Diamond Lake Recovery – **Again**

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Lake Description

Diamond Lake is a stunningly beautiful 1,226 ha lake located just 18 km north of Crater Lake. It is flanked by Mt. Thielsen on the east and by Mt. Bailey on the west. In a draft of the park boundary, Diamond Lake was included with the national park to provide a complementary experience to the breathtakingly beautiful, but difficult to touch Crater Lake. However, the final wrangling resulted in Diamond Lake staying with the Umpqua National Forest and developing into a more intensive recreational resource than might have occurred otherwise. There is a large privately run lodge, 445 Forest Service campsites in several campgrounds, and 102 private cabins on land adjacent to the lake leased from the Forest Service. This lineage factors into its current management challenges.

Diamond Lake was formed by tephra erupting from Mt. Mazama (now the site of Crater Lake) about 6,700 years ago. The ash and volcanic debris impounded a stream in a mountain meadow leaving a lake that was about 6 m deeper than its current condition. The lake remained fishless until about 1910 when trout were first introduced. The shallow lake (Z_{max}= 14.8 m; Z_{mean}= 6.9 m) supported a productive benthic fauna and probably a high density of large cladocerans and copepods often found in many fishless lakes in the Cascade Range. The introduced trout grew rapidly and for a period this was one of the largest fish egg collection stations in the region, with collections of over 18 million eggs. This bounty allowed the Oregon Game Commission, predecessor agency to the Oregon Department of Fish & Wildlife (ODFW), to rear 1 million of the young trout for planting back into the lake with the balance used to stock lakes throughout the state. Although two permanent streams enter Diamond Lake, both are derived from spring water so cold that they don't support much trout reproduction.

Collapse of the Trout Fishery

This scenario of trout egg collection/rearing/restocking worked well until the 1940s, when fish biologists noticed that growth, survival, and harvest of rainbow trout began to mysteriously decline. Multiple hypotheses were investigated until the biologists realized that the trout were being out-competed for their prey, zooplankton and benthic invertebrates, by an invasive small minnow, the tui chub (*Gila bicolor*). The tui chub was believed to have entered the lake via live bait dumped into the lake after a days' fishing. Biologists tried netting the chub and using spot-treatments of rotenone until they concluded that they would have to eradicate the tui chub. The original Diamond Lake recovery project consisted of dredging a channel to lower the lake stage by 2.4 m and applying powdered rotenone in September 1954. The lake was restocked and fishing was opened up again in spring 1956 and trout fishing continued successfully for over three more decades. Additional details on the lake history are available elsewhere (Eilers et al. 2001; 2007).

In 1992, fish biologists once again found tui chub in the lake. Although it was intensely disappointing to see their nemesis in the lake again, it also served to explain the decline in the trout fishery, which in retrospect, was beginning to be expressed in the late 1980s. From 1992, when the tui chub were first encountered until 2001, the only obvious sign that something was clearly wrong with the lake was the poor fishing. In this same year, ODFW began the practice of supplementing the stocking of fingerlings with legal-sized trout to maintain a fishery. The initial attempt by ODFW to proceed with a rotenone project, much as was conducted in the 1950s, was aborted when opposition to the treatment caused the project to be shelved. However, opposition to a repeated rotenone treatment quickly dissipated after the summer of 2001 when the lake was hit by an intense bloom of *Anabaena*. In addition, with zooplankton grazers being eaten by the tui chub, there was little control of the algae. However, it was found that the excretion of nitrogen and phosphorus by the large population of tui chub provided the primary nutrients to sustain the cyanobacteria blooms. With lake closures from the cyanobacteria blooms, recreational use declined dramatically and economic impacts to the local economy took their toll. It only took several years of the blooms before resistance to the proposed rotenone treatment faded and planning for a project at the lake resumed with the goal of restoring the lake to fishable and swimmable.

The Rotenone Treatment

In the 1950s, project planners didn't have to contend with environmental impact statements (EISs). Following completion of this tome for the current project, plans began for a repeat of the rotenone project (Umpqua National Forest 2004). With relatively modest changes to the original treatment design, the 20th century version of the Diamond Lake Restoration Project was launched. The original canal was re-dredged to allow for the drawdown that served three functions: (1) reduce the lake volume by 40 percent, thus reducing the amount of rotenone required; (2) allow for water to be held in the lake following the treatment, thus allowing the rotenone to degrade before water was released downstream; and (3) reduce the area of the lake with macrophyte coverage and thus increase the likelihood for a complete kill of the fish (Figure 1). The water was drawn down through the new headgate over a nine-month period to minimize hydraulic overload to the outlet stream. Tui chub were netted from the lake in the summer of 2006 to reduce the additional nutrient load from the mass of fish that would decay in the lake following the treatment. This resulted in removal of 30.8 metric tonnes of tui chub. Finally, the rotenone was applied on September 13-15, 2006. The first applications started by metering liquid rotenone at drip stations into the two tributaries to drive any tui chub that might have wandered into the cold inlet streams. The next sequence involved use of applicators on foot equipped with backpack units dispersing liquid rotenone along the shoreline. Simultaneously, smaller boats equipped with pumps to spray the liquid rotenone plied the shallow waters along the shoreline (Figure 2). Finally, nine large pontoon boats built for the project applied rotenone behind their crafts (Figure 3). In the end, 32.6 metric tonnes of liquid rotenone and 48.6 metric tonnes of powdered rotenone were applied to the lake to achieve a concentration of 0.11 ppm of active ingredient in the water column. All fish cages deployed throughout the lake indicated that the kill had been complete.

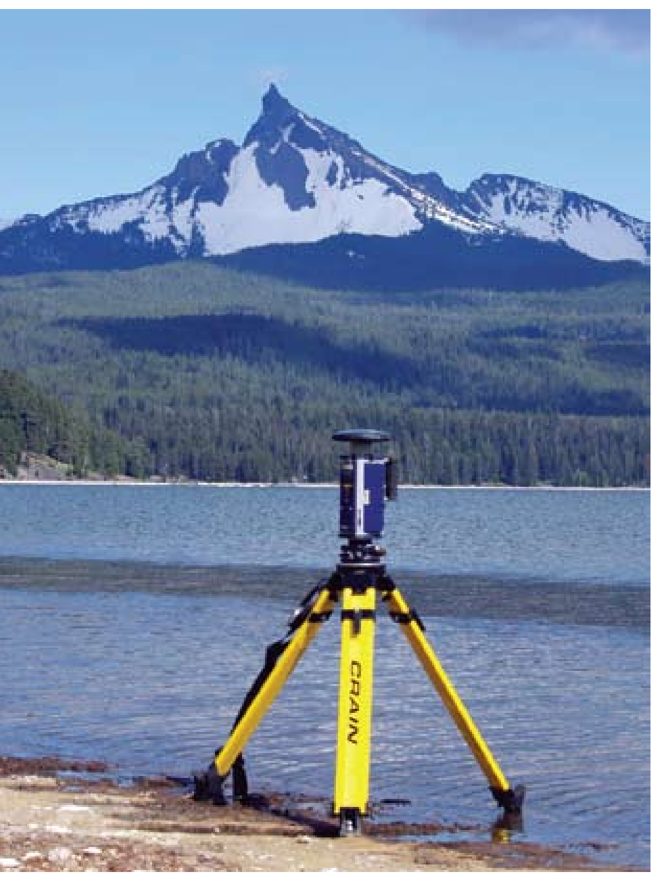

Figure 1. Diamond Lake with Mt. Thielsen in the background. Lake elevation was being checked as the drawdown proceeded in 2006. Photo by Joe Eilers.

Lake Response to Rotenone

The initial response was anticlimactic, although weather conditions were favorable for mixing the rotenone throughout the lake. A relatively small number of fish struggled to the surface and expired, but for the most part, nothing much happened. Several days later fish began to decompose, float to the surface, and accumulate on the shoreline, revealing the true magnitude of the dominance of the tui chub (Figure 4). During post treatment, another 15.9 metric tonnes of fish were raked up and disposed offsite. However, many of the dead tui chub simply decayed in the lake, fueling a vigorous *Anabaena* bloom that continued despite the declining lake temperatures (Figure 5). Rotenone and its immediate degradation product rotenolone were no longer detectable about eight weeks after treatment, making it possible to open the headgate. The process of refilling the lake began and was finally achieved in July of 2007. Conditions in the lake caused concern as oxygen continued to be consumed in waters below 6 m and cyanobacteria still thrived below the thickening ice layer. Upon ice-out, the ammonia that had accumulated under the ice was mixed throughout the water column and fueled a major *Synedra* (diatom) bloom. The bloom dissipated over the next several weeks as *Daphnia pulicaria*, a very large cladoceran, returned in abundance. Populations of *Daphnia*, which had been reduced to single digits per cubic meter, exceeded densities of over 75,000 individuals per cubic meter by the end of June 2007. The biomass of benthic organisms showed a similar response with numbers increasing from 2.3 g/m^2 before the treatment to 22.5 g/m^2 in 2007, 18.8 g/m^2 in 2008, and 38.3 g/m^2 in 2009. Species of benthic macroinvertebrates, which had been absent for years, returned rapidly, although new benthic species are still being observed annually. Fish growth returned to phenomenal levels with growth rates of 4.3 cm/mo in the first summer following the treatment, 4.7 cm/mo in 2008, and 3.4 cm/mo in 2009. The fish were fat, creels were full, and local cash registers rang announcing resurgence of the local recreation-based economy.

The *Anabaena* that had plagued the lake since 2001 virtually disappeared, replaced by low densities of cryptomonads and diatoms. Secchi disk transparency, which before treatment averaged about 1.6 meters in the summer prior to treatment, reached a maximum of 12.5 m in June 2007 (Figure 6). Light now reached the entire lake bottom. As a consequence, aquatic plants (both macrophytes and filamentous algae) colonized some areas of the lake that formerly were light-limited. Epilimnetic pH, which had averaged 9.5 in 2006, declined to an average of 8.4 in 2007 and 7.8 in 2008. Chlorophyll concentrations, which had averaged 15.3 ug/L prior to treatment, now averaged 2.7 ug/L in 2007 and 7.8 ug/L in 2008. The lake was meeting water quality standards for the first time in years. All this occurred without significantly altering the nutrient concentrations in Diamond Lake. What had changed was the rate of nutrient re-supply made possible by the abundant tui chub. Diamond Lake became the only lake to meet its TMDL targets by reducing the internal loading rate associated with waste products produced by the 200 metric tons of fish that had overwhelmed the lake (http://www.epa.gov/owow/nps/Success319/state/or_diamond.htm). Diamond Lake was only one of many lakes in Oregon suspected of not meeting water quality standards because of the overabundance of planktivorous or omnivorous fish. Reduction of watershed loading of nutrients will do little to improve water quality conditions in these lakes.

Figure 2. Crews spray liquid rotenone into the shallow areas to ensure no areas went untreated during the treatment. Photo by Oregon Department of Fish & Wildlife.

Figure 3. Boats follow prescribed GPS-driven paths to apply the rotenone. The light-colored paths represent application of powdered rotenone and the dark paths indicate application of liquid rotenone. The red dye at the entrance of Silent Creek was used to help guide shoreline-based application in this critical mixing zone. Photo by Joe Eilers.

Project Costs and Looking to the Future

The tally for the entire project through 2008 was about $5.2 million, of which $1.4 million was the actual cost of the rotenone and its application. Other major costs included the EIS ($0.7 M), the canal dredging and new headgate ($0.7 M), studies and monitoring ($0.65 M), and pre-/post-fish netting and collection ($0.38 M). Based on the analyses conducted for the EIS, the economic benefits from the project were realized in the first two years following the project. However, not all of the post-project results were rosy. Although the 2006 eradication of tui chub was a success, within the first year, ODFW biologists found another invasive minnow in Diamond Lake. The golden shiner (*Notemigonus crysoleucas*) population has not exploded as did the tui chub and previous history in Diamond Lake with this species suggests that it will not pose a problem. Monitoring effects continue at Diamond Lake to document continued recovery and to ensure that the current trout-stocking program does not interfere with its recovery.

The future of all managed lakes requires constant attention. In the case of Diamond Lake, extra vigilance is required because history has shown that it can be turned into a cyanobacterial quagmire with the inadvertent or intentional introduction of the wrong species of fish. To minimize a repeated invasion of tui chub or similar-behaving species, agencies have teamed up to work on aquatic invasive species and have posted boat ramps reminding fishermen to avoid the use of live bait, cash rewards have been offered to identify anyone attempting to introduce live fish into the lake, and a boat washing station has been installed to allow boats to be cleaned prior to launching. Hopefully, these and other actions will forestall what some opponents of the rotenone project believe is inevitable . . . namely, that the cycle will be repeated. For now, the Diamond Lake Restoration Project has returned the lake to a bountiful trout fishery and a gorgeous blue gem in the Cascades.

References

Eilers, J.M., C.P. Gubala, P.R. Sweets and D. Hanson. 2001. Effects of fisheries management and lakeshore development on water quality in Diamond Lake, Oregon. *Lake and Reservoir Management,* 17:29-47.

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Figure 4. Dead tui chub float across Diamond Lake on September 18, three days following the treatment. Photo by Joe Eilers.

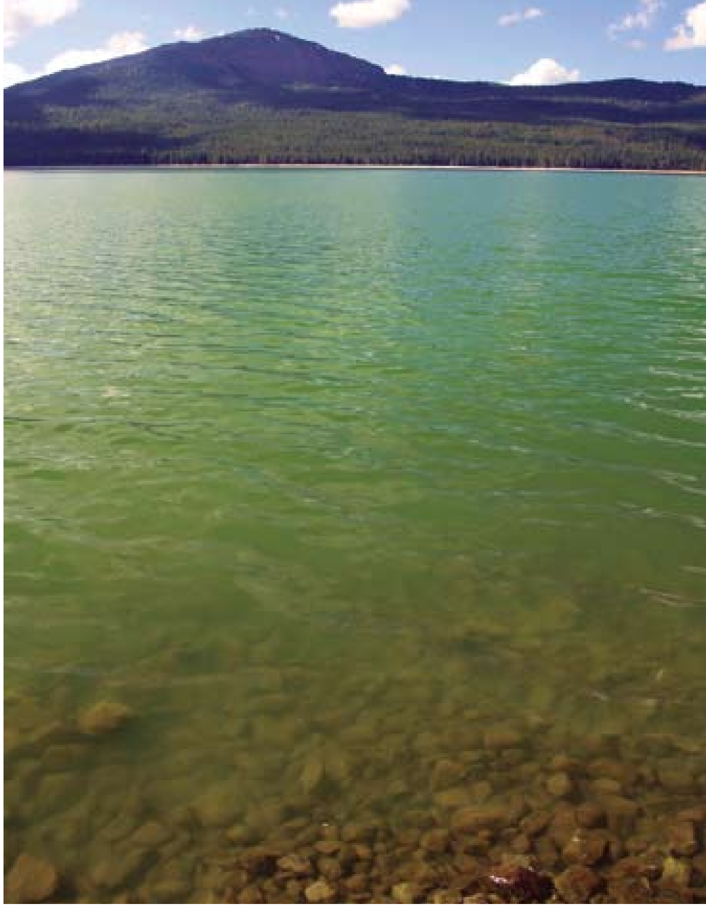

Figure 5. Diamond Lake turns green from Anabaena on October 2, two weeks following treatment. The intensity of the cyanobacteria was somewhat surprising given the declining lake temperatures. Photo by Joe Eilers.

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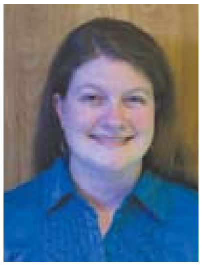
Umpqua National Forest. 2004. Diamond Lake Restoration Project. Final Environmental Impact Statement. Douglas County, Oregon. 580 p. + appendices.

Joe Eilers has worked as a limnologist in Oregon for the last 22 years. He is a certified lake manager, a registered professional hydrologist, and a certified fisheries biologist. He conducted the water quality investigations for the managing agencies leading up to and following the Diamond Lake Restoration Project.



Holly Truemper worked for many years on Lake Michigan with invasive species. She has worked for Oregon Department of Fish & Wildlife in Roseburg since 2003 and was a biologist on the Diamond Lake Restoration Project team.

Figure 6. An aerial view of the north end of Diamond Lake on June 20, 2007. The now-submerged canal is viewed as a line extending into the lake. The dark zones represent macrophytes. Photo by Mari Brick.