Featured Lake Waldo Lake

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WORLD'S MOST OLIGOTROPHIC LAKE?

Oregon is blessed with many spectacular lakes including 600-meter-deep Crater Lake in the Cascade Range and glacially carved Wallowa Lake in the northeastern corner of the state. Although the water quality of these lakes is exceptional, none surpasses the purity of Waldo Lake, located in the Willamette National Forest along the crest of the Cascade Range. This lake, nearly 10 kilometers long and 128 meters deep, was once regarded by limnologists as possibly the purest large lake in the world (Figure 1).

In August 1968, Dr. John Donaldson and I first visited Waldo Lake as part of an Oregon State University project to study and classify the lakes of Oregon. What we found was remarkable: A 20-centimeter-diameter Secchi disk was visible to depths of between 30 and 40 meters; the lake's water chemistry approximated that of distilled water; grappling hooks brought up mosses growing on the bottom at depths of more than 120 meters; phytoplankton primary production was barely measurable; and plankton nets towed vertically from depths of 60 to 80 meters yielded fewer than a dozen zooplankters.

These findings were consistent with observations made by earlier investigators, including F.C. Ziesenhenne of the Oregon Game Commission who, in 1938, made the first limnological survey of Waldo Lake. He reported that plankton was "scarce," that benthic organisms were "common," and that the Secchi disk was visible to an incredible depth of 48 meters.

Waldo Lake is a special lake indeed. But recent studies indicate that the lake's extraordinary waters have deteriorated over the past 40 years. The cause of this unfortunate circumstance is not certain, but recreational development and accelerated human encroachment are strongly suspected. Efforts are currently underway to halt the deterioration, or at least slow the lake's rate of decline. Whether the lake's earlier pristine qualities can be recovered is quite doubtful, particularly now that the lake has been culturally exploited. The lesson learned here is that lakes of this nature can respond unpredictably, and within a relatively short period of time, to disturbances induced by human intervention.

Figure 1. Waldo Lake, Oregon. Photo taken on September 11, 1995 from 12,000 feet (3,658 meters) looking north toward the Three Sisters Wilderness Area. The four volcanic peaks on the horizon are, from left to right: Middle Sister, South Sister, Broken Top and Bachelor Butte. Photo by Stephen D. Ward, Portland, Oregon.

Waldo Lake Setting

Waldo Lake is located approximately 193 kilometers south-southeast of Portland, Oregon at an elevation of 1,650 meters above mean sea level. The lake covers an area of about 26 square kilometers, has a shoreline length of 35 kilometers and lies in a glaciated depression dammed by end and lateral moraines (Figure 2). Lake volume varied from 760,000 to 780,000 acre-feet during years 1969 though 1984.

The lake receives no permanent streams, but rather is fed by numerous seasonally intermittent creeks, unchanneled runoff, groundwater seepages, and direct precipitation.

Since the watershed is only twice as large as the surface area of the lake, the amount of water supplied to the lake via surface runoff and ground-water seepage is a small portion of the lake's total volume. Thus, replacement of the lake's entire volume would require a volume of water equal to roughly 30 years of combined inflows from surface and ground-water runoff and direct precipitation.

The lake's major outlet, the North Fork of the Middle Fork of the Willamette River, exits at the northwest corner of the lake (Figure 3) and flows approximately 72 kilometers before joining the Middle Fork of the Willamette River at Westfir, Oregon. Some lake water seeps through an abandoned irrigation tunnel and head-gate structure (Figure 4) in the lake's south basin.

Figure 2. Color infrared photo of Waldo Lake, Oregon (upper left-hand corner). Photo taken by U-2 aircraft around noon on June 28, 1974 from 65,000 feet (19,817 meters). Odell Lake visible at bottom of photo. Photo courtesy of U.S. Army Corps of Engineers, Portland, Oregon.

Figure 3. North Fork of the Middle Fork of the Willamette River as it exits Waldo Lake, July 1973. U.S. Geological Survey stream-gaging house on stream's right bank. Photo by author.

Figure 4. Klovdahl tunnel entrance and head-gate at Waldo Lake, August 1990. Photo by author.

Basic Limnology

Waldo Lake is thermally stratified from late May through mid-October, with the thermocline usually found between 10 and 20 meters. Surface temperatures peak in August, usually reaching 18-19^{0}C. The lake is ice-covered during winter.

Dissolved-oxygen concentrations are generally 10 mg/liter or higher at all depths, corresponding to oxygen-saturation values that range from about 105 percent in the epilimnion to 120 percent in the hypolimnion. pH values rarely exceed 6.5 throughout the water column. Lake waters are extremely dilute and nutrient-deficient (Table 1).

Lake-water transparency is considerable, as indicated (Figure 5). Secchi disk readings obtained between 1986 and 1995 ranged between 18.5 and 37.5 meters (n=41, mean=26.64 meters). The phytoplankton community, as described by Sweet (2000), consists of 91 taxa, some of which are rare, and others that may be new species not yet identified. Species diversity is low, with the dinoflagellate *Glenodinium neglectum* comprising more than 75 percent of the total phytoplankton. Total phytoplankton density is small, averaging 57 organisms/ml. Picoplankton are present.

Three species of micro-crustaceans dominate the zooplankton community, including a cladoceran, *Bosminalongirostris*, and two copepod species, *Hesperodiaptomus kenai* x *shoshone* and *Leptodiaptomus signicauda*. Rotifers are also present, but much less common. The rotifer *Collotheca* sp. is predominant (Vogel and Li 2000).

Benthic bryophytes (mosses and liverworts) are distributed across the lake bottom, beginning at a depth of about 40 meters and extending into the deepest part of the lake, or 128 meters. At least 13 species have been identified (Wagner *et al*. 2000).

Lake Management

Waldo Lake and its watershed, which is managed by the U.S. Forest Service, is part of the Waldo Lake Wilderness Area established by the Oregon Wilderness Act of 1984. In 1983, the Oregon State Legislature added the lake and the North Fork of the Middle Fork of the Willamette River to the Oregon Scenic Waterway System.

The Forest Service has long maintained a special reverence for Waldo Lake and its environs. Unlike many of the national forest lakes scattered throughout the Oregon Cascades, Waldo Lake is free of lakeside homes, marinas and resorts. Overnight visitors have

Table 1. Chemistry of Waldo Lake, Oregon[a,b]

	n	*range*	*mean*
Specific conductance (μmos/cm)	155	2.9-3.8	3.29
Total alkalinity (mg/l as $CaCO_3$)	150	1.6-3.0	2.45
Total dissolved solids (mg/l)	135	<1.0-16.0	5.14
Calcium (mg/l)	4	0.123-0.130	0.129
Magnesium (mg/l)	4	all <0.015	
Sodium (mg/l)	4	0.098-0.125	0.116
Potassium (mg/l)	4	all <0.050	
Silica, dissolved (mg/l)	153	0.12-0.34	
Total carbon (mg/l)	5	0.95-5.41	1.88
Dissolved carbon (mg/l)	5	0.60-5.02	1.67
Total organic carbon (mg/l)	5	0.58-3.99	1.31
Dissolved organic carbon (mg/l)	5	0.50-3.40	1.12
Bicarbonate (mg/l)	150	0.39-0.71	0.59
Nitrite/nitrate-nitrogen (μg/l)	159	<1.0-3.0	
Ammonium-nitrogen (μg/l)	155	<1.0-19.0	
Total phosphorus (μg/l)	152	<1.0-13.0	
Soluble reactive phosphorus (μg/l)	150	<1.0-7.0	

[a] After Larson, 2000

[b] Water samples, collected in vertical profile between 1986 and 1995, were analyzed by the U.S. Forest Service's Cooperative Chemical Analytical Laboratory at Oregon State University, Corvallis.

Figure 5. James Sweet (far right) and author lower Secchi disk into Waldo Lake, August 1988. Photo by George Millener, staff photographer, Eugene Register-Guard.

access to only three relatively small campgrounds (Figure 6), each equipped with rudimentary toilet facilities and other sparse accommodations. Boats are held to a 10-mile per hour speed limit to ensure that visitors can fully experience the lake's aesthetic qualities in a wilderness setting. Logging is prohibited in the lake's entire drainage basin. Hikers, campers and other recreationalists must comply with strict Forest Service regulations concerning noise, garbage and sewage disposal, water pollution and the protection of native plants and habitat.

During the late 1960s, a 21-kilometer-long paved road linking the lake's campgrounds with State Highway 58 was constructed. This greatly improved lake access, which previously consisted of hiking trails and a primitive road described as "little more than a track marked down in the early part of this century by freight wagons traveling a wilderness route." Consequently, the number of people visiting Waldo Lake increased dramatically, from a few hundred visits in 1967 to around 170,000 visits in 1994.

Lake Fisheries

In 1938, the Oregon Game Commission (OGC) began stocking Waldo Lake with fish, with the first introduction consisting of 72,000 rainbow trout. Although the lake was originally fishless, like 90 percent of all Oregon Cascade lakes, fishery biologists had observed brook trout, rainbow trout and possibly mackinaw trout in scarce numbers prior to 1938. Between 1938 and 1990, roughly 20 million fish were planted including 10.3 million brook trout, 7.4 million rainbow trout, 450,000 cutthroat trout and 1.5 million kokanee salmon. Over one-half million opossum shrimp (*Mysis relicta*) were also introduced between 1965 and 1967 to supplement the diet of planktivorous kokanee.

Despite OGC's initial optimism about Waldo Lake's potential as a sport fishery, only a tiny fraction of the total fish stocked was ever caught. The total catch among 1,461 anglers surveyed by the Oregon Department of Fish and Wildlife (ODFW, formerly OGC) between 1957 and 1987, for example, amounted to 1,851 fish. The 32 anglers

Figure 6. North campground at Waldo Lake, September 11, 1995. Sailboats and dock sheltered by island. Islet campground and jetty visible at top of photo. Photo by author.

who were surveyed in 1969 had caught a grand total of two rainbows and a brook trout. Of the half-million cutthroat trout planted, only 11 were recaptured in the fish agency's gillnets, and nine others showed up in angler surveys. And, aside from the roughly 1,100 rainbows that were recaptured or counted during angler surveys, the fate of 7.4 million rainbows planted between 1938 and 1979 is unknown.

The opossum shrimp, unable to sustain its numbers in the face of a limited food supply and intensive predation, soon vanished. Likewise, zooplankton populations were decimated by the kokanee introduced between 1963 and 1970, resulting in the disappearance of some zooplankton species.

Nutrient Chemistry and Plankton Response

What exactly became of the millions of fish stocked in Waldo Lake remains an open question, but it is assumed that most fish simply could not survive in the lake's barren, nutrient-poor waters. Among the 159 water samples collected and analyzed for nutrients between 1986 and 1995 (Table 1), more than 75 percent fell below the minimum detection limits for nitrite/nitrate-nitrogen (76 percent <1.0 μg/liter), ammonium-nitrogen (87 percent <5.0 μg/liter), total phosphorus (89 percent <5.0 μg/liter) and soluble reactive phosphorus (83 percent <1.0 μg/liter). Dissolved silica concentrations ranged between 0.12 and 0.34 mg/liter.

Because of the lake's nutrient-impoverished condition, phytoplankton biomass and productivity were greatly restricted. In 1969 and 1970, total phytoplankton densities averaged 47 and 13 organisms/ml, respectively (Malueg *et al.*1972) Rates of phytoplankton primary production, obtained between 1969 and 1973, ranged from 0.107 to 9.880 mgC/m^2/hr. Mean productivity values for 1969, 1970 and 1973 were 3.993, 1.850 and 5.214 mgC/m^2/hr, respectively (Malueg *et al.* 1972, Larson 2000). These production values were the least ever reported for freshwater lakes.

Zooplankton and other fish-food organisms were equally scarce. During summer 1969, a zooplankton net (0.5-meter-diameter intake, 76 micron net mesh size) towed vertically from depths of 60 to 80 meters yielded an average of 0.50 organisms/m^3 (range: 0.13-1.4 organisms/m^3) (Larson and Donaldson 1970). Other investigators (Malueg *et al.* 1972) reported that 100-meter vertical tows, obtained in 1969 and 1970, "revealed no zooplankton at any time."

Lake Eutrophication?

There are indications that Waldo Lake has become increasingly productive over the past 40 years. This belief is based on three sets of data obtained between 1986 and 1998:

First, phytoplankton densities and primary production have increased considerably. Sweet (2000) reported an increase in phytoplankton abundance and a shift in species composition. Phytoplankton primary production rates have increased many times; mean productivity values for the period 1990 through 1994 ranged between 25.5 and 88.5 mgC/m^2/hr. The maximum value, 311 mgC/m^2/hr, was obtained on September 13, 1997 (Larson 2000).

Second, between 1969 and 1998, zooplankton density increased by three orders of magnitude, from <1 organism/m^3 to more than 600 organisms/m^3. Other changes included a decrease in both species diversity and body size (Vogel and Li 2000).

Third, although Secchi disk transparency has not diminished overall, the rate at which the blue bandwidth (of the radiation spectrum) is attenuated with depth has increased, whereas the rates of attenuation for both the green and red bandwidths have decreased. This change, more rapid attenuation of blue light accompanied by greater penetration of green and red, may be caused by an increase in suspended particulate matter, such as plankton and related detritus (Larson 2000).

Increased productivity likely resulted from nutrient enrichment, although this too remains open to question: nutrient concentrations are still extremely low (Table 1). Studies have shown, however, that oligotrophic lakes are extremely sensitive and responsive to even minimal nutrient additions (Goldman 1981). Phytoplankton populations in lakes that are nutrient-impoverished appear to be very efficient in the uptake, utilization, and recycling of scarce nutrients (Goldman and Wetzel 1963). Conceivably, phytoplankton in Waldo Lake are predominantly of this type, that is, well-adapted for low nutrient conditions. If so, seemingly negligible rates of nutrient loading could actually stimulate greater phytoplankton activity, leading perhaps to a higher trophic status.

Anthropogenic nutrient sources at Waldo Lake include: (1) sewage and other pollutants from tens of thousands of lake visitors annually; (2) human activities that disturb watershed soils and vegetation; and (3) pollutants from fish stocking. Additionally, in August 1996, a lightning-caused forest fire burned an area of about 5,000 hectares in the Waldo Lake watershed, including areas that reached the lake's shoreline (Figure 7). Subsequent runoff from burned areas during the following winter and spring may have contributed substantial nutrients and organic matter to the lake.

Lake Remediation

Prompted by reports of limnological change at Waldo Lake, the Forest Service recently implemented a plan to protect the lake from further degradation and, hopefully, reverse this downward trend. Protective measures include: (1) removal of pit toilets and the redesign of septic tank-drainfield systems to halt sewage contamination of lake waters; (2) tighter restrictions on recreational activities and other watershed uses to minimize cultural impacts; (3) a permanent ban on fish stocking; (4) a lake-monitoring program to determine how and to what extent the lake is changing; and (5) funding of research by other government agencies and academic institutions (Figure 8).

Certainly, these are prudent and necessary measures. But can the lake actually be preserved, or better yet, restored to an earlier pristine condition? Probably not. To truly protect Waldo Lake from further degradation would require that the lake and its watershed be closed to human entry. For various reasons, however, closure would not be feasible, or even acceptable to the public. At this point, the best that the Forest Service can do is simply to proceed with its remediation plan and hope that future visitors to Waldo Lake will see what Henry David Thoreau once envisioned about lakes: *Nothing so fair, so pure, and at the same time so large, as a lake, perchance, lies on the surface of the earth* (Figure 9).

References

Goldman, C.R. 1981. Lake Tahoe: Two decades of change in a nitrogen deficient oligotrophic lake. Verh. Internat. Verein. Limnol. 21:45-70.

Goldman, C.R. and R.G. Wetzel. 1963. A study of the primary productivity of Clear Lake, Lake County, California. Ecology 44(2):283-294.

Larson, D.W. 2000. Waldo Lake, Oregon: Eutrophication of a rare, ultraoligotrophic, high-mountain lake. J. Lake and Reserv. Manage.16(1,2):2-16.

Larson, D.W. and J.R. Donaldson. 1970. An Ultraoligotrophic Environment and Some Implications Concerning Recreational Development. Water Resources Research Institute Report No.WRRI-2, Oregon State University, Corvallis. 21 pages.

Malueg, K.W., J.R. Tilstra, D.W. Schults and C.F. Powers. 1972. Limnological observations on an ultra-oligotrophic lake in Oregon, U.S.A. Verh. Internat. Verein. Limnol.18:292-302.

Sweet, J. 2000. Phytoplankton composition and distributions in Waldo Lake, Oregon. J. Lake and Reserv. Manage.16(1,2): 63-70.

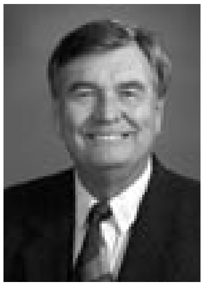
Vogel, A.H. and J. Li. 2000. Recent changes in

Figure 7. Burned area from 1996 forest fire extends to lake, September 28, 1998. Photo by author.

Figure 8. Professor Richard Castenholz (standing, blue coat), Department of Biology, University of Oregon, and limnology students arrive at primary sampling station on Waldo Lake, October 3, 1998. Photo by author.

Figure 9. Waldo Lake at dawn, October 4, 1990. Photo by author.

the zooplankton assemblage in Waldo Lake, Oregon. J. Lake and Reserv. Manage.16(1,2):114-123.
Wagner, D.H., J.A. Christy, and D.W. Larson. 2000. Deep-water bryophyte from Waldo Lake, Oregon. J. Lake and Reserv.Manage.16(1,2):91-99.



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