Water Quality Effects of Blue-Green Algal Blooms in Diamond Lake, Oregon

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In 2001, a serious bloom of potentially toxic cyanobacteria (blue-green algae) developed in Diamond Lake, a popular recreational lake in the Umpqua National Forest (UNF), Oregon. Toxins produced by cyanobacteria have been implicated in human health problems ranging from skin irritation and gastrointestinal upset, to death from liver or respiratory failure. Blooms have continued at Diamond Lake since 2001 and prompted a call for action to control the problem. In the interim, a strategy was developed to deal with the public health threat posed by cyanobacteria. UNF staff, working with private and government organizations, developed a plan to monitor the lake. Results from the monitoring program were interpreted in light of the World Health Organization (WHO) guidelines for toxic cyanobacteria species. We describe this effort and offer lessons learned to other lake managers faced with similar issues.

Keywords: *aquatic ecosystems, paleoecology, history, water quality, lakes, recreation, public health, cyanobacteria, blue-green algae, aquatic/riparian habitat*

Introduction

Diamond Lake is a 1300 ha lake located at an elevation of about 1600 m in the central Oregon Cascade Range (Figure 1). This relatively shallow lake (maximum depth 15 m) is located immediately north of Crater Lake National Park in the Umpqua National Forest. The lake watershed is wholly contained within the national forest and national park. Diamond Lake was probably fishless before 1910 when rainbow trout (*Oncorhynchus mykiss*) stocking began. In a typical year, the Oregon Department of Fish and Wildlife (ODFW) stocked as many as 1,000,000 trout fry from a hatchery at the lake. A lodge, 100 summer homes, and three Forest Service campgrounds were built from 1920 to the 1960s. A successful trout fishery was interrupted when tui chub (*Gila bicolor*) were introduced, likely as bait fish, and caused the sport fishery to collapse in the 1940s.

In 1954 the lake was treated with rotenone and rainbow trout were restocked the following spring. The trout fishery was successful and remained so until the 1990s when tui chub were discovered in the lake once again. Efforts began to respond to the tui chub and the decline in the trout fishery, but no one was prepared for the apparent effect of the chub on water quality in Diamond Lake. In 2001, following a routine sampling of the lake, we discovered that the lake contained a high density of *Anabaena flos-aquae*, a potentially toxic species of cyanobacteria.

This paper describes Diamond Lake, Oregon, and potentially harmful blue-green algae blooms. We recount the public health actions taken during dense blooms of the blue-green alga *Anabaena flos-aquae* during the summers of 2001-2004, and the role water quality monitoring played in recognizing and responding to the public health risk. Finally, we list some lessons learned by the UNF that may apply to other water bodies.

Diamond Lake Description and History

Diamond Lake is a popular recreational site in the Umpqua National Forest (Figure 2). The primary attraction in summer has always been the abundant trout fishery, although the proximity to Crater Lake, the spectacular scenery, and hiking opportunities draw many other visitors. At the height of its use in the late 1970s, Diamond Lake drew over 780,000 visitors per year. With the collapse of the trout fishery, that use is now a fraction of its peak.

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Figure 1. Diamond Lake, Oregon (photo by Joseph Eilers).

Efforts have been made to expand other uses, including water skiing.

The lake experienced algal blooms during the 1960s, and in 1998 Diamond Lake was placed on the Oregon 303(d) list of water bodies not meeting water quality standards for pH and nuisance algae. Earlier investigations indicated that the lake was productive either from natural inputs of phosphorus (Lauer et al. 1979), or from human development of the shoreline (Meyerhoff et al. 1977). Subsequent investigations also reinforced the notion that the lake was becoming culturally eutrophic (Salinas and Larson 1995). A sediment core collected in 1996 (Eilers et al. 2001) indicated that there might be a link between the fish populations and water quality in the lake, but no one was prepared for the rapid change in 2001 (USDA Forest Service 2004a, 2004b).

History of Diamond Lake, Oregon, 1910-2001

1910s - Fish stocking begins and fishery is highly successful
1920 - 1950 - Lodge, campgrounds and 100 summer homes built
1950s - Tui chub population explodes
1954 - Lake is treated with rotenone
1990s - Tui chub return and recreational fishery crashes
2001- Severe *Anabaena flos-aquae* blooms begin

The UNF routinely sampled Diamond Lake monthly each summer, beginning in 1992. The sampling included in-situ measurements of pH, dissolved oxygen and collection of zooplankton and phytoplankton samples (Table 1). During June 2001, the lake water appeared noticeably chalky and blue-green, but no attempt was made to expedite the analyses of the biological samples. An ad hoc sample collected in July was analyzed privately and the results revealed the presence of a dense population of *Anabaena flos-aquae* (JM Eilers, MaxDepth Aquatics, Inc., Bend, Oregon, personal communication, 2001). As of 25 July 2001 the bloom had a density of about 100,000 cells/mL and by early August the density reached 575,000 cells/mL. Samples analyzed by Wright State University, Dayton, Ohio, confirmed the presence of the algal toxins anatoxin-a and microcystin from 6 August through 28 August. Maximum anatoxin-a concentration was reported as 310 µg/L and represented a risk to human health from water contact and accidental ingestion (Eilers and Kann 2002). The 2001 peak anatoxin-a concentration was determined from a phytoplankton sample obtained by towing an 80-micron mesh net. The value was later revised to an estimate of 15.0 µg/L (Kann 2005). In previous sampling from 1992 to 2000, the highest estimated density of *Anabaena flos-aquae* was 8,540 cells/mL. The summer

Table 1 - Water quality and lake morphometry for Diamond Lake, Oregon (Eilers et al. 2001; Johnson et al. 1985; Salinas and Larson 1995).

Parameter	Median	1992-1995	1967-1995
pH	8.6	7.16-9.23	7.1-9.8
Chlorophyll a (µg/L)	6.8	2.6-8.3	1.0-39.8
Total phosphorus (µg/L)	45	17-62	17-62[a]
Total inorganic N (µg/L)	64	<16-88	<16-322[b]
Silica (mg/L)	3.8	1.9-3.7	1.9-6.5
Conductivity (µS/cm)	39.8	38.3-40.9	
Alkalinity (µeq/L)	412	396-421	
Morphometry			
Lake area (ha)	1,300		
Watershed area (ha)	13,600		
Maximum depth (m)	15.8		
Mean depth (m)	7.3		
Lake volume(hm)	95.1		
Hydraulic residence time (yr)	0.6[c]-1.6[d]		
Lake elevation (m)	1,580		
Max. watershed elevation (m)	2,799		

[a] *excluding one observation of 140 µg/L 1976.*
[b] *excluding one observation of 385 µg/L 1967.*
[c] *estimate based on precipitation volume inputs for the topographic watershed.*
[d] *estimate based on surface discharge from the lake outlet (Johnson et al. 1985).*

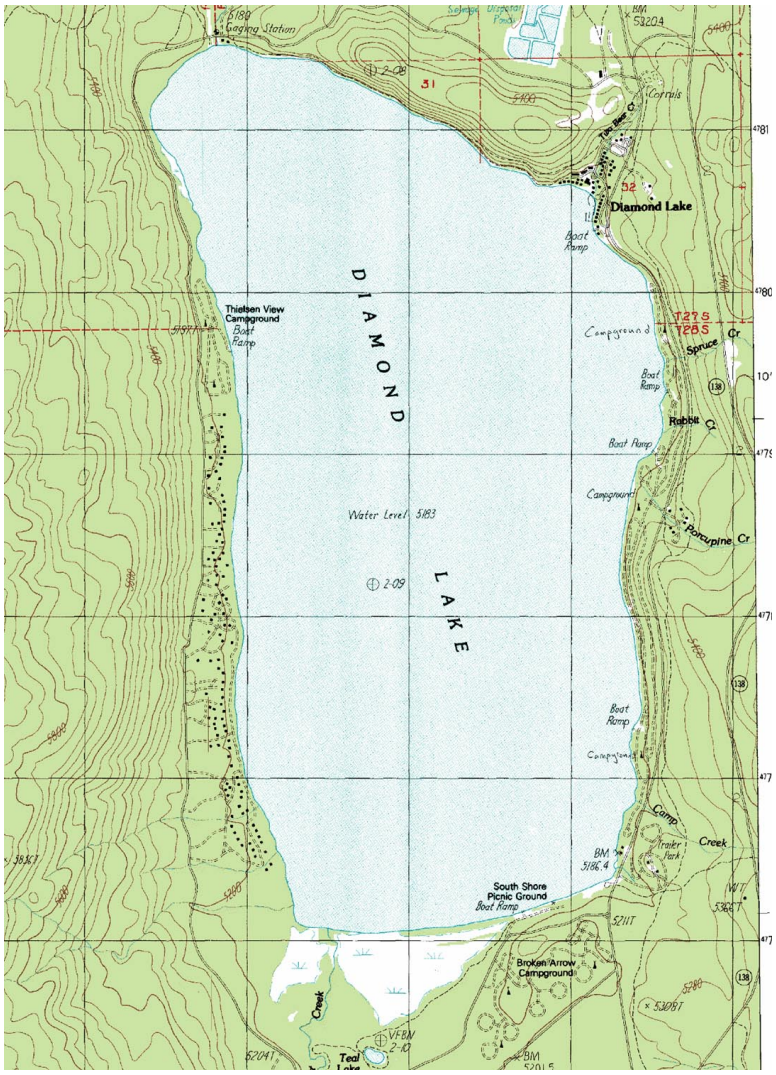


Figure 2.. Diamond Lake, Oregon map.

of 2001 was the first time since the UNF began systematic sampling of Diamond Lake, that potentially harmful blue-green algae made up 80 percent of the biomass of any given sample (Eilers and Kann 2002).

PUBLIC HEALTH ISSUES

The chalky, aqua-green appearance of the lake provided a visual clue that something was amiss with the lake, making it easier to communicate with the public and professionals alike (Figure 3). The UNF had to address several issues. These included:

1. What was the significance of the phytoplankton data, with respect to the public health threat of *Anabaena flos-aquae*?
2. If the blooms did present a public health concern, what action should be taken by the Forest Service and other agencies?
3. How should the UNF communicate with the public?
4. How should the UNF determine when the public health concern has abated?

First we needed to interpret the data. Forest Service hydrologists are not usually familiar with toxic cyanobacteria. At the time this issue arose, neither the State of Oregon nor the U.S. Environmental Protection Agency provided criteria or guidelines dealing with water pollution threats from cyanobacteria. To understand the problem, we turned to experts in the field of cyanobacteria (Dr. Jacob Kann) and cyanobacteria toxins (Dr. Wayne Carmichael). Their advice was to use the guidelines provided by the World Health Organization (WHO) regarding public health risks associated with cyanobacteria and their toxins.

The World Health Organization and American Water Works Association (Chorus and Bartram 1999; Yoo et al. 1995) recommend that blue-green algae densities exceeding 500 cells/mL should be monitored closely. This is Alert Level 1, where greater sampling frequency and

Figure 3. Diamond Lake, Oregon cyanobacteria bloom. Photo by Joseph Eilers.

spatial coverage may begin. Alert Level 2 occurs when cell densities reach 2,000 cells/mL and warnings are posted for the general public. Alert Level 3 occurs when density reaches 15,000 cells/mL and people are warned to avoid contact with lake water. Alert Level 4 is reached when blue-green algae density exceeds 100,000 cells/mL. At Alert Level 4 lakes all uses should be curtailed, including boating and fishing (Table 2). These human health guidelines are relatively conservative with respect to toxin concentrations expected at the above alert levels. However, because dense wind-driven shoreline accumulations can occur as these buoyant algal cells rapidly rise to the water surface, a sample of toxigenic algae may have a cell density from 100 to 1,000 times higher an hour later or a even few hundred yards away (Eilers and Kann 2002). Thus, these guidelines provide discrete levels of response to minimize the risk of exposure to toxic cyanobacteria.

During this investigation period we learned that there are multiple toxins produced by various species and strains of cyanobacteria, and that other countries are also coping with this threat (Chorus and Bartram 1999). The science of blue-green algae is complicated and evolving. Some species never produce harmful toxins, and some species produce toxin only at certain times. Sunlight, calm water, and warm temperatures often produce high densities of algae near the surface. Blue-green algae are most likely to produce toxin when cell density is high. The species dominant in Diamond Lake, *Anabaena flos-aquae*, most commonly produces anatoxin-a, a neurotoxin with a toxicity rivaling that of cobra venom on a mass basis (Table 3). However, *A. flos-aquae* is also capable of producing microcystin, a hepatotoxin with cumulative long-term effects. Symptoms of neurotoxin exposure include skin irritation or rash, diarrhea, nausea, cramps or general tiredness, sensations of numbness, dizziness, tingling and fainting, dermatitis and gastroenteritis (Douglas County 2004).

Occasional human illness and deaths occur around the world from cyanobacteria toxins in water. In Oregon, several dogs have died along the John Day River since 2001, and a young man died in Wisconsin in 2002 after swimming in a golf course pond (Wisconsin State Journal 2003). Toxins produced by blue-green algae can have acute and chronic effects. Mammals are vulnerable

Table 2. Guidelines for water contact and monitoring during cyanobacterial blooms (Chorus and Bartram 1999; Yoo et al.1995).

Alert Level	Cyanobacteria (cells/mL)	Advisory	Monitoring
1	500	None	Weekly phytoplankton only, increase shoreline sites
2	2,000	Avoid scums	Weekly phytoplankton and toxin at one site of maximum phytoplankton density
3	15,000	No swimming, waterskiing, or pets in water	Weekly phytoplankton and toxin at all sites with phytoplankton density greater than 15,000 cells/mL
4	100,000	Lake closed to all uses	Weekly phytoplankton and toxin at all sites with phytoplankton density greater than 15,000 cells/mL

Table 3. Comparison of toxins. Cyanobacteria toxins are in bold. From Skulberg et al.(1984).

Toxin	Source	LD_{50} (µg/kg)
Muscarine	Amanita mushroom	1,100
Anatoxin	**Anabaena**	250
Microcystin	**Microcystis**	60
Neurotoxin	Cobra snake venom	20
Aphantoxin	**Aphanizomenon**	10

to toxins, but less is known about immediate effects and bioaccumulation in fish. In 2004, the Oregon Department of Human Services advised people not to consume fish from Paulina Lake when *Anabaena flos-aquae* density was greater than 1,000,000 cells/mL (Oregon Department of Human Services 2004).

RESPONSE TO THE 2001 BLOOM

At Diamond Lake, it became clear that a real public health threat was present. The Forest Service asked for help from the Douglas County and State of Oregon health departments, the Oregon Department of Environmental Quality (ODEQ), and other scientists who had experience with blue-green algal blooms. The UNF established an incident management team with public communications, lake management, water quality and public health specialists. A plan was quickly developed and implemented based on the WHO guidelines. Water contact warnings were posted at the lake.

In order to increase the likelihood that the public response would comply with warnings, the team developed a public communications strategy. Communications involved the Diamond Lake Ranger District, Diamond Lake homeowners, and the Diamond Lake Lodge. The Forest Service and Douglas County posted signs at boat ramps, campgrounds, and entrance roads around the lake. Press releases were distributed to local and regional newspapers, television and radio. The blue-green algae bloom and the potential public health risk at Diamond Lake became well known.

The Umpqua National Forest and Douglas County Department of Health and Social Services closed two swimming beaches on 10 August. All swimming, water skiing and boating were prohibited from 17 August until 27 August, when *Anabaena flos-aquae*, anatoxin-a, and microcystin tests results showed that lake water was safe (Figure 4).

Once the public was warned, we focused our attention on monitoring cyanobacteria, in order to determine when the threat had diminished sufficiently to allow full use of the lake. Fortunately, Diamond Lake is not a public drinking water supply and monitoring only needed to address recreational contact. A monitoring program was designed (M. Jones, Umpqua National Forest, Roseburg, Oregon, personal communication, 2004) that linked the intensity and frequency of sampling to the density of the cyanobacteria. Although *Anabaena flos-aquae* density fell below 1,000 cells/mL by mid-August, water contact was restricted for 10 more days because toxins produced by cyanobacteria remain harmful after the cells have died and lysed. This additional period of safety is required during the post-bloom period. The incident management team met throughout the summer to manage water quality monitoring, public health measures, recreation activities and public information. No documented cases of human health effects from blue-green algae at Diamond Lake are known. Public health measures limited human exposure to blue-green algae during part of the bloom in 2001.

BEYOND 2001

Although the end of the bloom in 2001 provided a welcome relief from the work of responding to the

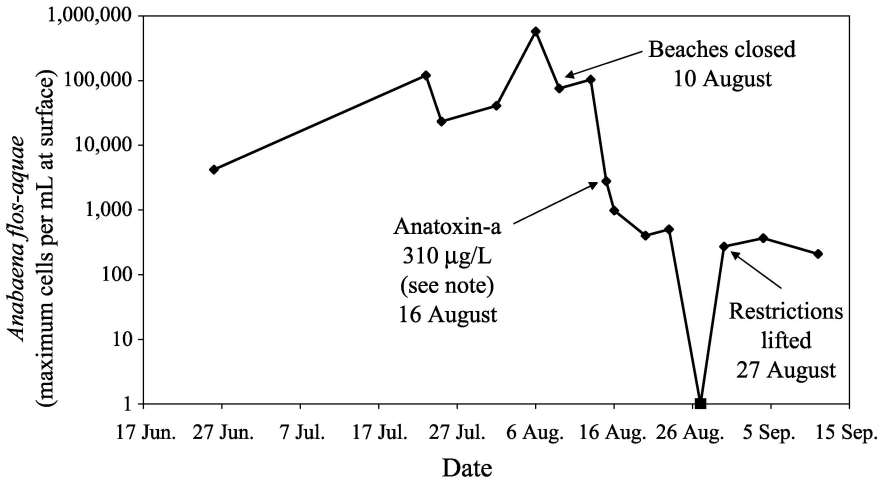


Figure 4. Cyanobacteria bloom, Diamond Lake, Oregon 2001. Anatoxin-a peak later revised to 15.0 ug/L (see text).

Table 4. History of management actions at Diamond Lake, Oregon, 2001-2004.

Alert Level	Action	Cyanobacteria (cells/mL)	Date Alert Level Reached in Each Year			
			2001	2002	2003	2004
Level 1	Begin sampling	500	26 June[a]	6 May	28 May	10 May
Level 2	Warning	2,000	10 Aug.	27 June	27 June[b]	16 July
Level 3	Water contact restriction	15,000	10 Aug.	23 July (to 7 Aug.)	1 July (to 8 Aug.)	None
Level 4	All uses (boat) restricted	100,000	17 Aug. (to 25 Aug.)	None	None	None
All Alerts Lifted			27 Aug.	31 Aug.[b]	28 Aug.[b]	27 Aug.[b]

[a] *Sampling began after Alert Level 1 (500 cells/mL) blue-green algae density was reached.*
[b] *Date is approximate, based on blue-green algae density records.*

cyanobacteria bloom, a number of questions needed to be answered before the summer of 2002. These included:

1. What was the cause of the cyanobacteria bloom in 2001?
2. Was this an isolated event or could another bloom be expected?
3. How should we monitor for blooms in the future?
4. What was the level of risk to the public?

To answer these and other questions, we needed a systematic way to organize the data collected in 2001 and earlier years. From 1992 to 2001, the UNF contracted to sample the lake about three times per summer. During 2001, the lake was sampled much more frequently and additional short-term investigations were conducted to evaluate spatial and temporal aspects of the cyanobacteria and associated water quality. These efforts by the Forest Service staff, ODFW, ODEQ, and contract scientists produced a tremendous amount of data that had not been organized. These data and others were arranged into a Microsoft Access®[1] database and interpreted in light of the questions listed above (Eilers and Kann 2002). The Access® database made it possible to both review the conditions associated with the bloom in 2001 and provide a framework for organizing data in the future. The data could then be easily shared among interested parties and researchers studying Diamond Lake.

One conclusion from the analysis of the 2001 data was that lake monitoring needed to begin earlier in the spring during rapidly changing conditions. We sampled more frequently in 2002, using pre-assigned stations for shoreline sampling when the bloom occurred. We made arrangements with phycologists for rapid analysis of the phytoplankton samples. We searched for information on cyanobacteria and prepared information sheets to answer frequently asked questions. Paleolimnological analysis of a sediment core collected in October 2000 (in a study funded by ODFW related to the effect of the tui chub) showed a strong linkage between fish populations and the abundance of cyanobacteria in Diamond Lake (Eilers et al. 2001). The serious cyanobacteria bloom in 2001 made it possible to accelerate several research projects on the lake. The result was a new bathymetric map of the lake, a map of the macrophyte beds, the discovery of ebullition zones (depressions with bubbles emerging), a substrate map of the lake, and a hydroacoustic analysis of fish abundance (Eilers and Gubala 2003).

By the time of ice-out in April 2002, new monitoring and communications plans were ready. Research was underway to better understand the relationship between fish populations and cyanobacteria blooms at Diamond Lake. The Diamond Lake Lodge cooperated by conducting daily measurements of lake transparency with a Secchi disk This low-cost information helped track phytoplankton population trends with immediate results (Figure 5).

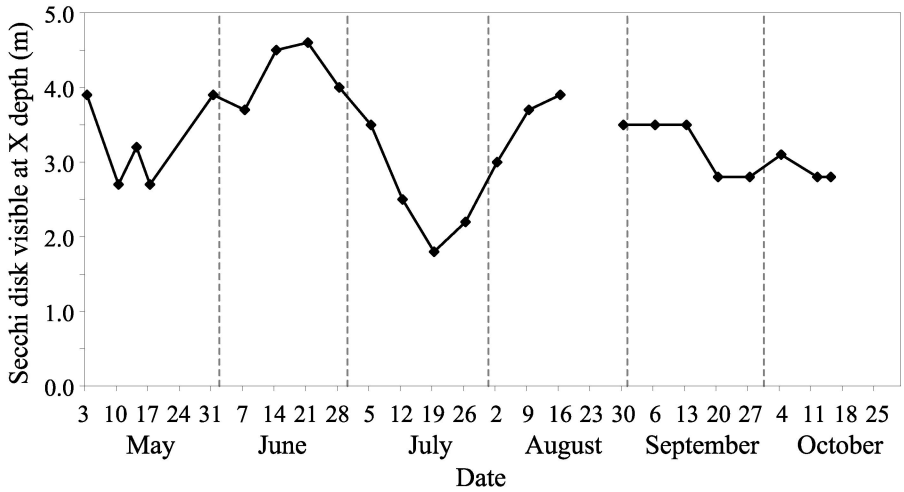
Dense blue-green algae blooms have occurred on Diamond Lake every summer since 2001. Three of four summers, *Anabaena flos-aquae* densities were higher than 15,000 cells/mL, and water contact by people and pets was prohibited for two to five weeks (Table 4).

CURRENT PROTOCOL FOR TOXIC ALGAE MONITORING AND ALERTS

From May through September Diamond Lake Ranger District collects phytoplankton samples from the center of the lake on Monday of each week. These samples are sent overnight to Aquatic Analysts laboratory for analysis of species composition and density. The results arrive the following Thursday. If *Anabaena flos-aquae* densities exceed 500 cells/mL, two additional shoreline sites are sampled the following week. If densities exceed 2,000 cells/mL, one sample is sent to Wright State University for toxin analysis.

[1]The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Figure 5. Secchi depth visibility, Diamond Lake, Oregon, 2004.



Toxin samples are collected from all sites with densities greater than 15,000 cells/mL (Table 2). Together, the Umpqua National Forest and Douglas County Department of Health and Social Services decide whether to change alert levels for the upcoming weekend.

The marina manager at Diamond Lake Lodge measures Secchi depth, water temperature and wind speed weekly, so we know quickly if algae density is increasing or decreasing.

All lake management decisions are based on blue-green algae densities, rather than specific toxin levels, because tests for phytoplankton identification and density cost about $100-250 per sample and results are available the same week. Toxin results can take as long as six weeks, and cost about $500. These samples are used to document whether toxin was present when swimmers were in the water. Cyanobacteria do not always produce toxin, even during a dense bloom. Lake managers can err by keeping people out of the water when no toxin is present, or by failing to issue warnings when toxin is present. Both errors have consequences. In the first case, people will be disappointed and business will suffer when there is little risk. In the second, people or pets may be harmed if they're exposed to algae toxin. Toxin tests are used to document whether water contact was restricted appropriately.

In order to avoid sending conflicting or complicated messages to the public, it's important not to change alert levels often. Health alerts and restrictions are the most useful when they are clear and consistent. At Diamond Lake, Level 2 advisories are usually posted June to August each summer, and a Level 3 water contact restriction issued once during the peak blue-green algae bloom. A Level 4 restriction on all lake uses, including boating, was used only once after *Anabaena flos-aquae* cell densities reached several hundred thousand cells/mL in the summer of 2001.

Water Quality Monitoring

Water quality monitoring can help recognize changes in lake ecology. In 1992, there was no reason to expect algae or water quality problems, but not much was known about Diamond Lake. The Umpqua National Forest and Rogue Community College, Grants Pass, Oregon, sampled Diamond Lake in June, July and August every summer from 1992 to 2002. Occasional March, April, May and September profiles in the deep lake center and other, shallower locations (including under-the-ice spring sample dates) were sampled in some years. Similar monitoring continues to the present.

Measurements taken in the middle of Diamond Lake in July 2004 are typical of the summer blue-green algae bloom. A Secchi disk was visible to only 1.8 meters, the surface water temperature was 20°C, and pH was 8.9. Dissolved oxygen at the surface was almost saturated at 9 mg/L (Raymond 2004). Lake pH is increasing, the lake bottom is increasingly anoxic, and algal blooms are changing nitrogen and phosphorus levels in the lake (Table 5). Algae consume the high natural phosphorus, and nitrogen fixation by blue-green algae adds organic nitrogen.

Lake biology is changing too. Introduced rainbow trout, and millions of tui chub, are feeding on invertebrates and zooplankton. Large benthic amphipods are declining, with a shift to smaller invertebrates. The lake is experiencing a loss of the large zooplankton taxa. Large cladocerans that fish prefer have disappeared. Fewer than 10 percent of the individual zooplankton in Diamond Lake in the 2003 summer were edible by planktivorous fish. The lake is now dominated by very small rotifers that are not effective phytoplankton grazers and provide little food for fish (Table 6). Phytoplankton samples also show that *Anabaena flos-aquae* are dominating the July and August algae bloom for the first time since 1992.

Table 5. Diamond Lake chemical changes.

Parameter	1900[a]	1975	2003
Lake PO_4 phosphorus	~30 µg/L	15 µg/L	0-5 µg/L
Lake TKN organic nitrogen	low	moderate	high
Surface pH	8.0	9.0	9.5
Anoxic hypolimnion	probably rare	50% of years	annual

[a] *Speculation based on paleolimnological data.*

Table 6. Diamond Lake biological changes.

Parameter	1900[a]	1975	2003
Benthos	amphipods	chironomids + amphipods	chironomids
Zooplankton	copepods	cladocerans	rotifers
Phytoplankton	chrysophytes + centric diatoms	mixed	cyanobacteria + pinnate diatoms
Macrophyte depth	~ 9 m	8 m	6 m
Fish	none	trout	tui chub

[a] *Speculation based on paleolimnological data.*

The experience acquired from 1992 to 2000 helped the Umpqua National Forest expand monitoring activities at Diamond Lake. We had already consulted knowledgeable limnologists, hydrologists and laboratories. We knew how to collect samples for physical and biological analyses, preserve the samples and interpret the results. When it was obvious that *Anabaena flos-aquae* presented a health risk to swimmers, we were able to collect algae and toxin samples and get results quicker.

Lessons Learned

Dense blue-green algae blooms have occurred on the Diamond Lake every summer since 2001. In three of four summers, *Anabaena flos-aquae* densities were higher than 15,000 cells/mL, and water contact by people and pets was restricted. Visitors to Diamond Lake Lodge and Forest Service campgrounds, and 100 summer home owners accommodate these restrictions by avoiding water contact, fishing from docks and boats, and following press releases to decide what activities are safe. The Umpqua National Forest and the Douglas County and Oregon health departments work together each summer to keep Diamond Lake open for all uses except when there is a risk to public health. Together, the agencies restricted swimming for up to five weeks during the summer since 2001 and no human health effects were documented.

The Umpqua National Forest now has a clear monitoring scheme and guidelines for swimming restrictions, so we can tell visitors quickly when there is a potential risk from cyanobacteria toxins. In 2001, we learned the value of recognizing a problem quickly, working with health officials, and using clear guidelines to tell the public what we knew.

Blue-green algae blooms can appear suddenly, and can be a serious health risk. We offer the following advice to others with potentially harmful blue-green algae blooms:

- Give lake managers the information they need to make good decisions in the midst of controversy. Blue-green algae blooms in water bodies that are used for drinking water may present the highest risk of exposure to toxins.
- Get help from experts, and work together with state and local health departments. Use the incident command system in emergency situations.
- Use clear guidelines. Health departments are trained to handle public health situations. Develop standard signs, warnings, and press releases.
- Increase sample frequency and sample locations as risk increases. If you have a routine monitoring program, you'll know where to send samples and what the results mean. Write a monitoring plan and document the research you used.
- Develop monitoring protocols, use quality control procedures, and manage your data. That includes keeping a record of when warnings were issued and when they were lifted.

Our experience at Diamond Lake is one example of how water quality monitoring can help recognize water quality problems and protect public health on National Forests.

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