FY 2008-2009 F&W Program Accords (MOA) Proposal Review

Narrative

Table 1. Proposal Metadata

Project Number	**200811100**
Proposer	**Confederated Tribes of the Colville Reservation**
Project Title	**Twin Lakes Enhancement**
Short Description	**Oxygenation of the hypolimnion in order to increase summer redband rainbow trout habitat and improve water quality**
Province(s)	**Intermountain**
Subbasin(s)	**Upper Columbia**
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Information transfer:

A. Abstract

The purpose of this project is to improve summer habitat and for native inland redband trout (*Onchorhynchus mykiss gairdneri)* in Twin Lakes, WA by enhancing dissolved oxygen levels in bottom waters. Additional benefits from oxygenation will include water quality enhancement and reduction in cycling of toxic materials such as mercury.

A pilot oxygenation system was installed and operated in North Twin Lake in late summer 2008. Full scale, season-long (summer stratification) implementation oxygenation of North Twin Lake is scheduled for 2009, during which time South Twin Lake will act as an anoxic reference lake. If the system proves successful, then oxygenation will be extended to South Twin in 2010. Substantial pre-treatment data have been collected in both lakes over the past four years, which will allow for before/after analysis of habitat, water quality, and biologic responses to oxygenation. During the critical ice-free months, both lakes will be monitored for: (1) trout distribution using sonic depth transmitters surgically implanted into selected redband trout and hydroacoustic monitoring; (2) zooplankton density and distribution using standard net sampling methods and hydroacoustic monitoring; (3) water quality profiles of DO, temperature, phosphorus, nitrate, ammonia, iron, manganese, and sulfide; and (4) methylmercury levels in lake water, sediment and zooplankton.

B. Problem statement: technical and/or scientific background

Although oxygenation has been utilized for water quality and some fisheries applications, to date it has not yet been implemented for native trout fisheries habitat improvements, either in the Columbia Basin or elsewhere. We also propose an especially robust and novel design, with paired lake systems and with extensive biological assessment tools to track oxygenation impacts on lake ecology, as well as on communities of trout and their prey. In addition, the project will include assessment of oxygenation impacts on cycling of mercury, which is a growing problem potentially affecting fisheries in lakes worldwide, including the Columbia Basin. The experimental setup with a full-scale treatment and reference lake is unique in its simplicity and statistical power.

This project will directly address a critical limiting factor identified by the Intermountain Province Subbasin Plan affecting trout in lakes throughout the subbasin – hypoxia in bottom waters during summertime. Many regional lakes have undergone cultural eutrophication as a result of human activities that have degraded cold-water fish habitats, and that have displaced native species that were resident prior to European settlement. Native cold-water fish production in these eutrophic lakes is severely impacted by summer "habitat squeeze" in which surface waters are too warm and bottom waters are too low in oxygen. Habitat squeeze produces excessive stress for trout and other salmonids, negatively impacts growth and survival, and precludes successful stocking efforts (e.g., Curlew Lake). This project, if successful, will contribute to direct improvements in the survival and productivity of native redband trout in the Columbia basin, and will be a model for subsequent lake oxygenation projects aimed at improving critical lake habitat for resident native trout.

<u>*Fisheries habitat*</u>

Once widely distributed throughout the Columbia Basin east of the Cascades, populations of native inland redband trout (*Onchorhynchus mykiss gairdneri)* have been substantially reduced due to the effects of dams, water quality deterioration, altered flow regimens, habitat degradation and loss, and competition with introduced species (Schweibert 1977, Behnke 1992, Behnke 2002). These pressures have impacted lake-adapted, as well as stream and river-adapted redbands. Hatchery stocking programs, historically using coastal rainbows *(O. mykiss irideus)*, have led to displacement and hybridization, so that pure populations of *gairdneri* are now rare (Behnke, 2002). Recently, success in Colville Tribal Hatchery rearing of redbands has kindled interest in replacing coastal rainbow stocking programs with these native fish, ideally with the goal of reestablishing self-sustaining breeding populations.

It has also been suggested that the lacustrine-adapted redbands, especially fish from populations within the Columbia basin lakes of eastern Oregon, Washington, and British Columbia, may be better adapted for higher temperatures than the most prevalent hatchery rainbows, and primarily derived from coastal rainbow trout stocks (Behnke 2002). The lake-adapted forms of redbands are sometimes referred to as "Kamloops" trout. True Kamloops is a geographically distinct lake-dwelling strain of rainbow/steelhead (coastal type) trout that has a different chromosome karyotype than redband trout and most closely resembles steelhead. The differences in appearance are substantial enough for early classification of redbands and coastals as separate species. However, modern genetic studies have confirmed that both are indeed *O. mykiss*, but that the forms east of the Cascade ranges are appropriately grouped as the subspecies, *O. mykiss giardneri* (Thorgaard 1983).

However, substantial hurdles exist for restoration of redband trout, most notably, the very environmental and ecological constraints that have contributed to the loss of redbands in northwest waters. For lake-adapted redband forms, our recent work over the past three years on Twin Lakes, within the reservation of the Colville Confederated Tribes (CCT), has provided a clearer picture of cumulative stresses that reduce native trout habitat and jeopardize re-establishment programs. Hundreds of lakes throughout the Columbia Basin suffer from similar impacts, so that Twin Lakes provide an excellent model for understanding their current impaired condition and factors that limit fisheries. Most importantly, the Twin Lakes provide an excellent model for implementing and testing an innovative technology to address a key and central stressor, loss of oxygen in the bottom waters during summer thermal stratification.

Historically, lakes provided critical habitat for feeding and thermal refuge for redband trout during warm summer periods. These oligotrophic lakes provided ample cold, well oxygenated water for trout populations that supported significant fisheries. Watershed disturbances, altered flow patterns, and even direct pollution have resulted in increased nutrient loading to lakes throughout the Columbia Basin, causing increased primary productivity, in the form of enhanced algal and macrophyte growth. Ultimately, the increased plant biomass dies and ends up in lake sediments where bacterial breakdown of decaying plant matter reduces available oxygen concentrations. This deoxygenation becomes critical during the period of summer thermal stratification, when the lower water column, or hypolimnion, is isolated from the atmosphere. In more heavily impacted lakes, summer hypolimnetic dissolved oxygen (DO) supply can be completely depleted by these decay processes. For cold-water fish species such as trout, which generally require water temperatures less than 20^{o} C and DO above 4 mg/L (Wydoski and Whitney 2003), the loss of oxygen essentially removes access to the deeper, colder portions of the lake that provide critical summer habitat. Suitable habitat is usually still available at mid-lake depths around the thermocline, within the transitional temperature stratum, the metalimnion. However, conditions within the metalimnion, although suitable, often can be less than optimum.

We have studied redband habitat selection as well as food web dynamics for trout and other species during the summer stratification in Twin Lakes (Christensen and Moore 2007, Christensen et al. 2007). Tagged redband trout released in early summer into North Twin Lake, were located almost exclusively within the metalimnion (Christensen et al. 2007). Because summer metalimnetic temperatures are relatively high, trout metabolic requirements are elevated. In Twin Lakes, we have found large crustacean zooplankton *(Daphnia pulex)* and chaoborids or phantom midges (*Chaoboridae*) form the majority of trout prey items (Christensen and Moore 2007). However, distributions of these prey species within the metalimnion may be insufficient, forcing the fish to range widely horizontally, yet confined within a narrow vertical band, in their quest for adequate forage. Both the daphnids and chaoborids can tolerate lower oxygen than the trout, and both display diurnal migrations to the upper waters at night to feed, seeking shelter in the hypolimnion during the day. With the trout excluded by low DO, the summer hypolimnion becomes a refuge from predation but a less than perfect one, as the prey themselves are also stressed by reduced oxygen. Therefore, oxygen is a key factor, not only for the fish, but also for prey abundance and distribution (Christensen, et al. 2007). Restoration of adequate oxygen levels can directly benefit all fish (Nurnberg 1997), especially other cold water species such as brook trout, and will have numerous long-term benefits for the overall lake ecology.

Water quality

Ancillary, but substantial, ecological benefits of oxygenation are reduced internal phosphorus loading (Nurnberg 1995, Beutel and Horne 1999), reduced summer ammonia levels, and reduced mobilization of toxic metals, such as mercury. Water quality monitoring and laboratory sediment incubations provide substantial documentation of the negative impacts of summer anoxia on Twin Lakes. These impacts include: enhanced phosphorus recycling from sediments, accumulation of ammonia in the hypolimnion, increased redox-sensitive metals (iron and manganese) in summer hypolimnion, depauperate benthic invertebrate populations, and potential for mobilization of sediment mercury into lake food webs. The results indicate a high likelihood that water quality declines will degrade the ability of the Twin Lakes to sustain their current fishery, recreational, and aesthetic uses.

Dissolved Oxygen.

Monitoring over the past several years has shown that both lakes lose hypolimnetic oxygen rapidly following the onset of summer stratification. For example, Tables 1 and 2 show temperature and DO profiles for 2008. Table 3 shows the same DO profiles as Table 2, but are expressed as percent of saturation. Sampling in 2008 began on May 27, at which time stratification was evident, with a 2^{o}C temperature gradient between 6 and 7 meters at both lakes, indicating a thermocline between those depths.

DO consumption was already evident at the first sampling date, even with the low temperatures of spring, showing that a high level of sediment oxygen demand (SOD) is present. Some preliminary calculations from the ambient monitoring provide rates for comparison with rates from the literature for lakes of varying trophic status. Assuming that stratification developed in North Twin around May 15 with temperatures close to 4^{o}C, total oxygen content of the hypolimnion is estimated at about 210,000 kg. On June 24, total hypolimnetic oxygen was reduced to about 55,000 kg, which is an average daily consumption of almost 4,000 kg (4.4 Tons/day). Expressed as the relative areal hypolimnetic oxygen deficit (RAHOD), the rate is 0.145 mg/cm^2/day. RAHOD values greater than about 0.033 mg/cm^2/day are typical of eutrophic lakes (Cornett and Rigler 1980, Horne and Goldman 1994).

For the month between July and June 2008 samplings, the apparent DO consumption was about 2000 kg/day (0.9 Tons/day), for a RAHOD of about 0.046 mg/cm^2/day. The drop in apparent consumption is due to reduced availability at the sediment water interface because of the slow molecular diffusion rate of oxygen. In other words, SOD becomes oxygen limited as the summer progresses. For purposes of estimating oxygenation requirements it is critical that the diffusion-limitation be accounted for by laboratory incubations of ambient sediments, rather than by extrapolation of environmental rates, because the latter is well known to substantially underestimate the true requirements. For a discussion of the physical and biological mechanisms, see Moore et al. (1996) and Moore (2004).

In the late summer of 2008, we performed a set of experimental chamber experiments to assess SOD in sediments from North Twin Lake. DO in water overlying Twin Lake sediments was monitored over time in three replicate chambers based on methods presented in Beutel et al. (2006) (Figure 1). While there was some variability between chambers, DO decreased in an exponential fashion from 8 mg/L to <1 mg/L after four to five days. Based on this data set, SOD as a function of DO concentration in overlaying water can be estimated (Figure 2). While the data are somewhat scattered, note that SOD tends to increase as DO increases. For example, at DO levels below 2 mg/L SOD is below 0.1 g/m2/d. Above 6 mg/L DO, SOD ranges from 0.2-0.4 g/m2/d. These SOD levels are typical of other eutrophic lakes (Beutel et al. 2006). While scaling up from a handful of experiments has its limitations, this experimental data can be used to estimate oxygen demand in the lake. For example, presuming a fairly high SOD of 0.3 g/m2/d and a hypolimnetic sediment surface area of 2.7 million m2, the lake-wide SOD is on the order of 0.8 metric tons/day. Assuming SOD makes up 50% of the entire hypolimnion oxygen demand, and an induced SOD factor of 3.0, total hypolimnetic oxygen demand during oxygenation is expected to be in the range of 3-3.5 metric tons per day. This is well below the approximate delivery capacity of the existing oxygenation system of 5 metric tons per day. Thus, the current North Twin oxygenation system appears to be adequately sized and will meet the oxygen demand in the hypolimnion, thereby maintaining a relatively constant DO concentration in the water column of the hypolimnion.

<u>Conductivity.</u>

Consequences of the anoxia are apparent in the water quality monitoring. Specific conductivity is a rough measure of the total dissolved materials in water. As oxygen is depleted, reducing conditions prevail and one consequence is a lowering of pH, and conversion of metal phosphates to a more soluble form. Conductivity profiles can indicate diffusion gradients and changes from one date to the next and can indicate general accumulation or loss of dissolved materials. In lakes with low productivity, conductivity varies little seasonally or with depth. Conductivity profiles in Twin Lakes for 2008 are shown in Table 4; Table 5 shows pH profiles. Changes in conductivity of about 5µS/cm represent significant increases in dissolved materials. For the Twin Lakes, increases in summer hypolimnetic conductivity exceeded 10 to 20µS/cm for most dates, and some extreme increases of over 100µS/cm were measured. The elevated conductivity profiles conform to a diffusion gradient from the sediments and provide strong indication of the redox-driven diffusion of nutrients and other materials with the depletion of oxygen.

<u>Phosphorus.</u>

For the Twin Lakes in 2008 hypolimnetic phosphorus profiles indicated strong diffusion gradient from the sediments, corresponding with the conductivity profiles and with summer stratification. Tables 6 and 7 show 2008 total and orthophosphorus profiles in Twin Lakes, respectively. For North Twin, epilimnetic total phosphorus ranged from about 11 to 34µg/L, while hypolimnetic total phosphorus concentrations were measured in excess of 100µg/L. South Twin showed even more dramatic phosphorus increases, with summer hypolimnetic values exceeding 200µg/L in bottom samples.

These are extremely high concentrations; the gradients indicate very high internal phosphorus loading rates. Given that total phosphorus greater than 30µg/L is generally accepted to indicate eutrophic lake conditions, the high values are particularly alarming for the general water quality trajectory in Twin Lakes. A rough calculation of total phosphorus loading for North Twin from the 2008 environmental data provides an apparent daily loading rate of about 2 mg/m^2, based on hypolimnetic phosphorus accumulation from May to July. The apparent phosphorus accumulation is a net rate; as with SOD, gross rates closer to the true internal loading may be better determined in the laboratory.

Using sediments collected from North Twin Lake, we performed a set of triplicate sediment-water incubations in November 2008 to evaluate the water quality impacts of aerobic versus anaerobic conditions following methods outlined in Beutel et al. (2007 and 2008) (Figure 3). Chambers were incubated for 11 days under aerobic conditions (bubbled with air) followed by nine days under anaerobic conditions (bubbled with nitrogen). Shortly after switching the chambers over to anoxic conditions, water started to accumulate phosphorus. Release rates under anoxic conditions averaged 9.0 mg-P/m^2/d, a release rate typical of eutrophic lake sediments (Figure 4). This experiment confirmed that sediments are highly sensitive to anoxic conditions with respect to phosphorus release, and the release rates are typical of those observed at similar sites. We conclude that maintenance of an oxygenated sediment-water interface in the lake will help to inhibit phosphorus release from sediments, and in turn decrease primary productivity in the lake.

Phosphorus release rates can be related to yearly internal loading with a powerful metric, known as the Anoxic Factor (AF) (Nurnberg 1195, 1997). AF is calculated as the product of the number of days of anoxia times the anoxic sediment surface area divided by the total lake surface area. This yields a value, in days, that expresses both the temporal and spatial extent of anoxia in a lake. Values of AF for temperate, eutrophic, dimictic lakes with summer hypolimnetic oxygen depletion typically range from about 30 to 80 days. AF factors for 2008 for North and South Twin Lakes were 59 and 57 days, respectively. One the most robust data utilities of the AF is its strong correlation with internal phosphorus load. Indeed, the product of AF and experimentally-determined areal sediment release rate has been shown to provide a reliable estimate of total annual internal load, as verified by annual nutrient budgets (Nurnberg 1984).

Internal phosphorus cycling is likely a crucial issue for Twin Lakes, and summer phosphorus load from this mechanism is likely to increase primary productivity and eutrophication. The implications for the current levels of recreational use and fishery are not good. Secchi transparency will likely decrease substantially as higher phosphorus causes increased phytoplankton in the lake, lowering aesthetic and recreational values. Phytoplanktonic community composition can be expected to shift to less desirable algae, such as blue-greens, which do not provide a suitable forage base for the desirable zooplankton and macroinvertebrates. Increased blue-greens can not only produce noxious surface scum, but can produce toxicity problems, decrease zooplankton concentrations, and decrease overall fish productivity. A complete discussion of the implications of continued high internal phosphorus loading is not appropriate here; however, the overall prognosis for Twin Lakes, without intervention, is poor.

Ammonia.

Nitrogen is another important nutrient that is redox-sensitive and can accumulate in the summer hypolimnion. Ammonia accumulates in the summer hypolimnion through bacterial decomposition of proteins, through increased internal cycling of sediment nitrogen compounds, and through decreased nitrification, the oxidation of ammonia to nitrite and nitrate. As with phosphorus, nitrogen compounds in general are macronutrients and can stimulate algae productivity. Ammonia is a known toxin to fish, and is another factor limiting fishery utilization of summer hypolimnetic waters. The un-dissociated form can cause irreversible damage to fish gills, so the ammonia toxicity is highly pH-dependent (Wetzel, 2001). During fall turnover, mixing of high levels of ammonia from the hypolimnion into the higher pH epilimnetic waters, can convert ammonium ion into the toxic un-dissociated form, and may be a substantial factor affecting fall fish health. Hypolimnetic oxygenation is known to prevent or lower ammonia levels in the hypolimnion by encouraging the function of oxidizing bacteria that convert ammonia to less toxic nitrites and nitrates (Burrell et. al.), so that this will be a substantial ancillary benefit from the proposed technology (Beutel and Horne, 1999; Beutel, 2001).

Tables 8 and 9 provide 2008 ammonia and nitrite/nitrate profiles in the Twin Lakes. As with phosphorus, the ammonia profiles show a pronounced diffusion gradient from the sediments, with concentrations of over 0.40 to 1.09 mg/L, as nitrogen, in waters adjacent to the bottom, compared to epilimnetic concentrations of about 0.005 to 0.05 mg/L. Whatever the predominant mechanism, the gradients indicate very high ammonia accumulation. Nitrite/nitrate values are also higher immediately adjacent to the sediments. However, there is no significant pattern of a diffusion gradient, so that the higher values may result from an accumulation from sestonic materials rather than from internal cycling processes. A consistent pattern of increasing concentrations from the sediment to the open water would clearly indicate diffusion of nitrate from the sediment. Since this is not the case, the source may be from the materials originating in the epilimnion that have “rained” into the hypolimnion.

Iron and Manganese.

Water quality monitoring this past season also documented hypolimnetic accumulation of iron and manganese in North Twin Lake (Figure 5). Iron levels in bottom waters were 1-2 mg/L compared to < 0.2 mg/L in surface waters. Manganese levels showed a similar trend with concentrations in bottom waters around 100-300ug/L. Accumulation of dissolved metals in bottom waters is a telltale sign that the sediment-water interface has gone anoxic and acidic. Under anoxic conditions bacteria reduce solid metal oxides in surfacial sediments. The reduction and dissolution of these metals is also the mechanism by which phosphorus is released from sediments. Under oxic conditions orthophosphate is sorbed to the metal oxides, but once the metals are reduced the orthophosphate is released with the dissolved metals into overlaying water. We anticipate that lake oxygenation will inhibit sediment release of metals and associated phosphorus by maintaining an oxygenated sediment-water interface and deeper water column.

This hypothesis was partly tested during the September 2008 oxygen test in North Twin Lake, when around five tons per day of liquid oxygen were added for approximately two weeks. This increased DO in bottom waters near the submerged oxygen diffuser from 0 to ~2.5 mg/L. The oxygen test took place after the entire hypolimnion had gone severely anoxic and the water column was full of reduced substances, a worst case scenario from a lake oxygenation stand point. A key to lake oxygenation is turning the system on early and maintaining DO in bottom waters, not playing 'catch-up' after anoxic conditions have begun. However, even under these conditions we found that oxygenation caused a shift in the metals speciation (Figure 6). On August 28, 2008 before the oxygen test, metals in bottom waters were mostly in the dissolved, reduced from (i.e. total metals = dissolved metals). On September 13, 2008 about two weeks after the oxygenation test metals were predominantly in the oxidized particulate form (i.e. total metals >> dissolved metals). These results show that lake oxygenation can result in the oxidation of reduced metals in bottom waters, and suggests that full-scale lake oxygenation implemented prior to the onset of anoxia has the potential to maintain iron and manganese in their insoluble, oxidized forms. These insoluble precipitates form a 'cap' on the sediment surface, preventing the release of soluble ions and nutrients into the water column, further discouraging problematic algal blooms.

Mercury.

Another potential major benefit of oxygenation that requires further investigation is the role of oxygen in preventing methyl-mercury formation and thus sequestering mercury in sediments. Mercury contamination of the lake biota is a looming environmental problem that can ultimately impact people who consume high levels of fish in their diet, even in fish from lakes remote from mercury sources. Mercury has already been detected in elevated levels in fish and sediments from lakes throughout Washington, including the Columbia Basin (various reports, Washington State Department of Ecology). Mercury is highly volatile and is transported worldwide in the atmosphere; deposition of atmospheric mercury as ionic mercury is a major pathway for entry into the aquatic environment (Lindquist and Rodhe, 1985; Bloom and Watras, 1989; Watras and Huckabee, 1995; Harris et al., 2007). Mercury is also naturally found in some rock deposits or active volcano vents in the Cascades, such as East Lake, central Oregon. Acidification of water releases Hg from rock and acid plus anaerobic conditions changes inorganic mercury into toxic methylmercury. In water and sediments, ionic mercury may be transformed to highly insoluble mercury sulfates or to highly toxic methyl- and dimethyl-mercury compounds, depending on the oxygen regimen and other factors (National Research Council, 1978). The organic nature of methyl-mercury results in its strong tendency to accumulate in biota (Eisler, 2006; Harris et al., 2007). Methyl mercury tends to bio-accumulate especially in filter-feeding and in predatory organisms (Eisler, 2006). There is evidence that summer anoxic hypolimnia constitute a major pathway for mobilization of mercury in lakes that may ultimately accumulate in fish (Slotton et al. 1995; Herrin et al., 1998). Therefore, we believe that oxygenation can reduce methyl-mercury formation by preventing or reversing the anoxic conditions that permit conversion of relatively non-bioavailable ionic mercury to this highly toxic organic form.

2009 Update

Temperature, dissolved oxygen, angler success, and fish depth are all being monitored in North Twin and South Twin Lakes in 2009. While results are preliminary at this time the difference between the two lakes is striking.

Temperature/DO. Temperature and dissolved oxygen profiles in both lakes were obtained on June 10, 2009. The South Twin monitoring station is near the deepest part of the lake. The North Twin mid lake station is approximately 35m north of the oxygenation system at the deepest part of the lake. The west lake station is 425 m west of the western end of the oxygenation system. The results are shown below.

	South Twin		North Twin			
	middle		Middle		West end	
Depth (m)	Temp ©	DO (mg/l)	Temp ©	DO (mg/l)	Temp ©	DO (mg/l)
0	20.19	8.99	19.92	9.02	19.92	9.05
1	19.6	9.07	17.67	9.16	19.87	9.09
2	19	9.04	18.62	9.3	19.76	9.08
3	18.75	9.05	18.48	9.35	18.67	9.23
4	17.62	9.33	18.26	9.44	17.8	9.25
5	13.82	9.81	13.26	12	13.65	11.69
6	11.24	9.36	10.81	12.04	10.35	12.83
7	10.09	8.26	8.95	13.41	8.72	12.06
8	8.49	5.64	7.93	10.89	7.9	10.2
9	7.74	4.3	7.54	9.95	7.42	7.8
10	7.35	2.88	7.36	9.52	7.09	7
11	6.72	0.89	7.25	9.18	7.02	7.2
12	6.41	0.82	7.15	8.8	6.77	6.65
13	6.19	0.18	7.06	8.46	6.64	5.4
14	6.09	0.32	6.83	6.81		
15	5.87	0.25	6.34	5.6		
16	5.75	0.24				

Angler success. Data are very preliminary at this time. Success rates for North Twin for the first two weeks of June substantially exceed catch rates for the same period in 2006-2009. Catch rates for South Twin are similar to those seen in previous years.

Fish depth. Fish depths are being monitored by hydro acoustics, sonic tracking and gill nets set at three different depths. Hydro acoustic analysis for June is incomplete. Initial observations show fish throughout the hypolimnion of North Twin and no fish in the hypolimnion of South Twin. Sonic tracking only occurs in North Twin. The May 28 tracking survey showed fish in the hypolimnion. Gillnets were set in each lake monthly during 2008 and are being set again in 2009. Nets are set at 2-5m, 5-8m and 9-12m.

Under stratified conditions (mid May-mid October) fish have never been captured in the 9-12m net. Nets were set in North Twin on June 10, 2009 when the lake was strongly stratified (by temperature in North Twin and both temperature and DO in South Twin). For the first time fish were captured in the deep nets. Large mesh deep nets captured more fish than large mesh shallow nets and an equal number to large mesh mid depth nets. Small mesh deep nets caught fish but not as many as shallow or mid depth nets. Deep nets in South Twin caught no fish.

C. Rationale and significance to regional programs

This project has direct linkages to identified priorities and objectives of both the 2000 Columbia River Basin Fish and Wildlife Program (Program) and the 2004 Intermountain Province Subbasin Plan (Subbasin Plan), as discussed in detail below. Most importantly, the main thrust of this proposal is directly related to the overarching mission of the Program: "the heart of the program is a set of immediate actions to improve conditions for fish and wildlife" (Section D9, p. 32). By preventing the bio-accumulation of methyl mercury we will be protecting both human and wildlife consumers of fish in Twin Lakes from mercury poisoning, which at sub lethal levels interferes with reproduction. We are very confident that our innovative project gets to the heart of efforts to actively, practically, and economically maintain and restore habitat for native fish in the Columbia River Basin.

Relevance to 2000 Fish and Wildlife Program

<u>(1) Project Compatible with Program Vision:</u> By experimentally evaluating how a simple engineered system, lake oxygenation, improves habitat for redband trout in Twin Lakes, this project fits directly with the vision outlined in the Program (Section A2, p. 13) in a number of ways: (i) the project is "habitat based" and aims to develop an economical strategy to improve and protect fish habitat; (ii) the project is a good example of a practical "non-natural intervention" aimed at restoring fishery habitat and protecting native trout from adverse impacts; and (iii) the project is framed as an experimental evaluation of a management strategy and directly integrates research with monitoring.

<u>(2) Project Addresses Program Objectives:</u> This project will help to meet a number of biological objectives identified in the Program (Section C1-2, p. 16-17). The project will provide a model for additional oxygenation projects aimed at economically improving summertime habitat for resident native trout and water quality in degraded lakes throughout the Columbia Basin. Program objectives addressed by the project include: (i) helping to restore native resident species to historic abundance and distribution, (ii) enhancing harvest opportunities of resident native fish for tribal and non-tribal fishers; (iii) providing mitigation opportunity for adverse effects to fish caused by hydropower development; and (iv) restoring healthy ecosystem function as a means to increase abundance of resident native fish.

<u>(3) Project Addresses Monitoring and Evaluation Criteria:</u> This project is designed to meet the monitoring and evaluation standards detailed in the Program (Section D9, p. 33) including: (i) the project has measurable biological objectives – the improvement of bottom water quality and the expansion of trout habitat; (ii) the project will collect data that measure the identified biological outcome – spatial and temporal patterns of water

quality and trout and prey item distribution; and (iii) all data will be made available to interested stake holders in a timely fashion.

Relevance to Intermountain Province Subbasin Plan

(1) Project Addresses key Limiting Factor: Many of these lakes have undergone cultural eutrophication as a result of human activities and likely provided suitable habitat for resident cold water fish prior to European settlement. Many regional lakes are eutrophic resulting in a summertime habitat squeeze for cold water fish between surface waters that are too warm and bottom waters that are too low in oxygen (Section 30.9.1.6, p. 30-48) for their survival. The result is very poor habitat for trout and salmonids and in some cases interferes with stocking efforts (e.g., Curlew Lake) (Section 30.10.3, p. 30-53). This project will directly address a critical limiting factor identified by the Subbasin Plan affecting trout in lakes throughout the subbasin – hypoxia in bottom waters during summertime.

(2) Project Addresses Plan Objectives: By enhancing habitat for redband trout via lake oxygenation, this project will help achieve a number of objectives identified in the Upper Columbia Subbasin Plan (Section 34.3, p. 34-5 to 34-16) including: (i) implement habitat strategies for addressing identified limiting factors for focal species and native fish (Objective 1B2); (ii) maintain, restore, and enhance wild populations of native fish to provide for harvestable surplus (Objective 2A2); (iii) evaluate metals contamination as a limiting factor on important species, especially reproductive and neurological impacts on anglers and wildlife that eat mercury contaminated fish (Objective 1B4); and (iv) if expanded slightly to include lentic environments, enhance, conserve, and protect riparian habitats (Objective 1B6). On a broader scale, the project addresses a key Province-level objective – mitigate for wildlife losses that have occurred through secondary effects of hydropower development (Objective 2A and 2B, Section ES.4.1, p. 34). Hydropower development has caused a number of critical secondary impacts that have directly impacted lake trout habitat. Secondary effects include a shift from a fishery-based economy to an agrarian/resource extraction-based economy (Section ES.2.1, p. 10). As a result regional lakes have undergone cultural eutrophication which exacerbates low oxygen conditions in bottom waters and robs trout of critical oxygen rich, cold water that historically provided refuge in the summertime.

D. Relationships to other projects

Although this is a new project it is based on work previously performed under the Colville Tribal Hatchery Project (1985-038-00) and the Twin Lakes Oxygenation Project, a Colville Tribal project (2008). Both projects are ongoing and will continue in 2009. The monitoring of fish populations and angler success will continue to be monitored under the Colville Tribal Hatchery Project.

Table 2. Relationship to existing projects

Funding Source	Project #	Project Title	Relationship (brief)
BPA	**198503800**	**Colville Tribal Hatchery O&M/M&E**	**Hatchery project stocks North and South Twin Lakes and monitors fish condition and angler success**
CRWMP		**Twin Lakes Oxygenation**	**Initial construction, operation and monitoring of the North Twin Lake oxygenation system**

E. Project history (for ongoing projects)
This is a new project that continues work begun by the Colville Confederated Tribes.

F. Proposal biological/physical objectives, work elements, methods, and metrics
Twin Lakes provide an ideal setting to evaluate scientifically the effect of lake oxygenation, an innovative lake management technology, on redband trout habitat. The two basins are very similar in morphometry. As a result, one basin can act as a “treatment” lake while the other can act as a “control”. This elegant experimental set up avoids a number of pitfalls associated with pilot-scale evaluation of lake management strategies tested at a single site including: (1) a lack of comprehensive pre-treatment water quality data to statistically compare with post-treatment data, and (2) the confounding effects of inter-annual variability (e.g., meteorology, inflow timing and magnitude) between treatment and non-treatment years. In addition, a number of fishery studies have already been performed at the site through collaboration between researchers at WSU and the CCT (Christensen and Moore 2007, Biggs 2007).

This project will be conducted in three phases.

Phase 1. 2010

Objective 1. Decrease mortality and increase growth potential of salmonids in North Twin Lake.

This objective will be met by oxygenating the hypolimnion of North Twin Lake using equipment installed in 2008 and tested in 2008 and 2009. Liquid Oxygen will be purchased from a local supplier and added to the hypolimnion. We have found that oxygenation is quantitatively and qualitatively distinct from “aeration”. Although the terms were used interchangeably in the past, we now distinguish between the two based on the ultimate source of oxygen (air=aeration, oxygen gas=oxygenation). Compared to aeration, the application of pure oxygen provides a number of technological, economic and ecological benefits, particularly in larger, more eutrophic lakes with relatively high hypolimnetic oxygen demand.

Objective 2. Decrease mortality and increase growth potential of salmonids in South Twin Lake.

The overarching project goal is to restore fish habitat and improve water quality in the Twin Lakes by restoring oxic conditions to the summer hypolimnia of both lakes. Oxygenation will be phased in, with North Twin system running in 2009, to be followed by the addition of South Twin in 2010. Therefore, 2009 will permit a 'side-by-side' comparison of oxygenated and un-oxygenated systems. After 2010, data analysis will focus on before/after implementation analyses.

This objective will be met by the installation of a South Twin Lake hypolimnetic oxygenation system that receives its oxygen from the exisiting North Twin oxygen supply. The primary goal is to install and test the South Twin oxygenation system. It will only be operated as much as time and budget allow.

Work element 1. Manage and administer (119).

Under this work element the Colville Tribes will supervise, coordinate and administer the project as well as subcontract for the supply of oxygen, the construction of the South Twin Lake oxygenation system and water quality monitoring.

Milestone A. Supervise contract.

Milestone B. Subcontract with a local oxygen supplier for sufficient oxygen supplies to oxygenate North Twin Lake from ice out (usually in April) until the end of October and to oxygenate South Twin Lake from the completion of the construction of the oxygenation system until the end of October.

Milestone C. Subcontract for the construction of the Twin Lakes oxygenation system.

Milestone D. Subcontract for the monitoring of water quality. This is discussed in detail under **section G, Monitoring and evaluation**.

Work element 2. Collect/Generate/Validate Field and Lab Data (157). Fish size, numbers, growth and distribution.

This work element will be performed in cooperation with the Colville Tribal Hatchery Project (198503800).

Milestone A. Collect, measure and evaluate salmonids monthly using gill nets placed at specific depths in North and South Twin Lakes. Capture depths will be noted and weights and length will be measured to determine condition factor, relative weight and monthly growth.

Milestone B. Determine fish distribution both vertically and horizontally each month using hydro acoustics.

Work element 3. Collect/Generate/Validate Field and Lab Data (157). Creel census.

This work element will be performed in cooperation with Colville Tribal Hatchery Project (198503800).

Milestone A. Perform creel roving study of North and South Twin Lakes shore and boat anglers using procedures and protocols developed in 2007 and 2008.

Work element 4. Analyze/Interpret data (162).

Milestone A. All fish and creel data will be analyzed using previously determined procedures and protocols.

Milestone B. All data will be compare with pre-oxygenation data to determine any water quality or fishery improvements.

Work element 5. Produce (annual) progress report (132).

Work element 6. Produce PISCES status reports (185).

Phase 2. 2011

Objective 1. Decrease mortality and increase growth potential of salmonids in South Twin Lake and North Twin Lake.

This objective will be met by operating both oxygenation systems beginning shortly after ice out in April and ending in October. Water quality and fish conditions will be monitored throughout the summer.

Work element 1. Manage and administer (119).

Under this work element the Colville Tribes will supervise, coordinate and administer the project as well as subcontract for the supply of oxygen and water quality monitoring.

Milestone A. Supervise contract.

Milestone B. Subcontract with a local oxygen supplier for sufficient oxygen supplies to oxygenate North and South Twin Lakes from ice out (usually in April) until the end of October.

Milestone C. Subcontract for the monitoring of water quality. This is discussed in detail under **section G, Monitoring and evaluation**.

Work element 2. Collect/Generate/Validate Field and Lab Data (157). Fish size, numbers, growth and distribution.

This work element will be performed in cooperation with the Colville Tribal Hatchery Project (198503800).

Milestone A. Collect, measure and evaluate salmonids monthly using gill nets placed at specific depths in North and South Twin Lakes.

Milestone B. Determine fish distribution both vertically and horizontally each month using hydro acoustics.

Work element 3. Collect/Generate/Validate Field and Lab Data (157). Creel census.

This work element will be performed in cooperation with Colville Tribal Hatchery Project (198503800).

Milestone A. Perform creel roving study of North and South Twin Lakes shore and boat anglers using procedures and protocols developed in 2007 and 2008.

Work element 4. Analyze/Interpret data (162).

Milestone A. All fish and creel data will be analyzed using previously determined procedures and protocols.

Milestone B. All data will be compare with pre-oxygenation data to determine any water quality or fishery improvements.

Work element 5. Produce (annual) progress report (132).

Work element 6. Produce PISCES status reports (185).

Phase 3. 2012

Objective 1. Decrease mortality and increase growth potential of salmonids in South Twin Lake and North Twin Lake.

This objective will be met by operating both oxygenation systems beginning shortly after ice out in April and ending in October. Water quality and fish conditions will be monitored throughout the summer.

Objective 2. Reduce the operating expenses of North Twin Lake and South Twin Lake hypolimnetic oxygenation systems.

This goal will be the construction of an oxygen production plant at the site of the present oxygen storage facility if economic analysis shows that oxygen production is cheaper than purchasing liquid oxygen from available suppliers. Preliminary analysis using 2008 costs shows that oxygen production at North and South Twin Lakes is considerably more economical. A 2012 analysis will take into consideration oxygen demands and fishery and water quality benefits determined by 2008, 2009, 2010 and 2011 monitoring and evaluation.

Work element 1. Manage and administer (119).

Under this work element the Colville Tribes will supervise, coordinate and administer the project as well as subcontracts for the supply of oxygen, the economic analysis of 2008-2011 oxygenation data to determine if construction of and oxygen generation facility is warranted, for the construction of the oxygen generation facility and the monitoring of water quality.

Milestone A. Supervise contract.

Milestone B. Subcontract with a local oxygen supplier for sufficient oxygen supplies to oxygenate North Twin Lake from ice out (usually in April) until the end of October and to oxygenate South Twin Lake from the completion of the construction of the oxygenation system until the end of October.

Milestone C. Subcontract for the economic analysis of oxygenation of North and South Twin Lakes.

Milestone D. Subcontract for the construction of and oxygen generation facility.

Milestone E. Subcontract for the monitoring of water quality. This is discussed in detail under **section G, Monitoring and evaluation**.

Work element 2. Collect/Generate/Validate Field and Lab Data (157). Fish size, numbers, growth and distribution.

This work element will be performed in cooperation with the Colville Tribal Hatchery Project (198503800).

Milestone A. Collect, measure and evaluate salmonids monthly using gill nets placed at specific depths in North and South Twin Lakes.

Milestone B. Determine fish distribution both vertically and horizontally each month using hydro acoustics.

Work element 3. Collect/Generate/Validate Field and Lab Data (157). Creel census.

This work element will be performed in cooperation with Colville Tribal Hatchery Project (198503800).

Milestone A. Perform creel roving study of North and South Twin Lakes shore and boat anglers using procedures and protocols developed in 2007 and 2008.

Work element 4. Analyze/Interpret data (162).

Milestone A. All fish and creel data will be analyzed using previously determined procedures and protocols.

Milestone B. All data will be compare with pre-oxygenation data to determine any water quality or fishery improvements.

Work element 5. Produce (annual) progress report (132).

Work element 6. Produce PISCES status reports (185).

G. Monitoring and evaluation

Data Evaluation. As detailed below the project has four Monitoring and Evaluation (M&E) objectives that include the monitoring of: (1) trout distribution; (2) zooplankton density and distribution; (3) water quality of conventional parameters, nutrients and redox-sensitive metals; and (4) mercury in lake water, fish and zooplankton.

M&E Objective 1: Evaluate effects of oxygenation on vertical distribution of redband trout.

Methods. Methods to measure the vertical distribution of trout will be based on those recently developed by Biggs (2007) and used in North Twin Lake during summer 2006. Up to 20 adult female redband trout from the CCT hatchery in Bridgeport, Washington, will be surgically implanted with pressure sensitive transmitters (Sonotronics, Inc., Tucson, Arizona). Transmitters weigh 10 g (in water) and are 72 mm long by 16 mm in diameter. Trout will be selected so that transmitters do not exceed 2% of trout weight. Transmitters will be inserted into trout anesthetized with tricaine methanesulfonate through a two to three cm incision made anterior to the pelvic girdle and one to two cm off the ventral midline. Incisions will be closed with monofilament nylon sutures using a simple interrupted suture pattern. Up to 10 trout each will then be released into North Twin Lake (treatment) and South Twin Lake (control). Trout will be tracked in both lakes for three days each month from May to November of 2008. Tracking will be conducted during day and night hours from an aluminum boat. A Sonotronics USR-96 narrow band receiver and DH-4 directional hydrophone will be used to receive impulses from transmitters during tracking. Trout location will be determined using the directionality of the hydrophone and signal strength. Hand-held digital sonar, Global Positioning System (GPS), laser rangefinder, and a bathymetric map will be used to document trout location. Trout will be manually tracked for one-hour periods with the vertical location of the trout recorded every minute. Hydro-acoustic data will be taken contemporaneously with the fish tracking. This will allow community assessments of other fish populations in the lake. Overall, we will attempt to characterize the lake fish community, in terms of numbers and distributions at four to eight hour internals over the tracking period.

In 2008 baseline studies of vertical distribution of salmonids were conducted in both North and South Twin Lakes using both horizontal and vertical gill nets set at specific depths each month. Both vertical and horizontal distribution of salmonids and zooplankton was determined each month using hydro acoustic surveys with a BioSonics DT-X unit using 200 and 420 khz transducers (Shallenberger, 2009). These surveys will continue for each year of the project.

Statistical Evaluation. Based on the data set of vertical distributions for each sampling time, a mean trout depth will be calculated and the time series of these values will be statistically compared between lakes. Note that 2008 distribution results from North and South Twin Lakes will also be compared to results from 2006 (Biggs 2007) by pairing months for both data sets.

Expected Outcome. Based on intensive monitoring in North Twin Lakes in summer 2006, redband trout are confined to a slab of metalimnetic waters around three to four m thick where temperatures are below 20^{o}C and oxygen levels greater than five mg/L (Biggs 2007). This "habitat squeeze" is thought to negatively impact the overall health of the fish. Oxygenation is expected to dramatically expand the vertical habitat of redband trout and improve trout health.

M&E Objective 2: Evaluate effects of oxygenation on density and distribution of zooplankton.

Methods. Monthly zooplankton monitoring will be performed from about May through November at the Mid-lake stations of both lakes. On at least two dates we will measure patterns of diel migration of pelagic zooplankton by complementing noon-time sampling with sampling around 12:00 am. At noon zooplankton are expected to be at their maximum depth to avoid predation in the photic zone, while at midnight they are at their minimum depth to filter feed in algae-rich surface waters. Monitoring and data evaluation will be based on methods presented in Christensen and Moore (2007a and b). Zooplankton samples will be collected with a zooplankton net fitted with a 64-mm mesh plankton bucket. Zooplankton samples will be collected at various intervals to characterize hypolimnetic, metalimnetic, and epilimnetic distributions. Samples will be preserved immediately after capture in a formalin solution. Zooplankton samples will be diluted as needed to facilitate identification and enumerated to the species level using various taxonomic keys. Biomass determinations will be made using measurements taken with the microscope and micrometer, using published length/volume regressions. Hydroacoustic methods will be employed to track the diurnal movements of larger zooplankton, such as daphnids and chaoborids. Coupled with the biomass and species data, we anticipate a thorough characterization of the diurnal distribution of prey species relative to the habitat requirements of the redbands (and other fish).

Statistical Evaluation. Two key values will be estimated for each sampling date for statistical comparison between basins: areal mean abundance and median vertical distribution. Areal mean abundance (#/m^2) will be estimated based on the counts from the zooplankton tows (#/m^3), multiplied by the volume (m^3) and divided by the surface area (m^2) of the corresponding two m slab of lake water. Vertical distribution will be quantified via the median depth of zooplankton (i.e., which 2-m slab contained the median zooplankton individual).

Expected Outcome. By providing a well-oxygenated bottom refuge for zooplankton, oxygenation is expected to increase both the quantity and distribution of zooplankton. Over the long-term higher zooplankton densities could have two significant and advantageous ecological side effects: (1) greater food resources for trout, and (2) more intensive predation pressure on phytoplankton resulting in greater water clarity.

Studies of artificial oxygenation in other lakes have shown decreased chaoborid (phantom midge) populations, as these organisms are highly vulnerable to sight predators such as trout (Doke et al. 1995). Chaoborids exhibit diurnal migration, moving upward in the water column at night, when they are less vulnerable, to feed on other zooplankton and obtain oxygen. During the day, they return to the hypolimnion and to the sediments. At Newman Lake, chaoborid populations declined dramatically following oxygenation, probably because of increased fish access and predation in the hypolimnion. Increase predation effects on other zooplankton appeared to be mitigated by decreased predation from chaoborids and by improved habitat due to higher oxygen (Doke et al. 1995).

M&E Objective 3: Evaluate effects of oxygenation on water quality in water column.

Methods. Monthly water quality monitoring of conventional redox-sensitive parameters will be performed from May through November 2008 at a deep water station in both North and South Twin Lakes. Monitoring and analyses will be performed in a similar fashion to Beutel and Moore (2007) and Beutel et al. (2007b) using standard methods (APHA 1998). Water quality parameters include: DO, pH, temperature, soluble reactive phosphorus, ammonia, nitrate, iron, manganese and sulfide. DO, pH and temperature profiles will be measured every one m with a Hydrolab Data Sonde-Surveyor 4a. Water samples will be collected with a pump sampler at 1 m intervals. Nutrient samples will be preserved by filtering through 0.45 µm filters and freezing. Samples for iron and manganese analyses will be preserved with nitric acid. If sulfide odor is detected, sulfide samples will be collected and preserved with zinc acetate. Sulfide samples will be analyzed on a Lachat QuikChem 8500 auto-analyzer in Dr. Beutel's Limnology Lab using standard colorimetric methods (APHA 1998), while nutrient (nitrogen and phosphorus) samples will be analyzed on a SEAL Analytical AA3 system at NATRS, using standard colorimetric methods (APHA 1998). Iron and manganese will be measured via inductively coupled plasma (ICP) mass spectrometry on apparatus housed at the WSU Chemistry Department. Standard quality control procedures will be followed including real-time evaluation of the recovery of duplicates, spikes, external standards, bottle blanks, and calibration standards.

Statistical Evaluation. For each water quality parameter (DO, pH, temperature, soluble reactive phosphorus, ammonia, nitrate, iron, manganese and sulfide) a mean hypolimnetic concentration will be estimated for each monitoring date. The hypolimnion will be split into meter slabs, and the volume of each slab will be multiplied by the concentration at the corresponding depth. The mass in each slab will then be summed and divided by the total volume of the hypolimnion, yielding a hypolimnetic mean concentration. The hypolimnion will be defined as waters below the thermocline (the point of maximum change in temperature with depth) and/or the oxygen chemocline (the point of maximum change in oxygen with depth). The time series of mean concentrations will then be statistically compared between the two lakes for all parameters of interest. Updated morphometric data will be obtained through hydroacoustic data analyzed on Bottom Typer software (Biosonics Corp., Seattle, WA) coupled with GIS (ArcInfo).

Expected Outcome. By maintaining a well-oxygenated sediment-water interface, we expect that oxygenation will result in the repression of hypolimnetic accumulation of various redox sensitive compounds including ammonia, manganese, iron, phosphate and sulfide. Inhibiting their release of redox-sensitive compounds from anaerobic sediments will dramatically improve bottom water habitat and water quality by reducing eutrophication (e.g., ammonia, phosphate, iron) and reducing toxicity to aquatic organisms (e.g. ammonia, sulfide).

M&E Objective 4: Evaluate effects of oxygenation on mercury levels in water column and zooplankton.

Methods. Monthly monitoring of mercury-related parameters will be performed from May through November 2008 at a deep water station in each lake. Parameters include total mercury, methyl-mercury, dissolved organic carbon and sulfate in the water column, and total mercury in zooplankton. Water samples (every 1-m) and zooplankton samples (full water column tow) will be collected as noted in M&E Objectives 2 and 3 with minor modifications to limit potential for mercury contamination. For example, water samples will be collected with a specialized non-metallic Teflon water sampler, intensive pre-cleaning of apparatus will be performed prior to fieldwork, and "dirty hands/clean hands" techniques will be employed during fieldwork (USEPA 1996). Total and methyl-mercury water samples and total mercury zooplankton samples will be collected in acid washed fluoropolymer bottles. Total mercury water samples will be preserved with bromine monochloride, methyl-mercury water samples with hydrochloric acid, and zooplankton samples via freezing. Total mercury analyses in water and zooplankton will be performed in a similar fashion to Beutel and Moore (2007) using cold-vapor atomic fluorescence spectrometry (USEPA 2002) on a Tekran 2600 Hg autoanalyzer in Dr. Beutel's mercury lab at WSU. Our median analytical detection limit for total mercury (three times the standard deviation of the blank) is around 0.5 ng L^{-1}. Note that zooplankton will first be digested via a hot acid digestion to liberate and convert all biologically bound mercury along the lines of Slotton et al. (1995). Methyl-mercury analyses will be performed in collaboration with Dr. Gary Gill at the Battelle Marine Sciences Laboratory in Sequim, Washington using EPA method 1630 - distillation, aqueous ethylation, purge and trap, and cold-vapor atomic fluorescence spectrometry (USEPA 2001). DOC and sulfate will be measured using conventional standard methods including high temperature catalytic oxidation for DOC and ion chromatography for sulfate. As with the conventional monitoring, standard quality control procedures will be followed including real-time evaluation of the recovery of duplicates, spikes, external standards, bottle blanks, and calibration standards.

Statistical Evaluation. As with the water quality parameter in M&E Objective 3, a mean hypolimnetic concentration will be estimated for total mercury and methyl-mercury in the water column and total mercury in zooplankton for each monitoring date. The time series of mean concentrations will then be statistically compared between the two lakes.

Expected Outcome. Though yet to be conclusively documented at the field scale, we expect oxygenation will inhibit hypolimnetic accumulation of total and methyl-mercury by inhibiting the activity of sulfate reducing bacteria that transform ionic mercury to methyl-mercury under anaerobic conditions. Over the long-term this should limit the amount of mercury available to bio-accumulate in the aquatic food web resulting in lower mercury levels in biota, particularly those at the top of the food web like trout.

H. Facilities and equipment

Phase 1, 2010.

North Twin Lake. No new equipment will be required.

South Twin Lake. An oxygenation system for South Twin Lake will be constructed in 2010. This system will be similar to the system constructed in 2008 at North Twin Lake. The system will be constructed by a subcontractor. No other equipment will be required.

Phase 2, 2011.

No additional major equipment will be required. Laboratory facilities and equipment will be provided by Washington State University, Pullman, Washington. Boats, hydro-acoustic equipment and analysis programs will be provided by the Tribes.

Phase 3, 2012.

An oxygen generation facility will be constructed at the present oxygen storage site near the south end of North Twin Lake. No additional major equipment will be required. Laboratory facilities and equipment will be provided by Washington State University, Pullman, Washington. Boats, hydro-acoustic equipment and analysis programs will be provided by the Tribes.

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Recent Publications

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N. Dasgupta, J. Spurrier, E. Martinez, B. C. Moore. 2000. “Comparison to control in logistic regression” *Simulation and Comparison 29(4):1039-1057.*

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Moore, B. C., P. H. Chen, W. H. Funk, and D. Yonge. 1996. A model for predicting lake sediment oxygen demand following hypolimnetic aeration. *Water Resources Bulletin 32(4):723-731.*

Doke, J. W. H. Funk, and B. C. Moore. 1995. Habitat availability and benthic invertebrate population changes following alum treatment and hypolimnetic oxygenation in Newman Lake, Washington. *Journal of Freshwater Ecology 10(2):87-102.*

B. C. Moore, Lafer, J. E., and W. H. Funk. 1994. The influence of macrophyte removal on sediment porewater chemistry in a freshwater wetland. *Journal of Aquatic Botany 49:137-148.*

Marc W. Beutel, Ph.D., P.E.
Assistant Professor
Department of Civil and Environmental Engineering, Washington State University
PO Box 642910, Pullman, WA 99164-2910, 509.335.3721

EDUCATION

Ph.D. University of California, Berkeley, Civil and Environmental Engineering, 2000

M.S. University of California, Berkeley, Civil and Environmental Engineering, 1994
B.S. University of California, Los Angeles, *Cum Laude*, Civil Engineering, 1990

EMPLOYMENT

2004 to Present Assistant Professor, Department of Civil and Environmental Engineering, Washington State University

2001 to 2004 Principal Engineer, Water Resources, Brown and Caldwell, Walnut Creek, CA

1993 to 2000 Graduate Student/Researcher/Teaching Assistant, Department of Civil and Environmental Engineering, University of California, Berkeley

1990 to 1993 Junior/Assistant Engineer, East Bay Municipal Utility District, Oakland, CA

RESEARCH PROGRAM

NFS 2008 CAREER Grant Program, Environmental Engineering. $400,300. M. Beutel (PI). Award pending. *Fundamental Understanding of Mercury Cycling in Lakes and Use of Reservation-Based Research to Recruit American Indians into Environmental Engineering and Science.*

Strategic Environmental Research and Development Program FY 2009. $566,000. M. Beutel (PI), H. Beyenal and R. Watts. Pre-proposal submitted. *Improved Fundamental Understanding of Oxidant Control of Mercury Bioavailability in Aquatic Sediments at Macro and Micro Scales.*

Centennial Clean Water Program, Washington State Water Pollution Revolving Fund. FY2009-2010. T. Erwin (PI), M. Beutel, R. Hummel, J. Ullman. *Clarks Creek Water Quality Science, Restoration and Education Implementation Program.*

Agouron Institute Kamen/Kaplan Graduate Student Grant in Microbial Ecology. 2008 to 2012. $160,000. M. Beutel (PI) and Stephen Dent (Graduate Student). *Microbial Ecology of Mercury Cycling in Freshwater Lakes.*

Colville Confederated Tribes, WA. FY2008 to FY2009. $250,000. M. Beutel (PI) and B. Moore. FY08-FY09. *A Lake Oxygenation Pilot Study to Improve Redband Trout Habitat in Twin Lakes.*

RECENT PUBLICATIONS

Palmer, H.R. and **M.W. Beutel**. 2009. High rates of ammonia removal in oxygen-activated nitrifying wetland mesocosm. ASCE Journal of Environmental Engineering. In press.

Churchill, J.J., **M.W. Beutel** and P. Burgoon. 2009. Evaluation of the optimal alum dose and mixing regime for alum treatment of Matthiesen Creek inflow to Jameson Lake, WA. Lake and Reservoir Management. In press. 24(1):TBD.

Beutel, M.W., N.R. Burley and S.R. Dent. 2008. Nitrate uptake rate in anoxic profundal sediments from a eutrophic reservoir. Hydrobiologia. 610(1):297-306.

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Beutel, M.W., A.J. Horne, W.D. Taylor, R.F. Losee and R.D. Whitney. 2008. Effects of oxygen and nitrate on nutrient release from profundal sediments from a large, mesotrophic reservoir, Lake Mathews, California. Lake and Reservoir Management. 24(1):18-29.

Beutel, M.W., I. Hannoun, J. Pasek and K. Bowman Kavanagh. 2007. Hypolimnetic oxygenation pre-design study for a large eutrophic raw water reservoir, San Vicente Reservoir, CA. ASCE Journal of Environmental Engineering. 133(2):130-138.

Beutel, M.W. 2006. Inhibition of ammonia release from anoxic profundal sediments in lakes using hypolimnetic oxygenation. Ecological Engineering. 28:271-279

Sheri Sears

Sheri L. Sears
Resident Fish Division Manager
Colville Confederated Tribes
Nespelem Fish and Wildlife Office

Education:
Eastern Washington University, 1995, B.S. Environmental Biology
Kaiser Foundation School of Nursing, 1972 R.N. ICU CCU Certified
Contra Costa College, California, 1972 A.A.S. Nursing

Employment History:
July 2006 – Present ~ Colville Confederated Tribes
Resident Fish Division Manager Biologist IV

November 2001 – June 2006 ~ Colville Confederated Tribes
Lake Roosevelt Habitat Improvement Project Manager Biologist II

June 1999 – November 2001 ~ Colville Confederated Tribes
Habitat Biologist I

March 1999 – June 1999 ~ USGS – Biological Division
Rufus Woods Total Dissolved Gas Impact Assessment Project Field Biologist

September 1997 – November 1998 ~ Steven County Conservation District
Field Technician Stream surveys Steven's county watersheds.

1996 –1997 ~ Department of Ecology, ERO
Environmental Intern - Worked with Washington State Attorney General on development of Grass Seed burning ban and developed library of literature to support rule decision.

March 1995 – July 1995 ~ Waste Water Treatment Intern City of Cheney
Tested effluent and wrote manual on identification of aquatic organisms beneficial to waste water treatment.

Professional Affiliations:

2009 - President of the Columbia Basin Fish and Wildlife Authorities (CBFWA) Resident Fish Advisory Committee
2008 – Vice President of the Columbia Basin Fish and Wildlife Authorities (CBFWA) Resident Fish Advisory Committee
2007 – Present - Columbia Basin Water Management Plan representative and conducted assessment for EIS on proposed actions impacts to Lake Roosevelt.
2006 – Present - CCT Representative Lake Roosevelt Managers

2008 - Present - Member of Army Corp of Engineer's (USACE) Technical Management Team (TMT) working with the Bureau of Reclamation (BOR), USACE, various tribes, and the states of Washington, Oregon, Idaho, and Montana on Columbia River and Snake River dam operations and flow coordination
2003 – Present - Wildland Fire Situation Analysis (WFSA) Team Leader
2001 – Present - Burned Area Emergency Rehabilitation (BAER) Team – Wildfire impacts to fish and wildlife and documentation of Emergency Stabilization and Rehabilitation Plans for all fires on the Colville Reservation.
2001 – Present Upper Columbia River Remedial Investigation and feasibility study (RI/FS)

EDWARD W. SHALLENBERGER

Senior Resident Fisheries Biologist
Colville Confederated Tribes

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EDUCATION

Willamette University, Salem Oregon
B.A.—Biology, 1964
Stanford University, Stanford, California
M.A. – Vertebrate Zoology, 1966
University of California, Los Angeles, California
Ph.D. – Animal Behavior, 1970

PREVIOUS WORK EXPERIENCE

May 1994 to April 2006

Columbia River Fish Farms, LLC., Omak, Washington 98841
General Manager: Responsible for the design, permitting and construction and operation of a 4,000,000 pound/year fish farm. In 1994, with the help of a single partner I purchased Stolt Sea Farm's Columbia River assets and designed, permitted and built Columbia River Fish Farms. Under my guidance the farm grew from its initial 8,000 m3 of cage space to its present 80,000 m3.

July 1992 to November 1993

Stolt Sea Farms, Port Angeles, Washington 98362.
Manager, Columbia River Site: In charge of pilot project fish farm on the Columbia River. In charge of all day to day operations at the Columbia River Site. Tests at this site led to the development of Columbia River Fish Farms.

March 1992 to July 1992

Mariculture Inc., Augusta, Maine.
General Manager: Hired by Key Bank of Maine to manage Mariculture Inc. which Key Bank was in the process of repossessing.

March 1988 to December 1991	Tailfin, Inc., 820 D Ave., Anacortes, Washington 98221 **General Manager:** Responsible for construction, installation and operation of a 32-pen salmon farm.

Sheri Sears

Mark Mobley

Summary of Experience and Qualifications:

Mark Mobley has been responsible for the design and installation of over twenty dissolved oxygen enhancement systems at hydropower and water supply reservoirs for goals including dissolved oxygen improvement, anoxic product reductions and establishment of fish habitat. Mark Mobley has also been involved in the evaluation of alternatives for water quality enhancements at over forty reservoirs. Innovative solutions are offered to meet site-specific objectives at each project.

Mobley Engineering Inc., 1999 to Present

Founded Mobley Engineering Inc. (MEI) in 1999 to offer dissolved oxygen enhancement feasibility studies, aeration system designs and installation of the line diffuser reservoir oxygenation system. MEI provides; detailed diffuser designs, installation crews and expertise for application of the line diffuser to diverse projects from large-scale hydropower projects (Shepaug Hydroelectric Station, First Light Power) to small water supply reservoirs (Calaveras Reservoir, City of San Francisco). Serves as a member of a team of experts that evaluate aeration and temperature enhancement alternatives for site-specific hydropower re-licensing or water quality objectives. Recent clients include: the U. S. Army Corps of Engineers, Northeast Generation Services, Idaho Power Company, Western Virginia Water Authority, Consumers Energy, East Bay Municipal Utility District, Duke Power, Mirant and Ameren. For more info: www.mobleyengineering.com.

Tennessee Valley Authority Engineering Laboratory, 1983 to 1999

Over 12 years of experience in selecting, designing, installing, operating and testing systems to improve the water quality conditions of hydropower releases as an Engineer and Project Manager. Responsible for developing the line diffuser technology, and directing design and installation of enhancement systems representing an investment of over $12 million by TVA and other utilities from 1992 to 1998

Education and Licenses:

- **B.S., Mechanical Engineering, Georgia Institute of Technology, Atlanta, Georgia, 1983**
- Licensed Professional Engineer, Mechanical Engineering, State of Tennessee, 1998
- California State Contractor's License Number 779173
- Virginia State Contractor's License Number 2705096356

Special Honors or Awards:

- National Performance Review "Hammer Award" Ocoee Olympic Whitewater Project Team, July 1997

Patents and Publications:

- U.S. Patent 5,065,921, "Bicycle Rack for Mounting on a Van," November 1991.
- Author of over 30 papers or reports on aeration/oxygenation technology. A listing of selected publications is available on request.

Recent Hydropower Projects:

Richard B. Russell Reservoir, US Army Corps of Engineers, Savannah District, 2001 – 2002: **Elberton, GA.** Engineering design and supervision of reservoir diffuser system replacement. Over 40,000 feet of line diffuser installed. The system is capable of delivering over 200 tons per day of oxygen to maintain water quality goals in releases. Through Draper & Associates.

J. Strom Thurmond Reservoir, US Army Corps of Engineers, Savannah District, 2008: Augusta, GA. Bubble plume modeling and conceptual diffuser layout designs to support modeling efforts for fish habitat enhancement. Through Reservoir Environmental Management Inc.

Mongaup River Projects, Mirant NY-Gen, LLC, 2004: Part of a team that provided a study of DO enhancement alternatives, and turbine venting tests to assist client meet state water quality targets below three hydro projects. Through Devine Tarbell Associates.

Lake Wallenpaupack, Pennsylvania Power and Light, 2004: Installation of 4,500 foot reservoir diffuser aeration system using compressed air to eliminate hydrogen sulfide odors in release.

Lake Lillinonah, Shepaug Dam, Northeast Generation Services (now First Light Power), 2006: Design and installation of 11,160 feet of reservoir oxygen diffuser system to distribute up to 90 tons per day of oxygen to meet FERC license requirements.

Recent Water Supply Projects:

Bellwood Quarry Reservoir, City of Atlanta, 2008: Provide conceptual diffuser designs, costs and technical presentation for oxygenation of Bellwood Quarry Reservoir to meet water quality standards. Through Jordan, Jones & Goulding.

Calaveras Reservoir, City of San Francisco Public Utilities Commission, 2005: Design and installation of a reservoir diffuser oxygenation system to create fish habitat and reduce anoxic products in the hypolimnion, and chemical treatments required to treat taste and odor problems. Two 1,000-foot long diffuser lines located to place oxygen to meet goals.

Carvins Cove Reservoir, Western Virginia Water Authority, 2005: Installation of 4,000 foot reservoir diffuser oxygenation system to reduce anoxic products in the hypolimnion, and chemical treatments required to treat taste and odor problems.

Upper San Leandro Reservoir, East Bay Municipal Utility District, 2002: Installation of 4,800 foot reservoir diffuser oxygenation system to reduce anoxic products in the hypolimnion, nutrients and chemical treatments required to treat taste and odor problems.

Paul Gantzer

Paul A. Gantzer, Ph.D., P.E.

Summary of Experience and Qualifications:

Gantzer Water Resources Engineering, LLC, 2008 to Present

Founded Gantzer Water Resources Engineering, LLC in 2008 to provide water quality monitoring in addition to feasibility studies and design specialty for lake and reservoir management, specifically in the field of aeration and oxygenation. Designed and implemented automated operation of the oxygenation system installed in Carvins Cove Reservoir. Currently offering oxygenation expertise for Occaquan Reservoir operated by Fairfax Water in DC. Currently developing a completely remote automated water profiling apparatus for improved water quality monitoring/management.

Western Virginia Water Authority 2000 to 2008

- Carvins Cove Reservoir – (2004-2008)
    - Feasibility Study: Study investigated the feasibility of using a pure oxgyen line diffuser system to increase hypolimnion DO during summer stratification.
    - Oxygenation design: Responsible for oxygenation system design.
    - Oxygenation installation: Project manager and lead engineer responsible for building all piping between diffuser and LOx tank.
    - Oxygenation operation / performanc evaluation: Responsible for oxygenation system operation and performance to evaluate oxygen demand, soluble metals control and future system operational requirements.
- Spring Hollow Reservoir – (2000-2008)
    - Aeration performance and line-diffuser evaluation
    - Aeration system upgrade to LOx: Responsible for diffuser oxygem supply sizing design and served as project manager.
    - Oxygenation performance and operation evalutaion

Education and Licenses:

- Ph.D., Civil Engineering, Virginia Tech, Blacksburg, VA, 2008
- Licensed Professional Engineer, Environmental Engineering, State of Virginia, 2007
- M.S., Environmental Engineering, Virginia Tech, Blacksburg, VA, 2002
- B.S., Civil Engineering, Virginia Tech, Blacksburg, VA, 2000

Publications:

- Gantzer, P.A. and Little, J.C. (2008). Effect of hypolimnetic oxygenation on oxygen depletion rates in two water-supply reservoirs, *Water Research*, Submitted.
- Gantzer, P.A. and Little, J.C. (2008). Controlling soluble iron and manganese in a water-supply reservoir using hypolimnetic oxygenation, *Water Research*, Submitted.
- Singleton, V.L., Gantzer, P., Little, J.C. (2007), Linear Bubble Plume Model for Hypolimnetic Oxygenation: Full-scale Validation and Sensitivity Analysis, *Water Resource Research,* 43, W02405, doi:10.1029/2005WR004836

K. Tables and Figures

Table 1. Temperature profiles in Twin Lakes, 2008. All measurements are in degrees C.

North Twin

	West	*Mid*	*Mid*	*Mid*	*3N*	*2N*	*1N*	*4N*	*5N*	*Mid*	*Mid*	*Mid*	*Mid*
Depth (m)	***5/27***	***5/27***	***6/24***	***7/22***	***7/31***	***7/31***	***7/31***	***7/31***	***7/31***	***8/12***	***9/1***	***9/13***	***10/21***
0	16.0	15.9	19.4	22.4	22.4	22.3	22.3	22.3	22.3	21.5	19.5	17.4	10.9
1	15.9	15.8	19.2	22.5	22.4	22.3	22.2	22.3	22.3	21.5	19.3	17.4	10.9
2	15.4	15.3	18.9	22.5	22.2	22.1	22.1	22.2	22.2	21.5	19.2	17.4	10.8
3	15.2	15.0	18.1	22.5	21.8	21.9	21.8	22.1	22.1	21.4	19.1	17.4	10.8
4	14.6	14.5	15.2	22.4	21.7	21.7	21.6	21.7	22.0	21.3	19.1	17.4	10.7
5	13.0	12.9	12.7	19.8	18.7	20.0	20.2	20.4	21.2	20.6	19.0	17.3	10.7
6	11.4	11.0	10.5	14.5	14.7	13.5	13.0	14.8	15.4	17.2	18.9	17.2	10.7
7	9.0	8.7	8.8	10.6	11.2	10.8	16.5	10.2	11.3	12.4	18.9	11.8	10.7
8		7.4	7.6	8.4	8.9	8.6	8.6	8.1	8.4	9.3	12.8	9.5	10.7
9		6.9	6.8	7.2	7.5	7.4	7.5	7.3	7.0	7.7	8.6	9.2	10.7
10		6.4	6.2	6.5	6.6	6.6	6.6	6.6	6.3	6.6	7.9	8.8	10.0
11		*6.1*	5.8	6.0	6.1	6.1	6.0	6.2	5.8	6.0	7.5	8.7	8.7
12		5.7	5.5	5.8	5.7	5.7	*5.8*	5.8	5.6	5.6	*7.2*	*8.5*	8.2
13		5.4	5.4	5.6	5.5	5.6		5.6	5.4	5.5	6.7	8.3	7.9
14		5.4	5.3	5.5	5.4	5.6		5.4	5.4	5.4	6.2	8.0	7.3
14.5		-		5.4	5.4			-	5.4	5.4	-	7.4	
15		5.4						5.4			5.8		

South Twin

	Mid	*Mid*	*S1*	*S3*	*S2*	*S4*	*S5*	*Mid*	*Mid*	*Mid*	*Mid*
Depth (m)	***6/24***	***7/22***	***7/31***	***7/31***	***7/31***	***7/31***	***7/31***	***8/12***	***8/30***	***9/13***	***10/21***
0	19.5	23.4	21.9	22.1	21.95	22.3	22.3	21.9	20.2	18.6	11.1
1	19.2	23.4	21.9	22.0	21.9	22.3	22.1	21.8	20.1	18.5	11.2
2	19.0	23.4	21.8	21.9	21.8	21.9	21.9	21.7	20.0	18.4	11.2
3	18.8	23.4	21.7	21.8	21.8	21.8	21.9	21.4	19.7	18.2	11.3
4	17.3	23.4	21.6	21.8	21.7	21.8	21.8	21.2	19.6	18.1	11.3
5	15.9	23.4	21.5	21.2	21.3	21.7	21.7	21.1	19.6	18.0	11.3
6	11.6	16.5	17.0	17.7	18.2	17.4	16.8	18.6	19.5	17.8	11.3
7	9.3	13.1	12.5	13.2	12.7	12.7	12.6	15.4	19.3	16.6	11.3
8	7.9	9.9	10.1	10.6	10.5	10.6	10.0	11.2	15.5	13.1	11.3
9	7.0	8.3		9.0	9.9	9.4	8.8	9.2	11.1	10.7	11.2
10	6.5	7.4		8.2	7.9	8.1	7.5	8.2	9.2	9.2	10.7
11	6.2			7.0		7.1	6.8	7.1	7.7	8.1	8.3
12	6.0			6.4		6.5	6.4	6.5	7.7	*7.2*	7.2
13	5.8					6.1	6.2	6.1	6.5	6.6	6.7
13.5	-					6.0	-	-	-	-	-
14	5.6						5.9	6.0	6.3	6.3	6.4
15	5.4						5.7	6.0	6.1	6.1	6.3
16							5.6				
16.5							5.6				

Table 2. Dissolved oxygen profiles in Twin Lakes, 2008. All measurements are in mg/L.

North Twin

	West	*Mid*	*Mid*	*Mid*	*3N*	*2N*	*1N*	*4N*	*5N*	*Mid*	*Mid*	*Mid*	*Mid*
Depth (m)	***5/27***	***5/27***	***6/24***	***7/22***	***7/31***	***7/31***	***7/31***	***7/31***	***7/31***	***8/12***	***9/1***	***9/13***	***10/2***
0	10.4	10.4	7.9	6.7	6.2	6.0	6.1	6.4	6.3	6.3	8.2	8.7	8.0
1	11.0	10.4	7.9	6.4	6.0	6.0	6.0	6.0	6.0	6.0	8.2	8.7	8.0
2	10.5	10.5	7.9	6.3	6.0	6.0	6.0	6.0	6.0	5.9	8.3	8.7	8.0
3	10.5	10.5	8.2	6.3	6.1	6.1	6.0	6.0	6.0	5.9	8.2	8.7	8.0
4	10.5	10.6	8.5	6.2	6.1	6.1	6.0	6.0	6.0	5.9	8.2	8.7	7.9
5	10.6	10.7	9.0	7.1	7.3	6.8	6.2	6.8	6.9	5.8	8.2	8.7	7.9
6	10.9	11.0	7.1	6.5	7.7	6.6	5.5	7.7	7.3	7.1	8.1	8.6	7.9
7		11.5	4.6	3.5	4.3	3.5	2.8	3.0	4.0	4.3	8.0	4.4	7.8
8		6.8	*2.8*	0.9	1.1	0.7	0.9	1.4	1.4	1.3	4.3	4.4	7.7
9		6.0	2.8	0.4	0.7	0.6	0.4	0.5	0.4	0.5	3.9	4.0	*7.3*
10		5.8	2.4	0.2	0.3	0.4	0.3	0.3	0.3	0.3	3.5	4.0	4.1
11		4.8	2.4	0.2	0.3	0.2	0.2	0.3	0.3	0.3	2.9	3.9	0.7
12		*3.8*	0.5	0.2	0.2	0.2	0.2	0.2	0.2	0.3	2.6	3.5	0.3
13		2.9	0.2	0.2	0.2	0.1		0.2	0.2	0.2	0.3	2.7	0.3
14		2.6	0.2	0.2	0.2	0.1		0.1	0.1	0.2	0.9	1.9	0.3
14.5		-		0.2	0.1			-	0.1	0.2	-	1.1	
15		2.5						0.1			6.3		

South Twin

	Mid	*Mid*	*S1*	*S3*	*S2*	*S4*	*S5*	*Mid*	*Mid*	*Mid*	*Mid*
Depth (m)	***6/24***	***7/22***	***7/31***	***7/31***	***7/31***	***7/31***	***7/31***	***8/12***	***8/30***	***9/13***	***10/2***
0	8.7	6.6	6.5	6.3	6.5	6.4	6.3	6.2	8.5	8.0	8.1
1	8.6	6.4	6.5	6.3	6.4	6.2	6.2	6.1	8.5	8.7	7.7
2	8.6	6.4	6.5	6.2	6.4	6.3	6.2	6.1	8.5	8.7	7.6

3	8.5	6.5	6.5	6.3	6.5	6.2	6.3	6.1	8.4	8.6	7.6
4	8.6	6.4	6.5	6.3	6.5	6.2	6.2	6.1	8.4	8.6	7.5
5	8.0	6.4	6.6	6.9	6.4	6.2	6.2	6.1	8.4	8.5	7.5
6	7.8	7.2	4.5	6.9	6.1	7.3	7.2	5.5	8.4	8.0	7.6
7	8.5	6.6	3.7	4.9	5.6	5.4	5.0	5.8	7.7	5.2	7.6
8	4.1	3.8	1.3	3.2	3.0	3.3	2.0	1.6	4.5	0.4	7.6
9	1.2	0.6		0.5	1.3	0.8	0.5	0.4	0.5	0.3	7.4
10	0.3	0.3		0.3	0.4	0.4	0.4	0.3	0.4	0.4	0.5
11	0.3			0.2		0.3	0.2	0.2	0.3	0.3	0.3
12	0.2			0.1		0.2	0.2	0.2	0.2	0.2	0.3
13	0.2					0.2	0.1	0.2	0.2	0.2	0.3
13.5	-					0.1	-	-	-	-	-
14	0.2						0.1	0.2	0.2	0.2	0.3
15	0.2						0.1	0.2	0.2	0.2	0.3
16							0.1				
16.5							0.1				

Table 3. Dissolved oxygen profiles in Twin Lakes, 2008. All values are expressed as temperature-correcte

North Twin

	West	*Mid*	*Mid*	*Mid*	*3N*	*2N*	*1N*	*4N*	*5N*	*Mid*
Depth (m)	***5/27***	***5/27***	***6/24***	***7/22***	***7/31***	***7/31***	***7/31***	***7/31***	***7/31***	***8/12***
0	111	111	91	81	75	73	74	75	76	76
1	111	111	90	78	74	73	73	73	73	72
2	111	111	90	77	74	73	72	73	73	71
3	110	110	90	77	73	73	73	73	72	71
4	110	109	89	76	73	73	72	73	72	70
5	106	107	90	82	83	79	72	80	81	68
6	106	105	66	67	79	67	55	81	77	79
7	104		42	32	41	33	26	28	39	42

8	60	21	8	10	7	8	13	9	12
9	52	25	3	6	6	4	4	4	5
10	51	20	2	3	3	3	3	2	3
11	39	19	2	2	2	2	2	2	2
12	32	2	2	2	2	2	2	2	2
13	25	2	2	2	1		1	2	2
14	22	1	2	1	1		1	2	2
14.5	-		-	1			-	1	1
15	21		2				0		

South Twin

	Mid	*Mid*	*S1*	*S3*	*S2*	*S4*	*S5*	*Mid*
Depth (m)	***6/24***	***7/22***	***7/31***	***7/31***	***7/31***	***7/31***	***7/31***	***8/12***
0	99	81	78	77	78	27	76	75
1	97	80	78	76	78	75	75	73
2	97	80	78	75	77	76	75	73
3	96	80	79	76	78	75	75	72
4	94	80	79	76	77	75	75	72
5	85	79	79	83	77	75	74	72
6	75	79	49	77	69	80	78	62
7	78	67	35	49	55	53	47	61
8	34	36	12	31	27	30	18	15
9	8	6		4	12	7	5	7
10	3	3		3	4	3	3	3
11	3			2		2	2	2
12	2			1		2	2	2
13	2					1	1	1
13.5	-					1	-	-
14	2						1	1
15	2						1	2
16							1	
16.5							1	

North Twin

Depth (m)
0
1
2
3
4
5
6

Table 4. Specific Conductivity profiles in Twin Lakes, 2008. All values are in uS/cm.

North Twin

	West	*Mid*	*Mid*	*Mid*	*3N*	*2N*	*1N*	*4N*	*5N*	*Mid*	*Mid*	*Mid*	*Mid*
Depth (m)	***5/27***	***5/27***	***6/24***	***7/22***	***7/31***	***7/31***	***7/31***	***7/31***	***7/31***	***8/12***	***9/1***	***9/13***	***10/21***
0	51	50	51	52	52	52	52	52	52	53	56	57	57
1	51	50	51	52	53	52	52	52	52	53	56	56	57
2	51	51	50	52	52	52	52	52	52	53	57	56	58
3	50	51	50	52	51	52	52	52	52	53	56	56	57
4	50	50	50	52	52	52	52	52	52	53	56	57	57
5	50	8	52	51	51	51	52	51	51	53	56	56	57
6	50	51	53	53	52	53	53	51	51	52	56	57	58
7	53	54	54	54	53	54	54	54	54	54	56	61	57
8		54	55	57	56	56	54	56	55	56	60	63	58
9		54	55	57	55	55	55	57	58	57	69	61	58
10		55	55	59	56	56	57	57	56	59	69	63	60
11		55	56	60	57	58	59	58	58	62	69	63	63
12		55	58	68	65	61	68	58	68	72	70	63	65
13		57	62	70	72	73		70	74	79	62	62	77
14		57	65	75	76	74		77	77	81	76	63	104
14.5		-		-	80			-	78	81	-	70	
15		57		79				77			82		

South Twin

	Mid	*Mid*	*S1*	*S3*	*S2*	*S4*	*S5*	*Mid*	*Mid*	*Mid*	*Mid*
Depth (m)	***6/24***	***7/22***	***7/31***	***7/31***	***7/31***	***7/31***	***7/31***	***8/12***	***8/30***	***9/13***	***10/21***
0	80	82	82	82	82	82	82	83	86	86	85
1	80	82	82	83	82	82	82	83	86	86	86
2	79	82	82	83	82	82	82	83	87	86	86
3	79	82	82	82	82	82	82	83	86	86	86
4	79	82	82	82	82	82	82	83	85	86	86
5	79	82	82	82	82	82	82	83	86	86	86
6	81	80	82	81	81	80	80	83	86	86	85
7	82	81	84	81	81	82	82	83	86	86	85
8	82	83	87	83	83	83	84	84	87	88	85
9	83	85		85	86	84	84	85	88	90	86
10	83	86		87	107	84	83	84	88	88	89
11	82			87		83	86	86	89	89	96
12	83			172		87	86	91	90	93	106
13	88					97	94	99	100	106	116
13.5	-					224	-	-	-	-	-

14	91	99	103	103	112	120
15	148	105	147	109	115	125
16		106				
16.5		147				

Table 5. Profiles of pH in Twin Lakes, 2008. All values as the negative log of the hydrogen ion activity.

North Twin

	West	*Mid*	*Mid*	*Mid*	*3N*	*2N*	*1N*	*4N*	*5N*	*Mid*	*Mid*	*Mid*	*Mid*
Depth (m)	***5/27***	***5/27***	***6/24***	***7/22***	***7/31***	***7/31***	***7/31***	***7/31***	***7/31***	***8/12***	***9/1***	***9/13***	***10/21***
0	8.2	8.1	7.3	7.8	7.7	7.4	7.4	7.5	7.5	7.5	7.6	7.6	7.2
1	8.2	8.1	7.3	7.8	7.7	7.5	7.5	7.6	7.6	7.6	7.5	7.6	7.2
2	8.3	8.2	7.3	7.8	7.7	7.6	7.5	7.6	7.6	7.6	7.5	7.7	7.2
3	8.3	8.2	7.2	7.8	7.7	7.6	7.6	7.6	7.6	7.6	7.6	7.7	7.2
4	8.2	8.2	7.1	7.8	7.7	7.7	7.6	7.6	7.6	7.6	7.6	7.7	7.2
5	8.0	7.9	7.0	7.1	7.8	7.7	7.2	7.7	7.7	7.6	7.6	7.7	7.2
6	7.8	7.8	6.5	7.1	7.4	7.1	7.0	7.3	7.4	7.4	7.6	7.6	7.2
7	7.7	7.7	6.3	6.7	6.8	6.7	6.6	6.7	6.8	6.9	7.6	6.9	7.2
8		6.9	6.2	6.6	6.5	6.4	6.5	6.6	6.5	6.6	7.0	6.8	7.2
9		6.8	6.1	6.5	6.5	6.4	6.4	6.5	6.5	6.5	6.8	6.7	7.2
10		6.8	6.1	6.4	6.4	6.4	6.4	6.4	6.4	6.5	6.8	6.7	6.9
11		6.7	6.0	6.4	6.4	6.3	6.3	6.4	6.4	6.5	6.8	6.7	6.7
12		6.7	5.9	6.4	6.4	6.4	6.4	6.4	6.4	6.6	6.8	6.7	6.6
13		6.6	5.9	6.4	6.5	6.4		6.4	6.5	6.6	6.8	6.7	6.7
14		6.6	5.9	6.4	6.5	6.4		6.5	6.5	6.5	6.8	6.7	6.8
14.5		-		-	6.5			-	6.5	6.5	-	6.7	
15		6.6		6.4				6.4			6.8		

South Twin

		Mid	*Mid*	*S1*	*S3*	*S2*	*S4*	*S5*	*Mid*	*Mid*	*Mid*	*Mid*

Depth (m)	***6/24***	***7/22***	***7/31***	***7/31***	***7/31***	***7/31***	***7/31***	***8/12***	***8/30***	***9/13***	***10/21***
0	8.0	8.5	8.2	8.2	8.3	8.2	8.2	8.4	8.4	8.0	7.4
1	8.0	8.5	8.3	8.2	8.3	8.2	8.2	8.4	8.4	8.1	7.5
2	7.9	8.5	8.2	8.3	8.3	8.2	8.2	8.4	8.4	8.2	7.5
3	7.9	8.5	8.3	8.3	8.3	8.2	8.2	8.4	8.5	8.1	7.5
4	7.8	8.5	8.3	8.3	8.3	8.2	8.2	8.4	8.4	8.1	7.5
5	7.3	8.5	8.3	8.3	8.2	8.2	8.2	8.4	8.4	8.1	7.5
6	6.9	7.8	7.0	7.6	7.4	7.8	7.6	7.5	8.4	8.0	7.5
7	6.9	7.5	6.9	7.0	7.1	7.1	7.1	7.3	8.2	7.4	7.6
8	6.5	7.0	6.7	6.7	6.8	6.8	6.8	7.0	7.4	7.0	7.6
9	6.6	6.8		6.7	6.7	6.7	6.7	6.8	7.2	6.9	7.5
10	6.2	6.7		6.6	6.6	6.6	6.6	6.8	7.1	6.9	7.4
11	6.1			6.5		6.5	6.5	6.7	7.0	6.9	6.9
12	6.1			6.3		7.4	6.5	6.7	7.0	6.8	6.9
13	6.1					6.5	6.5	6.7	6.9	6.8	6.8
13.5	-					6.3	-	-	-	-	-
14	6.1						6.5	6.6	6.9	6.8	6.8
15	6.0						6.4	6.5	6.9	6.8	6.8
16							6.4				
16.5							6.4				

Table 6. Total phosphorus concentrations in Twin Lakes, 2008. All values are in mg/L, as phosphorus. All samples were taken at Mid-lake stations for each respective lake.

North Twin

Depth (m)	***5/27***	***6/11***	***6/24***	***7/22***	***8/13***	***8/30***	***9/13***	***10/20***	***11/10***
0	0.024	0.024	0.012	0.029	0.015	0.011	0.021	0.015	0.033
1	-	0.029	0.022	0.018	0.018		0.018	0.024	0.029
2	-	0.021	0.020	-	0.023		0.011	0.016	0.029

2.5	0.025	-	-	-	-		-	-	-
3	-	0.026	0.024	0.020	0.022		0.016	0.023	0.032
4	-	0.021	0.014	0.020	0.017		0.021	0.028	0.025
5	0.022	0.028	0.019	0.022	0.020		0.023	0.020	0.025
6	-	0.033	0.033	0.020	0.023		0.018	0.011	0.034
7	-	0.028	0.037	0.040	0.029		0.025	0.017	0.031
7.5	0.069	-	-	-	-		-	-	-
8	-	0.034	0.038	0.031	0.028		0.044	0.021	0.027
9	-	0.024	0.028	0.031	0.025		0.024	0.018	0.040
10	0.011	0.020	0.023	0.030	0.033		-	0.023	0.007
11	-	0.025	0.030	0.045	0.038		0.047	0.029	0.026
12	-	0.029	0.033	0.095	-		0.039	0.030	0.027
12.5	0.030	-	-	-	-		-	-	-
13			0.049	0.104	0.104		0.036	0.076	0.047
14			0.075	0.141	0.112		0.055		

South Twin

Depth (m)	***5/27***	***6/11***	***6/24***	***7/22***	***8/13***	***8/30***	***9/13***	***10/20***	***11/10***
0	0.022	0.019	0.013	0.009	0.012	0.011	0.013	0.023	0.011
1	-	0.023	0.016	0.014	0.017		0.015	0.010	0.011
2	-	0.024	0.014	0.011	0.011		0.010	0.010	0.022
3	0.016	0.029	0.012	0.017	0.015		0.004	0.012	0.014
4	-	0.026	0.020	0.015	0.017		0.015	0.010	0.022
5	-	0.021	0.018	0.031	0.002		0.011	0.013	0.024
6	0.034	0.027	0.033	0.027	0.011		0.013	0.011	0.025
7	-	0.029	0.034	0.027	0.025		0.017	0.015	0.019
8	-	0.032	0.072	0.026	0.017		0.027	0.014	0.011
9	0.034	0.041	0.045	0.012	0.022		0.025	0.015	0.024
10	-	0.038	0.061	0.025	0.028		0.018	0.011	0.030
11	-	0.037	0.067		0.042		0.038	0.024	0.023
12	0.054	0.028	0.051		0.078		0.046	0.067	0.038
13		0.063	0.041		0.164		0.140	0.265	
14			0.074		0.170		0.171	0.281	
15			0.189						

Table 7. Orthophosphorus concentrations in Twin Lakes, 2008. All values are in mg/L, as phosphorus. All samples were taken at Mid-lake stations for each respective lake.

North Twin

Depth (m)	**5/27**	**6/11**	**6/24**	**7/22**	**8/13**	**8/30**	**9/13**	**10/20**
0	0.006	0.005	0.005	0.005	0.005	0.005	0.005	0.005
1	-	0.005	0.005	0.005	0.011		0.005	0.006

2	-	0.006	0.005	0.005	0.005		0.005	0.005
2.5	0.006	-	-	-	-		-	-
3	-	0.005	0.006	0.005	0.005		0.005	0.005
4	-	0.005	0.005	0.005	0.005		0.005	0.006
5	0.006	0.006	0.005	0.008	0.005		0.006	0.007
6	-	0.006	0.005	0.007	0.006		0.005	0.005
7	-	0.006	0.006	0.008	0.006		0.006	0.005
7.5	0.012	-	-	-	-		-	-
8	-	0.006	0.006	0.011	0.007		0.013	0.006
9	-	0.006	0.006	0.011	0.008		0.012	0.005
10	0.006	0.006	0.006	0.010	0.006		0.011	0.007
11	-	0.006	0.006	0.039	0.006		0.013	0.011
12	**-**	0.009	0.011	0.029	0.017		0.014	0.011
12.5	0.007		-	-	-		-	-
13			0.012	0.060	0.048		0.013	0.025
14			0.010		0.089		0.012	

South Twin

Depth (m)	**5/27**	**6/11**	**6/24**	**7/22**	**8/13**	**8/30**	**9/13**	**10/20**
0	0.003	0.003	0.002	0.002	0.002	0.002	0.002	0.002
1	-	0.004	0.002	0.002	0.002		0.002	0.002
2	-	0.002	0.002	0.003	0.002		0.002	0.002
3	0.003	0.003	0.003	0.002	0.002		0.002	0.002
4	-	0.002	0.002	0.002	0.002		0.002	0.002
5	-	0.003	0.002	0.002	0.002		0.002	0.002
6	0.002	0.002	0.002	0.002	0.002		0.002	0.002
7	-	0.002	0.002	0.003	0.002		0.002	0.002
8	-	0.003	0.003	0.007	0.005		0.005	0.002
9	0.003	0.003	0.003	0.010	0.004		0.002	0.002
10	-	0.002	0.005		0.003		0.002	0.002
11	-	0.006	0.003		0.003		0.003	0.008
12	0.003	0.003	0.003		0.006		0.003	0.044
13			0.003		0.020		0.011	0.033
14			0.013		0.014			0.147
15			0.015					0.100

Table 8. Ammonia nitrogen concentrations in Twin Lakes, 2008. All values are in mg/L, as nitrogen. All samples were taken at Mid-lake stations for each respective lake.

North Twin

Depth (m)	**5/27**	**6/11**	**6/24**	**7/22**	**8/13**	**8/30**	**9/13**	**10/20**
0	0.031	0.040	0.042	0.003	0.005	0.027	0.015	0.039
1	-	0.013	0.034	0.009	0.038		0.026	0.046
2	-	0.040	0.026	0.002	0.008		0.019	0.059
2.5	0.012	-	-	-	-		-	-
3	-	0.030	0.032	0.004	0.005		0.026	0.065
4	-	0.024	0.054	0.012	0.017		0.020	0.075
5	0.016	0.014	0.051	-	0.006		0.030	0.058
6	-	0.067	0.073	0.054	0.018		0.018	0.050
7	-	0.108	0.039	0.005	0.020		0.059	0.038
7.5	0.028	-	-	-	-		-	-
8	-	0.122	0.129	0.033	0.016		0.154	0.011
9	-	0.058	0.124	*	0.000		0.111	0.020
10	0.037	0.028	0.066	0.011	0.005		0.116	0.005
11	-	0.036	0.076	0.099	0.018		0.180	0.021
12	-	0.027	0.006	0.211	0.409		0.121	0.011
12.5	0.025		-	-	-		-	-
13			*	0.274	0.646		0.148	0.068
14			*	0.469	*		0.245	

South Twin

Depth (m)	**5/27**	**6/11**	**6/24**	**7/22**	**8/13**	**8/30**	**9/13**	**10/20**
0	0.041	0.064	0.038	0.013	0.014	0.053	0.056	0.073
1	-	0.036	0.057	0.006	0.013		0.020	0.040
2	-	0.044	0.038	0.011	0.008		0.030	0.033
3	0.038	0.035	0.019	0.015	0.017		0.025	0.045
4	-	0.035	0.049	0.010	0.009		0.017	0.048
5	-	0.021	0.061	0.013	0.006		0.015	0.007
6	0.082	0.050	0.151	0.014	0.003		0.015	0.036
7	-	0.057	0.134	0.051	0.043		0.016	0.019
8	-	0.080	0.119	0.169	0.047		0.050	0.013
9	0.054	0.070	0.012	0.124	0.010		0.015	0.017
10	-	0.054	0.011		0.031		0.013	0.037
11	-	0.084	0.108		0.035		0.065	0.125
12	0.068	0.016	0.085		0.356		0.291	0.472
13			0.079		0.822		0.686	1.416
14			0.255		1.086			1.653
15			0.011					1.429

* sample could not be analyzed

Table 9. Nitrate/nitrite concentrations in Twin Lakes, 2008. All values are in mg/L, as nitrogen. All samples were taken at Mid-lake stations for each respective lake.

North Twin

Depth (m)	**5/27**	**6/11**	**6/24**	**7/22**	**8/13**	**8/30**	**9/13**	**10/20**
0	0.004	0.001	0.006	0.014	0.004	<DL	0.001	0.029
1	-	0.004	0.005	0.004	0.007		<DL	0.042
2	-	0.005	0.004	0.013	0.003		0.001	0.068
2.5	0.001	-	-	-	-		-	-
3	-	0.001	0.005	0.006	0.003		0.001	0.034
4	-	0.001	0.026	0.006	0.006		0.001	0.029
5	0.007	0.000	0.004	0.013	0.003		<DL	0.009
6	-	0.002	0.003	0.011	0.006		0.001	0.017
7	-	0.001	0.068	0.014	0.006		0.009	0.014
7.5	0.008	-	-	-	-		-	-
8	-	0.001	0.010	0.009	0.006		0.006	0.017
9	-	0.004	0.009	0.008	<DL		0.004	0.013
10	0.002	0.003	0.010	0.009	0.005		0.003	0.124
11	-	0.010	0.013	0.010	0.005		0.008	0.118
12	-	0.025	0.177	0.015	0.010		0.014	0.123
12.5	0.027		-	-	-		-	-
13			0.206	0.018	0.010		0.007	0.118
14			0.121		0.122			

South Twin

Depth (m)	**5/27**	**6/11**	**6/24**	**7/22**	**8/13**	**8/30**	**9/13**	**10/20**
0	0.004	0.007	0.014	0.011	0.008	<DL	0.003	0.242
1	-	0.009	0.004	0.010	0.005		<DL	0.414
2	-	0.006	0.009	0.009	0.007		0.001	0.566
3	0.003	0.007	<DL	0.013	0.008		<DL	0.519
4	-	0.004	0.007	0.009	0.004		0.002	0.461
5	-	0.004	0.004	0.011	0.003		0.001	0.297
6	0.003	0.006	0.012	0.004	0.000		<DL	0.337
7	-	0.032	0.010	0.012	0.010		0.001	0.350
8	-	0.015	0.005	0.010	0.013		0.006	0.130
9	0.008	0.003	0.180	0.020	0.005		0.001	0.390
10	-	0.003	0.230		0.003		0.002	0.091
11	-	0.020	0.013		0.007		0.001	0.130
12	0.030	0.008	0.008		0.011		0.007	0.130
13			0.003		0.281		0.009	0.130
14			0.036					0.130
15			0.130					0.193

Table 10. Alkalinity profiles in Twin Lakes, 2008. All values are in mg/L, as calcium carbonate.

North Twin

Depth (m)	**5/27**	**6/11**	**6/24**	**7/22**	**8/13**	**8/30**	**9/13**	**10/20**
0	22.006	26.113	23.754	23.801	24.560	23.754	20.116	21.861
1	-	26.779	23.487	26.559	25.950		20.097	26.264
2	-	25.870	22.988	26.848	25.970		21.859	12.847
2.5	17.225	-	-	-	-		-	-
3	-	26.337	23.452	22.344	23.540		20.849	22.743
4	-	23.090	24.047	24.866	25.133		22.460	27.905
5	25.003	27.496	26.447	24.208	25.001		23.815	28.437
6	-	28.319	25.777	26.435	25.828		22.682	28.484
7	-	27.822	27.486	28.510	25.548		24.253	29.470
7.5	112.609	-	-	-	-		-	-
8	-	28.993	26.989	28.449	26.404		26.227	29.881
9	-	25.828	28.176	29.676	26.610		24.328	28.625
10	25.854	29.315	27.046	27.121	27.362		21.240	32.141
11	-	29.097	28.957	30.580	28.060		25.274	29.639
12	-	28.940	29.254	29.040	28.205		23.130	35.174
12.5	20.244		-	-	-		-	-
13			26.634	29.262	30.444		23.799	37.433
14			28.853		27.406		26.239	

South Twin

Depth (m)	**5/27**	**6/11**	**6/24**	**7/22**	**8/13**	**8/30**	**9/13**	**10/20**
0	21.364	35.944	37.861	38.962	38.948	39.171	40.148	39.977
1	-	37.646	36.987	40.198	39.322		39.132	40.064
2	-	33.385	35.799	39.601	35.658		39.663	39.735
3	14.994	27.846	37.109	40.5	39.576		39.08	39.595
4	-	37.758	37.63	38.249	38.851		38.991	39.642
5	-	38.262	38.51	38.588	40.77		39.464	34.014
6	36.679	36.764	39.508	39.617	39.795		39.287	37.522
7	-	40.099	41.312	41.136	41.219		38.194	36.989
8	-	40.524	39.768	41.642	41.791		38.21	35.288
9	40.384	37.427	40.436	17.016	41.13		39.469	38.464
10	-	40.175	38.501		41.533		40.545	37.931
11	-	<DL	23.469		41.126		41.708	40.69
12	39.65	21.197	40.907		42.952		42.456	41.553
13			37.937		43.742		43.68	43.43
14			<DL		44.814			40.667
15			38.221					32.336

Table 11. Secchi depths in Twin Lakes, 2008. All values are in meters.

North Twin	***5/27***	***6/24***	***7/23***	***7/31***	***8/13***	***9/1***	***9/13***	***10/21***
West	3.20							
Mid	2.50	5.40	3.25		4.50	6.50	6.25	5.75

South Twin	***6/24***	***7/22***	***7/31***	***8/12***	***8/30***	***9/13***	***10/21***
Mid	5.25	3.25		4.5	4.5	6.25	4.75

Table 12. Total dissolved solids in Twin Lakes, 2008. All values are in mg/L, calculated from specific conductivity.

North Twin

	3N	*2N*	*1N*	*4N*	*5N*	*Mid*	*Mid*	*Mid*
Depth (m)	***7/31***	***7/31***	***7/31***	***7/31***	***7/31***	***8/12***	***9/1***	***9/13***
0	0.033	0.033	0.033	0.034	0.033	0.034	0.036	0.036
1	0.033	0.033	0.033	0.033	0.033	0.034	0.036	0.036
2	0.033	0.033	0.033	0.033	0.033	0.034	0.036	0.036
3	0.033	0.033	0.033	0.033	0.033	0.034	0.036	0.036
4	0.033	0.033	0.033	0.033	0.033	0.034	0.036	0.036
5	0.033	0.033	0.033	0.033	0.033	0.034	0.036	0.036
6	0.033	0.033	0.034	0.033	0.033	0.033	0.036	0.036
7	0.034	0.034	0.034	0.035	0.034	0.035	0.036	0.038
8	0.036	0.036	0.035	0.036	0.035	0.036	0.040	0.040
9	0.035	0.035	0.036	0.036	0.037	0.036	0.043	0.040
10	0.036	0.036	0.036	0.036	0.036	0.038	0.045	0.040
11	0.037	0.037	0.037	0.037	0.037	0.040	0.044	0.040
12	0.041	0.040	0.044	0.037	0.043	0.046	0.045	0.040
13	0.047	0.045		0.045	0.047	0.051	0.039	0.040
14	0.049	0.047		0.049	0.050	0.052	0.050	0.040
14.5	0.051			-	0.050	0.052	-	-
15				0.050			0.053	0.045

South Twin

	S1	*S3*	*S2*	*S4*	*S5*	*Mid*	*Mid*	*Mid*
Depth (m)	***7/31***	***7/31***	***7/31***	***7/31***	***7/31***	***8/12***	***8/30***	***9/13***
0	0.053	0.053	0.053	0.053	0.053	0.053	0.055	0.0552
1	0.053	0.053	0.052	0.053	0.053	0.053	0.055	0.0554

2	0.053	0.053	0.053	0.053	0.052	0.053	0.055	0.0552
3	0.053	0.053	0.053	0.053	0.052	0.053	0.055	0.0549
4	0.053	0.053	0.053	0.053	0.053	0.053	0.544	0.0549
5	0.053	0.052	0.052	0.052	0.053	0.053	0.055	0.0549
6	0.053	0.052	0.053	0.051	0.052	0.053	0.055	0.0551
7	0.053	0.053	0.052	0.052	0.052	0.053	0.055	0.0554
8	0.056	0.053	0.053	0.053	0.053	0.054	0.055	0.0562
9		0.054	0.055	0.054	0.054	0.054	0.056	0.0567
10		0.055	0.056	0.054	0.053	0.054	0.056	0.0561
11		0.055		0.053	0.055	0.055	0.057	0.0568
12		0.104		0.055	0.055	0.058	0.058	0.0597
13				0.063	0.060	0.064	0.064	0.0678
13.5				0.142	-	-	-	0.0713
14					0.063	0.066	0.066	-
15					0.067	0.095	0.066	0.0736
16					0.068			
16.5					0.093			

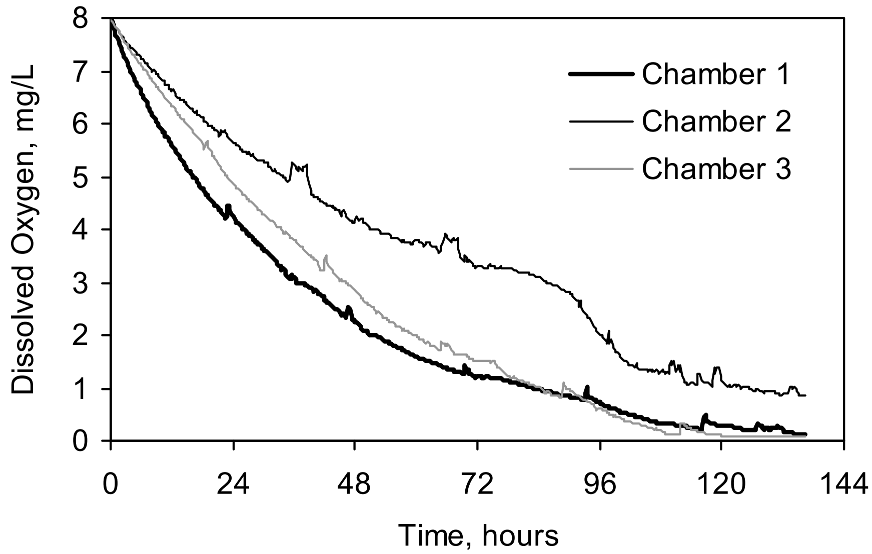

Figure 1. DO uptake in water in replicate experimental chambers containing sediment-water interface samples from North Twin Lake.

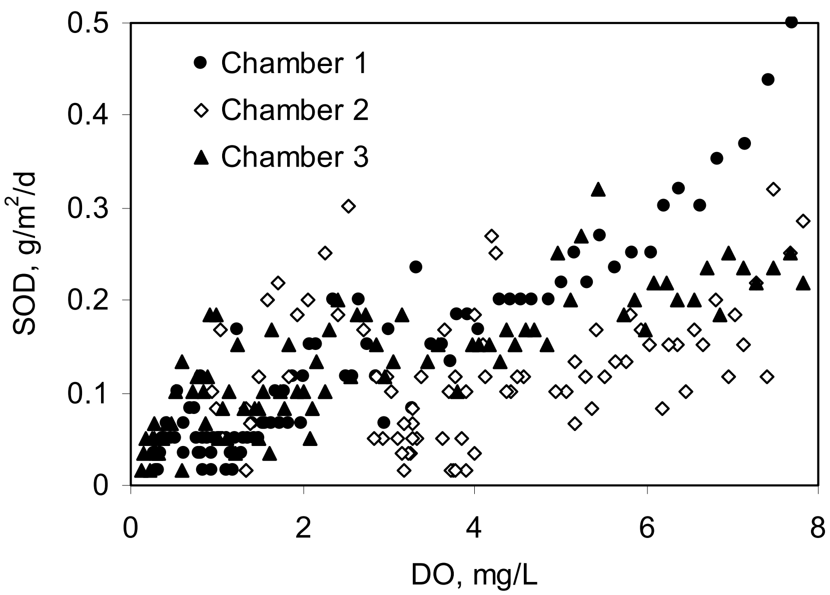

Figure 2. Sediment Oxygen Demand (SOD) as a function of DO in overlaying water based on data set presented in Figure 1. While there is quite a bit of variability in the data, SOD tends to increase with increasing DO in overlaying water.

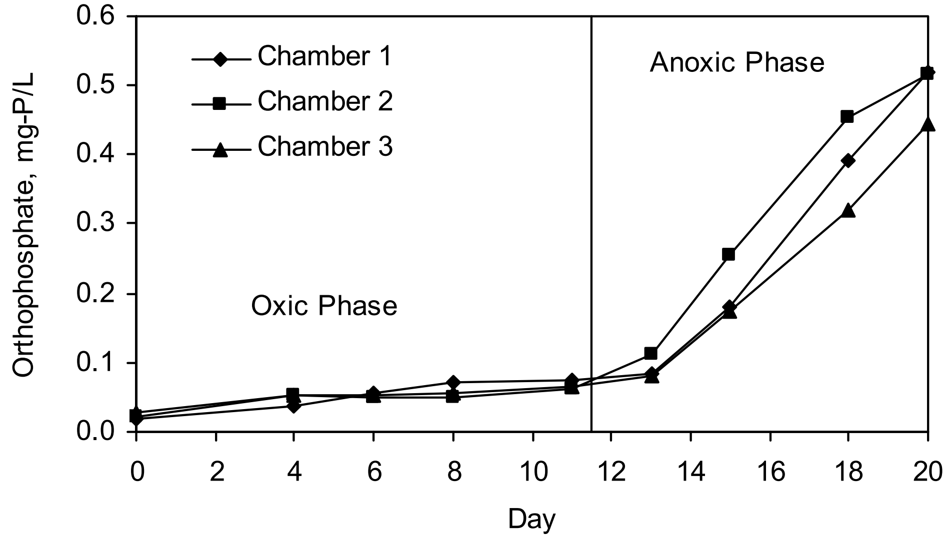

Figure 3. Ortho-P in water overlying sediments in North Twin Lake sediment incubations. Note that shortly after switching the chambers over to anoxic oxygen-free conditions, water started to accumulate P.

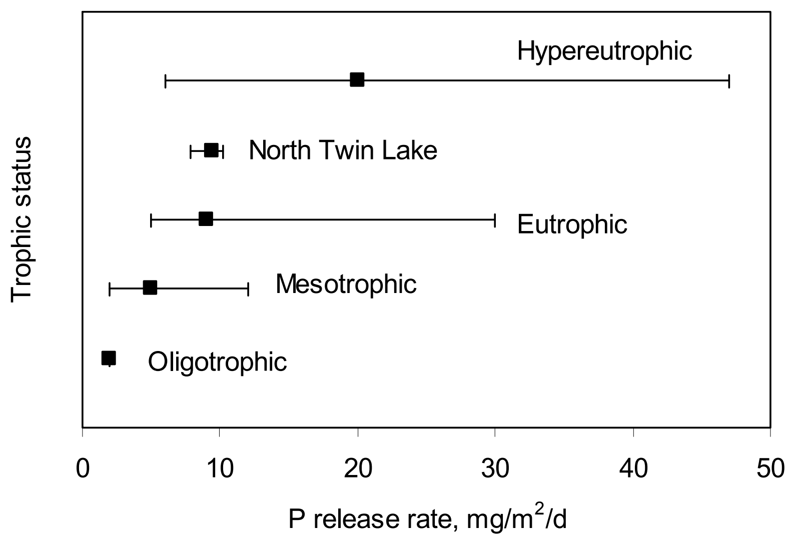

Figure 4. Typical range of anaerobic P release from lake sediments as a function of lake trophic status. Symbol is median and error bars are 95% confidence limits. Based on Nurnberg (1988, Can. J. Fish. Aquat. Sci. 45:453-462) and Auer et al. (1993, Hydrobiol 253:301-309; 1993). Note that the P release rates measured in North Twin Lake are typical of other eutrophic lakes.

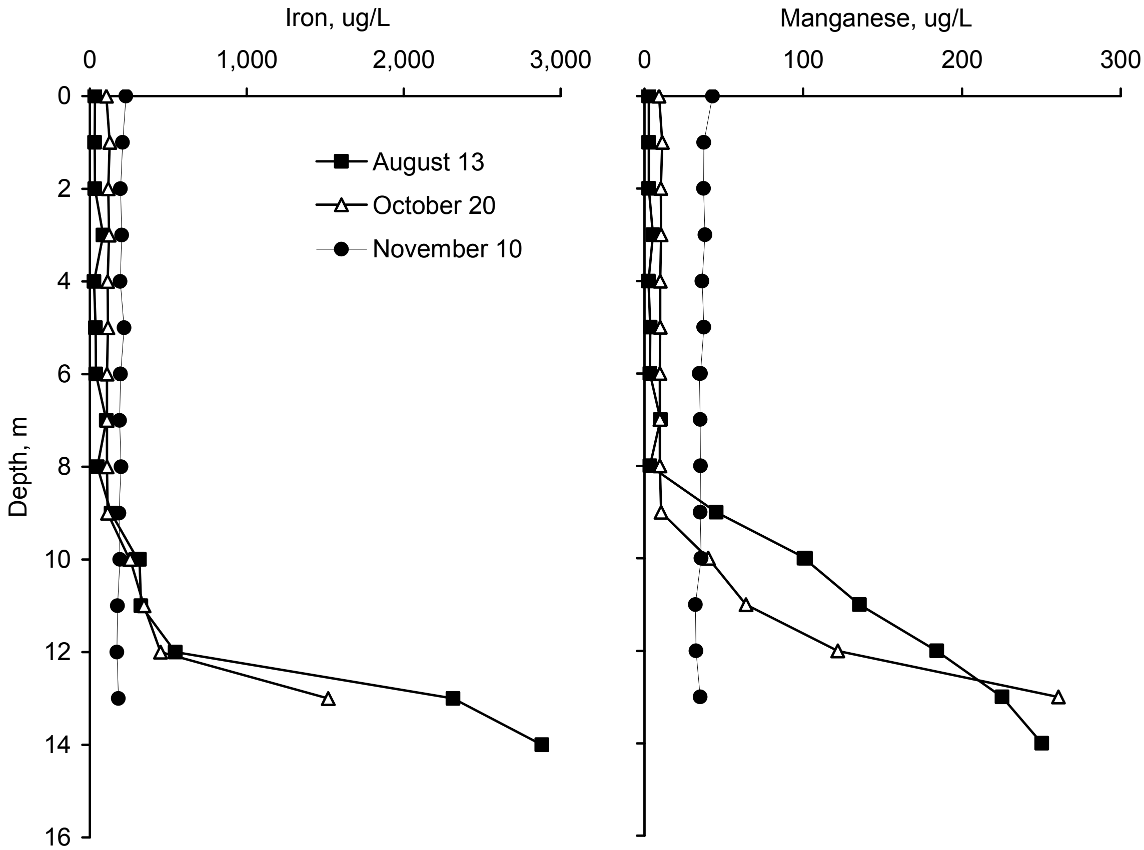

Figure 5. Selected seasonal profiles for iron and manganese in North Twin Lake. Data shows that metals accumulate in bottom waters during summer and fall thermal stratification as a result of anaerobic conditions. Upon turnover in early November metals were mixed throughout the water column.

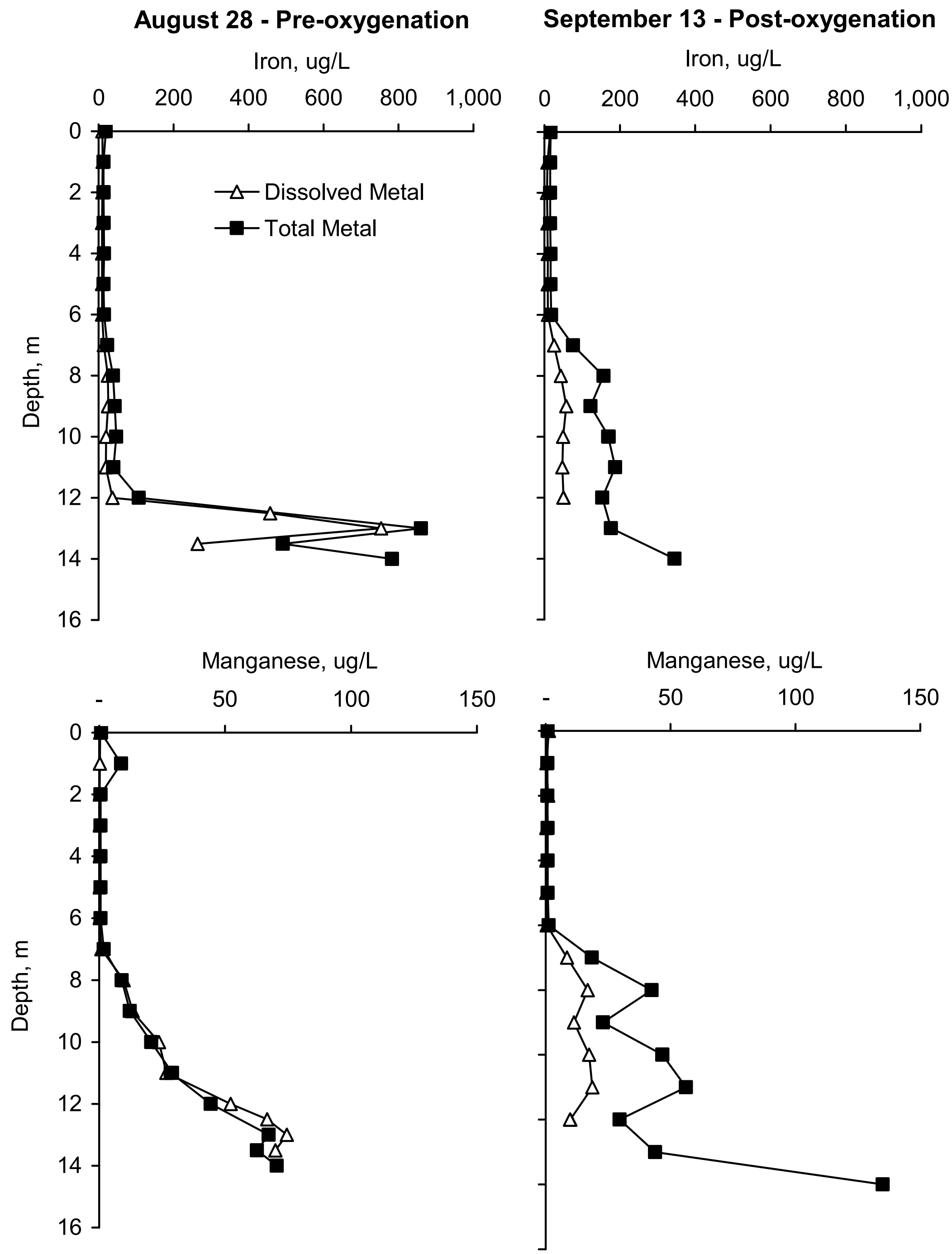

Figure 6. Total (square) and dissolved (triangle) iron (top) and manganese (bottom) in North Twin Lake before and after test oxygenation in early September, 2008. Before oxygenation, metals were in the reduced, dissolved form (dissolved equaled total) in the bottom of the lake as a result of anaerobic conditions in the hypolimnion. After oxygenation, much of the iron and manganese was transformed to the oxidized, particulate form (the difference between dissolved and total).