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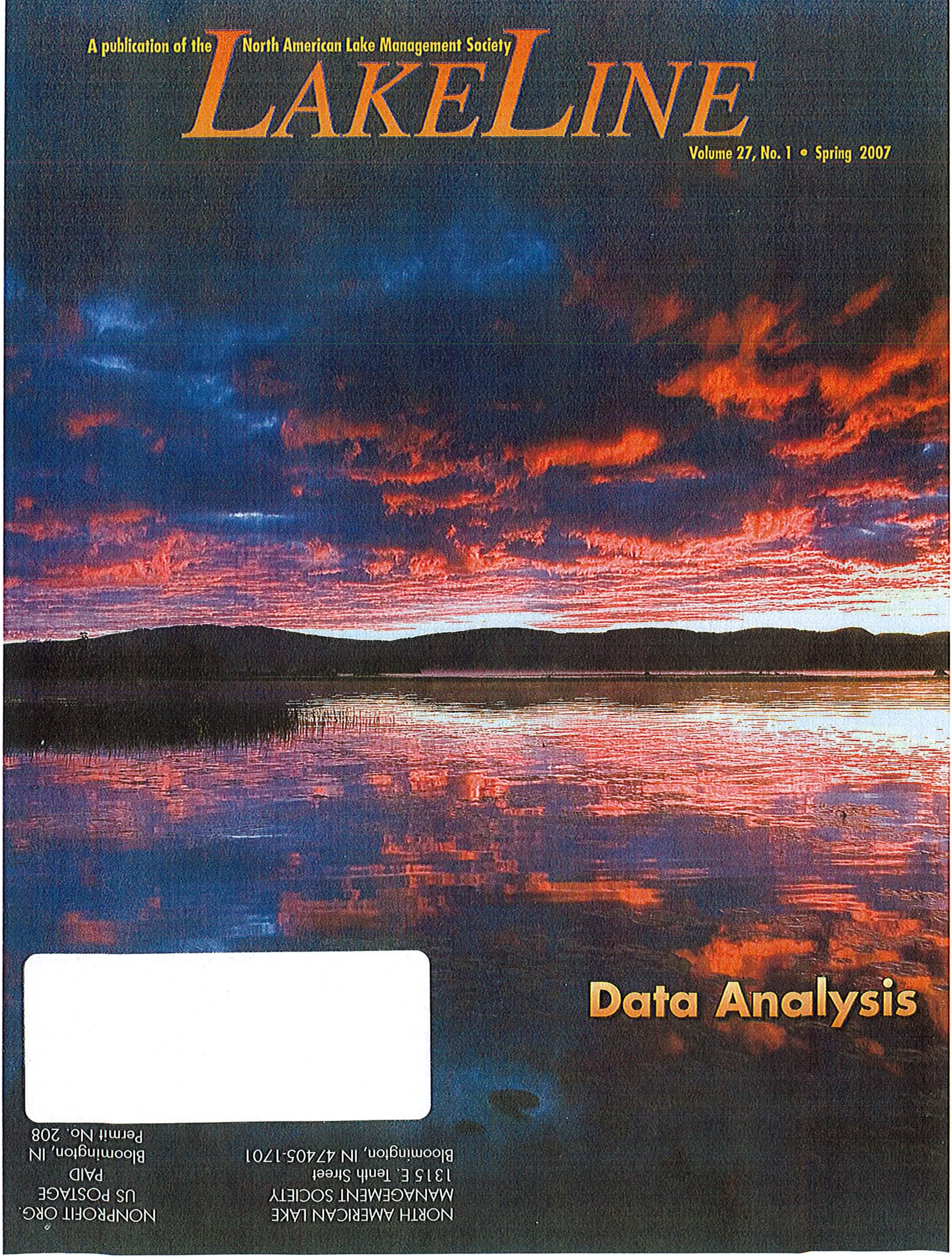

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Featured Lake

Crater Lake

Douglas W. Larson

Crater Lake, Oregon: Probing the Nation's Deepest Lake on a Shoestring

Oregon's Crater Lake, with a maximum depth of nearly 600 meters, is the deepest lake in the United States and eighth-deepest in the world. Situated in a volcanic caldera roughly 10 kilometers wide, it is considered one of the most remarkable lakes on earth (Figure 1). Noted for its intensely blue color and extraordinary water transparency, Crater Lake was described by Hutchinson (1957) as "almost optically pure." The late Dr. Arthur Hasler, professor of zoology and limnology at the University of Wisconsin, recorded Secchi transparency depths of 36, 39, and 40 meters in August 1937. In July 1969, limnologists from Oregon State University observed a 100 cm-diameter Secchi disk to a depth of 44 meters, reported then as a record Secchi depth for freshwater lakes (Larson 1972, 2002).

Figure 1. Crater Lake surrounded by a snow-covered caldera rim. Date unknown. Photo courtesy of the National Park Service.

Yet, despite its wondrous scenic qualities and rare limnological features, Crater Lake was seldom studied over a period of nearly 70 years following the lake's designation as a national park in May 1902. Between 1902 and 1966, roughly a dozen limnological investigations were conducted at Crater Lake, most of which were short-term (some lasting for only a day or two), narrow in scope, and conducted during summer months by independent, self-funded scientists. Consequently, a long-term, reliable limnological database and a thorough understanding of the lake's limnological nature were never obtained. This situation—the scarce and fragmentary existence of historic limnological data—precluded periodic lake-quality evaluations by the National Park Service, the agency responsible for the management and protection of Crater Lake. Thus, during the late 1970s, after a study had indicated that the lake's clarity had possibly diminished by 25 to 30 percent (Larson 1984), investigators found it virtually impossible to determine if and to what extent the lake had changed.

The discovery of possible optical deterioration had been made by three visiting scientists working in the Park Service's Volunteers in Parks Program. This project, carried out between 1978 and 1984, was performed on a shoestring budget funded almost entirely by the scientists themselves. As one of the three volunteer scientists, I was interested primarily in the abundance, vertical distribution, and species composition of the lake's phytoplankton, all of which were poorly understood at the time. Little did we know then where our research would lead us.

Geography, Geology, Hydrology

Crater Lake is located in the southern portion of the Oregon Cascade Range, approximately 280 km south-southeast of Portland, and 104 km north of the Oregon-California border (Figure 2). The caldera was formed roughly 7,000 years ago by the climatic eruption and collapse of Mount Mazama that was perhaps 3,500 to 4,000 meters high. The recurrence of smaller eruptions and lava flows produced an

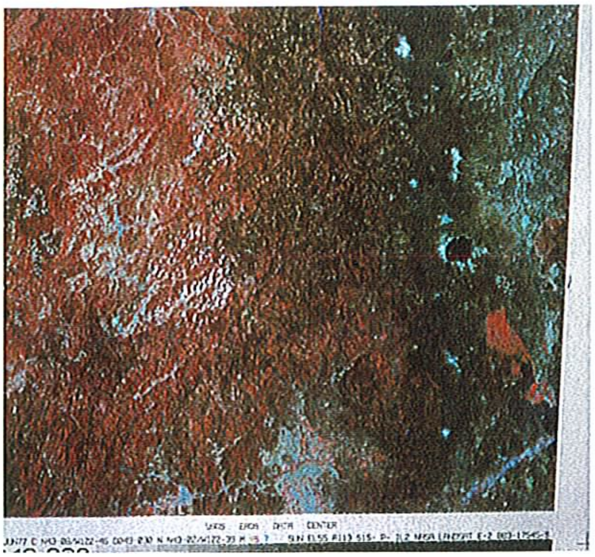

Figure 2. NASA Landsat color infrared photograph of southern Oregon Cascade Range showing Crater Lake (center right in photo), approximately 45 km north of Upper Klamath Lake (at bottom of photo). Photo, taken October 13, 1976, courtesy of the U.S. Geological Survey.

Figure 3. Wizard Island, a cinder cone approximately 250 m tall and about 1,000 m in diameter at its base (above-water dimension), August 1987. Photo by author.

Figure 4. Tourist boat cruises toward the island Phantom Ship, a remnant volcanic cone, June 1978. Photo by author.

emergent cinder cone, known as Wizard Island (Figure 3), a submerged cinder cone (Merriam Cone) and a dome on the floor of the basin. The lake is enclosed by steep caldera walls that ascend from 150 to 610 meters above the surface of the lake (Figure 4). In places, the walls rise vertically to the caldera rim (Cranson 2005).

The lake is a closed basin, meaning that no permanent streams enter or exit. Water is lost through seepage and evaporation, the latter accounting for 30 to 50 percent of the loss. Water enters as precipitation falling directly on the lake (about 80 percent of the yearly total water input) and as snowmelt and rain runoff from caldera walls. Precipitation occurs mostly as snowfall, which averages about 13 m annually.

Since about 1900, lake surface elevation has fluctuated nearly five meters, reaching its highest recorded elevation (1,883.93 m above msl) in 1975, and falling to its lowest recorded elevation (1,879.02 m above msl) in September 1942. Lake-water residence time is about 150 years.

Initial Lake Explorations and Fish Introductions: 1883-1910

Scientists first explored Crater Lake in 1883. Joseph Diller and Everett Hayden of the U.S. Geological Survey "tumbled logs over the cliffs to the water's edge, lashed them together with ropes to make a raft, and paddled over to the island." They also observed that the lake was extremely clear, stating that "a white dinner plate ten inches in diameter may be seen at a depth of nearly 100 feet."

During the summer of 1886, Clarence Dutton and Mark Kerr, also of the USGS, sounded the lake in a leaky rowboat at 168 scattered locations (Figure 5). Using piano wire to measure depth, the men recorded the lake's maximum depth at 609 m.

In August 1896, Barton Evermann of the U.S. Fish Commission made the first temperature measurements in Crater Lake. Lowering a Negretti-Zambra deep-sea thermometer to the lake bottom, Evermann recorded temperatures of 15.6°C at the surface, 3.9°C at 169 m, 5.0°C at 317 m, and 7.8°C at 495 m. He concluded from these measurements that "the waters of Crater Lake are still receiving heat from the rocks upon which they rest." Joseph Diller was skeptical, however, arguing that the lake's bottom water should not be warmer since there was no evidence of volcanic heat emanating from the caldera floor; nor were there visible fumaroles or hot springs around the lake. In July 1901, Diller deployed two thermometers in

Figure 5. Clarence Dutton and colleagues sound Crater Lake from the Cleetwood, July 1886. Wizard Island appears in the background. Photo courtesy of the National Park Service.

tandem, including the Negretti-Zambra instrument and an ordinary thermometer. He found that temperatures ranged from 11.1°C at the surface to a constant 3.9°C between about 100 m and lake bottom. Based on these measurements—which were later verified by temperature gradients recorded over the next 70 years—Diller concluded that the bottom of Crater Lake "contains no appreciable volcanic heat."

Evermann also collected zooplankton in surface waters near shore. His identifications, representing perhaps the earliest information about the lake's zooplankton community, included a cladoceran (*Daphnia pulex*), two copepods (*Cyclops albidus*, *Cyclops serrulatus*), and a form misidentified as *Allorchestes dentate*, which is actually a marine amphipod.

Fish were introduced to Crater Lake in 1888. Prior to that time, the lake was presumably fishless. On September 1, William Steel, S.S. Nicoline, and E.D. Dewart transported 600 rainbow trout to the lake from a ranch 41 miles away; only 37 fish survived the trip. The first trout—some measuring nearly 80 cm in length—was caught in 1901. Beginning in 1910, the National Park Service officially stocked the lake with fish, including Coho salmon, rainbow trout, cutthroat trout, and brown trout. Periodic fish-stocking was finally discontinued during the early 1940s (Figure 6).

Currently, the lake's fish populations consist entirely of rainbows and kokanee salmon. Kokanee, which first appeared in 1939, were never stocked in the lake; their means of introduction remains unknown. All other species have apparently disappeared, although a brown trout was reportedly caught in 1966.

Earliest Water-Chemistry and Secchi-Disk Measurements: 1912-1913

In August 1912, Walton Van Winkle and N.M Finkbinder of the USGS collected a water sample for chemical analyses from a depth of two meters approximately one mile from shore. These analyses, the first ever for Crater Lake water, were nearly identical to those obtained 52 years later by K.N. Phillips and A.S. Van Denburgh, also of the USGS (Table 1).

During August and September 1913, fishery biologists George Kemmerer, J.F. Bovard, and W.R. Boorman of the U.S. Bureau of Fisheries conducted the first bonafide limnological survey of Crater Lake. They recorded the lake's temperature gradient and obtained the first measurements of dissolved oxygen (orthograde curve, with near-oxygen saturation throughout the water column) and carbon dioxide. They also deployed a Secchi disk for the first time in the lake, obtaining readings of 25 and 27 m, but did not provide information about weather, time of day, and lake-surface conditions during the deployments. Phytoplankton, collected from depths reaching nearly 200 m, consisted of *Asterionella* sp. (described as the "only diatom found in the lake") and "fairly large numbers" of filamentous green algae thought to be *Mougeotia* sp. Zooplankton collections consisted of rotifers (*Keratella quadrata*, *Asplanchna* sp., *Notholca longispina*) and two cladocerans (*Daphnia pulex*, *Bosmina longispina*).

Figure 6. Ernest P. Leavitt (left), Superintendent of Crater Lake National Park, and Chief Ranger Carlisle Cronch, pose with fish caught in Crater Lake, 1940. Photo courtesy of the National Park Service.

plays a dominant role in the maintenance of populations and stocking, by present methods, only a minor one."

Table 1. Chemistry of Crater Lake.

	1912[a]	*1961*[b]	*1964*[c]
Total dissolved solids, mg/l	80	79	75
Calcium, mg/l	7.1	7.0	7.0
Magnesium, mg/l	2.8	2.6	2.5
Sodium, mg/l	11	11	11
Potassium, mg/l	2.2	1.7	1.6
Chloride, mg/l	11	10	9.5
Sulfate, mg/l	11	10	10
Silica (SiO_2), mg/l	18	18	16
Bicarbonate, mg/l	34	37	35
Nitrate, mg/l	0.38	0.1	0.0
Phosphate, mg/l	0.01	NR[d]	NR
Iron, mg/l	0.02	NR	NR

[a] Data from Van Winkle, 1914.
[b] Data from Phillips and Van Denburgh, 1968; surface sample collected near shore at Cleetwood boat landing.
[c] Data from Phillips and Van Denburgh, 1968; surface sample collected roughly 7 km north of Crater Lake lodge.
[d] Not Recorded.

More recent surveys have found that the zooplankton community consists of two cladocerans (*Daphnia pulicaria* and *Bosmina longirostris*) and nine rotifer species, including *Collotheca pelagica*, *Conochilus unicornis*, *Filinia terminalis*, *Keratella cochlearis*, *Keratella quadrata*, *Kellicottia longispina*, *Philodina* cf.*acuticornis*, *Polyarthra dolichoptera*, and *Synchaeta oblongata* (Karnaugh 1990). Uncertainty still exists, however, as to whether *Daphnia pulicaria* and *Bosmina longirostris* might actually be *Daphnia pulex* and *Bosmina longispina*.

Limnology and Fisheries Research: 1934-1940

Twenty years passed before anyone attempted another limnological study of the lake. Between 1934 and 1936, J.S. Brode, a biology professor at Santa Monica Junior College in California, proceeded with an independent limnological research project while working at Crater Lake National Park during summers as a ranger-naturalist. Brode, routinely recording lake temperatures between surface and bottom, and, using a light meter (Weston photronic cell), was the first scientist to measure the depth of light penetration. He found that light penetrated to a depth of at least 120 m due to the lake's high transparency, which explained further why phytoplankton could exist at depths of 200 m or deeper.

Brode also collected and identified numerous lake-dwelling organisms, including fish, amphibians, insects, plankton and benthic algae and invertebrates. His compilation of these identifications became the original species list for Crater Lake, which contained many plant and animal types never before reported for the lake. By integrating his biological information with some of the lake's physical attributes, Brode formulated the first conceptual model of the lake's complex ecosystem in a paper published in 1938.

Arthur Hasler, who spent three summers (1937-1940) at Crater Lake as a ranger-naturalist (Figure 7), was interested primarily in the lake's fish populations, but also recorded vertical temperature gradients and Secchi depths. Using an Ekman dredge, Hasler (1938) collected green mosses growing on the lake bottom at a depth of 120 m, which he referred to as his "most startling biological finding at Crater Lake."

Although Brode had been the first scientist to study the food habits of Crater Lake fish, Hasler carried the research a step further by determining the growth rates of fish. Based on data collected between 1937 and 1940, Hasler and Donald Farner, also a ranger-naturalist, concluded that (1) both rainbow trout and Coho salmon were reproducing naturally in the lake; (2) stocking the lake was ineffective; and (3) "natural reproduction

Refining Crater Lake Limnology: 1940-1964

During the period 1940 through 1964, the limnology of Crater Lake was described with greater precision using state-of-the-art methodologies and instruments. On July 18, 1940, a team of oceanographers from the University of Washington -- led by Clinton Utterback, Lyman Phifer, and Rex Robinson (Figure 8)—lowered a light meter (Weston submarine photometer) in the lake and for the first time measured the vertical penetration of blue, green, and red bandwidths in the visible light spectrum. They discovered that (1) light penetration is considerable, with one percent of surface incident radiation still remaining at depths of between 80 and 100 m; and (2) the lake's highly transparent water transmitted blue light much deeper than either green or red, principally because of the scarcity of phytoplankton and other suspended particles. Thus, instead of particulate matter, water molecules tend to scatter penetrating light, although the light being scattered is predominantly the short wavelengths in the visible light spectrum. The backscatter of this light produces the lake's deep-blue color, but an increase in particulate matter will diminish this effect.

Utterback and his colleagues also discovered that 90 percent of the lake's phytoplankton was concentrated between 70 and 150 m, with maximum densities found at 76 m, only a few at 300 m, and none at 430 m. Other findings about phytoplankton included: (1) virtually no phytoplankton existed in the surface-to-20 m stratum; (2) most algae consisted of filamentous blue-green algae (*Anabaena* sp.); and (3) diatoms constituted only about 15 percent of the total phytoplankton collected.

In 1947 and again in 1950, attached benthic algae collected from submerged rocks and sediments along the shores of Wizard Island was examined by algologist H.E. Sovereign, who identified 112 diatom species, several of which were described as new and rare. During the summer of 1954, while conducting routine limnological surveys of the lake, C.W. Fairbanks, a ranger-naturalist, and John Rowley, a University of

Figure 7. Dr. Arthur Hasler, second from left, poses with other ranger naturalists and park employees at snow-covered Crater Lake National Park, June 29, 1938. Photo courtesy of the National Park Service.

Figure 8. University of Washington oceanographers pose together at Crater Lake in July 1940. They are, from left, Thomas Thompson, Lyman Phifer, Rex Robinson, Clinton Utterback, and park ranger-naturalist Donald Farner. Photo courtesy of the National Park Service.

Minnesota professor, collected mosses from depths ranging from 30 to 130 m. They also collected and identified six species of flowering plants and an unusual invertebrate called a "water bear" (Class Tardigrada). And, from samples collected in July 1959, Kuno Thomasson of the Vaxtbiologiska Institutionen of Uppsala, Sweden identified several new phytoplankton species, noting that the phytoplankton was "very sparse."

Also during the summer of 1959, R.E. Williams of the U.S. Coast and Geodetic Survey sounded the lake with more than 4,000 echo-soundings from which a bathymetric map based on ten-fathom intervals was developed. Guided by this map, ranger-naturalist C.H. Nelson collected deep-water sediment samples from 130 locations during the summer of 1960 as part of his thesis research at the University of Minnesota (Figure 9). Using Ekman- and Petersen-type dredges, Nelson hauled up sediment samples from as deep as 550 m. He reported that (1) heavy accumulations of diatomaceous and moss ooze covered vast portions of the lake bottom; (2) clay deposits may have helped to seal the caldera floor, thus allowing water to accumulate; and (3) landslides from caldera walls frequently entered the lake, producing powerful turbidity currents across the bottom.

In 1961 and again in 1964, the USGS repeated Walton Van Winkle's 1912 chemical analyses (Table 1).

The Donaldson Era: 1966-1971

In 1966, Dr. John R. Donaldson, a fisheries professor at Oregon State University (OSU) and later the director of the Oregon Department of Fish and Wildlife, established a limnological program at the lake in cooperation with the National Park Service. Donaldson's graduate students, including Harold Kibby, Owen Hoffman, James Malick and I, were brought into the program in 1966 and 1967 (Figure 10). This program contributed more to an understanding of Crater Lake limnology than had any of the previous studies. Various discoveries included: (1) surface currents tend to travel counterclockwise, or cyclonic, around the lake's near-perfect-circle shoreline, and that maximum current speeds reach 0.40 km/hr (Kibby et al. 1968); (2) zooplankton migrate vertically thought the water column, with *Daphnia* migrating from depths of more than 60 m during the day to the lake surface at night (Hoffman 1969); and (3) maximum phytoplankton primary production (ppn) occurs between depths of 70 and 120 m despite low temperature (around 3.9° C) and low light conditions (about 4 percent of surface incident radiation) at that depth, and phytoplankton ppn is measurable to depths of at least 200 m (Larson 1972).

The Donaldson team also provided field assistance and logistical support for other visiting scientists, including Herbert Volchok of the U.S. Atomic Energy Commission, H. J. Simpson and W.S. Broecker of Columbia University's Lamont-Doherty Geological Observatory, V.T. Bowen of Woods Hole Oceanographic Institute, and W.F. Libby of the Institute of Physics at UCLA. During the summer of 1967, they analyzed water and sediment samples for tritium, strontium-90, and cesium-137 as part of a study to determine whether the fall-out of these radioisotopes from nuclear weapons testing was greater over

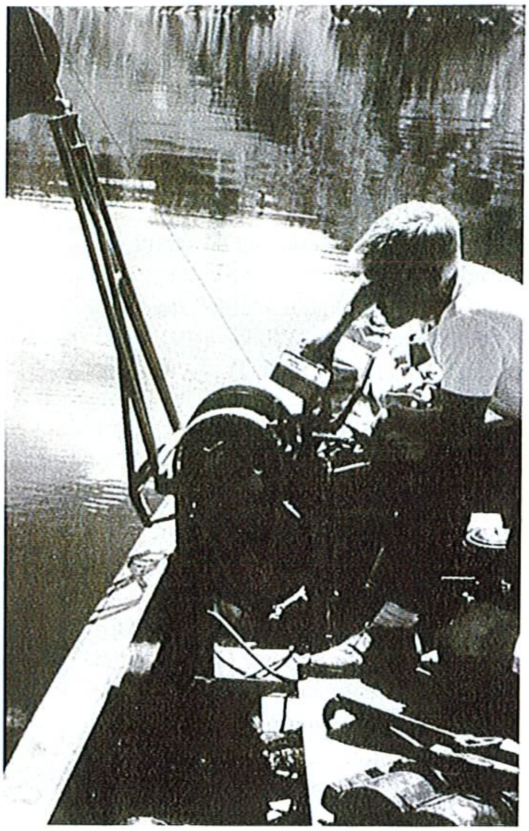

Figure 9. Hans Nelson lowers a Petersen-type dredge into Crater Lake, August 12, 1960. Photo courtesy of the National Park Service.

oceans than over land. Crater Lake was regarded as an ideal study site because its surface area comprises nearly 80 percent of the lake's entire drainage basin.

In August 1966 and again in July 1969, Raymond Smith and John Tyler of Scripps Institution of Oceanography measured the distribution of natural light to a depth of about 110 m using an instrument called the Scripps Spectroradiometer. Their optical measurements confirmed earlier reports about the lake's exceptional optical properties and provided precise baseline optical data.

In February 1971, Victor Neal, Stephen Neshyba and Warren Denner of Oregon State University's School of Oceanography became the first scientists to conduct research on the lake during the winter. In doing so, they risked snow avalanches and hypothermia as they negotiated a single, precipitous trail that switchbacked for over a mile down the steep caldera wall. Since the lake rarely freezes over, Neal and his colleagues launched their raft in open waters with surface temperatures near 0° C.

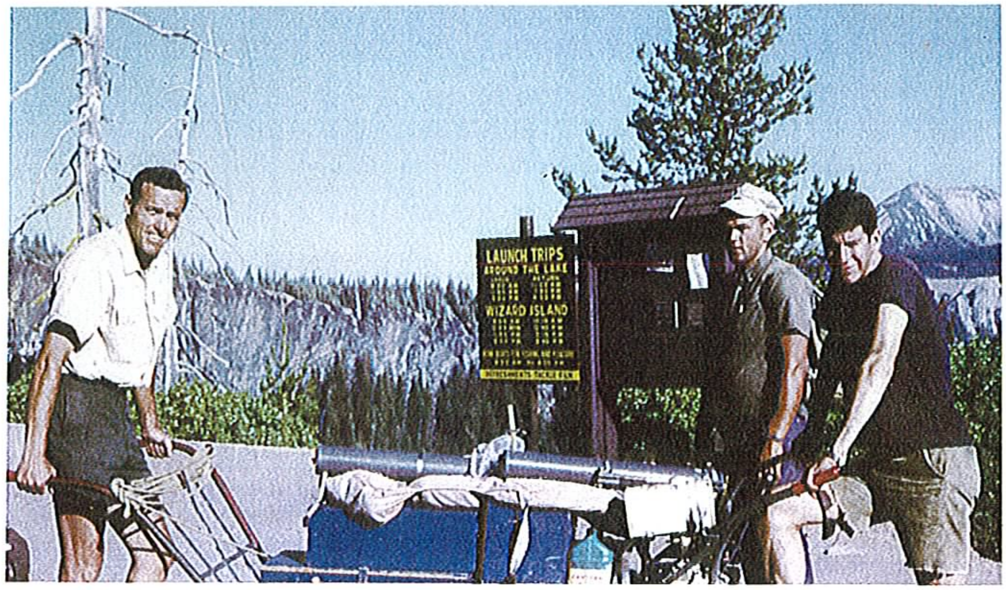

Figure 10. John Donaldson, James Malick and Owen Hoffman (left to right) prepare to go down the Cleetwood trail with their limnological equipment loaded on a motorized trail packer, July 1968. Photo by author.

Probing Crater Lake on a Shoestring: 1978-1984

In June 1978, I returned to Crater Lake to continue my studies of the lake's phytoplankton and other limnological features. I was joined later by Stan Geiger, a Portland algologist and Cliff Dahm, professor of biology at the University of New Mexico.

The National Park Service loaned us a two-person rubber dinghy and a park employee to operate the boat's three-horsepower outboard motor. We lowered water-sampling gear and various instruments into the lake with a homemade wooden winch and cable reel containing 610 m of rope (Figure 11). Various field and laboratory equipment—including a transmissometer, a photometer, a Millipore-filtration system and zooplankton nets—were borrowed from the U.S. Army Corps of Engineers' limnological laboratory at nearby Lost Creek Reservoir on the Rogue River.

Between 1978 and 1983, approximately 900 samples were collected throughout the water column for phytoplankton analyses. From these, Geiger identified 140 species, nearly all of which were new. Diatoms comprised 73 percent of the phytoplankton community. The research also found that the three predominant species are distributed vertically in distinct, environmentally disparate depth zones, as follows: (1) *Nitzschia gracilis*, a diatom, occupies the extremely high light-high temperature stratum between the surface and 20 m; (2) *Stephanodiscus hantzschii*, also a diatom, occupies the extremely low light-low temperature stratum between 160 and 200 m; and (3) *Tribonema affine*, a yellow-green alga, is sandwiched in a zone between the upper and lower strata where light and temperature conditions are more moderate (Larson et al. 1987).

During these studies we discovered that the lake's clarity was possibly diminishing. Accordingly, among the more than 50 summertime Secchi readings obtained between 1978 and 1984, 80 percent were 30 m or less (range: 22-37 m, mean: 29 m). Although this possible loss of clarity could not be explained, we believed that it was related to an unusual abundance of phytoplankton in the lake's upper stratum, particularly *Nitzschia gracilis*. Unfortunately, due to the scarcity of pre-1978 phytoplankton data, we were unable to determine if the late-summer proliferation of *N. gracilis* was a typical occurrence or a newly developing one. We speculated that the phytoplankton had become more abundant because of an unnatural increase in nitrogen, which occurs in the lake in extremely small concentrations (most values <1.0 μg/liter). Additions of nitrogen from anthropogenic sources, such as sewage, could greatly stimulate phytoplankton growth. The source of the nutrient enrichment, we suspected, was the park's sewage disposal facilities on the caldera rim (Figure 12), specifically the septic tank-drainfield system that processed an estimated 16 million gallons of raw sewage every

Figure 11. Ranger-naturalist Seth Phalen of the National Park Service operates a three-horsepower outboard motor on the research boat used by Cliff Dahm, Stan Geiger and the author between 1978 and 1984, August, 1978. A small plankton net hangs from the wooden winch in the center of the raft. Photo by author.

summer. This system, designed in the mid-1940s to accommodate about 200,000 visitors each summer, had become inadequate by the 1970s when the summertime visitation rate had increased to nearly 600,000 people annually.

Alarmed that Crater Lake was being contaminated with sewage, Oregon Congressman Denny Smith sponsored legislation in Congress directing the National Park Service to study the clarity problem at Crater Lake and "to immediately implement such actions as may be necessary to assure retention of the lake's pristine quality." In September 1982, Congress passed Public Law 97-250 authorizing a limnological monitoring and research program to investigate possible lake pollution. This program, initiated in 1983, has been actively maintained since 1983 at a cost of several million dollars (Larson 1996).

In 1991, four years after admitting that sewage was entering the lake, the National Park Service finally removed the septic tanks from the rim and diverted the sewage through a new $3 million pipeline. The question of whether sewage caused possible lake optical deterioration or other impacts was never answered or even addressed. Nevertheless, the sewage threat is now gone, and a scientifically based limnological program is in place, enabling scientists to make new discoveries and acquire a long-term limnological database to track lake conditions and, hopefully, preserve Crater Lake for future generations.

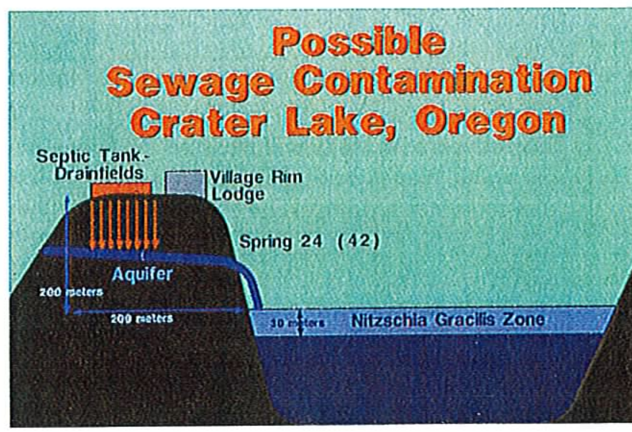

Figure 12. Hypothetical source of nutrient enrichment from septic tank-drainfields in Crater Lake National Park. Vertical and horizontal distances (200 m) are estimates.

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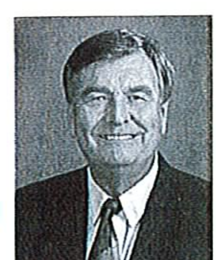

Douglas W. Larson is a water quality consultant and adjunct assistant professor in the Department of Environmental Sciences and Resources at Portland State University. He retired from the U.S. Army Corps of Engineers in 1991. He studied the limnology of Crater Lake periodically between 1967 and 1986.