MaxDepth Aquatics, Inc.

Chemical and Biological Metrics
For Assessing the Condition of
Diamond Lake, Oregon

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ABSTRACT

A revised lake condition index was developed to better reflect changes in water quality in Diamond Lake as a function of trout stocking and introduction of non-controlled invasive species. The revised index is comprised of twelve individual metrics of lake condition representing four elements of lake ecology: water quality, primary production, secondary production, and fisheries. Redundant indicators of each of the four elements are offered because they allow for the lake index to be computed with incomplete data, if necessary. Index scores for many of the metrics have been revised based on data collected in 2007, following the rotenone treatment in 2006. Additionally, some of the previous metrics have been eliminated in favor of introducing metrics that reflect important species in Diamond Lake. Phytoplankton biovolume was eliminated and substituted with Anabaena density and percent rotifers or edible zooplankton was replaced with the density of large Daphnia species. Three metrics for fish condition, growth rate, K-factor, and survival, have been added, because they provide additional insight into potential competition from invasive species. However, from the perspective of assessing lake condition (dependent variable) to fish stocking (independent variable), it may be best to compute the lake index without the inclusion of the fish metrics.
INTRODUCTION

From the late 1980s until September 2006, tui chub were present in Diamond Lake, a repeat of the process that occurred from circa 1940 to 1954 (Eilers et al. 2007). Although little is known about the response of Diamond Lake from measurements in the earlier period, except for reduction of benthic macroinvertebrates, a considerable amount of information was collected following documentation of the second introduction of tui chub to Diamond Lake in October 1992. The data that was collected during this period through efforts of the Oregon Department of Fish & Wildlife (ODFW) and the USDA-Forest Service (USFS) helped to document the loss of much of the benthic invertebrates, the reduction in large cladocerans and copepods, and the increase in cyanobacteria and associated water quality problems.

Although the information base on Diamond Lake is very limited prior to 1971 with the inception of the study by the US Environmental Protection Agency (Lauer et al. 1979), several paleolimnological investigations provide insight into the changes that have occurred in Diamond Lake during the 20th century (Meyerhoff et al. 1978; Eilers et al. 2001; Eilers et al. 2007). The paleolimnological studies revealed that water quality changes, as indicated by changes in diatom community composition, occurred in Diamond Lake prior to the first introduction of tui chub and appeared to be associated with early stocking of rainbow trout circa 1910 (Eilers et al. 2001).

During discussions leading up to the rotenone treatment of Diamond Lake in 2006, concern was expressed that high rates of trout stocking following eradication of the tui chub could continue internal loading of nutrients and thus sustain undesirable levels of water quality. ODFW plans to continue to stock trout at rates that are in concert with lake water quality goals and provided funding study to help guide future trout stocking efforts (Eilers 2003). It was recognized that this document was constrained from the viewpoint that the amount and
types of data available for assessing the water quality condition in Diamond Lake in the absence of tui chub was limited primarily to the EPA study (Lauer et al 1979). This report provided useful information, but it was limited for the purposes of guiding trout stocking decisions because zooplankton data were lacking, there were high detection limits for some of the analytical data, and limited information on fish growth rates were readily available. Consequently, the initial guidance document for trout stocking stated that “The index is subject to change as new data becomes available”. Important data has become available since the Eilers (2003) report and are derived mostly from 2006 and 2007.

The purpose of this report is to revisit the metrics proposed by Eilers (2003) and reassess available information based on the recent years of data, with particular emphasis on the 2007 data. Once again, the metrics proposed in this report should be periodically reviewed and revised, as needed, if future data provide better insight into the processes that affect the water quality in Diamond Lake.

**APPROACH**

The approach employed here is similar to that used in 2003 which identified three tasks:

- Compilation and analysis of data on Diamond Lake
- Compilation and analysis of fish-stocking studies on other lakes
- Integration of these information sources into a revised stocking strategy.

In addition, it is also necessary to review how the earlier fish-stocking indices performed in identifying water quality problems and to determine if those metrics need to be revised or deleted. One of the major omissions in the earlier stocking indices was any incorporation of fish condition. Metrics of fish condition were not included in the earlier document because the presence of the tui chub obscured trout performance that was expected without the chub.
Consequently, we needed to wait until 2007 to measure what was believed would be an indication of actual recovery levels for optimal growth rates for trout under a chub-free scenario and the lake’s overall ecological condition shortly after a rotenone treatment.

The 2003 draft index identified nine metrics for assessing water quality changes associated with fish stocking, but other than the desire to incorporate metrics that represented different time scales for response, there was little conceptual linkage among the metrics. We sought to improve upon this through better organization of the metrics by response groups and thus lend some additional clarity to the stocking guidance. We re-assessed the metrics using the following criteria:

- It must reflect some ecological response
- It can be measured repeatedly
- It can be measured with existing technology
- It can be measured with reasonable cost
- As a group, they should reflect a variety of important processes
- They should be scientifically robust, yet have results that can be understood by an informed public.

The key elements of lake condition that we thought should be incorporated into the measurement process included water chemistry, primary production, secondary production, and fisheries. Another component which we thought should be incorporated into the new stocking index should be an assessment not only of current status, but also of trend.

**REVIEW OF ECOLOGICAL METRICS FOR DIAMOND LAKE**

The four components of lake condition that should be reflected in the stocking index are (1) water chemistry, (2) primary production, (3) secondary production, and (4) fisheries. Metrics for water chemistry are desirable because they can be readily measured, relate directly to
issues of lake condition, and are the factors identified in the 303(d) list for water quality factors not meeting water quality standards. The 2003 guidance document listed pH, summer epilimnetic dissolved oxygen (percent saturation), and hypolimnetic dissolved oxygen (expressed as the minimum depth in the water column with DO $\leq$ 1.0 mg/L). We considered other chemical parameters such as nutrients (total phosphorus, ortho- phosphorus, total nitrogen, etc.), but rejected these because it would be possible to have increases in nutrient concentrations and improving water quality conditions. For example, phosphorous concentrations in the lake could increase if uptake rates of phytoplankton decline. Other factors that favor using in-situ metrics is that analytical chemistry is costly and there can be a considerable delay in receiving the results. Thus, we see no rationale for altering the three metrics originally proposed for lake chemistry.

The three metrics proposed for representing primary production-related aspects of the lake were summer epilimnetic chlorophyll $a$ concentrations, Secchi disk transparency, and summer epilimnetic phytoplankton biovolume. Chlorophyll $a$ remains a valuable metric because it is a reasonable integrator of phytoplankton standing crop and because it relates to DEQs’ guidance criteria and the Diamond Lake TMDL. Secchi disk transparency is easy to collect and relates directly to peoples’ perception of water quality.

Phytoplankton biovolume is more problematic. There were high phytoplankton biovolumes for selected periods in 2006 and 2007, but much of the abundance was associated with diatoms and not cyanobacteria (Figure 1). Furthermore, algae abundance per se has not been the problem in Diamond Lake. It has been the high densities of cyanobacteria ($Anabaena$) that have been responsible for the lake closures and declaration of “nuisance algae” conditions causing Diamond Lake to be placed on the 303(d) list. We conclude that the use of phytoplankton biovolume does not directly relate to the historical water quality problems in the lake and this metric should be substituted for one reflecting problems associated with cyanobacteria. We propose using cell densities of $Anabaena$ as a more appropriate metric in
lieu of total phytoplankton biovolume. *Anabaena* has been a critical species in the lake and its return to dominance would provide strong indication that internal loading had once again become a serious problem.

![Figure 1. Algal biovolume from 1 m samples collected at site DLA in 2006 and 2007.](image)

The three metrics originally chosen to represent secondary production were benthic biomass, percent amphipods, and percent rotifers/edible zooplankton. Benthic biomass has been shown to relate well to the degree of exploitation of the resource by tui chub. Also, it has been used as an indication of trout stocking pressure on the food base up until 1980 when ODFW switched to use of a fish condition factor as a less-expensive method of determining whether the food base was adequate. Benthic biomass was highly responsive to tui chub
exploitation in the 1940s and 1950s and starting again in 2002 (Figure 2; Truemper 2007). We expect that it will also be responsive to over-predation by trout as it appeared to be in the 1960s.

![Benthic Biomass in Diamond Lake](image)

Figure 2. Biomass of benthic macroinvertebrates in Diamond Lake from 1949 to 2007.

There are a variety of potentially important species of benthic macroinvertebrates in Diamond Lake that historically have served as indicators of fish predation, including snails, leeches, and amphipods. However, the fisheries biologists have noted that the amphipods, in particular, have been an important food source for trout and were also among those taxa that were rapidly eliminated by the tui chub. Only two amphipod individuals were sampled in Diamond Lake from 2004-2006 (Truemper 2007). In contrast, 678 amphipods (all *Hyalella sp.*) were sampled in Diamond Lake in October 2007 (Eilers 2007). Consequently, we feel
justified if retaining some metric of amphipods as an indicator of fish predation on the benthic community. The current metric is amphipods as a percentage of the total number of benthic organisms sampled. As more is learned about the ecology of amphipods in Diamond Lake, other metrics such as amphipod density might prove to be better indicators.

The last original indicator proposed for secondary production was percent rotifers or percent “edible” zooplankton, where “edible” was defined by Dr. Allan Vogel in his taxonomic analysis. We have observed that the use of percent rotifers is not suitable because it doesn’t necessarily reflect the actual amount of zooplankton available for trout consumption. In addition, the rotifer population in Diamond Lake has been highly variable in 2006 and 2007 (Figure 3). One could still have a high percentage of rotifers in the zooplankton population, yet still have abundant densities of large cladocerans present which was the case in 2007. The use of percent “edible” is problematic because there is no universal agreement on what species constitute edible zooplankton taxa. Thus, the concept of “edible” could vary among taxonomists, a feature that is not conducive to a stable long-term indicator. We propose to substitute two other important species to represent the condition of the zooplankton community: *Daphnia pulicaria* and *Daphnia rosea*. These are large cladocerans that have not been present in densities greater than 1000 individuals/m³ in Diamond Lake since 1995, but appeared in great numbers in 2007. Their abundance is important because these two species have high algal grazing rates and because they serve as a major food source for trout.
ADDITION OF TROUT ATTRIBUTES TO THE FISH STOCKING INDEX

The original Diamond Lake fish stocking index did not incorporate elements of the fishery into the assessment of lake condition. Numerous other investigators have included metrics of fish populations in defining the ecological condition of lakes and streams because as the top predator in the lake, fish serve as an important integrator of ecological processes. This deficiency should be rectified by the incorporation of three metrics for the introduced trout population: trout condition, trout growth rate, and trout survival. Trout condition is expressed as a “K” factor which is defined as:

\[ K = \frac{100 \times W}{L^3} \]
where $W$ is weight of fish in grams and $L$ is fork length of fish in centimeters. Essentially, the $K$-factor provides an indication of how the fat the fish appears. Historical measurements of the $K$-factor of fish from Diamond Lake have ranged from 0.87 to 1.89, with an average value of 1.35. The management goal for trout in Diamond Lake is to maintain a $K$-factor between 1.3 to 1.4 for catchable-size trout (> 8 inches). The $K$-factor has already proven insightful in Diamond Lake (albeit, in retrospect) because the average value had declined to 1.1 in 1996, one year after tui chub were found in detectable numbers in the lake.

Growth rate of the stocked trout is a second proposed metric for assessing fish condition in Diamond Lake. Growth rates are based on the increase in trout length between the time when the fingerlings (typically 3-4 inch fish) are stocked in June and when they are sampled again in October. Diamond Lake historically had a management goal of 4 to 6 inches of growth for stocked fingerling trout. Values substantially less than this are indicative that competition for food resources has become acute and either the stocking density needs to be reduced or other factors (such as introduced tui chub) are contributing to the low growth rates.

The survival rate represents total mortality, including those fingerlings large enough to be caught and retained from the previous fall for those years (such as 2007) where growth rates were high. The survival rate reflects a variety of unmeasured losses of trout from disease, predation by osprey, predation by otters, out-migration to Lake Creek, and losses associated with angling mortality.

Thus, the conceptual approach for the revised fish stocking index includes monitoring for the four major groups of lake condition and three metrics for assessing the lake condition under each of the four headings (Figure 4). Once the metrics have been identified, the next step is to allocate a response curve for each of the metrics.
RATING METRICS OF LAKE CONDITION

The rating metrics from the 2003 report were used as a starting point for developing a table of values for ranking the condition of the lake. One change was to reverse the values so that high index values represented high water quality (Table 1). Thus an index value of 10 represents the highest water quality rating attainable for an individual metric. For the six...
metrics of water quality and primary production, we have based the metrics on samples collected in the centroid of the lake (site DLA) at a depth of 1 m, where applicable. Metrics were evaluated for measurements collected during open-water periods (April-November), but the final rankings were based on summer values which are defined here as June through September.

Table 1. Proposed index values for assessing current status of Diamond Lake
<table>
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<tr>
<th>Metric</th>
<th>Water Chemistry</th>
<th>Primary Production</th>
<th>Secondary Production</th>
<th>Trout Fisheries</th>
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<td>Epi-DO</td>
<td>Hypo-DO</td>
<td>Chlorophyll</td>
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<td>Median, % Sat.</td>
<td>Min, meters</td>
<td>Median, µg/L</td>
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**pH:** The range for pH was reduced from 7.9-9.9 to 8.0-9.5 and the chosen statistic was median, *in-situ*, epilimnetic (1 m) pH measured between June through September. pH values change over a 24-hr period, but it is assumed that most of the water quality sampling occurs during or near the afternoon, which should reasonably reflect the higher rates of photosynthetic activity during the day. The range is skewed to reflect the desire to keep pH values at or below 8.5, the water quality standard for Diamond Lake. pH values near 7.9 reflect what the expected pH of the surface waters of Diamond Lake would be given the concentration of alkalinity. Values higher than this reflect decreased concentrations of carbon dioxide attributed to photosynthetic activity. For 2006, all surface pH values measured from June-September exceeded 8.5, whereas in 2007, only one major excursion above pH 8.5 was observed (Figure 5).

![Figure 5. Surface (1 m) pH values from Diamond Lake in 2006 and 2007. The red line represents the water quality standard for Diamond Lake.](image-url)
**Dissolved Oxygen (percent saturation):** The range for dissolved oxygen (DO) was reduced from 80-140 percent to 85-105 percent and the chosen statistic selected was median, *in-situ*, epilimnetic (1 m) DO saturation measured from June through September. DO values also exhibit strong diel behavior and as with pH, we assume that most of the field data will be collected during or near the afternoon. The percent saturation for distilled water at the elevation of Diamond Lake is about 83 percent (this will vary slightly with changes in atmospheric pressure). Values greater than this reflect oxygen generated by photosynthetic activity that has not yet equilibrated with the atmosphere. The data show that under conditions of high primary production, as observed in 2006, dissolved oxygen saturation can often exceed 100 percent in Diamond Lake, but that when phytoplankton biomass was reduced in 2007, DO saturation never exceeded 93 percent (Figure 6).

![Dissolved Oxygen Graph](image.png)

Figure 6. Dissolved oxygen (percent saturation) in Diamond Lake at a depth of 1m for 2006 and 2007.
**Depth To Anoxia:** Once a lake stratifies, the hypolimnion has limited ability to mix with surface waters and thus acquire additional dissolved oxygen. Consequently, the degree of oxygen depletion in the hypolimnion is a measure of the consumption of oxygen by bacteria in the process of decomposing organic matter in the sediment or from dead phytoplankton cells (and to a lesser degree zooplankton) sinking into the hypolimnion. We have represented this hypolimnetic oxygen consumption as the depth (in meters) to which oxygen concentrations are less than 1 mg/L. We modified the original range from 7-14 m to 6-12 m to reflect the minimum values that were measured in Diamond Lake in 2001. In 2007, the depth to anoxia (defined as ≤ 1 mg/L) was 11 meters (Figure 7).

![Figure 7. Selected profiles of dissolved oxygen in Diamond Lake in 2007. Minimum hypolimnetic DO occurred on or about August 6, 2007.](image)
**Chlorophyll a:** Chlorophyll $a$ is an indicator of the standing crop of phytoplankton present. Although there is no water quality standard in Oregon for chlorophyll, there is a guidance value of 10 µg/L to reflect the upper concentration desirable in a lake. Chlorophyll values over 50 µg/L have been measured in Diamond Lake in recent years (Figure 8). We have modified the original range from 1-60 µg/L to 2-22 µg/L and selected the statistic chosen was the median, epilimnetic (1 m)value measured from June through September.

![Figure 8. Concentrations of surface (1 m) chlorophyll a in Diamond Lake for 2003, 2006, and 2007.](image)

**Secchi Disk Transparency:** Secchi disk transparency is an easy variable to measure and provides some of the same information as chlorophyll, although transparency is subject to problems associated with time of measurement, wind and wave conditions, and ambiguities associated with the size of phytoplankton cell or colonies present. Nevertheless, because it is easily understandable and is low-cost to measure, it is a valuable metric for water quality.
The statistic selected for transparency is the median value (reported in meters) measured from June through September. The original range was expanded slightly from 1.5-7 m to 1-8 m. Data from selected years illustrates how responsive Diamond Lake can be to changes in fish community composition (Figure 9).

![Secchi disk transparency in Diamond Lake for 2001, 2006, and 2007.](image)

**Anabaena Cell Density**: The original metric for representing phytoplankton abundance directly was to use total epilimnetic biovolume. Upon further review, we rejected this metric because it didn’t necessarily relate to the primary concern in Diamond Lake which is the abundance of cyanobacteria. The metric could have been extended to include all cyanobacterial taxa, but historically all cyanobacteria blooms have been associated with *Anabaena*. If other taxa, such as *Gloeotrichia*, were included in the metric, a single colony of *Gloeotrichia* in the analysis of phytoplankton community composition would unduly skew
the results. There are two approaches that could be pursued for representing *Anabaena* cell density: (1) use of median, summer, epilimnetic values, or (2) use of maximum density measured in the lake center. The use of the median value will reflect the central tendency, but the management concerns may best be represented in this case by the extreme condition. Consequently, we recommend using the summer, epilimnetic (open-water, not shore sampling) maximum *Anabaena* cell density from a depth of 1 meter. Considering the uncertainty in taxonomy of *Anabaena* (St. Amand et al. 2007), we recommend that these counts be based on the genus. The data from 2006 and 2007 suggest that this metric is a sensitive indicator of conditions in Diamond Lake (Figure 10).

![Figure 10. Density of *Anabaena* spp. in Diamond Lake in 2006 and 2007.](image)

**Large Daphnia Density:** The original index metric for zooplankton that would be readily consumed by fish was represented by the percent of “edible” zooplankton as defined by Dr.
Allan Vogel. The edible taxa are based on the professional judgment of Dr. Vogel. We have no reason to doubt the accuracy of this classification, but this classification has not been reviewed or published and thus is difficult to reference or defend. However, since the dominant edible taxa in Diamond Lake are the large cladocerans, it would be easy to identify those taxa explicitly and base the metric on these organisms. The two largest *Daphnia* currently present in Diamond Lake are *D. pulicaria* and *D. rosea*. Using the sum of these two taxa, based on vertical tows from the deepest area of the lake, appears to provide a reasonable indication of the predation pressure on the zooplankton community (Figure 11).

![Figure 11. Density of *Daphnia pulicaria*+ *Daphnia rosea* in Diamond Lake from 1992 to 2007 based on vertical tows using a 64 micron mesh net.](image)

**Amphipods**: Amphipods historically were a major component of the benthic biomass and are a preferred food for trout. Amphipods (as a percent of the total benthic invertebrate sample based on 23 sites, excluding shoreline sampling) have increased from less than five
individuals to over 600 animals in the total sample. However, their percentage of the total benthic invertebrate sample remains low. We are unclear if amphipods require a longer period to recover from the high rates of predation under the tui chub or whether the response of other benthic macroinvertebrates has been so great as to keep the percent of amphipods low. Another possibility is that ODFW staff are now doing a more thorough job of sorting specimens from the sample compared to the methods used in earlier years. This would yield a higher percentage of smaller organisms causing the sample to be biased relative to the OGC methodology. We have adjusted the scaling from the original range of 1-60 percent amphipods to 0-30 percent to reflect this possible undocumented change in methods. This metric will need to be followed to ascertain if further adjustment is warranted. Note that this metric is based solely on the October benthic sample to be consistent with historical approaches for assessing trout predation of the benthos in Diamond Lake.

**Benthic Biomass:** Benthic biomass was not included in the original index, but is included here because of its response to predation by fish, which should translate to other components in the lake food web. Additionally, there is considerable historical data on benthic biomass in Diamond Lake that should allow managers to judge the effects of over-stocking of trout or introduction of a non-trout invasive. The benthic production is scaled to encompass the range of values measured from 1949 to 2007. This value is determined from the October sampling using the methodology described by Truemper (2007). The data show that the benthic biomass showed a steady recovery through 2007 (Figure 12).
**Trout Growth Rate:** Trout growth rate is based on fork length of trout measured at the time of stocking in June to capture in net sets in October of the same year. The management goal for Diamond Lake fish growth historically has been 5 inches (± 1 in) for that four month period. Values approaching 3 inches have generally indicated less than satisfactory growth attributed to either over-stocking or competition from invasive species. Fingerling growth rates averaged 7.6 inches from June 12 to October 31, 2007, which was an average rate of 1.7 inches per month.

**K-Factor Rating:** The K factor is a biological index that reflects the relative plumpness of a rainbow trout, whereby the larger the K factor, the “fatter” the fish for a given length. The trout stocking management goal for Diamond Lake is to achieve a K factor of at least 1.35 (±
The historical K factors for trout in Diamond Lake illustrate that this metric is sensitive to invasive species, such as tui chub which presumably was introduced prior to 1990. The K factor increased considerably from 1960 to 1975, but apparently this was at the expense of benthic organisms that experienced a decline during this period (Figure 13). By accepting a lower K factor from 1975-1985, the benthic biomass recovered. The sharp decline of the K factor starting in the late 1980s coincides with the introduction of the tui chub and the likely decline in benthic biomass. The average K factor in 2007 was 1.51

![Figure 13. Trout condition (K-factor) in Diamond Lake from 1960 to 1997. The three periods represented by the different line fits of the observed data are discussed in the text.](chart)
**Trout Survival:** The trout survival rate is calculated as the percent of trout fingerlings that survive from stocking to the spring of the following year. Consequently, we will have no data for this metric until spring 2008. The number of yearling trout present in the lake is based on creel census data from the subsequent year. The survival rate represents total mortality, including those fingerlings large enough to be caught and retained from the previous fall for those years (such as 2007) where growth rates were high. Because of the lag in determining trout survival, its utility as a warning of ecological response is limited. However, trout survival remains an important metric for long-term evaluation of the success of the trout fishery.

**COMPUTATION & INTERPRETATION OF LAKE CONDITION INDEX**

The index is calculated by summing the individual component scores and dividing by the number of components used in the calculation to yield an average index value (Figure 14). However, we believe that the composite index value will be of less value to managers than the individual component scores and trends in component scores. This is because information is lost as different metrics are consolidated into one number. Furthermore, unless there are drastic changes, such as that associated with the rotenone treatment, we would not necessarily expect all metrics to respond similarly to modest levels of perturbation. Also, having a fast growth rate of trout or a high K Factor might yield negative responses with regard to zooplankton density or benthic invertebrate biomass. Consequently, it may be desirable under some conditions to separate the response of the trout from the responses of the other lake condition components. This will provide managers with information for optimizing for a reasonably balanced lake ecosystem, while still achieving adequate target goals for the fisheries.
Another feature of the revised index is that component values can be weighted to reflect either the amount of data used to compile that component score or the perceived importance of that metric to characterizing the condition of the lake. For example, if funding for lake monitoring declines and only several samples are analyzed for chlorophyll, then the weight of this component could be devalued compared to another metric, such as Secchi disk transparency, where more frequent measurements might be available.

Figure 14. Bar chart of index results from 2007 for Diamond Lake. The “All” bar shows the median index value for all index values and the “All-no fish” bar shows the same, excluding the fisheries components.
REFERENCES


