Colville Confederated Tribes
Fish and Wildlife Department
M E M O R A N D U M

November 23, 2009

To: Linda Hermeston

From: Ed Shallenberger

Subject: Revised Twin Lakes Oxygenation Proposal

As a result of the conference call with the ISRP on November 16 we have revised our Twin Lakes Oxygenation Proposal to address the concerns raised by the ISRP in the conference call.

The major modifications to the proposal are highlighted in green. Additional tables have been added as well. The specific areas that we have addressed are:

1. Describe in more detail the fisheries problems at Twin Lakes.
2. Explain in detail why we consider oxygenation the best choice for improving conditions and restoring the fishery at Twin Lakes.
3. Give a more detailed description of the dissolved oxygen conditions at Twin Lakes.
4. Describe the effects of oxygenation on water quality and fish populations in North Twin Lake in 2009 and compare with the conditions in South Twin Lake which was not oxygenated.
5. Describe in more detail plans for monitoring fish growth, mortality and catch rates during 2010 and subsequent years.
6. Describe the methods of evaluating the effects of oxygenation on mercury levels in the water column, zooplankton and fish.

We hope that this more detailed proposal meets all of the ISRP's concerns. As always, we accept the ISRP's comments and concerns as constructive criticism in an effort to design a more defensible project.

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**
Contact Name	**Ed Shallenberger**
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Information transfer:

A. Abstract

North and South Twin Lakes have been a popular recreational destination for nearly one hundred years. A number of studies have been implemented by the Colville Confederated Tribes (CCT) over the past two decades to evaluate apparent changes in water quality, decreasing angling success, and the results of restoration efforts related to the control of nutrient loading to the lakes (Juul, 1987; Juul and Hueftle, 1992). More recent studies have focused on the impaired health of the trout fishery (Christensen and Moore. 2007b; Christensen and Moore, 2008; Christensen et al. 2007), and these studies have concluded that poor habitat during the summer, including no dissolved oxygen in cool bottom waters, is the main cause of the problem.

The purpose of this project is to improve summer habitat 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 internal cycling of nutrients and toxic chemicals such as phosphorous, ammonia and hydrogen sulfide.

A pilot oxygenation system was installed and operated in North Twin Lake in late summer 2008. For 2009, full scale, season-long (summer stratification) implementation of oxygenation in North Twin Lake is currently in operation. South Twin Lake is acting as an anoxic reference lake. If the system proves successful, then oxygenation will be extended to South Twin in 2010, with full scale operation anticipated in 2011.

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 are being and will continue to 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) total mercury and/or methylmercury levels in lake water, zooplankton and fish.

B. Problem statement: technical and/or scientific background

Water quality problems in Twin Lakes were first investigated by Juul (1987). Juul identified the sources of external nutrient loading (stream runoff, wastewater from resorts, and septic tanks) and estimated their contribution to the total nutrient load. Juul hypothesized that although external nutrient loading was significant, internal nutrient recycling contributed a greater portion of the total nutrient load, particularly in South Twin which has a longer water retention time (9.4 years vs. 2.7 years for North Twin). Juul stated that while water quality was still relatively good there was evidence that it was degrading. Juul concluded with suggestions for eliminating external loading and possible methods of controlling internal nutrient loading.

As a result of Juul's work several steps were taken to control water quality in Twin Lakes:

1. An effort was made to release as much water as possible through the South Twin Lake outlet in order to reduce the hydrologic retention time of that lake.
2. Five miles of four-wire fence were installed along the southern and western boundaries of the lakes. Two cattle guards were placed at road crossings.
3. The Environmental Trust Department of the Colville Confederated Tribes prepared a watershed management plan which has since been followed.
4. In 1989 a winter drawdown of North Twin was attempted in order to freeze out macrophytes. In 1990 a drawdown of South Twin Lake was attempted using a siphon.
5. In 1989 an attempt was made to remove sediment and macrophytes from the channel area between the two lakes. Approximately 22,000 cubic yards of material were removed.
6. Sewage and septic systems were modified in order to prevent input to the lakes.
7. A moratorium was placed on development in areas not already developed

In a follow up study Juul and Hueftle (1992) reported on the restoration efforts and reassessed water quality conditions of both lakes and concluded that the primary nutrient load was caused by internal recycling within the lakes. External phosphorous loading was effectively reduced by the above management actions but internal recycling of nutrients continued to be problematic.

In spite of these management efforts water quality did not improve and the quality of the fishery appeared to decline. In 2003 Washington State University and the Fish and Wildlife Department of the Colville Confederated Tribes began a cooperative effort to reassess both water quality and fishery status. These studies have been reported by

Shallenberger in the Hatchery Project's annual reports (2007, 2008, and 2009 annual reports).In 2006, under the Hatchery Project (1985-038-00), the CCT Fish and Wildlife Department initiated a detailed creel study in order to assess catch rates and angling pressure. This study has been reported in 2006, 2007, and 2008 Hatchery Project annual reports (Shallenberger, 2007, 2008 and 2009). It continues today as a Hatchery Project work element and although not part of the Twin Lakes Enhancement Project it will be used to help monitor the effect of oxygenation on the Twin Lakes Fishery.

As a result of the work by Juul (1987 and 1992) and later work by the CCT/WSU cooperative studies it was concluded that salmonids in North and South Twin Lakes were not healthy and that the Colville Tribes would have to make substantial improvements if management goals were to be met.

1. Creel census studies indicated that return to creel numbers were less than 5% of the number of fish planted.
2. Summer mortality was very high, possibly as much as 90%.
3. Winter mortality was low. Fish planted in the fall have little mortality until the following summer.
4. Fish growth was good in both spring and fall, but very poor in summer months. Fish planted in the spring left the hatchery with a high relative weight (W_r) which actually increased in May, June and early July but decreased during August and September (Christensen and Moore, 2008). This was confirmed in 2008 and 2009 gill net studies. Salmonid growth in North and South Twin Lakes was found to be considerably less than in other reservation lakes. Spring entry redbands planted in La Fleur Lake and sampled in late September had 47% more growth than their cohorts that were planted in North and South Twin Lakes.
5. During summer months North and South Twin Lakes are strongly stratified. Water temperatures in the epilimnion are high and the hypolimnion is anoxic with dissolved oxygen layers less than 1mg/L.

Several possible remedies were considered and are discussed in Christensen and Moore's 2008 report. Changes in stocking strategies and size of fish stocked, stocking of native redbands, further reductions in external nutrient loading, public education and hypolimnetic oxygenation have all been implemented.

Alum treatment, aeration and hypolimnetic oxygenation were considered as possible remedies of improving water quality. Hypolimnetic oxygenation was chosen as the best remedial solution for a number of reasons.

1. The primary problem that we were trying to address was anoxic conditions in the hypolimnion. Oxygenation does this directly. By binding phosphorus, alum treatment might improve anoxic conditions over the long term by decreasing internal nutrient cycling, but it does not do it directly and immediately. However, a number of studies have shown that alum addition does not improve oxygen conditions in the hypolimnion in the near term. Steinman and Ogdahl (2008) reported declined dissolved oxygen readings at all sites sampled with levels being observed below 1 mg/l during the year following a full-lake alum treatment of Spring Lake in Michigan. . The Michigan Department of Environmental Quality (2008) found that alum chemical treatments of Morrison Lake were effective at reducing the effects of phosphorus; however, oxygen levels also declined throughout the water column.

2. Alum treatments generally require multiple treatments and are not a one-time fix. Lewandowski et al. (2003) reported on long-term effects of alum application as a restoration technique and showed that the buried P sorbing layer (the alum cap) was ineffective on phosphorus release of the upper most fresh sediment layers. They concluded that repeated applications of alum are necessary to improve effectiveness of P sorbtion.
3. This is a fisheries project. We therefore want to maintain a healthy benthos, not one capped with alum. See Stienman and Ogdahl (2008) above.
4. While alum treatment has been shown to improve water quality in some shallow, highly eutrophic lakes, we did not consider it appropriate for Twin Lakes because of their size, depth, internal water movements, and trophic state. Several causes of alum treatment failures were identified in a report by the Minnehaha Creek Watershed District. Two common lake characteristics that contributed to low success of alum treatments were light fluffy sediments and internal waves or seiching. Alum floc was observed to sink or be mixed in with loose or fluffy sediments, and non uniform sediment coverage resulted from the floc being unevenly distributed from internal waves and wind-induced mixing. Our sediment and hydrodynamic studies show that North and South Twin Lakes have both fluffy sediments and seiching.
5. The anoxic condition of the hypolimnion in North and South Twin Lakes is caused by the high sediment oxygen demand (SOD) that has built up over decades. Oxygenation provides the means to satisfy the latent carry-over oxygen demand historically observed in the sediments, whereas alum treatment forces the underlying sediments to remain anoxic, thus prolonging their complete oxidation and providing an environment conducive to the formation and potential mobilization of reduced compounds.
6. While oxygenation needs to be applied regularly, in contrast to alum there is a diminishing cost over time. Alum treatment must be redone every 7-10 years. Oxygenation over time reduces the SOD, eventually reducing the need to oxygenate. This was observed in Spring Hollow Reservoir and Carvins Cover Reservoir in Roanoke, VA (Gantzer et al., 2009b). In Spring Hollow Reservoir for example, net oxygen addition was reduced from 18,000 kg each year in 2005 and 2006 to 5,000 kg in 2009.
7. Both alum treatment and oxygenation are not inexpensive, but our cost analysis (attached) shows oxygenation to be less costly. The cost to treat Green Lake (in Seattle, WA) with alum in 2004 was in excess of $1.5 million (Hererra Environmental Consultants, 2003). An earlier alum treatment of green lake was around half this cost. The oxygenation system in North Twin Lake cost approximately $210,000 to construct and $80,000 per year to operate.
8.

   Oxygenation also is a better alternative than aeration (Beutel and Horne, 1999), particularly in a large lake like North Twin. Aeration, while appropriate for smaller lakes, requires approximately five times as much air to inject an equivalent amount of oxygen into the lake. This would require a distribution system five times as large. Oxygen transfer to the hypolimnion is far less efficient with aeration and it is unlikely that similar dissolved oxygen levels could be reached. An aeration and oxygenation test was performed in Spring Hollow Reservoir during the summer of 2003 (Gantzer, unpublished), comparing the same oxygen mass addition from a compressed air application and a pure oxygen addition.

The net overall efficiency of the aeration system was observed to be approximately 25%, whereas the pure oxygen addition was observed in excess of 95%. Additionally, the aeration/oxygenation test revealed a significant increase of dissolved nitrogen. The elevated concentration of nitrogen can result in fish kills as the aquatic life travels from the deeper super-saturated hypolimnion to the surface waters under atmospheric conditions. While the cost of oxygen would be eliminated, large compressors would have to be installed and significant electrical costs would be incurred. Structures to eliminate sound effects of the compressor units would also have to be built. Oxygenation is silent and requires no electricity or containment.

9. Aeration at the level required to oxygenate the hypolimnion carries significant risks. Destratification, increased turbidity, and nitrogen supersaturation all need to be considered.

Lake Oxygenation in Twin Lakes

Money was obtained for a two year pilot project through resident fish enhancement funds from the Columbia River Water Management Plan (CRWMP) under a Memorandum of Agreement between the State of Washington and the Colville Confederated Tribes. An oxygenation system was installed and briefly operated in North Twin Lake in 2008. This system is being operated and monitored in 2009, again funded with CRWMP money. This funding is scheduled to end in June of 2010 and a transition to BPA funding for the project was included in the 2008 Fish Accords.

This proposal is the culmination of more than 25 years of research, implementation of water quality control measures and ultimately the construction and testing of hypolimnetic oxygenation. It is the primary goal of this project to improve the water quality conditions in North and South Twin Lakes to significantly increase summer survival of native salmonids.

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 in North Twin and a reference lake in South Twin is unique in its simplicity and statistical power. In addition to the side-by-side evaluation for North versus South Twin Lakes for 2009 and 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.

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.

Fisheries Habitat

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). The discovery in 2001 of genetically pure populations of native interior redband rainbow trout in Reservation streams above barriers and the success of the Colville Tribal Hatchery in the rearing of these redbands has led to the complete replacement of the coastal rainbow stocking program 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 more prevalent hatchery rainbows 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 (including anadromous steelhead) 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 increases the biological oxygen demand (BOD) reducing available oxygen concentrations. This de-oxygenation 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 are often less than optimum. The reduction of available habitat decreases the carrying capacity of the lake and increases stress levels leading to greater susceptibility to disease and parasites.

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 cold water species and will have numerous long-term benefits for the overall lake ecology.

Prior to 1985 Twin Lakes was planted with costal rainbow trout and brook trout, initially raised at federal hatcheries and later raised at the Colville Tribal Hatchery. Although no mortality data are available it is apparent from Marco and Warren creel study (Marco and Warren, 1981) that summer survival was adequate, based on the year classes of angler catches and the frequent observation of large spawning brook trout in the fall.

In the late 1980s largemouth bass were illegally introduced and shortly thereafter golden shiners were also illegally introduced. One of the goals of the CCT/WSU studies was to determine what effects the bass and shiner populations were having on trout survival. Results are summarized in reports by Christensen and Moore (2004, 2005, and 2008) and Biggs, et al. (2006) and in Christensen and Moore (2007 a and b, 2008, and 2009). These studies indicate that while bass predation plays a significant role in trout mortality it is not the major cause of poor summer survival. It is more likely the severe "habitat squeeze" caused by high water temperatures in the epilimnion and lack of oxygen in the hypolimnion was the primary limiting factor in trout summer survival.

Two distinct fisheries have developed at Twin Lakes. The largemouth bass fishery is managed by regulation only. Season and bag limits are designed to maximize predation on golden shiners. This strategy appears be successful. The bass fishery is thriving and the shiner population appears to have reached a steady state condition. The trout fishery is managed both by regulation and by hatchery stocking. Under present conditions the most effective strategy is to plant a large number of sub-catchable fish in the fall and a smaller number of catchable fish in the spring. The spring entry fish make up the bulk of the reported catch until the fall entry fish reach catchable size (mid June). The fall entry fish provide the bulk of the catch throughout the summer. There are few trout caught in the fall-winter cold weather season although there is a small subsistence ice fishery.

Although CCT creel studies (Shallenberger, 2007, 2008, and 2009) were directed primarily towards determination of catch rates and angling efforts, it is apparent from differential tagging that winter mortality is very low, but summer mortality is extremely high, possible greater than 90%. Fish planted in the spring are rarely caught in the late fall or the following summer. Fish planted in the fall make up a substantial portion of the catch the following summer. Return to creel of sub-catchable and catchable rainbow trout is typically near 5%. Return to creel of fry plants is negligible.

In addition to poor summer survival, rainbow trout (both coastal and redband) have shown declining relative weight (Wr) as the summer progresses (Christensen and Moore, 2008). Fish stocked in spring had a Wr of 88 ± 9.4. This increased to 94 ± 8.7 in July and then decreased to 82 ± 7.7 in August and 79 ± 5.9 by September.

In recent years the Colville Tribal hatchery has moved from planting only coastal rainbow trout to planting only the native redband rainbow trout. Different stocks of rainbow trout planted into Twin Lakes have been differentially marked. To date there appears to be little difference in survival rates between the two stocks. In 2009 only redband rainbow trout were stocked. The Tribes no longer raise any coastal stocks therefore we cannot continue planting coastal stocks until the nutrient problem has been resolved.

While triploid coastal rainbow trout were stocked for many years few if any of these "put-grow-and-take" fish remain in the system. Some natural spawning does occur in a few to the tributaries that flow into the lakes and genetic analysis has indicated these are hybrids (planted coastal and native redband admixture). Historically diploid coastal trout were planted in Twin Lakes. Natural shoreline spawning of Eastern brook trout does occur and because of Tribal Member preferences, brook trout continue to be planted into the terminal waters.

Data indicate that the largemouth bass are effectively controlling the golden shiner population and that food source has improved the bass fishery. The high summer temperatures in the epilimnion have led to effective habitat partitioning the bass and golden shiners are occupying the warmer epilimnion and the trout the metalimnion. With the oxygenation the trout are now utilizing the hypolimnion as well.

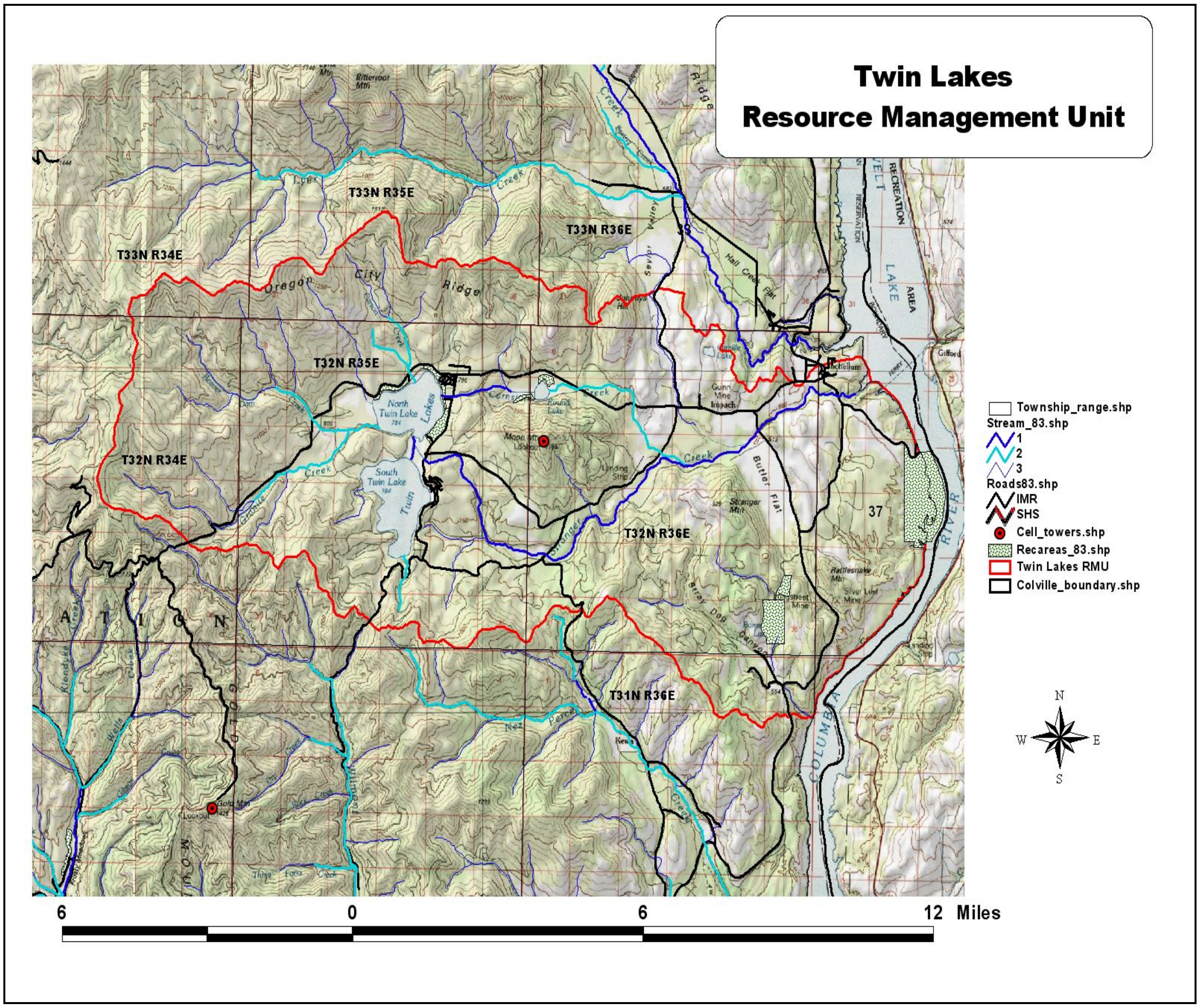
Watershed analysis

The Twin Lakes are on the Colville Indian Reservation within Ferry County in the Upper Columbia Subbasin. This rural area is sparsely populated and the closest town is the City of Inchelium that is located east of the Twin Lakes on Lake Roosevelt (Columbia River). The majority of the land 70% is in Trust status, 24% is in Fee lands and 6% is in Allotment status with the majority of fee and allotment lands to the east of Twin Lakes (please see Figure 1, page 9). North Twin Lake is predominately in Section 10 of Township 32N, Range 35E of the 33 Willamette Meridian. From the center of the lake the Latitude is 48°17’ 14.54” North and the Longitude is 118° 22’ 57.44” West at 2572 feet above mean sea level (please see Figure 2, page 11). South Twin Lake is predominately in Section 22 of Township 32N, Range 35E of the 33 Willamette Meridian. From the center of the lake the latitude is 48°15’ 48.36” North and the Longitude is 118° 23’ 4.34” West at 2572 feet above mean sea level (please see Figure 3, page 12).

Agriculture, grazing, recreation, and timber harvest are predominate land uses. Twin Lakes are one of the most important member and non-member recreational areas on the Reservation. The Twin Lake Resource Management Unit is 95.7 square miles (61,265 acres) and contains 400.3 miles of roads for a density of 4.2 miles/square mile. The boreal forest is predominately (42%) ponderosa pine, with 28% in mixed fir, 18% Douglas fir and 12% is un-forested. Elevation ranges from 1290-feet at Lake Roosevelt (full pool) to 5410-feet at peak west of the lakes in Township 32N, Range 34E. The average rainfall is 23-inches with a high percentage of this falling in the winter as snow pack.

Currently two ESA listed species are found at the lake (please see Figures 2 and 3, pages 11-12). There are four bald eagle nests along the lakes two between the lakes and two to the west of South Twin on the lower half of the lake. Three loon nests (State listed and Federal species of concern) are located at the lakes one on the west end of North Twin, one at the outlet from North Twin Lake to the channel connecting the lakes and the third on the Southwest corner of South Twin Lake. These nests are among the few in Washington State actively producing young annually. Both of these birds are listed as Tribal Priority Species (CCT F&W Management Plan 2007). The lake has a large beaver population with several lodges in the channel between the lakes and the shallow areas near the Stranger Creek outlet. Deer, moose, elk, and bear have all documented around the Twin Lakes area. The eagles and loons have been noted actively fishing on the lakes and following the recent death of one of the male loon feather samples were sent for analysis to determine the cause of the two-year old bird’s death. Mercury and lead contamination are suspected sediment samples are being collected with the sediment monitoring and analysis will be paid with CRWMP money but the results of this work will be included in the annual reports

Figure 1 Twin Lakes Resource Management Unit



Over the years different resorts have existed around the lakes. The Bailey resort on the south end of North Twin was abandoned and razed in the mid1940's the Log Cabin resort on South Twin has been in existence since the 1920s and Rainbow Beach resort since the mid 1930s. The lack of sewer systems at these resorts significantly contributed to the nutrient loading of the lakes over the years. In the late 1980s and early 1990's new development was prohibited and new sewer systems were developed to transport and treat sewage off site away from the lake.

Table 1. Basic physical data

Attribute	North Twin Lake	South Twin Lake
Elevation (m)	784	784
Surface area (ha)	371	413
Volume (*$10^7 m^3$)	3.6	4.2
Maximum depth (m)	15.2	17.4
Mean depth (m)	9.7	10.4
Watershed area (ha)	11,580 (both lakes are in the same resource unit)	

The majority of development is along the eastern shoreline of both North and South Twin Lakes. A Tribal campground and RV park is on the north side of North Twin Lake. At the northeast corner of North Twin a single residence and a small private community development (Lakeview Homes) exists. Immediately south is the Tribal Youth Camp and South of that is the Rainbow Beach Resort which is tribally owned and operated. Hidden Beach is to the south of Rainbow Beach and consists of a dock with swim area. A narrow shallow channel connects the North and South lakes and the Log Cabin Resort is along the northeastern shoreline of South Twin Lake. South of this are some seasonally used lake homes. To the south and along the western shorelines of both lakes there is no development. Cattle have been ranged in this area in the past but with the construction of the fencing along the south and west shoreline following the Juul's report in 1987 they were excluded from access to the lake.

Figure 2. Map of North Twin Lake.

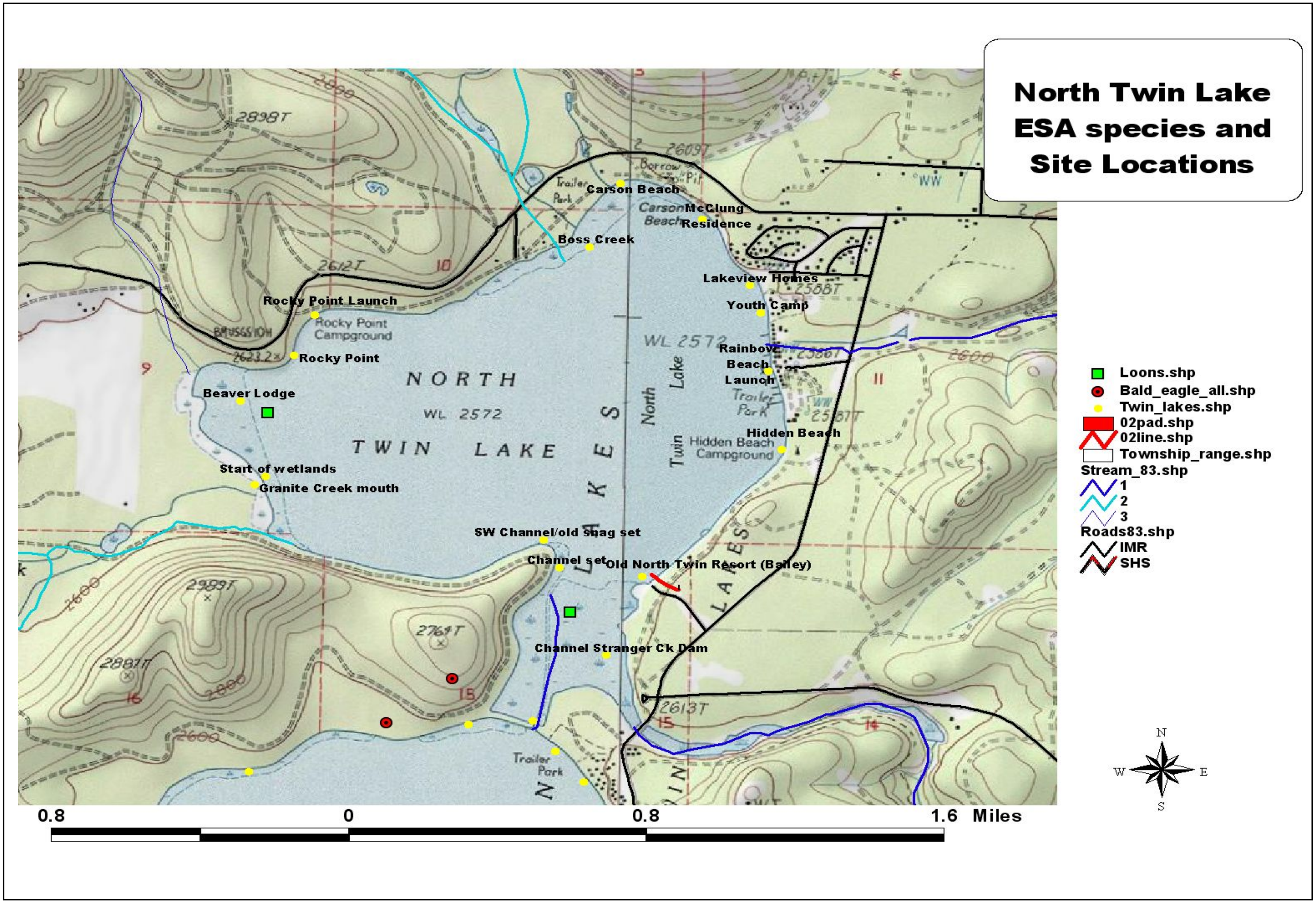
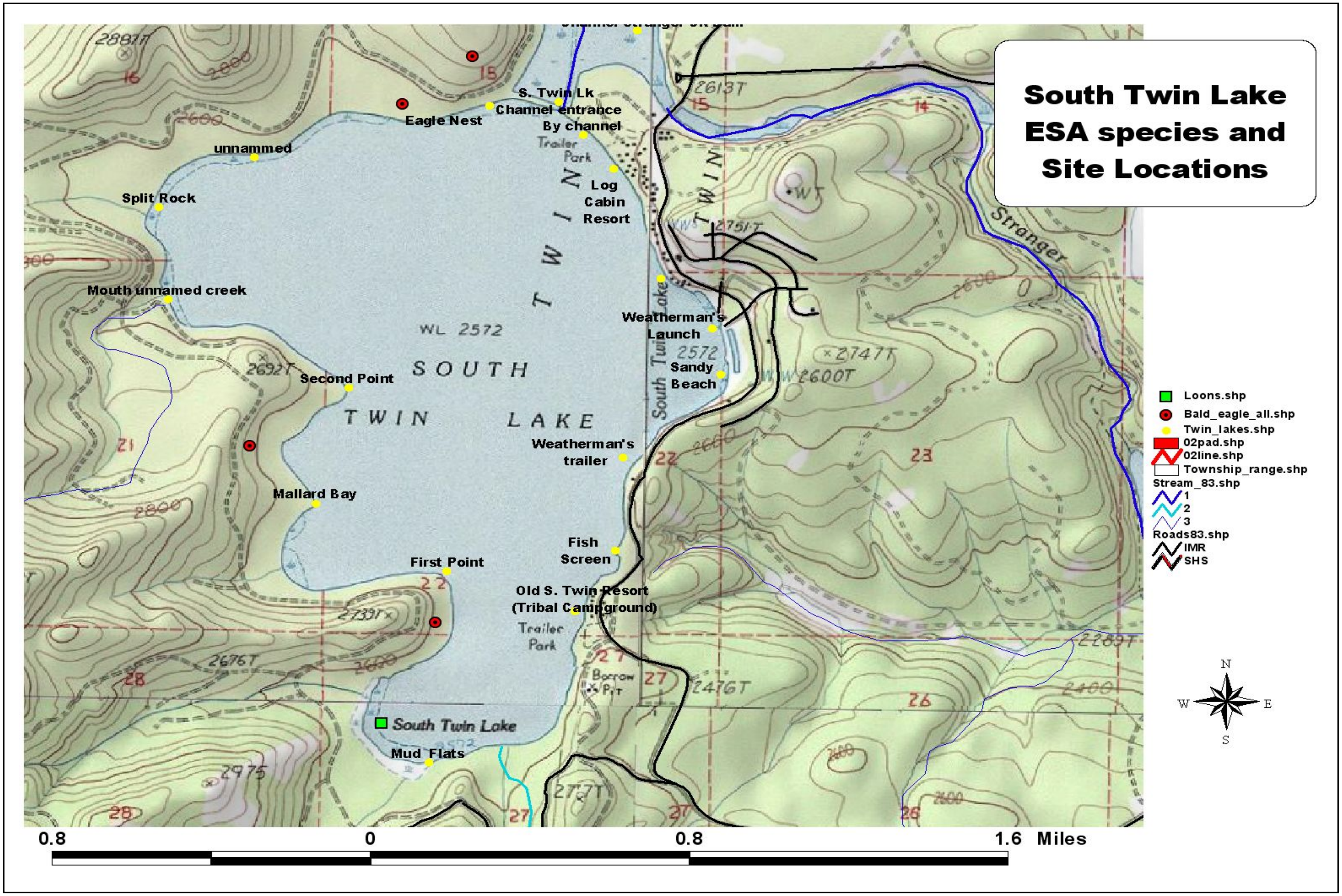


Figure 3. Map of South Twin Lakes



Water Quality

Ancillary, but substantial, ecological benefits of oxygenation include 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.

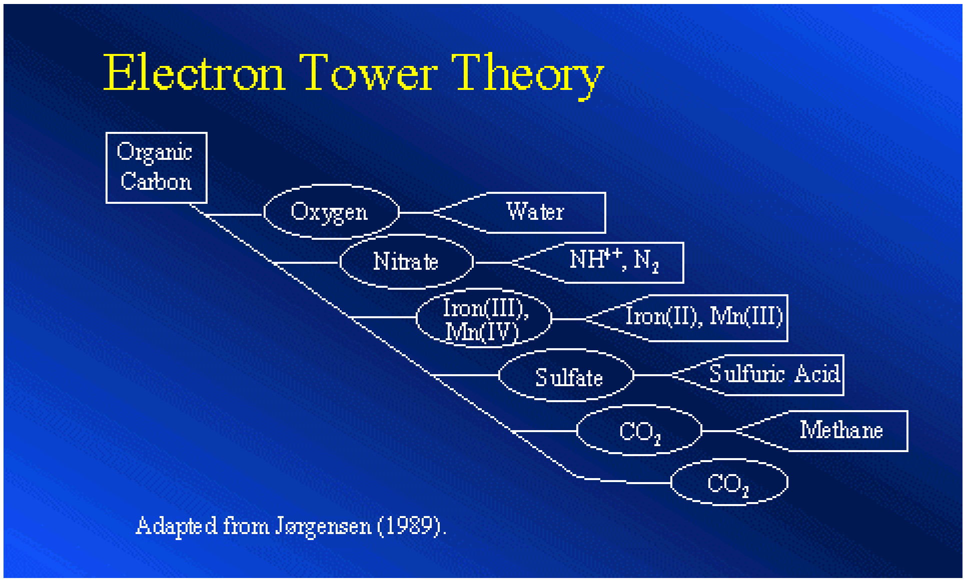
Dissolved Oxygen.

Dissolved oxygen (DO) is a vital component in the aquatic environment. It is necessary to sustain the fish habitat and it provides the most energy for biological decomposition of organic matter. A vital part of the lake ecosystem is providing sufficient energy to address the sediment oxygen demand (SOD) created over the years as detritus settles to the bottom and becomes incorporated into the sediment.

Oxygen has an oxidation state of -2, which means it has the capacity to accept two electrons. The basic concept of organic matter (OM) decomposition is a reduction/oxidation (REDOX) reaction. In a REDOX reaction electrons are transferred from one substance to another. The substance giving up electrons is being oxidized and the substance gaining electrons, also referred to as the terminal electron acceptor is being reduced. For the lake bottom, OM is giving up electrons thus being oxidized; however, if there is not a viable source to accept the electrons, the REDOX process slows or halts. The amount of energy available to support the REDOX reaction is best explained with the electron tower.

The electron tower shows the list of compounds that are terminal electron acceptors and their corresponding energy for REDOX. For simplification, the following image illustrates terminal electron acceptors for organic carbon and their corresponding bi-product. Oxygen tops the list because of its ability to accept two electrons. Once oxygen is depleted from the system, Nitrate becomes the next viable source of energy. Once Nitrate is used up, iron (Fe) and manganese (Mn) are next in line as the most viable source of energy. As stated before, the terminal electron acceptor is reduced during the REDOX process; therefore, as Fe becomes a terminal electron acceptor it transitions for a solid Fe^{+3} (Ferric) state to a soluble Fe^{+2} (Ferrous) state. Iron, like aluminum has a plus 3 charge in its precipitate (oxidized) form. Iron is commonly bound with phosphorus forming $FePO_4$ under oxic conditions. As Fe is reduced by accepting an electron to facilitate OM decomposition in the absence of oxygen, phosphorus (PO_4^{-3}) is release to the overlying sediments and subsequently to the water column. Hence, the longer oxygen is depleted from the system, the more ferrous iron and soluble phosphorus is observed.

Figure 4 Electron Tower Theory.



Monitoring over the past several years has shown that both lakes lose hypolimnetic oxygen rapidly following the onset of summer stratification. For example, Tables 2 and 3 show temperature and DO profiles for 2008. Table 4 shows the same DO profiles as Table 3, but is 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, the 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.

According to data collected during the 2009 stratified period (May – November), it was observed that the majority of the oxygen depletion was a result of SOD and only minor contribution from water column demand (WOD). The combination of these components plus those resulting from REDOX at the sediment-water interface makes up the overall hypolimnetic oxygen demand (HOD). This observation is based on high resolution water column profiles collected with a Seabird Electronics SBE 19PlusV2. Data collected a 10 cm resolution was analyzed to determine precise hypolimnion, metalimnion, and epilimnion boundaries. The metalimnion was divided in half making the assumption that the top half was influenced by the mixing from the epilimnion, whereas the bottom half was influenced by the hypolimnion. Therefore, when metalimnion analyses are performed, they are conducted only on the lower half where the contributions of oxygen addition from the hypolimnion were predicted to be negligible. Other eutrophic reservoirs commonly undergo a natural phenomenon each summer termed a metalimnetic minimum, which is caused by detritus settling through the thermocline and exerting a localized oxygen demand, hence creating the decreased DO or 'minimum' (Gantzer et al. 2009a). For the instance of Spring Hollow and Carvins Cove Reservoirs in VA, DO levels observed in the metalimnion approached zero each year. As the reservoirs destratify and the detritus settles through the hypolimnion, DO in this region is restored. Water column analysis reveals a significant contribution of oxygen demand exerted in the water column as the detrtitus settles for these reservoirs. The observations in both North and South Twin Lakes revealed very little WOD, because the metalimnion DO levels remained near saturation throughout the year. Therefore, it was determined that the oxygen demand was dominated by SOD, thus supporting the design parameters of the oxygenation system. 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.

Conductivity.

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 5; Table 6 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.

Phosphorus.

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 7 and 8 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 1995, 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.

<u>Ammonia.</u>

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 9 and 10 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 surficial 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.

Table 2. Dissolved oxygen profiles in Twin Lakes, 2008 and 2009. All measurements are in mg/L.

North Twin 2008													
Location	*West*	*Mid*	*Mid*	*Mid*	*3N*	*2N*	*1N*	*4N*	*5N*	*Mid*	*Mid*	*Mid*	*Mid*
Date	***5/27/08***	***5/27***	***6/24***	***7/22***	***7/31***	***7/31***	***7/31***	***7/31***	***7/31***	***8/12***	***9/1***	***9/13***	***10/21***
Depth (m)													
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

South Twin Lake 2008											
Location	*Mid*	*Mid*	*S1*	*S3*	*S2*	*S4*	*S5*	*Mid*	*Mid*	*Mid*	*Mid*
Date	***6/24/08***	***7/22***	***7/31***	***7/31***	***7/31***	***7/31***	***7/31***	***8/12***	***8/30***	***9/13***	***10/21***
Depth											
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				

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		

North Twin Lake 2009					
Location	*Mid*	*West*	*Mid*	*Mid*	*West*
Date	**5/15/09**	**5/15**	**5/28**	**6/10**	**6/10**
Depth					
0	10.6	10.9	10.1	9.0	9.1
1	11.2	10.9	10.2	9.2	9.1
2	11.3	11.1	10.2	9.3	9.1
3	11.3	11.2	10.2	9.4	9.2
4	11.2	11.3	11.2	9.4	9.3
5	11.3	11.1	11.5	12.0	11.7
6	11.1	10.9	11.7	12.0	12.8
7	10.6	10.5	11.1	13.4	12.1
8	9.9	9.2	10.5	10.9	10.2
9	9.5	7.5	9.9	10.0	7.8
10	9.0	7.1	9.7	9.5	7.0
11	8.8	6.8	9.6	9.2	7.2
12	8.6	6.5	9.3	8.8	6.7
13	8.3	6.3	9.2	8.5	5.4
14	7.0	6.2	8.5	6.8	
14.5				5.6	
15	6.1		4.0		

South Twin Lake 2009			
Location	*Mid*	*Mid*	*Mid*
Date	**5/14/09**	**5/28**	**6/10**
Depth			
0	11.9	11.5	9.0
1	12.0	11.6	9.1
2	12.0	11.5	9.0
3	12.0	11.4	9.1
4	12.0	12.2	9.3
5	11.9	12.2	9.8
6	11.9	10.5	9.4
7	10.6	9.7	8.3
8	9.0	6.8	5.6
9	5.3	4.7	4.3
10	5.2	3.3	2.9
11	5.2	2.0	0.9
12	4.3	0.9	0.8
13	3.3	0.3	1.2
14	2.2	0.3	0.3
15	1.4		0.3
16	0.8		0.2
16.5			
17			

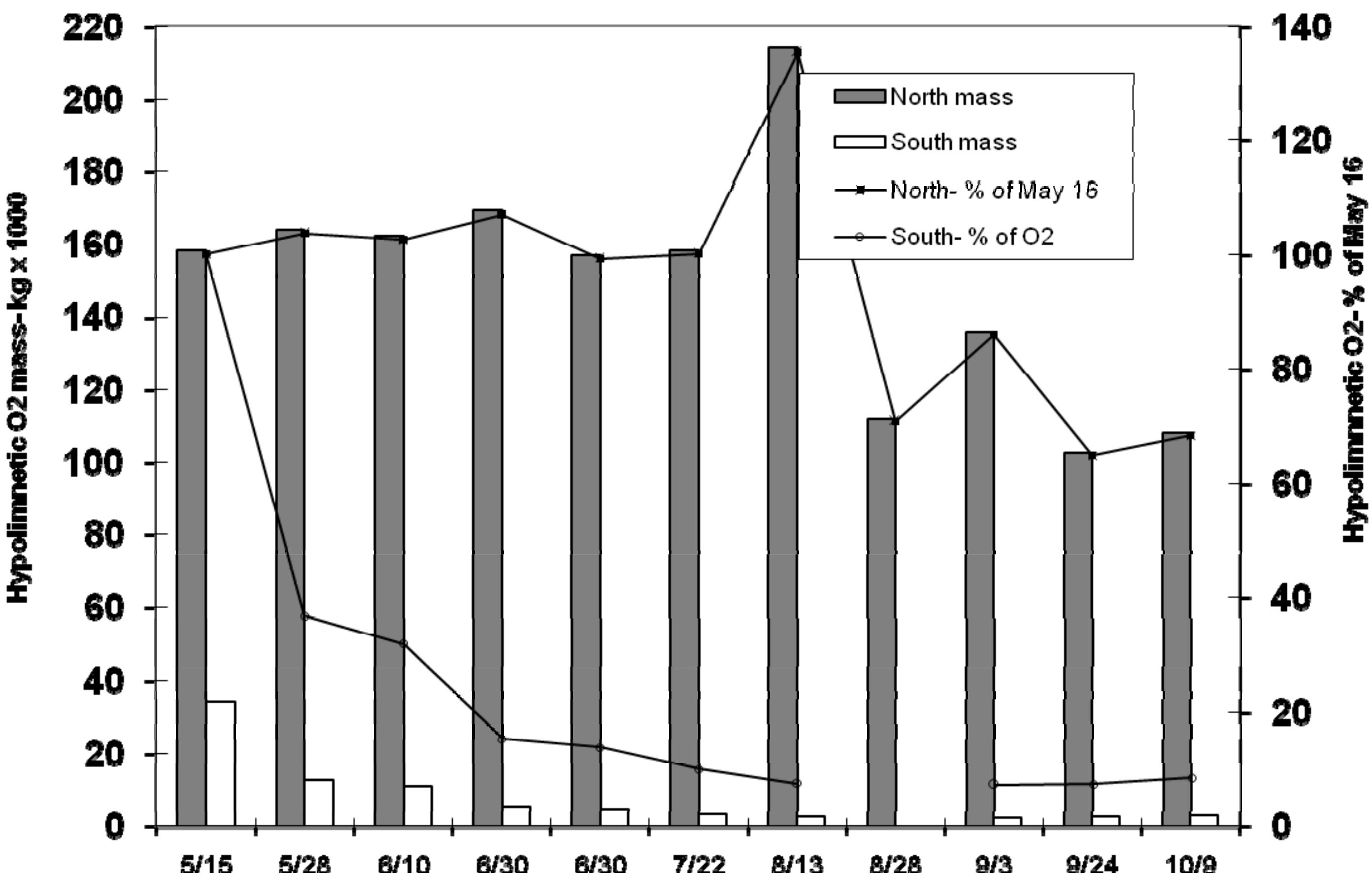
A Preliminary Report on Dissolved Oxygen and Total Phosphorus in Twin Lakes, with Oxygenation in North Twin, 2009

Barry C. Moore and Marc Beutel November 2009

Oxygen for Fishery Habitat Enhancement

The North Twin line diffuser system appears to be very successful in maintaining acceptable levels of hypolimnetic oxygen to support cold-water fishery requirements. A graph of hypolimnetic oxygen mass for the 2009 stratification season is presented below. Note that hypolimnetic oxygen is calculated as the sum of the products of oxygen concentration times volume for each 1m depth stratum. So that comparable volumes are compared for each date, the average thermocline depth is assumed to be 8m for all sampling periods. This is the first year since the early 1980s that North Twin lake monitoring has not shown the summer hypolimnion to be anaerobic for most of the season. In all previous years, oxygen regimens for both lakes have essentially been the same as that for South Twin in 2009, below.

Figure 5. Hypolimnetic Dissolved Oxygen (8m and below) for Twin Lakes, 2009



Examples showing seiche in North Twin

Figure 6. 2008 North Twin Lake oxygenation test, showing substantial internal wave motion spearing the oxygen plume. The point of view is facing west. The apparent direction of seiche is in the south-westerly direction.

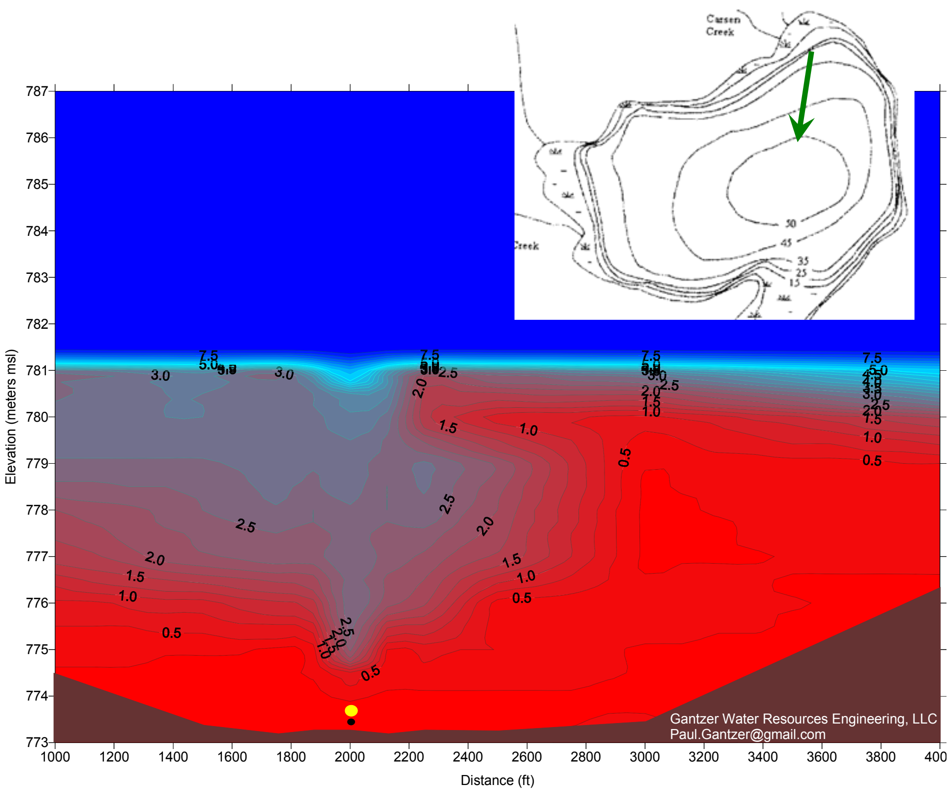


Figure 7. North Twin Lake showing distance in feet above bottom that 5 mg/l threshold was observed. Green arrow indicates the apparent direction of seiche.

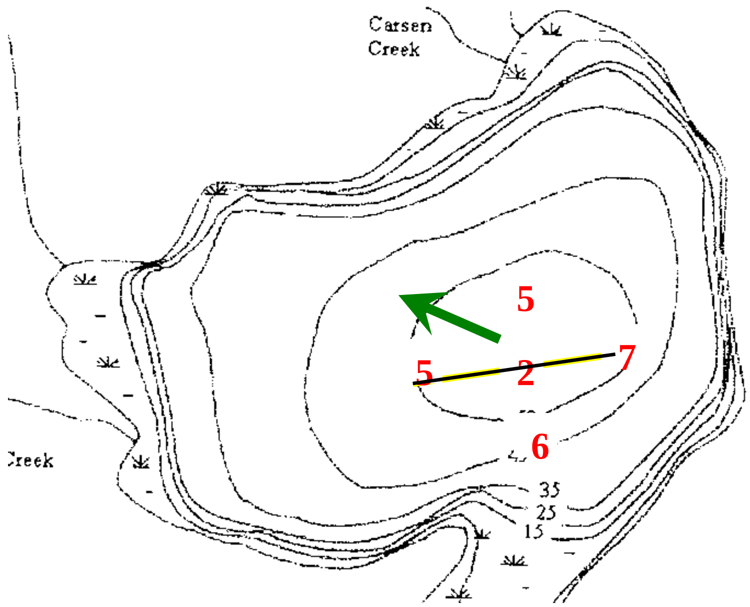
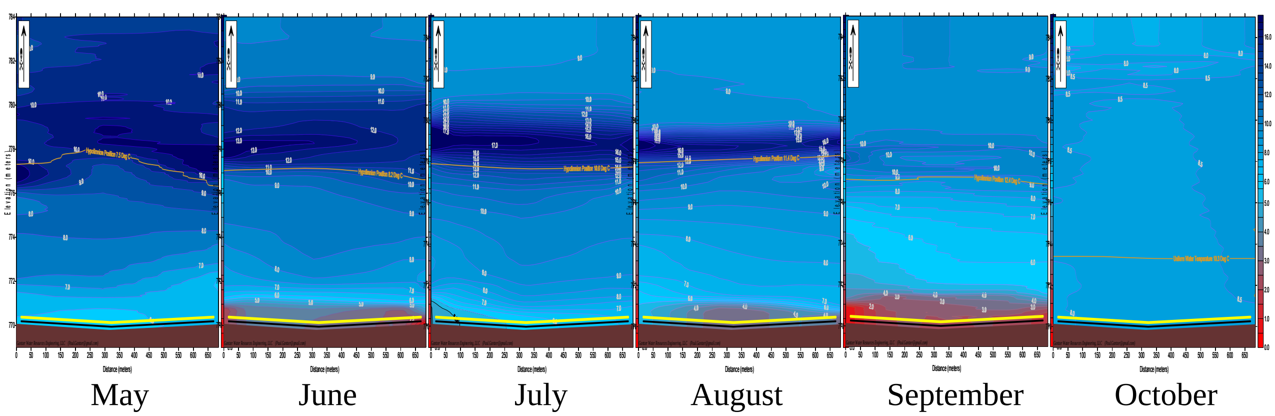
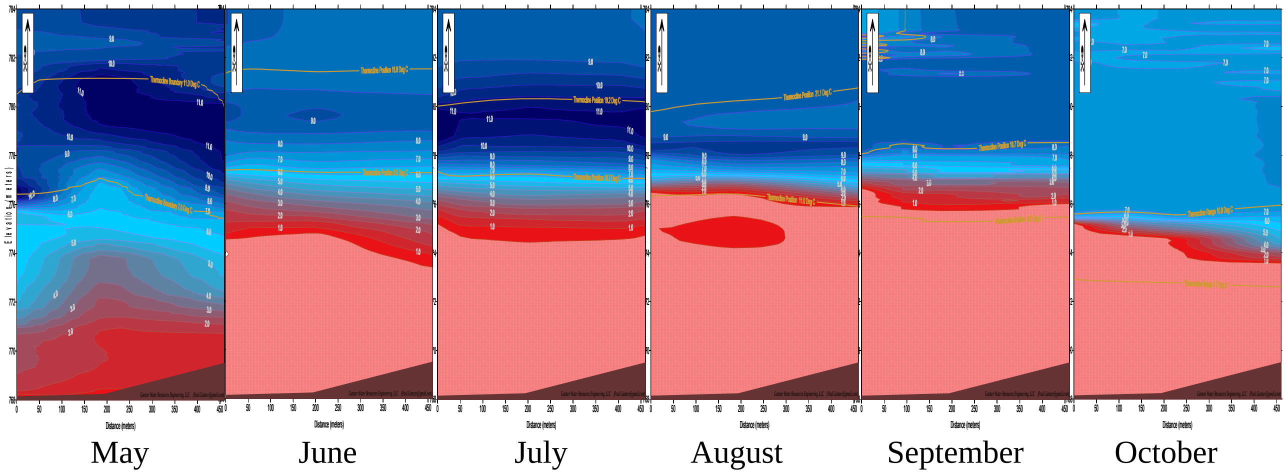


Figure 8. North & South Twin Lakes DO Over Time.





Fish movements in 2009 were monitored by gill nets set in the epilimnion, metalimnion and hypolimnion; monthly hydroacoustic surveys and monthly tracking of tagged fish. While analysis is incomplete at this time, summaries are included here and in the appendix.

Table 3 Results of 2009 Gill net sets.

Monthly Gill Net Surveys						
	North Twin			South Twin		
Date	**Epilimnion**	**Metalimnion**	**Hypolimnion**	**Epilimnion**	**Metalimnion**	**Hypolimnion**
May	67%	33%	0	61%	29%	0
June	27%	60%	13%	42%	58%	0
July	4%	67%	29%	0	100%	0
August	0	50%	50%	0	100%	0
September	0	62%	38%	0	100%	0
October	92%	3%	5%	97%	0	3%

The number of trout captured per set in each lake each month ranged from a low of 10 for South Twin in July to more than 100. Except for the July South Twin set at least 35 trout were captured from each lake each month.

The tracking study of North Twin showed a similar pattern.

Table 4 Results of monthly tracking on North Twin

Monthly Tracking During Stratification	
Depth	**North Twin**
Epilimnion	6%
Metalimnion	47%
Hypolimnion	47%

Analysis of monthly hydro acoustic surveys is incomplete, but the general picture is similar. Fish were seen in both the metalimnion and hypolimnion of North Twin in approximately equal numbers and were only seen in the metalimnion of South Twin.

These data clearly show that in 2009 the hypolimnion of North Twin in which dissolved oxygen levels kept above 6 mg/L was utilized by trout while the hypolimnion of South Twin which remained below 1 mg/L of oxygen was not utilized.

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

(1) Project Compatible with Program Vision: 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.

(2) Project Addresses Program Objectives: 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.

(3) Project Addresses Monitoring and Evaluation Criteria: 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 (2008-9). 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 5. 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 in 2008 and 2009

E. Project history (for ongoing projects)

This is a new project that continues work begun by the Colville Confederated Tribes under non-BPA funds.

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, for 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, which are outlined below.

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 late 2010. Therefore, 2009 and 2010 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 existing 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. Submit construction proposal for Inter-Departmental Tribal review, hydraulic permit, shoreline permit, and 106 Consultation.

Milestone B. Coordinate with THPO on archaeological survey requirements.

Milestone C. Supervise contract.

Milestone D. 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 E. Subcontract for the construction of the South Twin Lake oxygenation system.

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

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 by Hatchery Project personnel. Work elements for fishery monitoring will be included under the Hatchery Project. Water quality monitoring will be by subcontract under this project.

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 4. Analyze/Interpret data (162).
All fish and creel data supplied by Hatchery Project personnel and water quality data supplied by the contractor will be analyzed using previously determined procedures and protocols. The primary goal will be to determine if water quality has significantly improved and if these improvements have resulted in a meaningful, cost effective enhancement of the fishery.

Milestone A. Collect data supplied by subcontract and Hatchery Project and test statistical significance of observed changes.

Milestone B. Prepare cost effectiveness analysis of water quality/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 by Hatchery Project staff.

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. The goals of this analysis are: (1) determine if the improvements to the Twin Lakes trout fishery justify the expense of hypolimnetic oxygenation and (2) determine if the cost of construction and operation of an oxygen generating plant is cost effective.

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 4. Analyze/Interpret data (162).

Milestone A. Collect data supplied by subcontract and Hatchery Project and test statistical significance of observed changes.

Milestone B. Prepare cost effectiveness analysis of water quality/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) trout growth and mortality; (3) angler success; (4) zooplankton density and distribution; (5) water quality of conventional parameters, nutrients and redox-sensitive metals; and (6) mercury in lake water, fish and zooplankton.

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

Although fish movements will be monitored by Hatchery Project staff a discussion of methods used is included here.

Methods. Sonic tracking of redband trout was used by Biggs (2007) to monitor vertical movement of fish in North Twin Lake during summer stratification. The same technique was used in 2009 in North Twin while the oxygenation system was operating. Tagged trout were found in the hypolimnion 47% of the time. This technique will not be used during the course of this proposal.

All fish monitoring for the Oxygenation project will be performed by hatchery project staff. The details of these studies will be included in the Hatchery Project reports. Study design and results will also be included in this proposal as well as in the oxygenation project reports. In 2010 100 redband trout will be fitted with internal depth monitoring tags and an external floy tag for identification. Fifty fish will be released into North Twin and 50 fish will be released into South Twin. A $25 reward will be offered to anglers who turn tags in. Tags may also be recovered by monthly gill net sets. During previous tracking studies approximately 15% of the tagged fish were captured by anglers. It is anticipated that during the course of this study that the rewards program and sufficient publicity will allow us to recover at least 15% of the tags.

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).

In 2009 Hatchery Project staff conducted monthly gill net surveys in both North and South Twin Lakes three pairs of horizontal gillnets, 3 m x 30 m x 2 inch (stretch measurement) and 3 m x 30 m x 3 inch (stretch) set at 2 m (depth of top of net), 5 m and 9 m in each lake. Captured fish were weighed and measured to determine condition factor and growth. Presence or absences of tags and/or fin clips were noted in order to determine when fish were stocked. Stomach samples were taken.

Monthly gill net surveys will continue in 2010. Only horizontal gill nets will be used. As in 2009, six nets will be used, but rather than used nets consisting of a single mesh size, each net will be made up of eight randomly placed panels. Four different mesh sizes will be used. There will be two panels of each mesh size.

Hydroacoustic surveys of North and South Twin Lakes were initiated in fall of 2007 and carried out monthly in 2008. East/West tracks every 500 meters were made across each lake. A single North/South track was also made across each lake. Tracks were made between the same waypoints during each survey. Each lake was divided into five vertical strata and fish densities were measured in each stratum for each track. These surveys are continuing during 2009 and will continue for the term of this proposal.

<u>Statistical Evaluation.</u> 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.

<u>Expected Outcome.</u> Based on intensive monitoring in North Twin Lake during the summer of 2006, redband trout are confined to a slab of metalimnetic waters around three to four meters 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 the effects of oxygenation on fish growth, mortality and angler success.

Methods. Since 2006 angler usage and success at North and South Twin Lakes has been measured with a roving creel study. Each year improvements have been made to increase the statistical defensibility of this study. In 2008 the study was evaluated by Dr. John Skalski of the University of Washington and suggestions were made to improve the study. These suggestions have been implemented.

There are four primary goals to the study.

1. Measure angling pressure throughout the fishing season.
2. Measure angling catch rates (CPUE).
3. Identify which group of fish each observed fish is from. All stocked fish are marked with a combination of fin clips, elastomer tags or coded wire tags in order to identify when it was planted. These data can be used to determine mortality and optimum planting strategies.
4. Weigh and measure each observed fish in order to determine growth, condition factor and relative weight.

In order to determine angling pressure, both boats and shore anglers are counted every two hours throughout the day on each lake. Weekdays and weekends/holidays are calculated separately. At least 10 weekdays and five weekends/holidays are creeled each month. Data are summarized monthly.

Angler catch rates are determined by a roving survey. While it is recognized that an exit survey would be preferable, there are so many exit locations at Twin Lakes that it would be difficult to cover all exit locations. Therefore a roving creel survey is used. Both shore and boat anglers are interviewed throughout the day. All trout observed are weighed and measured. Angling start and end times are noted as well as the number of fish kept and the number released.

Statistical Evaluation. Data from gill nets and creel surveys will be used to independently calculate fish growth. Since the stocking group to which each fish belongs can usually be identified the average weight and condition factor for each group can be calculated on a monthly basis. Data from any fish whose stocking group cannot be identified with certainty is not included in the calculation.

Catch rates and angler usage are easily calculated from the data, but care must be used when comparing to earlier studies. Many of the conclusions from these studies were based on very limited data and the conclusions may not be valid.

Expected Outcome. All studies to date clearly show that once oxygenated the hypolimnion will be used by trout. In theory this will reduce stress and therefore reduce mortality. Biological systems are complex with many variables. Oxygenating the hypolimnion will also affect zooplankton populations as well, and will also give trout access to these populations that are currently unavailable. Ultimately mortality should decrease and growth increase but stocking strategies will have to change as well.

M&E Objective 3: **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 4:* Evaluate effects of oxygenation on water quality in water column.**

Methods. Monthly water quality monitoring of conventional redox-sensitive parameters were 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 meter 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). We anticipate being able to compare the lakes side-by-side (oxygenation in North versus 'natural anoxia' in South) for 2009 and 2010, before oxygenation (2008) and after oxygenation (2009-2012) for North, and before oxygenation (2008-2010) and after oxygenation (2011 and 2012) for South.

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 5:* Evaluate effects of oxygenation on mercury levels in water column zooplankton and fish.**

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. In addition, fish tissue samples will be taken from fish (bass, shiners and trout) collected as a part of past and ongoing trophic level studies. Total mercury water samples will be preserved with bromine monochloride, methyl-mercury water samples with hydrochloric acid, and zooplankton and fish tissue samples via freezing. Total mercury analyses in water 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}. Methyl-mercury analyses in water 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). Total mercury in zooplankton and fish tissue will be measured in a newly purchased Milestone Direct Mercury Analyzer in Dr. Beutel’s mercury lab at WSU. 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.

We anticipate being able to compare the lakes side-by-side (oxygenation in North versus 'natural anoxia' in South) for 2009 and 2010, before oxygenation (2008) and after oxygenation (2009-2012) for North, and before oxygenation (2008-2010) and after oxygenation (2011 and 2012) for South. Mercury levels in fish, taking into account fish species, size and age, and their presences in oxygenated versus non-oxygenated conditions, will be evaluated for trends over time.

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

Office space, office equipment, and vehicles will be shared with existing Hatchery and M&E Project located at the CCT Fish and Wildlife Office, Nespelem, Washington.

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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Education:

Ph.D., Engineering Science, Washington State University (Aug., 1985)
M.S., Environmental Science, Washington State University (June, 1981)
B.S., Environmental Science, Birmingham-Southern College (June, 1975)

Recent Publications

Christensen, D.R. and B.C. Moore. 2008. Using stable isotopes and a multiple mixing model to evaluate fish dietary niches in a mesotrophic lake. sub Jan. 2008 to *Journal of Lake and Reservoir Management.* accepted

Beutel, M., T. Leonard, S. Dent, and B.C. Moore. 2008. Effects of aerobic and anaerobic conditions on P, N, Fe, Mn and Hg accumulation in waters overlaying profundal sediments of an oligo-mesotrophic lake. *Water Research 42(8-9):1953-1962.*

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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

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Education:
Eastern Washington University, Cheney, WA, 1995, B.S. Environmental Biology
Kaiser Foundation School of Nursing, Oakland, CA1972 R.N. ICU CCU Certified
Contra Costa College, San Pablo, CA 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 - Chairman of the Columbia Basin Fish and Wildlife Authorities (CBFWA) Resident Fish Advisory Committee (RFAC)
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)

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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.

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

North Twin													
Location	*West*	*Mid*	*Mid*	*Mid*	*3N*	*2N*	*1N*	*4N*	*5N*	*Mid*	*Mid*	*Mid*	*Mid*
Date	***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***
Depth (m)													
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													
Location			*Mid*	*Mid*	*S1*	*S3*	*S2*	*S4*	*S5*	*Mid*	*Mid*	*Mid*	*Mid*
Date			***6/24***	***7/22***	***7/31***	***7/31***	***7/31***	***7/31***	***7/31***	***8/12***	***8/30***	***9/13***	***10/21***
Depth (m)													
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 7. Dissolved oxygen profiles in Twin Lakes, 2008. All measurements are in mg/L.

North Twin

Location	*West*	*Mid*	*Mid*	*Mid*	*3N*	*2N*	*1N*	*4N*	*5N*	*Mid*	*Mid*	*Mid*	*Mid*
Date	***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***
Depth (m)													
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													
Location			*Mid*	*Mid*	*S1*	*S3*	*S2*	*S4*	*S5*	*Mid*	*Mid*	*Mid*	*Mid*
Date			***6/24***	***7/22***	***7/31***	***7/31***	***7/31***	***7/31***	***7/31***	***8/12***	***8/30***	***9/13***	***10/21***
Depth (m)													
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 8. Dissolved oxygen profiles in Twin Lakes, 2008. All values are expressed as temperature-corrected percent of saturation.

North Twin													
Location	*West*	*Mid*	*Mid*	*Mid*	*3N*	*2N*	*1N*	*4N*	*5N*	*Mid*	*Mid*	*Mid*	*Mid*
Date	***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***
Depth (m)													
0	111	111	91	81	75	73	74	75	76	76	96	98	78
1	111	111	90	78	74	73	73	73	73	72	96	98	78
2	111	111	90	77	74	73	72	73	73	71	96	93	77
3	110	110	90	77	73	73	73	73	72	71	96	98	77
4	110	109	89	76	73	73	72	73	72	70	95	98	77
5	106	107	90	82	83	79	72	80	81	68	95	98	77
6	106	105	66	67	79	67	55	81	77	79	94	97	77
7	104		42	32	41	33	26	28	39	42	93	44	76
8	60		21	8	10	7	8	13	9	12	44	41	75
9	52		25	3	6	6	4	4	4	5	36	38	71
10	51		20	2	3	3	3	3	2	3	32	37	39
11	39		19	2	2	2	2	2	2	2	26	35	8
12	32		2	2	2	2	2	2	2	2	23	32	3
13	25		2	2	2	1		1	2	2	3	24	3
14	22		1	2	1	1		1	2	2	8	18	2
14.5	-			-	1			-	1	1	-	9	
15	21			2				0			2		

South Twin													
Location			*Mid*	*Mid*	*S1*	*S3*	*S2*	*S4*	*S5*	*Mid*	*Mid*	*Mid*	*Mid*
Date			***6/24***	***7/22***	***7/31***	***7/31***	***7/31***	***7/31***	***7/31***	***8/12***	***8/30***	***9/13***	***10/21***
Depth (m)													
0			99	81	78	77	78	27	76	75	101	100	80
1			97	80	78	76	78	75	75	73	101	100	75
2			97	80	78	75	77	76	75	73	101	100	75
3			96	80	79	76	78	75	75	72	100	98	75
4			94	80	79	76	77	75	75	72	100	98	74
5			85	79	79	83	77	75	74	72	99	97	75
6			75	79	49	77	69	80	78	62	99	91	75
7			78	67	35	49	55	53	47	61	89	57	75
8			34	36	12	31	27	30	18	15	49	4	75
9			8	6		4	12	7	5	7	5	3	73
10			3	3		3	4	3	3	3	4	4	6
11			3			2		2	2	2	2	3	3
12			2			1		2	2	2	2	2	3
13			2					1	1	1	2	2	2
13.5			-					1	-	-	-	-	-
14			2						1	1	2	2	2
15			2						1	2	2	2	2
16									1				
16.5									1				

Table 9. Specific Conductivity profiles in Twin Lakes, 2008. All values are in uS/cm.

North Twin													
Location	*West*	*Mid*	*Mid*	*Mid*	*3N*	*2N*	*1N*	*4N*	*5N*	*Mid*	*Mid*	*Mid*	*Mid*
Date	***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***
Depth (m)													
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													
Location			*Mid*	*Mid*	*S1*	*S3*	*S2*	*S4*	*S5*	*Mid*	*Mid*	*Mid*	*Mid*
Date			***6/24***	***7/22***	***7/31***	***7/31***	***7/31***	***7/31***	***7/31***	***8/12***	***8/30***	***9/13***	***10/21***
Depth (m)													
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 10. Profiles of pH in Twin Lakes, 2008. All values as the negative log of the hydrogen ion activity.

North Twin													
Location	*West*	*Mid*	*Mid*	*Mid*	*3N*	*2N*	*1N*	*4N*	*5N*	*Mid*	*Mid*	*Mid*	*Mid*
Date	***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***
Depth (m)													
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													
Location			*Mid*	*Mid*	*S1*	*S3*	*S2*	*S4*	*S5*	*Mid*	*Mid*	*Mid*	*Mid*
Date			***6/24***	***7/22***	***7/31***	***7/31***	***7/31***	***7/31***	***7/31***	***8/12***	***8/30***	***9/13***	***10/21***
Depth (m)													
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 11. 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								
Date	***5/27***	***6/11***	***6/24***	***7/22***	***8/13***	***8/30***	***9/13***	***10/20***
Depth (m)								
0	0.024	0.024	0.012	0.029	0.015	0.011	0.021	0.015
1	-	0.029	0.022	0.018	0.018		0.018	0.024
2	-	0.021	0.020	-	0.023		0.011	0.016
2.5	0.025	-	-	-	-		-	-
3	-	0.026	0.024	0.020	0.022		0.016	0.023
4	-	0.021	0.014	0.020	0.017		0.021	0.028
5	0.022	0.028	0.019	0.022	0.020		0.023	0.020
6	-	0.033	0.033	0.020	0.023		0.018	0.011
7	-	0.028	0.037	0.040	0.029		0.025	0.017
7.5	0.069	-	-	-	-		-	-
8	-	0.034	0.038	0.031	0.028		0.044	0.021
9	-	0.024	0.028	0.031	0.025		0.024	0.018
10	0.011	0.020	0.023	0.030	0.033		-	0.023
11	-	0.025	0.030	0.045	0.038		0.047	0.029
12	-	0.029	0.033	0.095	-		0.039	0.030
12.5	0.030	-	-	-	-		-	-
13			0.049	0.104	0.104		0.036	0.076
14			0.075	0.141	0.112		0.055	

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

Table 12. 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								
Date	**5/27**	**6/11**	**6/24**	**7/22**	**8/13**	**8/30**	**9/13**	**10/20**
Depth (m)								
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								
Date	**5/27**	**6/11**	**6/24**	**7/22**	**8/13**	**8/30**	**9/13**	**10/20**
Depth (m)								
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 13. 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								
Date	**5/27**	**6/11**	**6/24**	**7/22**	**8/13**	**8/30**	**9/13**	**10/20**
Depth (m)								
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 14. 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								
Date	**5/27**	**6/11**	**6/24**	**7/22**	**8/13**	**8/30**	**9/13**	**10/20**
Depth (m)								
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 15. Alkalinity profiles in Twin Lakes, 2008. All values are in mg/L, as calcium carbonate

North Twin								
Date	**5/27**	**6/11**	**6/24**	**7/22**	**8/13**	**8/30**	**9/13**	**10/20**
Depth (m)								
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								
Date	**5/27**	**6/11**	**6/24**	**7/22**	**8/13**	**8/30**	**9/13**	**10/20**
Depth (m)								
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 16. Secchi depths in Twin Lakes, 2008. All values are in meters.

North Twin								
Date	***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								
Date		***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 17. Total dissolved solids in Twin Lakes, 2008. All values are in mg/L, calculated from specific conductivity.

North Twin									
Location	*3N*	*2N*	*1N*	*4N*	*5N*	*Mid*	*Mid*	*Mid*	*Mid*
Date	***7/31***	***7/31***	***7/31***	***7/31***	***7/31***	***8/12***	***9/1***	***9/13***	***10/21***
Depth (m)									
0	0.033	0.033	0.033	0.034	0.033	0.034	0.036	0.036	0.037
1	0.033	0.033	0.033	0.033	0.033	0.034	0.036	0.036	0.037
2	0.033	0.033	0.033	0.033	0.033	0.034	0.036	0.036	0.037
3	0.033	0.033	0.033	0.033	0.033	0.034	0.036	0.036	0.038
4	0.033	0.033	0.033	0.033	0.033	0.034	0.036	0.036	0.037
5	0.033	0.033	0.033	0.033	0.033	0.034	0.036	0.036	0.037
6	0.033	0.033	0.034	0.033	0.033	0.033	0.036	0.036	0.037
7	0.034	0.034	0.034	0.035	0.034	0.035	0.036	0.038	0.037
8	0.036	0.036	0.035	0.036	0.035	0.036	0.040	0.040	0.037

9	0.035	0.035	0.036	0.036	0.037	0.036	0.043	0.040	0.037
10	0.036	0.036	0.036	0.036	0.036	0.038	0.045	0.040	0.038
11	0.037	0.037	0.037	0.037	0.037	0.040	0.044	0.040	0.040
12	0.041	0.040	0.044	0.037	0.043	0.046	0.045	0.040	0.042
13	0.047	0.045		0.045	0.047	0.051	0.039	0.040	0.049
14	0.049	0.047		0.049	0.050	0.052	0.050	0.040	0.067
14.5	0.051			-	0.050	0.052	-	-	
15				0.050			0.053	0.045	

South Twin									
Location	*S1*	*S3*	*S2*	*S4*	*S5*	*Mid*	*Mid*	*Mid*	
Date	***7/31***	***7/31***	***7/31***	***7/31***	***7/31***	***8/12***	***8/30***	***9/13***	
Depth (m)									
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 9. DO uptake in water in replicate experimental chambers containing sediment-water interface samples from North Twin Lake.

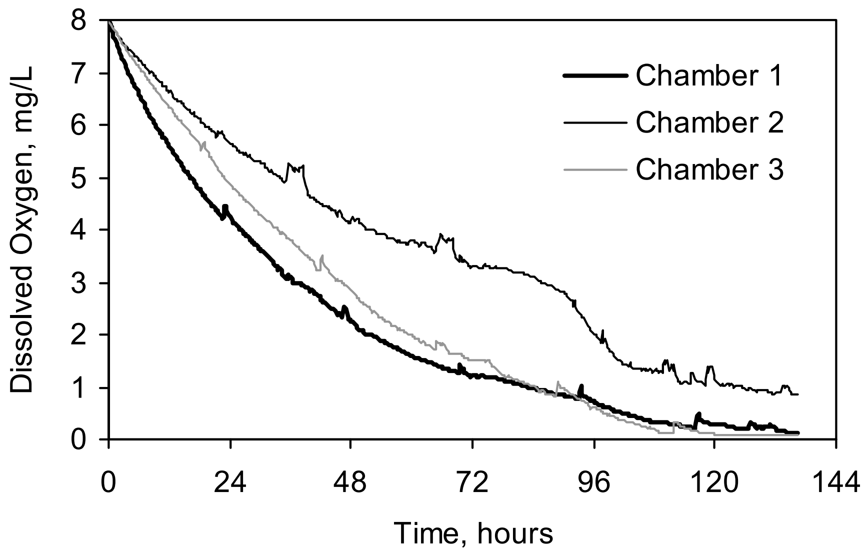


Figure 10. Sediment Oxygen Demand (SOD) as a function of DO in overlaying water based on data set presented in Figure 4. While there is quite a bit of variability in the data, SOD tends to increase with increasing DO in overlaying water.

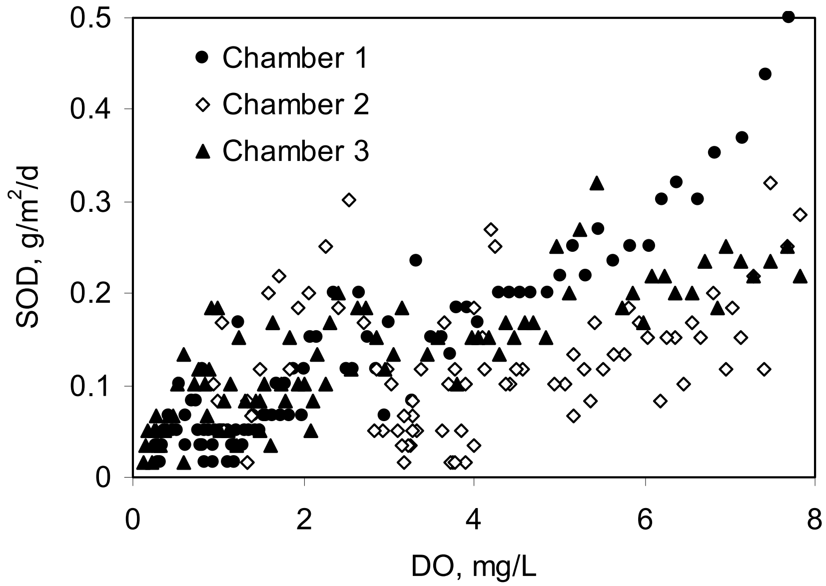


Figure 11. Ortho-P in water overlying sediments in North Twin Lake sediment incubations. Note that shortly after switching the chambers over to anoxic oxygen-free conditions, water started to accumulate P.

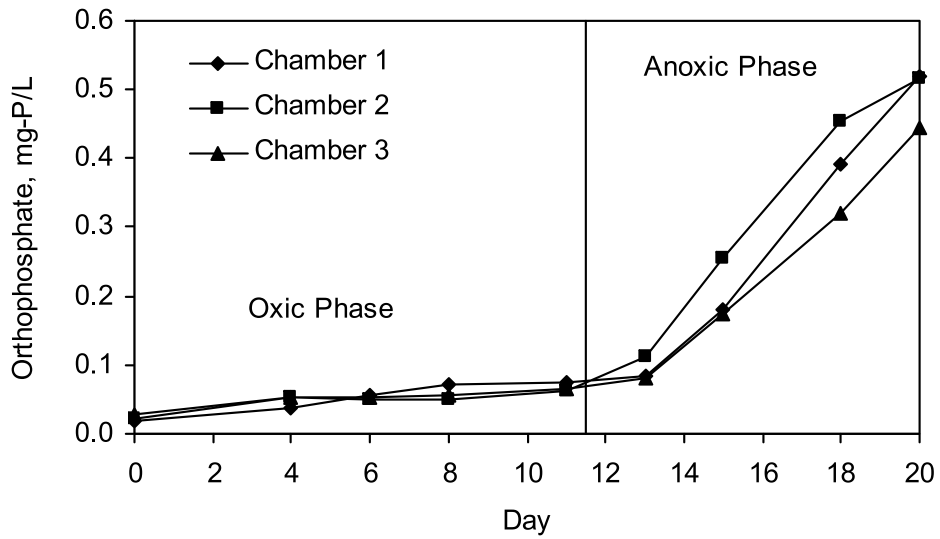


Figure 12. Typical range of anaerobic P release from lake sediments as a function of lake trophic status. Symbol is median and error bars are 95% confidence limits. Based on Nurnberg (1988, Can. J. Fish. Aquatic Sci. 45:453-462) and Auer et al. (1993, Hydrobiol 253:301-309; 1993). Note that the P release rates measured in North Twin Lake are typical of other eutrophic lakes.

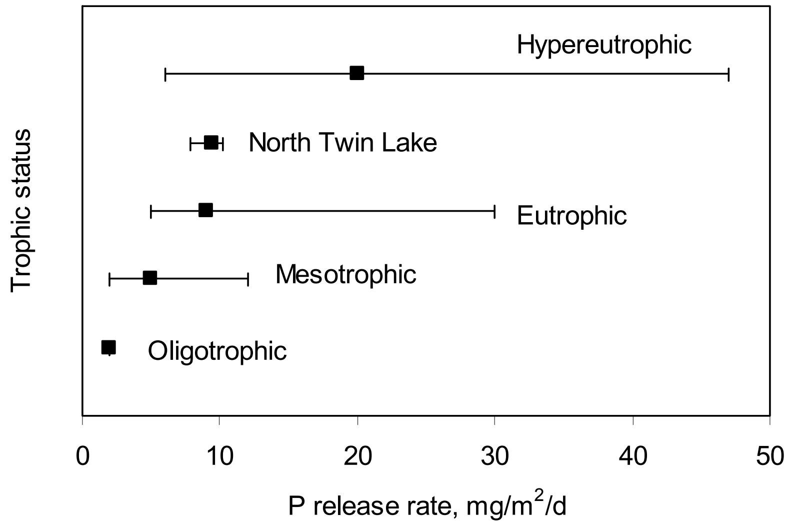


Figure 13. Selected seasonal profiles for iron and manganese in North Twin Lake. Data shows that metals accumulate in bottom waters during summer and fall thermal stratification as a result of anaerobic conditions. Upon turnover in early November metals were mixed throughout the water column.

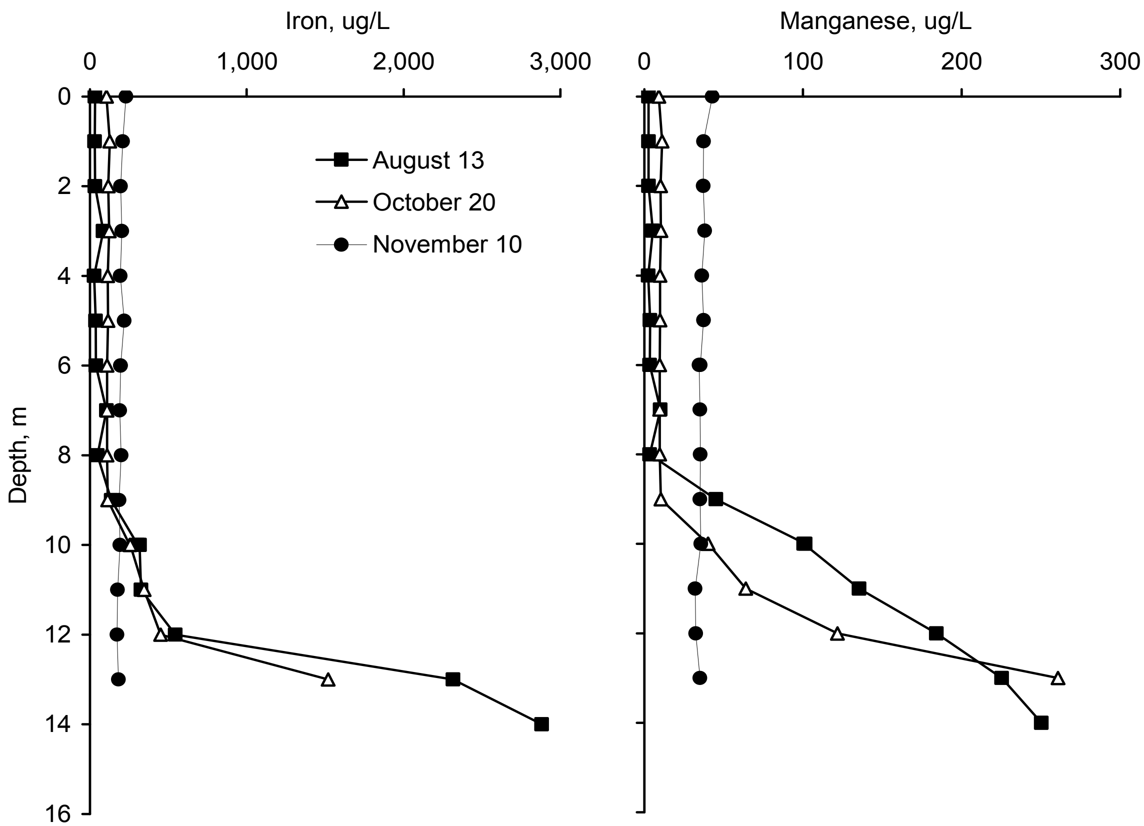


Figure 14. Total (square) and dissolved (triangle) iron (top) and manganese (bottom) in North Twin Lake before and after test oxygenation in early September, 2008. Before oxygenation, metals were in the reduced, dissolved form (dissolved equaled total) in the bottom of the lake as a result of anaerobic 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).

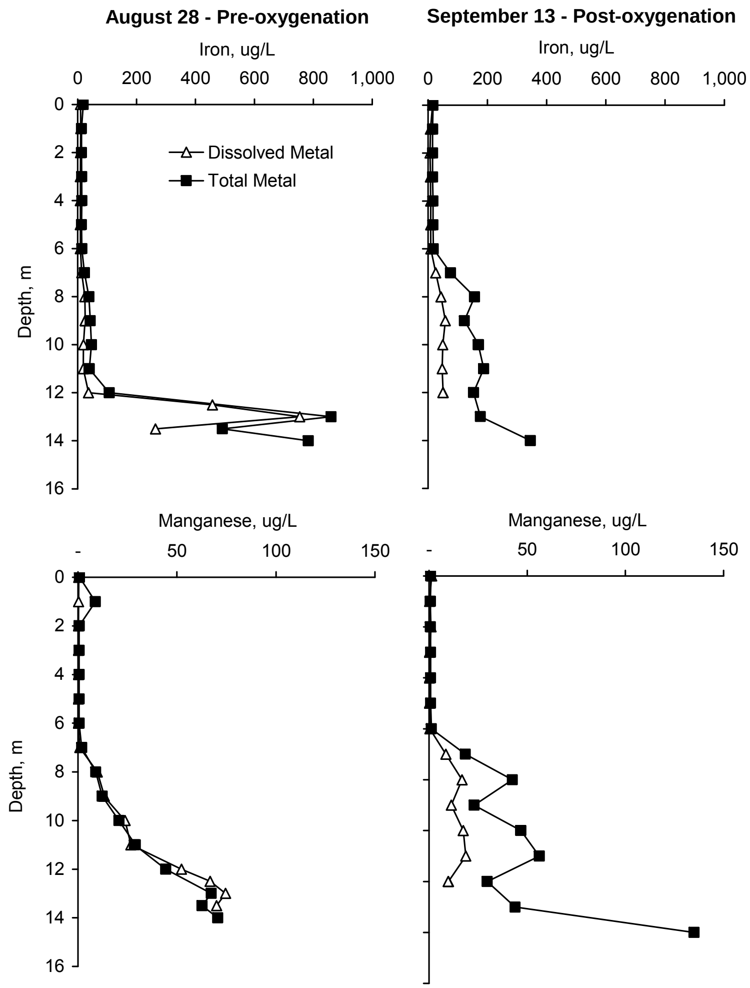


Table 18. Cost comparison, Green Lake (alum) and North Twin (oxygenation)

Green Lake

Surface area	260 acres	
Maximum depth	30 feet	
Mean depth	13 feet	
Volume	4.43E+07	cubic feet

Initial cost	$1,509,156	Assumes alum treatment lasts for 10 years
Less monitoring	$123,900	
10 year total	$1,385,256	
20 year cost	$2,770,512	

North Twin Lake

Surface area	917 acres	
Maximum depth	50 feet	
Mean depth	32 feet	
Volume	1.29E+09	cubic feet

Initial Cost	$209,801	
2009 O2 cost	$79,097	
10 year cost	$1,000,771	Assumes equal amount of O2 needed each year
20 year cost	$1,791,741	Studies (Gantzer et al) show demand decreases

Table 19 Gill net and tracking data, 2009.

Monthly Tracking During Stratification

Depth	North Twin
Epilimnion	6%
Metalimnion	47%
Hypolimnion	47%

Monthly Gill Net Surveys

	North Twin			South Twin		
Date	Epilimnion	Metalimnion	Hypolimnion	Epilimnion	Metalimnion	Hypolimnion
May	67%	33%	0	61%	29%	0
June	27%	60%	13%	42%	58%	0
July	4%	67%	29%	0	100%	0
August	0	50%	50%	0	100%	0
September	0	62%	38%	0	100%	0
October	92%	3%	5%	97%	0	3%

Average Rainbow Trout Weight in October

North Twin	285 grams
South Twin	156 grams

Colville Confederated Tribes

Fish and Wildlife Department

M E M O R A N D U M

November 14, 2009

TO: Erik Merrill
Independent Science Program Manager

FROM: Ed Shallenberger
Senior Resident Fisheries Biologist

SUBJECT: Twin Lakes Oxygenation, CCT response to ISRP review

Thank you for the opportunity to discuss our proposal with the ISRP. There have obviously been some miscommunications and perhaps some scientific disagreement (not a bad thing). In this conference call we would like to address the ISRP's concerns, clear up any miscommunications, fill in any data gaps, give a brief summary of the 2009 results and show the ISRP why we think that hypolimnetic oxygenation is the best choice for Twin Lakes. I have outlined the items we would like to discuss and detailed some of points we wish to make. Where appropriate I have attached data summaries. The people participating in the call will be myself; Sheri Sears, CCT resident fisheries division manager; Dr. Barry Moore, WSU, the lead WSU scientist on the Twin Lakes research project for more than five years; Dr. Marc Beutel, WSU, knowledgeable in oxygenation and one of the lead WSU scientists in this year's study of the affects of oxygenation; and Dr. Paul Gantzer, Gantzer Water Resources Engineering, an expert in the design and operation of oxygenation systems.

1. **Alum treatment vs. oxygenation.** Perhaps we were remiss in not discussing the possibility of alum treatment in the proposal, but it was rejected several years ago for a number of reasons.
   a. This is a fishery related project designed to address anoxia, not external phosohorus loading which has previously been addressed.. We have shown through several years of studies that both the epilimnion and the hypolimnion were theoretically unavailable to

salmonids. Two years of fish tracking and gillnetting showed that the hypolimnion was not being utilized by salmonids during summer stratification. Salmonids were apparently being limited to less than 5% of the volume of the lake. We decided to attack the problem directly with oxygenation. We hypothesized that if the hypolimnion were oxygenated salmonids would utilize the hypolimnion. This hypothesis was tested in 2009 when North Twin was oxygenated and South Twin was not. Monthly gillnet sets and fish tracking clearly showed that the hypolimnion was utilized in North Twin but not in South Twin. These data are attached.

b. There is a large sediment oxygen demand (SOD) in both lakes that has built up over many years. One of the goals of this project is to address this demand directly, not to cap the sediment.

c. Oxygen is the primary concern, not phosphorus. External phosphorus loading was successfully addressed more than 20 years ago.

d. This is a fisheries project. To this end we want to have a healthy benthos, not one that is capped with alum.

e. In our opinion alum treatment is a temporary solution that that must be redone every 7-10 years. Oxygenation, on the other hand, directly addresses anoxia and reduces the SOD that has developed over previous decades. Gantzer et al have shown that the amount of oxygen required is reduced over time as the sediments are oxidized. If the addition of oxygen is eliminated the lake will not necessarily return to its previous as long as the SOD has been sufficiently reduced.

f. Over several years of study we have shown at there is considerable water movement within the lakes. Because of this movement, evenly coating the sediment with alum would be difficult is not impossible which would leave much of the sediment exposed.

g. Cost. Green Lake which is shallower than North Twin and has approximately 1/4th the surface area was treated with alum at a cost of $1,509,156. The cost of installation of the North Twin Lake oxygenation system was $210,000. It cost <$80,000 to operate in 2009. A more detailed cost analysis is attached.

h. In 2008, Barry Moore and Marc Beutel, with cooperation from the Colville Tribes, submitted a similar proposal for oxygenation of North Twin Lake under the innovative projects program. Although this proposal was less thorough and lacked the data acquired from a year of oxygenation it was highly rated by the ISRP and would have been funded if sufficient funds were available. No discussion of alum treatment was included.

2. **Prior years data.** As we have stated on numerous occasions, Twin Lakes have been for many years. As early as 1978 catch rates and angler usage were studied. These studies were repeated in the late 1980s and again from 2006-2009. The results of these studies have been reported in the Hatchery Project annual reports for 2006, 2007 and 2008. Phosphorus loading was studied in the late 1980s and again in the early 1990s and numerous recommendations were made and later adapted by the Colville Tribes. These have been summarized in the proposal. For the last five years the CCT and WSU have worked collaboratively to study fisheries issues in these lakes and reached the conclusion

that oxygenation is the preferred treatment of the lakes. Both physical and biological parameters have been measured.

a. **Physical parameters.** Physical parameters are easier to measure. These measurements clearly led to the conclusion that there is a temperature/DO squeeze.

b. **Biological parameters.** These include a number of measurements (growth, mortality, predation, food sources, catch rates etc.). Long term conclusions are difficult because of the large number of variables and the fact that these studies were not performed with solely research goals, but with fisheries management goals. For instance, as a result of stable isotope studies it was concluded that bass predation on salmonids, particularly when fish have just been planted, may result in as much as 30% mortality. Because of these results we now plant trout at a larger size and plant them earlier in the season in the spring and later in the season in the fall when water temperatures are colder and the bass are less active. Catch rates and sizes are highly dependent on planting numbers, schedules and sizes. In order to keep catch rates at an acceptable level planting schedules have been adjusted to achieve the best results. In spite of these variables we have reached a number of conclusions:
   1. Return to creel is very low, typically <5%.
   2. Fish planted during the spring of any given year are rarely seen in the catch of subsequent years. While fall planted fish are abundant the year after they are planted, few carry over to the next year.
   3. Fish planted during the fall are seen in the following years catch in a proportion equal to the numbers planted, therefore winter mortality is low.
   4. Relative weights (Wr) are typically high when fish are planted, increase (for both spring and fall plants) in the spring and early summer but decrease as the summer progresses.
   5. Catch rates and average size were greater during the late 1970s and early 1980s even though fishing pressure was much greater at this time. Catch rates are currently being kept up by planting strategies.
   6. Mortality models indicate that first year mortality may be >90%.

3. **2009 data.** Both physical and biological parameters have been measured in 2009 in both North and South Twin. These measurements are ongoing and analysis is far from complete, but they clearly show that oxygenation is working well.

a. **Physical data.** Oxygenation kept the North Twin hypolimnion at acceptable DO levels throughout the summer while the hypolimnion on South Twin remain anoxic. Data showing dissolved oxygen as well as other parameters are attached.

b. **Biological data.** Tracking, gill nets and hydro acoustics clearly showed that the hypolimnion was being utilized by salmonids during stratification while only one trout was captured in the hypolimniion of South Twin and that was at the end of the stratification period. These data are attached. In April and May gill net catch rates of rainbow trout were approximately. At the end of summer, gill net catch rates of rainbow trout in North Twin exceeded those in South Twin by a factor of five. These data are also included.

4. **Miscellaneous information.** The ISRP asked several questions which should be addressed.

a. **How can survive with so many other dominant species in the lakes?** Largemouth bass and golden shiners are abundant in both North and South Twin. Brook trout and coastal stocks of rainbow trout have previously been planted into both lakes. We do not see establishing a population of redband rainbows to be a difficult problem for several reasons.

   1. For the most part, all introductions of coastal strains of rainbow trout have been sterile fish.
   2. Summer mortality of salmonids is so high it is unlikely that many non sterile coastal rainbow trout exist in either lake.
   3. Salmonids are not sympatric with largemouth bass during summer stratification and have limited contact with golden shiners.
   4. There is an existing population of redbands in the two major inlets (Beaverdam and Granite Creeks) to North Twin. There has been some incursion of coastal rainbow trout genes, but this is limited and is being diluted by plants from the Colville Tribal Hatchery.
   5. The Colville Tribe maintains a population of redband broodstock at its hatchery. Only offspring from this population are planted at Twin Lakes. The purity of this population is tested annually.

b. **Can golden shiners be used to monitor changes in methyl mercury?** Yes. Shiners could be used, but they are not necessarily the best species. All species in the lake should be tested for methyl mercury. Perhaps one will emerge as a good indicator species.

5. Questions for the ISRP. The ISRP's reviews have left several questions in our minds. Some of these have been addressed in the discussion items listed above. I will itemize them here.

a. Why did the ISRP rate this project so highly in 2008 when it was submitted by Moore and Beutel under the innovative proposal program and judge the proposal submitted by the Colville Tribes as not meeting scientific criteria even though the same principals were involved, it was more thorough and has sufficient supporting data to show that it works?

b. Can the ISRP show us a case where alum treatment has been successfully used to treat a hypolimnetic oxygen deficiency?

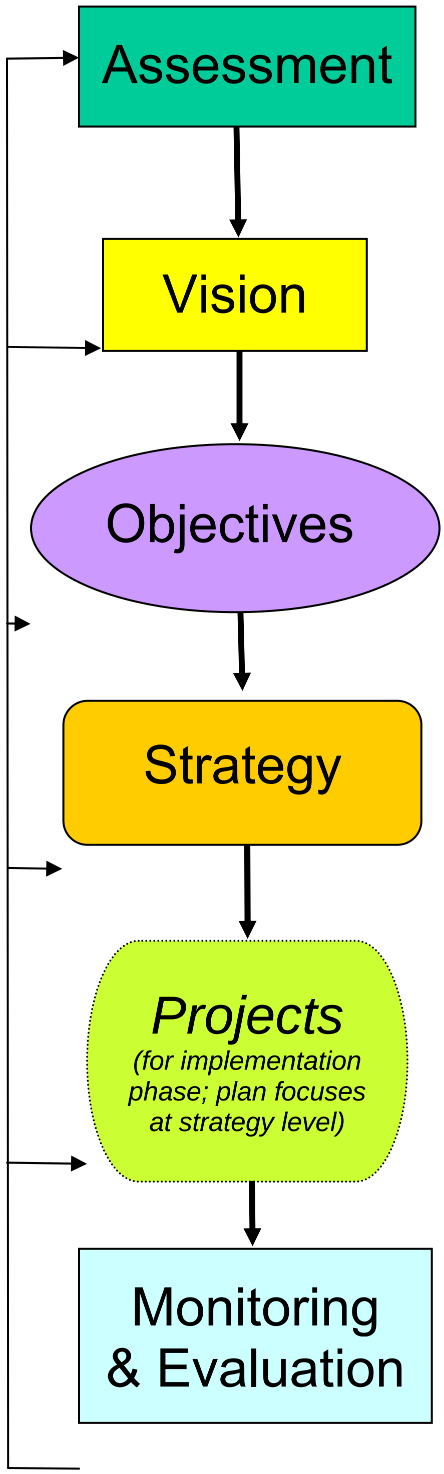
c. Why does the ISRP say that alum treatment is cheaper? The attached cost analysis shows that although Green Lake is much smaller than North Twin Lake, alum treatment of Green Lake is much more expensive than oxygenation of North Twin Lake.

d. We don't understand the ISRP's comments about oxygenation having no lasting effects. In our opinion the affects of alum treatment last 7-10 years and must be redone while oxygenation addresses the oxygen debt that has built up in the sediments over years. Gantzer, Bryant and Little (2009) have clearly shown that the amount of oxygen required is reduced as the SOD is reduced.

Erik, thanks again for arranging the teleconference. I wish we could do this on all of our projects.

List of Figures and Tables

Attachment: ISRP Flowchart: Subbasin Plan Logic Path



Identifies Limiting Factors

Spawning habitat loss due to development in headwaters, passage problems at culverts, high water temperature in lower reaches, extinct coho run

Guides and Prioritizes Actions

Establish protected and rebuilt self-sustaining fish runs; maintain genetic integrity; reconnect habitats

Type 1, Population: Return 5,000 spring Chinook & 1,000 coho

Type 2, Habitat: Water temperature <70 in lower reaches

Build from Strength - *protect all actively spawning redds*
Restore Ecosystem - *recover riparian functions in lower reach*
Artificial Production - *restoration of coho run*

Habitat Acquisition in Headwaters 1985-045-01	Culvert Replacement and Fencing Exclosure 2001-000-01
Coho Reintroduction (RFP)	

Indicators: water temperature, sediment load, redd and juvenile counts
Performance Standards: lower reach water temperatures not to exceed 70

Note: the numbers given above are hypothetical and, for habitat projects, the ISRP and ISAB have recommended that performance standards may be more usefully articulated by coupling the potential range of parameter conditions (i.e., median, range, and variance) with a predicted rate of change from the current to the desired state. See the ISAB's report: A Review of Strategies to Recover Tributary Habitat (ISAB 2003-2) www.nwcouncil.org/library/isab/isab2003-2.htm.

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