National Park Service
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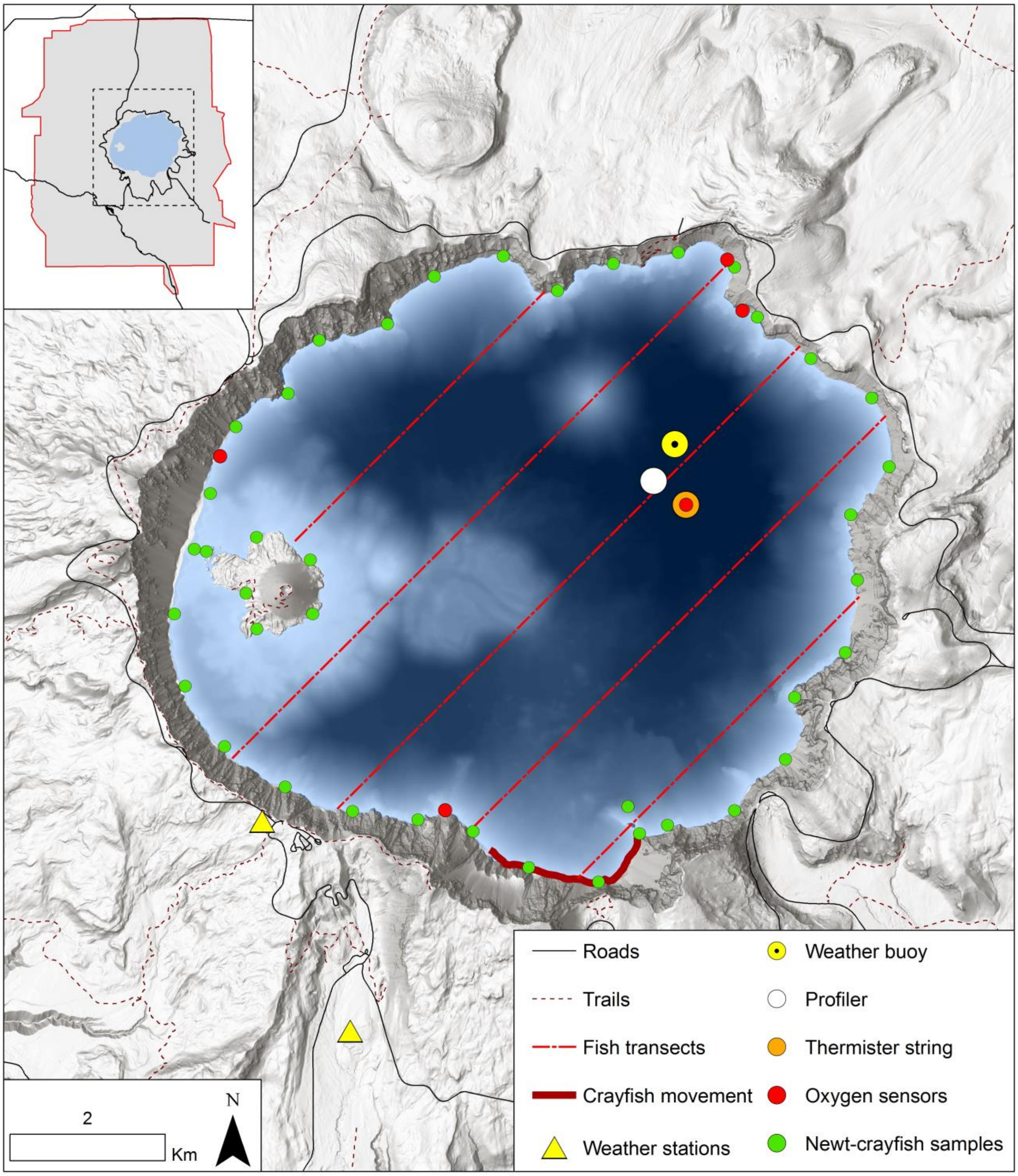
Natural Resource Stewardship and Science

Crater Lake Long-term Limnological Monitoring Program

State of the Lake Report: 2020



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Map showing some of the long-term sampling and sensor locations throughout Crater Lake.
Map courtesy of the National Park Service

ON THE COVER

Photograph of Crater Lake
Photograph courtesy of the National Park Service

Crater Lake Long-term Limnological Monitoring Program

State of the Lake Report: 2020

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Crater Lake National Park
Crater Lake, Oregon

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Executive Summary

The goal of the long-term limnological monitoring program (LTLMP) at Crater Lake is to ensure the health and preservation of this national treasure. The program serves as a monitoring and research platform to develop and communicate a better understanding of biological, physical, geochemical, and climatological processes that affect the lake. Protected areas like Crater Lake National Park play a key role in answering important questions in ecosystem and earth sciences. Crater Lake's isolation from direct human influence and its protected status within a National Park make it an ideal case-study for how a lake interacts with the surrounding environment and is affected by longer-term changes in climate.

This *State of the Lake Report* presents updated data related to the long-term health of the lake through 2020 and presents our current and evolving understanding of how the lake functions. It includes overall trend-analyses, which are updated on approximately five-year intervals (section 2.0 – Analysis of Long-term Trends). It also includes sections summarizing recent projects that focus on important, emerging issues, such as impacts of non-native crayfish and nearshore algae blooms (section 3.0 – Emerging Issues). This report is primarily intended to inform park management and the general public about Crater Lake. It is not an exhaustive review of all pertinent limnological literature but does present examples from other lakes and research studies where appropriate. For a more detailed scientific review, please see the 2007 Hydrobiologia Journal special issue on Crater Lake (http://link.springer.com/journal/10750/574/1/page/1).

As one of the clearest lakes in the world, Crater Lake is widely known for its extreme clarity and stunning deep-blue color. Concern that clarity might be declining was the impetus for initiating long-term studies in 1982. Analyses included in this report reaffirm that Crater Lake does not show a reduction in water clarity over time (section 4.0 – Optical Properties). Moreover, both Secchi disk depth and depth of light penetration indicate a slight increase in clarity over the last 40+ years. Long-term data also shows that clarity can be highly variable from year to year, driven by various factors. In particular, the presence or absence of deep-water mixing in winter and the corresponding upward flux of nutrients are dominant drivers of near-surface algal abundance and water clarity in summer (section 7.0 – Mixing Processes).

The LTLMP has recently focused additional monitoring and research efforts on nearshore areas of the lake due to both the spread of non-native crayfish along the shoreline and a nearshore algae bloom that occurred in fall 2016 (section 3.0 – Emerging Issues). Crayfish distribution has increased from approximately 50% of the shoreline in 2008 to nearly 95% in 2020, and crayfish are poised to dominate the entire shoreline within a few years. From an ecological standpoint, crayfish appear to cause a "greening" of the shoreline by allowing more attached algae to grow on the rocks, resulting in an increase of overall nearshore productivity. It is currently unclear if the greening of the shoreline is caused by a massive reduction in benthic insect grazers due to crayfish feeding or an influx of nutrient availability caused by crayfish excretion.

Also in the nearshore, an algae bloom (phytoplankton) in fall 2016 turned the nearshore waters around Cleetwood Cove a greenish-yellow, which was the first time this has been observed. The algae bloom consisted of motile algae known as Dinoflagellates, which appeared to concentrate in the nearshore following several days of calm wind conditions. The LTLMP is working to answer three fundamental questions about nearshore algal blooms in Crater Lake: 1) what is the frequency, duration, and size with which blooms form, 2) how does water temperature, wind speed, and time of year affect bloom formation, and 3) are the locations of blooms around the lake associated with locations of other organisms (i.e. crayfish) or specific areas of the lake (sunny versus shaded). It still remains to be seen whether the distribution of non-native crayfish, warmer surface water, lack of wind, or some other factor influences the frequency, duration, and magnitude of nearshore algal blooms.

Some of the most conspicuous long-term trends documented at Crater Lake involve changes in air temperature and summertime thermal structure of the lake (section 5.0 – Climate and section 6.0 – Thermal Properties). Increases in air temperature have increased surface water temperature during summer by 3.2°C (5.6°F) since 1965 and the onset of summer stratification (warm water floating on the surface) has trended earlier by approximately 33 days. Likewise, the average thickness of warm water floating on the surface in summer (thermocline depth) has shallowed by a staggering 46% since 1978. Hydrodynamic modeling of Crater Lake by cooperating researchers at Rensselaer Polytechnic Institute (RPI) in New York suggests that shallowing of thermocline depth is due to reduced wind speed in spring and summer but not warmer surface water. The cooperating researchers at (RPI) recently investigated the specific reasons behind the thermal structure changes in Crater Lake using a hydrodynamic modeling approach. Modeling was used because thermal structure can be simultaneously impacted by multiple climate (air temperature, humidity, precipitation, wind shear) and in-lake processes (vertical mixing, in-flow). Results of the modeling study were published in the journal *Limnology and Oceanography*. Trends in thermal properties are critical to recognize because they can affect various other lake processes and parameters.

Unlike thermal properties, which indicate significant trends through time, biological variables are more variable or exhibit cyclic change (section 8.0 – Biological Properties). For example, abundance of non-native fish has shown 9-10 year cycles, from very low, to relatively high density (up to 24 orders of magnitude). As a result, zooplankton exhibit similar cycles. The monitoring data show that predation from kokanee salmon controls *Daphnia* abundance, the lake's largest zooplankton. An important biological component of the nearshore area of the lake that has shown a signficant increase is non-native crayfish and subsequent decline in the endemic Mazama newt. Signal crayfish have expanded dramatically over the last decade and are having serious impacts on native taxa. Crayfish have spread to nearly 80% of the lake shoreline while newts have disappeared from most of these same areas. Crayfish, and their impact on newts, has been the focus of collaborative studies with the University of Nevada Reno and the U.S. Geological Survey (USGS). These studies have shown that newts in Crater Lake are genetically distinct from newts outside the caldera and consequently have been proposed as a distinct sub-species. Studies indicate multiple replacement mechanisms may be at work. Continued spread of crayfish will likely lead to further declines in newt abundance and distribution, and perhaps elimination.

As mentioned above, mixing of the lake in winter is an important process that affects nutrient availability,algal biomass, and water clarity the following summer. Deep-water mixing is also the critical process that replenishes oxygen at the lake bottom that is otherwise depleted by decomposing algae raining down from above. Long-term monitoring shows that some winters are already too warm for deep mixing to occur. Detailed modeling by the USGS Oregon Water Sciences Center predicts that the frequency of deep-water mixing over the next 100 years could be greatly reduced or eliminated depending on how quickly air temperature rises. Profound ecological changes to Crater Lake could occur if deep-water mixing ceases.

The LTLMP has long recognized that studying Crater Lake during fall, winter, and spring is crucial for understanding the health and functioning of the lake. As a result, the monitoring program has incorporated year-round sampling using high-frequency, autonomous sensors. In 2013, an innovative, state-of-the-art profiling instrument was added to the program (section 9.0 – Year-round Lake Monitoring). This instrument provides unprecedented detail both vertically within the water column (every 1 m), and over time scales (daily, year round) that are simply not feasible with traditional boat-based sampling. Similarly, dissolved oxygen sensors installed in 2018, and discussed above, provide a level of detail that can be used to better understand year-round algae production, which in Crater Lake, is typically low. Dissolved oxygen can act as a "canaray in a coal mine" for the overall health of a lake. By adding this type of monitoring to the LTLMP, especially at a large spatial scale, we have added another tool that allows us to provide managers the best information needed to preserve the resources of Crater Lake.

RV Neuston docked at Wizard Island, Crater Lake National Park.

Acknowledgments

The long-term monitoring program is a collective effort by many scientists, managers, summer technicians, and students. We are particularly indebted to Aquatic Ecologist Mark Buktenica and the late Dr. Gary L. Larson. Mark Buktenica retired after 35 years working on the long-term limnology program at Crater Lake. Dr. Larson retired in 2007 as the NPS and USGS Principle Investigator of the program after nearly 25 years. Gary's direction and leadership set the stage for the successful and creditable lake monitoring and research program that exists today. We would also like to acknowledge several researchers from the Oceanography program at Oregon State University who have been key partners in integrating monitoring technology and advancing our understanding of Crater Lake. In particular, Robert Collier, Jack Diamond, Chris Moser, Jim McManus, and Greg Crawford. The present monitoring program is funded by Crater Lake National Park.

Aquatic Ecologist Mark Buktenica.

1.0 Introduction

The overall mission of the U.S. National Park Service (NPS) has been "... to conserve the scenery and the natural and historic objects and the wild life therein and to provide for the enjoyment of the same in such manner and by such means as will leave them unimpaired for the enjoyment of future generations" (National Park Service Organic Act 1916). Park managers are therefore tasked with making decisions to preserve the natural resources within parks. One tool that managers can use to aid these decisions, is up-to-date scientific information from long-term monitoring programs that are designed to understand ecological processes and how they respond to natural and anthropogenic influences.

1.1 Long-term Lake Monitoring Program

Limnological studies of Crater Lake occurred as early as 1886. Studies conducted from 1978 to 1981 suggested that water quality might have deteriorated compared to observations made years earlier. A review of existing lake data by the NPS and a panel of limnologists in 1982 concluded that the existing data was insufficient to determine if the lake had actually changed and recommended monitoring to document the basic characteristics of the lake. In the fall of 1982, Congress passed Public Law 97-250 that directed the Secretary of the Interior to conduct a 10-year study on Crater Lake to examine the lake for possible deterioration of water quality.

The long-term limnological monitoring program (LTLMP) at Crater Lake began in 1983 and included four major goals:

1. Develop a reliable database for the lake to be used for comparisons of future conditions.
2. Develop a better understanding of physical, chemical, and biological processes occurring in the lake.
3. Investigate the possibility of short- and long-term changes in the lake.
4. And if changes are found, and human-caused (e.g., pollution), recommend mitigation techniques.

The results from the mandated 10-year program concluded that the lake had not declined in water quality or clarity, within the limits of the methods used and the period of time studied. Additional funding has permitted the LTLMP to continue and expand the scope of monitoring efforts. To date, the LTLMP has spanned 37 years (1983-2020) and has amassed more than 25 datasets that help us understand and preserve the unique system of Crater Lake. The following annual report contains a summary of LTLMP monitoring efforts through 2020 and provides an update on the state of our knowledge and understanding of the Crater Lake ecosystem. This report is primarily intended to inform non-scientists about variables affecting the health of Crater Lake. Possible reasons for some trends are presented using statistical inferences between datasets and comparisons to other lake studies. More detailed analysis and discussion within the context of lakes worldwide is reserved for articles submitted to scientific journals that benefit from editorial peer review.

The first research expedition was conducted from the research vessel "Cleetwood" in 1886 (NPS photo).

1.2 Crater Lake Overview

Crater Lake is located at the crest of the Cascade Mountains in southern Oregon. The lake partially fills a caldera that formed roughly 7,700 years ago following the eruption of Mt. Mazama (Figure 1). Widely known for its extremely clear water and blue color, Crater Lake is the deepest lake in the United States and 8th deepest in the world. Unlike other Cascade Mountain lakes, Crater Lake rarely freezes over in the winter due to the heat content of the enormous water volume.

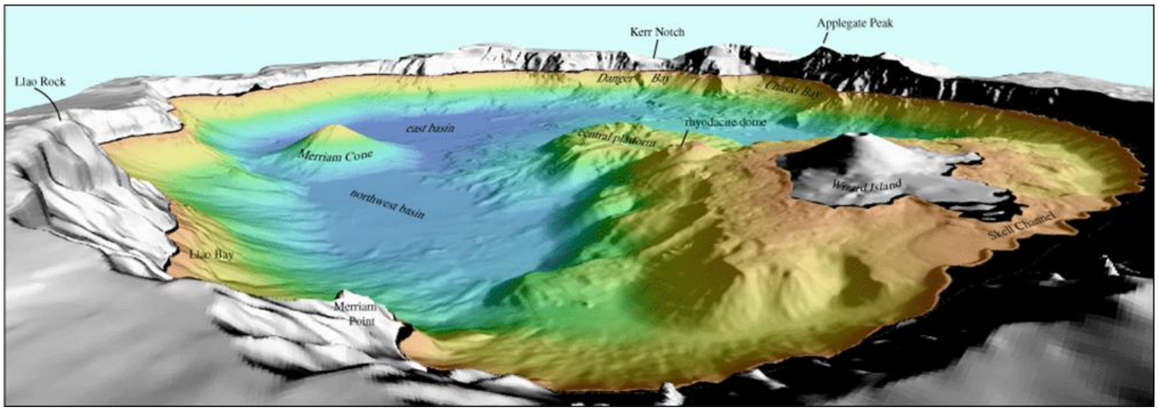


Figure 1. USGS shaded relief perspective image of Crater Lake looking southwest

Limnologically, Crater Lake is a large dimictic lake which means periods of vertical mixing in fall and spring, thermal stratification in summer and reverse stratification in winter. The lake is extremely unproductive (i.e., ultra-oligotrophic) with peak chlorophyll concentration less than 2 µg/l. The remarkable water clarity allows for a summertime chlorophyll maximum typically between 100-120 m (330-395 ft), which is astonishingly deep for a lake.

Biologically, Crater Lake is home to 160 taxa of phytoplankton, 12 taxa of zooplankton, and larger organisms including kokanee salmon, rainbow trout, signal crayfish, and Mazama newts. The latter is endemic to Crater Lake, whereas the others were introduced to the lake between 1888 and 1941. Although few aquatic macrophytes occur near the surface, a deep-water moss community exists between 26-140 m (85-460 ft) that hangs like ice-cycles on the near vertical walls of the caldera and forms thick fields on gentler slopes around Wizard Island.

Table 1. Characteristics of Crater Lake

Characteristic	Measurement (Metric)	Measurement (Imperial)
Basin	Closed (no outlet)	
Elevation	1882 m	6173 ft
Depth (Maximum)	592 m	1943 ft
Depth (Average)	350 m	1148 ft
Surface area	53.4 km^2	21 mi^2
Shoreline	31 km	21 mi
Volume	19 trillion liters	5 trillion gallons
Precipitation (Average)	165 cm	65 in
Snowfall (Average)	1295 cm	510 in
Secchi depth (Average)	31 m	102 ft
Summer surface temperature (Average)	14 °C	57 °F
Winter surface temperature (Average)	3.5 °C	38 °F

1.3 Sampling Variables

Data monitored as part of the LTLMP can be grouped into four main types (Table 2): biological, chemical, climatological, and physical. The frequency that individual parameters are measured vary from once per year to continuous. For example, acoustic surveys for population estimates of fish occur once in summer, whereas lake temperature is measured continuously using autonomous sensors. Monthly trend data are collected once per month throughout the sampling season, which is normally June through September, with occasional sampling occurring in May depending on the weather. Sampling efforts summarized in the table below allow us to understand the processes that influence Crater Lake. Some sampling has evolved overtime as technologies changed and below is only a snapshot of the datasets that make up the LTLMP.

Collecting a water sample for dissolved oxygen analysis (NPS photo).

Table 2. Summary of lake monitoring activities at Crater Lake.

Types	Parameter	Measurement	Frequency
Biological	Phytoplankton	Abundance	Monthly – trend, Continuously
		Composition	Yearly
		Growth	Monthly – trend
	Zooplankton	Abundance, Composition	Monthly – trend
	Fish	Abundance, Population density, Condition	Yearly
	Crayfish-Newts	Abundance, Distribution	Yearly
Chemical	Water chemistry	Alkalinity, Conductivity, Dissolved oxygen, Nutrients, pH, Trace elements	Monthly – trend
	Spring chemistry	Alkalinity, Conductivity, Dissolved oxygen, Nutrients, pH, Trace elements	Monthly – trend
Climatological	Weather	Air temperature, Precipitation, Relative humidity, Snow depth, Snowfall, Wind speed and direction	Daily, Continuously
Physical	Water clarity	Secchi depth, light penetration	Monthly – trend
	Water temperature	Temperature	Continuously
	Lake level	Elevation	Daily

2.0 Analysis of Long-term Trends

One of the primary goals of the monitoring program is to identify whether long-term change is occurring in Crater Lake. When measuring natural systems, it often takes many seasons of measurements to distinguish between the range of natural variability and actual long-term change. Most of the Crater Lake datasets are of sufficient duration that long-term trends can be evaluated over the sampling period. This section summarizes the assessment of trends for individual variables using statistical trend analyses (Table 3). We utilize common statistical techniques to detect trends because most parameters we measure have strong variability on a daily, monthly, and/or seasonal basis that mask underlying trends that are not evident by just looking at a scatterplot of data. Seasonal Kendall Test for Trends and Mann-Kendall techniques were chosen because they provide adjustments for serial correlations (daily, seasonal, annual), have less stringent technical requirements for the techniques themselves (normality and equal variance not required), are insensitive to outliers, and are common and accepted techniques for analyzing water quality parameters.

The table below summarizes results of trend analyses for the parameters included in this report. More detailed discussion of the specific variables can be found within this report. Several climatological variables indicate changes, including a trend toward warmer summer air temperature over the period of the monitoring program (since 1983) (5.2) and a reduction in snowpack (5.3). Consistent with the increase in summer air temperature, summer surface water temperature (6.1), onset of stratification (6.3), and thermocline depth (6.5) all show significant trends. Two optical properties, Secchi disk clarity (4.1) and depth of light penetration (4.3), indicate clearer water conditions through time. The only biological variable in the LTLMP indicating uni-directional long-term change is deep-water phytoplankton density represented as particle density (8.1). Other biological characteristics vary widely annually or cyclically (e.g. fish and zooplankton) or were not part of long-term trend analyses per se (e.g. movement of crayfish and the corresponding decline of the endemic Mazama Newt).

Table 3. Summary of lake monitoring activities

Variable	Measurement	Years	Season	P-value	Trend	Slope
Climate	Night air temperature	1983-2014	Winter	0.76	None	N/A
	Night air temperature	1983-2014	Spring	0.47	None	N/A
	Night air temperature	1983-2014	Summer	0.003	Warmer	0.049
	Night air temperature	1983-2014	Fall	0.33	None	N/A
	April snowpack	1935-2014	Annual	0.046	Lower	-0.143
Optical	Secchi disk depth	1978-2014	Summer	0.028	Deeper	0.082
	Particle density 0-30 m	1988-2014	Summer	0.11	None	N/A
	Depth of 1% light penetration	1980-2014	Summer	0.053	Deeper	0.48
Thermal	Onset of stratification	1966-2014	annual	0.01	Earlier	-0.5
	Thermocline depth	1978-2014	Summer	<0.001	Shallower	-0.241
	Surface water temperature	1965-2014	Summer	0.05	Warmer	0.054
	20 m water temperature	1983-2014	Summer	<0.001	Cooler	-0.050
	100 m water temperature	1983-2014	Summer	0.14	None	N/A
	300 m water temperature	1988-2014	Summer	0.07	None	N/A
	500 m water temperature	1988-2014	Summer	0.003	Cooler	-0.002
Biological	Chlorophyll 0-30 m	1991-2014	Summer	0.28	None	N/A
	Chlorophyll 40-180 m	1991-2014	Summer	0.12	None	N/A
	Primary productivity 0-30 m	1987-2014	Summer	0.22	None	N/A
	Primary productivity 40-180 m	1987-2014	Summer	0.13	None	N/A
	Particle density 0-30 m	1988-2014	Summer	0.11	none	N/A
	Particle density 31-200 m	1988-2014	Summer	0.004	larger	<0.001

3.0 Emerging Issues: Impacts of Spreading Crayfish

Although crayfish were introduced into Crater Lake in 1915, they have only spread to a significant portion of the shoreline relatively recently, over the last several decades. Warmer winter water temperature and longer summers appear to allow more crayfish to survive from year to year and spread faster along the shoreline. Currently, non-native crayfish are poised to take over the entire shoreline within a few years. Previous studies in collaboration with the University of Nevada Reno and the USGS focused on movements and food habits of crayfish, along with the impact of crayfish on native Mazama Newts. Several emerging issues regarding the spread of crayfish have the potential to impact the long-term ecology of Crater Lake. In particular, the shoreline of Crater Lake appears to be greening as crayfish spread along the shoreline due to excessive algae growth.

Belly coloration of a Mazama newt from Crater Lake (NPS photo).

3.1 Crayfish Movement and Warming Climate

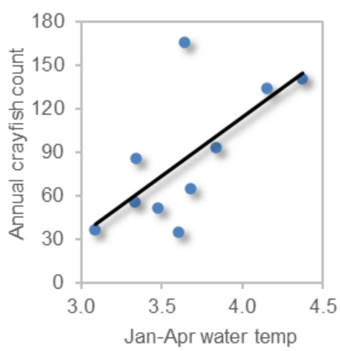


Figure 2. Relationship between annual crayfish density and previous winters water temperature

Crayfish were introduced to Crater Lake in 1915 as food for nonnative trout and salmon. The first systematic lake-wide distribution survey in 2008 indicated that crayfish occupied 50% of the shoreline at the time (Figure 3). Mazama newts (*Taricha granulosa mazamae*), which are endemic to Crater Lake and a proposed subspecies of the more widely distributed rough-skinned newt (*T. granulosa*), remained in areas that crayfish had yet to invade but were virtually absent from areas occupied by crayfish (25% of the shoreline).

Annual surveys by park scientists suggest that long-term changes in weather affect both abundance and movement of crayfish. Average winter temperatures at Crater Lake have increased 1.6 °C since 1965, and the length of summer (defined as warm water floating on the lake surface) is ≈ 33 days longer. Warmer water temperature in winter allows more crayfish to survive (Figure 2), and longer summers give crayfish more time to spread spatially around the lake when surface water is warm. These results suggest that warming climate at northern latitudes and higher elevations may allow signal crayfish to invade and survive in lake systems that were previously too cold.

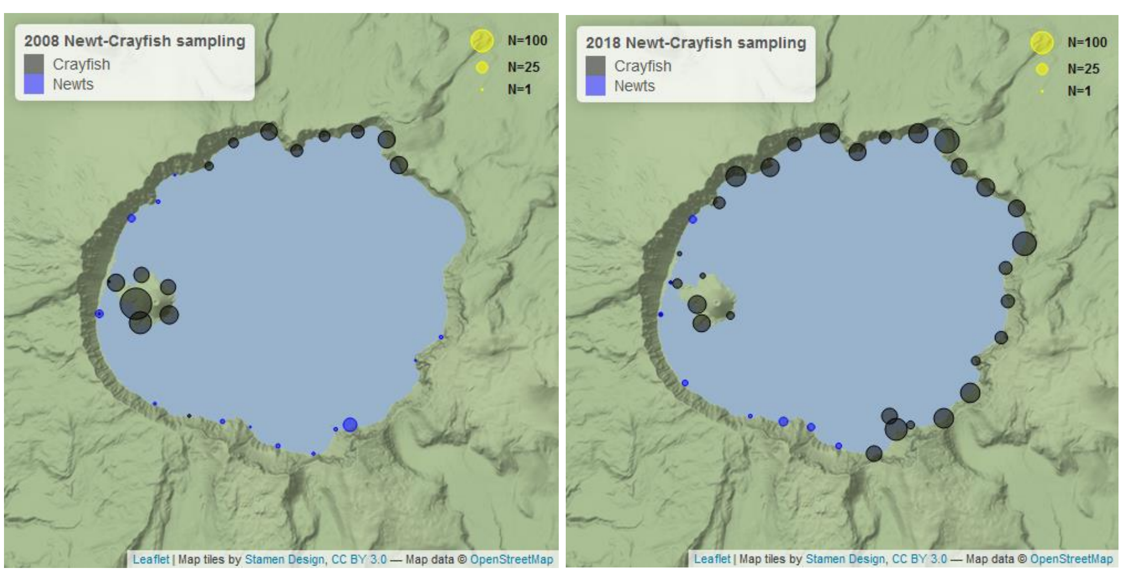


Figure 3. Spatial distribution and abundance of crayfish and Mazama newts at 40 locations around Crater Lake in 2008 and 2018. Circle size is relative to abundance

3.2 Crayfish and the "Greening" of the Crater Lake Shoreline

As non-native crayfish spread around Crater Lake, they appear to result in a "greening" of the shoreline because more attached algae (called periphyton) grow on rocks in areas with crayfish present. Samples collected at eight shoreline locations during summer 2020 showed that attached algal biomass (chlorophyll concentration) was 15 times higher at crayfish present locations compared to locations without crayfish (Figure 5). The difference in attached algae between crayfish present and crayfish absent locations was visually obvious. Likewise, park scientists measured growth of attached algae at the eight shoreline locations by placing rocks in acrylic chambers along with recording oxygen sensors. Productivity of the attached algae (i.e oxygen production via photosynthesis) was twice as high on average at locations with a crayfish presence.

It is unclear exactly why the shoreline appears to be greening. We hypothesize that algal biomass is higher where crayfish reside because crayfish have consumed most of the benthic insects that once grazed on the attached algae, especially snails and caddisflies (see Section 3.3). Alternatively, crayfish could alter the cycling of nutrients in the nearshore, which subsequently affects the abundance and/or community structure of the attached algae. Further studies designed to control for crayfish presence, insect abundance, and/or nutrients would be needed in order to determine the specific mechanisms leading to higher algal concentrations and whether this trend is likely to continue. The LTLMP is working with scientists at the University of Nevada Reno and the USGS Oregon Water Sciences Center in Portland to explore reasons behind the elevated algal biomass. Is Crater Lake destined to have a greener shoreline? It is still unclear what long-term effects crayfish may have.

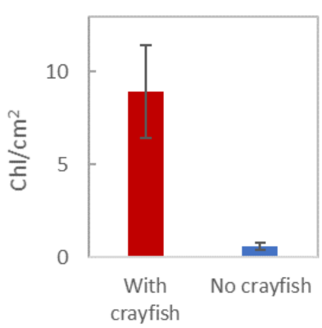
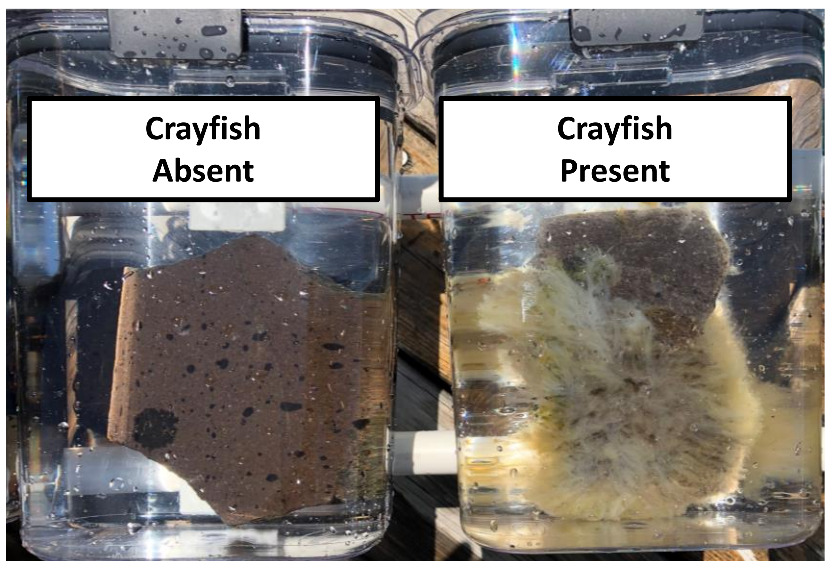


Figure 4. Mean chlorophyll concentration on rocks at crayfish (N=4) and non-crayfish (N=4) locations during summer 2020



Rocks from the shoreline were placed in acrylic chambers and incubated in the lake to measure oxygen production of the attached algae. The rock from the crayfish present location covered in green filamentous algae is the most extreme example of attached algae observed in 2020.

3.3 Impact of Crayfish on Benthic Insects

Aquatic insects living along the bottom are a natural component of lake ecosystems, where they form an integral part of lake food webs and species diversity. The most common benthic insect taxa in Crater Lake include snails, caddisflies, midges, worms, scuds, leeches, beetles, and mayflies. Some of these insects are also the primary food of Mazama newts.

Signal crayfish are opportunistic predators, eating just about anything they can capture. As the non-native crayfish spread around the shoreline of Crater Lake, aquatic insects living along the rocky bottom drastically decline. On average, the biomass of insects in Crater Lake are reduced by 95% once crayfish become established in an area (Figure 6). Snails and caddisflies are especially hard hit by crayfish as they virtually disappear. Studies in other lakes have identified similar changes in benthic insects following crayfish invasion, especially taxa like snails and caddisflies that are unable to avoid being caught and eaten by crayfish. The loss of snails, caddisflies, and scuds in Crater Lake are especially significant as they are the primary grazers of attached algae growing on the rocky bottom. Consequently, the spread of crayfish appears to result in a "greening" of the Crater Lake shoreline, by allowing more attached algae to grow. See Section 3.3 for details.

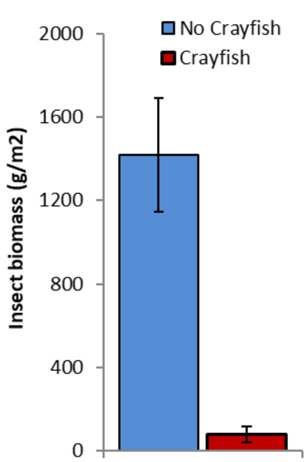


Figure 5. Average benthic insect biomass at locations without crayfish (N=39) and with crayfish (N=63)

Park scientists collect benthic insects from the rocky shoreline using a battery powered vacuum. The samples are preserved, and insects are identified and counted later in the park water laboratory.

3.4 Impact of Crayfish on Attached Algae Growth

As crayfish invade the shoreline of Crater Lake, the loss of snails, caddisflies, and scuds are especially significant as they are the primary grazers of attached algae growing on rocks. Logically, one might expect more algae to grow on rocks in crayfish areas, unless crayfish also eat the algae. High-frequency dissolved oxygen sensors were installed at several shoreline areas in 2018 to monitor algal productivity following a 2016 phytoplankton bloom (floating algae) near Cleetwood Cove (see section 3.6). Evidence from high-frequency dissolved oxygen sensors suggest that crayfish might increase nearshore attached algae productivity. During summer and fall, sites with heavy crayfish presence almost always had higher net ecosystem productivity (NEP) compared to non-crayfish locations (Figure 7).

Although nearshore oxygen sensors were installed to measure the productivity of floating algae (phytoplankton), it has become evident that the nearshore sensors primarily record the growth of algae growing on the rocky shoreline

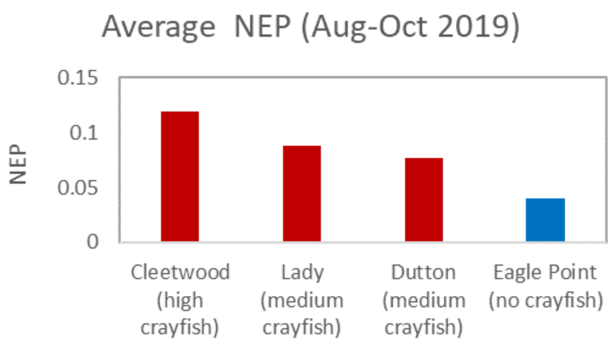


Figure 6. Average net ecosystem productivity of nearshore water at four locations in August – October of 2019

To quantify the impact of crayfish on algal productivity, scientists collected rocks from crayfish and non-crayfish areas in summer 2020 and placed them in acrylic chambers. The chamber experiments carefully measured algae growth on the rocks themselves and verified the results of nearshore monitoring. Rocks collected in crayfish areas had higher productivity than non-crayfish areas supporting the idea that the loss of insect grazers allow more algae to grow when crayfish are present.

Productivity of attached algae was measured over several days by placing a rock in an acrylic chamber and measuring dissolved oxygen changes with an optical sensor. Inset shows a closeup of the rock and oxygen sensor.

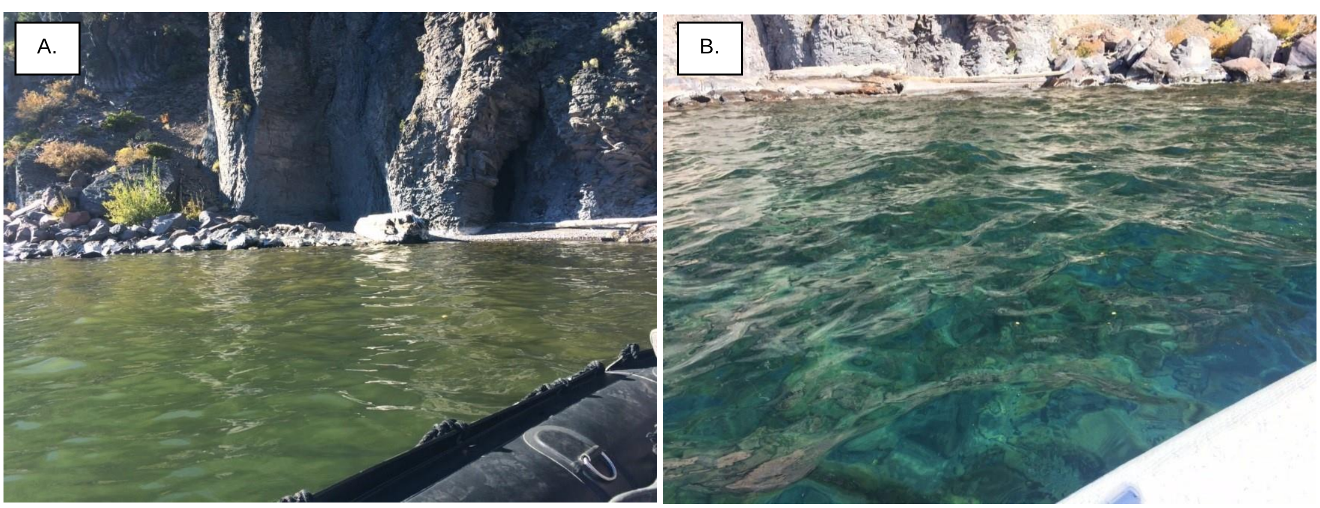
3.5 Phytoplankton Algae Bloom

In late September 2016, a bloom of phytoplankton algae turned the clear blue water of Crater Lake into a yellowish-green along the north shoreline. This was the first time that such a bloom of floating algae had been seen in Crater Lake. There is increasing occurrence and awareness of Harmful Algal Blooms (HABs) in lakes around the country, including similar Lake Tahoe and local lakes such as Klamath, Diamond, and Lost Creek. A water sample showed that the cloudiness was due to high numbers of a type of algae called dinoflagellates, which are notorious for forming blooms. Dinoflagellates are mobile algae that can concentrate in areas and are known to migrate toward nutrients or other food sources.

Long-term monitoring shows that dinoflagellates commonly occur in Crater Lake, where they tend to dominate in surface waters later in summer and in years when the water is warmer. In the open waters of Crater Lake, these algae are known to migrate toward the surface when the weather is calm but are dispersed when wind mixes the water. When this bloom occurred, the winds had been calm for several days. After the bloom was first observed on Sept 28, 2016, winds increased overnight and the bloom had been greatly dispersed by the next morning (see pictures below).

Because the bloom occurred along the north shore in an area of high crayfish density, there is concern that the dinoflagellates were attracted to this area due to nutrient changes associated with crayfish presence. It also could be associated with warmer water temperatures, a naturally occurring short-lived event, or it may be an indicator or some other unknown factor.

The LTLMP is working to answer three fundamental questions about nearshore algal blooms in Crater Lake: 1) what is the frequency, duration, and size with which blooms form, 2) how does water temperature, wind speed, and time of year affect bloom formation, and 3) are the locations of blooms around the lake associated with locations of other organisms (i.e. crayfish) or specific areas of the lake (sunny versus shaded).



An algal bloom (A) was observed along the shoreline in Cleetwood Cove on September 28, 2016. Conditions had improved by the next day (B; September 29, 2016) as winds picked up and dispersed the algae, increasing the clarity of the water.

3.6 Technology to Monitor Algae

Monitoring for nearshore algal blooms begins with measuring when they occur and under what conditions. Because algae blooms can be short-lived and easily influenced by changes in wind (like the 2016 event) monitoring for blooms requires high-frequency measurements; i.e. multiple times per day and night. In 2018, the monitoring program installed several high-frequency dissolved oxygen sensors capable of tracking small scale changes over long periods of time. These sensors take and record measurements every 10 minutes using regular lithium batteries that last for more than 1 year. The sensors were attached to moorings installed in nearshore areas of the lake at Cleetwood Cove, Lady of the Lake, Dutton Cliff, Eagle Point, and Devils Backbone.

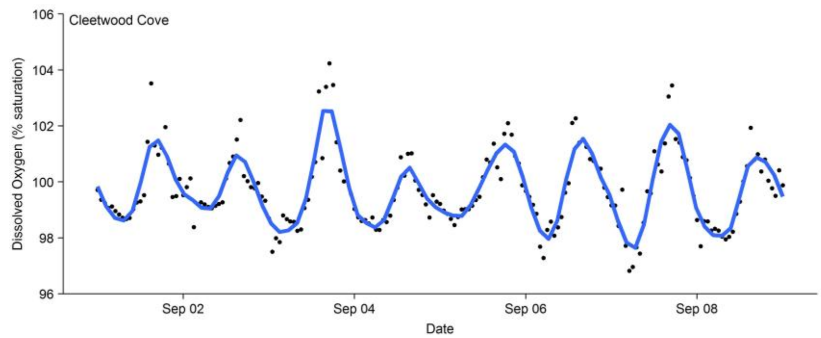
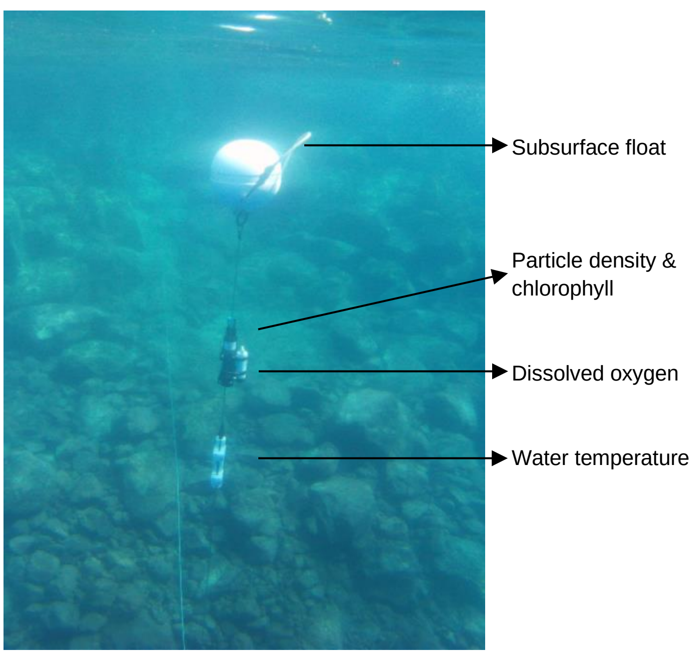
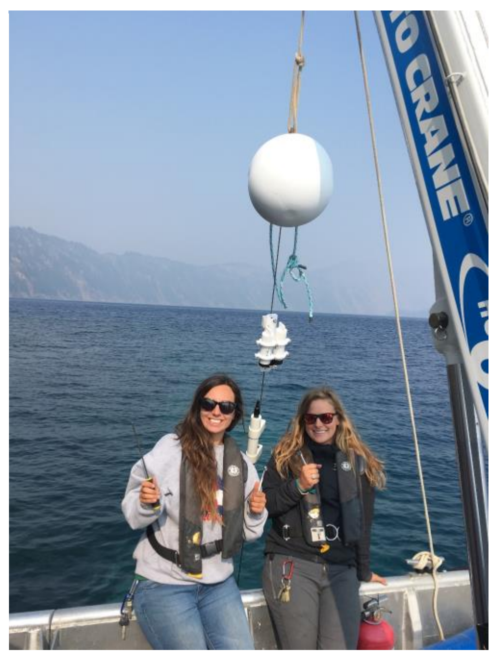


Figure 7. Hourly dissolved oxygen concentration measured at Cleetwood Cove, September 1-8, 2018. Blue line represents fit of locally weighted regression (bandwidth=0.2)

Data from the sensors are analyzed using a technique, known as the diel-oxygen method. This technique uses daily fluctuations of oxygen to calculate gross primary production of algae during the day (oxygen increase), respiration at night (oxygen decrease), and the difference between the two, which is known as net ecosystem production. Figure at right shows one week of oxygen readings at Cleetwood Cove in September. Daily fluctuations are evident and one would expect these fluctuations to greatly increase during an algae bloom, depending on the size of the bloom. Since installed, it has become apparent that the nearshore sensors also capture growth of algae attached to rocks along the shoreline. See section 3.5 for details.





Underwater mooring with high frequency sensors attached. Servicing the instruments necessitates the crane on the research vessel.

3.7 Nearshore clarity: Monitoring Spatial Distribution of Algae

We investigated the spatial distribution of algae along the entire nearshore area of the lake in response to an algal bloom that occurred in fall 2016. Our existing CTD instrument package, which normally samples vertically in the water column, was modified so that it could be towed alongside the research vessel. The instruments continuously measured water clarity, algal fluorescence, and water temperature. We collected data in August 2017 and July 2018.

Sampling of water temperature and chlorophyll fluorescence in the nearshore of the lake on July 26, 2018 showed more spatial variability than expected (Figure 9). Water temperature ranged over 5°C (16.3-21.8°C) around the shoreline and chlorophyll fluorescence ranged from 0.224 to 0.537 µg/L. Spatially, fluorescence was higher on the north and west side of the lake and had pockets of elevated levels in cove-like areas along the shoreline.

Equipment and setup of CTD sensors for a near shore tow along the shoreline of Crater Lake.

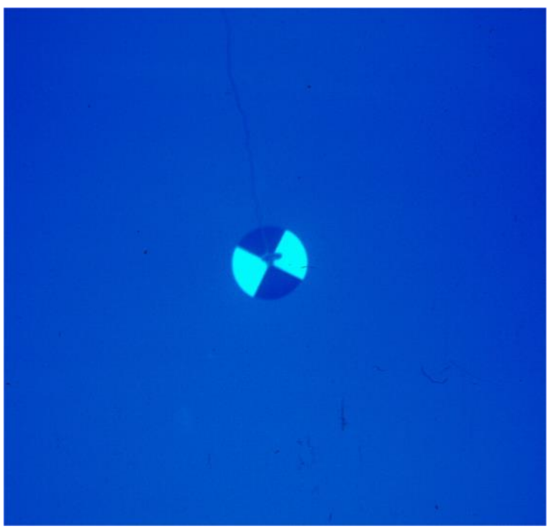
Figure 8. Temperature (A) and fluorescence (B) data collected from nearshore areas of Crater Lake on July 26, 2018

4.0 Optical Properties

4.1 Water Clarity: Secchi Depth (since 1978)

The Secchi disk has been used to measure water clarity in lakes and oceans around the world since the 1860's. Father Pietro Angelo Secchi, an advisor to the Pope, is credited with developing and testing the disk in 1864 as a way to measure the transparency of the Mediterranean Sea. The depth at which the simple round disk disappears is known as the Secchi disk depth. At Crater Lake, the Secchi disk depth is calculated as the average of three descending depths where the observer loses site of the disk as it is lowered into the water and three ascending depths, where the observer regains site of the disk as it is raised. To standardize the process, measurements are only taken between the hours of 10:00 am and 2:00 pm, and only when the lake surface is calm. Crater Lake is known to be one of the clearest lakes in the world with average summer Secchi disk readings of 30 m and a maximum individual reading of 41.5 m.

The first clarity measurement in Crater Lake was conducted by USGS researcher Joseph Diller in 1896 using a white dinner plate lowered into the lake. Consistent summer measurements have been collected since 1978, prior to the start of the long-term monitoring program. Although there can be high year-to-year variability, Secchi clarity has not declined through time. If anything, readings have become slightly deeper in depth over the study period (Figure 10; $p < 0.001$).



Secchi disk within Crater Lake (NPS photo).

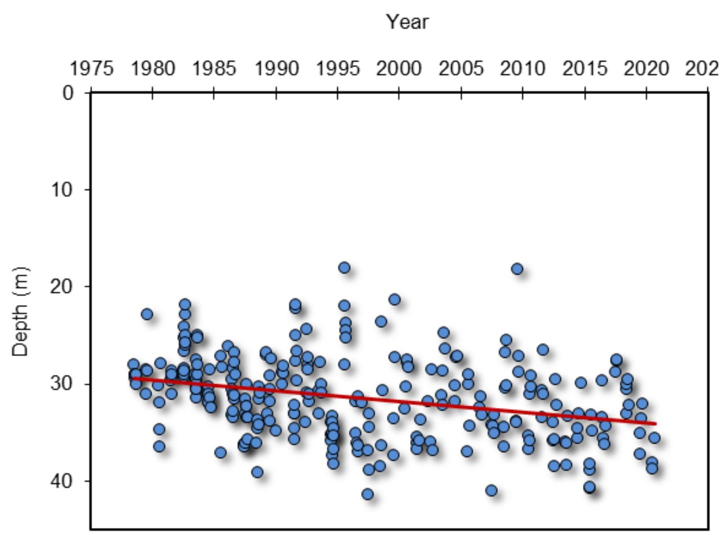


Figure 9. Long-term record of Secchi disk depth in Crater Lake (1978-2020)

4.2 Water Clarity: Particle Density (since 1988)

The beam transmissometer is one of our best tools for measuring water clarity and has been used at Crater Lake since 1988. The instrument provides continuous estimates of particle density as it is lowered through the water column. The advantage of the transmissometer over the Secchi disk is that it can be deployed at any time of the day or night and in any weather conditions. Accurate Secchi measurements must occur mid-day when the lake surface is flat and calm, resulting in fewer occasions when the Secchi disk can be used.

Particles in the water reduce water clarity, whether they are biotic particles (e.g. phytoplankton, zooplankton, pine pollen) or abiotic particles (e.g. dust and minerals from landslides). Although most of the phytoplankton in the lake are below 30 m, it is the density of phytoplankton near the surface that impacts Secchi clarity in Crater Lake. Average particle density in the top 30 m of the lake is highly correlated with Secchi disk depth measured on the same day (Figure 11) and can be used as a surrogate for Secchi disk water clarity. Neither Secchi disk, nor "apparent Secchi," which is calculated from particle density, indicate a decline in water clarity, near the surface, through time (Figure 9, 12).

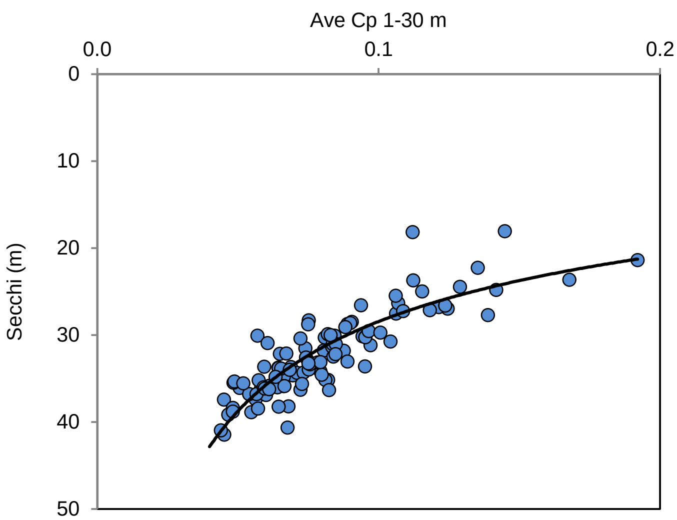


Figure 10. Relationship between average particle density (Cp) and Secchi depth in Crater Lake

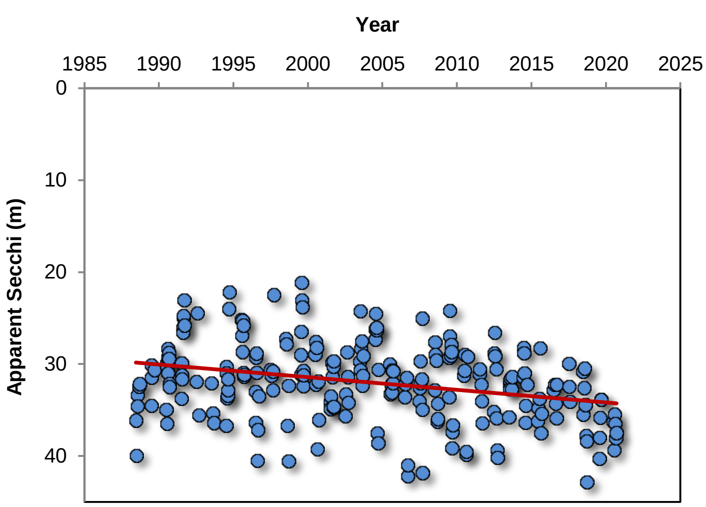


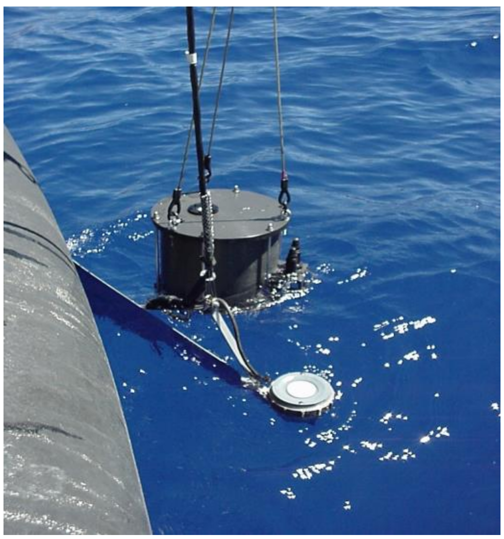
Figure 11. Long-term record of apparent Secchi depth calculated from Cp in Crater Lake (1988-2020)

CTD package that measures physical and biological parameters throughout the Crater Lake water column. Tall black sensors on left and right are transmissometers (NPS photo).

4.3 Water Clarity: Light Penetration (since 1980)

The ability of light to penetrate through water is an important optical property of lakes as it fundamentally affects the vertical distribution of phytoplankton, zooplankton, and fish, the absorption of heat, and the color of the water perceived by your eyes. Light penetrates deeper in clear lakes that have fewer particles like phytoplankton, pollen, or dirt. Crater Lake is well known for its remarkable clarity and extremely deep light penetration.

The penetration of light throughout the upper water column of Crater Lake has been measured since the early 1980's. Several instruments have been used over the past three decades as technology has advanced, including a Kahl photometer (1980-1989), Licor scanning radiometer (1995-2009), and Biospherical 8-channel reflectance radiometer (2010-present). The blue wavelength of light (~475 nm) often penetrates the deepest in Crater Lake, part of the reason why the lake appears blue. The depth where 1% of the surface blue-light intensity remains is typically around 100 m in depth in Crater Lake (Figure 13). This is an astonishingly deep depth compared to almost all other lakes. The long-term trend indicates a slight increase in light penetration (*P*=0.05).



Two of the sensors used to measure light penetration in Crater Lake, Kahl photometer in the foreground and the Licor spectra-radiometer behind (NPS photo).

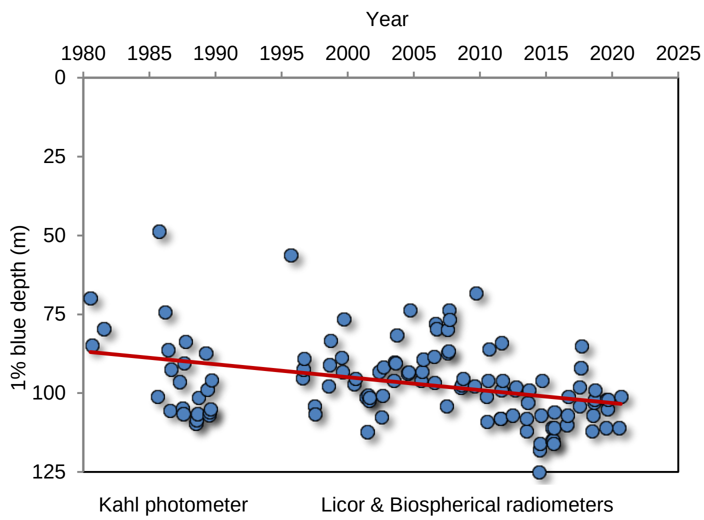


Figure 12. Long-term record of the depth to which 1% of blue light reaches in Crater Lake (1980-2020)

5.0 Climate

5.1 Present and Future Air Temperature

Meteorological-driven processes exert large and diverse impacts on lakes. Climate is the driving force for a lakes internal heating, cooling, mixing and circulation, which in turn affect nutrient cycling, food-web characteristics, and other important features of limnology. Trends in climate are thus potential drivers of trends in various limnological variables. In Crater Lake, air temperature appears to strongly influence the timing of summer stratification, thermocline depth, surface water temperature, near-surface phytoplankton taxa, winter mixing, and vertical nutrient flux.

Figure 14 shows maximum and minimum air temperature that has already occurred at Crater Lake combined with the best available estimates of possible future climate conditions. Although there is much year-to-year variability in the historic data, both maximum and minimum air temperature at Crater Lake showed a period of general decline from the 1930's to the 1970's. Over the last 30 years, minimum temperature tended to increase whereas maximum was more variable.

The predicted temperatures shown below use one of the more moderate climate change scenarios [Representative Concentration Pathway (RCP) 4.5] to estimate conditions at Crater Lake over the next 90 years. Both minimum and maximum daily air temperature are predicted to rise 2-3 °C (4-6 °F) over today's values. Based on these data, average air temperature within the next few decades will become warmer at Crater Lake than any time in the past 86 years.

(RCP data courtesy of Susan Wherry, USGS. These data have been smoothed by using a two-year running average to remove seasonal variation).

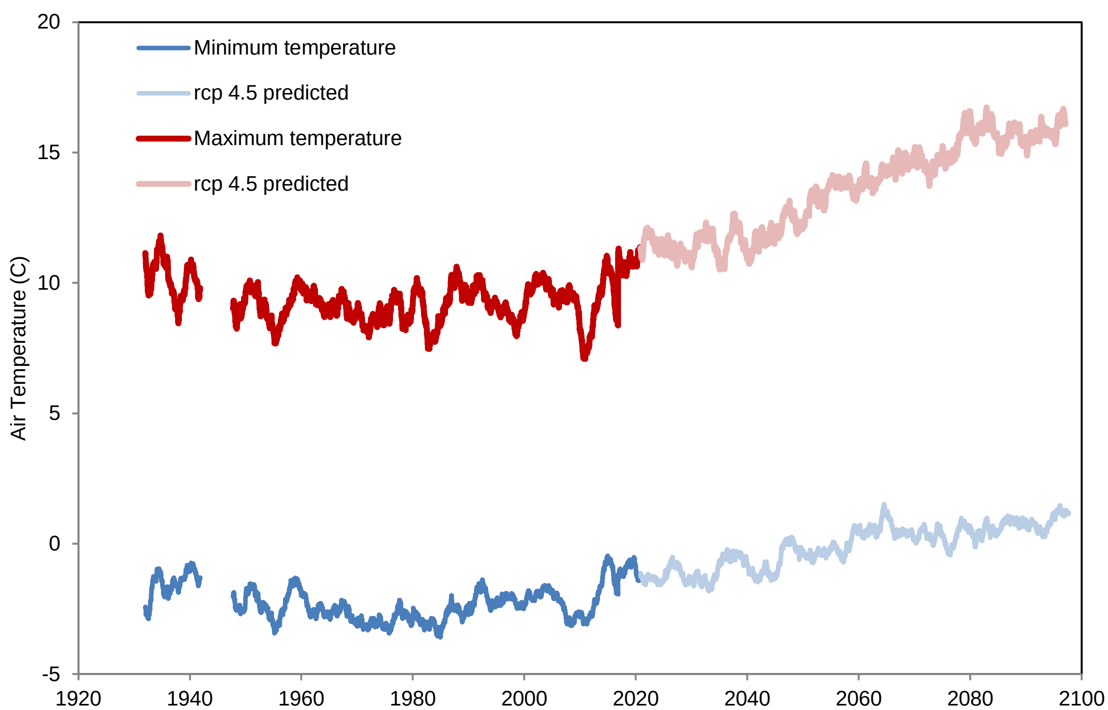


Figure 13. Observed and predicted maximum and minimum air temperatures at Crater Lake National Park headquarters.

5.2 Air Temperature by Season (since 1931)

Long-term changes in air temperature at Crater Lake differ by season (Figure 15A-D). Summer air temperatures play an important role as they influence the thermal structure of the lake during stratification. Summer (Jul-Sep) air temperature at Crater Lake shows a period of general decline from the 1930's through the mid 1970's, followed by a period of increasing temperature to present (Figure 15A). This shift is in close agreement with other studies across western North America.

The increase in average summer temperature since the beginning of the lake monitoring program in 1983 was 1.75 °C (3.1 °F). Although the increasing trend since the 1980's was significant, these air temperatures were still within the range of previous variability recorded at Crater Lake during the first half of the twentieth century. Average daily air temperature during 2020 was extremely warm, the 3rd highest on record (88 years). The high daily air temperature in summer 2020 were driven by especially warm nighttime temperatures. For example, daily minimum temperature was the #1 warmest in 88 years, whereas daily maximum in summer 2020 was the 23rd warmest. Long-term trends in fall temperature shows a slight decline since 1931 (Figure 15B), whereas winter shows a period of slight warming since the 1950's (Figure 15C). Spring tends to be quite variable over the period of record (Figure 15D) with slight cooling early in the century.

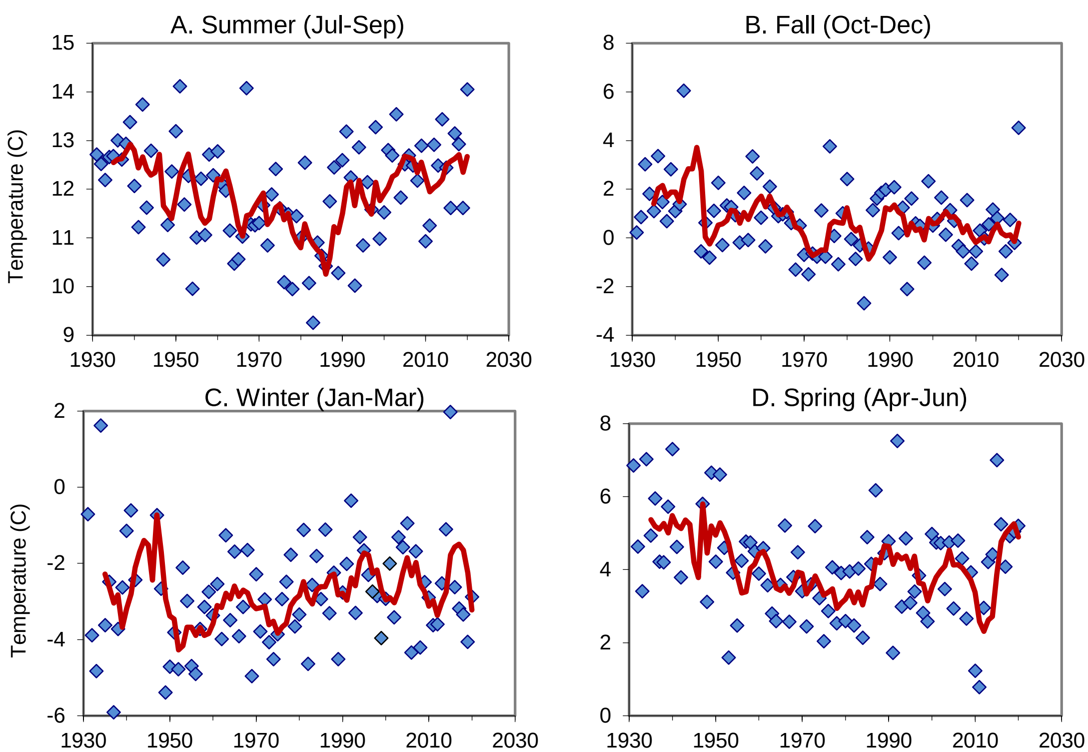


Figure 14. Long-term seasonal air temperature at Crater Lake National Park headquarters (1931-2020). Red line represents five year running average

5.3 Snowpack (since 1935)

Many aspects of weather are highly variable from year-to-year, including snowfall and the resulting snowpack. Water content within the snowpack is a commonly measured value that is used by water managers to forecast streamflow later in the season. The long-term trend in snowpack at Park headquarters at the beginning of April indicates a statistically significant decline ($p<0.05$) at an average rate of 1.6 inches (water equivalent) per decade (Figure 16). In terms of actual snow depth, this decline is about 3 inches per decade. Below average water content has been more common in recent decades, with 20 of the last 31 years less than average. This is similar to many mountain areas of the pacific-northwest. During 2020, the depth of the snowpack was below average most of the calendar year (Figure 17).

Automated weather station encrusted in snow along the rim of the caldera at Crater Lake National Park.

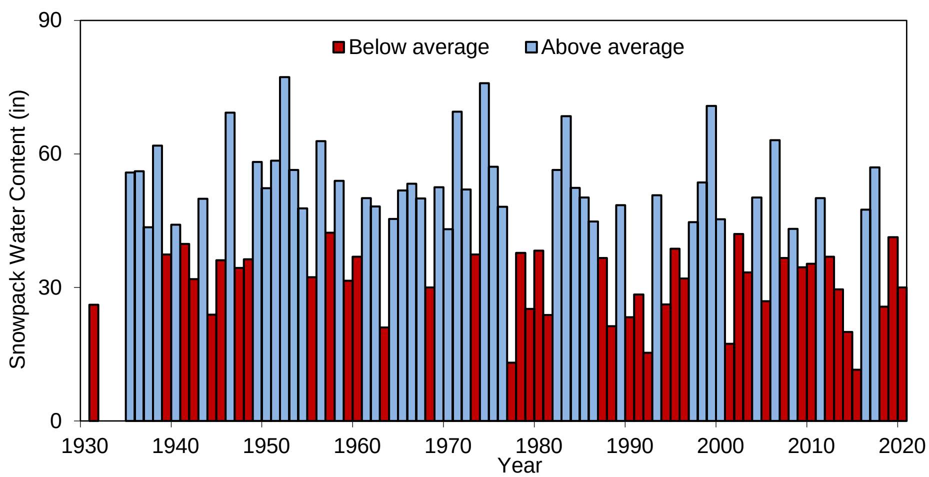


Figure 15. Snowpack water content at the beginning of April at Crater Lake National Park headquarters (1931-2020)

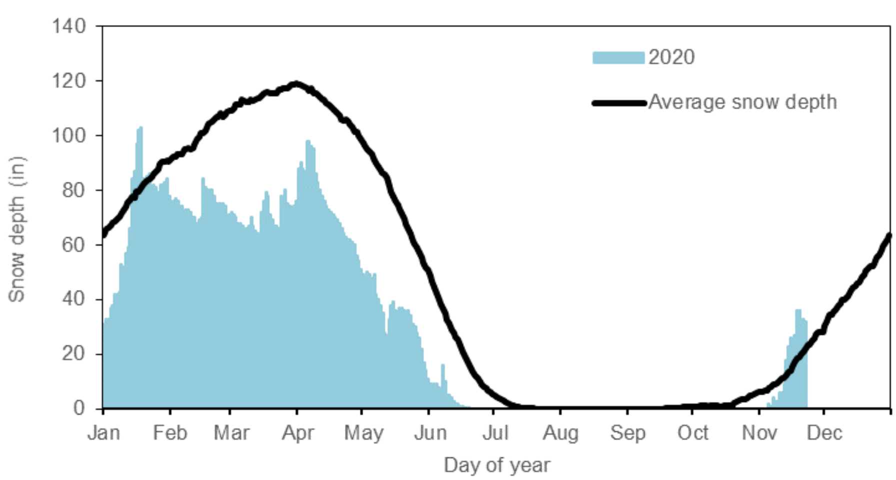


Figure 16. Daily snow depth during calendar year 2020 (blue) and long-term (1931-2019) daily snow depth (black) at Crater Lake National Park headquarters

5.4 Climate and Lake Level (since 1961)

Crater Lake acts like a giant leaky rain gauge. The elevation of the lake's surface becomes a balance between loses, from seepage and evaporation, and gains, from springs and precipitation. The majority of water input comes from precipitation, which falls directly on the lake as rain or snow, or it builds up as snowpack on the caldera walls and on Wizard Island where it is then released into the lake during snowmelt season. Given the difference in seasonal weather patterns, where winter precipitation is modest in intensity but frequent, and summer precipitation is much less common and showery, most precipitation occurs as snow. Therefore, winter snowfall has a strong influence on the water level of Crater Lake.

Weather conditions have been measured at Park Headquarters since 1931, with only significant interruptions during World War II. Measurements of precipitation, snowfall, snow depth, and maximum and minimum temperature are made once daily around 8 AM. Water levels have been measured in some form as early as 1896, when the first of six gauges were installed. Most early measurements were sporadic and from the warm portion of the year when the lake was accessible. Water levels are now continuously measured by USGS, which started their monitoring at Cleetwood Cove in 1961.

Over the period 1962-2020, increases in average lake elevation in a water year (October 1 of the previous year through September 30 of the current year) follow increases in water year snowfall totals (Figure 18). Peaks and dips in surface elevation followed a corresponding peak or dip in snowfall total by approximately two years. There was also an overall decrease, throughout this period, in the rate of both water level and snowfall totals.

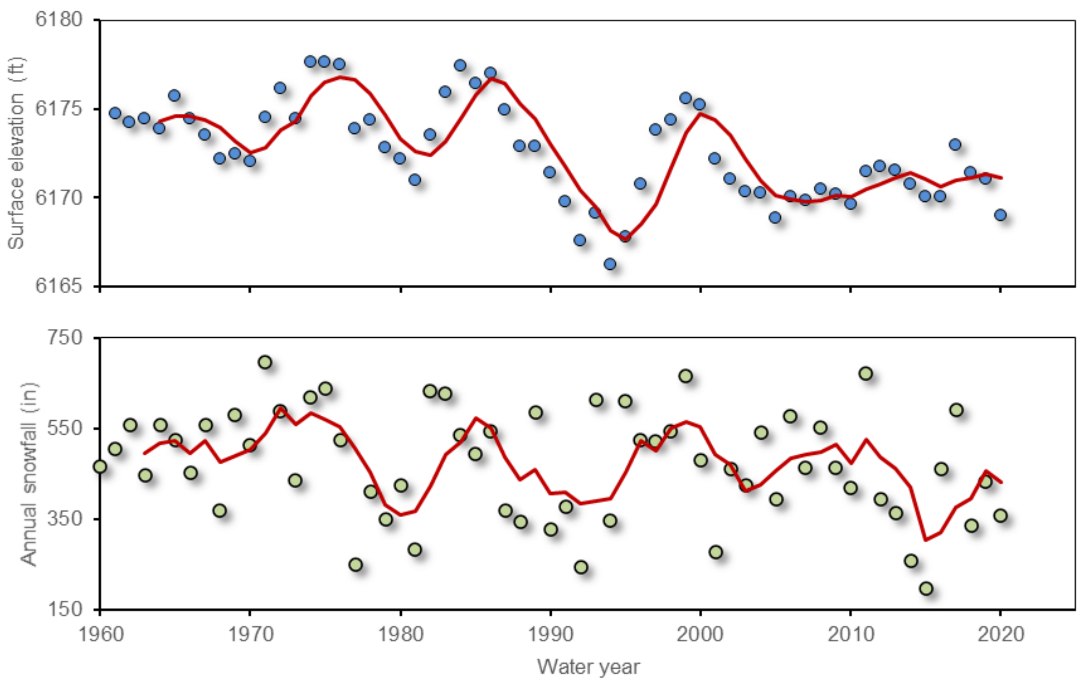


Figure 17. Snowfall (bottom) and lake surface elevation (top) from Crater Lake National Park over the period 1962 to present. Red lines represent four year running average

6.0 Thermal Properties

6.1 Summer Surface Water Temperature (since 1965)

The temperature of surface water during summer has increased by 3.2°C (5.6°F) since temperature records began in 1965 (Figure 19A). In the 25 years prior to 1990, mean summer surface temperature was greater than 14°C in only two years (8%). Since 1990, 74% (23 of 31) of the years were warmer than 14°C.

The increase in surface water temperature appears to be driven largely by an increase in air temperature (Figure 19B). The variation in mean summer air temperature accounts for 73% of the variation in surface water temperature (using linear regression). On average, summer surface water temperature increased 1°C for each 1°C increase in mean summer air temperature.

Increasing summer surface water temperature has been documented in numerous large lakes in North America including lakes Superior, Huron, Mendota, Washington, and Tahoe. Results from studies conducted on these lakes strongly implicated higher air temperature as a primary cause of increasing water temperature, higher air temperature in concert with earlier onset of thermal stratification (Lake Superior), or changes in cloud cover.

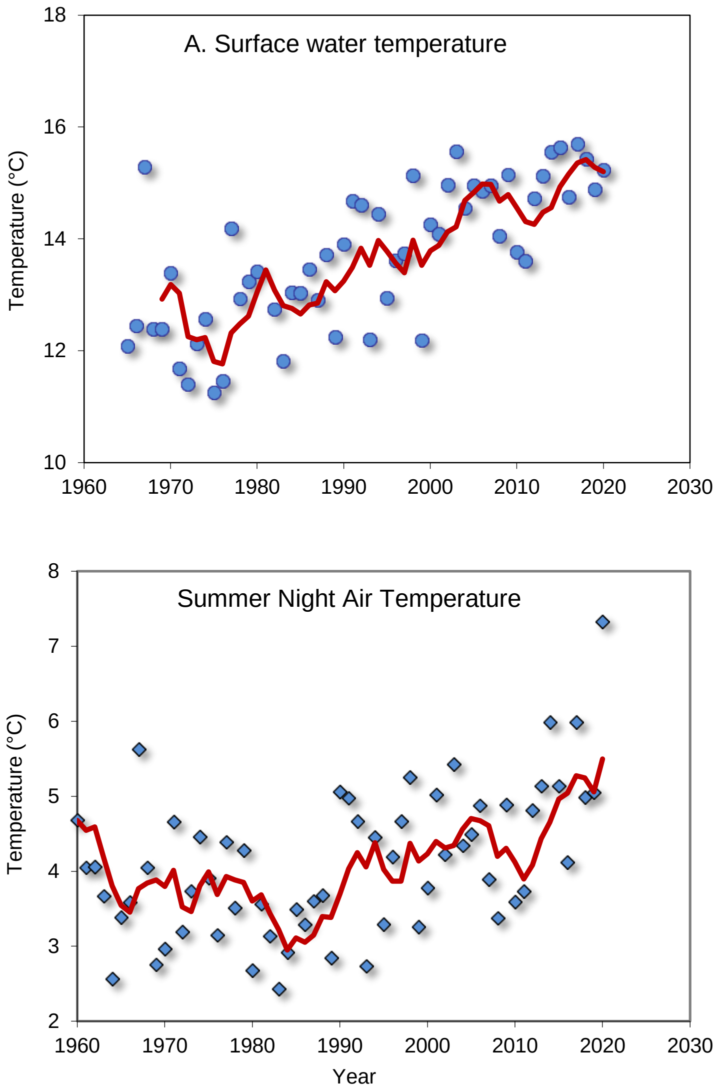


Figure 18. Long-term records of surface water temperature (A) and summer air temperature (B) at Crater Lake National Park. Red lines represent 5 year running average

Automated weather station attached to a buoy on Crater Lake. The sensor used for tracking surface water temperature is located under the buoy at a depth of approximately 1 meter (NPS photo).

6.2 Summer Water Column Temperature (start date depth dependent)

Long-term trends in summer water temperature are noticeably different depending on depth within the lake. This is because different depths in the water column are affected by air temperature at different times of the year. For example, near surface waters are more affected by air temperature during summer because summer stratification greatly reduces the depth of the mixed layer and effectively seals-off deeper layers. Deeper water tends to be more influenced by conditions in winter and the depth to which the lake mixes.

Surface water temperature (Figure 20) shows a statistically significant increase since 1965 ($p<0.05$) which corresponds with increasing summer air temperature. At 20-m depth, an opposite trend is observed ($p<0.001$). The apparent cooling at 20-m is associated with reduced thickness of warm water floating on the surface (i.e., decrease in thermocline depth). Because thermocline depth has been moving closer to the surface over the same period (section 6.5), the water at 20-m is now more characteristic of the deeper and colder water column than when the monitoring program began in the early 1980's. Water temperatures at and below 100-m in the summer are much colder and do not show statistically significant long-term trends or changes. These temperatures are primarily influenced by the depth of mixing in winter.

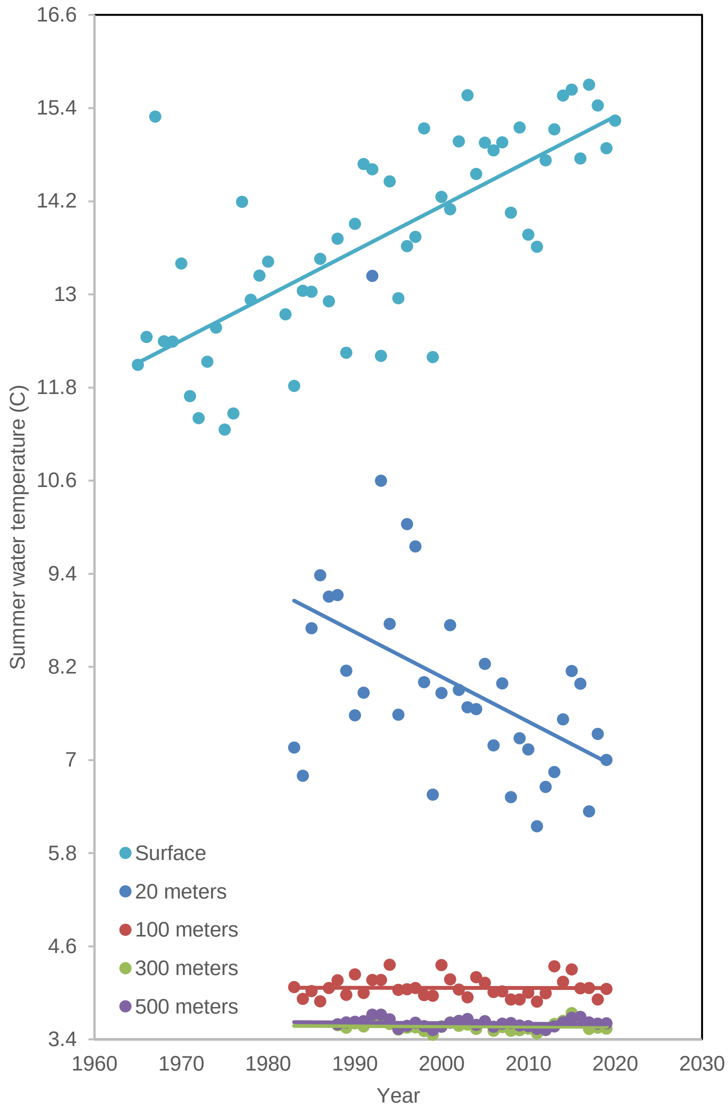


Figure 19. Long-term record of water column temperature in Crater Lake. The length of this record is based on depth. For example, the record of surface temperature started in 1965, whereas deep water monitoring began in the late 1980's

The RV Neuston is the Park's primary vessel for monitoring and research activities. The aluminum vessel was constructed in 1994 and refurbished in 2017. (NPS photo).

6.3 Onset of Thermal Stratification (since 1966)

Thermal stratification in summer results in warmer water floating on the lake surface. The onset of stratification signifies the seasonal end of deep vertical mixing of the water column. Ecologically, this shift is important because stratification effectively separates the surface waters from the rest of the lake. The end of deep vertical mixing allows phytoplankton and zooplankton to stabilize and grow at discrete depths in the water column. Water clarity is typically highest soon after onset of stratification.

From a long-term change perspective, stratification occurs approximately 33 days earlier today than it did in 1966, albeit with considerable year to year variation (Figure 21). Prior to 1990, stratification began after June 1 80% of the time (13 of 16 years). Since 1990, only 8 of 31 years (26%) began on or later than the June 1. The statistically significant trend toward earlier onset of stratification ($p<0.01$) appears to be driven by warmer air temperature in spring. See section 6.4 for more detail.

The ecological significance of stratification can be seen in Figure 22, which shows daily algal chlorophyll concentration in the upper 300 meters of the lake over a one year period. Prior to stratification, algae are spread throughout the upper 300 meters because the lake is mixing vertically to this depth. As soon as the lake stratifies on June 1st, chlorophyll concentration drops throughout the water column and algae shift to maximum chlorophyll below 100 meters. Consequently, timing of stratification is important to biological, chemical, and physical processes in lakes.

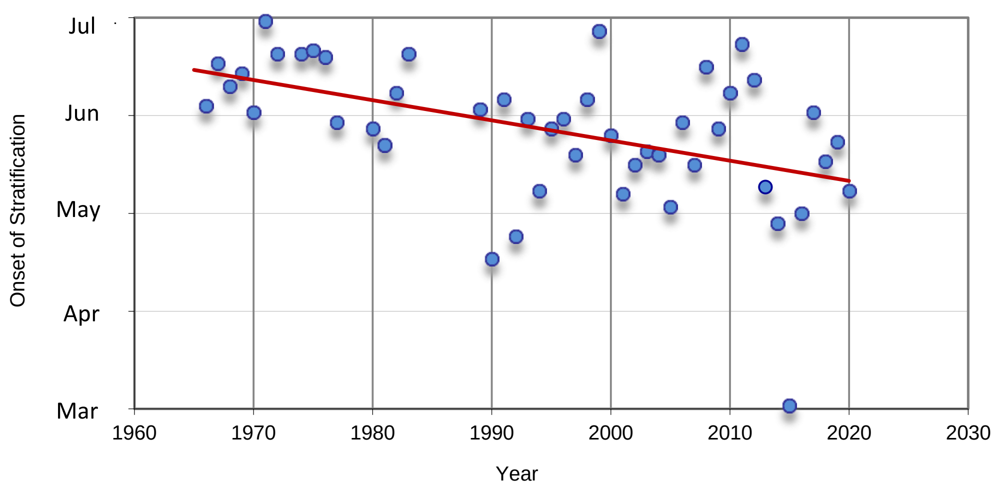


Figure 20. Long-term record of onset of thermal stratification in Crater Lake

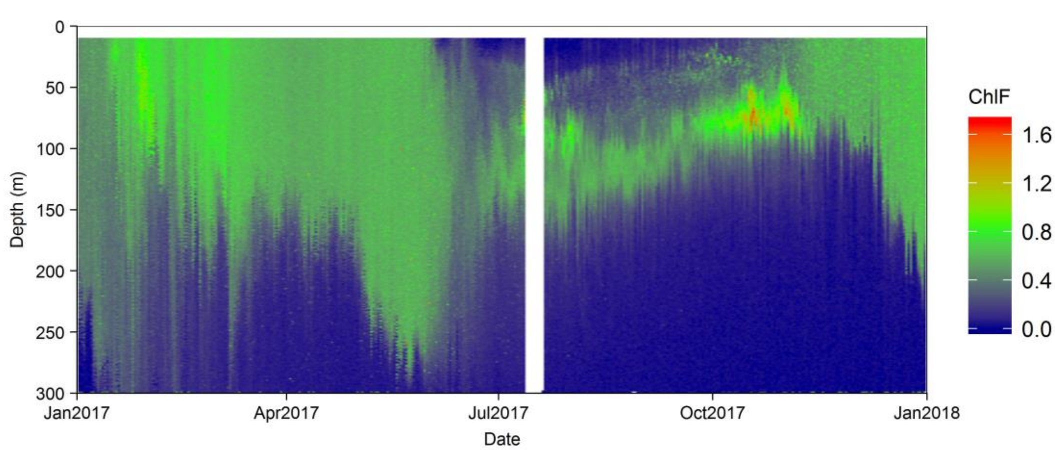


Figure 21. Chlorophyll fluorescence from 1/2017 to 1/2018 in Crater Lake. Vertical dashed white line represents onset of stratification

6.4 Drivers of Thermal Stratification Onset

Some of the most significant changes observed in Crater Lake concern thermal stratification, which is the annual formation of warm water floating on the surface in summer. The timing with which warm water floats on the surface of Crater Lake in spring or early summer is quite variable from year to year and has trended earlier by over a month since 1966. The onset of stratification is a fundamentally important process in lakes because it isolates the upper water from the rest of the lake and provides warm water habitat.

Limnology researchers at Rensselaer Polytechnic Institute (RPI) in New York investigated causes behind thermal structure changes in Crater Lake. The researchers used a hydrodynamic modeling approach because thermal stratification can be simultaneously impacted by multiple climate (air temperature, humidity, precipitation) and in-lake processes (vertical mixing, in-flow). Results of the modeling suggest that the trend toward earlier onset of stratification is primarily driven by warming spring air temperatures. Springs with warmer air temperature allow the upper water column to heat up earlier and hastens the onset of stratification (Figure 23).

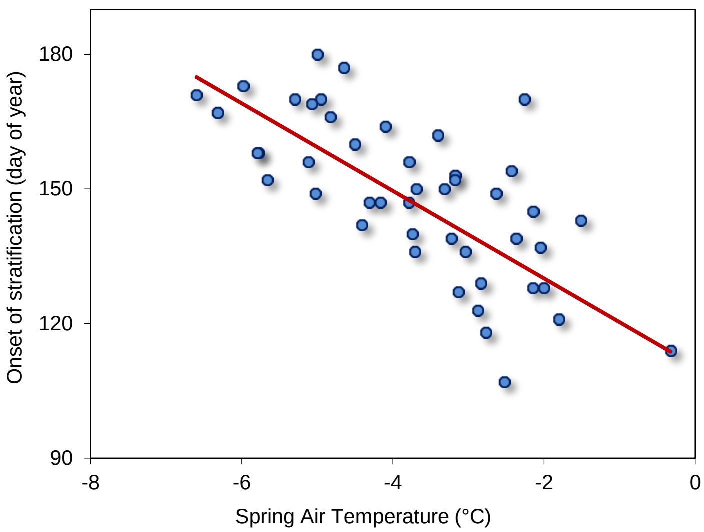
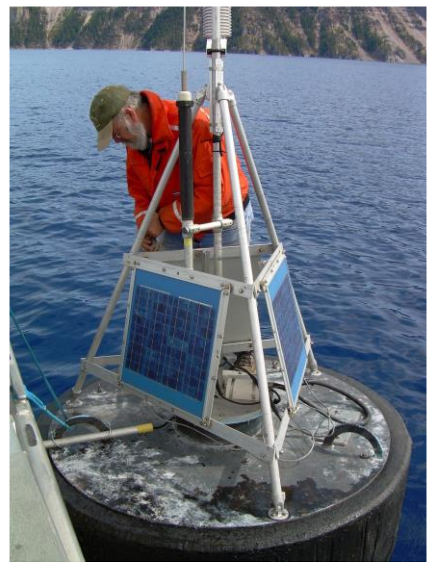


Figure 22. Relationship between spring air temperature and onset of thermal stratification in Crater Lake



Dr. Robert Collier (Oregon State University) working on the floating weather buoy. The temperature sensor used for tracking onset of stratification is located under the buoy (NPS photo).

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Atmospheric stilling and warming air temperatures drive long-term changes in lake stratification in a large oligotrophic lake

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Results of the study were published in the scientific journal Limnology and Oceanography. Special thanks to doctoral student Jon Stetler and Professor Dr. Kevin Rose at RPI.

6.5 Summer Thermocline Depth (since 1978)

During summer, warmer water floats on the surface of the lake because it is less dense than the water below. The thermocline is the depth of transition between the warmer water floating on the surface and the colder water below. Figure 24 shows water temperature and thermocline depth in the upper 200 m of the lake over a summer-fall period. In summer, the thermocline is usually less than 20 m deep in Crater Lake but increases in depth as the water temperature cools in the fall and wind pushes the thermocline deeper. The depth of the thermocline is important as it determines the amount of warm-water habitat near the surface and thus the distribution of warm water taxa, and it influences the volume of water that interacts with the climate.

Over 43 years, the average thickness of the summer thermocline has decreased by approximately 46% (Figure 25), moving closer to the surface of the lake by more than 6 m (20 feet). The average thermocline depth in summer 2020 was 10.3 meters, which is the 23rd shallowest over the last 43 years. Hydrodynamic modeling by researchers at Rensselaer Polytechnic Institute (RPI) in New York (see section 6.4) suggests that the shallowing of thermocline depth is due to reduced wind speed in spring and summer but not warmer surface water. Hydrodynamic modeling was used for the study because thermal stratification properties can be simultaneously impacted by multiple climate (air temperature, humidity, precipitation) and in-lake processes (vertical mixing, in-flow of water, heat flow). Considering both thermocline depth and stratification onset (section 6.4), the volume of warm water habitat in Crater Lake has declined by about half and it occurs for a longer period of time.

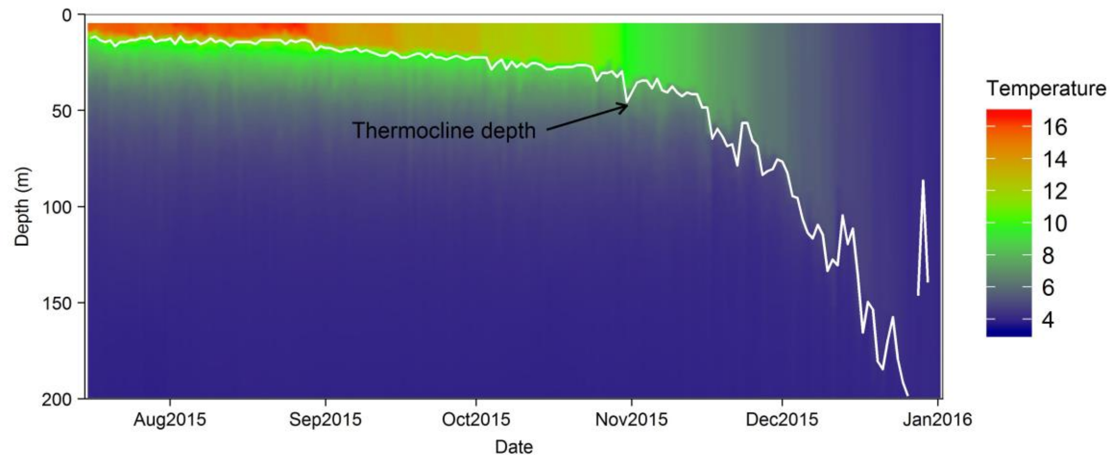


Figure 23. Water temperature from 7/2015 to 1/2016 in Crater Lake. White line shows thermocline depth

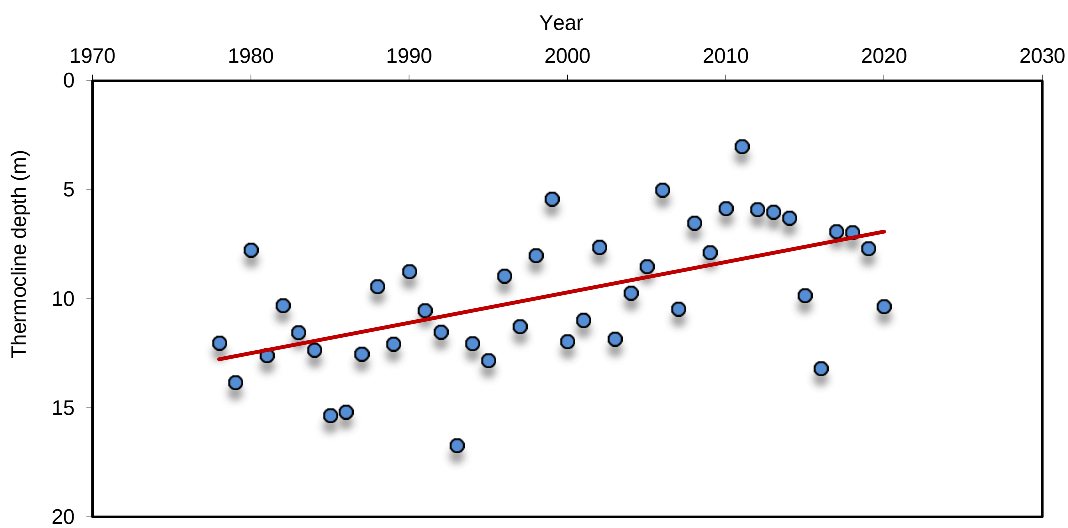


Figure 24. Long-term record of summer thermocline depth in Crater Lake

7.0 Mixing Processes

7.1 Episodic Deep-Water Mixing Events (since 1992)

Depth, timing, and frequency of vertical mixing are among the most important processes in lakes. In deeper lakes, vertical mixing often controls algal biomass in the upper water column by redistributing nutrients stored deep in the lake. Vertical mixing also replenishes dissolved oxygen at the lake bottom that is otherwise depleted by decomposition of organic material.

The monitoring program uses detailed water temperature data to track deep-water mixing events. Temperature at the bottom of the lake is variable through time, showing periods of increase due to geothermal heating (Figure 26). Downward spikes indicate mixing events where cold water floating on the surface gets forced down to the bottom through a process called thermobaric instability. Significant mixing events have occurred in 15 of the last 28 years.

Deep-water mixing in Crater Lake requires reverse stratification of the water column, which occurs when extremely cold water floats on top of the lake in winter. In figure 22 below, reverse stratification (green and blue colors) is apparent in late February, reaching a depth greater than 200 m. A mixing event occurred at the beginning of March, characterized by the sudden appearance of colder water at the lake bottom. The sinking of higher oxygenated water from above replenishes oxygen at the bottom and displaces deep, relatively nutrient rich water upwards. One concern is that warming air temperatures might prevent reverse stratification and as a result, prevent deep-water mixing events. The loss of deep-water mixing could have profound effects on the ecology of Crater Lake. Personnel from USGS and University of Trento have used modeling techniques to assess how warming air temperature would affect mixing of the Crater Lake over the next 100 years (section 7.4).

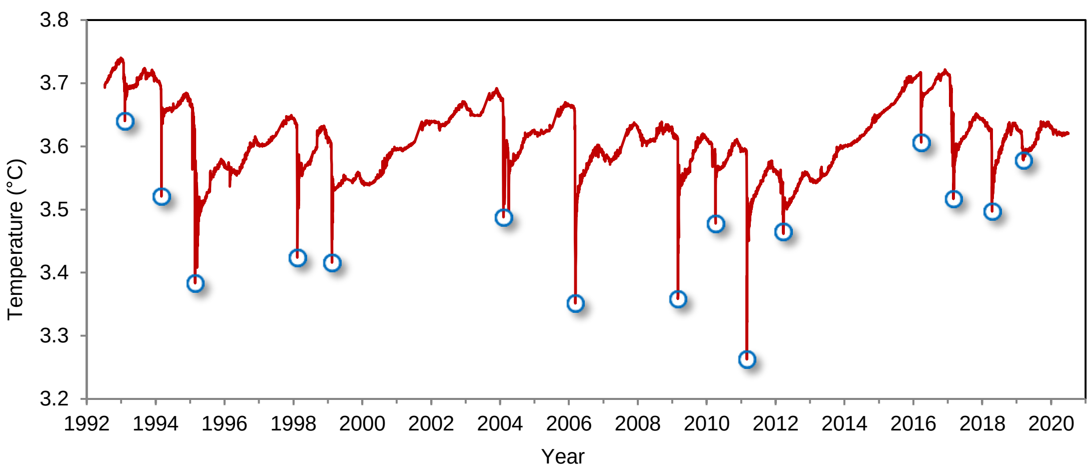


Figure 25. Long-term record of deep-water temperature in Crater Lake. Blue circles highlight deep-water mixing events

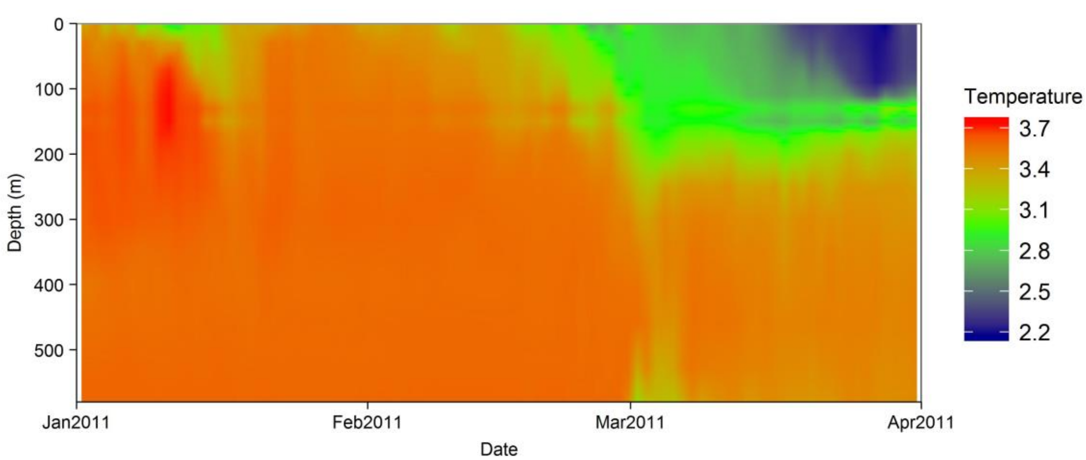


Figure 26. Temperature data showing a deep-water mixing event in 2011 in Crater Lake

7.2 Influence of Winter Mixing on Deep-Water Nitrate Storage (since 1989)

The degree to which the water column mixes in winter is critical to lake ecology because it controls vertical movement of nutrients within the lake. Nitrate dissolved in the water is near zero in the upper part of the lake because it is rapidly taken up by phytoplankton (Figure 29). Nitrate increases with depth because organic material "rains" down into deeper parts of the lake and releases nitrogen when it decomposes. It is not taken up by algae because it is too dark for algal growth. Because nitrate is the primary nutrient limiting algal growth in Crater Lake, more nitrate in the upper lake means more algae and less clarity.

Long-term fluctuations in deep-water nitrate mirror that of deep-water temperature (Figure 28). Sudden drops in temperature due to deep-water mixing events coincide with drops in deep-water nitrate. Cold water from the surface sinks to bottom during a mixing event, cooling the deep water and displacing nitrate rich water upward. The impact of a deep-water mixing event on nitrate movements can be seen when comparing nitrate in 2010 and 2011 (Figure 29). In the absence of mixing events, nitrate levels slowly rise due to the decomposition of algae falling down from above and water temperature increases due to geothermal heating from the lake floor. Tracking the vertical movements and deep-water storage of nitrate is critical to understanding the clarity of the lake and impacts of a long-term warming climate.

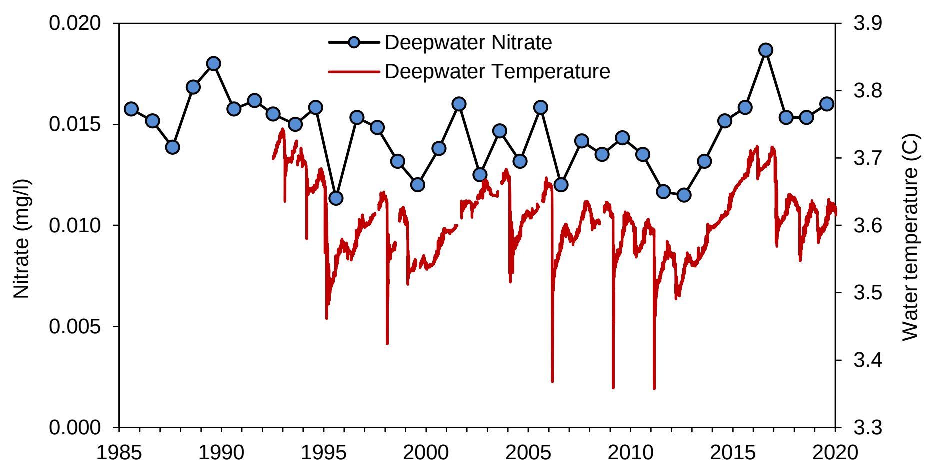


Figure 27. Long-term changes in deep-water nitrate and deep-water temperature in Crater Lake

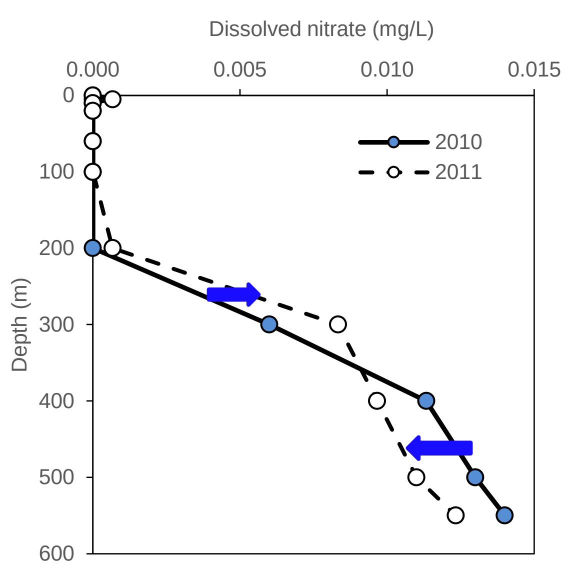


Figure 28. Changes in dissolved nitrate in the Crater Lake water column between summer 2010 and 2011

7.3 Impact of Winter Mixing on Surface Water Clarity (since 1988)

Long-term monitoring of water column particle density and Secchi depth over the last 33 years shows that nutrients forced upward by deep-water mixing events in winter results in higher algal density and reduced water clarity the following summer. Average summertime water column particle density following the 5 biggest mixing years was significantly higher in the upper 80 meters compared to the 5 least mixing years (Figure 30). Water clarity, measured as Secchi depth, is similarly reduced in summers following deep-water mixing years (Figure 31).

Because vertical flux of nutrients within the water column affects algal growth and water clarity, it is important to understand how weather impacts water column mixing. Warming climate is likely to continue (section 5.1) and cutting edge modeling by the USGS Oregon Water Sciences Center (section 7.4) predicts that vertical mixing in winter is likely to decline or cease entirely in the next 50-100 years.

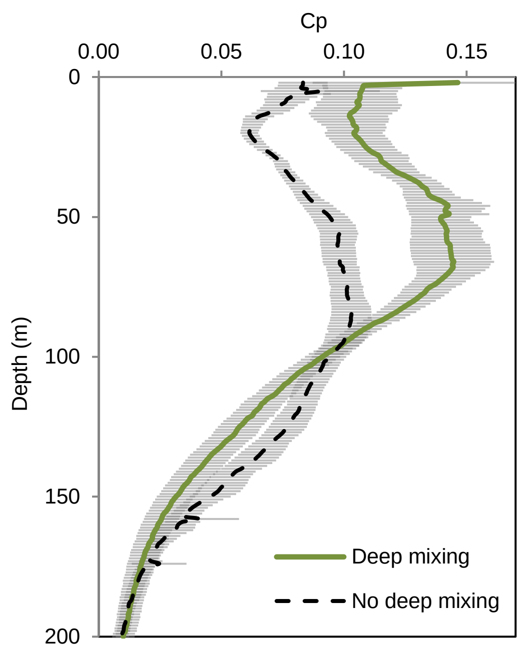


Figure 29. Comparison of summer particle density in the upper water column in the five biggest mixing years and five non-mixing years

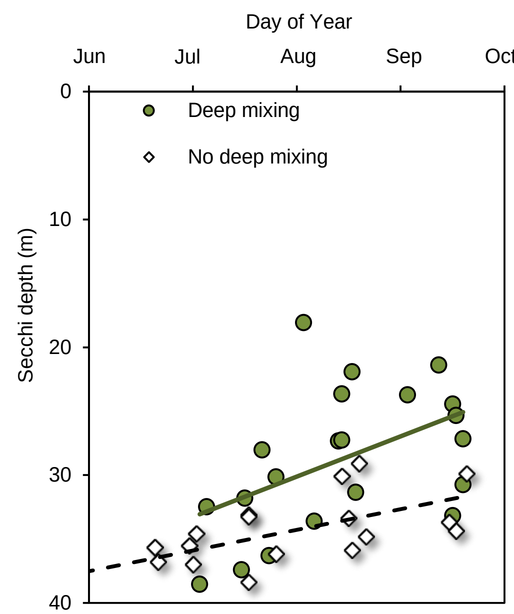


Figure 30. Summertime Secchi depth in the five biggest mixing years and five non-mixing years

Secchi Depth & Particle Density (Cp)

Although much of the algae in Crater Lake live below 30 m, it is the density of algae in near-surface waters that impacts Secchi depth. Particle density in the top 30 m of the lake is highly correlated with Secchi depth and can therefore be used as a surrogate for water clarity. Particle density measurements from the transmissometer on the profiling CTD is one of our best tools for studying long-term water clarity.

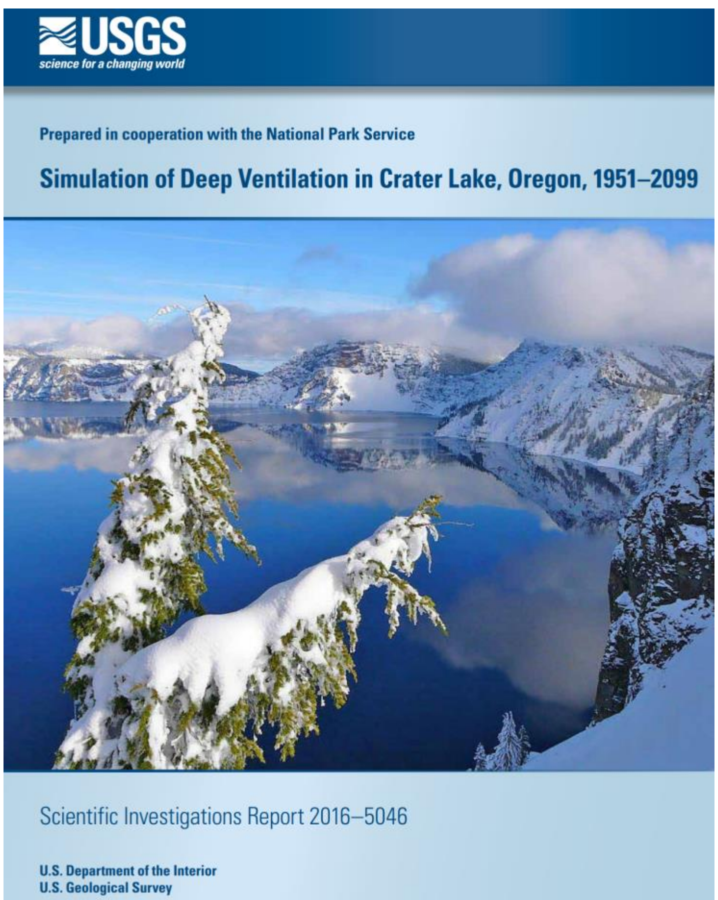
7.4 Predicting Winter Mixing in a Warming Climate

Previous sections highlight how deep-water mixing events impact nutrient dynamics and deep-water oxygen. How will mixing respond to future climate? Researchers from USGS Oregon Water Sciences Center and University of Trento (Italy) used special modeling techniques to address this very question. Using a recently developed computer model, designed specifically for cold, deep lakes, like Crater Lake, they were able to simulate lake dynamics under future climate conditions.

The model uses inputs of weather conditions (e.g., air temperature, wind speed, and solar radiation) and lake geometry to predict water temperature and the frequency of mixing to the bottom of the lake. The accuracy of the model was carefully tested by its ability to reproduce past lake conditions (temperature and mixing) based solely on model inputs. This gives us confidence in its ability to predict mixing under predicted weather conditions. Downscaled global climate change scenarios for the Crater Lake region were used to assess how warmer climate conditions would affect deep-water mixing of Crater Lake over the next 100 years.

The modeling results (Figure 32) show that Crater Lake is indeed vulnerable to major changes in lake mixing in the immediate future. However, the degree to which mixing declines and the speed with which they occur strongly depend on how quickly warming proceeds, especially warming air temperature in the fall and early winter.

See the full peer-reviewed report for more details about the model development, calibration, climate change scenarios used, and effects on deep-lake mixing (Wood, Tamara M., Susan A. Wherry, Sebastiano Piccolroaz, and Scott F. Girdner. Simulation of deep ventilation in Crater Lake, Oregon, 1951–2099. No. 2016-5046. US Geological Survey, 2016.)



Technical report published in collaboration between NPS, USGS, and the University of Trento, simulating mixing dynamics of Crater Lake given future climate conditions.

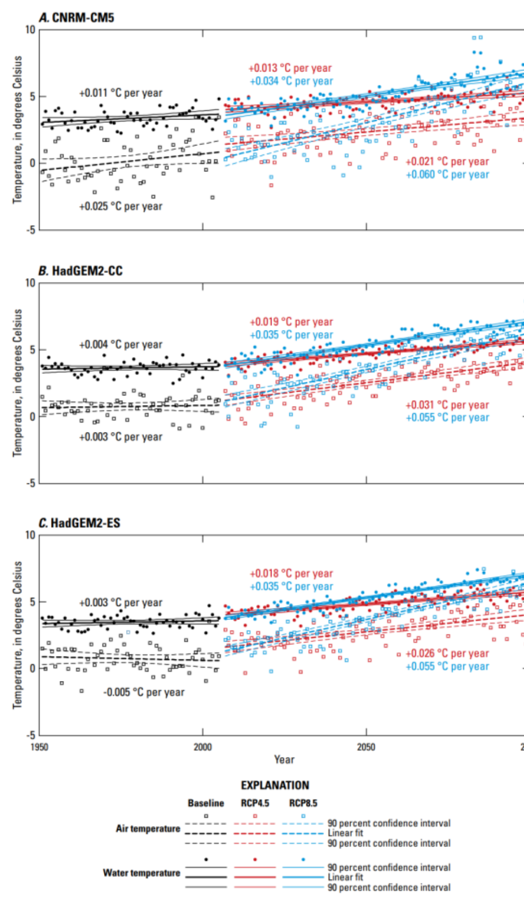


Figure 31. Results of model simulations predicting water temperature in Crater Lake under future climate conditions

8.0 Biological Properties

8.1 Phytoplankton Abundance: Particle Density (since 1988)

Particle density is a good proxy for estimating phytoplankton abundance in Crater Lake because phytoplankton are the primary source of particles within the water column. One method of measuring particle density is with an instrument known as a beam transmissometer. This instrument measures the amount of beamed light reaching a light detector a set distance away. The amount of light that is scattered by particles in the water is then used to calculate particle density.

The monitoring program collects particle density data multiple times per month during summer. Vertical profiles of the entire water column are taken with a beam transmissometer that is attached to a CTD instrument. In Crater Lake, two phytoplankton communities typically develop in summer, one in warm water floating near the surface and a deeper group typically peaking around 60 m (Figure 33). Long-term trend data indicates that particle density of both communities have decreased slightly over the monitoring period (Figure 34; $p<0.001$). Summer 2020 was the lowest Cp on record (32 years) in the upper 30 m and 3rd lowest for 31-200m.

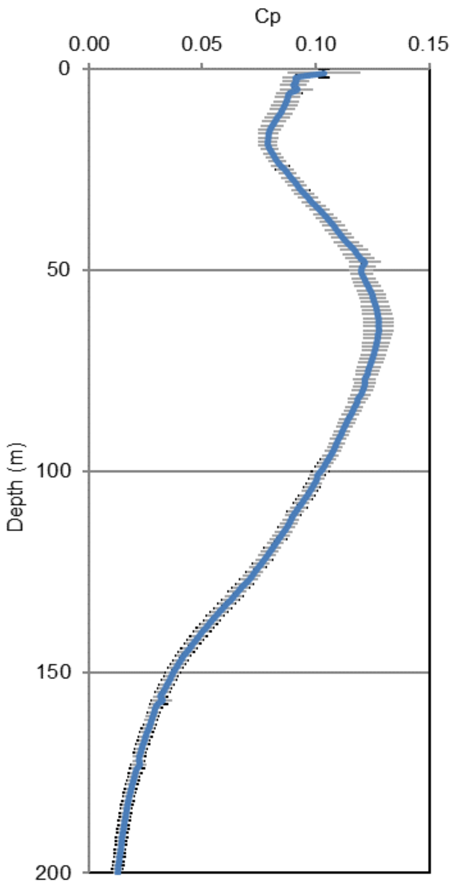


Figure 32. Average particle density by depth in Crater Lake

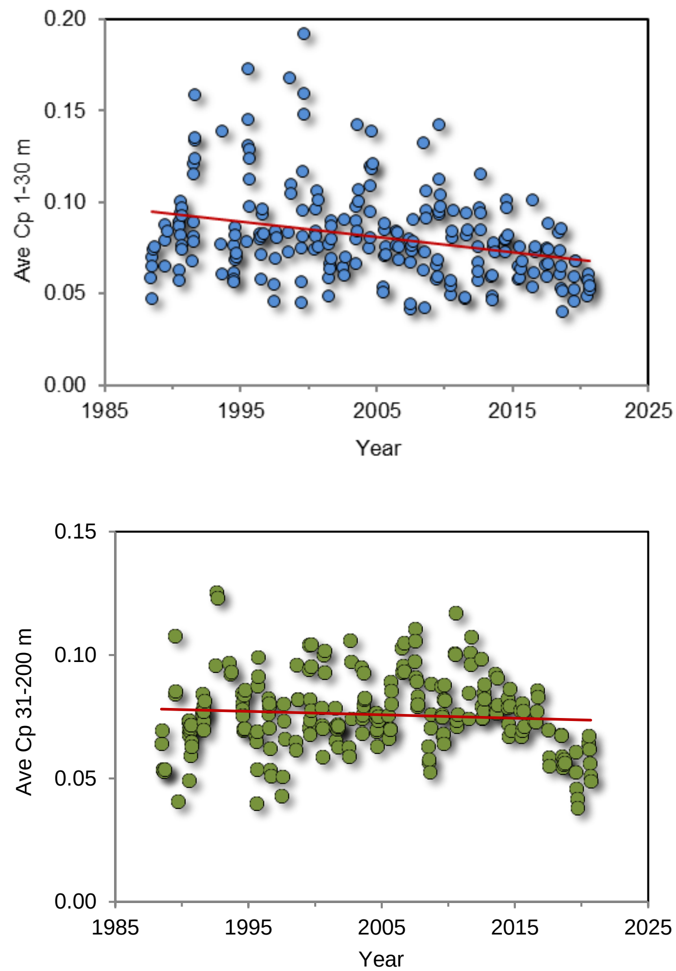


Figure 33. Long-term record of particle density in surface (1-30 m) and deeper water (31-200 m) in Crater Lake

8.2 Phytoplankton Growth: Primary Productivity (since 1987)

Primary productivity measures the growth rate of phytoplankton by estimating carbon uptake (i.e., CO_2 assimilation). Estimates of primary productivity are different from other measures of algae since it is not evaluating the amount of algae directly but rather how much that algal community is growing. The monitoring program uses an *in-situ* $^{14}CO_2$ uptake method, where a known amount of radiolabeled (^{14}C) bicarbonate is added to sample bottles containing a known amount of dissolved inorganic carbon (CO_2). The samples are then incubated at 13 depths within the water column (surface to 180 m). After the incubation period, samples are recovered, and returned to the lab for filtering and analysis. Carbon uptake is estimated based on the fact that uptake of ^{14}C is proportional to ^{12}C found in CO_2. Primary productivity estimates (µg C m^{-2} h^{-1}) are calculated for the 13 depths of the lake.

Light and dark bottle incubation in Crater Lake (NPS photo).

Primary productivity throughout the water column follows a similar pattern seen in particle density – rates peak near the surface and around 60 m, where two phytoplankton communities typically develop in summer (Figure 35). There is a high degree of year-to-year variability in primary productivity, especially deeper in the water column, where rates have slightly decreased over time (Figure 36; green circles).

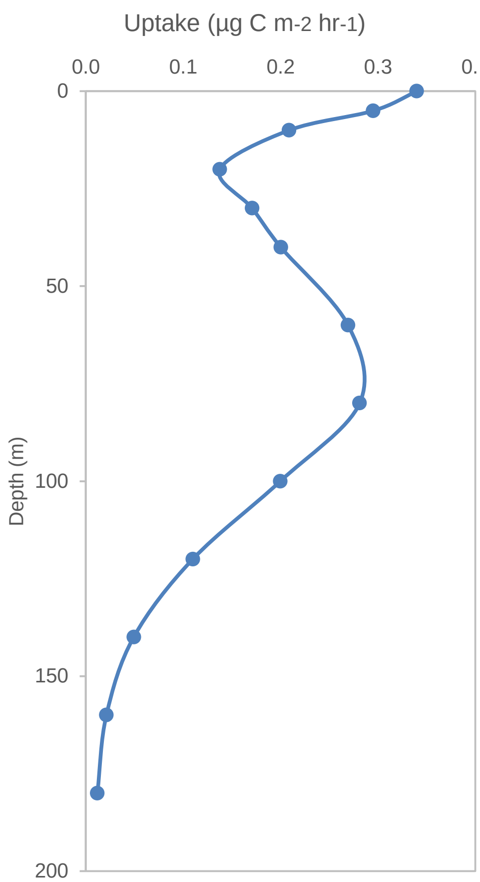


Figure 34. Average carbon uptake measured at 13 depths during mid-day in Crater Lake

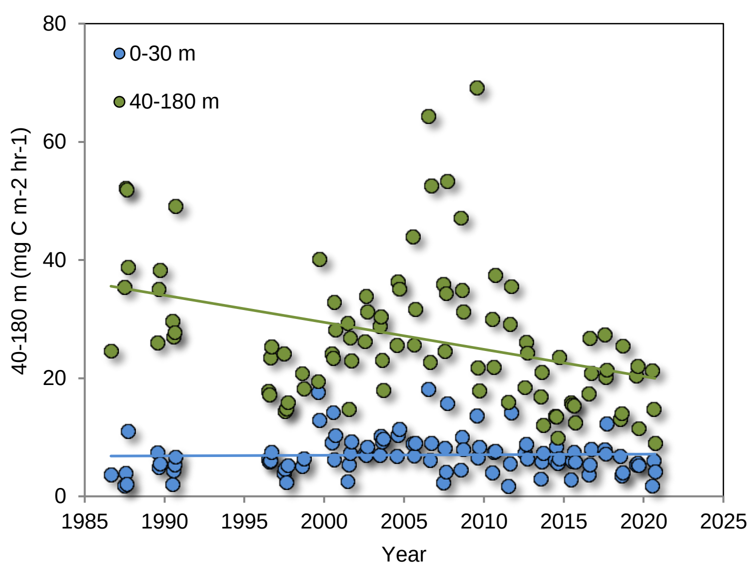


Figure 35. Long-term record of carbon uptake integrated over two depth intervals: 1-30 m (blue) and 40-180m (green)

8.3 Phytoplankton Composition (since 1989)

Free-floating phytoplankton form the base of the food-chain in deep lakes. They support larger organisms, such as zooplankton, which in turn are food for even larger organisms like fish. In summer, the phytoplankton in Crater Lake form two distinct communities separated by the thermocline. One community inhabits warm water near the surface and are almost completely dominated by a few relatively large diatoms and dinoflagellates (Figure 37A). The second community, which inhabits deeper depths is much more diverse (Figure 37B). Since 1989, the near-surface community has not shown obvious long-term changes except for a possible reduction in Chrysophyta beginning around 1996. Chrysophyta also appear to show long-term reductions in the 60-80 m range.

Microscope image of the chrysophyte algae *Dinobryon sertularia* from Crater Lake (NPS photo).

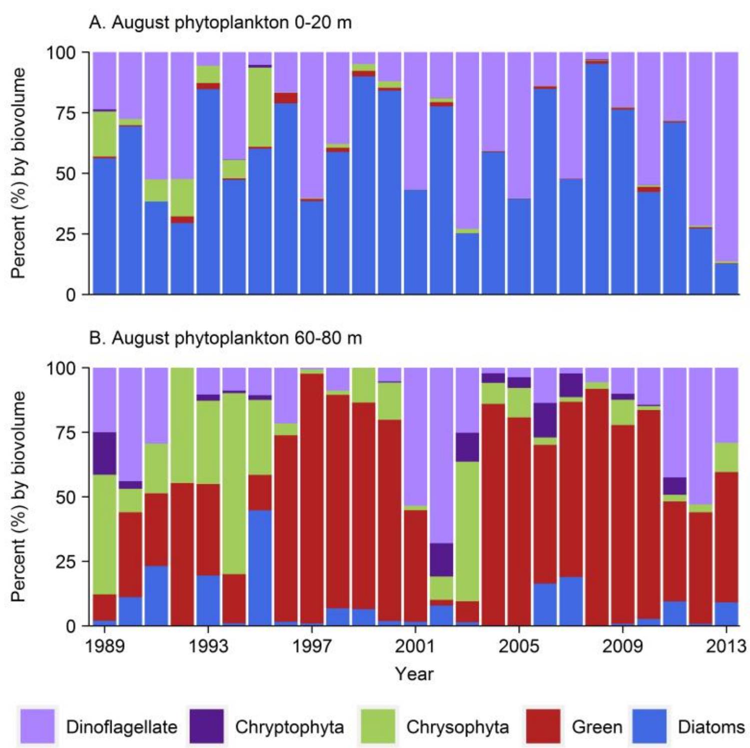
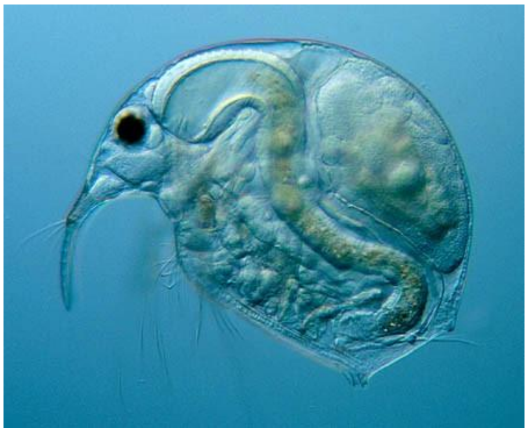


Figure 36. Long-term record of phytoplankton assemblages in Crater Lake in August at two locations within the water column: (A) 0-20 m and (B) 60-80 m

8.4 Zooplankton Composition (since 1985)

Zooplankton (animal plankton) are collected once each summer month from 8 depth zones in the water column. There are relatively few zooplankton species in Crater Lake: two crustaceans, *Daphnia* and *Bosmina*, and nine rotifers dominate the offshore community (Figure 38). *Daphnia*, known as the water flea, is the lake's largest zooplankter (~2 mm long) and its abundance through time is strongly controlled by predation from introduced kokanee salmon (section 8.5). *Bosmina* is almost always present. Dominance within the rotifer community has shifted from *Keratella cochlearis* early in the monitoring program to one dominated mostly by *Kellicottia* and/or *Polyarthra* for the last two decades. The zooplankton community in Crater Lake is unusual because there are few taxa and no pelagic copepods, a relatively large zooplankter common in other mountain lakes.



Bosmina longirostris (Photo: Florida Sea Grant).

Keratella cochlearis (Photo: Malcom Storey).

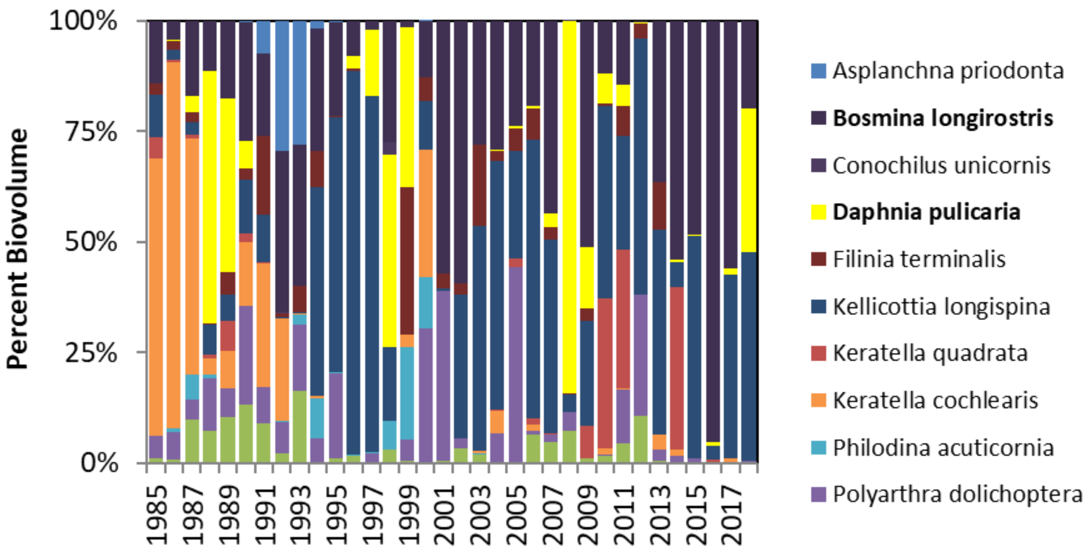


Figure 37. Long-term record of zooplankton assemblages in summer in Crater Lake

8.5 Impact of Fish on Zooplankton (since 1986)

Daphnia is Crater Lake's largest zooplankter (~2 mm long) and its abundance through time is strongly controlled by predation from kokanee salmon (*Oncorhynchus nerka*). Kokanee salmon are landlocked Sockeye salmon and are primarily plankton feeders that were introduced to the lake in the early 1900's. In Crater Lake, kokanee show a distinct "boom and bust" pattern where they experience wide fluctuations in density, weight, and maturity. The lake monitoring program has recorded four kokanee "boom and bust" cycles with a full sequence taking 9-10 years. When kokanee density (Figure 39A; red) is high, the fish literally "eat themselves out of house and home' and nearly all of the *Daphnia* (Figure 39A; green) disappear from the water column. The kokanee population then slowly declines due to food scarcity with few if any fish reaching sexual maturity (Figure 39C). After 6-7 years of declining fish density, food resources recover and the remaining fish attain large size (Figure 39B), which leads to successful spawning and a rapid rise in density – continuing the cycle.

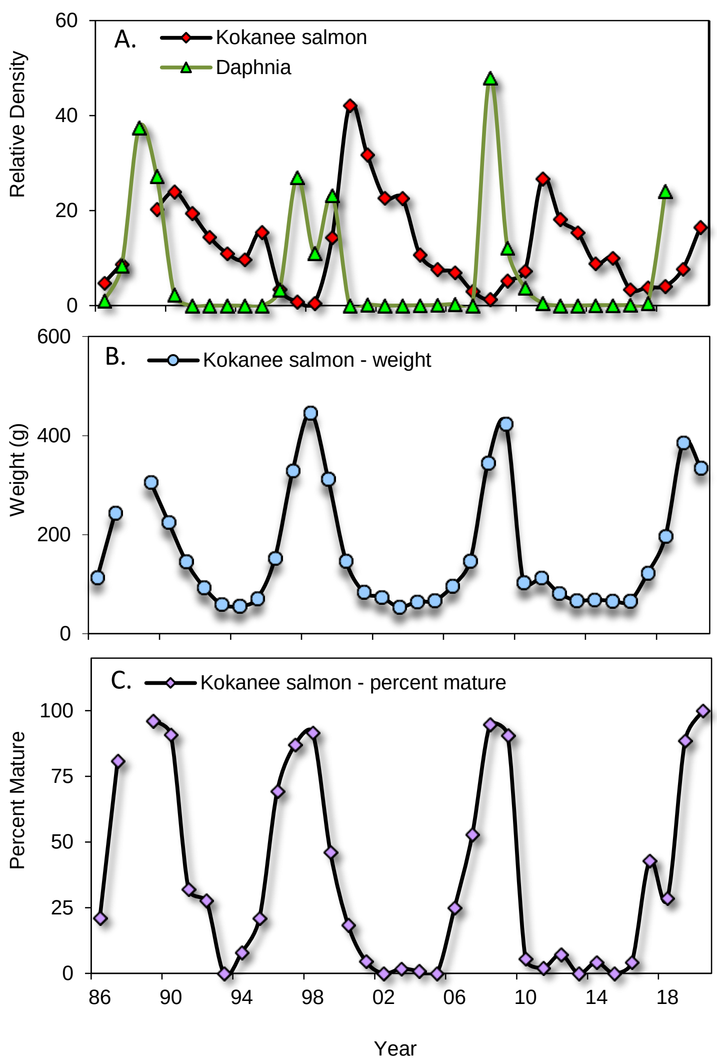


Figure 38. Long-term record of population dynamics of kokanee salmon and their main food source, *Daphnia*, including (A) abundance, (B) weight, and (C) percent of the population that is mature

Daphnia represent a main food source for kokanee salmon in Crater Lake and as a result, follow a similar "boom and bust" population abundance cycle (Photo: Paul Hebert).

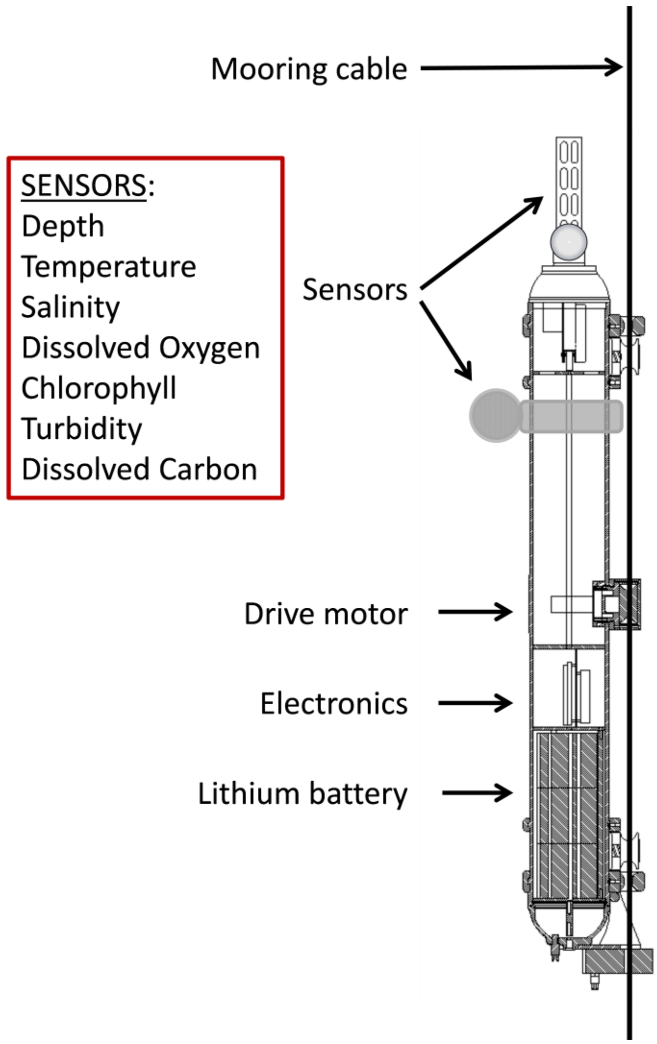
9.0 Year-round Lake Monitoring

9.1 Profiling Instrument (since 2013)

Crater Lake's monitoring program has long recognized that studying the lake during non-summer periods is crucial for understanding the overall health and function of the lake system because important physical, chemical, and biological processes occur during these times. However, weather conditions at Crater Lake make it extremely difficult for boat-based access to the lake in the fall, winter, and spring. Beginning in July 2013, year-round monitoring of the water column occurred using a state-of-the-art profiling instrument [Ice-Tethered Profiler (ITP), McLane Labs, Falmouth, MA].

Woods Hole Oceanographic Institute initially designed the ITP instrument for studying ocean conditions under the floating Arctic ice-pack. There, the instrument is deployed through an 11" ice-auger hole and placed on a wire mooring hanging below the ice-pack. In Crater Lake, the instrument crawls up and down a wire mooring anchored to the bottom of the lake that is kept upright with floats near the surface. The ITP instrument travels up and down the wire mooring once per day and provides high resolution (1 m) data on chlorophyll concentration, particle density (i.e., water clarity), dissolved oxygen, dissolved organic matter, temperature, and salinity.

See section 9.2 to find out what we have learned about the lake in seasons other than summer.



Schematic of the ITP instrument in Crater Lake.

Recovering the ITP instrument from its 580 m long wire mooring line after spending an entire year in Crater Lake (NPS photo).

9.2 Profiler: Chlorophyll Results (since 2013)

Chlorophyll produced by floating algae growing in the water column is an important biological property of lakes. The chlorophyll data collected by the profiler permits in-depth observation of how algae changes over time, both within a single year and between multiple years. Two concepts that the monitoring programs tracks are the establishment of a deep chlorophyll maximum (DCM) in summer and algal growth during winter-spring mixing events.

Figure 40 displays annual chlorophyll concentration down to 300 m over the course of four years. The establishment of a DCM in summer and subsequent shallowing throughout fall is a reoccurring pattern in Crater Lake. The presence of a DCM is a characteristic common to unproductive lakes and ocean systems and the vertical location of the DCM is a sensitive indicator of overlying water clarity. When interpreting long-term chlorophyll data that is collected on a less-frequent basis (e.g. once monthly), it is critical to understand that DCM depth shallows over summer and timing of summer stratification onset is going to drive when that process begins.

As stratification breaks down in fall and vertical mixing deepens, the DCM is eventually eroded and mixed vertically up to the surface. A subsequent bloom of algae occurs throughout the mixed layer during the winter-spring period. Prior to the data provided by the ITP profiler, the monitoring program had only sampled the lake during spring mixing once in 1989. Variability in the duration and depth of a spring bloom may affect the availability of nutrients and clarity of the water during summer. Moreover, the amount of algae growing within the mixed layer and the depth to with mixing reaches, prior to the onset of summer stratification, may be important in determining the amount of nutrients that make it to the deep lake for long-term storage.

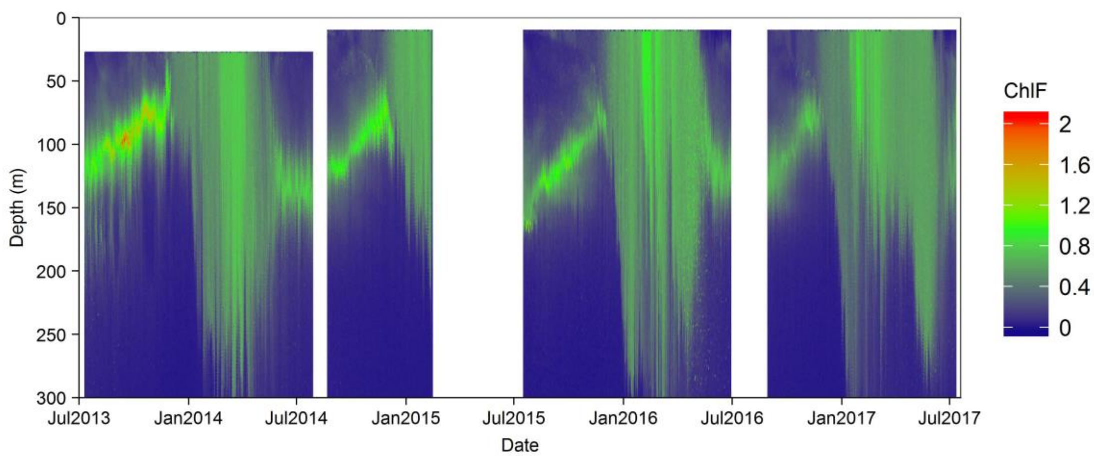


Figure 39. Daily measurements of chlorophyll fluorescence throughout the water column in Crater Lake, collected by an autonomous profiling instrument. White spaces represent missing data

9.3 Profiler: Particle Density Results (since 2013)

Similar to chlorophyll, particle density is a measure of algal abundance but it is based on scattering of light by algal particles, whereas chlorophyll is a measure of how "green" the water is due to algae. Figure 41 is similar to Figure 40 but shows annual particle density down to 300 m over the course of four years.

Particle density shows patterns similar to chlorophyll concentration with a few important differences. Unlike chlorophyll, particle density captures the concentration of algae living in the warm water floating on the surface during the summer. Chlorophyll is not accurate near the surface in the summer because chlorophyll within algae are muted by the extremely bright sun light near the surface. The opposite occurs at extremely deep depths where algal cells greatly increase chlorophyll levels because light levels are very low. These changes in chlorophyll at the cellular level are referred to as "photoacclimation" and are extremely important to quantify because they greatly affect the accuracy of chlorophyll as a measure of algae. Particle density, on the other hand, is a more accurate measure of algal biomass, especially when considering water clarity near the surface.

Clarity at the surface tends to be lowest in the fall, especially when deepening of the thermocline erodes the deep algal group and re-suspends the particles up to the surface. During winter and spring when the lake is mixing to great depth, particle density increases throughout the layer that is mixing. These year-round data show that total biomass of algae in the lake during the winter and spring can actually be higher than during summer. We suspect that the amount of algae that grow in the winter and the depth of mixing prior to the onset of stratification may drive how much nutrients end up making it into deep-water storage in any given year.

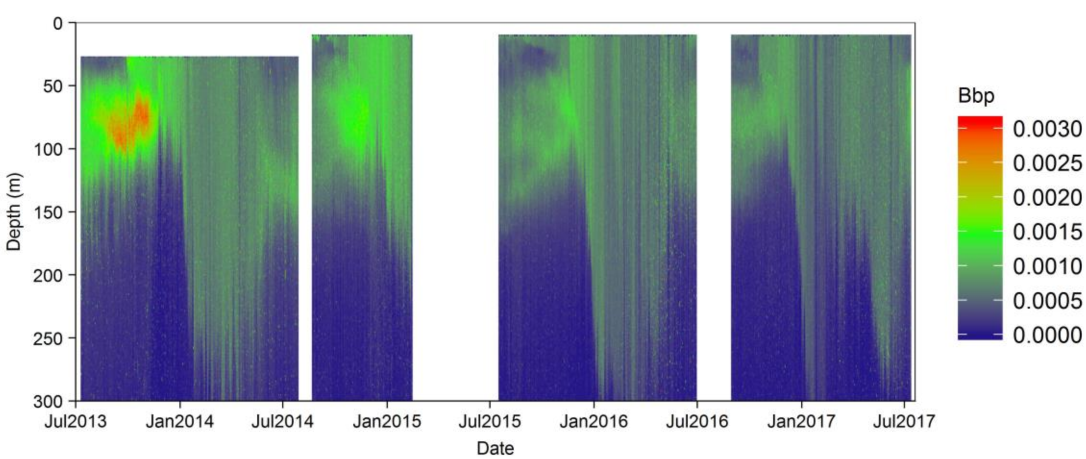


Figure 40. Daily measurements of particle density throughout the water column in Crater Lake, collected by an autonomous profiling instrument. White spaces represent missing data

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