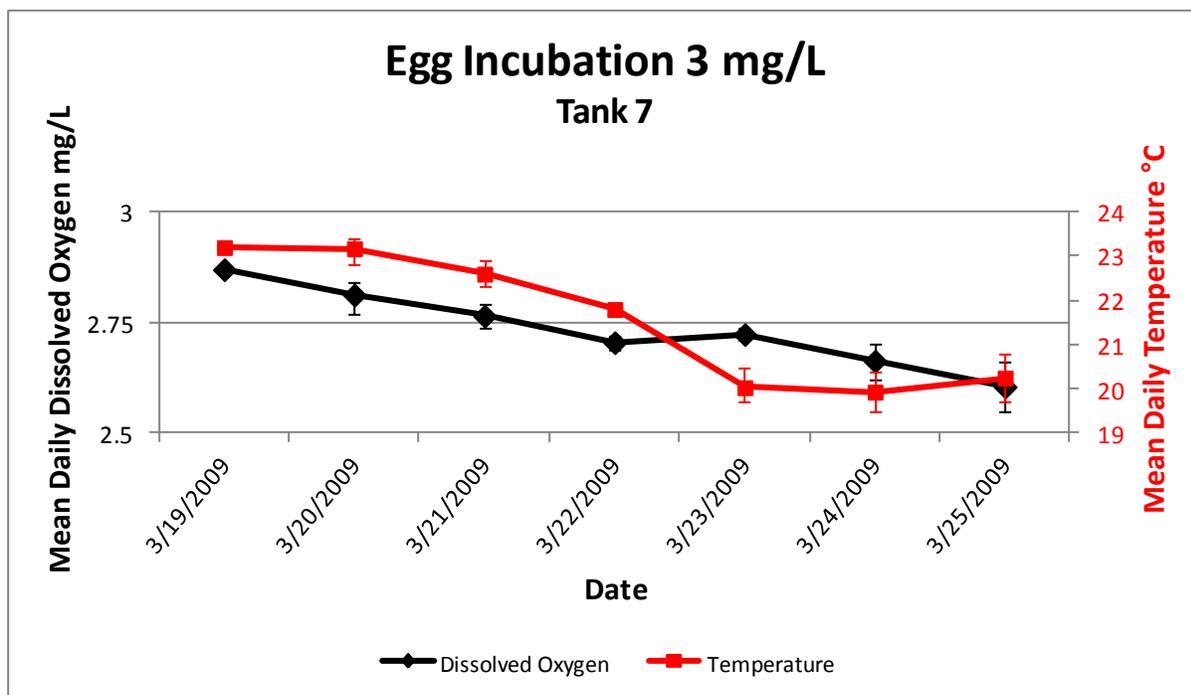


Figure 7.—Mean daily DO, mean daily temperature, and daily ranges (line projections) for 3-mg/L egg trial replicate (tank 7).

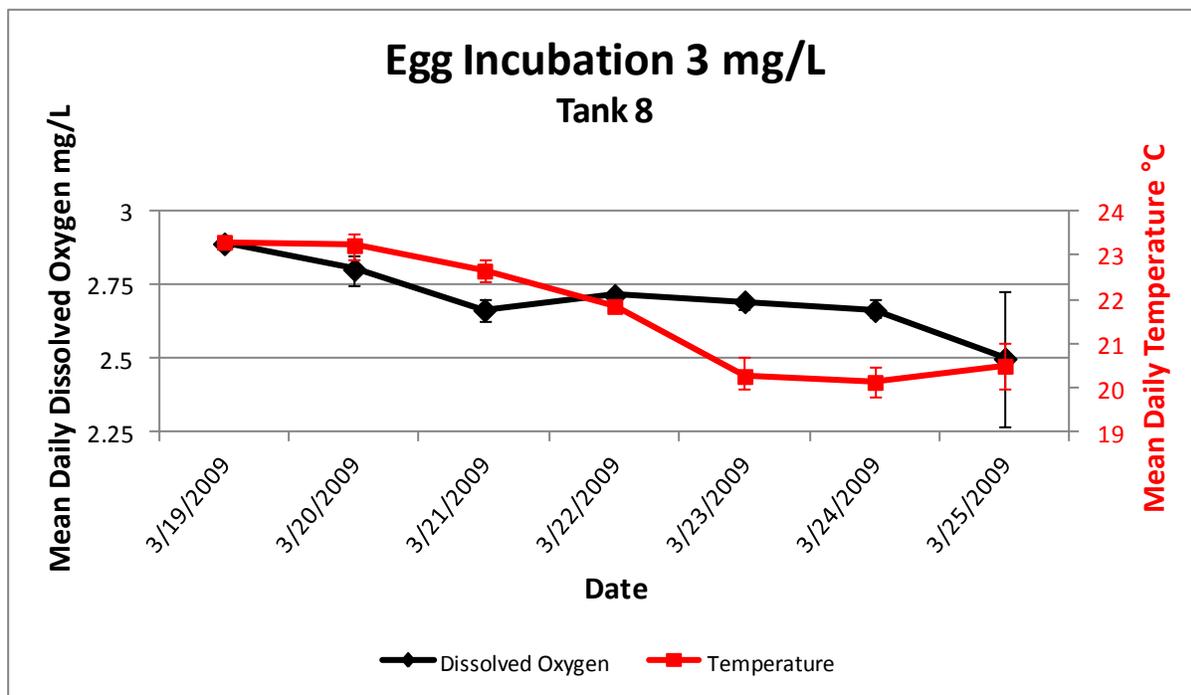


Figure 8.—Mean daily DO, mean daily temperature, and daily ranges (line projections) for 3-mg/L egg trial replicate (tank 8).

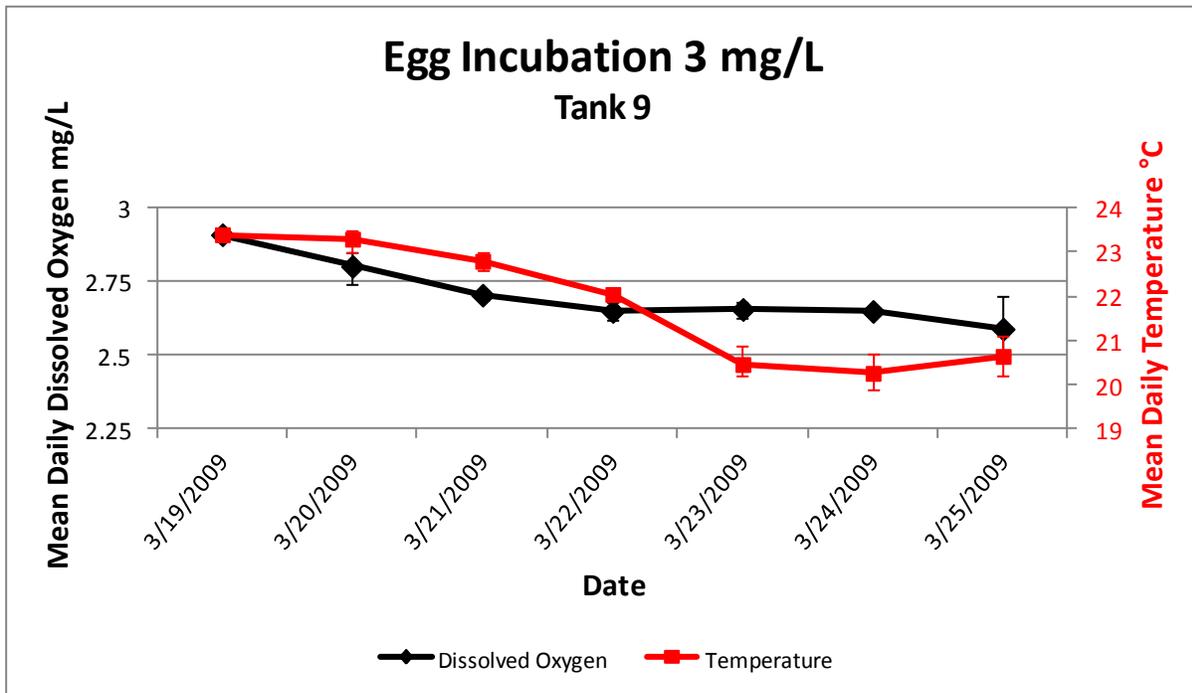


Figure 9.—Mean daily DO, mean daily temperature, and daily ranges (line projections) for 3-mg/L egg trial replicate (tank 9).

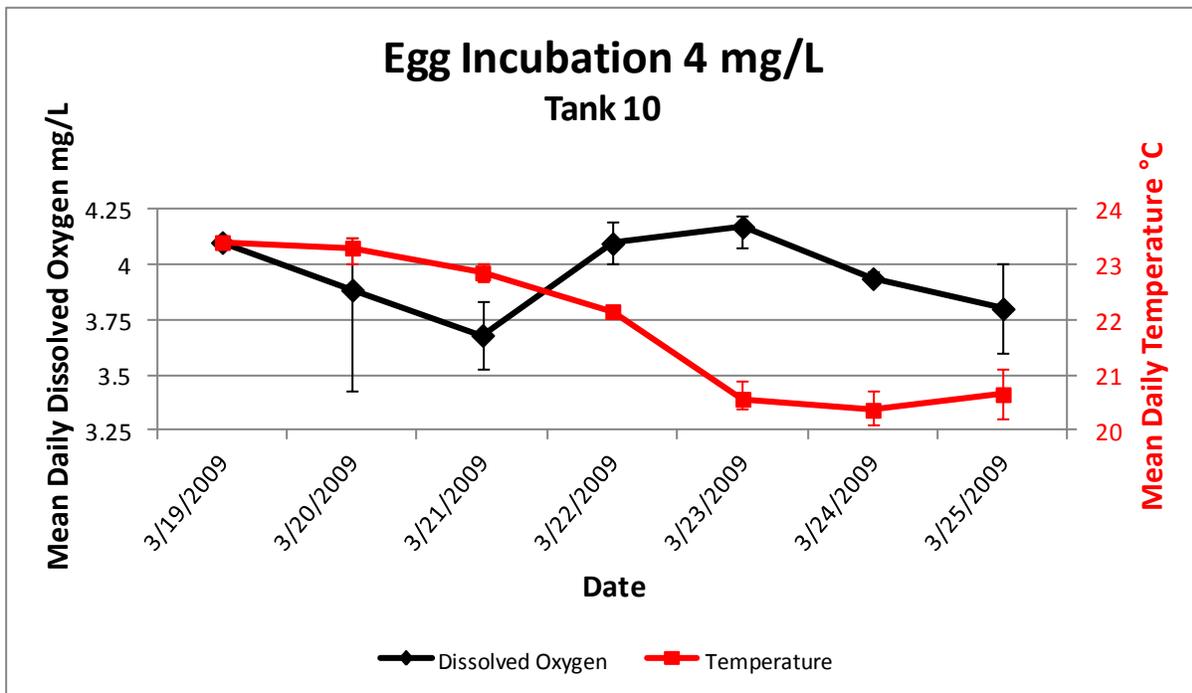


Figure 10.—Mean daily DO, mean daily temperature, and daily ranges (line projections) for 4-mg/L egg trial replicate (tank 10).

Dissolved Oxygen Tolerances for Egg and Larval Stages of Razorback Sucker

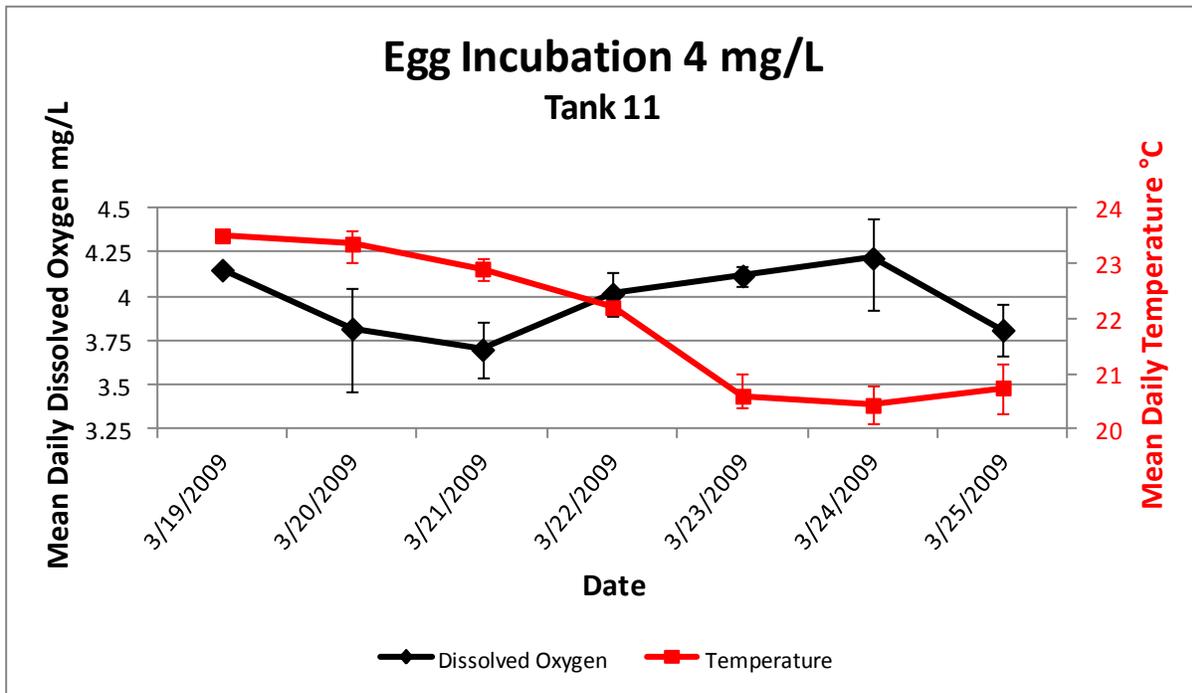


Figure 11.—Mean daily DO, mean daily temperature, and daily ranges (line projections) for 4-mg/L egg trial replicate (tank 11).

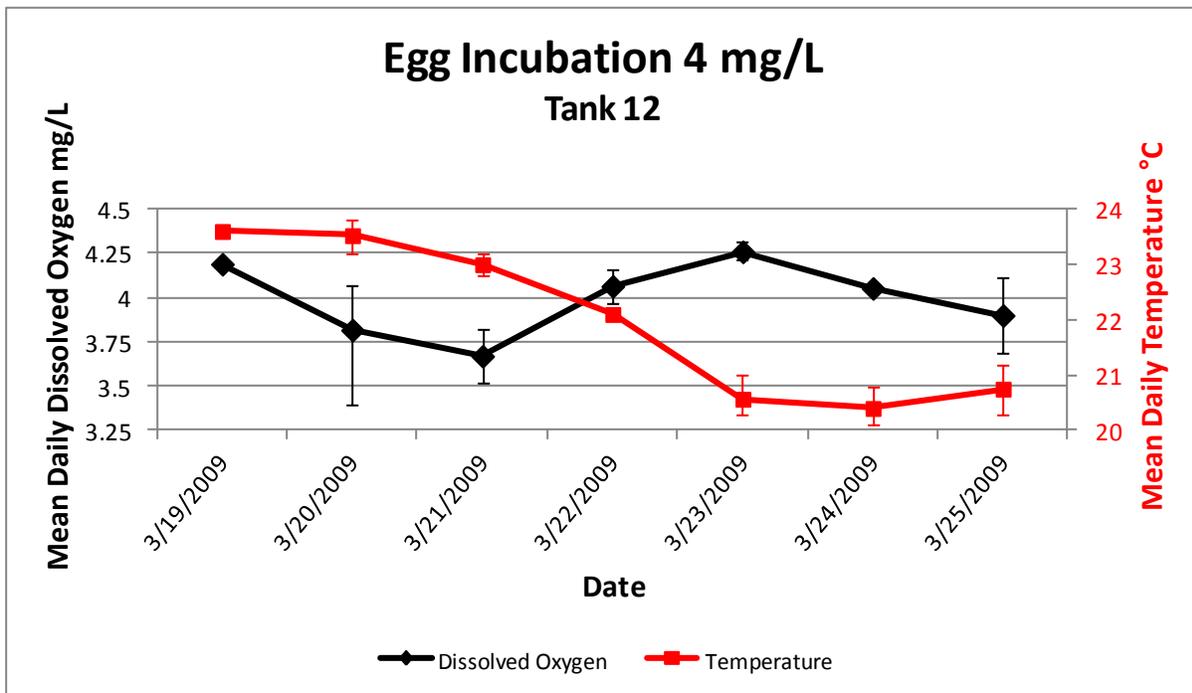


Figure 12.—Mean daily DO, mean daily temperature, and daily ranges (line projections) for 4-mg/L egg trial replicate (tank 12).

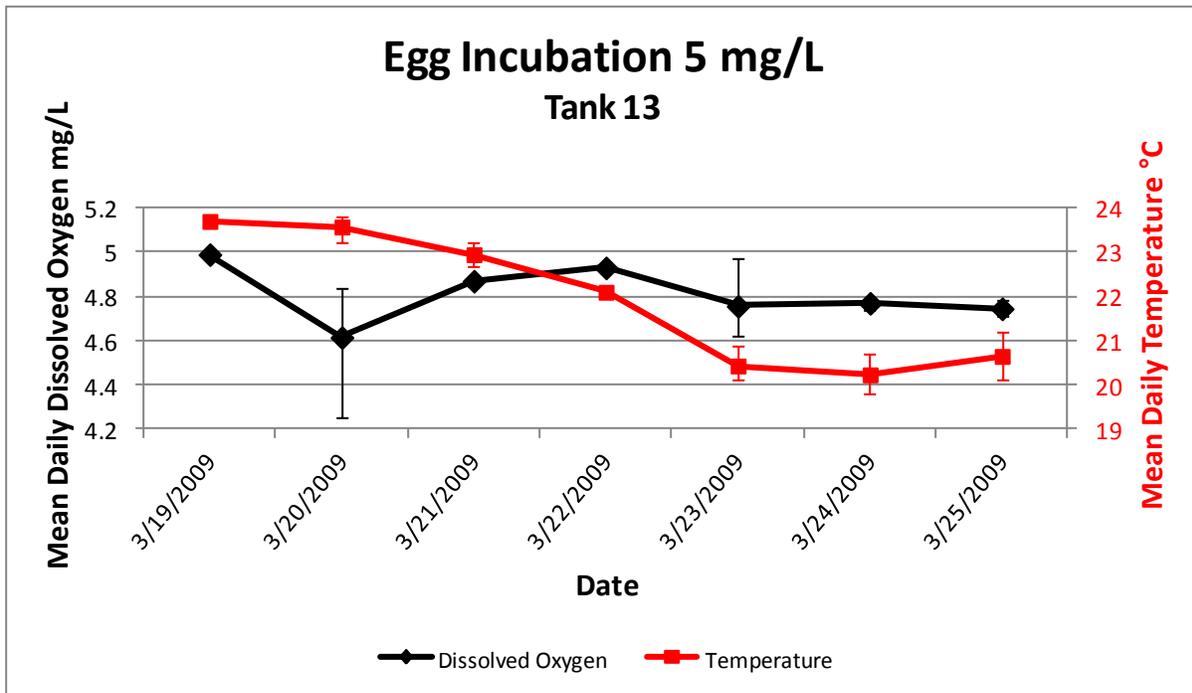


Figure 13.—Mean daily DO, mean daily temperature, and daily ranges (line projections) for 5-mg/L egg trial replicate (tank 13).

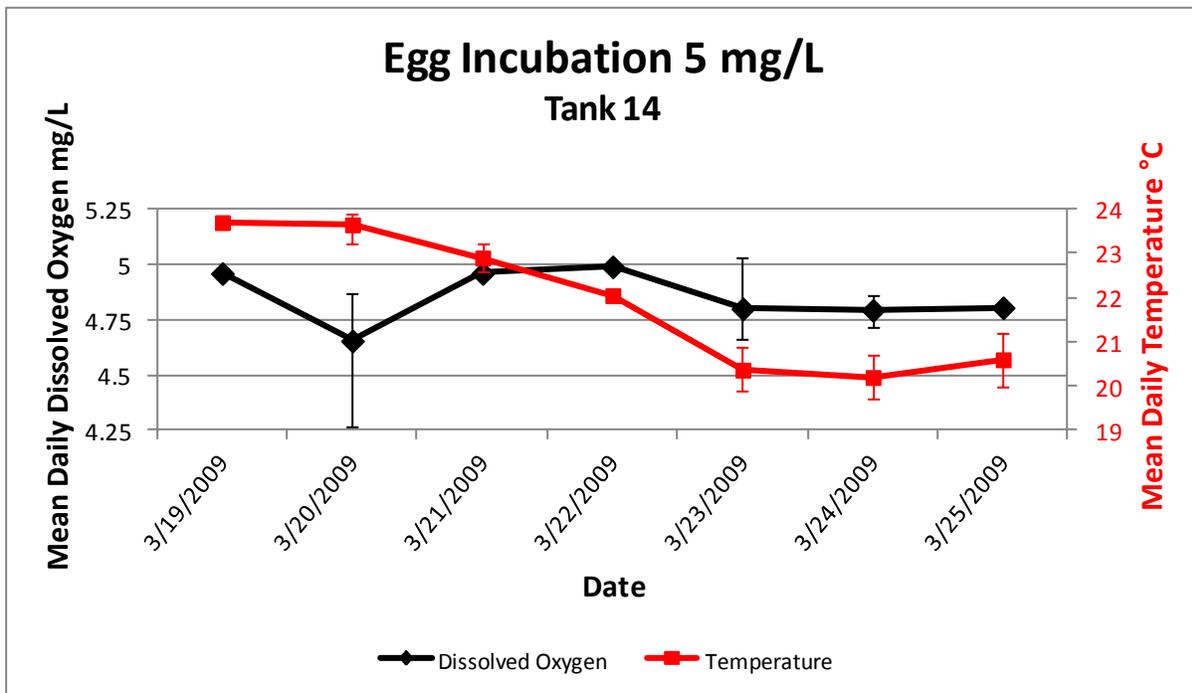


Figure 14.—Mean daily DO, mean daily temperature, and daily ranges (line projections) for 5-mg/L egg trial replicate (tank 14).

Dissolved Oxygen Tolerances for Egg and Larval Stages of Razorback Sucker

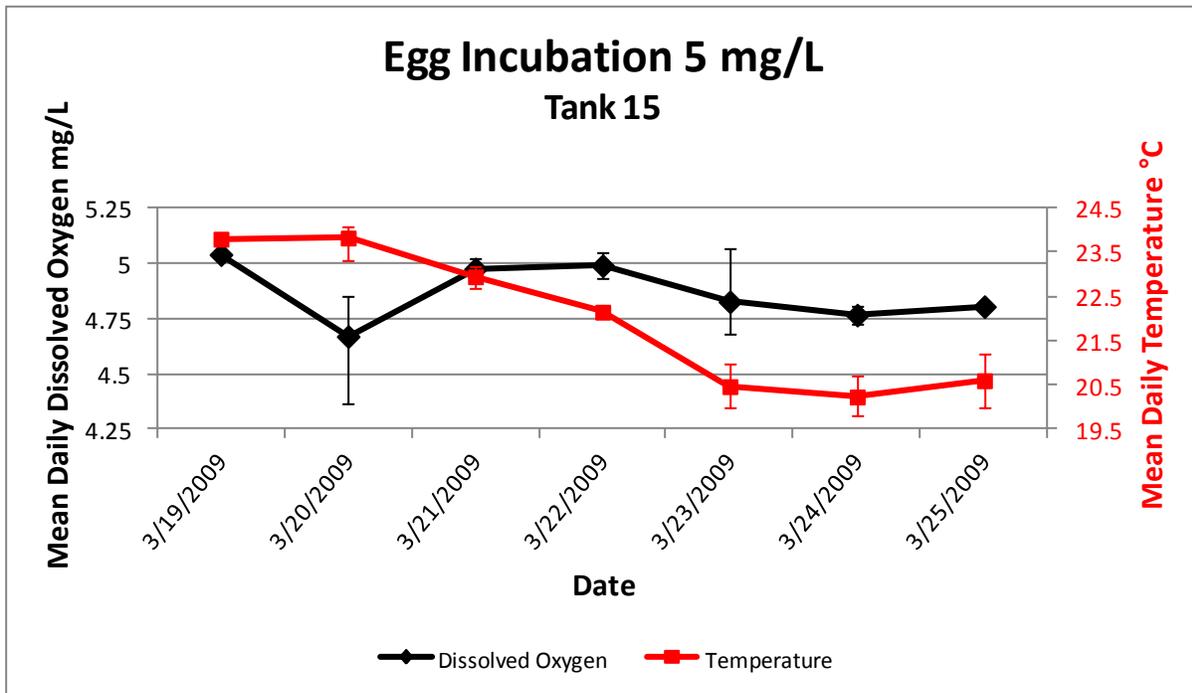


Figure 15.—Mean daily DO, mean daily temperature, and daily ranges (line projections) for 5-mg/L egg trial replicate (tank 15).

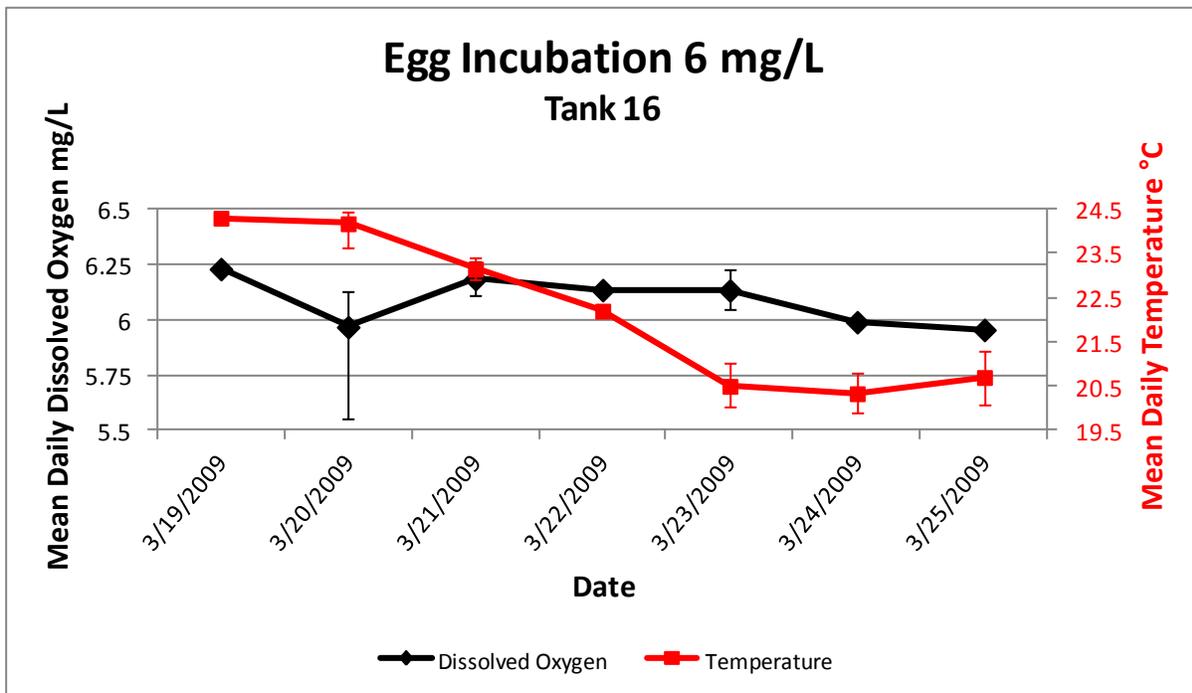


Figure 16.—Mean daily DO, mean daily temperature, and daily ranges (line projections) for 6-mg/L egg trial replicate (tank 16).

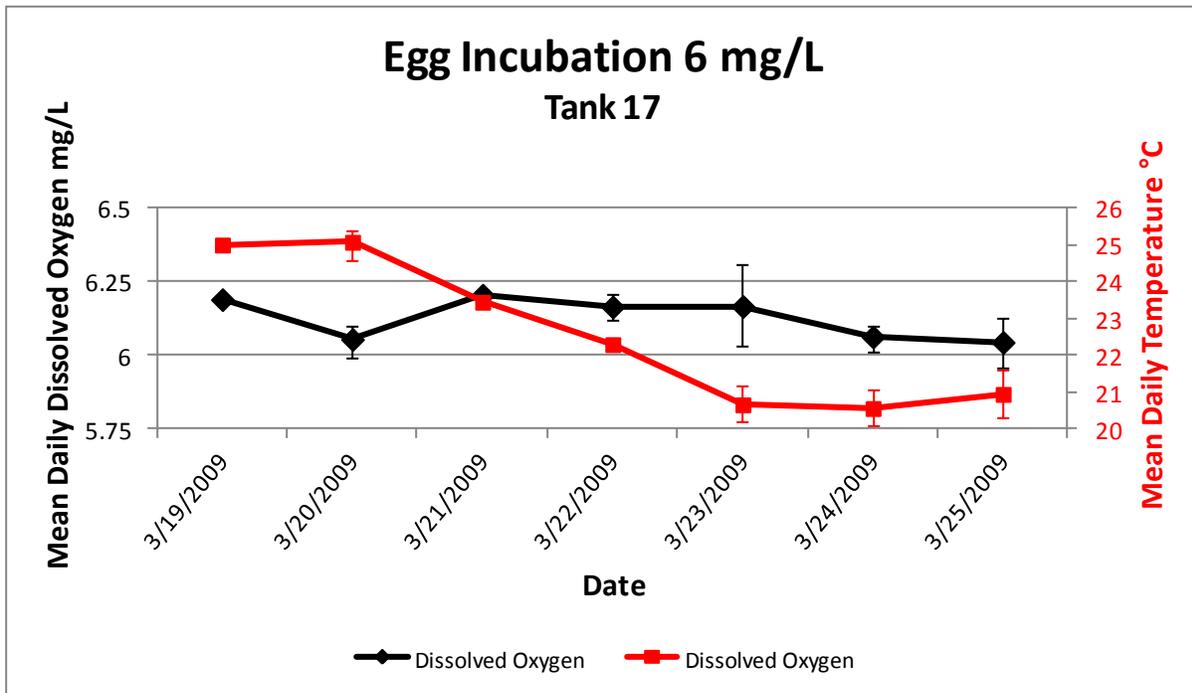


Figure 17.—Mean daily DO, mean daily temperature, and daily ranges (line projections) for 6-mg/L egg trial replicate (tank 17).

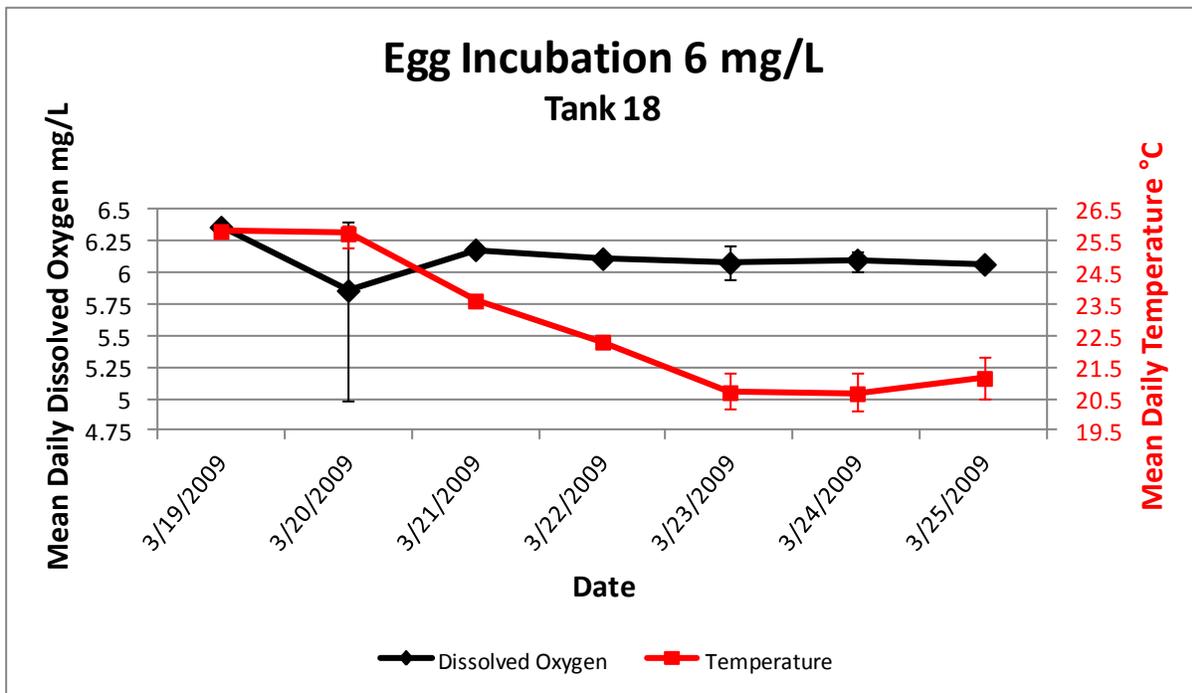


Figure 18.—Mean daily DO, mean daily temperature, and daily ranges (line projections) for 6-mg/L egg trial replicate (tank 18).

Dissolved Oxygen Tolerances for Egg and Larval Stages of Razorback Sucker

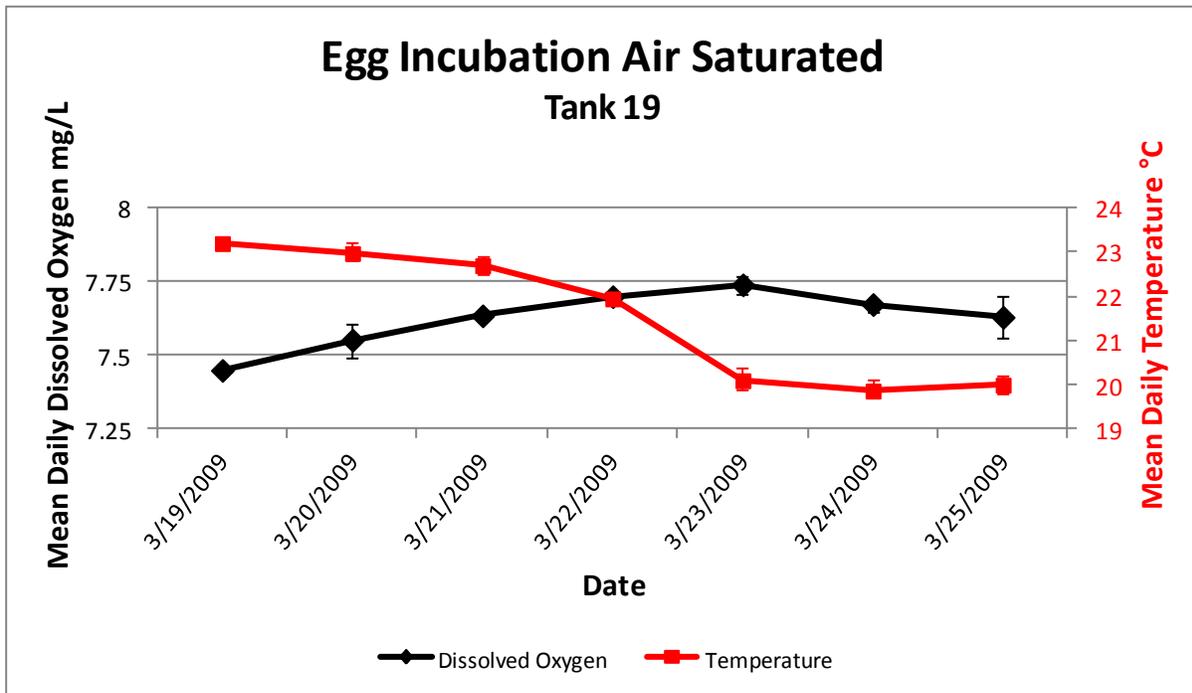


Figure 19.—Mean daily DO, mean daily temperature, and daily ranges (line projections) for air-saturated (8-mg/L) egg trial replicate (tank 19).

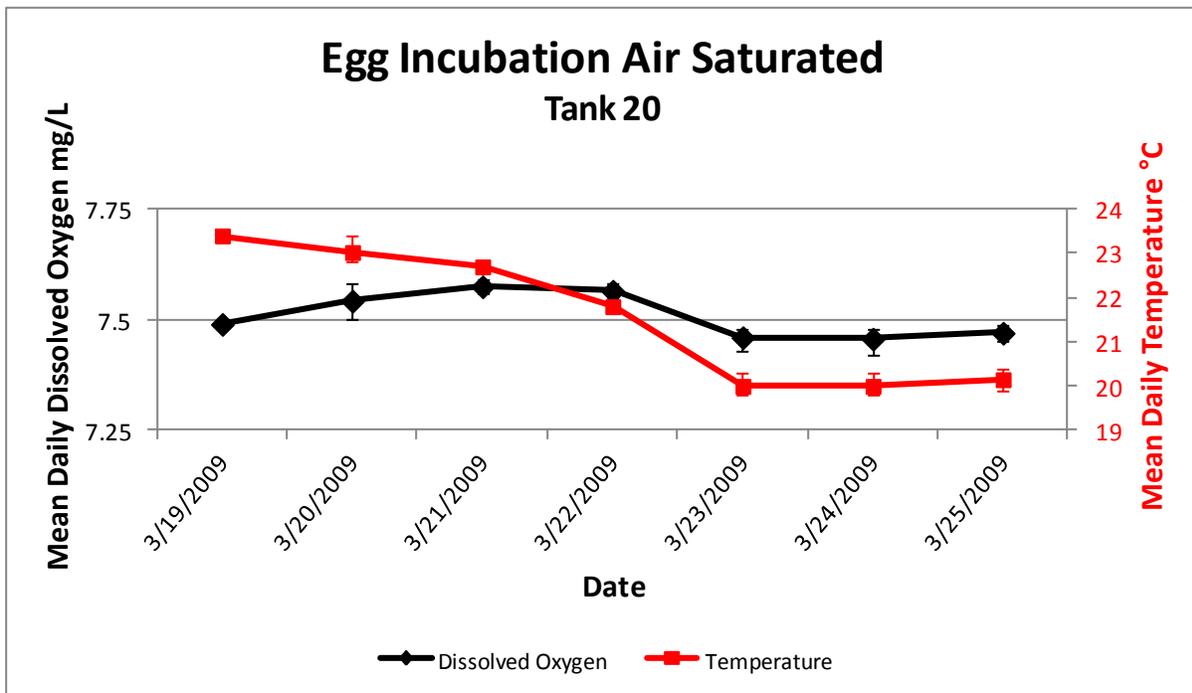


Figure 20.—Mean daily DO, mean daily temperature, and daily ranges (line projections) for air-saturated (8-mg/L) egg trial replicate (tank 20).

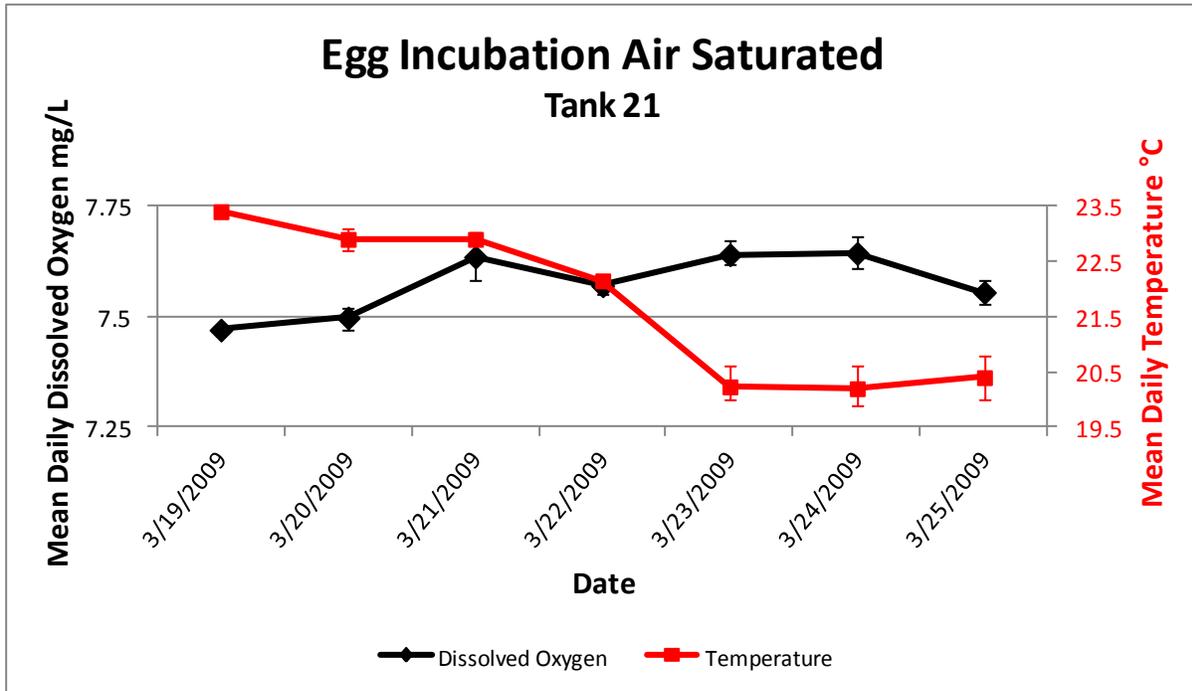


Figure 21.—Mean daily DO, mean daily temperature, and daily ranges (line projections) for air-saturated (8-mg/L) egg trial replicate (tank 21).

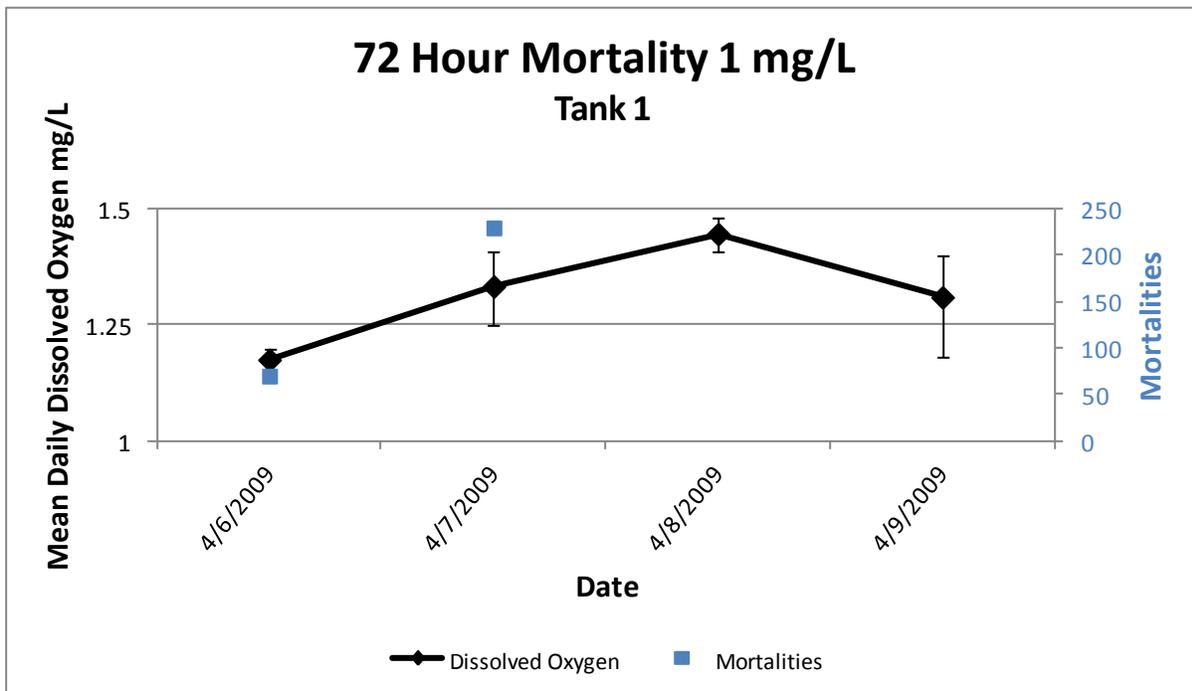


Figure 22.—Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 1).

Dissolved Oxygen Tolerances for Egg and Larval Stages of Razorback Sucker

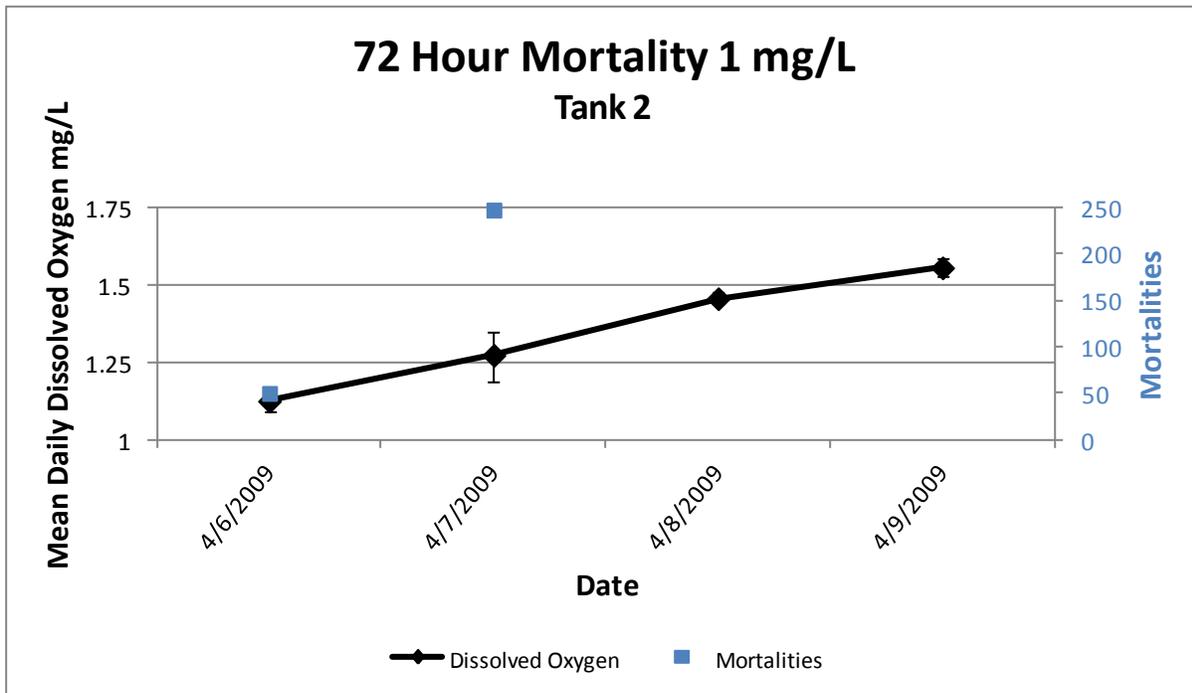


Figure 23.—Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 2).

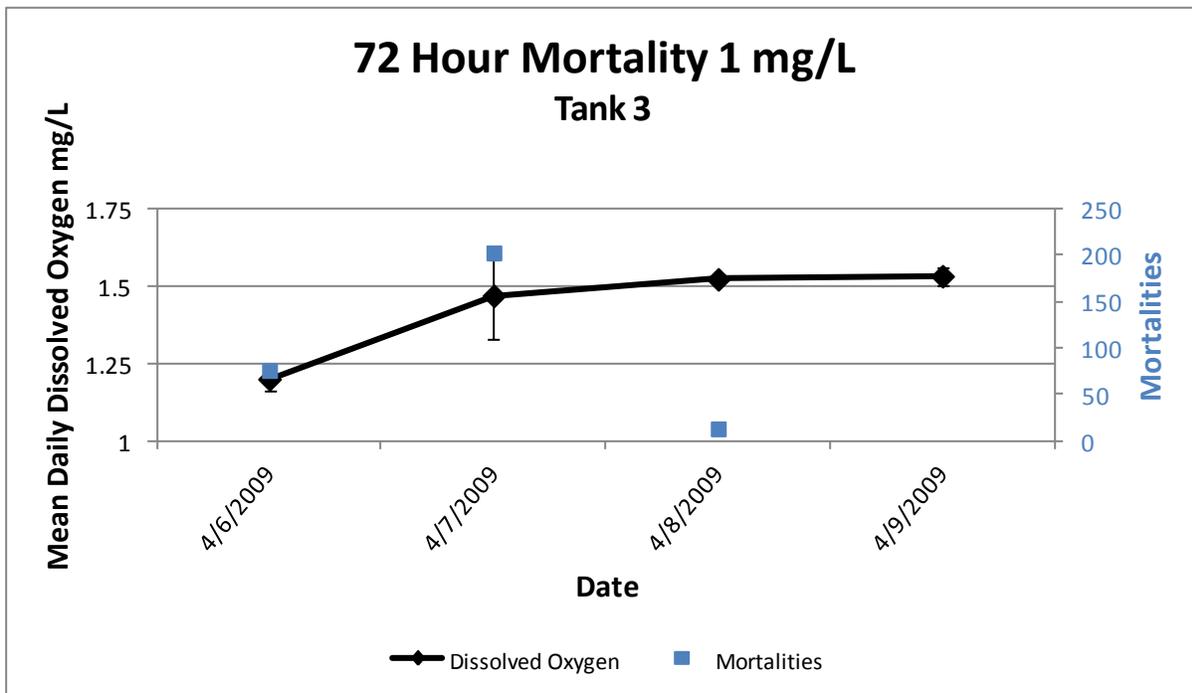


Figure 24.—Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 3).

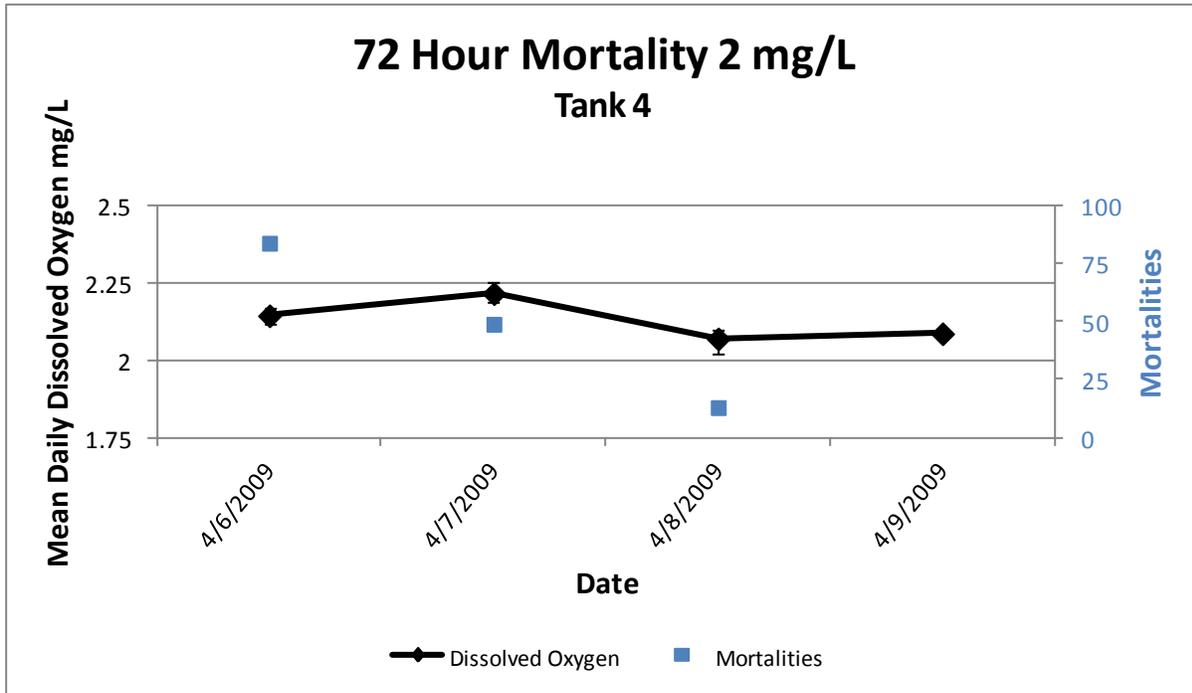


Figure 25.—Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 4).

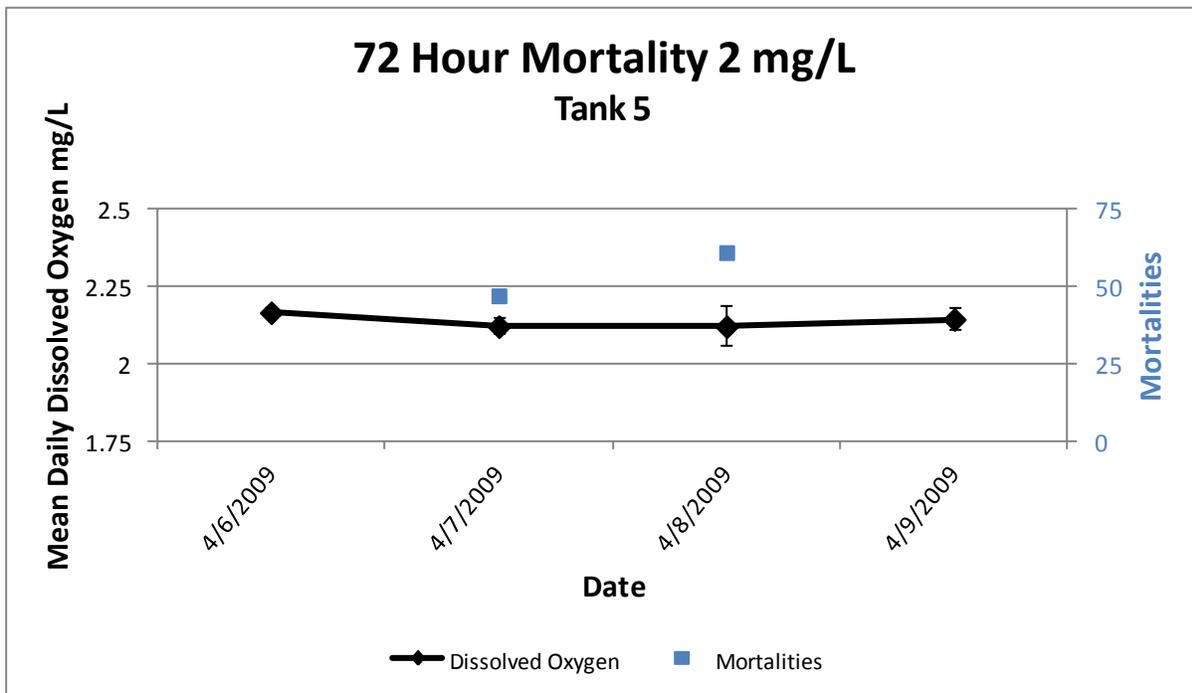


Figure 26.—Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 5).

Dissolved Oxygen Tolerances for Egg and Larval Stages of Razorback Sucker

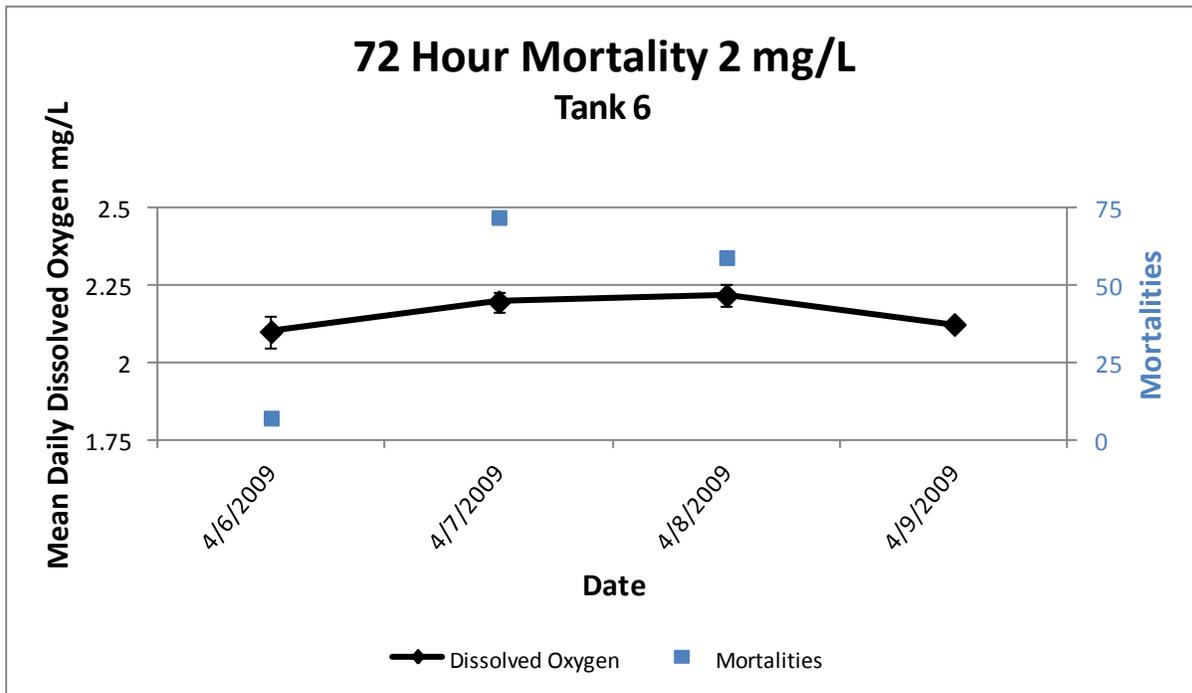


Figure 27.—Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 6).

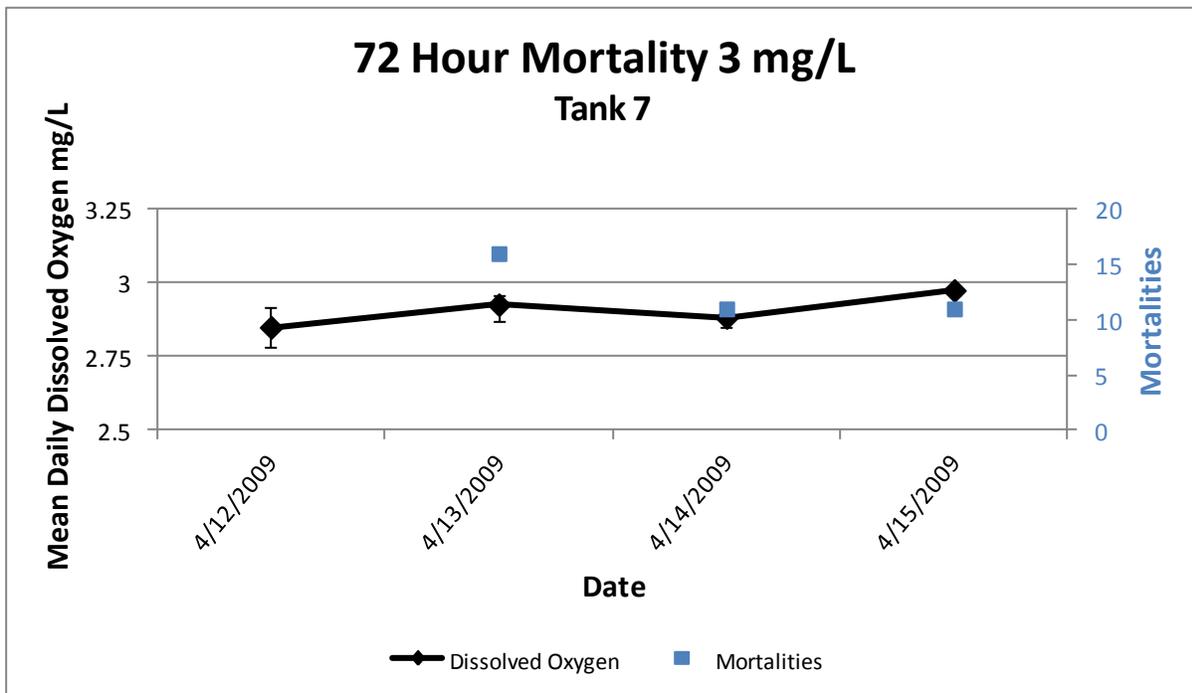


Figure 28.—Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 7).

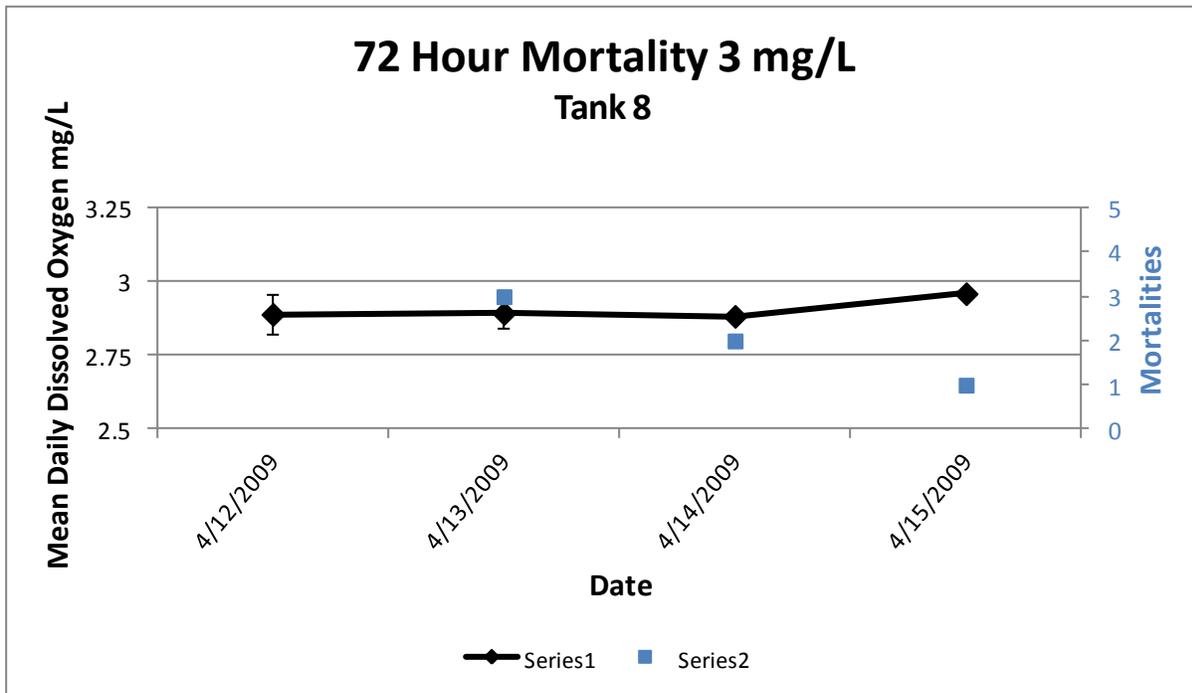


Figure 29.—Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 8).

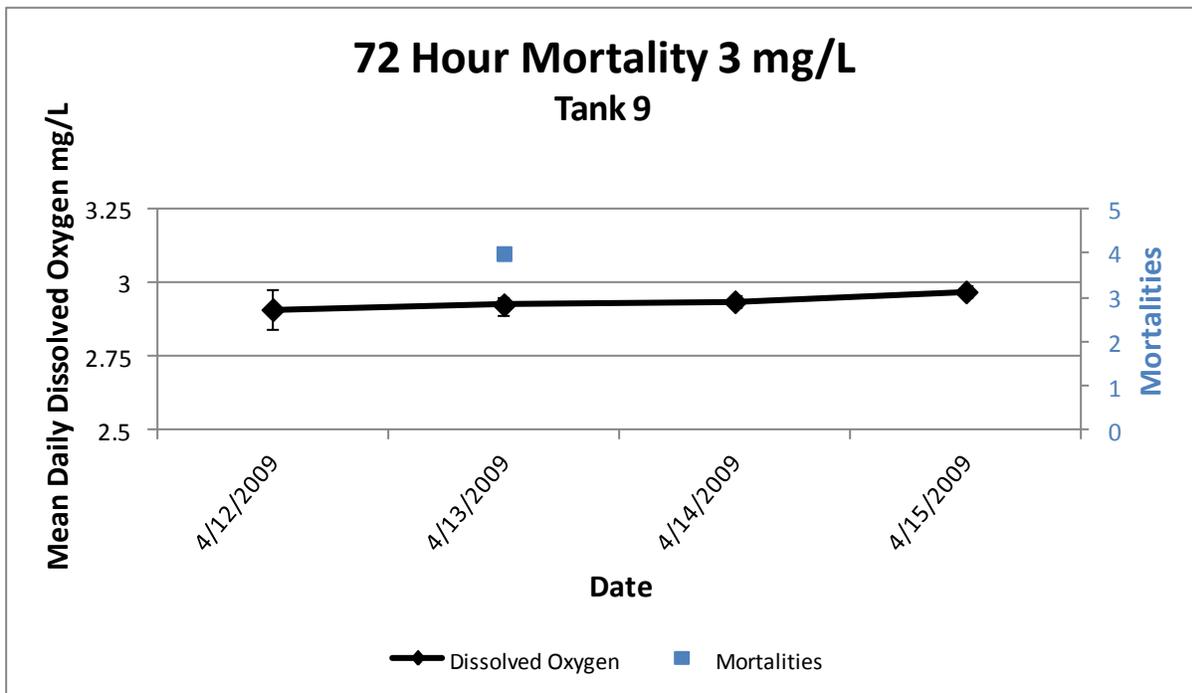


Figure 30.—Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 9).

Dissolved Oxygen Tolerances for Egg and Larval Stages of Razorback Sucker

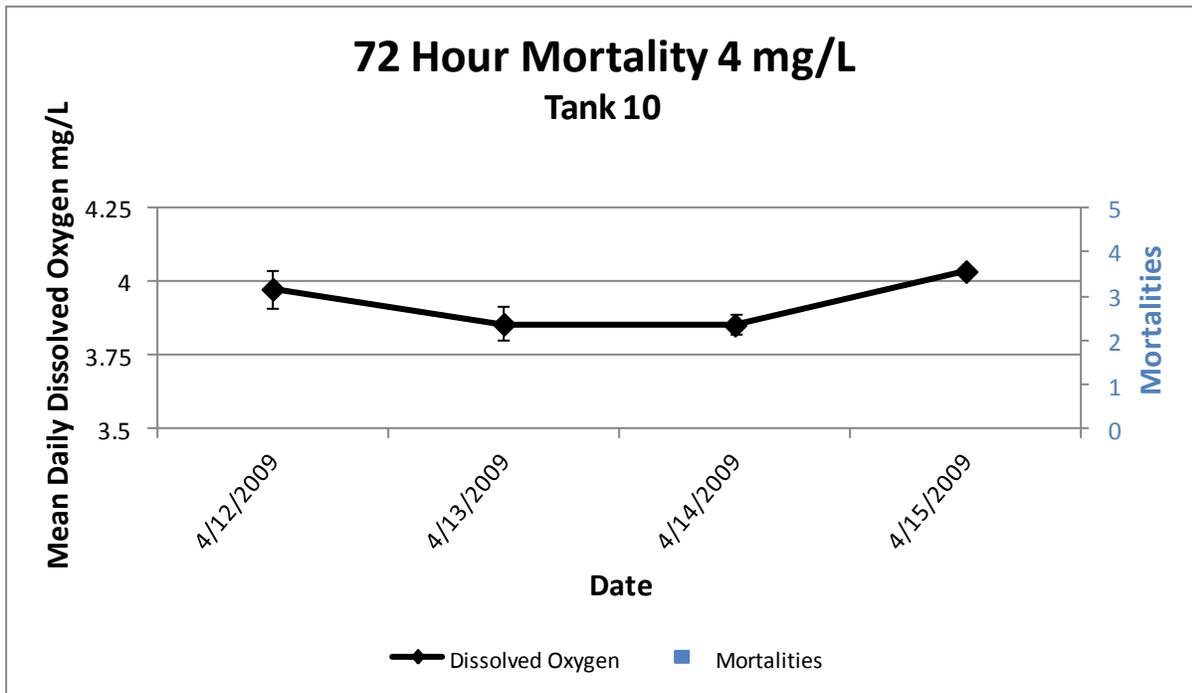


Figure 31.—Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 10).

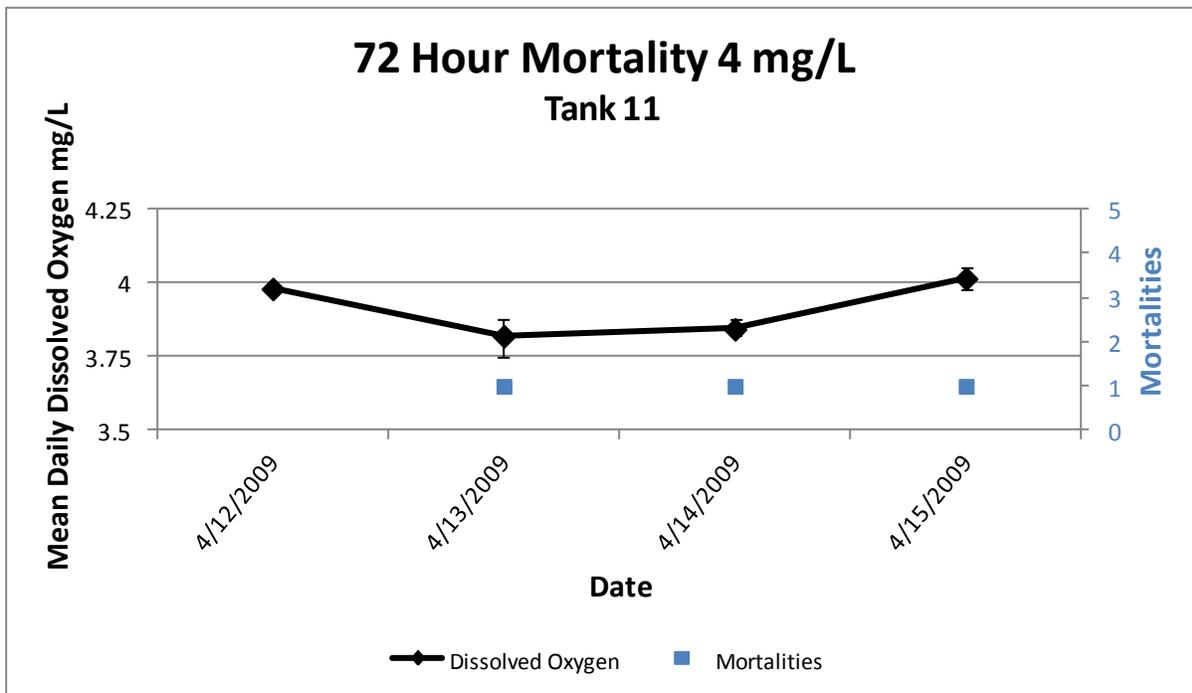


Figure 32.—Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 11).

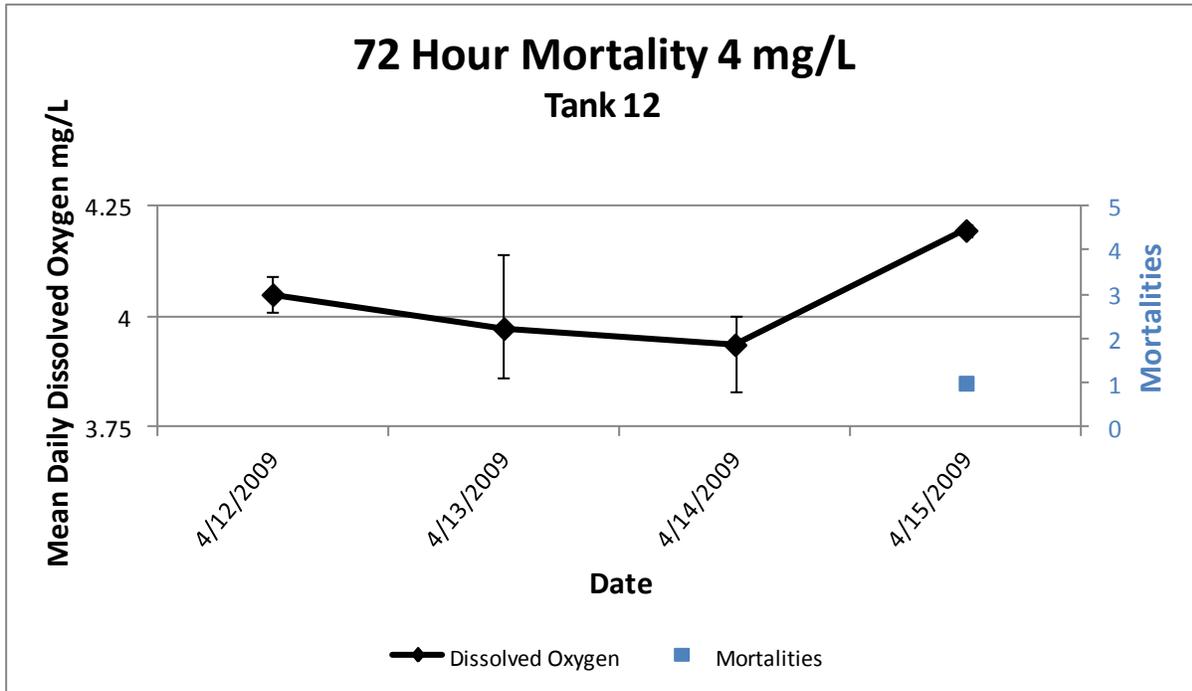


Figure 33.—Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 12).

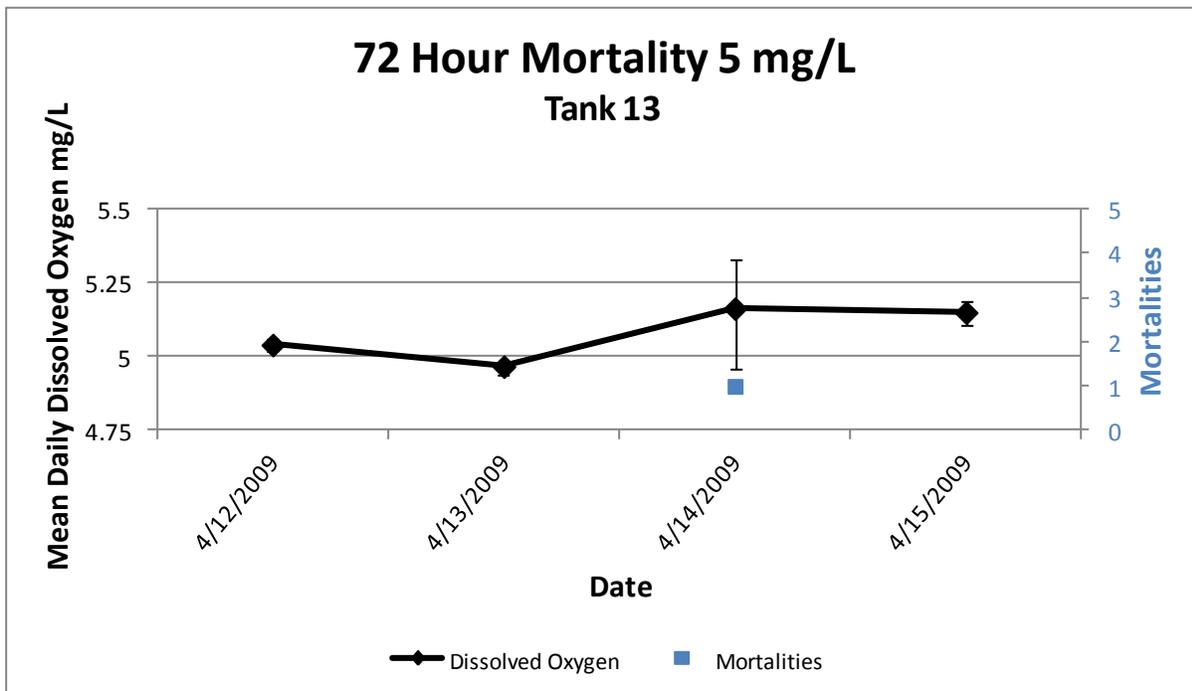


Figure 34.—Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 13).

Dissolved Oxygen Tolerances for Egg and Larval Stages of Razorback Sucker

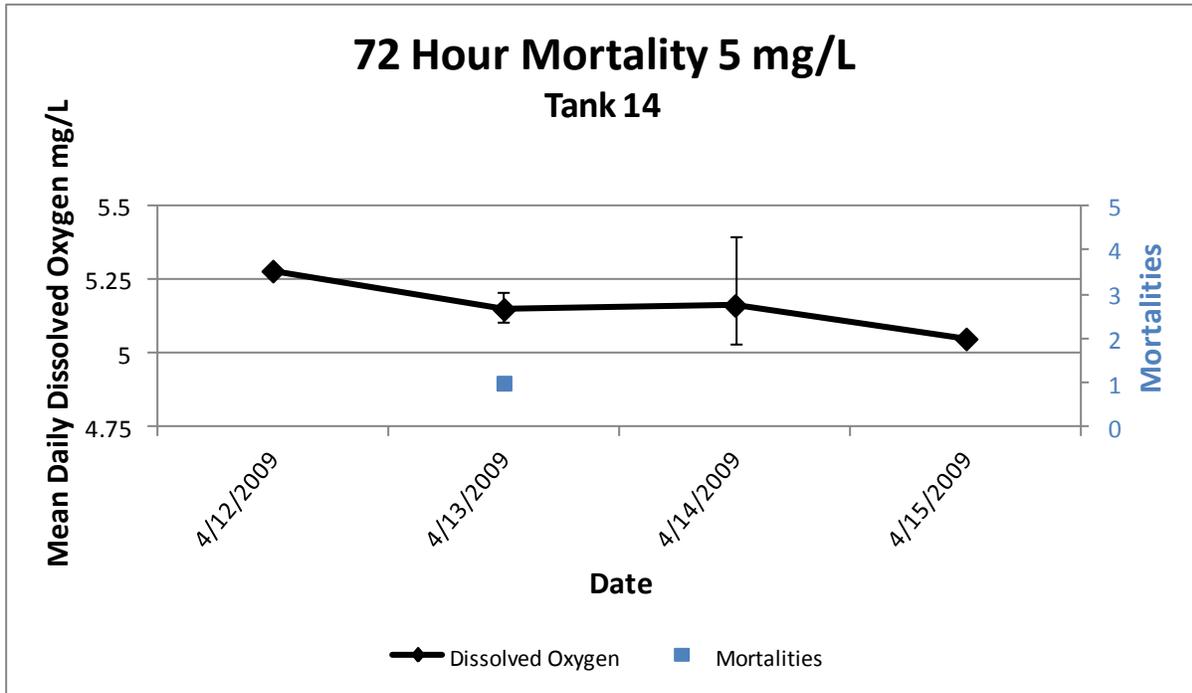


Figure 35.—Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 14).

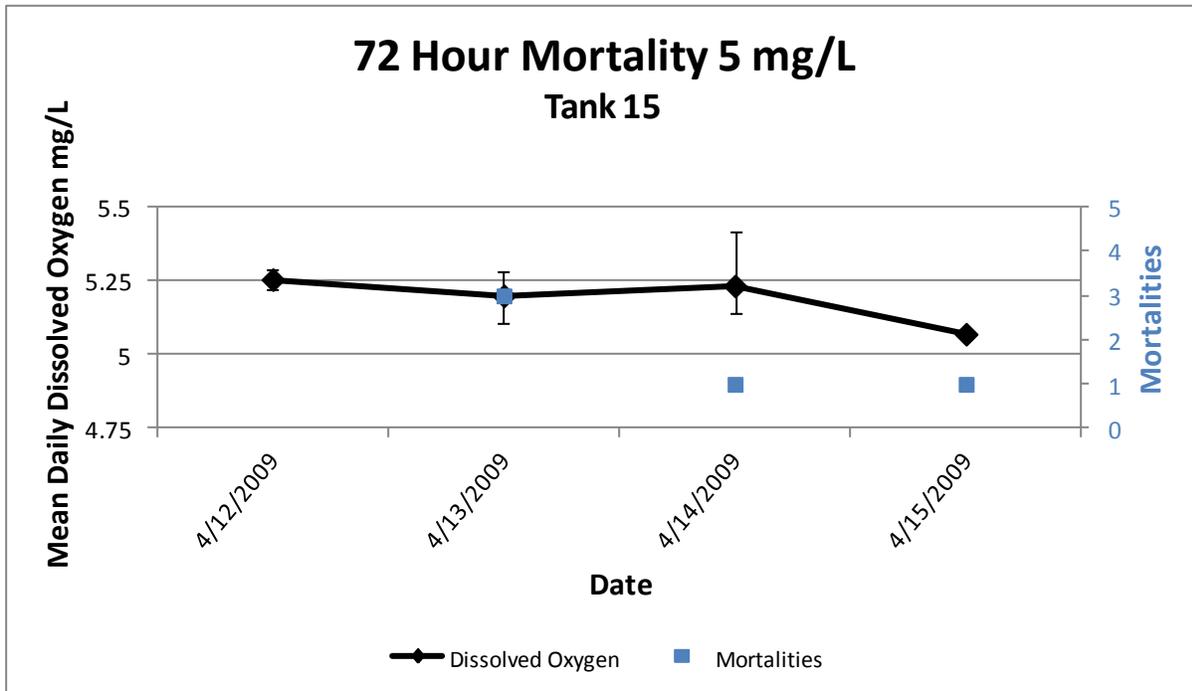


Figure 36.—Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 15).

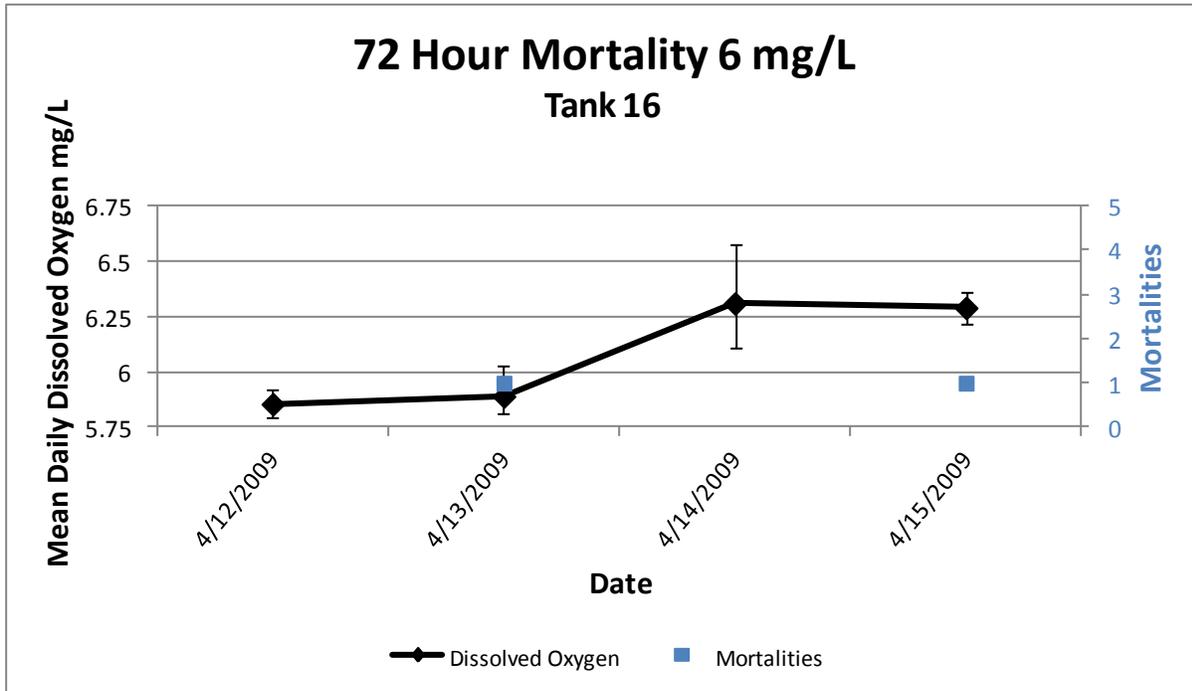


Figure 37.—Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 16).

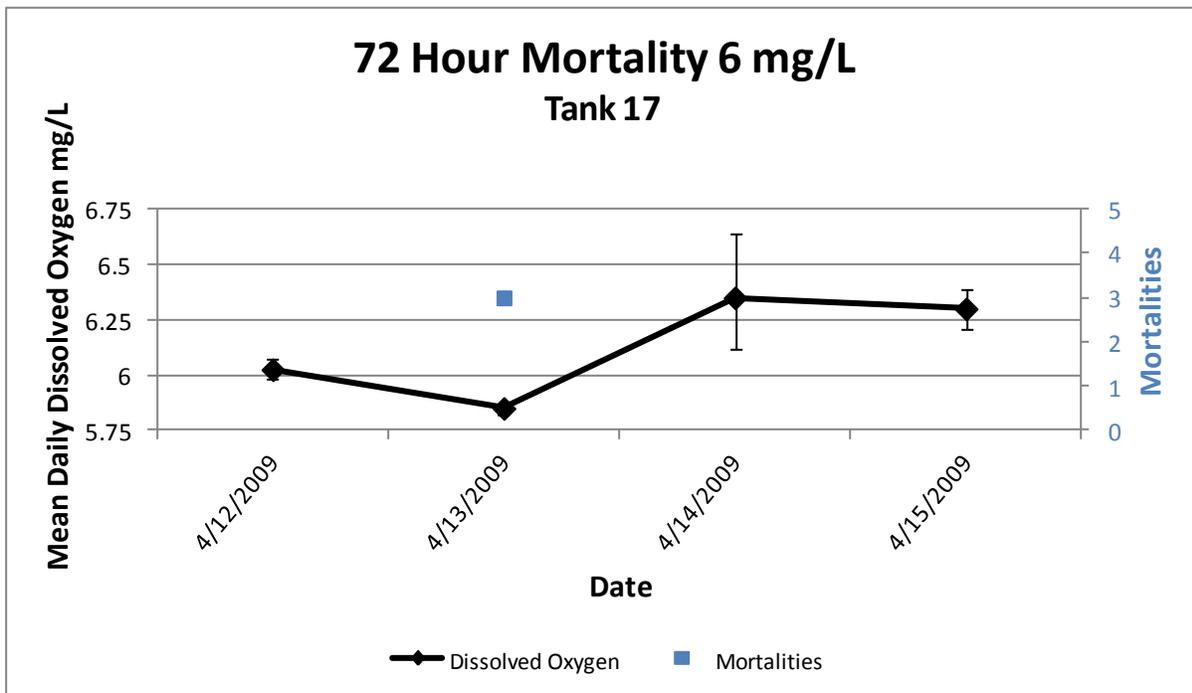


Figure 38.—Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 17).

Dissolved Oxygen Tolerances for Egg and Larval Stages of Razorback Sucker

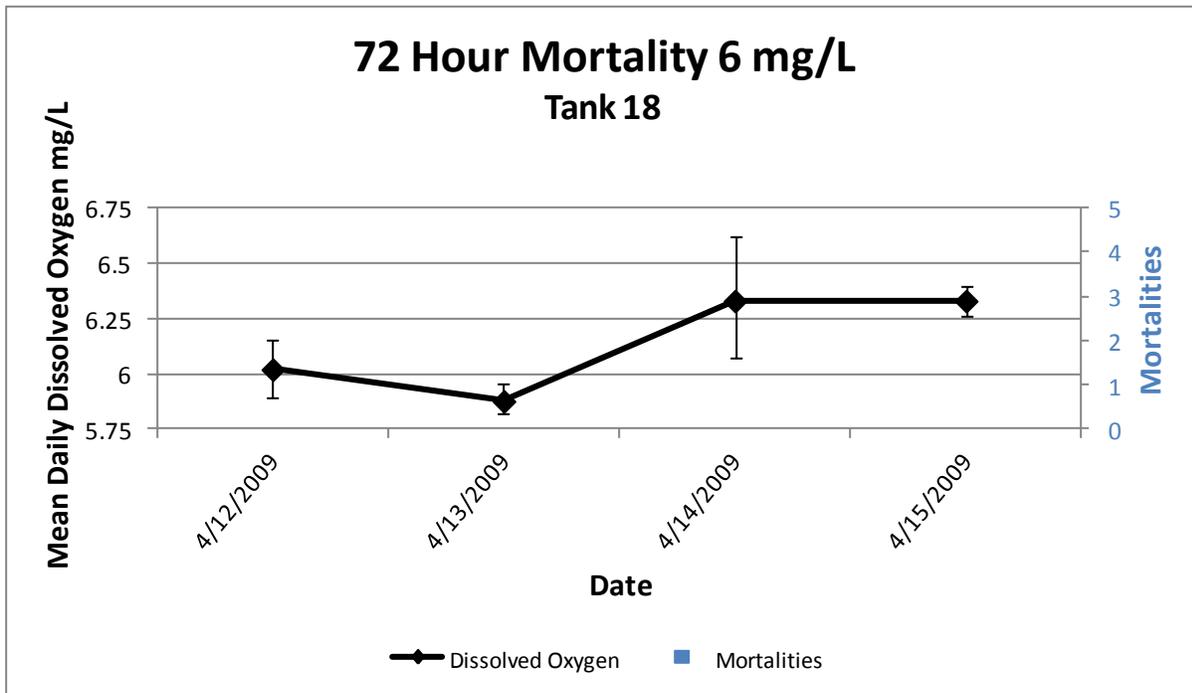


Figure 39.—Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 18).

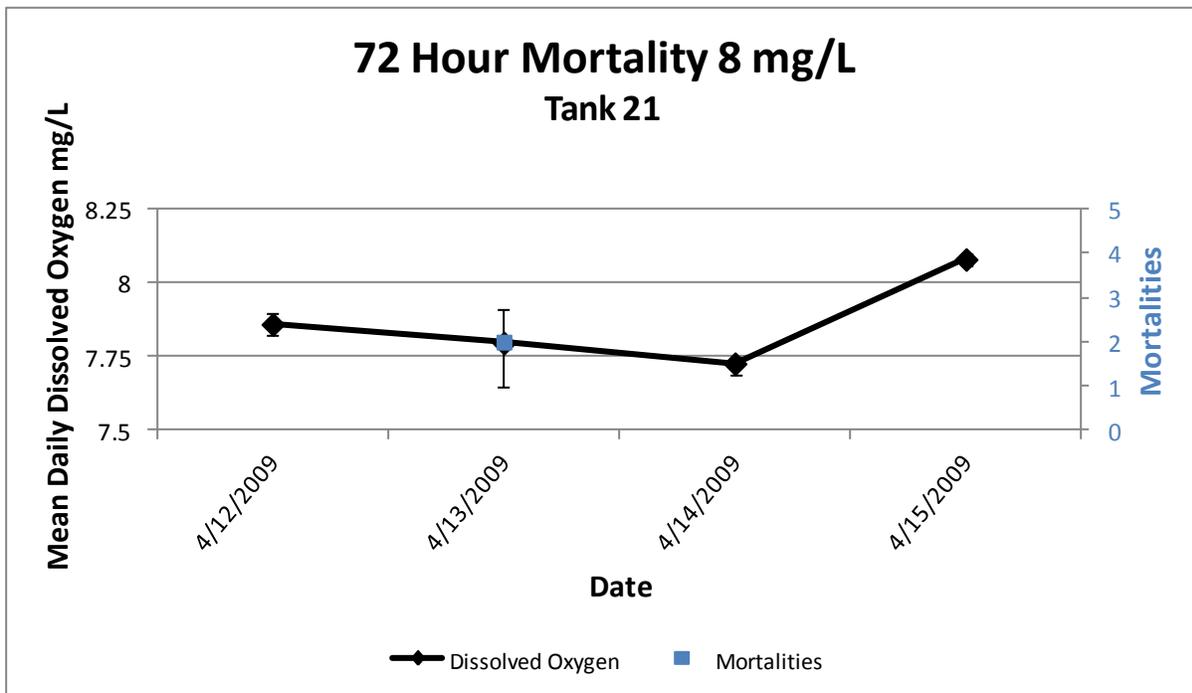


Figure 40.—Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 21).

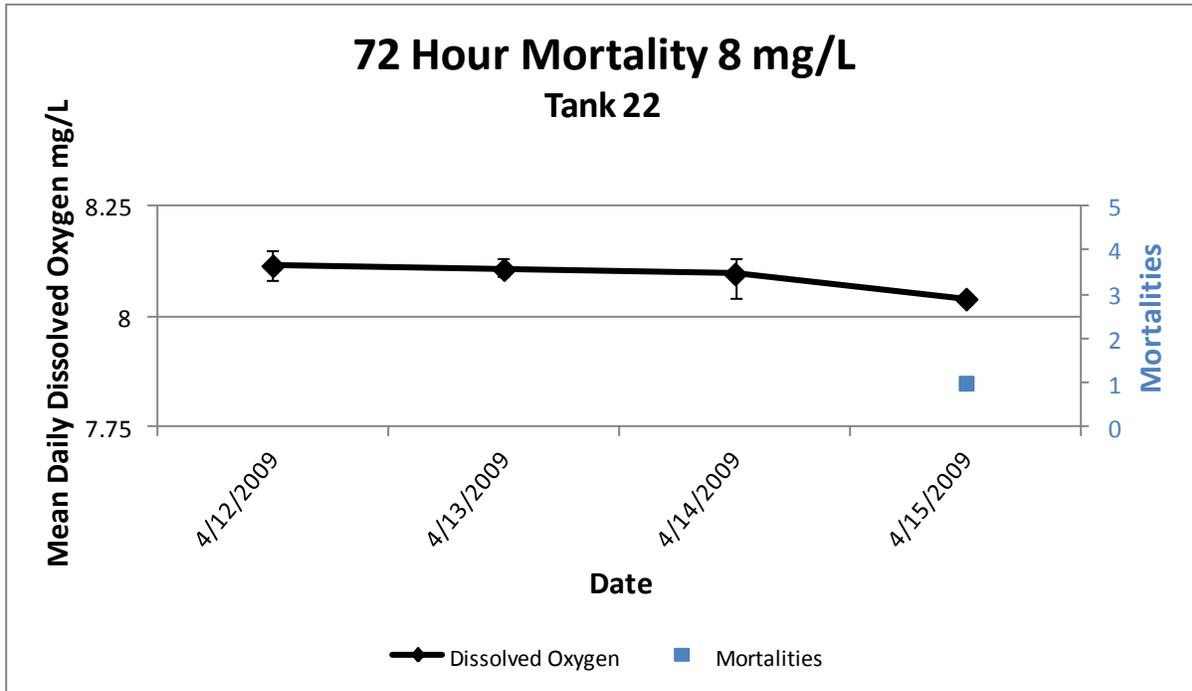


Figure 41.—Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 22).

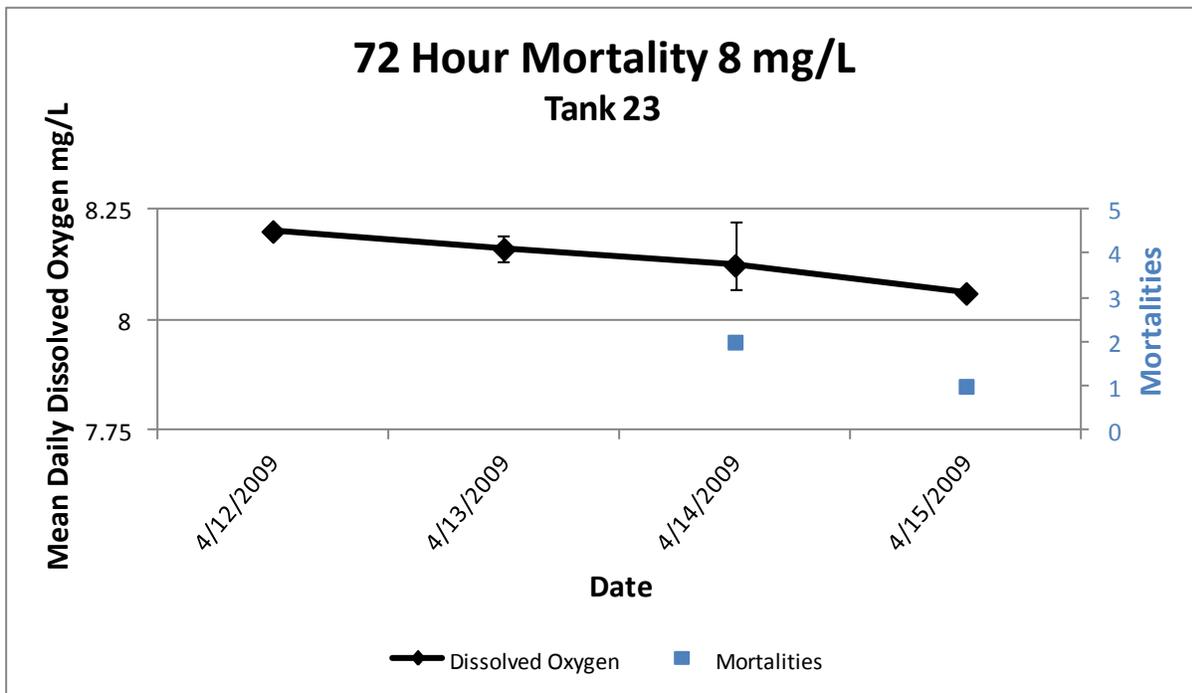


Figure 42.—Mean daily DO and observed mortality for 72-hour larval trials. Line projections represent daily DO ranges (tank 23).

Dissolved Oxygen Tolerances for Egg and Larval Stages of Razorback Sucker

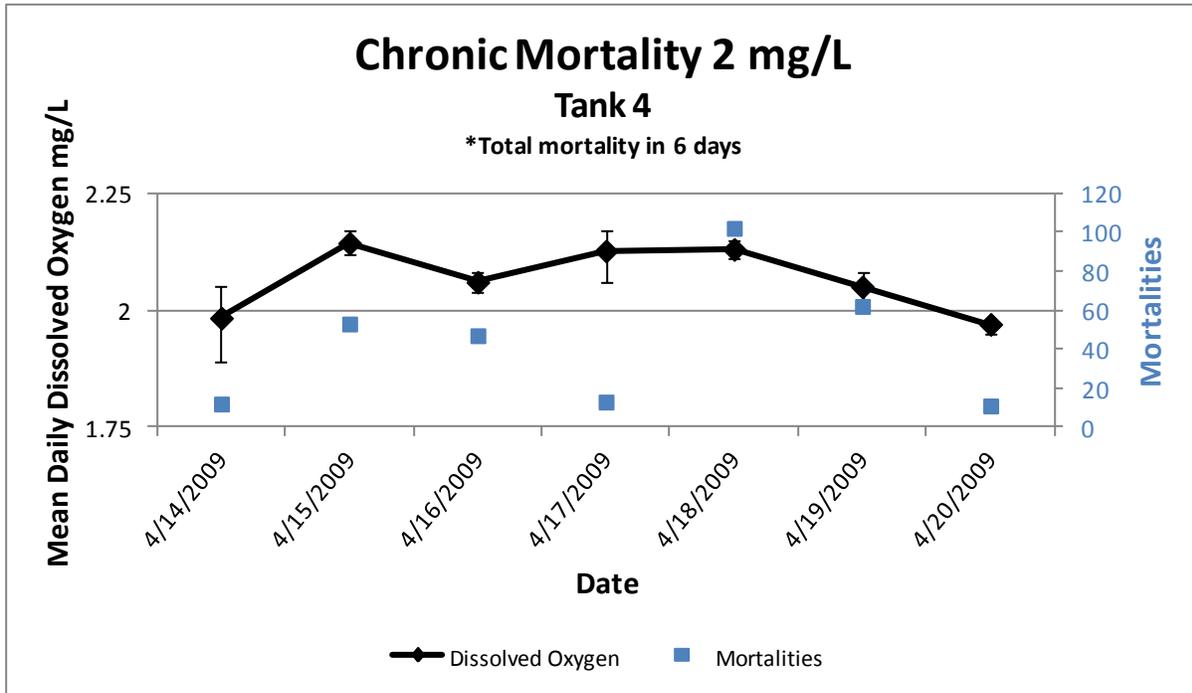


Figure 43.—Mean daily DO and observed mortality for 20-day (chronic) larval trials. Line projections represent daily DO ranges (tank 4).

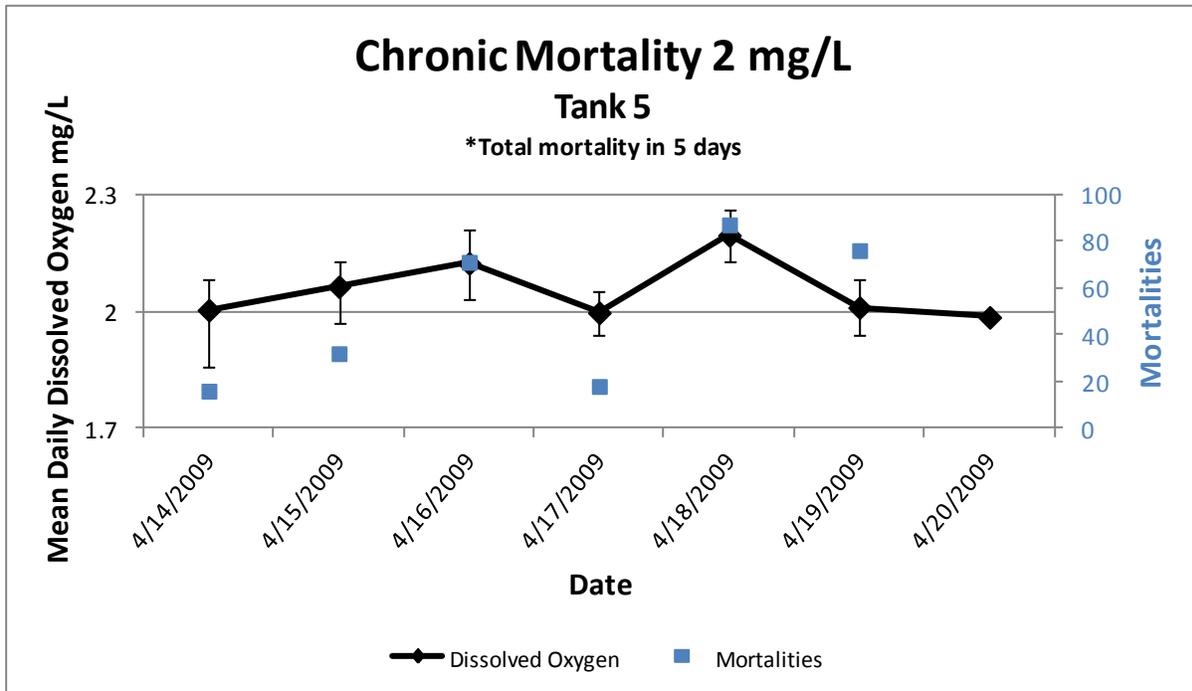


Figure 44.—Mean daily DO and observed mortality for 20-day (chronic) larval trials. Line projections represent daily DO ranges (tank 5).

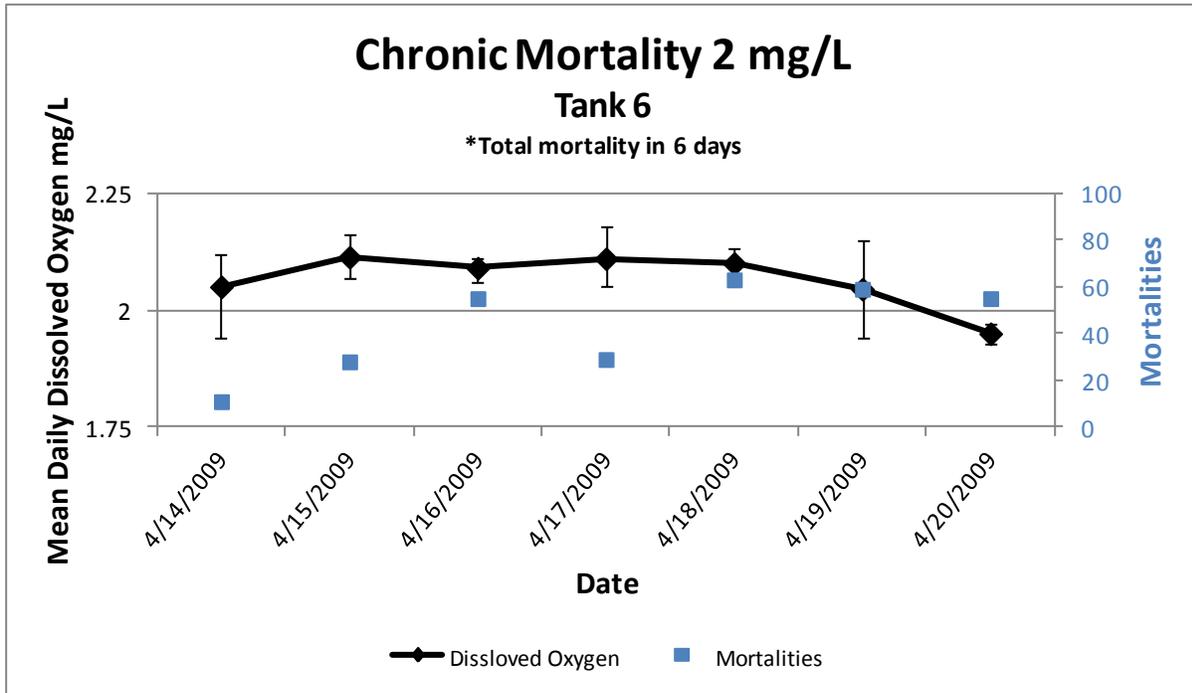


Figure 45.—Mean daily DO and observed mortality for 20-day (chronic) larval trials. Line projections represent daily DO ranges (tank 6).

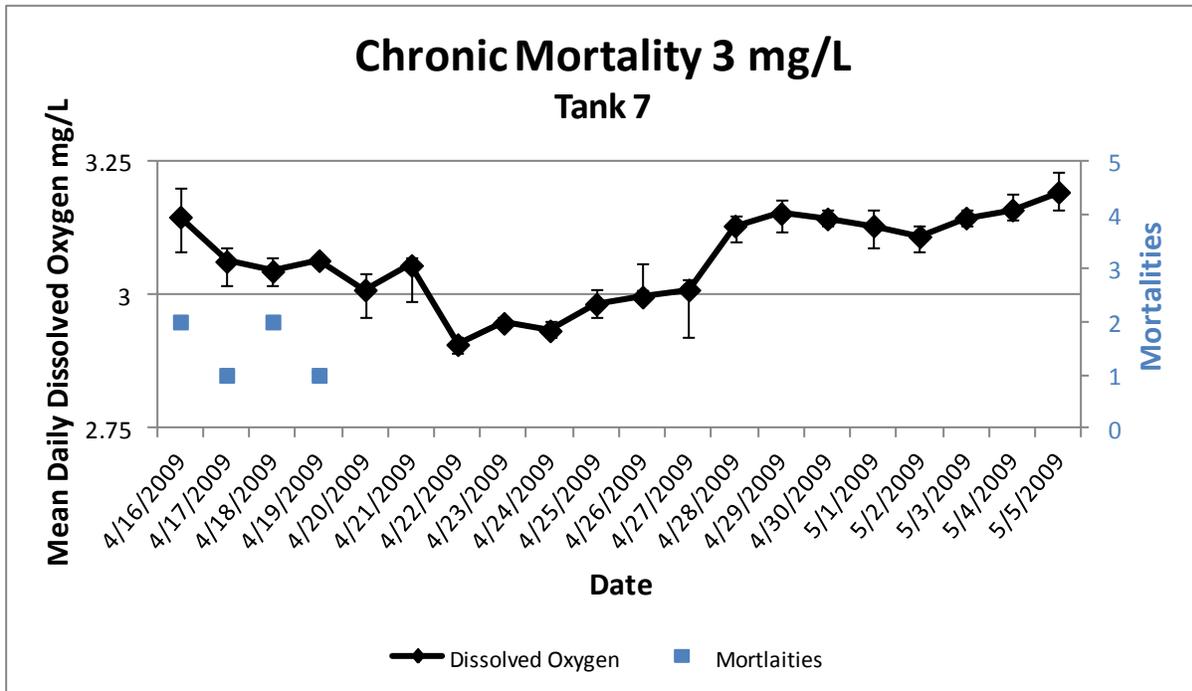


Figure 46.—Mean daily DO and observed mortality for 20-day (chronic) larval trials. Line projections represent daily DO ranges (tank 7).

Dissolved Oxygen Tolerances for Egg and Larval Stages of Razorback Sucker

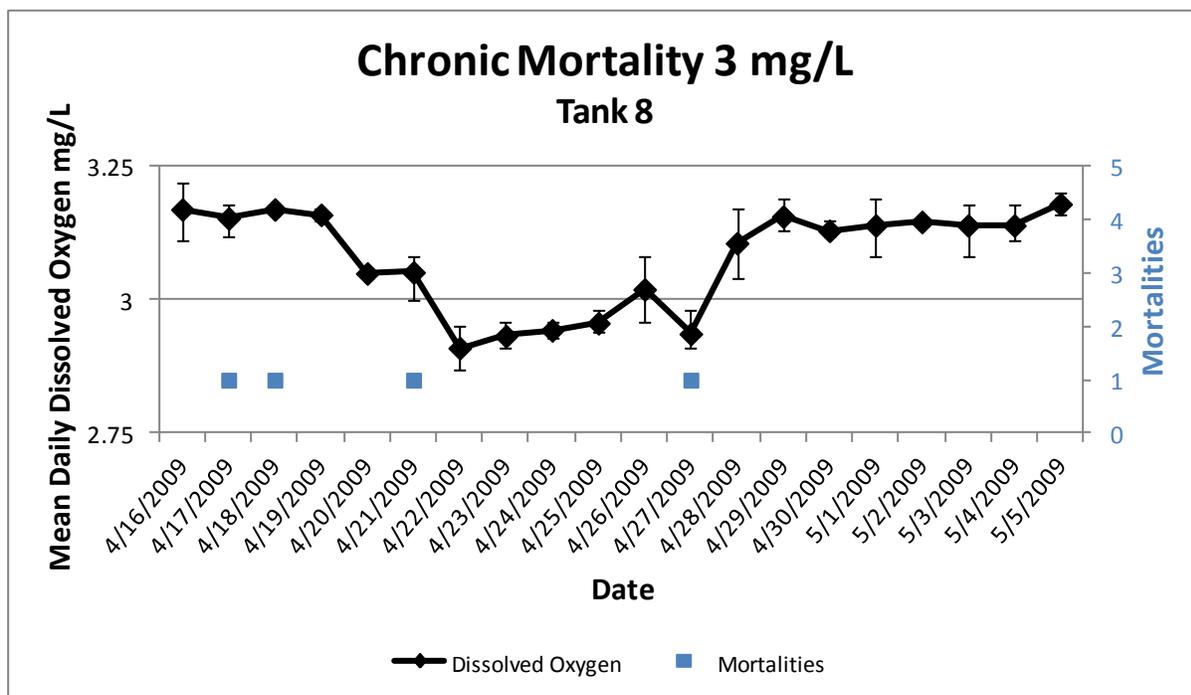


Figure 47.—Mean daily DO and observed mortality for 20-day (chronic) larval trials. Line projections represent daily DO ranges (tank 8).

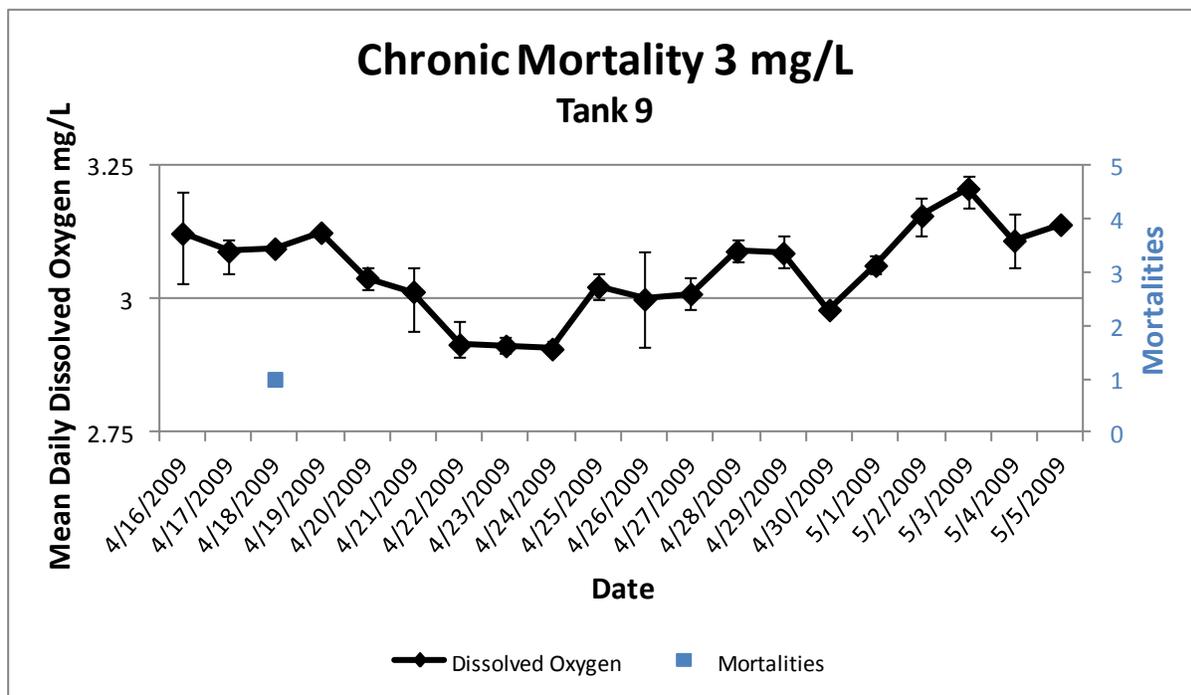


Figure 48.—Mean daily DO and observed mortality for 20-day (chronic) larval trials. Line projections represent daily DO ranges (tank 9).

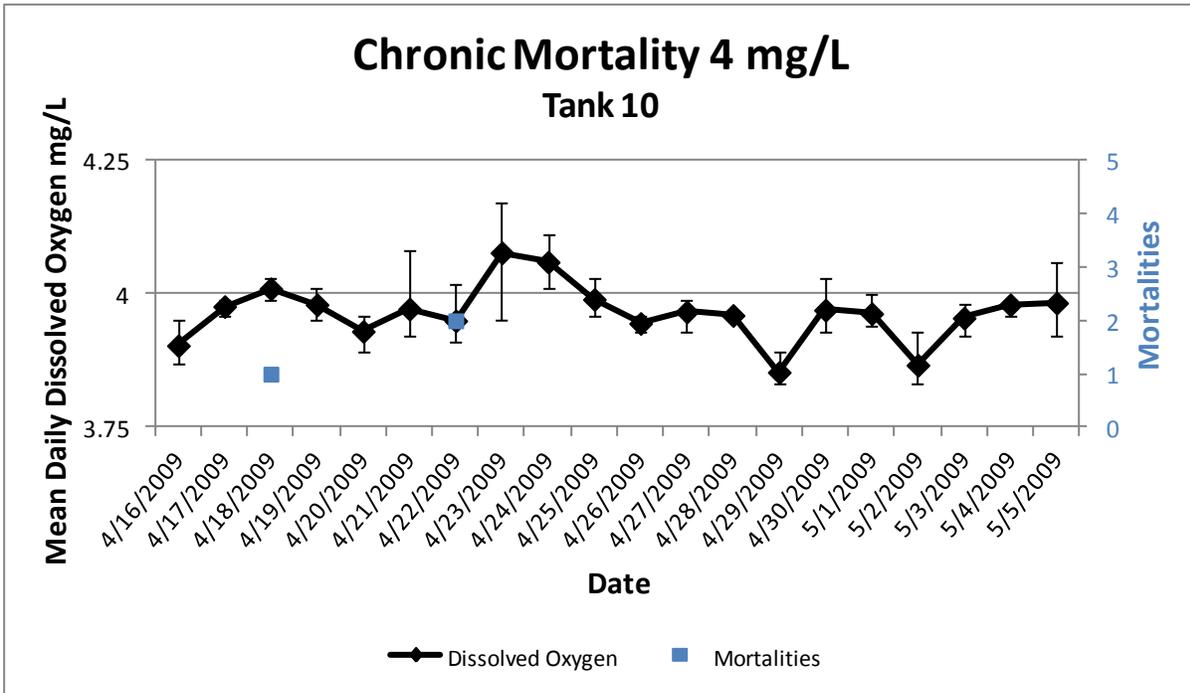


Figure 49.—Mean daily DO and observed mortality for 20-day (chronic) larval trials. Line projections represent daily DO ranges (tank 10).

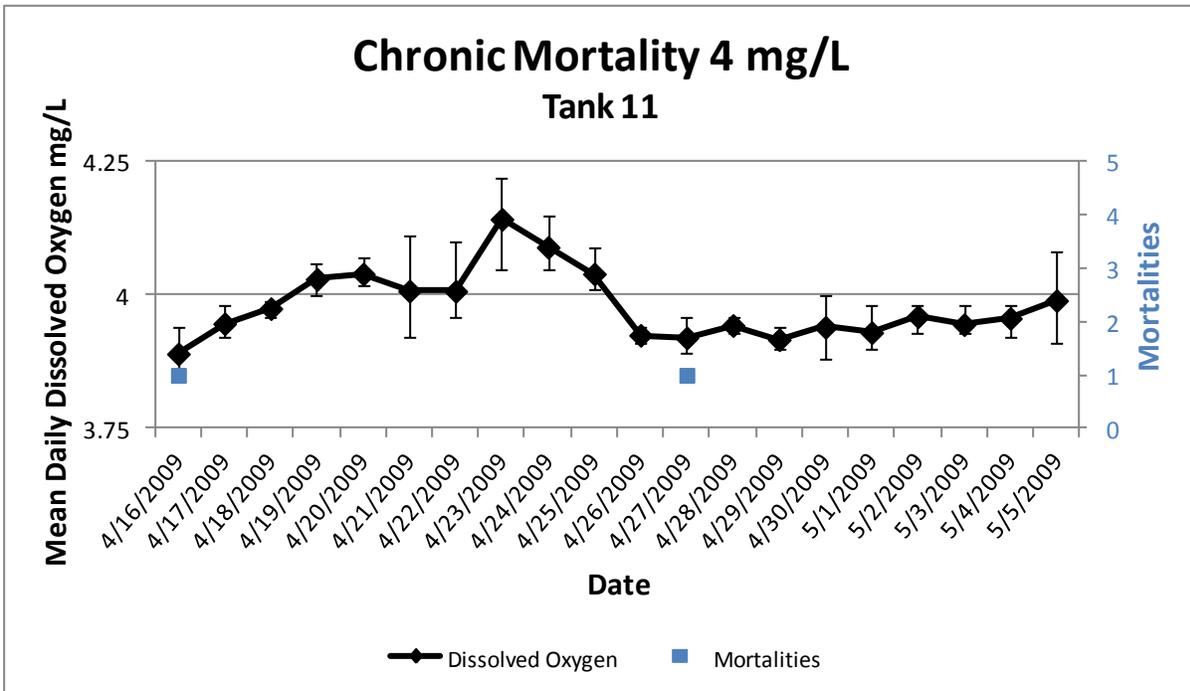


Figure 50.—Mean daily DO and observed mortality for 20-day (chronic) larval trials. Line projections represent daily DO ranges (tank 11).

Dissolved Oxygen Tolerances for Egg and Larval Stages of Razorback Sucker

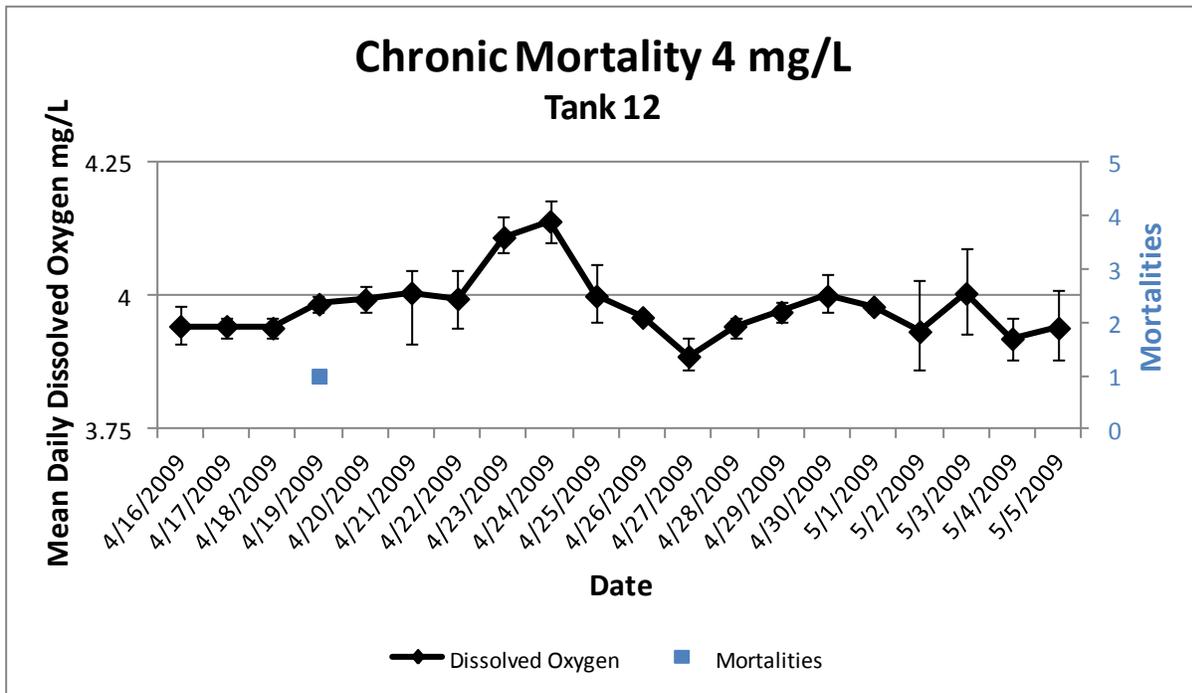


Figure 51.—Mean daily DO and observed mortality for 20-day (chronic) larval trials. Line projections represent daily DO ranges (tank 12).

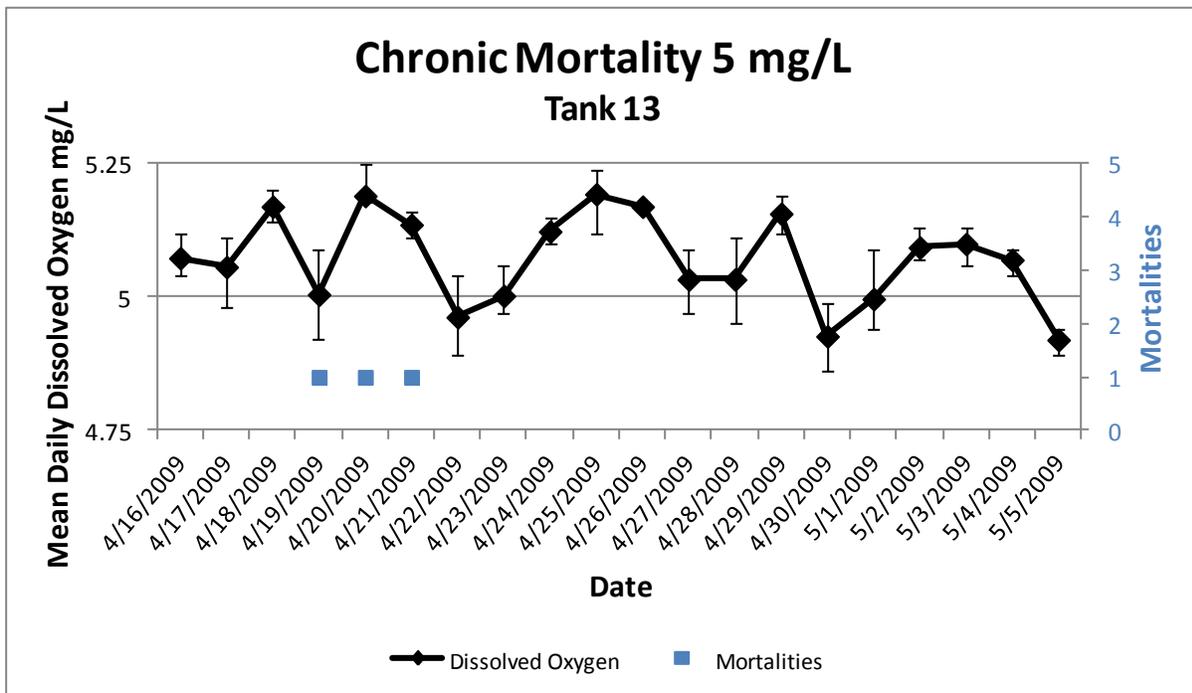


Figure 52.—Mean daily DO and observed mortality for 20-day (chronic) larval trials. Line projections represent daily DO ranges (tank 13).

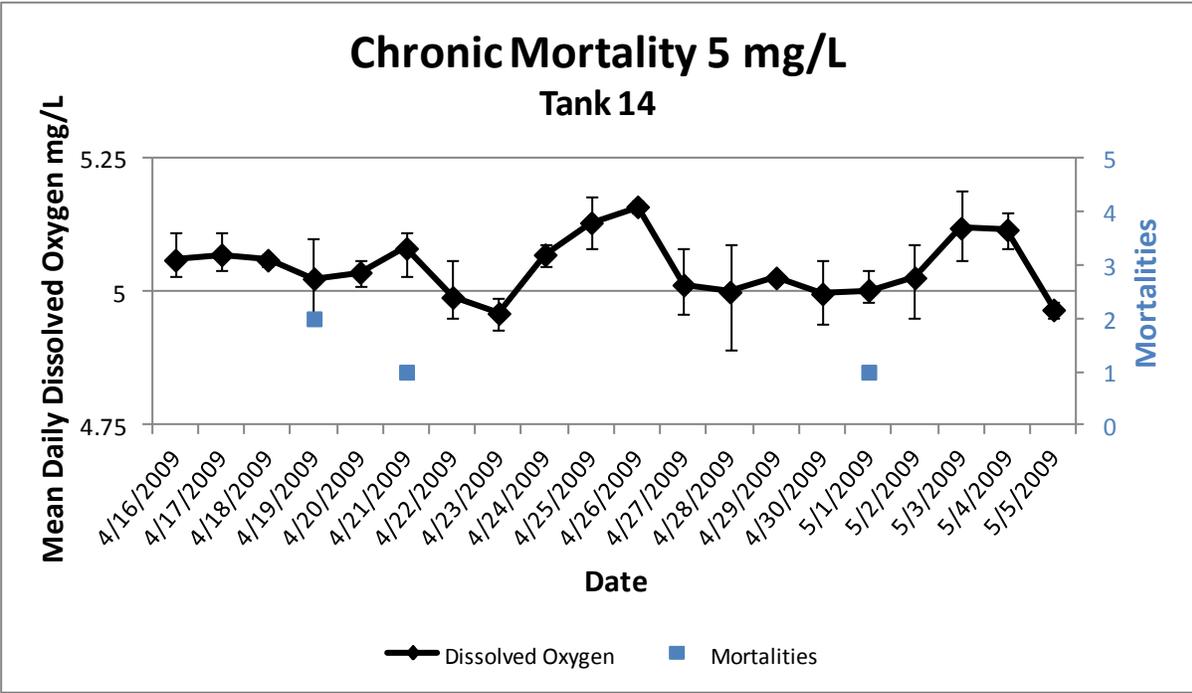


Figure 53.—Mean daily DO and observed mortality for 20-day (chronic) larval trials. Line projections represent daily DO ranges (tank 14).

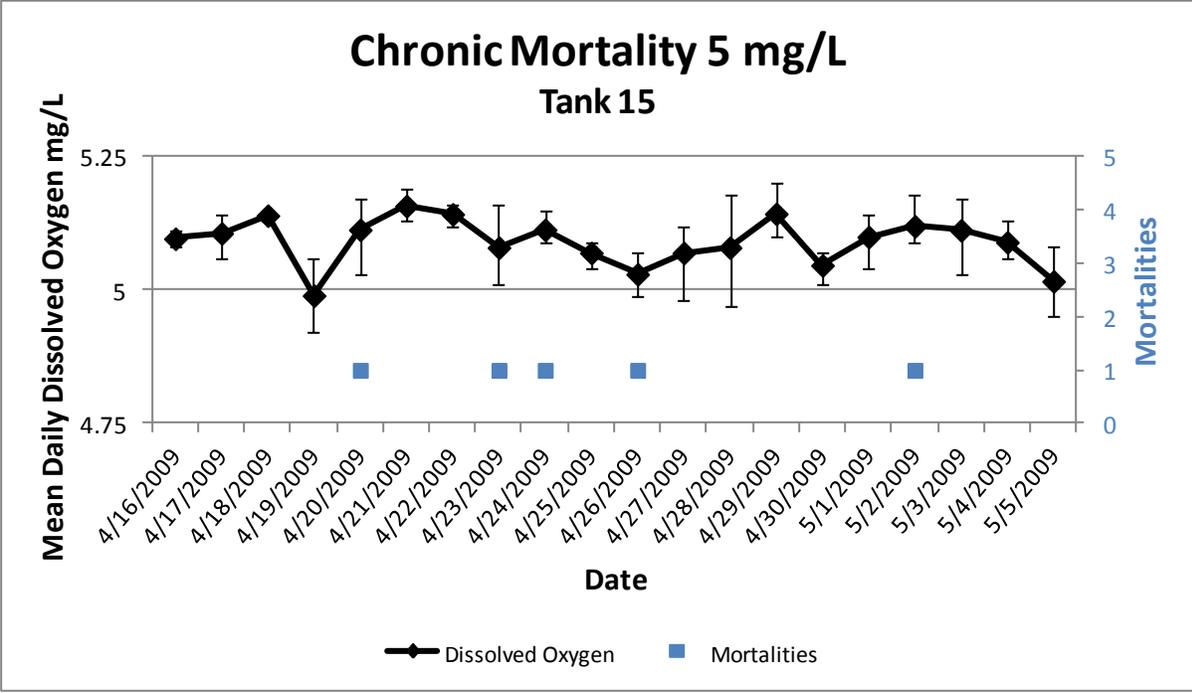


Figure 54.—Mean daily DO and observed mortality for 20-day (chronic) larval trials. Line projections represent daily DO ranges (tank 15).

Dissolved Oxygen Tolerances for Egg and Larval Stages of Razorback Sucker

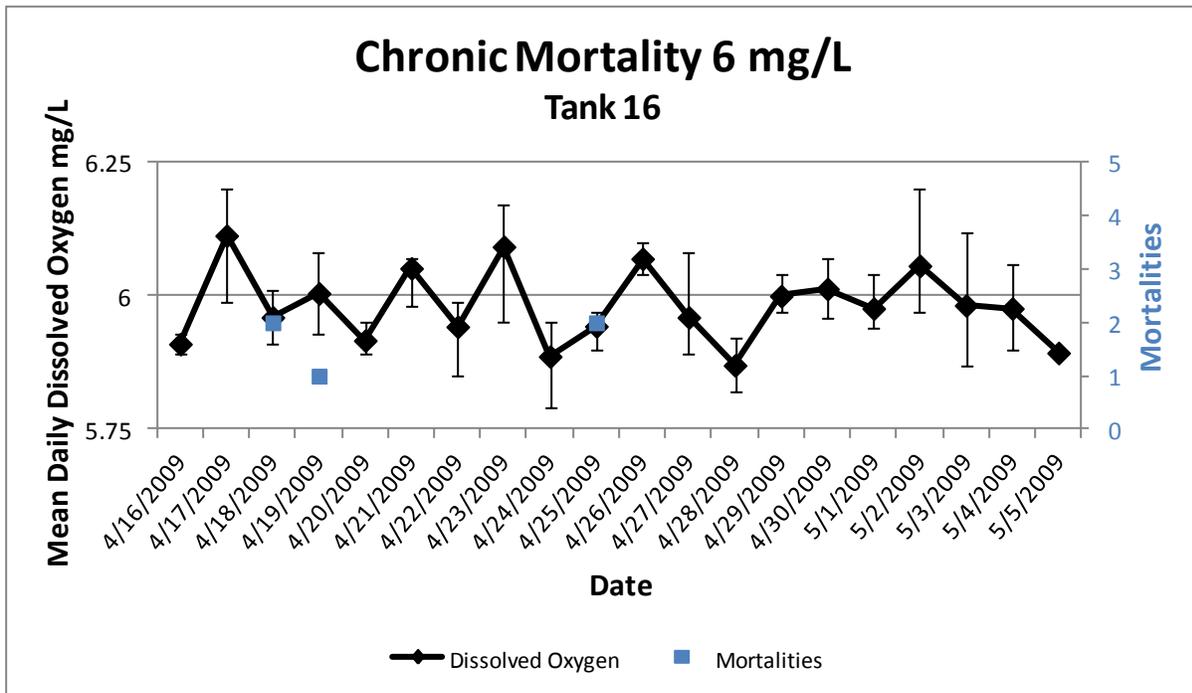


Figure 55.—Mean daily DO and observed mortality for 20-day (chronic) larval trials. Line projections represent daily DO ranges (tank 16).

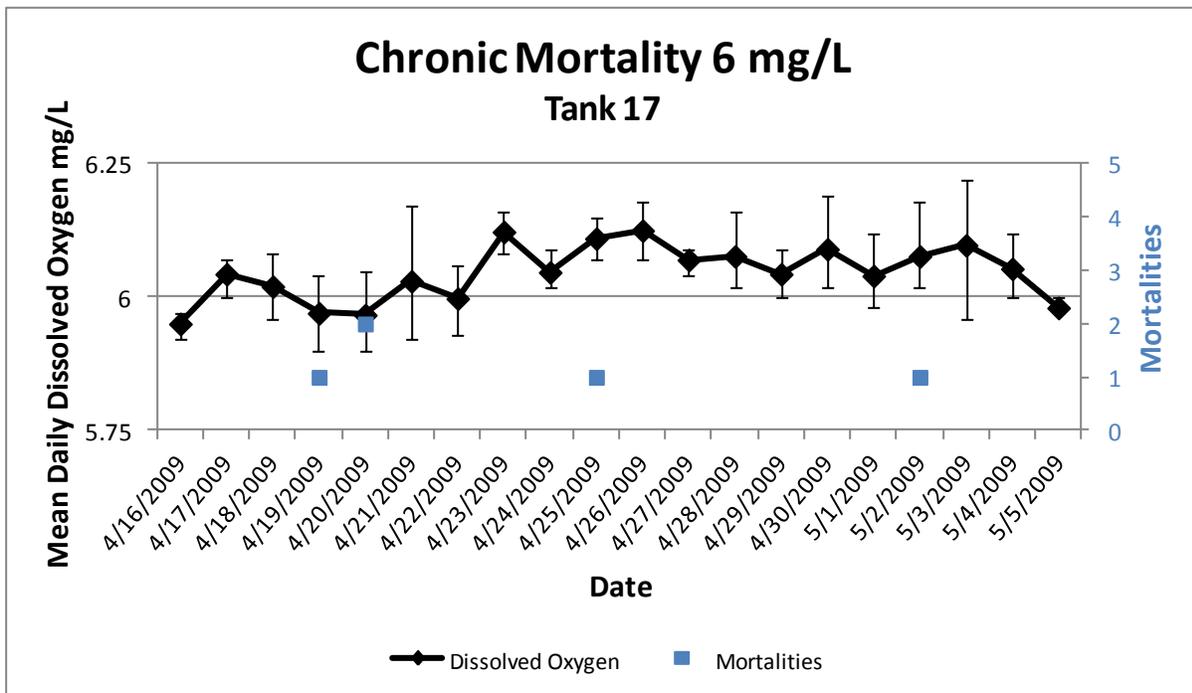


Figure 56.—Mean daily DO and observed mortality for 20-day (chronic) larval trials. Line projections represent daily DO ranges (tank 17).

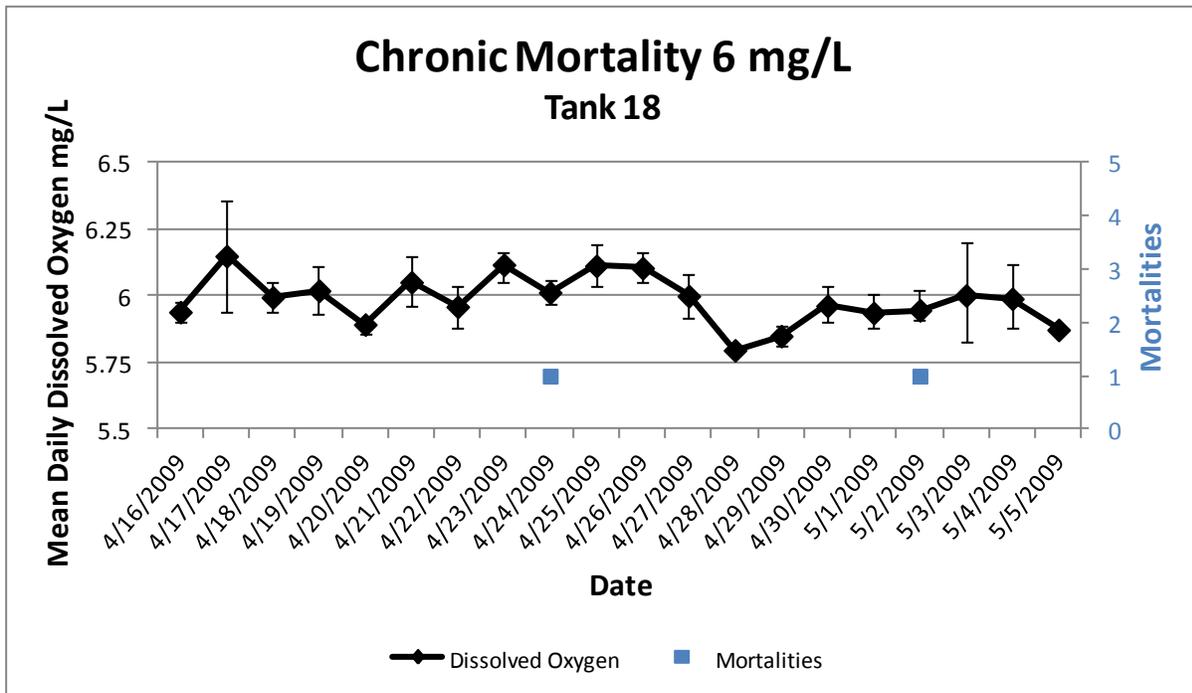


Figure 57.—Mean daily DO and observed mortality for 20-day (chronic) larval trials. Line projections represent daily DO ranges (tank 18).

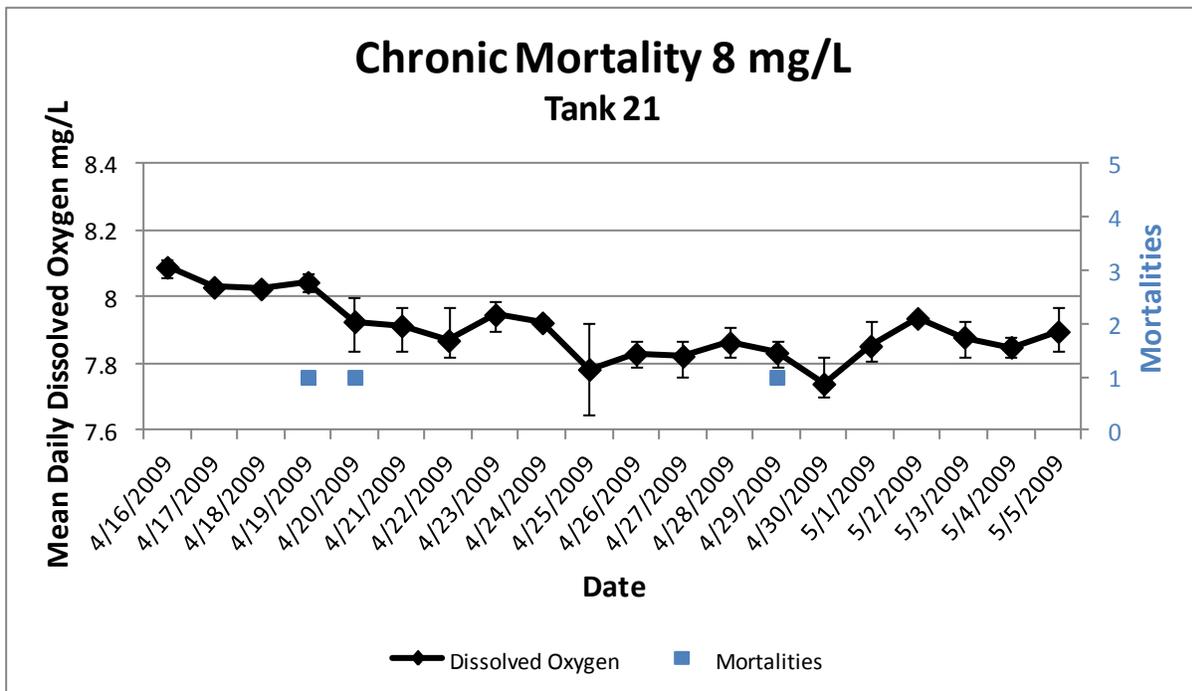


Figure 58.—Mean daily DO and observed mortality for 20-day (chronic) larval trials. Line projections represent daily DO ranges (tank 21).

Dissolved Oxygen Tolerances for Egg and Larval Stages of Razorback Sucker

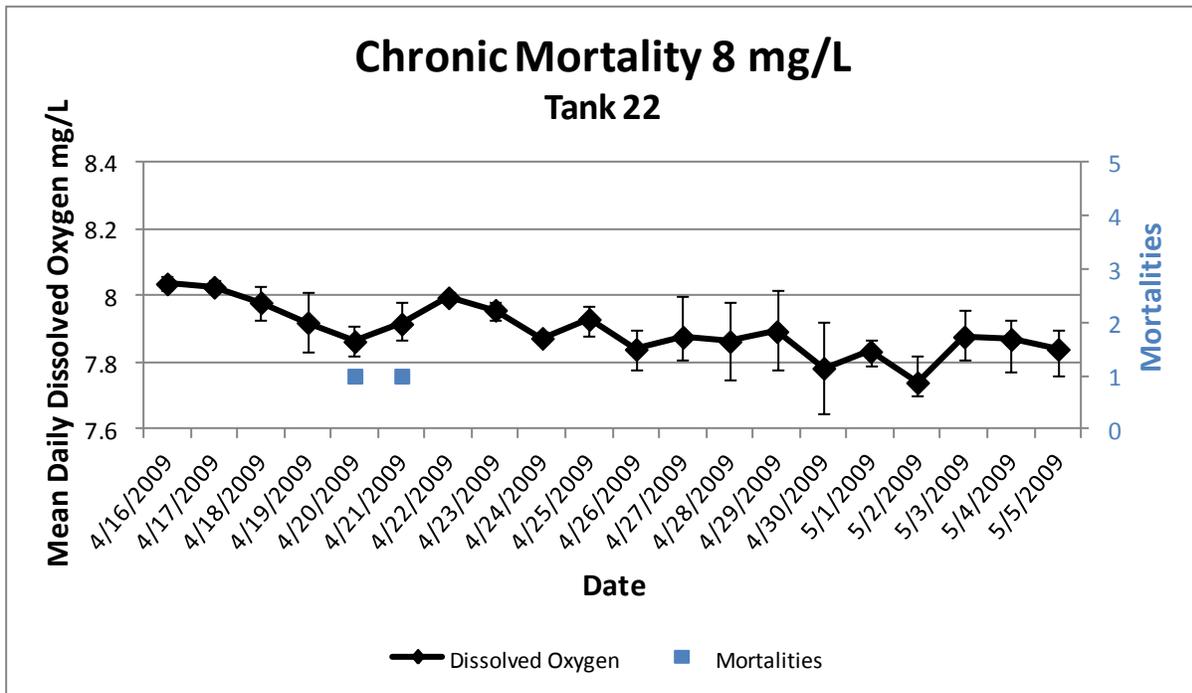


Figure 59.—Mean daily DO and observed mortality for 20-day (chronic) larval trials. Line projections represent daily DO ranges (tank 22).

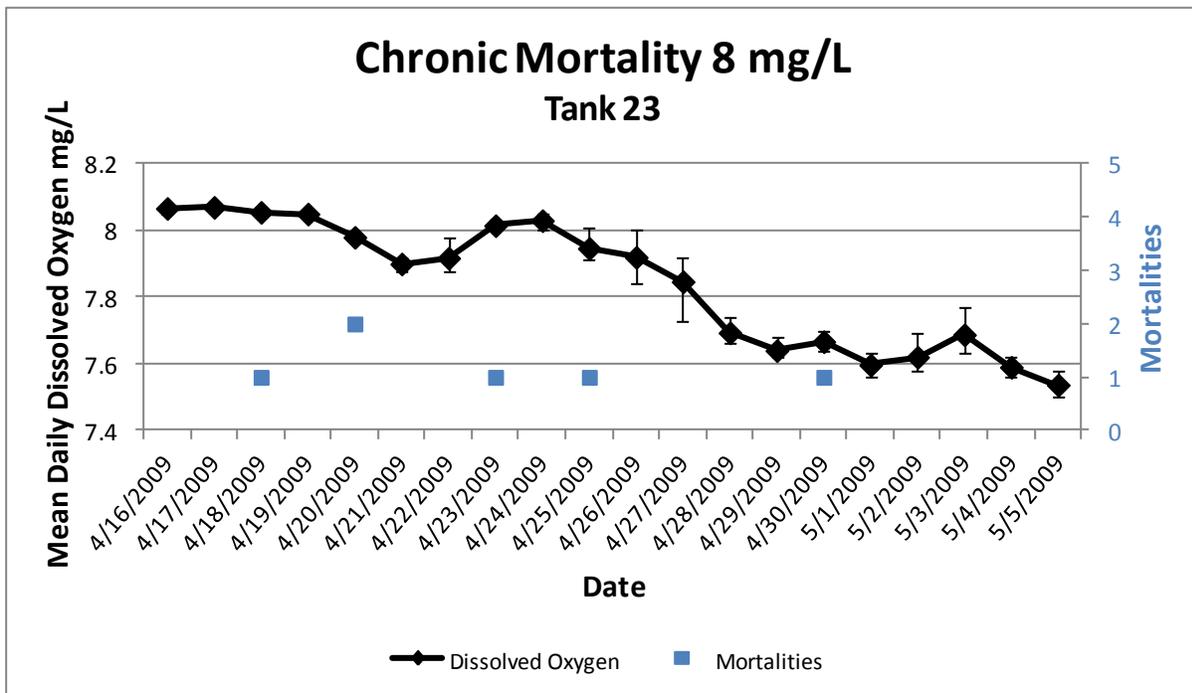


Figure 60.—Mean daily DO and observed mortality for 20-day (chronic) larval trials. Line projections represent daily DO ranges (tank 23).

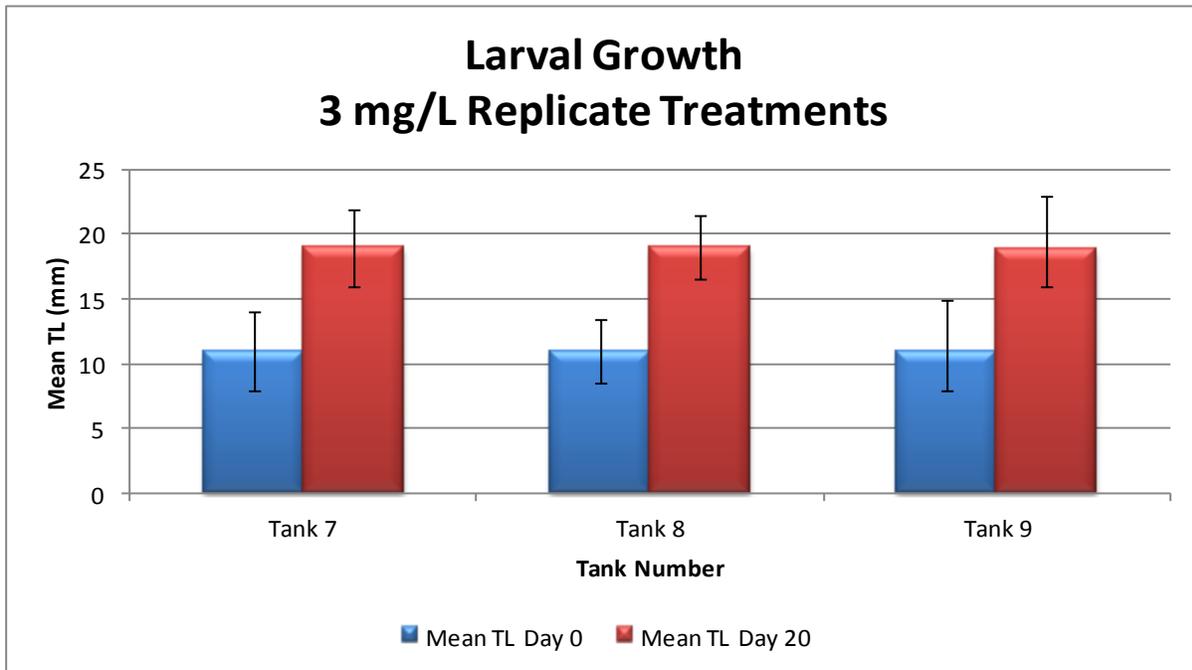


Figure 61.—Growth of razorback sucker larvae exposed to DO concentrations of 3 mg/L for 20 days. Mean TL for day 0 and for day 20 was calculated using 10% (n = 30) of the treatment group from each tank. Line projections represent the range of TL measurements.

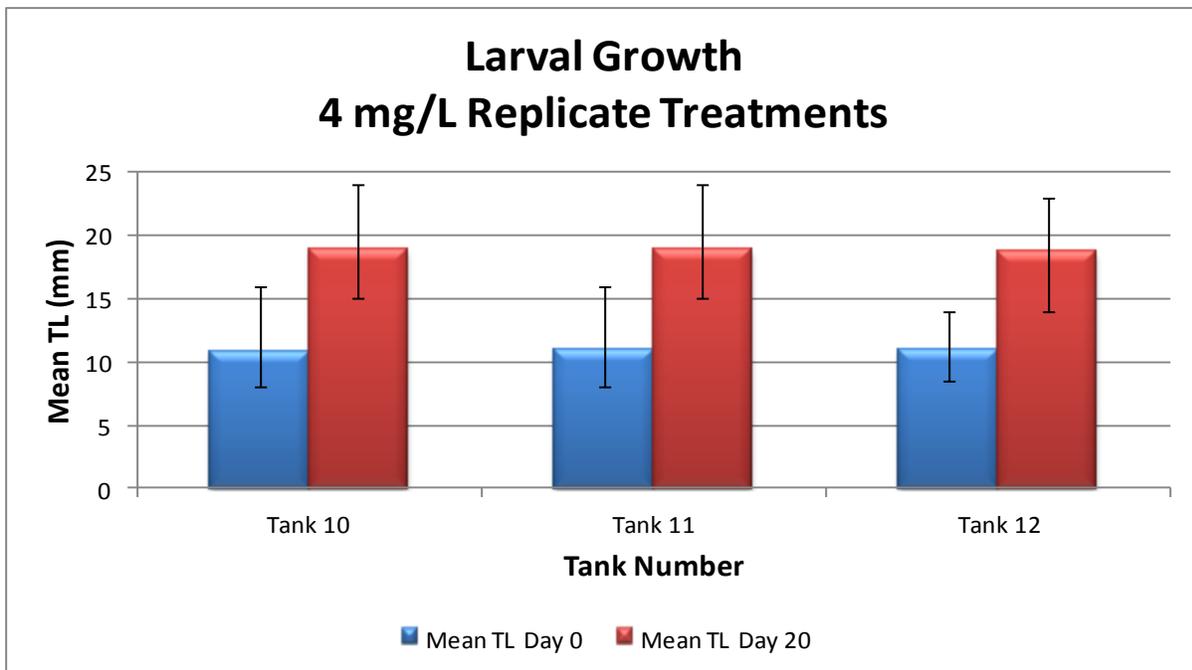


Figure 62.—Growth of razorback sucker larvae exposed to DO concentrations of 4 mg/L for 20 days. Mean TL for day 0 and for day 20 was calculated using 10% (n = 30) of the treatment group from each tank. Line projections represent the range of TL measurements.

Dissolved Oxygen Tolerances for Egg and Larval Stages of Razorback Sucker

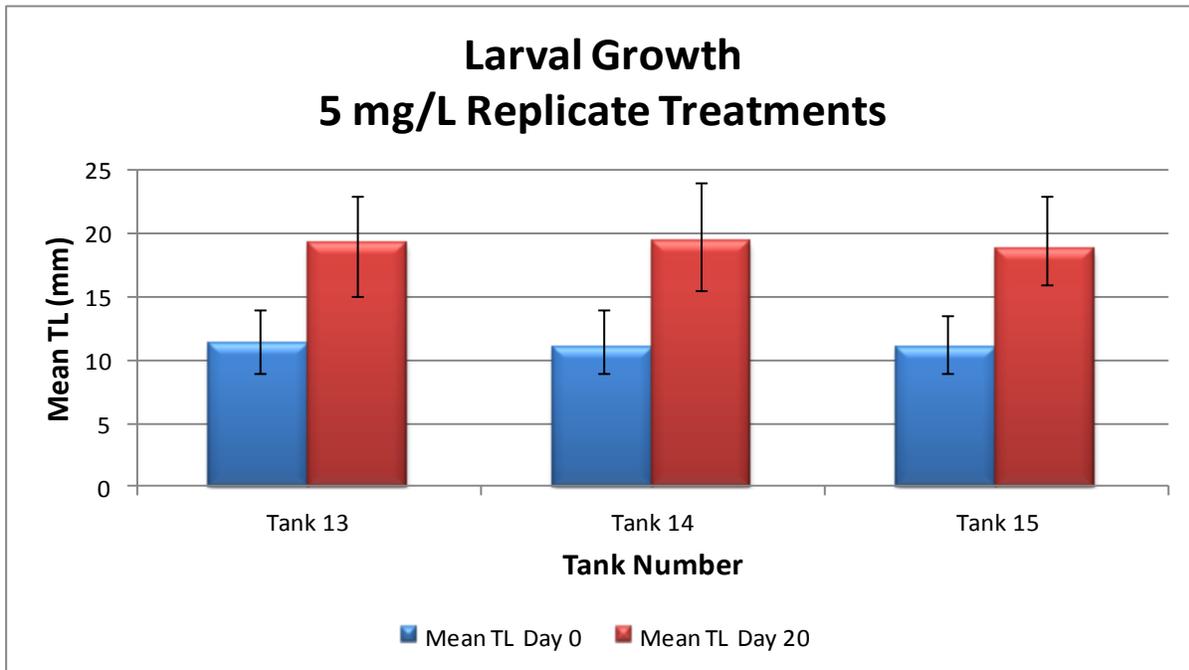


Figure 63.—Growth of razorback sucker larvae exposed to DO concentrations of 5 mg/L for 20 days. Mean TL for day 0 and for day 20 was calculated using 10% (n = 30) of the treatment group from each tank. Line projections represent the range of TL measurements.

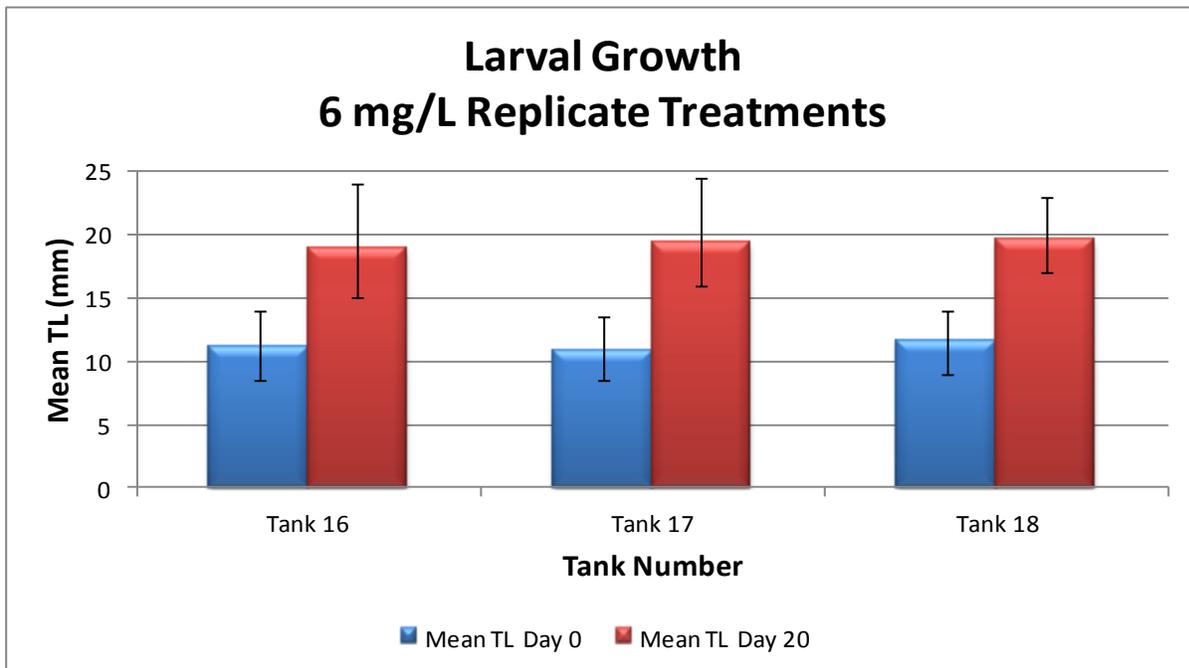


Figure 64.—Growth of razorback sucker larvae exposed to DO concentrations of 6 mg/L for 20 days. Mean TL for day 0 and for day 20 was calculated using 10% (n = 30) of the treatment group from each tank. Line projections represent the range of TL measurements.

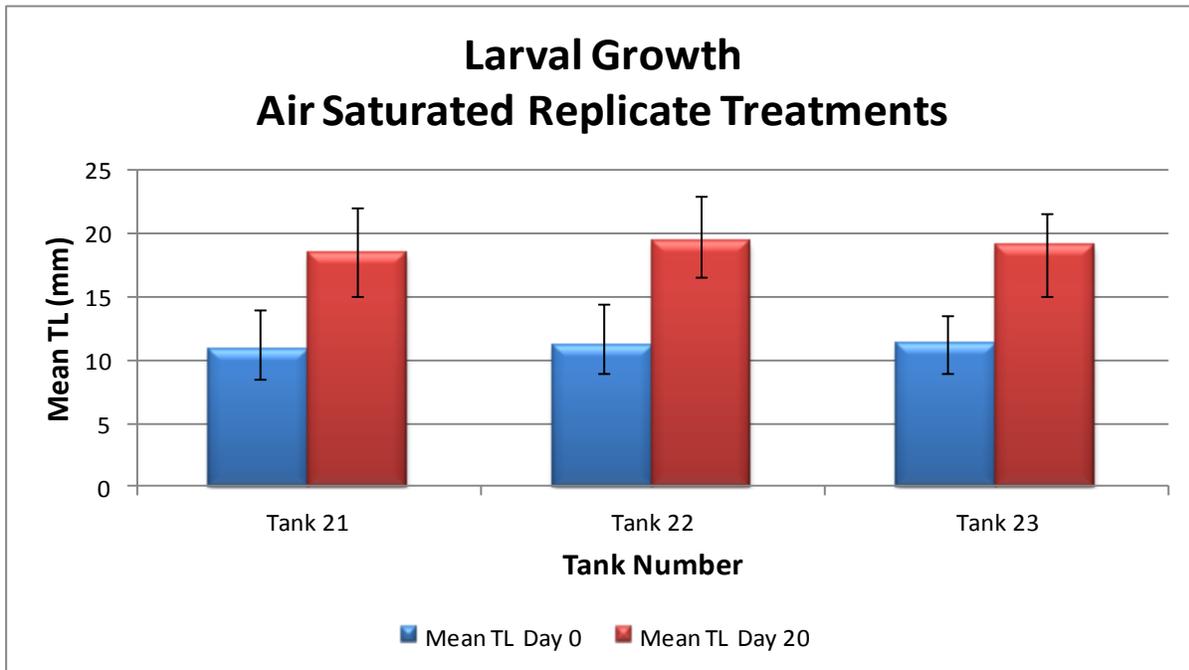


Figure 65.—Growth of razorback sucker larvae reared in air-saturated tanks for 20 days. Mean TL for day 0 and for day 20 was calculated using 10% (n = 30) of the treatment group from each tank. Line projections represent the range of TL measurements.

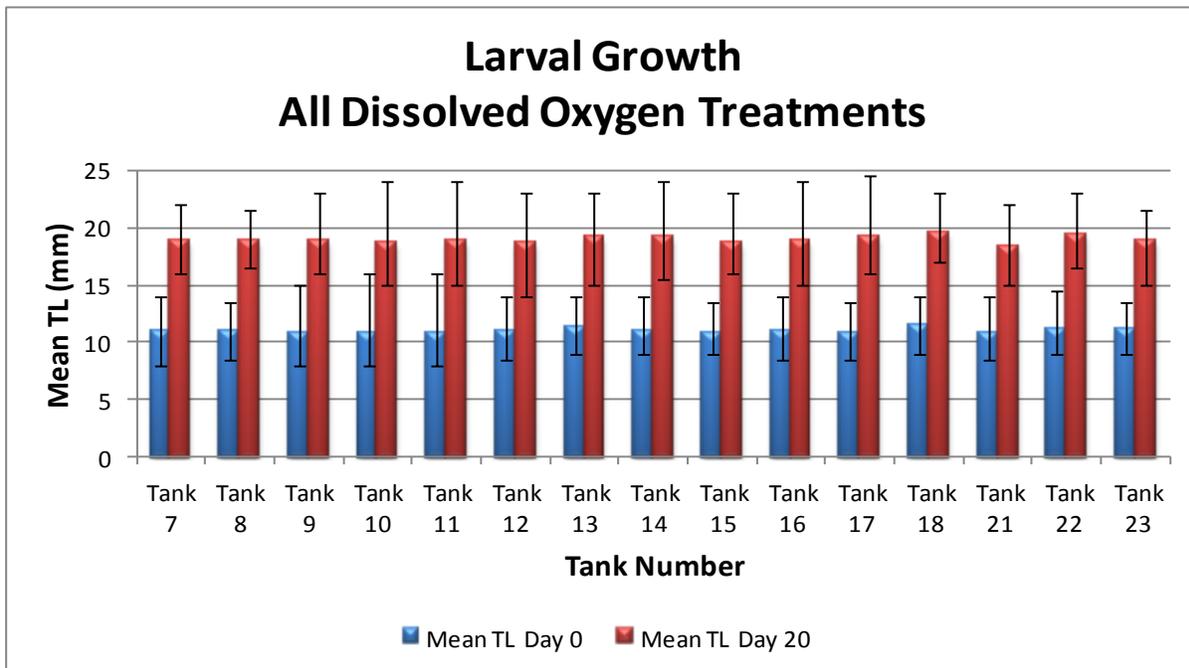


Figure 66.—Comparative growth of razorback sucker larvae reared in all experimental DO concentrations for 20 days. Day 0 and day 20 mean TL were calculated using 10% (n = 30) of the treatment group from each tank. Line projections represent the range of TL measurements.

## LITERATURE CITED

- Bestgen, K.R. 2008. Effects of water temperature on growth of razorback sucker larvae. *Western North American Naturalist* 68(1):15–20.
- Boyd, C.E. 1985. Chemical budgets for channel catfish ponds. *Transactions of the American Fisheries Society* 114:291–298.
- Bozek, M.A., L.J. Paulson, and G.R. Wilde. 1990. Effects of ambient Lake Mohave temperatures on development, oxygen consumption, and hatching success of razorback sucker. *Environmental Biology of Fishes* 27:255–263.
- Bureau of Reclamation. 2010. Lower Colorado River Contaminant Monitoring Program 2003–2006 Report, Phase I. Lower Colorado Region, Resources Management Office, Boulder City, Nevada.
- Dean, T.L. and J. Richardson. 1999. Responses of seven species of native freshwater fish and a shrimp to low levels of dissolved oxygen. *New Zealand Journal of Marine and Freshwater Research* 33:99–106.
- Dudley, R.G. and A.W. Eipper. 1975. Survival of largemouth bass embryos at low dissolved oxygen concentrations. *Transactions of the American Fisheries Society* 104(1):122–128.
- Fry, F.E. 1971. The effect of environmental factors on the physiology of fish. *Fish Physiology* 6:1–99. New York & London: Academic Press.
- Haines, G.B. 1995. Effects of Temperature on Hatching Success and Growth of Razorback Sucker and Flannelmouth Sucker. Final Report. U.S. Fish and Wildlife Service, Vernal, Utah.
- Kramer, D.L. 1987. Dissolved oxygen and fish behavior. *Environmental Biology of Fishes* 18(2):81–92.
- Maitland, P.S. 1978. *Biology of Fresh Waters*. New York & Toronto: Halsted Press.
- Marsh, P.C. 1985. Effect of incubation temperature on survival of embryos of native Colorado River fishes. *Southwestern Naturalist* 30(1):129–140.
- Martinez, A.M. 1996. Observed growth, survival, and caudal fin ray deformities of intensively cultured razorback suckers. *The Progressive Fish-Culturist* 58(4):263–267.

**Dissolved Oxygen Tolerances for Egg  
and Larval Stages of Razorback Sucker**

Oseid, D.M. and L.L. Smith. 1971a. Survival and hatching of walleye eggs at various dissolved oxygen levels. *The Progressive Fish-Culturist* 33(2):81–85.

\_\_\_\_\_. 1971b. Survival and hatching of white sucker eggs at various dissolved oxygen levels. *The Progressive Fish-Culturist* 33(3):158–159.

Stanley, D.W. and S.W. Nixon. 1992. Stratification and bottom-water hypoxia in the Pamlico River estuary. *Estuaries* 15(3):270–281.

Stolberg, J.R. 2012. Salinity tolerances for egg and larvae stages of razorback sucker 2007–2008. Lower Colorado River Multi-Species Conservation Program. Bureau of Reclamation, Boulder City, Nevada.

Wetzel, R.G. 1983. *Limnology* (2nd ed.). Chicago: Saunders College Publishing.