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INDUCED WINTERKILL AS A MANAGEMENT TOOL FOR RECLAIMING MINNESOTA WALLEYE REARING PONDS[1]

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Abstract.-- During the winters of 2002-2006, Minnesota Department of Natural Resources staff attempted to induce winterkill of undesirable fish in 22 small natural lakes used for rearing walleye *Sander vitreus* fingerlings. This was done by disturbing the sediment and moving anoxic water vertically and horizontally under ice cover using air diffusers or outboard mud motors (commonly known as "reverse aeration"). Six of the reverse aeration treatments induced declines in maximum dissolved oxygen concentration (DO) of at least 2.0 mg/L, at rates exceeding 1.0 mg/L per day. In all of these cases, anoxia-intolerant species such as carryover walleyes, sunfish *Lepomis* spp., and white suckers *Catostomus commersonii* were reduced or eliminated by the end of the winter; however, we never observed significant reductions of black bullhead *Ameiurus melas* or fathead minnow *Pimephales promelas* populations. Most of the treatments that did not induce substantial declines in maximum DO probably failed due to ineffective mixing or inadequate snow cover to inhibit photosynthesis. Advantages of reverse aeration relative to rotenone treatments are that reverse aeration is a more natural chemical-free alternative and potentially costs less. Disadvantages are 1) reverse aeration is less reliable; 2) reverse aeration is unlikely to control black bullhead or fathead minnow populations; 3) reverse aeration treatments can only be done opportunistically as ice, snow, and dissolved oxygen conditions permit; and 4) if the winter is severe enough for reverse aeration to have an effect, some lakes may winterkill naturally anyway. Despite these limitations, in some situations reverse aeration could be a useful management tool for controlling anoxia-intolerant fish species in shallow eutrophic-hypereutrophic water bodies less than 100 acres in surface area.

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Introduction

Most of the walleye *Sander vitreus* fingerlings that are stocked in Minnesota are reared in shallow, undrainable, naturally formed ponds that are stocked with walleye fry in the spring and harvested using small-mesh trap nets in the fall. In 2001, approximately 119 million walleye fry were stocked into 324 rearing ponds (Anonymous 2002). Rearing ponds with sparse or nonexistent fish communities at the time of stocking are necessary for good survival and growth of stocked fry, and efficient harvest of fingerlings (Bandow 1989). Ponds are typically used for walleye fingerling production opportunistically after natural winterkills substantially reduce or eliminate other fish populations. Many ponds used for walleye fingerling production winterkill only intermittently, which can limit production capability. Ponds are sometimes reclaimed with rotenone, but this is an expensive and sometimes controversial option. If winterkill could be artificially induced, it might be an environmentally benign, chemical-free, and cost-effective method of improving walleye fingerling production. Even if the method were only effective in eliminating species such as carryover walleyes and sunfish *Lepomis* spp., but not hardier fishes such as black bullheads *Ameiurus melas* or fathead minnows *Pimephales promelas*, it might still be a useful tool to help maintain rearing ponds between natural winterkills or rotenone treatments.

The primary cause of winterkill of fishes is low dissolved oxygen concentration (DO) resulting from seasonal depletion (Greenbank 1945; Scidmore 1956). Oxygen is depleted when biochemical oxygen demand (BOD) exceeds oxygen production as snow-covered ice inhibits photosynthesis and prevents replenishment of oxygen through the lake's surface (Greenbank 1945). Because seasonal oxygen depletion occurs unevenly in some lakes, fish may congregate in small refuges with higher than average oxygen levels (Moyle and Clothier 1959; Johnson and Moyle 1969; Klinger et al. 1982; Magnuson et al. 1985). Winterkills can be expected if maximum DO remains below about 1 mg/L for at least a few days (Greenbank 1945; Cooper and Washburn 1946; Johnson 1965; Johnson and Moyle 1969; Bandow 1986). Game fish may die if DO drops below about 2 mg/L (Moore 1942; Moyle and Clothier 1959; Bandow 1986), but hardier species such as black bullheads may survive DO as low as 0.2 mg/L or even less (Cooper and Washburn 1946; Johnson 1965). Large or small individuals of a species may be more susceptible to winterkill than average-sized individuals (Moore 1942; Casselman and Harvey 1975). A complete winterkill is rare; usually, winter anoxia results in a fish community dominated by resistant species and sizes (Greenbank 1945; Cooper and Washburn 1946; Bandow 1980). Even in shallow ponds with high BOD and histories of winterkill, the frequency and severity of natural winterkills fluctuate widely from year to year and pond to pond due to large variability in ice cover, snowfall, and other factors.

Operation of aeration equipment with the intent to prevent winterkill has often initially resulted in a decrease rather than increase in DO (Patriarche 1961; Halsey 1968; Lackey and Holmes 1972; Johnson and Skrypek 1975; Smith et al. 1975; Bandow 1986). Artificial vertical and horizontal mixing of water in an ice-covered lake may reduce DO by two distinctly different mechanisms: by increasing the BOD of microorganisms in the water column and sediments so oxygen is depleted (Lindeman 1942; Ellis and Stefan 1989); and secondly by mixing any oxygenated water with previously existing anoxic water so maximum oxygen concentrations are reduced to a uniformly low average. Lindeman (1942) produced anaerobic conditions under the first mechanism by mixing pond water and bottom sediment in sealed quart jars. Fisheries managers in Minnesota have coined the term "reverse aeration" to describe attempting to induce winterkill of undesirable fish by vertical and horizontal mixing of water and sediment in an ice-covered lake.

The objectives of this study were to determine: 1) conditions under which reverse aeration can consistently lower the dissolved oxygen concentration of a walleye rearing pond to a level that is potentially lethal to undesirable fish; 2) conditions under which rearing ponds treated with reverse aeration have a significantly higher frequency and severity of winterkills than untreated ponds; and 3) whether reverse aeration results in significantly better walleye fingerling production than in untreated ponds.

Study Ponds

Fisheries management personnel in each of 11 Minnesota Department of Natural Resources (MNDNR) area field offices were informed of the study objectives, and then asked to use their local experience and professional judgment to select at least four representative rearing ponds for inclusion in the project. Factors considered in pond selection included: winterkill history; size (preferably 100 acres or less); fertility (preferably eutrophic to hypereutrophic); potential confounding factors such as springs or connections to other water bodies; existing fish communities; plans for future use; and access. Thirty-nine rearing ponds were selected in 2002. Eight of 11 participating fisheries management areas were initially represented by at least four ponds; three areas had fewer candidates due to a shortage of suitable ponds. In subsequent years the list of study ponds was modified slightly due to landowner or public use issues, new information about unfavorable pond characteristics, etc. Ponds were widely scattered over much of the area of the state containing good walleye rearing ponds (Figure 1). Sizes of selected ponds ranged from 9 to 168 acres, with a median of 55 acres; maximum depths ranged from 4 to 24 feet, with a median of 8 feet (Table 1). Some ponds were clear and macrophyte dominated, but most were turbid and phytoplankton dominated during the open water season.

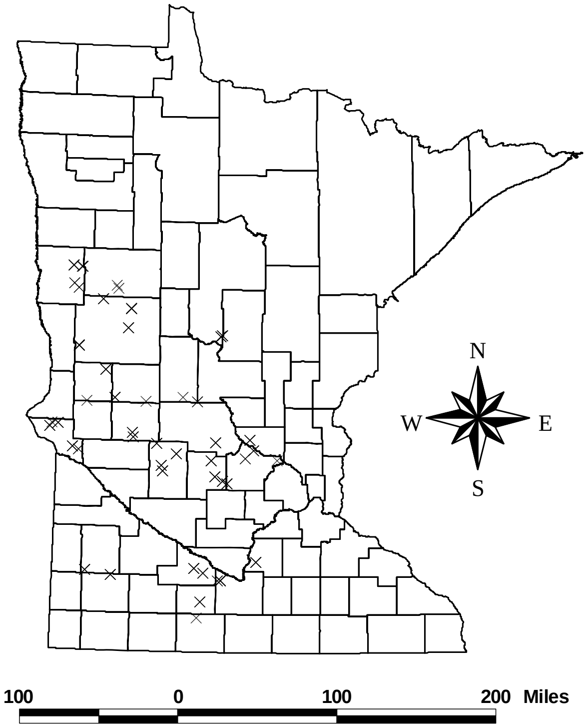

Figure 1. Locations of Minnesota walleye rearing ponds selected as candidates for reverse aeration in 2002-2006.

Table 1. Walleye rearing ponds selected as candidates for reverse aeration treatments in 2002-2006. Acreages are those listed by the Waters Section (1968) unless noted.

Area	Years	Pond	County	DOW ID[1]	Acres	Maximum depth (ft)	Latitude	Longitude
Brainerd	2002-2006	Bass	Cass	11021500	28	10	46.37500	-94.35436
Brainerd	2002-2006	Stephens	Cass	11021300	104	6	46.38515	-94.33603
Detroit Lakes	2003-2005	Christianson	Clay	14002000	19	9	46.78786	-96.24215
Detroit Lakes	2003-2005	Doran	Clay	14008900	100	7	46.82325	-96.30716
Detroit Lakes	2002-2005	Rustad	Clay	14008800	39	7	46.98140	-96.20964
Detroit Lakes	2002-2005	Tatlie	Clay	14009200	60	10	46.98770	-96.32387
Detroit Lakes	2002-2003	Elbow	Becker	03025100	75	10	46.79389	-95.71874
Detroit Lakes	2002-2003	Neuner	Becker	03028200	36	10	46.82192	-95.73980
Fergus Falls	2002-2006	Dalman	Otter Tail	56057900	10	9	46.69048	-95.91991
Fergus Falls	2002-2006	Dorrow	Otter Tail	56019900	14	5	46.43440	-95.57466
Fergus Falls	2002-2006	Shasky	Otter Tail	56021900	23[2]	11	46.61388	-95.53706
Fergus Falls	2002-2006	Swenson	Otter Tail	56096500	26	8	46.26206	-96.20918
Glenwood	2003-2006	Anderson	Pope	61008900	58	10	45.44395	-95.46595
Glenwood	2003-2006	Kolstad	Pope	61008200	80	6	45.49012	-95.47641
Glenwood	2002-2006	Iverson	Grant	26008400	50	12	46.05066	-95.85201
Glenwood	2002-2006	Roland	Douglas	21028100	93	6	45.79861	-95.72167
Glenwood	2002-2003	Lovera (Lovers)	Douglas	21004600	112	24	45.77344	-95.31230
Glenwood	2002-2003	Towner	Grant	26021700	48	6	45.76354	-96.08116
Hutchinson	2002-2006	Butternut	Meeker	47000500	84	8	45.05922	-94.30642
Hutchinson	2002-2006	Chelgren (Little)	Wright	86025600	67	23	45.03972	-94.23999
Hutchinson	2002-2006	Rohrbeck	Meeker	47010000	56	9	45.24180	-94.45216
Hutchinson	2002-2006	Turtle	Meeker	47007400	43	10	45.09640	-94.39602
Little Falls	2003-2005	Schreiers	Todd	77000200	33	7	45.77875	-94.64592
Little Falls	2002-2003	Bunker	Todd	77010100	46	12	45.81465	-94.83854
Montrose	2004-2005	Praught	Wright	86000700	15	7	45.25039	-93.59824
Montrose	2002-2006	Fink	Stearns	73007800	41	7	45.41111	-94.39556
Montrose	2002-2006	Masford	Sherburne	71012600	90	8	45.43140	-93.96079
Montrose	2002-2005	Melrose	Wright	86017600	76	23	45.33810	-93.90361
Montrose	2002-2004	Otter	Wright	86015300	40[2]	24	45.26533	-94.01200
Ortonville	2003-2005	Danielson	Big Stone	06029900	19[2]	5	45.31800	-96.16358
Ortonville	2002-2006	Golf Course	Big Stone	06014000	66	17	45.55079	-96.44546
Ortonville	2002-2006	North Haukos	Big Stone	06045300	19[2]	8	45.34031	-96.24425
Ortonville	2002-2006	Taffe	Big Stone	06025100	45	9	45.52206	-96.55089
Ortonville	2002-2003	Kleindl	Big Stone	06017800	71[2]	6	45.55525	-96.52948
Spicer	2002-2006	Hanson	Kandiyohi	34018200	20	7	45.14233	-95.07165
Spicer	2002-2006	Hogan	Kandiyohi	34019400	55	11	45.19051	-95.09877
Spicer	2002-2006	Knutson	Kandiyohi	34058400	37[2]	6	45.39071	-95.15763
Spicer	2002-2006	Mortenson	Kandiyohi	34015002	9[2]	9	45.30000	-94.90451
Waterville	2004-2006	Juni	Brown	08001600	65	4	44.21813	-94.53003
Waterville	2002-2006	Bachelor	Brown	08002900	100	4	44.25644	-94.65161
Waterville	2002-2006	Lieberg	Blue Earth	07012400	71	6	44.15304	-94.31276
Waterville	2002-2006	Savidge	LeSueur	40010700	168	4	44.32559	-93.86518
Waterville	2002-2004	Armstrong	Blue Earth	07012500	125	5	44.15324	-94.34508
Windom	2002-2006	Clear	Murray	51004700	105	6	44.18432	-95.70433
Windom	2002-2006	Sanderson	Lyon	42007100	95	8	44.22346	-96.03433
Windom	2002-2005	Bullhead	Watonwan	83003300	75	6	43.95598	-94.56379
Windom	2002-2003	Round	Martin	46008400	41	7	43.80962	-94.60742

[1] Minnesota Department of Natural Resources Division of Waters Identification Number.

[2] Estimated from 1991 aerial photos using ArcView GIS 3.3.

Methods

DO and temperature

Dissolved oxygen and temperature profiles were measured regularly throughout the winter at 4-8 index stations on each pond using calibrated dissolved oxygen meters with integrated thermistors. Holes were drilled through the ice using hand augers, taking care not to agitate the water more than necessary. Measurements were taken at 1 ft intervals at stations < 12 ft deep, and 2 ft intervals at deeper stations. In most cases the shallowest measurements were taken 1 ft below the surface of the water in the holes, but in some cases when ice thickness was > 1-2 ft, the shallowest measurements were taken at 2-3 ft. Snow depths were measured at the index stations.

The maximum DO measured in a pond at a given time was considered more relevant than other statistics such as the mean, median, or minimum because fish tend to find the maximum DO available as they begin to experience critical DO levels (Moyle and Clothier 1959; Johnson and Moyle 1969; Klinger et al. 1982; Magnuson et al. 1985). Also, other statistics were influenced by variability in exactly how closely the deepest DO measurements approached the bottom, because water near the bottom was often anoxic even when DO was high throughout most of the water column. Preliminary analyses indicated trends in mean or median DO were similar to trends in maximum DO, but trends in minimum DO were often uninformative.

Selection of treatment and reference ponds

Ponds were considered treatable if maximum DO declined below 50% of saturation, indicating that BOD exceeded oxygen production. A mid to late February deadline was chosen for treatments because after this time in southern and central Minnesota DO often naturally begins to rise due to thawing and increasing photosynthesis. The experimental design was for at least two ponds in each fisheries management area to reach the DO threshold each year; once at least two ponds in the area reached the threshold, then one would randomly be chosen for treatment and another as an untreated reference pond. In reality, a few ponds were nonrandomly chosen for treatment due to a lack of other treatable ponds or for logistical reasons, and in these cases no comparable reference ponds were available. In some areas in some years no ponds reached the DO threshold by mid to late February, so no treatments were attempted.[2] Occasionally ponds were eliminated as candidates for treatment because they became anoxic on their own early in the winter.

Treatments

Details of individual treatments are found in the appendices. We used three types of equipment to disturb the sediment and move water vertically and horizontally. In ponds with maximum depths of approximately 7-15 ft, we used Superior Lake Aeration 9 (SL9) destratification systems sold by Aquatic Ecosystems, Inc., Apopka, Florida. The SL9 consists of a 1 hp electric high-volume rotary vane compressor, four control valves, four lengths of tubing (½ in polyethylene terminated by 25 ft of ½ in self weighted tubing), and four air diffusers. In most cases we used the standard air diffuser manifolds (Model ALA6GL**)** that came with the systems, but removed the square plastic shields to enhance disturbance of the sediment. In a few cases the standard air diffuser manifolds were replaced by 5 ft Bio-Weave air diffusers to facilitate deployment and retrieval through the ice. We powered the systems with 5500 W portable AC generators (one or two systems per generator), and generally ran the systems continuously for 2-3 days except for brief overnight periods when the generators ran out of fuel. The SL9 systems did not produce enough air pressure for diffusers to function well in water over approximately 15 ft deep. Therefore, in two deeper ponds we used custom-made airlift pumps (Appendix 23), with air supplied by portable gasoline powered air compressors rented from local tool rental centers. In ponds with maximum depths < 7 ft, or shallow areas of deeper ponds, we used outboard mud motors. Mud motors had 24 hp

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[2] None of the study ponds in the southernmost management area (Windom) ever reached the treatment threshold by mid to late February.

engines, 85 in shafts and 9 in X 6 in two-bladed stainless steel propellers. They were attached to small flat-bottomed boats and towed onto the ice, and then elongated holes were cut with gasoline-powered ice augers and ice spuds to allow inserting the shafts at about 30° angles under the ice (Appendix 24). The boats were immobilized before starting the motors, and then the motors were run at maximum throttle for 30 min at each site. In most cases, all mud motor sites were treated in a single day.

Water quality

Surface water samples were collected in fall (September – October) and spring (April). The samples were placed on ice and taken to the Minnesota Department of Agriculture laboratory in St. Paul, where they were assayed for total alkalinity, total phosphorus, carbonaceous biochemical oxygen demand, and total suspended solids. To examine potential changes in water quality from the fall before a treatment to the spring following a treatment, we used univariate repeated measures ANOVA in Systat® 8.0 with water quality variables as dependent variables; season (spring or fall) as a trial factor; and treatment (treated pond or untreated reference pond) as a grouping factor (Wilkinson 1998).

Fish sampling

Fish communities were sampled with small-mesh (0.25 – 0.50 in bar) trap nets during late summer or fall as part of the normal walleye rearing pond harvest procedure. Daily catches were recorded as 0, 1-9, 10-99, 100-999, or ≥ 1000 for walleyes, black bullheads, and fathead minnows; other species present were noted. Similar data were collected again in early spring, as soon as possible after ice out. Numbers of nets, mesh sizes, and numbers of nights fished were variable; therefore, catches represented presence-absence, but not necessarily relative abundance.

Walleye harvest data for selected rearing ponds were obtained by querying the MNDNR Fisheries Information System. Harvests were recorded in the database as numbers and weights of fingerlings, yearlings, and "adults."

Results

DO

Rates of decline in maximum DO were significantly greater during reverse aeration treatments than immediately before the treatments (Table 2). Rates of decline exceeding 1.0 mg/L per day were never observed in treated ponds before treatments or in untreated reference ponds (Table 3), but did occur during eight of 24 treatments. Six treatments resulted in reductions in maximum DO that were considered biologically significant: Anderson, Mortenson, Doran, and Turtle in 2004; Dalman in 2005; and Dalman again in 2006. In these cases, rates of decline not only exceeded 1.0 mg/L per day, but also maximum DO declined at least 2.0 mg/L from initial values of 3.37 – 6.45 mg/L (Figure 2; Table 2). Four other cases (Dorrow and Rustad in 2003; Armstrong in 2004; and Hanson in 2005) were considered inconclusive because treatments were initiated too late, after maximum DO had naturally declined below 2.0 mg/L; initial DO was lower than intended due to time lags for logistical reasons after learning that ponds were treatable.

Winterkill in the treated ponds where biologically significant declines in DO occurred

In September 2003, age 0 and older walleyes and large numbers of black bullheads were captured in Anderson Pond (Figure 3). Maximum DO dropped precipitously to approximately 1 mg/L by the end of the reverse aeration treatment on 6 Feb 2004, then remained at or below this level for at least six days (Figure 2). In April 2004, black bullheads were still abundant and fathead minnows were also present, but walleyes were not captured (Figure 3). This indicates that carryover walleyes were probably eliminated by winterkill, but there was little or no winterkill of black bullheads and fathead minnows. The untreated reference pond (Iverson) contained only age 0 and older walleyes in September 2003 (Figure 4). In contrast to Anderson Pond, maximum DO in Iverson Pond declined gradually over the winter and barely dipped below 1 mg/L for a short time in late February (Figure 2). April 2004 netting showed no evidence of winterkill in Iverson Pond (Figure 4).

Table 2. Changes in maximum DO immediately before and during reverse aeration treatments. Rates of decline were significantly greater during treatments than before treatments (Wilcoxon Signed Rank Test: *n* = 24; W= -128; T+ = 86; T- = -214; one-tailed *P* = 0.035).

	Before treatment						During treatment					
Pond	Time interval		Initial DO (mg/L)	Final DO (mg/L)	Δ DO (mg/L)	Rate (mg/L/d)	Time interval		Initial DO (mg/L)	Final DO (mg/L)	Δ DO (mg/L)	Rate (mg/L/d)
Anderson	1/20/04 12:00	2/3/04 12:00	9.32	6.45	-2.87	-0.21	2/3/04 12:00	2/6/04 12:00	6.45	1.34	-5.11	-1.70
Mortenson	2/2/04 12:00	2/5/04 11:00	4.30	3.37	-0.93	-0.31	2/5/04 11:00	2/6/04 10:00	3.37	0.57	-2.80	-2.92
Turtle	2/13/04 12:00	2/18/04 10:00	3.40	3.50	0.10	0.02	2/18/04 10:00	2/20/04 14:00	3.50	0.70	-2.80	-1.29
Dalman	1/24/05 12:00	1/25/05 11:00	4.10	3.77	-0.33	-0.34	1/25/05 11:00	1/27/05 9:00	3.77	0.98	-2.79	-1.46
Dalman	1/25/06 12:00	2/6/06 11:15	7.82	4.69	-3.13	-0.26	2/6/06 11:15	2/8/06 10:00	4.69	2.11	-2.58	-1.32
Doran	2/5/04 12:00	2/12/04 10:00	4.84	4.04	-0.80	-0.12	2/12/04 10:00	2/13/04 12:00	4.04	1.64	-2.40	-2.22
Tatlie	1/12/05 12:00	1/18/05 12:00	4.75	3.31	-1.44	-0.24	1/18/05 12:00	1/21/05 12:00	3.31	1.99	-1.32	-0.44
Armstrong	2/10/04 12:00	2/19/04 10:00	4.29	1.50	-2.79	-0.31	2/19/04 10:00	2/20/04 14:00	1.50	0.37	-1.13	-0.97
Swenson	2/5/04 12:00	2/11/04 9:00	4.45	3.15	-1.30	-0.22	2/11/04 9:00	2/11/04 13:30	3.15	2.40	-0.75	-4.00
Danielson	2/2/04 12:00	2/5/04 9:00	4.44	2.59	-1.85	-0.64	2/5/04 9:00	2/6/04 12:00	2.59	1.86	-0.73	-0.65
Golf Course	2/5/03 12:00	2/12/03 10:00	7.66	7.10	-0.56	-0.08	2/12/03 10:00	2/14/03 12:00	7.10	6.25	-0.85	-0.41
Otter	2/18/03 12:00	2/19/03 10:00	2.50	2.39	-1.11	-0.12	2/19/03 10:00	2/21/03 13:45	2.39	1.62	-0.77	-0.36
Shasky	2/19/03 12:00	2/27/03 9:30	3.60	3.00	-0.60	-0.08	2/27/03 9:30	2/28/03 10:15	3.00	2.40	-0.60	-0.58
Melrose	1/20/04 12:00	1/27/04 10:00	6.40	5.05	-1.35	-0.20	1/27/04 10:00	1/30/04 12:00	5.05	4.51	-0.54	-0.18
Golf Course	2/18/03 12:00	2/25/03 12:00	7.19	7.35	0.16	0.02	2/25/03 12:00	2/28/03 12:00	7.35	9.73	2.38	0.79
Dorrow	2/7/03 12:00	2/14/03 9:00	3.10	0.87	-2.23	-0.32	2/14/03 9:00	2/14/03 11:00	0.87	0.39	-0.48	-5.76
Savidge	2/7/05 10:40	2/8/05 10:00	8.07	7.90	-0.17	-0.17	2/8/05 10:00	2/9/05 12:00	7.90	7.61	-0.29	-0.22
Rustad	1/31/03 12:00	2/12/03 12:00	2.70	1.94	-0.76	-0.06	2/12/03 12:00	2/20/03 12:00	1.94	1.75	-0.19	-0.02
Chelgren	2/7/06 12:00	2/9/06 11:00	5.70	5.62	-0.08	-0.04	2/9/06 11:00	2/10/06 13:30	5.62	5.44	-0.18	-0.16
Hanson	1/31/05 12:00	2/7/05 9:00	1.24	1.56	0.32	0.05	2/7/05 9:00	2/8/05 15:00	1.56	1.46	-0.10	-0.08
Stephens	1/31/05 12:00	2/2/05 8:00	5.70	5.40	-0.30	-0.16	2/2/05 8:00	2/3/05 10:00	5.40	5.50	0.10	0.09
Kolstad	2/9/05 12:00	2/10/05 9:30	3.79	3.48	-0.31	-0.35	2/10/05 9:30	2/11/05 12:15	3.48	3.81	0.33	0.30
Otter	2/26/03 12:00	2/28/03 11:00	0.66	0.67	0.01	0.01	2/28/03 11:00	2/28/03 14:00	0.67	1.16	0.49	3.92
Hanson	1/19/06 12:00	1/26/06 10:00	9.10	5.51	-3.59	-0.52	1/26/06 10:00	1/27/06 12:15	5.51	10.92	5.41	4.95

Table 3. Greatest observed rates of change of maximum DO in untreated reference ponds.

Pond	Time interval		Initial DO (mg/L)	Final DO (mg/L)	∆ DO (mg/L)	Rate (mg/L/d)
Juni	1/12/05 12:15	1/19/05 12:00	15.20	7.90	-7.30	-1.0
Bass	1/4/05 12:00	1/11/05 12:00	15.30	10.60	-4.70	-0.7
N. Haukos	1/20/04 12:00	2/2/04 12:00	10.15	3.16	-6.99	-0.5
Christianson	1/6/05 12:00	1/12/05 12:00	9.82	7.28	-2.54	-0.4
Dalman	12/31/02 12:00	1/30/03 12:00	12.50	2.00	-10.50	-0.4
Tatlie	2/5/04 12:00	2/13/04 12:00	6.49	3.74	-2.75	-0.3
Otter	1/13/04 12:00	1/20/04 12:00	3.50	1.57	-1.93	-0.3
Iverson	1/7/05 12:00	1/28/05 12:00	11.88	7.50	-4.38	-0.2
Shasky	1/27/05 11:00	2/3/05 12:00	2.24	0.94	-1.30	-0.2
Iverson	1/23/04 12:00	2/4/04 12:00	4.20	2.28	-1.92	-0.2
Swenson	12/22/05 12:00	1/4/06 12:00	8.96	7.20	-1.76	-0.1
Doran	1/30/03 12:00	2/12/03 12:00	2.55	1.72	-0.83	-0.1

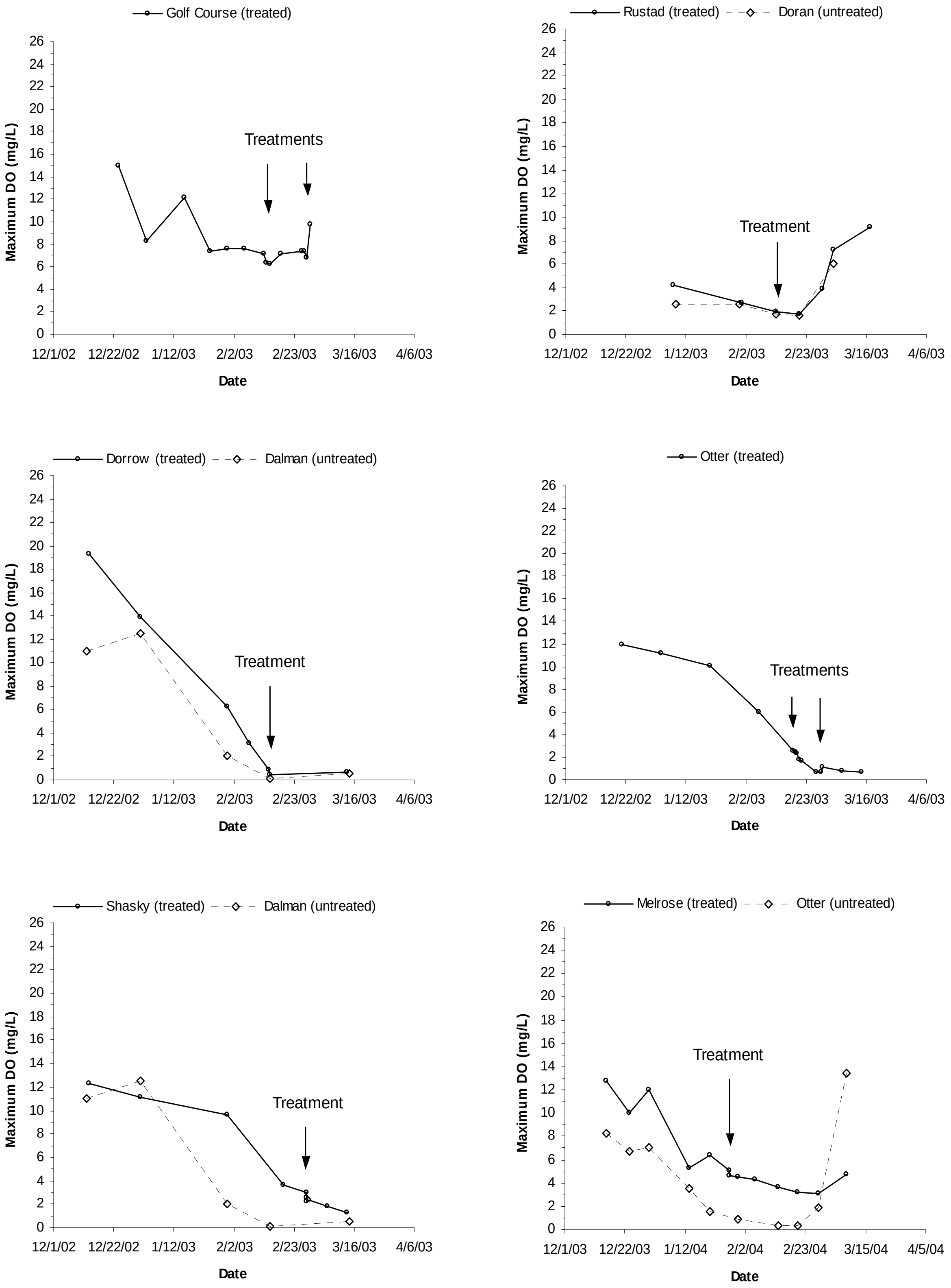
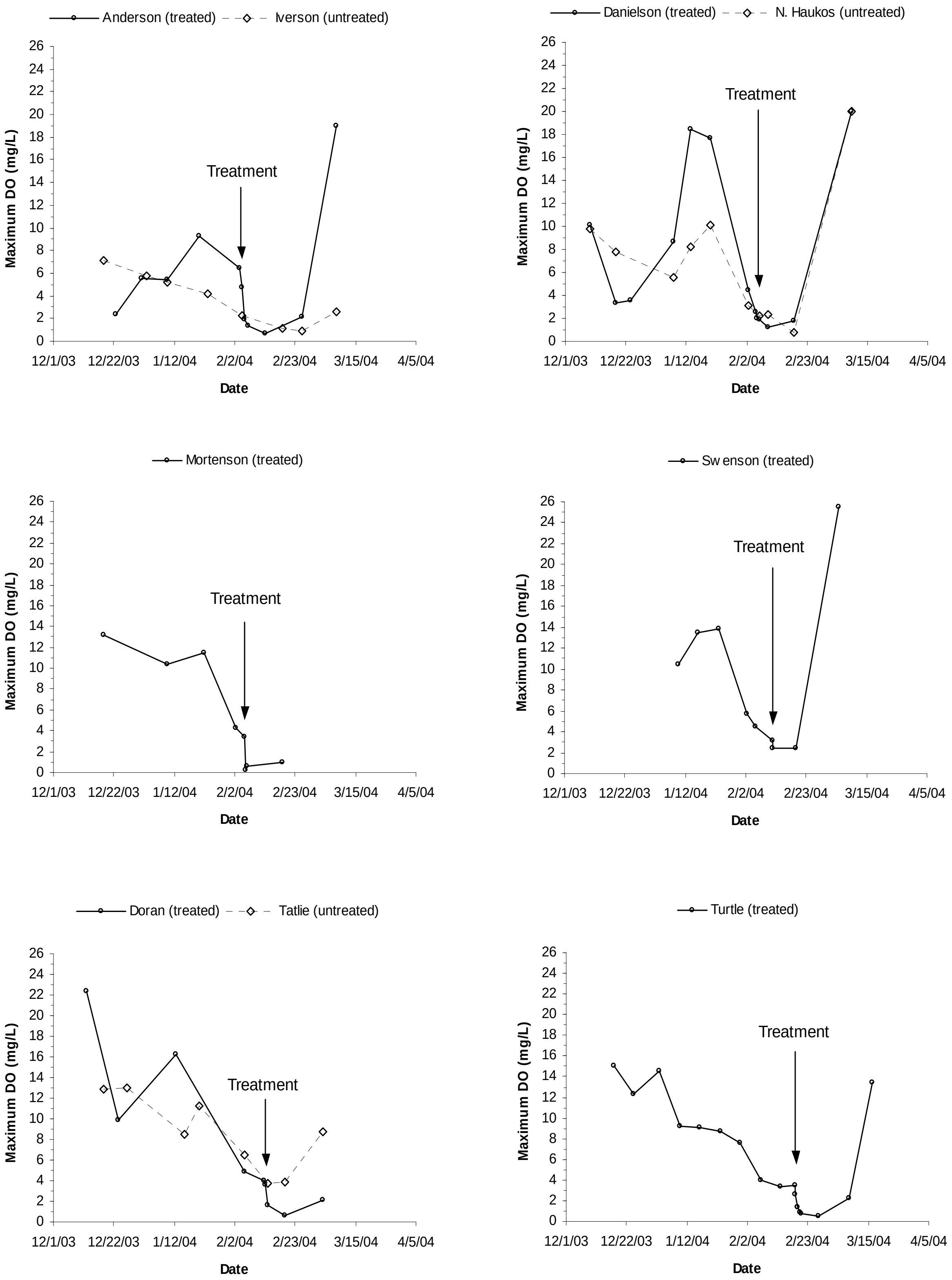


Figure 2. Changes in maximum DO over time in ponds that underwent reverse aeration treatments, and in untreated reference ponds.



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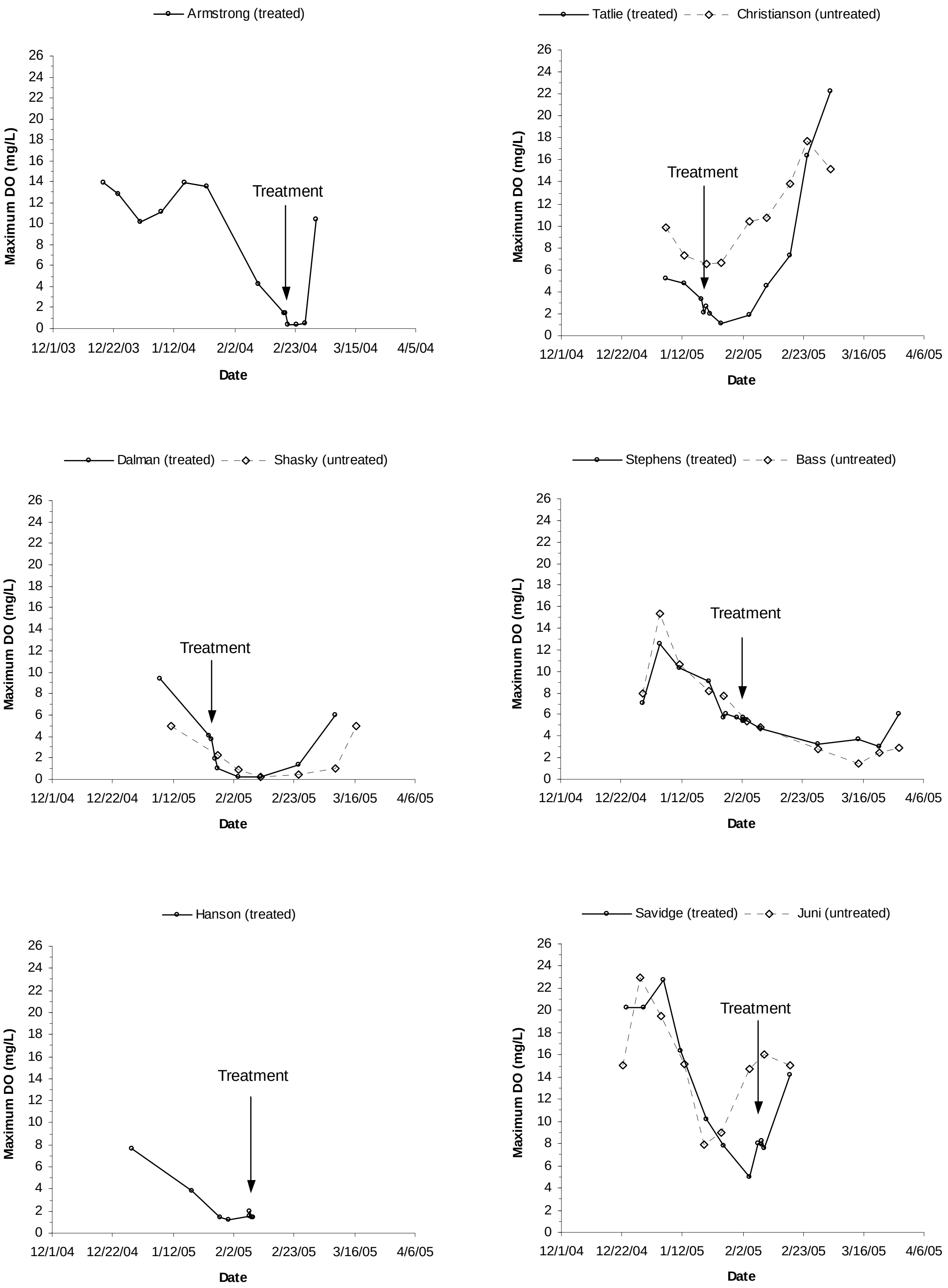

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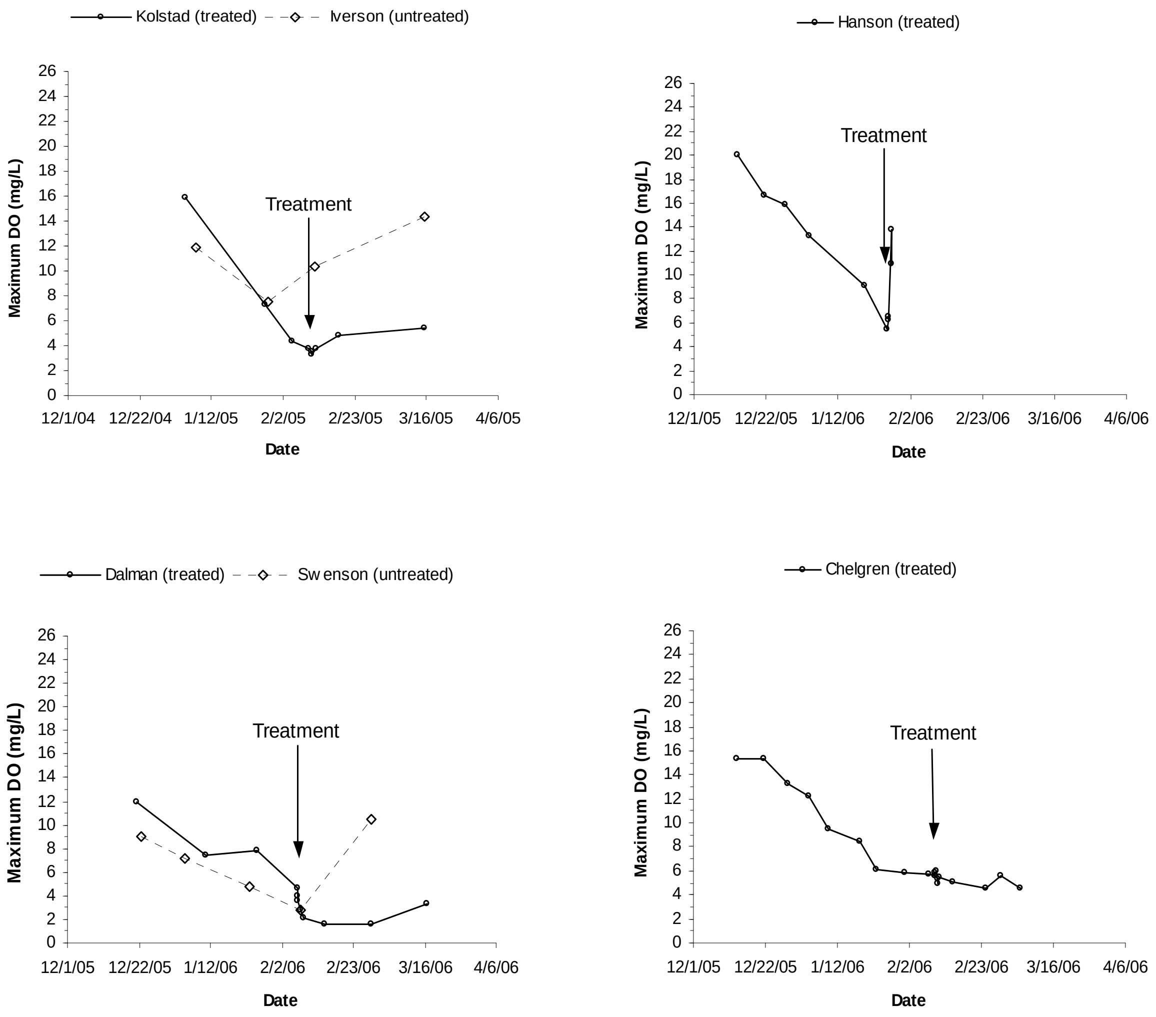

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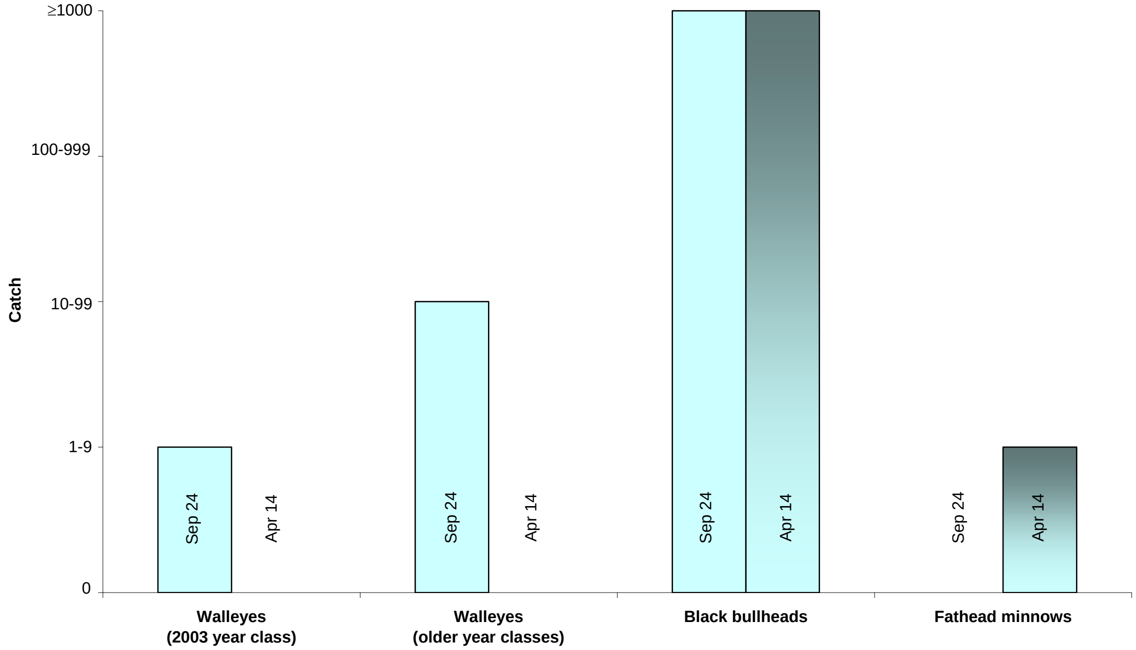

Figure 3. Trap net catches in Anderson Pond (Pope Co., Minnesota) in fall 2003 and spring 2004. The pond received a reverse aeration treatment during the winter.

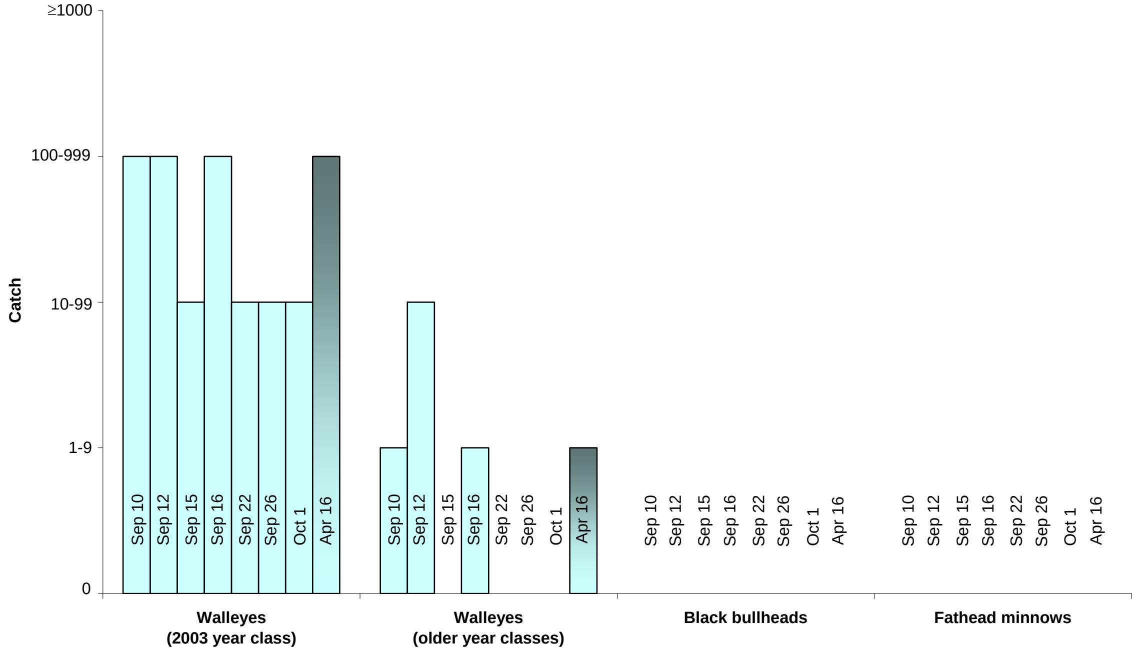

Figure 4. Trap net catches in Iverson Pond (Grant Co., Minnesota) in fall 2003 and spring 2004. The pond was an untreated reference for Anderson Pond.

Age ≥ 1 walleyes and fathead minnows were present in Mortenson Pond in August 2003 (Figure 5). Adult white suckers *Catostomus commersonii* and green sunfish *Lepomis cyanellus* were also present. Maximum DO dropped precipitously to < 1 mg/L during the reverse aeration treatment on 5-6 Feb 2004 and remained < 1 mg/L for at least 12 days (Figure 2). In April 2004, fathead minnows were still abundant but no other fish species were captured (Figure 5). The resident landowner reported many dead white suckers were washed up on shore after ice out, but were quickly removed by gulls *Larus* spp. These results indicate virtually complete winterkill of all species except fathead minnows.

In September 2003, Doran Pond contained carryover walleyes, plus large numbers of black bullheads and fathead minnows (Figure 6). Maximum DO dropped precipitously to < 2 mg/L immediately after the reverse aeration treatment on 13 Feb 2004, and subsequently declined below 1 mg/L by 19 Feb 2004 (Figure 2). No walleyes were captured in April 2004, but black bullheads and fathead minnows were still present (Figure 6). These results indicate a virtually complete winterkill of walleyes, but at most a partial winterkill of black bullheads and fathead minnows. In the untreated reference pond (Tatlie), black bullheads were abundant in October 2003 (Figure 7); hybrid sunfish were also present. Maximum DO in Tatlie Pond only declined to slightly below 4 mg/L before increasing again in late winter (Figure 2). In April 2004, black bullheads were still abundant and fathead minnows were present (Figure 7); adult walleyes and white suckers were also captured, indicating little or no winterkill.

Age ≥ 1 walleyes, black bullheads, and fathead minnows were captured in low to moderate numbers in Turtle Pond in September 2003 (Figure 8); golden shiners *Notemigonus crysoleucas* were also present. Maximum DO plummeted below 1 mg/L by the end of the reverse aeration treatment on 20 Feb 2004 and remained < 1 mg/L for at least six days (Figure 2). Soon after ice out in late March 2004, one carryover walleye was captured, and catches of black bullheads and fathead minnows were no lower than the previous September (Figure 8). Hybrid sunfish, golden shiners, central mudminnows *Umbra limi*, and brook sticklebacks *Culaea inconstans* were also captured after ice out. Although the netting data do not provide evidence of winterkill, at the time of netting 550 dead adult walleyes and 180 dead adult bluegills *Lepomis macrochirus* were counted along the entire shoreline, so there apparently was substantial winterkill of these species.

Age 0 walleyes were abundant in Dalman Pond in fall 2004 (Figure 9). Maximum DO dropped below 1 mg/L by the end of the reverse aeration treatment on 27 Jan 2005 and remained < 1 mg/L for at least 15 days (Figure 2). No walleyes were captured in spring 2005, consistent with a virtually complete winterkill of walleyes; however, fathead minnows were present, indicating a viable population survived the winter (Figure 9). Similarly, trap net results for the untreated reference pond (Shasky) indicated a virtually complete winterkill of age 0 walleyes, but survival of a fathead minnow population (Figure 10). Maximum DO in Shasky Pond declined more gradually than in Dalman Pond, but still dropped below 1 mg/L for over 13 days (Figure 2).

Age 0 walleyes were present in Dalman Pond in fall 2005 (Figure 11). Maximum DO dropped to 2.1 mg/L by the end of the reverse aeration treatment on 8 Feb 2006, then gradually declined to 1.6 mg/L before rising again in early March (Figure 2). No walleyes were captured in spring 2006, again suggesting a complete winterkill of walleyes. As in spring 2005, fathead minnows were present in spring 2006. Trap net results for the untreated reference pond (Swenson) showed that walleyes were still present in spring 2006, so the pond experienced at most a partial winterkill (Figure 12). Maximum DO in Swenson Pond was not observed to drop below 2 mg/L and rebounded earlier than in Dalman Pond (Figure 2), consistent with the survival of walleyes.

Walleye fingerling production

In the six rearing ponds where reverse aeration treatments resulted in substantial and rapid declines in maximum DO, walleye

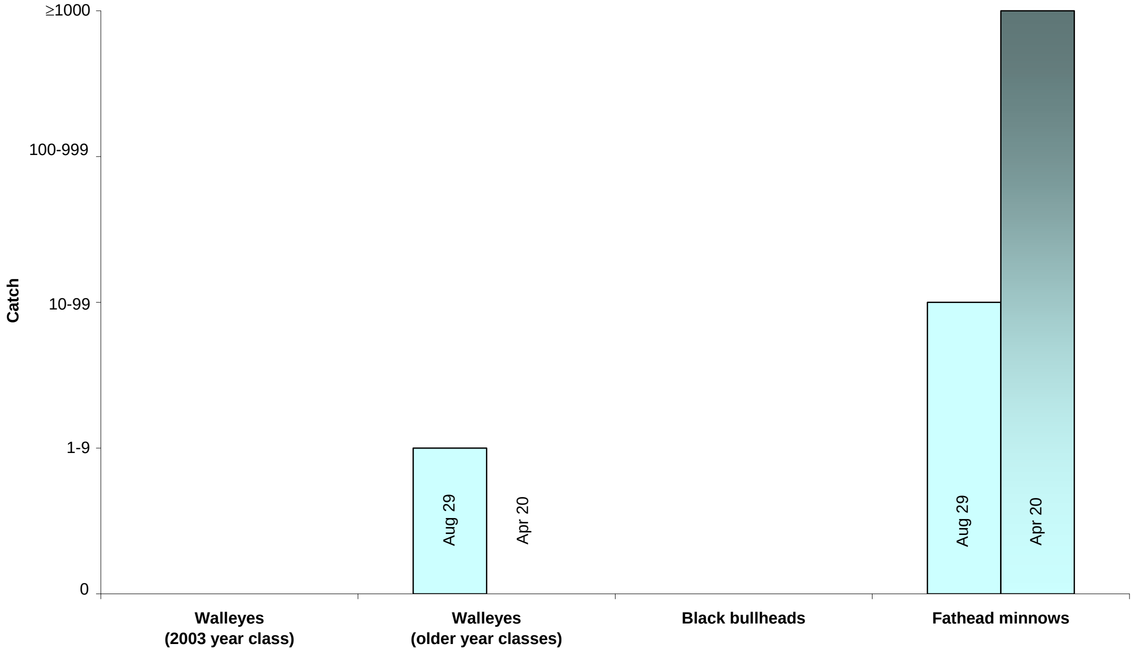

Figure 5. Trap net catches in Mortenson Pond (Kandiyohi Co., Minnesota) in fall 2003 and spring 2004. The pond received a reverse aeration treatment during the winter.

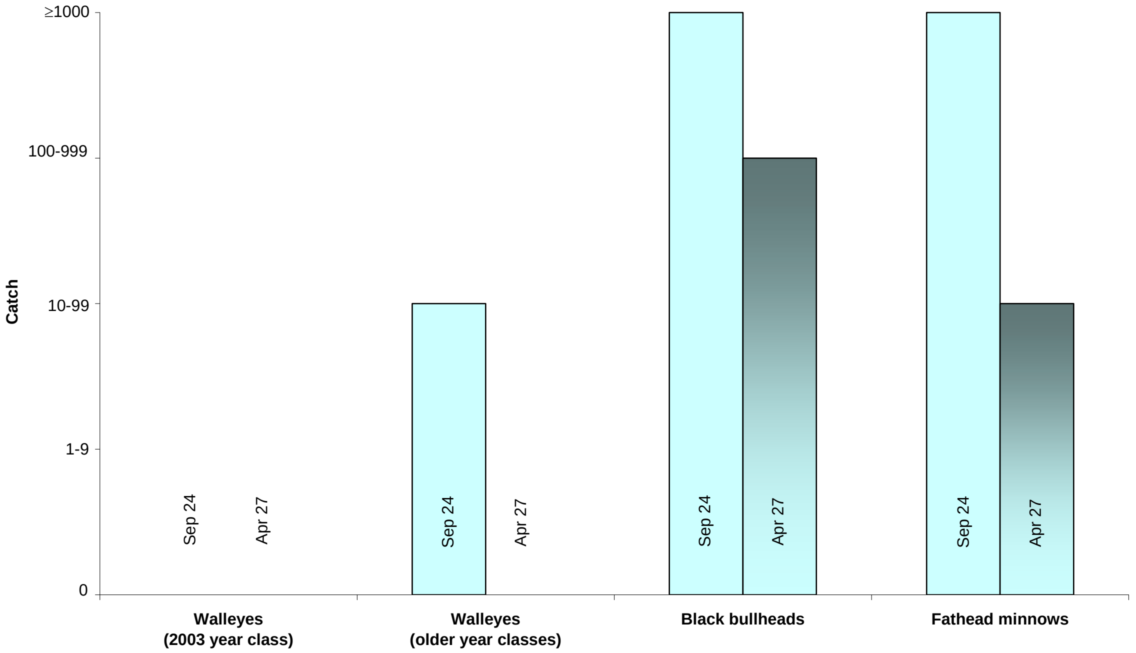

Figure 6. Trap net catches in Doran Pond (Clay Co., Minnesota) in fall 2003 and spring 2004. The pond received a reverse aeration treatment during the winter.

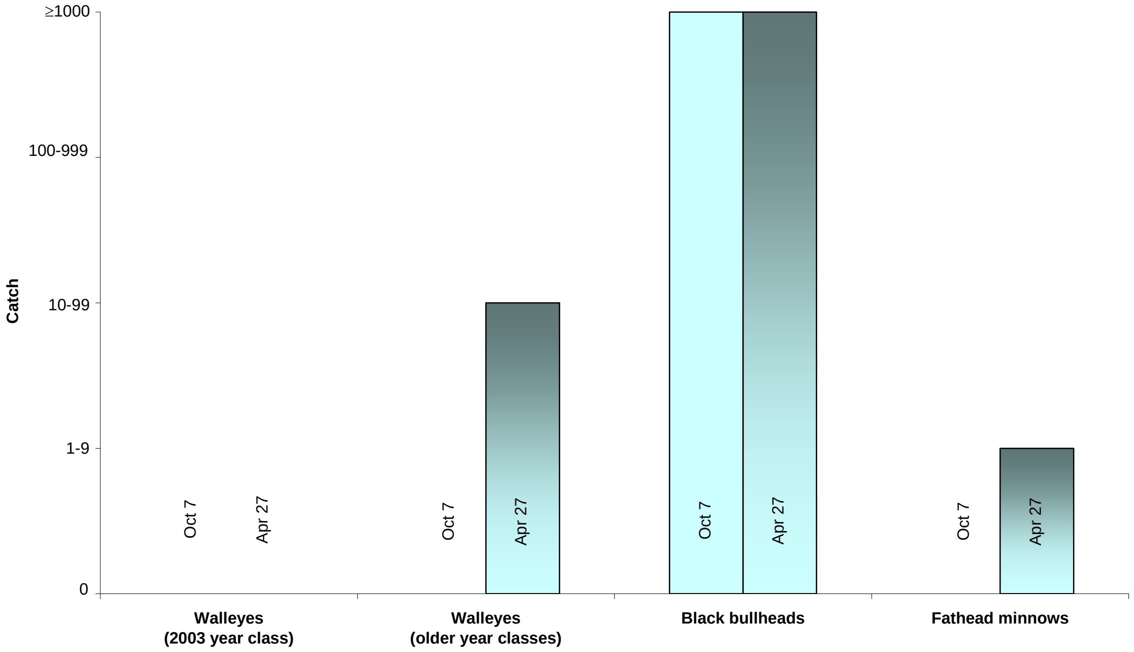

Figure 7. Trap net catches in Tatlie Pond (Clay Co., Minnesota) in fall 2003 and spring 2004. The pond was an untreated reference for Doran Pond.

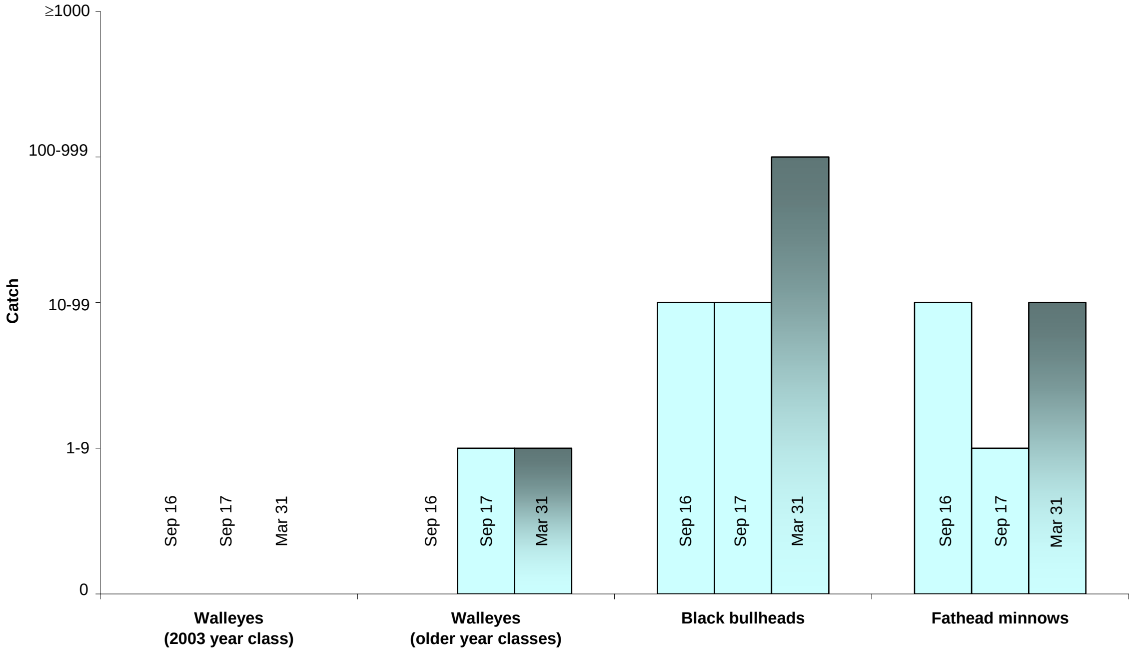

Figure 8. Trap net catches in Turtle Pond (Meeker Co., Minnesota) in fall 2003 and spring 2004. The pond received a reverse aeration treatment during the winter.

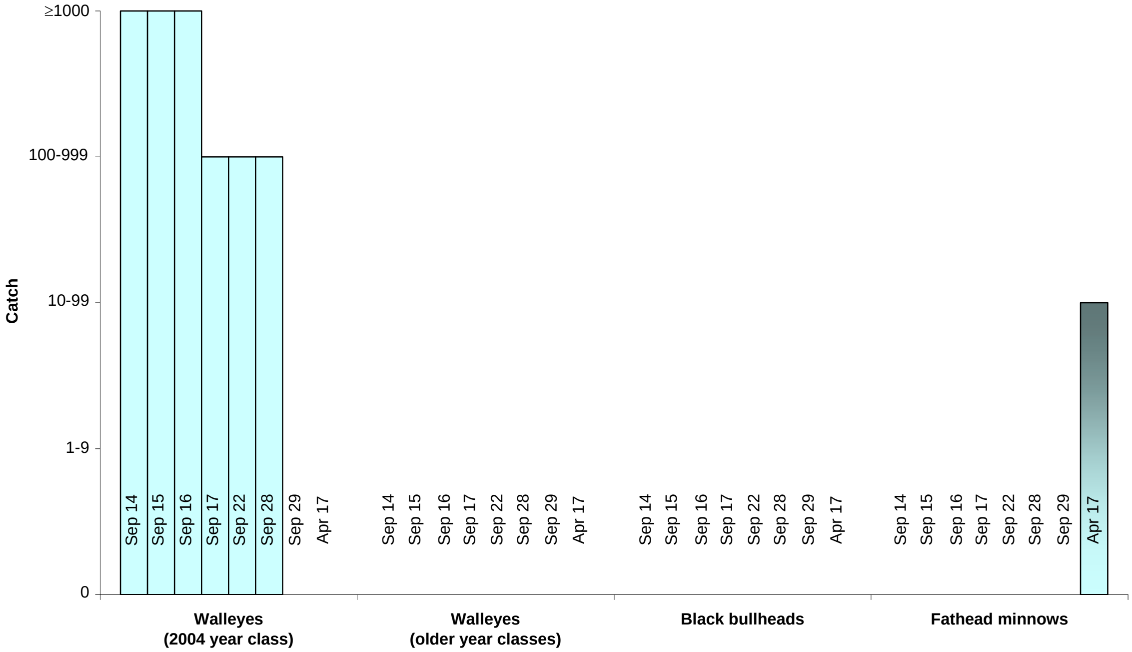

Figure 9. Trap net catches in Dalman Pond (Otter Tail Co., Minnesota) in fall 2004 and spring 2005. The pond received a reverse aeration treatment during the winter.

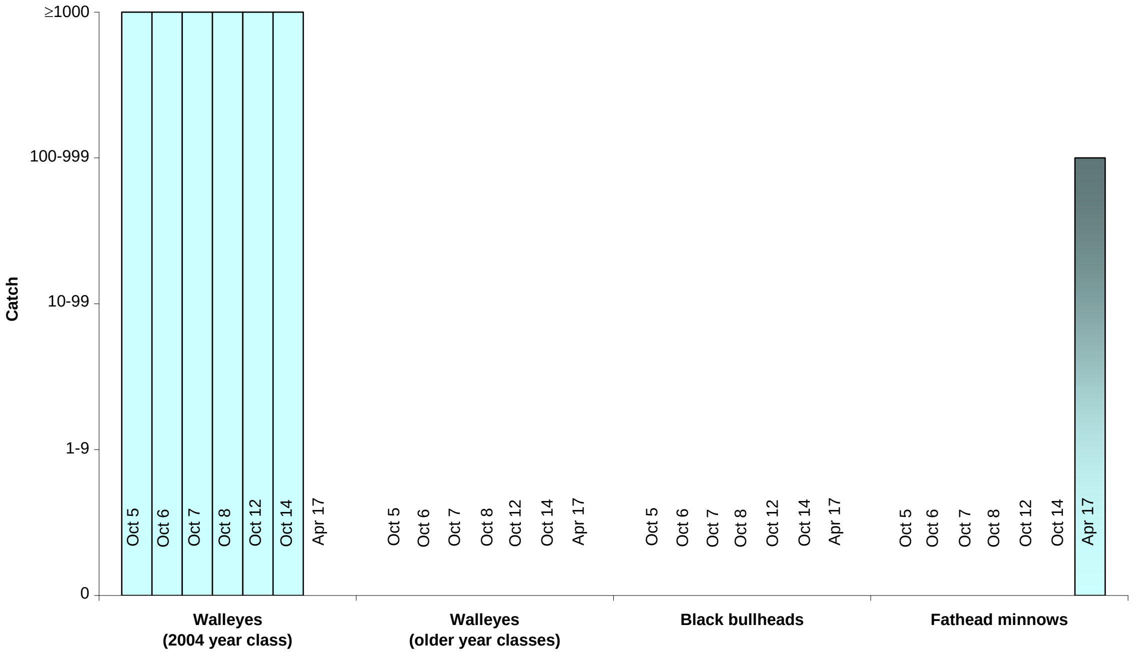

Figure 10. Trap net catches in Shasky Pond (Otter Tail Co., Minnesota) in fall 2004 and spring 2005. The pond was an untreated reference for Dalman Pond.

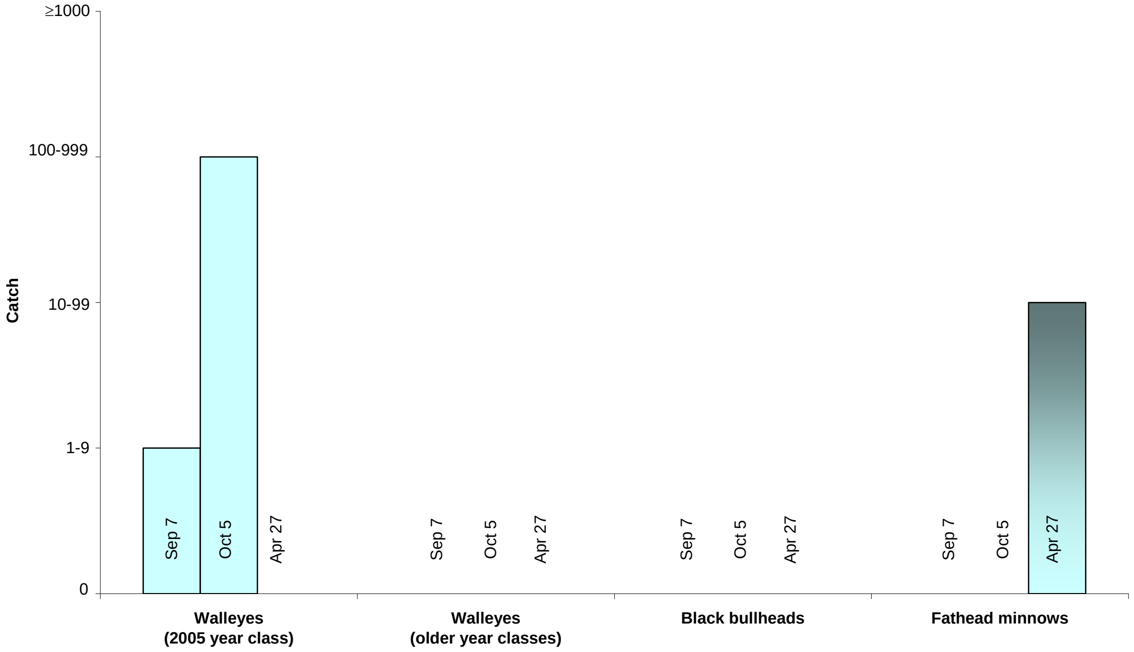

Figure 11. Trap net catches in Dalman Pond (Otter Tail Co., Minnesota) in fall 2005 and spring 2006. The pond received a reverse aeration treatment during the winter.

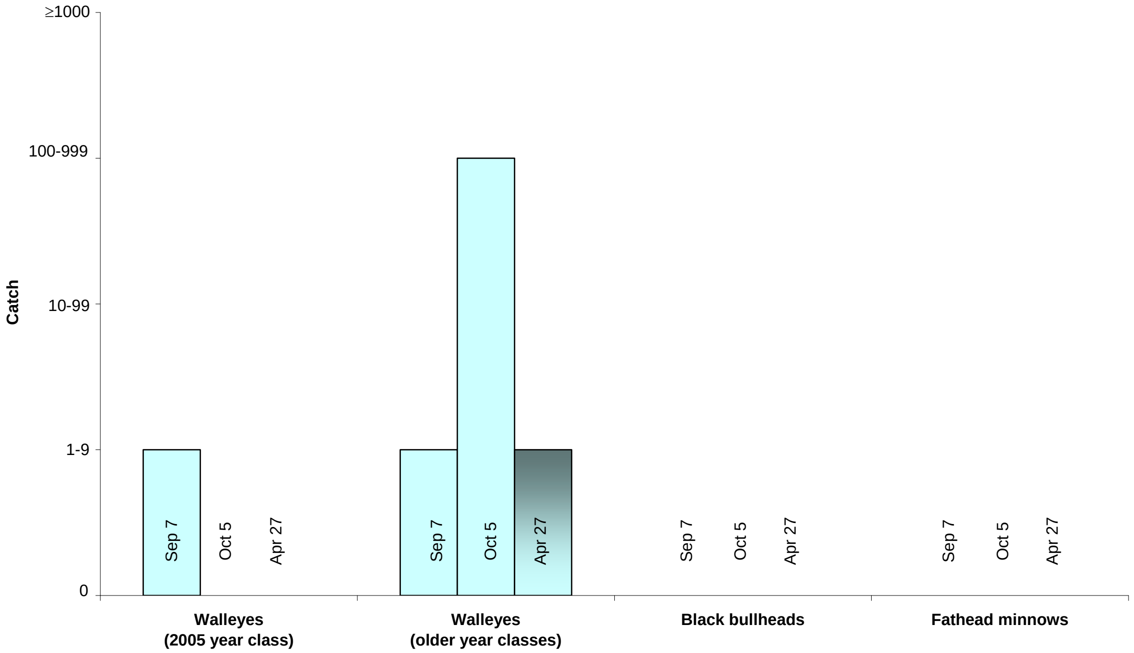

Figure 12. Trap net catches in Swenson Pond (Otter Tail Co., Minnesota) in fall 2005 and spring 2006. The pond was an untreated reference for Dalman Pond.

fingerling production in the growing seasons immediately following the treatments tended to be greater than in untreated reference ponds (Table 4). The positive effect of winterkill on walleye fingerling production is illustrated by the observations that the one untreated reference pond that produced walleye fingerlings (Shasky) winterkilled naturally, and no fingerlings were produced from the same ponds that produced carryover yearlings or adults. However, statistical power was low due to the small sample of ponds and high variability, and therefore the only difference between treated and untreated ponds that approached statistical significance was the number of fingerlings produced (Mann-Whitney rank sum test, $P = 0.067$).

Water quality

There were wide ranges of water quality variables among study ponds (Table 5). However, there were no significant differences between successfully and unsuccessfully treated ponds (*t*-tests or Mann-Whitney rank sum tests**,** $P > 0.10$; Table 6). In addition, there were no significant ($P < 0.10$) overall differences between treated ponds and untreated reference ponds, and no significant ($P < 0.10$) effects of the treatments on measured water quality variables (Table 7); however, there were significant overall seasonal differences in total alkalinity ($P < 0.001$; 11% higher in spring) and total suspended solids ($P = 0.002$; 71% lower in spring). Based on total phosphorus concentrations, approximately 75% of the treated ponds were eutrophic to hypereutrophic, but a few ponds bordered on mesotrophy (Table 6; Wetzel 1983).

Factors influencing success or failure of treatments

Water temperatures under the ice typically range from 0 °C near the ice to 4 °C near the bottom because water at 4 °C has the greatest density (Wetzel 1983). Effective mixing, therefore, reduces the maximum water temperature by moving relatively warm bottom water toward the surface, where it is cooled. Treatments that resulted in substantial and rapid declines in maximum DO were also associated with decreases in maximum temperature exceeding 0.5 °C; rates of decline in these cases ranged from 0.3 – 2.9 °C/d (Table 8). Treatments of Danielson, Shasky, Swenson, and Kolstad ponds resulted in substantial decreases in maximum temperature similar to those that were associated with treatments that did successfully induce substantial declines in DO (Table 8). This suggests that these ponds were effectively mixed, but the treatments failed for other reasons. Ten of the 14 unsuccessful treatments did not result in decreases in maximum temperature exceeding 0.5 °C, suggesting a primary reason for failure in these cases probably was ineffective mixing.

Table 4. Walleye production in rearing ponds where reverse aeration treatments resulted in biologically significant declines in maximum DO, and in untreated reference ponds. Production is divided into fingerlings (FGL), yearlings (YRL), and "adults" (ADL).

		Number			Pounds			Number/lb			lb/acre		
Pond	Year	FGL	YRL	ADL	FGL	YRL	ADL	FGL	YRL	ADL	FGL	YRL	ADL
							Treated						
Anderson	2004	2,392	0	0	184	0	0	13			3.2	0.0	0.0
Dalman	2005	442	0	0	34	0	0	13			3.4	0.0	0.0
Dalman	2006	9,432	0	0	524	0	0	18			52.4	0.0	0.0
Doran	2004	96	0	0	12	0	0	8			0.1	0.0	0.0
Mortenson	2004	12,150	0	0	270	0	0	45			30.0	0.0	0.0
Turtle	2004	11,096	0	0	146	0	0	76			3.4	0.0	0.0
							Untreated						
Iverson	2004	0	1,310	0	0	327	0		4		0.0	6.5	0.0
Shasky	2005	3,910	0	0	170	0	0	23			7.4	0.0	0.0
Swenson	2006	0	284	0	0	188	0		1.5		0.0	7.2	0.0
Tatlie	2004	0	0	12	0	0	24			0.5	0.0	0.0	0.4

Table 5. Mean values for total phosphorus, total alkalinity, carbonaceous biochemical oxygen demand (BOD), and total suspended solids (TSS) in the study ponds, from surface grabs collected during September – October. Values of *n* represent the numbers of annual samples.

	Total P (μg/L)		Total alk. (mg/L)		BOD (mg/L)		TSS (mg/L)	
Pond	Mean	*n*	Mean	*n*	Mean	*n*	Mean	*n*
Anderson	376.0	3	140.7	3	12.23	3	29.60	3
Armstrong	61.5	2	185.0	1	2.60	2	3.65	2
Bachelor	119.5	4	219.7	3	4.70	4	7.70	4
Bass	32.3	4	14.2	3	2.33	4	2.18	4
Bullhead	187.7	3	324.0	2	8.33	3	26.80	3
Bunker	23.5	2	53.0	1	1.10	2	1.00	2
Butternut	305.8	4	157.3	3	9.35	4	18.20	4
Chelgren	74.0	4	176.3	3	4.85	4	12.00	4
Christianson	86.0	3	219.7	3	5.97	3	15.20	3
Clear	227.3	3	165.5	2	5.57	3	9.77	3
Dalman	178.0	4	171.3	3	5.43	4	16.00	4
Danielson	248.0	2	392.5	2	9.85	2	38.80	2
Doran	105.8	4	208.7	3	5.95	4	27.50	4
Dorrow	139.0	4	131.3	3	1.70	4	1.48	4
Elbow	24.0	1		0	2.50	1	4.10	1
Fink	137.0	4	87.3	3	4.43	4	6.88	4
Golf Course	523.0	4	304.3	3	13.83	4	63.45	4
Hanson	206.0	4	122.0	3	4.18	4	4.70	4
Hogan	37.5	4	187.7	3	1.90	4	2.95	4
Iverson	109.5	4	262.0	3	3.20	4	10.23	4
Juni	51.5	2	173.0	2	1.50	2	1.10	2
Kleindl	1,080.0	1		0	3.70	1	58.00	1
Knutson	61.0	4	185.0	3	3.90	4	6.75	4
Kolstad	127.0	3	186.3	3	7.37	3	48.40	3
Lieberg	145.0	4	197.0	3	10.08	4	25.50	4
Lovera	28.0	1		0	2.20	1	11.20	1
Masford	23.3	4	117.3	3	1.70	4	1.48	4
Melrose	62.7	3	86.0	2	3.60	3	9.17	3
Mortenson	46.3	4	139.0	3	2.03	4	4.35	4
Neuner	35.0	1		0	2.00	1	3.20	1
North Haukos	2,107.5	4	495.3	3	4.85	4	23.28	4
Otter	2,326.7	3	190.5	2	7.23	3	31.00	3
Praught		0		0		0		0
Rohrbeck	371.3	4	125.7	3	7.18	4	42.35	4
Roland	214.3	4	152.3	3	9.25	4	40.00	4
Round	259.0	1		0	5.30	1	15.60	1
Rustad	53.5	4	209.7	3	3.23	4	5.50	4
Sanderson	155.3	3	231.5	2	7.27	3	27.73	3
Savidge	161.3	4	155.0	3	6.55	4	19.40	4
Schreiers	173.5	2	50.5	2	3.30	2	4.30	2
Shasky	152.0	4	144.7	3	7.30	4	31.10	4
Stephens	59.3	4	19.3	3	1.50	4	2.50	4
Swenson	457.3	3	297.3	3	10.87	3	46.40	3
Taffe	479.8	4	378.0	3	4.93	4	28.20	4
Tatlie	109.5	4	211.7	3	5.83	4	25.40	4
Towner	215.0	1		0	11.30	1	36.80	1
Turtle	41.3	4	108.3	3	2.83	4	6.93	4

Table 6. Water quality variables in the six ponds where reverse aeration treatments resulted in substantial and rapid declines in maximum DO (Success = Yes), compared to the ponds where reverse aeration treatments did not result in substantial and rapid declines in maximum DO (Success = No). The four ponds with inconclusive treatment results are excluded. Variables were measured the fall before treatment, except three ponds unsuccessfully treated during the winter of 2002-2003 did not have total alkalinity measured until the fall after treatment.

		Total phosphorus (μg/L)				
Success	*n*	Minimum	25 percentile	Median	75 percentile	Maximum
Yes	6	33	46	110	147	445
No	12	48	56	152	255	2080

		Total alkalinity (mg/L)				
Success	*n*	Minimum	25 percentile	Median	75 percentile	Maximum
Yes	6	116.0	139.0	153.5	162.0	223.0
No	12	16.0	137.3	185.5	233.8	391.0

		Total suspended solids (mg/L)				
Success	*n*	Minimum	25 percentile	Median	75 percentile	Maximum
Yes	6	1.9	6.8	13.6	18.5	42.0
No	12	0.5	3.4	16.3	27.5	76.0

		Carbonaceous biochemical oxygen demand (mg/L)				
Success	*n*	Minimum	25 percentile	Median	75 percentile	Maximum
Yes	6	1.9	3.9	4.4	5.0	11.4
No	12	0.9	1.9	4.0	7.8	16.0

Table 7. Results of univariate repeated measures ANOVA of water quality variables in all ponds treated with reverse aeration, and in all untreated reference ponds. Water samples were collected during the fall before a treatment and again in the spring following a treatment. The Treatment effect represents an overall difference between treated ponds and untreated reference ponds; the Season effect represents an overall difference between fall and spring samples; and the Season X Treatment interaction represents a difference between fall and spring samples that is attributable to the treatments.

Total phosphorus

Source	SS	df	MS	F	*P*
Between subjects					
Treatment	1.236	1	1.236	2.315	0.137
Error	18.148	34	0.534		
Within subjects					
Season	0.001	1	0.001	0.078	0.782
Season X Treatment	0.014	1	0.014	1.176	0.286
Error	0.392	34	0.012		

Total alkalinity

Source	SS	df	MS	F	*P*
Between subjects					
Treatment	11,481.046	1	11,481.046	0.648	0.427
Error	513,544.671	29	17,708.437		
Within subjects					
Season	6,249.805	1	6,249.805	29.432	0.000
Season X Treatment	0.563	1	0.563	0.003	0.959
Error	6,158.042	29	212.346		

Total suspended solids

Source	SS	df	MS	F	*P*
Between subjects					
Treatment	182.048	1	182.048	0.437	0.513
Error	14,156.756	34	416.375		
Within subjects					
Season	960.238	1	960.238	10.774	0.002
Season X treatment	56.413	1	56.413	0.633	0.432
Error	3,030.242	34	89.125		

Table 7. Continued.

	Carbonaceous biochemical oxygen demand				
Source	SS	df	MS	F	*P*
Between subjects					
Treatment	25.567	1	25.567	1.073	0.308
Error	810.451	34	23.837		
Within subjects					
Season	1.805	1	1.805	0.206	0.652
Season X treatment	1.206	1	1.206	0.138	0.713
Error	297.268	34	8.743		

Table 8. Changes in maximum temperature (T) associated with reverse aeration treatments. "Successful" treatments were those where maximum DO declined at least 2.0 mg/L at rates exceeding 1.0 mg/L/d. Inconclusive treatments were those where initial maximum DO was < 2.0 mg/L.

Pond	Time interval		Initial T (°C)	Final T (°C)	Δ T (°C)	Rate (°C/d)	Successful?
Danielson	2/5/04 9:00	2/5/04 15:00	2.39	0.50	-1.89	-7.6	No
Dalman	1/25/05 11:00	1/27/05 9:00	4.40	2.90	-1.50	-0.8	Yes
Shasky	2/27/03 9:30	2/28/03 10:15	5.00	3.50	-1.50	-1.5	No
Dalman	2/6/06 11:15	2/8/06 10:00	4.30	2.90	-1.40	-0.7	Yes
Turtle	2/18/04 10:00	2/20/04 14:00	4.50	3.60	-0.90	-0.4	Yes
Swenson	2/11/04 9:00	2/11/2004 12:45	2.80	2.00	-0.80	-5.1	No
Anderson	2/3/04 12:00	2/6/04 13:00	4.30	3.50	-0.80	-0.3	Yes
Kolstad	2/10/05 9:30	2/11/05 12:15	4.50	3.80	-0.70	-0.6	No
Armstrong	2/19/04 10:00	2/20/04 14:00	3.30	2.60	-0.70	-0.6	Inconclusive
Doran	2/12/04 10:00	2/12/04 15:00	3.30	2.70	-0.60	-2.9	Yes
Hanson	1/26/06 10:00	1/27/06 10:00	6.20	5.70	-0.50	-0.5	No
Savidge	2/8/05 10:00	2/9/05 12:00	4.30	3.80	-0.50	-0.5	No
Chelgren	2/9/06 11:00	2/10/06 13:30	4.90	4.50	-0.40	-0.4	No
Stephens	2/2/05 8:00	2/2/05 15:00	3.80	3.40	-0.40	-1.4	No
Rustad	2/13/03 8:45	2/20/03 12:00	4.10	3.70	-0.40	-0.1	Inconclusive
Melrose	1/27/04 10:00	1/30/04 12:00	4.20	3.90	-0.30	-0.1	No
Golf Course	2/12/03 10:00	2/13/03 12:00	2.20	2.00	-0.20	-0.2	No
Golf Course	2/25/03 12:00	2/26/03 12:00	2.33	2.22	-0.11	-0.1	No
Dorrow	2/14/03 9:00	2/14/03 11:00	3.80	3.80	0.00	0.0	Inconclusive
Hanson	2/7/05 9:00	2/8/05 15:00	4.50	4.60	0.10	0.1	Inconclusive
Otter	2/19/03 10:00	2/20/03 12:00	3.90	4.00	0.10	0.1	No
Tatlie	1/19/05 14:00	1/21/05 12:00	3.50	3.90	0.40	0.2	No
Otter	2/28/03 11:00	2/28/03 14:00	4.10	4.50	0.40	3.2	No
Mortenson[1]	2/5/04 11:00	2/6/04 10:00	n/a	n/a	n/a	n/a	Yes

[1] Temperature data were not collected.

Successfully treated ponds tended to be smaller than unsuccessfully treated ponds, although the difference was not statistically significant (*t*-test, $P = 0.253$; Table 9). There was also not a statistically significant difference in maximum depths of the two groups of ponds (Mann-Whitney rank sum test, $P = 1.000$), but the successfully treated ponds had a much narrower range of depths: 7 - 10 ft, in contrast to 4 – 24 ft for the unsuccessfully treated ponds (Table 9). Five of the six successful treatments utilized air diffuser systems, either alone or in combination with mud motors. Neither of the two treatments of deep ponds with the airlift system was successful.

All successful treatments were conducted when there was at least 2 in of snow cover on the ponds during the treatments and for at least a week afterward (Figure 13). Six of the 12 unsuccessful treatments were initiated when there was < 2 in of snow cover, or when substantial thawing occurred during or immediately after treatments (e.g., Hanson Pond in 2006).

The only unsuccessful treatments that could not conclusively be explained by ineffective mixing or poor snow and ice conditions were Shasky in 2003, Danielson in 2004, and Swenson in 2004. These were all small ponds (22 – 26 ac), and as mentioned above, temperature data indicated all of them were effectively mixed. Shasky Pond (maximum depth 11 ft) was treated with a combination of air diffusers and mud motors, while the other two ponds (maximum depths 5 – 8 ft) were treated with mud motors only. Thawing was not an issue during any of these treatments. Snow depths during the Shasky and Danielson treatments were only 2.0 – 2.6 in. These ponds each had at least one station where DO was > 2.0 mg/L near the bottom when treatment was initiated, suggesting the snow cover was not enough to prevent photosynthesis (Figures 14-15). However, during the Swenson treatment snow depth was 5.5 in, and all DO stations had at least some anoxic water when the treatment was initiated (Figure 16).

Discussion

Effectiveness at reducing maximum DO

Overall, reverse aeration treatments did have a statistically significant effect, but only six of the 24 treatments (25%) resulted in biologically significant declines in maximum DO. Excluding the four treatments that were initiated when maximum DO was already < 2 mg/L and the six treatments that were done when snow and ice conditions were clearly unfavorable would increase incidence of biologically significant DO declines to 50%. Most of the unsuccessful treatments that were conducted under favorable snow and ice conditions probably failed due to ineffective mixing. Managers may be able to achieve biologically significant declines in maximum DO in at least 50% of attempts in ponds similar to those in this study if they avoid treating ponds under unfavorable snow and ice conditions, and ensure effective mixing. Maximum temperatures should be monitored and mixing should be considered incomplete if temperature declines are less than 0.5 °C. Mixing should continue until maximum temperature

Table 9. Areas and maximum depths of ponds treated with reverse aeration. "Successful" treatments were those where maximum DO declined at least 2.0 mg/L at rates exceeding 1.0 mg/L/d. Inconclusive treatments were excluded.

	Successful		Unsuccessful	
	Area (ac)	Maximum depth (ft)	Area (ac)	Maximum depth (ft)
Minimum	9.0	7.0	20.0	4.0
25 percentile	10.0	9.0	25.3	6.0
Median	26.5	9.0	63.0	9.0
75 percentile	54.3	9.8	77.0	18.5
Maximum	100.0	10.0	168.0	24.0

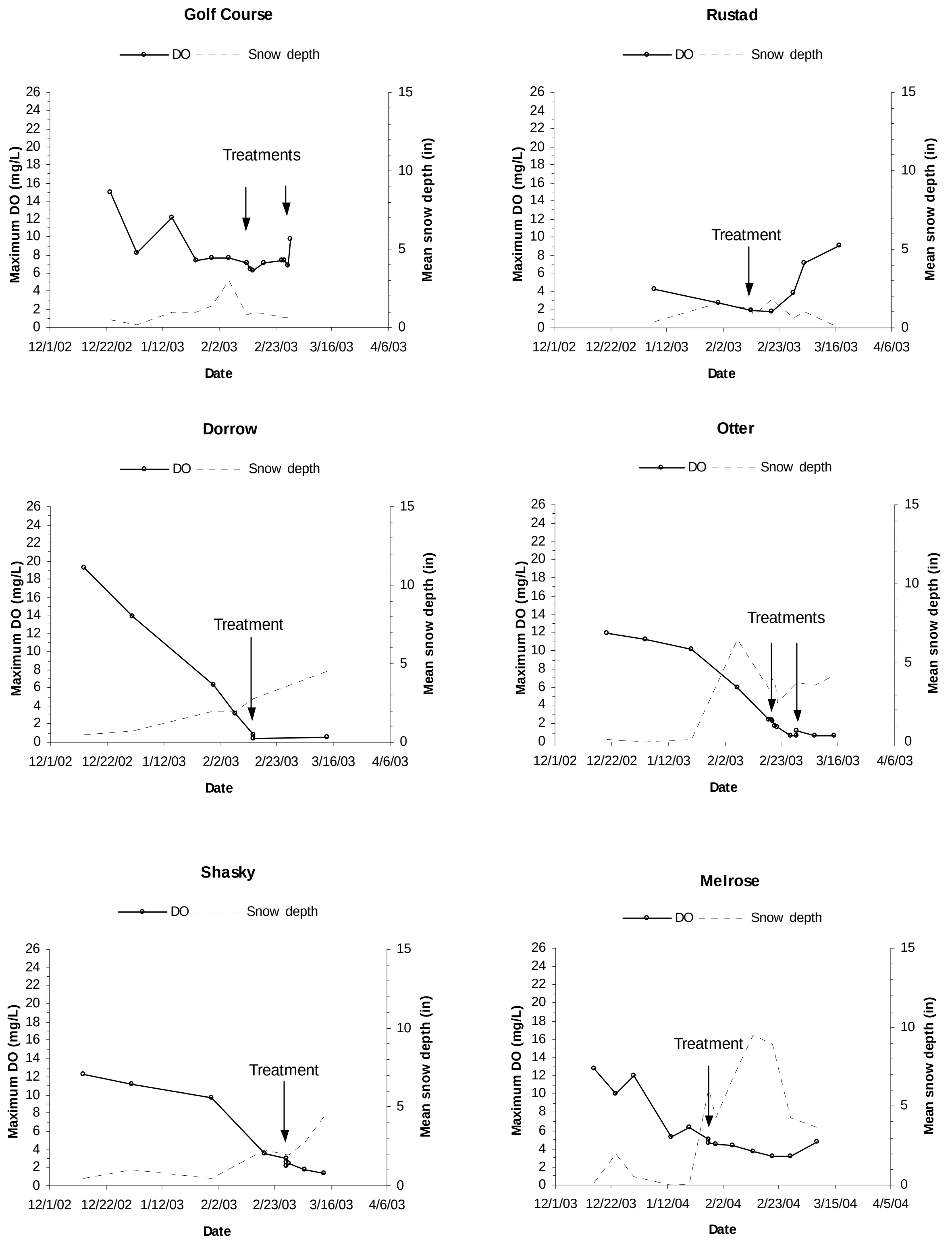

Figure 13. Maximum DO and mean snow depth for ponds that underwent reverse aeration treatments

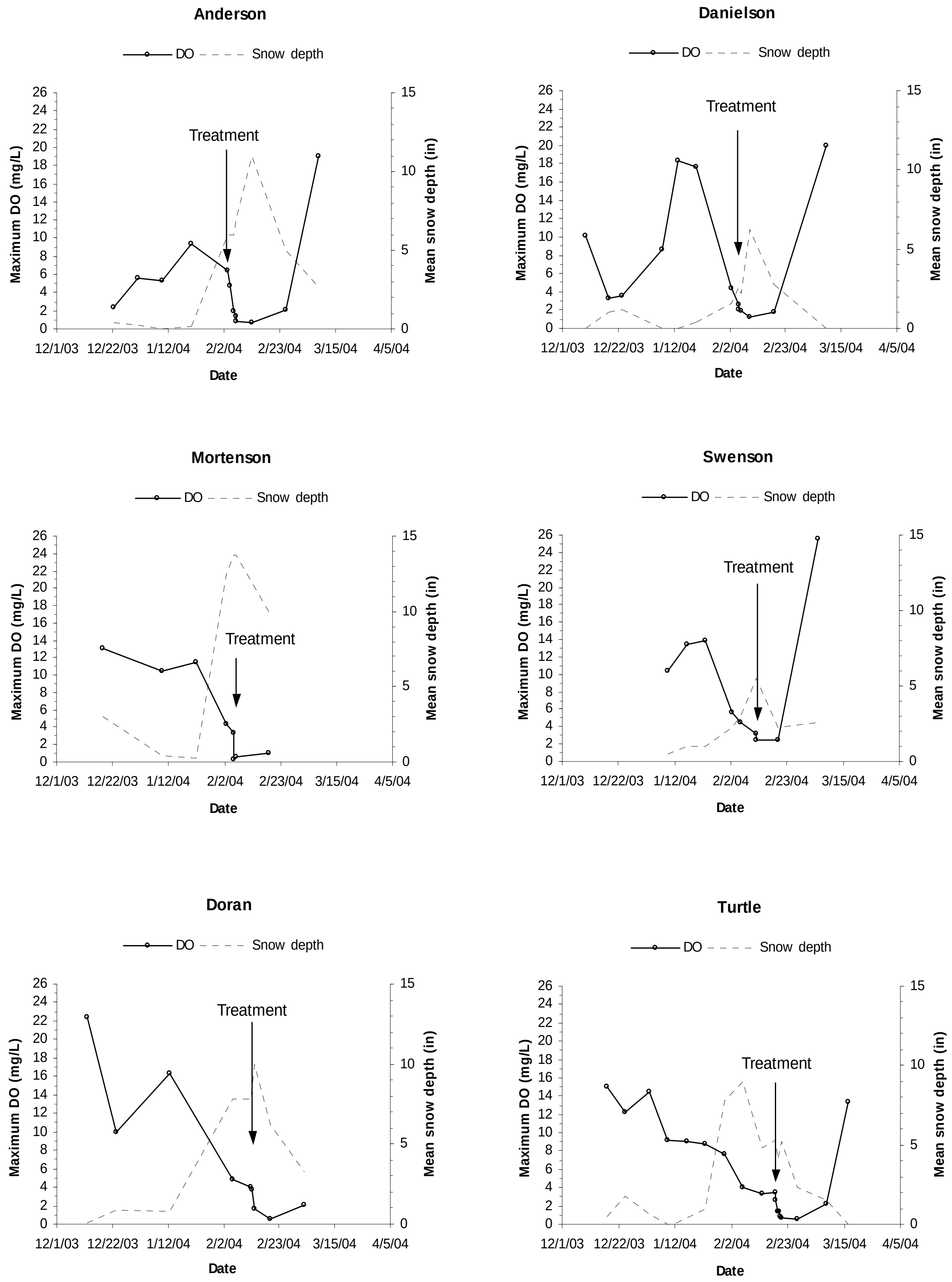

Figure 13. Continued.

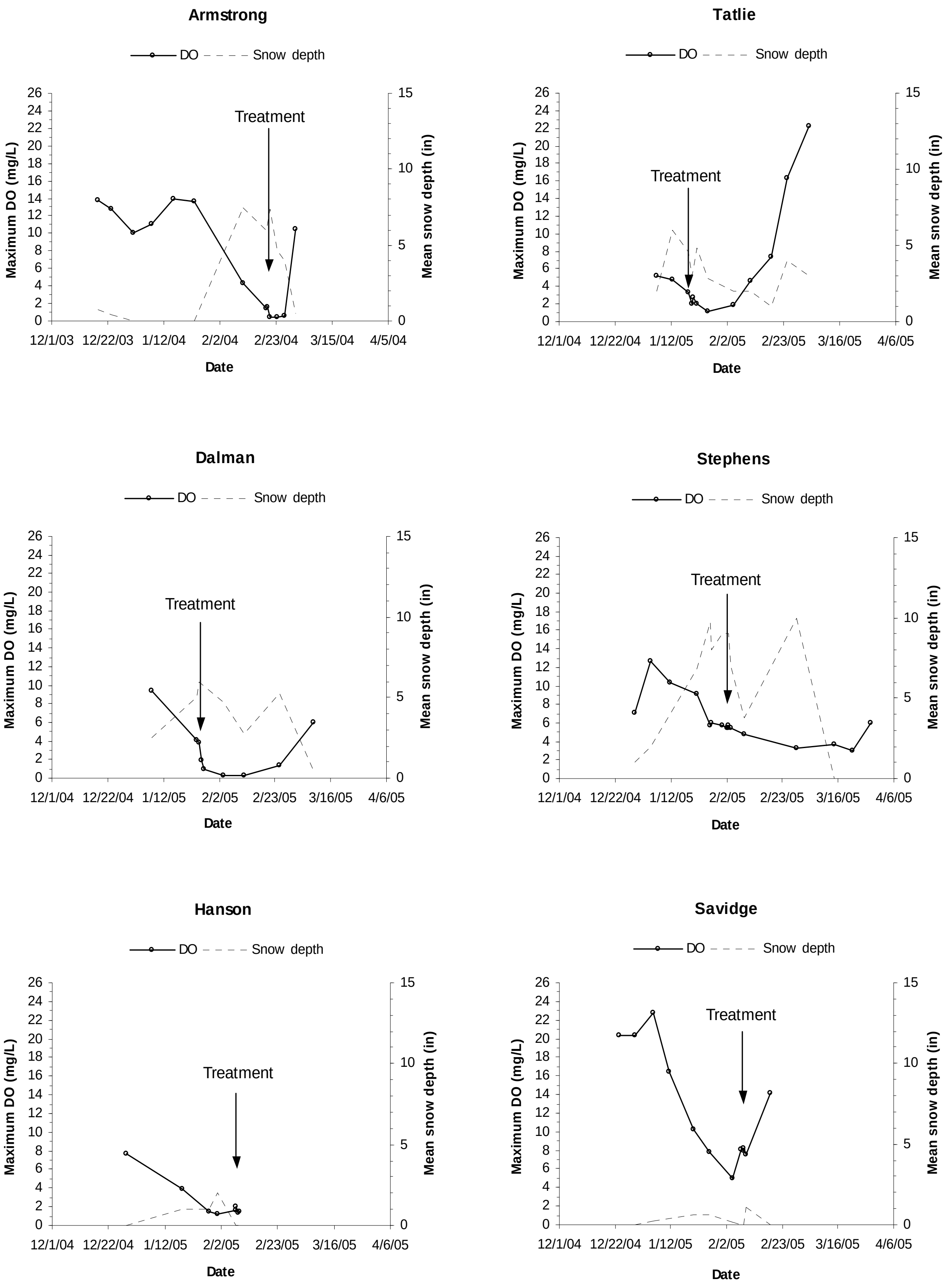

Figure 13. Continued.

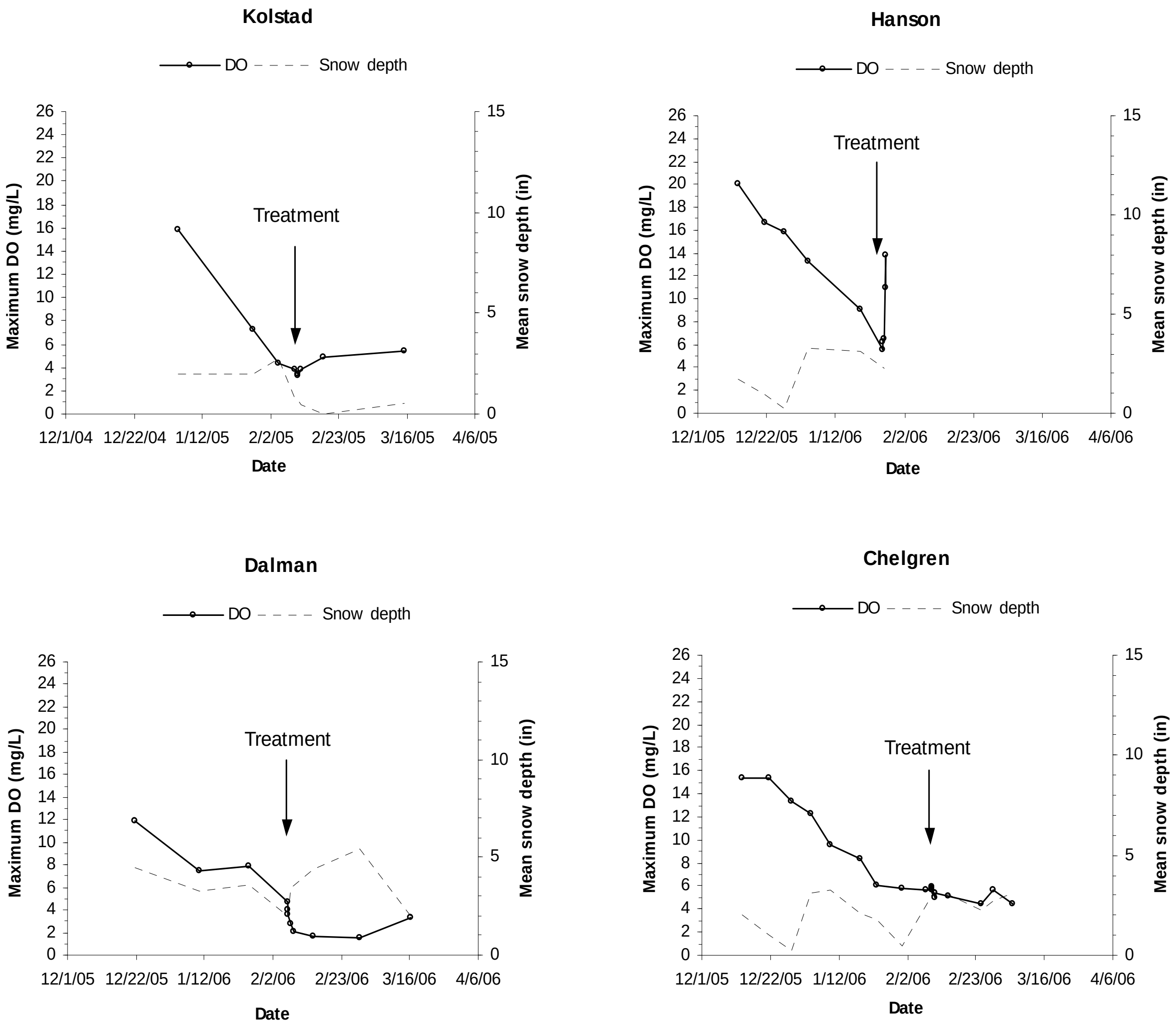

Figure 13. Continued.

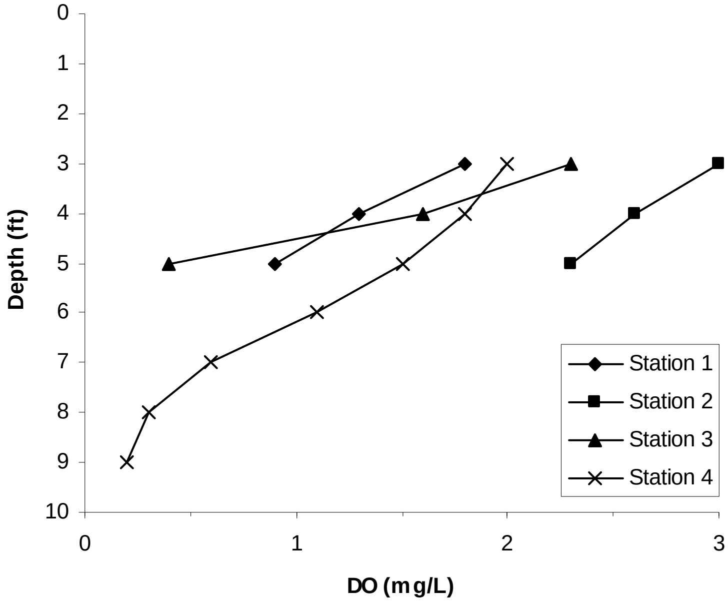

Figure 14. Dissolved oxygen profiles at index stations in Shasky Pond just before an unsuccessful reverse aeration treatment was initiated on 27 Feb 2003.

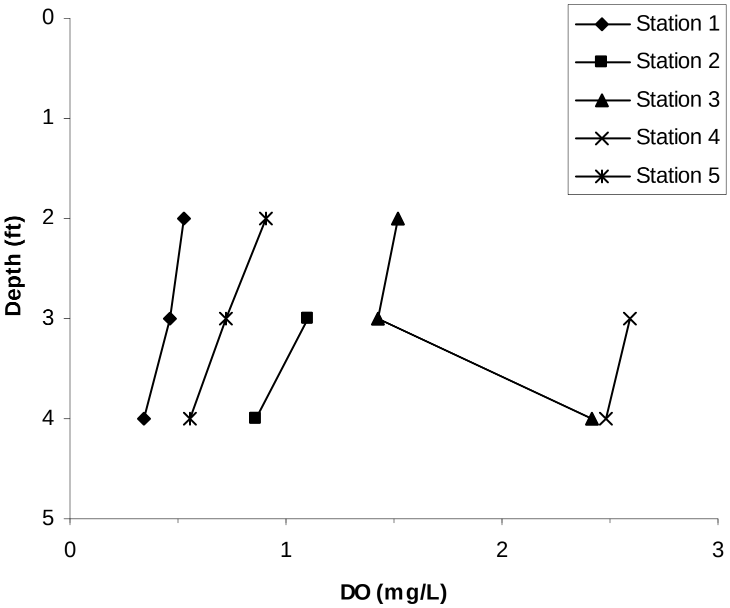

Figure 15. Dissolved oxygen profiles at index stations in Danielson Pond just before an unsuccessful reverse aeration treatment was initiated on 5 Feb 2004.

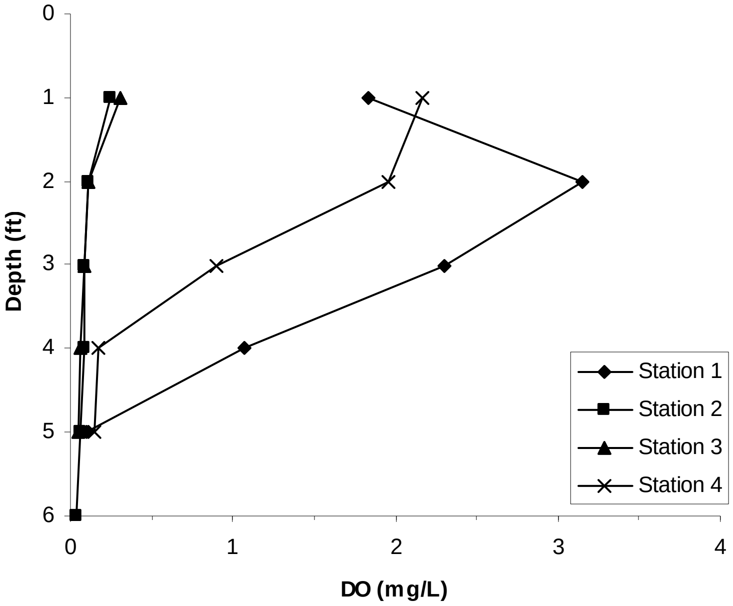

Figure 16. Dissolved oxygen profiles at index stations in Swenson Pond just before an unsuccessful reverse aeration treatment was initiated on 11 Feb 2004.

declines at least 0.5 °C, as long as doing so does not create an excessive amount of open water. Some ponds may require more treatment time than we spent during this study.

Effectiveness at inducing winterkill

In all six cases where treatments were associated with large and rapid declines in maximum DO, some species including walleyes, sunfish, and white suckers were substantially reduced or eliminated. The maximum DO did not necessarily drop low enough to induce winterkill during the treatment itself, but the decrease in DO associated with the treatment insured that winterkill would occur before snow and ice conditions deteriorated. In five of these six cases substantial winterkill probably would not have occurred without treatment. The treatment of Dalman Pond in 2005 induced a longer period of anoxia than would have occurred naturally, but based on observations of an untreated reference pond, the treated pond might have winterkilled anyway.

Although we successfully induced winterkill of some species, maximum DO levels never dropped low enough for long enough to kill more than an inconsequential proportion of bullhead or fathead minnow populations. If future Minnesota winters are similar to or milder than those during this study, it is unlikely that reverse aeration will be a useful management tool for controlling extremely anoxia-tolerant species.

Predictability of winterkill

Minnesota fisheries managers have sometimes had difficulty predicting winterkill. In this study, winterkill was predictable from maximum DO measurements at multiple index sites and multiple depths per site. Consistent with the literature (Moore 1942; Greenbank 1945; Cooper and Washburn 1946; Moyle and Clothier 1959; Johnson 1965; Johnson and Moyle 1969; Bandow 1986), winterkill of most species except bullheads and fathead minnows always occurred when maximum DO dropped below 1.0 mg/L for at least six days, and in one case winterkill of carryover walleyes occurred when the maximum DO reached 1.0 – 2.0 mg/L and remained at this level for at least 14 days. However, maximum DO in a pond was often quite variable vertically and horizontally on a given day, so reliance on only a few measurements to predict winterkill could have been misleading. I suspect much of the difficulty fisheries managers have had with predicting winterkill is due to not measuring DO at enough sites and depths (including the ice/water interface) to accurately determine the maximum DO levels actually available to fish.

Advantages and disadvantages relative to rotenone treatments

Major disadvantages of reverse aeration relative to rotenone treatments are that results are less assured; reverse aeration is unlikely to control extremely anoxia-tolerant species such as bullheads or fathead minnows; and reverse aeration can only be done opportunistically when DO, snow, and ice conditions are favorable. Extremely mild winters with little snow cover provide little or no opportunity for reverse aeration. On the other hand, if winters are severe enough for reverse aeration to be effective, some ponds may winterkill naturally anyway. Nonetheless, reverse aeration may be worth considering as a management tool if somewhat anoxia-intolerant species such as sunfish, carryover walleyes, or white suckers are the main concern. Reverse aeration could replace rotenone treatments in some cases, or at least extend the period of successful walleye fingerling production between rotenone treatments.

Cost for rotenone is roughly US $20 per acre-foot of water treated (Hugh Valiant, Minnesota DNR Division of Fish and Wildlife, personal communication). Therefore, the typical size of pond that was successfully treated with reverse aeration in this study (25 ac), assuming an average depth of 4 ft, would require approximately $2,000 worth of rotenone; the maximum size of pond successfully treated with reverse aeration (100 ac) would require approximately $8,000 worth of rotenone (again assuming an average depth of 4 ft). Costs of reverse aeration equipment purchased for this study in November 2002 were:

Aquatic Ecosystems SL9 systems	$2,193 each
24 hp mud motors	$2,940 each
5500 W portable generators	$ 960 each

Thus, startup costs for reverse aeration can be greater than or equal to the cost of a single rotenone treatment on a small water body. However, the reverse aeration equipment can be used for many treatments, can potentially be shared among several field offices, and can be used for other purposes besides reverse aeration. In addition, there may be effective lower-cost alternatives to purchasing SL9 systems and generators – such as the air lift tubes (Appendix 23) and rented air compressors that we used unsuccessfully in two deep ponds but did not compare to the SL9 systems in shallower ponds.

A reverse aeration treatment could be more labor-intensive than a rotenone treatment of the same water body, depending on the amount of DO monitoring before, during, and after the reverse aeration treatment; the size, depth, and shape of the pond; and the methods used. However, reverse aeration is done during a time of the year when Minnesota DNR fisheries personnel typically are not busy with other fieldwork, so labor is readily available. A team of 2-3 people can set up an SL9 system in less than two hours. Once an SL9 system is started, it can be left running unattended except for visits approximately every 18 h to refuel the generator and make sure the system is still operating properly. Each mud motor used requires a team of 2-3 people to cut holes in the ice and position the boat and motor. Each mud motor treatment site requires approximately 15 minutes to cut a hole in the ice and position the boat and motor, in addition to the amount of time that the motor is run. A small pond such as Dalman with a shape and depth favorable for efficient operation of a single SL9 system can be treated with minimal effort. A larger, shallow, irregularly shaped pond such as Doran may require up to three mud motor crews working simultaneously for at least an 8-hour day. Due to the amount of labor and equipment that is required to effectively mix a large volume of water in a short period of time, reverse aeration is best suited to ponds < 100 acres or to small isolated areas within larger lakes (e.g., after partial drawdowns).

Recommendations for conducting treatments

In southern and central Minnesota, late January to early February is the ideal time for conducting reverse aeration treatments. If lakes naturally become anoxic before this time they are likely to winterkill on their own, whereas reverse aeration treatments done later than mid February have a high risk of being negated by thawing and increasing photosynthesis. Shallow eutrophic-hypereutrophic lakes are most likely to provide opportunities for effective reverse aeration treatments. Managers should begin collecting dissolved oxygen and temperature profiles weekly at 4-8 well-spaced index sites on each lake of interest beginning in early to mid January. Dissolved oxygen probes should be calibrated each day at 0-4 °C following the manufacturers' instructions, and if possible the same meter should always be used on a given pond within a season to avoid potential inconsistencies between meters. Depth intervals should be the same as those described in the Methods – do not skip depths to save time, because sometimes the maximum DO does not occur where one expects. The shallowest readings should always be 1 ft below the surface of the water in the hole (even if the ice is thicker than 1 ft) to insure that thin layers of oxygenated water that may occur just under the ice are sampled, and to allow consistent comparisons among sampling dates. The opportunity for an effective treatment exists if maximum DO at all of the index sites has declined below 50% of saturation, snow cover on the pond averages at least 2 in with no substantial areas of thinner cover or bare ice, and no above-freezing temperatures are anticipated for at least a week or two after the treatment would be initiated. Dissolved oxygen and temperature profiles should be collected and evaluated just before and during the treatment to allow determination of whether mixing is effective, and methods should be adjusted if necessary to insure that maximum temperature declines at least 0.5°C by the end of the treatment. Ideally, to document the ultimate magnitude and rate of DO decline and to predict the degree of winterkill, profiles should be collected the day after the treatment ends and at weekly intervals thereafter until maximum DO rebounds above 50% of saturation.

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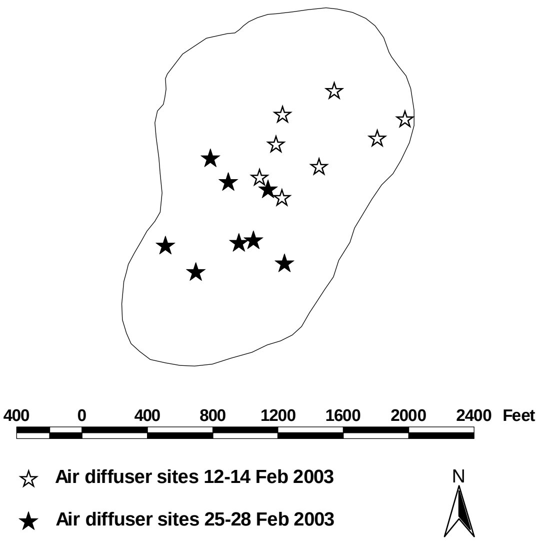
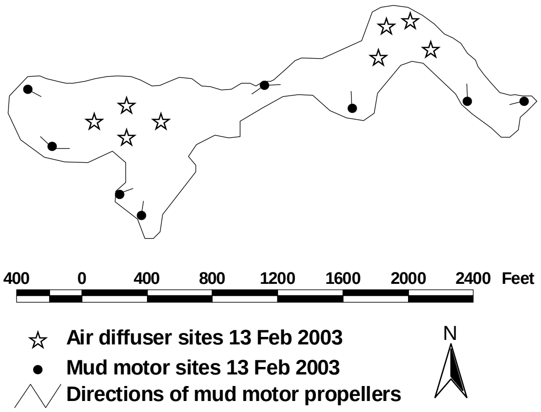
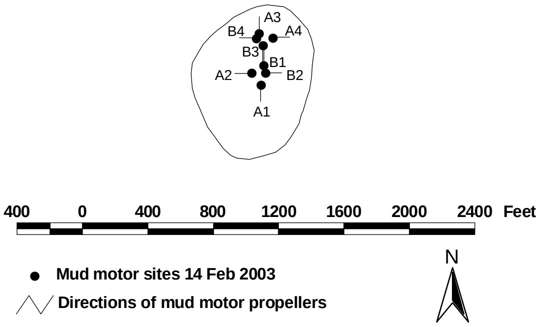
Appendices



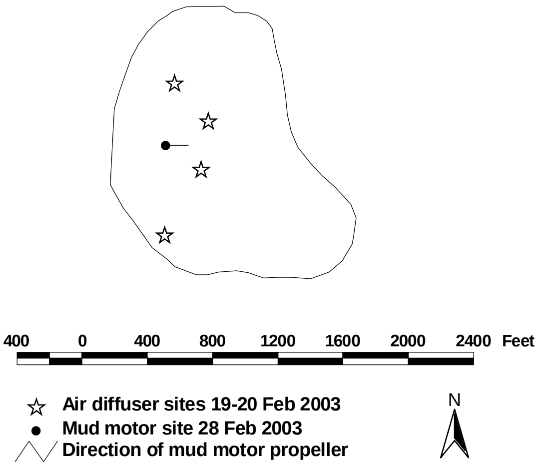
Appendix 1. Air diffuser sites on Golf Course Pond (Big Stone Co., Minnesota) during reverse aeration treatments on 12-14 Feb and 25-28 Feb 2003.



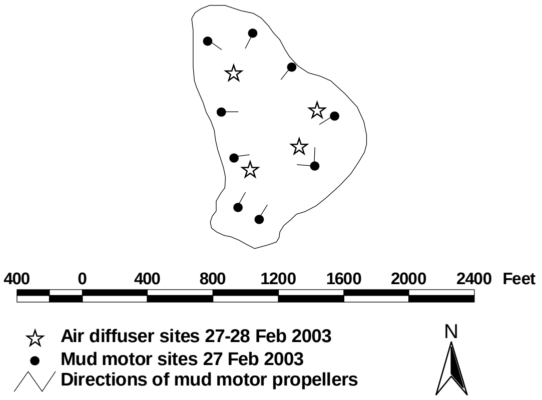
Appendix 2. Air diffuser and mud motor sites on Rustad Pond (Clay Co., Minnesota) during a reverse aeration treatment on 13 Feb 2003.



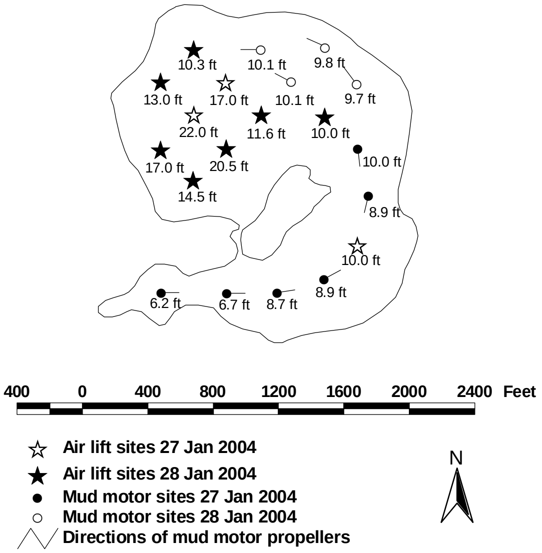
Appendix 3. Mud motor sites on Dorrow Pond (Otter Tail Co., Minnesota) during a reverse aeration treatment on 14 Feb 2003. Capital letters signify two mud motors operating simultaneously, and numerals indicate the order in which sites were treated by each motor.



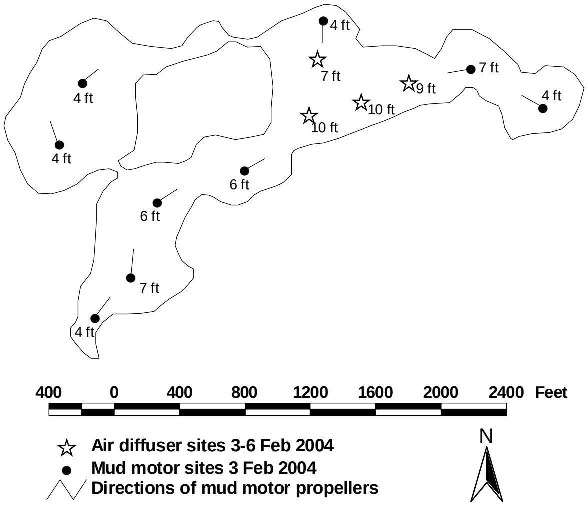
Appendix 4. Air diffuser and mud motor sites on Otter Pond (Wright Co., Minnesota) during reverse aeration treatments on 19-20 Feb and 28 Feb 2003.



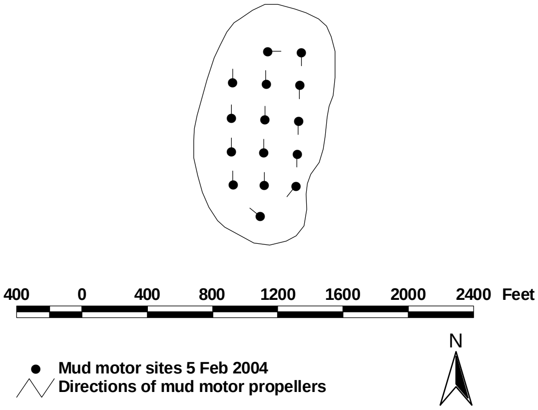
Appendix 5. Air diffuser and mud motor sites on Shasky Pond (Otter Tail Co., Minnesota) during a reverse aeration treatment on 27-28 Feb 2003.



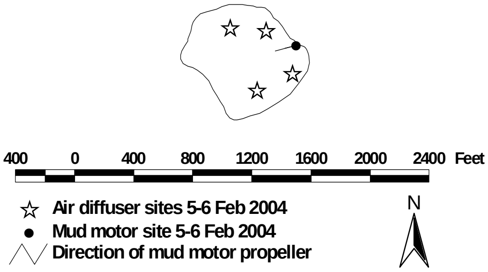
Appendix 6. Air lift and mud motor sites on Melrose Pond (Wright Co., Minnesota) during a reverse aeration treatment on 27-28 Jan 2004. A single air lift tube was run for 30 min at each air lift site.



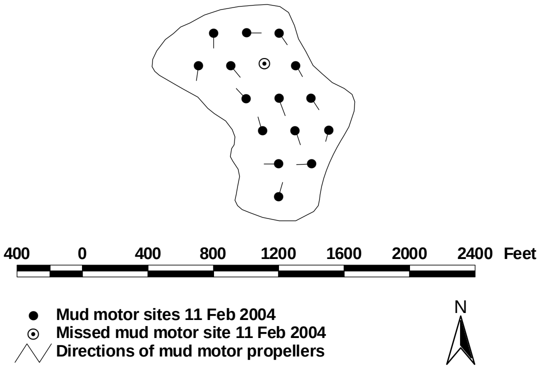
Appendix 7. Air diffuser and mud motor sites on Anderson Pond (Pope Co., Minnesota) during a reverse aeration treatment on 3-6 Feb 2004.



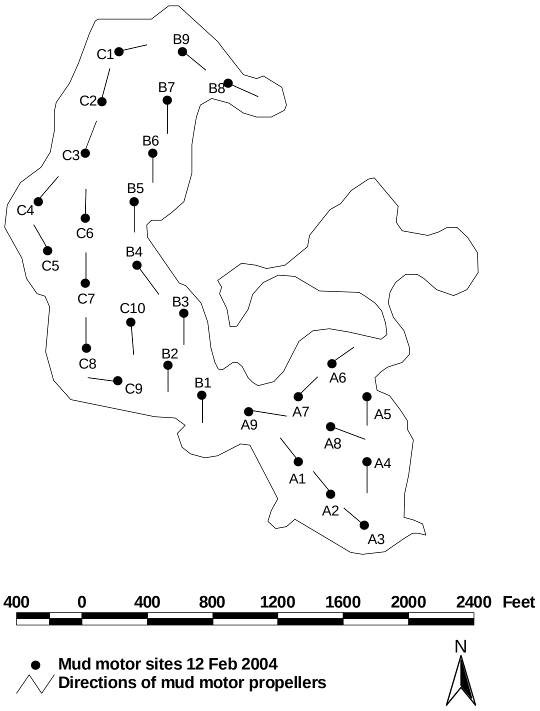
Appendix 8. Mud motor sites on Danielson Pond (Big Stone Co., Minnesota) during a reverse aeration treatment on 5 Feb 2004.



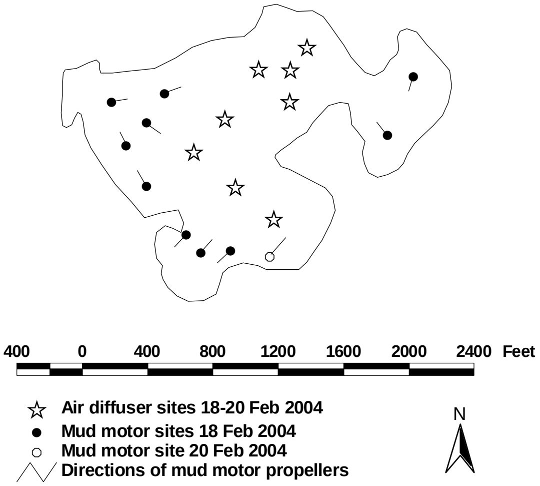
Appendix 9. Air diffuser and mud motor sites on Mortenson Pond (Kandiyohi Co., Minnesota) during a reverse aeration treatment on 5-6 Feb 2004.



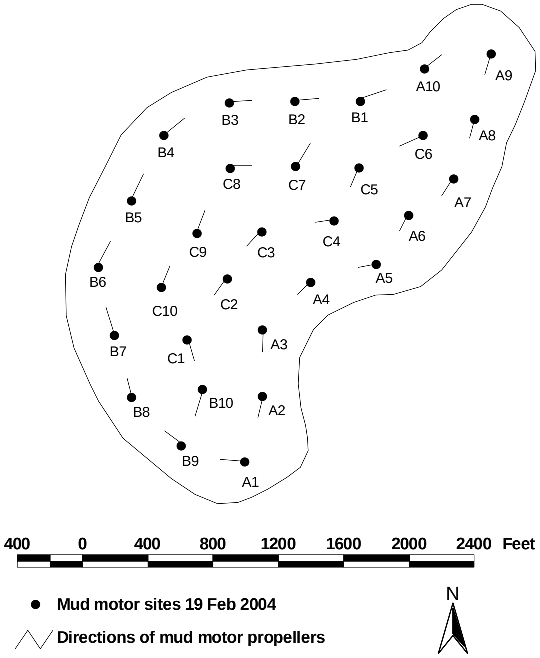
Appendix 10. Mud motor sites on Swenson Pond (Otter Tail Co., Minnesota) during a reverse aeration treatment on 5 Feb 2004. One intended mud motor site was accidentally omitted.



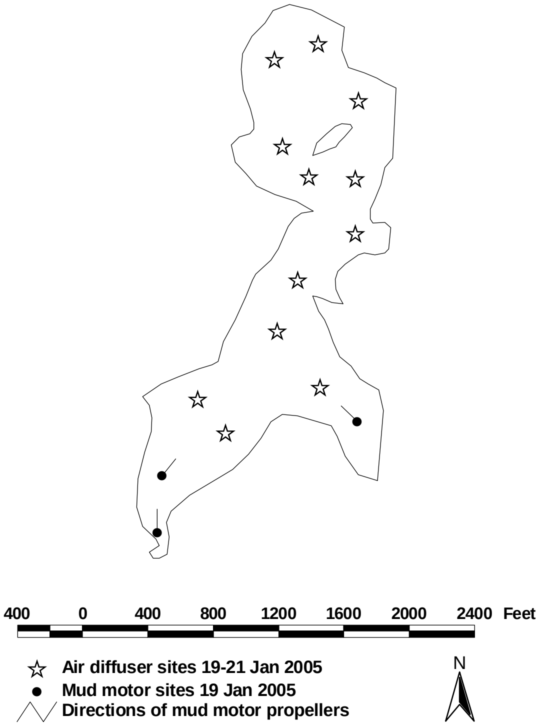
Appendix 11. Mud motor sites on Doran Pond (Clay Co., Minnesota) during a reverse aeration treatment on 12 Feb 2004. Capital letters signify three mud motors operating simultaneously, and numerals indicate the order in which sites were treated by each motor. The large bay was not treated because there was < 1 ft of water under the ice, and it was already anoxic.



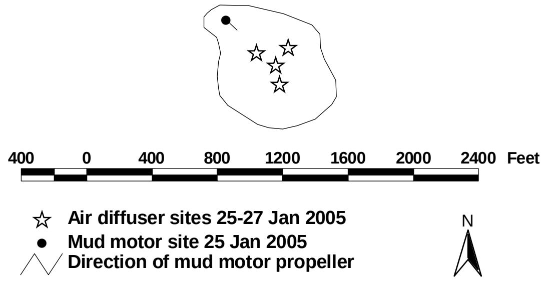
Appendix 12. Air diffuser and mud motor sites on Turtle Pond (Meeker Co., Minnesota) during a reverse aeration treatment on 18-20 Feb 2004.



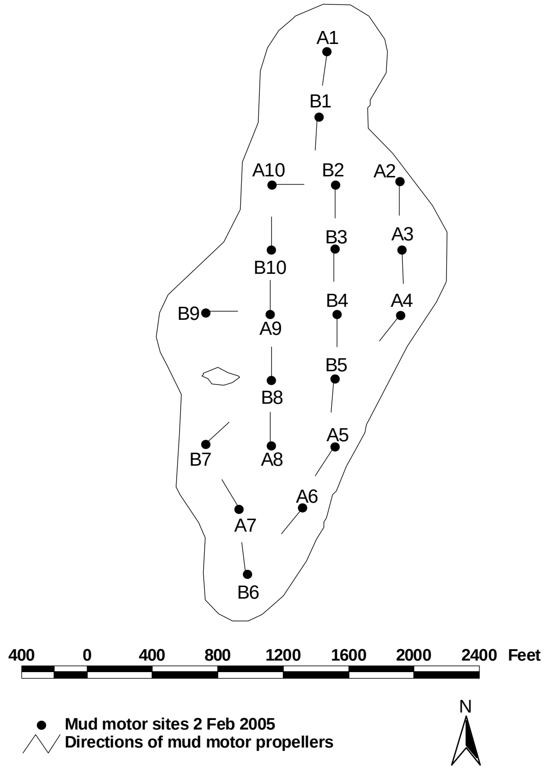
Appendix 13. Mud motor sites on Armstrong Pond (Blue Earth Co., Minnesota) during a reverse aeration treatment on 19 Feb 2004. Capital letters signify three mud motors operating simultaneously, and numerals indicate the order in which sites were treated by each motor.



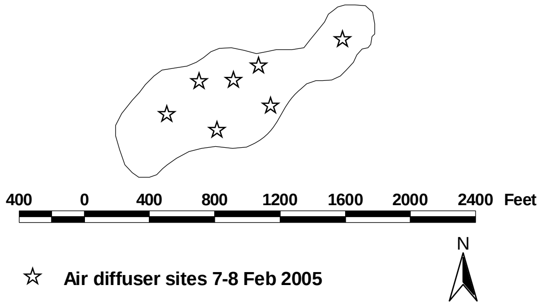
Appendix 14. Air diffuser and mud motor sites on Tatlie Pond (Clay Co., Minnesota) during a reverse aeration treatment on 19-21 Jan 2005.



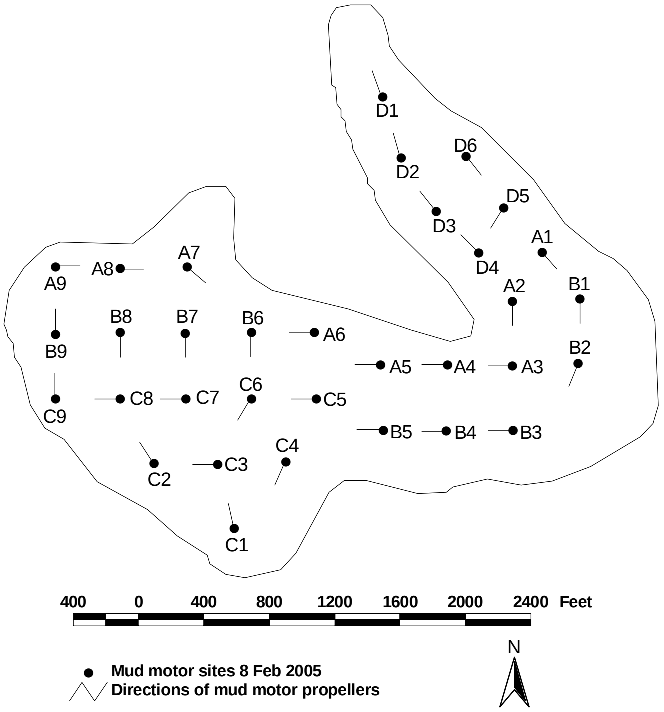
Appendix 15. Air diffuser and mud motor sites on Dalman Pond (Otter Tail Co., Minnesota) during a reverse aeration treatment on 25-27 Jan 2005.



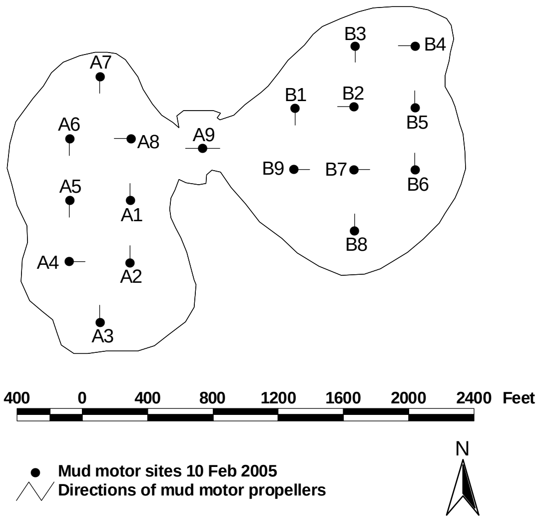
Appendix 16. Mud motor sites on Stephens Pond (Cass Co., Minnesota) during a reverse aeration treatment on 2 Feb 2005. Letters represent two mud motors operating simultaneously; numerals indicate the order in which sites were treated.



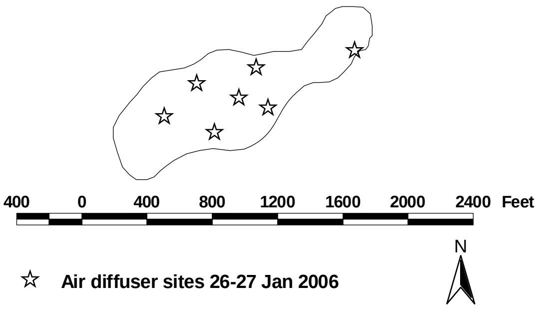
Appendix 17. Air diffuser sites on Hanson Pond (Kandiyohi Co., Minnesota) during a reverse aeration treatment on 7-8 Feb 2005.



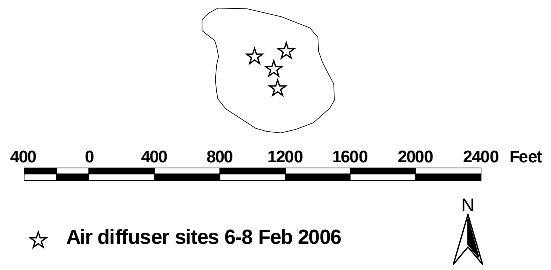
Appendix 18. Mud motor sites on Savidge Pond (LeSueur Co., Minnesota) during a reverse aeration treatment on 8 Feb 2005. Letters A-C represent three mud motors operating simultaneously; numerals indicate the order in which sites were treated. Sites D1-D6 were treated immediately after the others were finished.



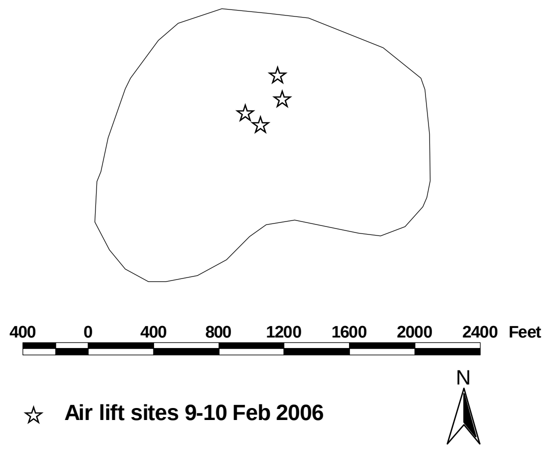
Appendix 19. Mud motor sites on Kolstad Pond (Pope Co., Minnesota) during a reverse aeration treatment on 10 Feb 2005. Letters represent two mud motors operating simultaneously; numerals indicate the order in which sites were treated.



Appendix 20. Air diffuser sites on Hanson Pond (Kandiyohi Co., Minnesota) during a reverse aeration treatment on 26-27 Jan 2006.



Appendix 21. Air diffuser sites on Dalman Pond (Otter Tail Co., Minnesota) during a reverse aeration treatment on 6-8 Feb 2006.



Appendix 22. Air lift sites on Chelgren Pond (Wright Co., Minnesota) during a reverse aeration treatment on 9-10 Feb 2006. Four air lift tubes were run simultaneously from a single air compressor in a manner similar to an air diffuser system.

Appendix 23. Airlift tube and air line manifold used for treating ponds > 15 ft deep. The manifold was constructed from standard hardware; it allowed running up to 4 airlift tubes from a single air compressor. The airlift tube was made from 6 in diameter by 4.5 ft long SDR sewer pipe. About 6 in of ready-mix concrete was poured in the bottom and held in place with a horizontal piece of steel rod stuck through two holes in the pipe before adding the concrete. There were eight 2.25 in diameter holes in two rows just above the top of the concrete. Inside the main tube was an air diffuser made from ½ in diameter PVC pipe, capped on both ends, with a standard air-line fitting screwed into the top, and several air escape slits cut near the bottom with a hacksaw. The diffuser assembly was attached to the inside of the sewer pipe near the top and bottom with standard hardware, and was flush with the top of the pipe. The bottom of the diffuser extended down to just above the holes at the bottom of the pipe. A rope was attached to the top of the pipe for raising and lowering the tube without pulling on the air line.

Appendix 24. Outboard mud motor in operation during a reverse aeration treatment of Danielson Pond (Big Stone Co., Minnesota), 5 Feb 2004.