Relationship Between Chlorophyll *a* and Beneficial Uses

TO: Snake River Use Refinement Project Sponsors

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The Snake River Use Refinement project is evaluating appropriate beneficial uses and related water quality criteria and/or targets for the Snake River mainstem from river mile 409 (Idaho/Oregon border) to river mile 285 (Brownlee Dam). This Use Refinement project is intended to inform the ongoing Snake River-Hells Canyon (SR-HC) Total Maximum Daily Load (TMDL) process.

This memorandum summarizes a review of scientific literature related to chlorophyll *a* (chl *a*) and its effects on beneficial uses, specifically on human uses and fisheries. United States and Canadian standards related to chl *a*, and the basis for developing them, were also reviewed to assist in this evaluation.

Literature Review Process

A literature review was performed with the following databases: Aquatic Sciences and Fisheries Abstracts, Biological and Agricultural Abstracts, Biosis, Expanded Academic Index, Applied Science and Technology Abstracts, Compendex Engineering Index, and Web of Science. Keywords used in the search included: fisheries, fish, chlorophyll, algae, phytoplankton, dissolved oxygen, criteria, nutrients, aesthetics, impairment, and nuisance. Additional literature was derived from references cited in the ***Nutrient Criteria Technical Guidance Manual*** (USEPA 2000).

In addition, several states were contacted directly (Debra Sturdevant, Oregon Department of Environmental Quality [ODEQ] and Steven Heiskary, Minnesota Pollution Control Agency [MPCA]) to obtain background information on how standards were (or will be) developed.

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Literature data related to human uses (aesthetics and swimming) and aquatic life uses (fisheries) are summarized below.

Aesthetics and Swimming

Human perceptions of aesthetics and swimability are subjective and dependent on the expectations and tolerances of the public. One way to quantify the effect of chl *a* on these uses is to survey users of a waterbody and correlate their response to water quality variables (e.g., chl *a*, Secchi disk depth, and phosphorus). This method has been used by several authors. Heiskary and Walker (1988) collected user perception data from three groups of lake monitors in Minnesota: 1) MPCA staff, 2) Metropolitan Council staff, and 3) citizen lake monitors. This paper was intended to set out the methodology for evaluating user data and had only analyzed data from MPCA staff. User surveys were used to define the level of chl *a* that was considered a nuisance or non-swimmable level. Professional judgement was then used to determine how often the nuisance level could be exceeded. Statistics of lake monitoring data were used in the last step for a group of lakes or an individual lake to identify a ***mean*** chl *a* level such that a nuisance level will not be exceeded more than "x" times or percent in a given year (see below: **How Chl *a* Standards or Guidance Values are Expressed**). Based on this methodology, the authors proposed preliminary, state-wide chl *a* criteria from MPCA staff surveys as shown in Appendix A (Figure A-1, Heiskary and Walker, 1988).

Smeltzer and Heiskary (1990) further evaluated all the Minnesota data collected in the Heiskary and Walker (1988) paper and additional user surveys from Vermont. By pooling this larger data set, they were able to divide user survey data in a state by ecoregion. The survey responses revealed that there are regional differences in user perceptions of lake water quality with regard to what level of chl *a* is considered eutrophic (e.g., people in northern Minnesota expected greater clarity than people in southern Minnesota and hence their view of eutrophic was different). The perception of impaired was also different in Vermont when compared to Minnesota. In Vermont where the average Secchi depth is 4.6 m, a lake with a 2.6 m Secchi disk depth was viewed as slightly impaired. In contrast, the median Secchi depth in southwestern Minnesota lakes is 0.8 m and a Secchi depth of 1.9 m is considered "crystal clear."

User survey responses from MPCA staff were used to assign four support levels of the "swimmable" designated use (Smeltzer and Heiskary 1990). The four support levels are presented in Table 1. MPCA staff equated each support level with a particular frequency of high algal levels.

TABLE 1
State-Wide (MN) Swimmable Designated Use Support Levels (Smeltzer and Heiskary, 1990)

Support Level	Frequency of High Algal Levels (%)
Fully Supporting	<10
Fully Supporting-Threatened	11-25
Partial Support-Impaired	26-50
Non-Support-Impaired	>50

The user survey approach developed in Minnesota and Vermont was later applied to Lake Pepin, Minnesota-Wisconsin (Heiskary and Walker 1995). Lake Pepin is a run-of-river reservoir on the Mississippi River. From user survey data (survey recipients were part of the citizen lake monitoring program for Lake Pepin) collected for Lake Pepin, a ***mean*** chl *a* concentration of >30 µg/L was defined as "swimming impaired", chl *a* >40 µg/L was "nuisance", and chl *a* >60 µg/L was "severe-nuisance." The ***mean*** summer chl *a* goal was set at 30 µg/L. This goal was set as a mean value to minimize the frequency of algal blooms that can be defined as nuisance (chl *a* >40 µg/L) or severe nuisance (chl *a* >60 µg/L). The acceptable frequency of nuisance or severe nuisance conditions for a particular ***mean*** summer chl *a* level was predicted with a statistical model derived from monitoring data.

Types of Algal Species

As discussed above, chl *a* values have often been used as an indicator of use attainment. However, it is also commonly recognized that the types of algal species present and their relative abundance can be an important consideration (USEPA 2000). In particular, blooms of blue-green algae are often the most problematic because of their ability to form surface scum, clog water intakes, produce toxins, and adversely affect the taste and odor of water body (Smith 1985, Pitois 2000) and have been identified by the Idaho DEQ as "…prominent population types in major algae blooms in the Upstream Snake River and Brownlee Reservoir segments…" (SR-HC TMDL; October 5, 2001; Nutrient Loading Analysis).

Our search of the scientific literature did not reveal studies that attempted to develop chl *a* standards as correlated with blue-green nuisance conditions. However, several studies were found that developed models for lakes relating total phosphorus (TP) concentrations to: 1) percent blue-green algae (Trimbee and Prepas 1987), 2) biovolume of several blue-green types (Smith 1987), and 3) blue-green biomass (Smith 1985). However, these studies generally did not attempt to define percent, biovolume, or biomass values that would constitute specific types of impairment or nuisance condition (other than the suggestion by Smith (1985) that the summer mean blue-green biomass should not exceed 1.5 grams per cubic meter to avoid nuisance odors).

A qualitative conclusion that can be drawn from these studies that may be relevant to the SR-HC TMDL is that, over the range of TP concentrations present in the Upstream Snake River and Brownlee Reservoir segment, reductions in TP would be expected to lead to reductions in the percent, biovolume, and biomass of blue-green algae. The magnitude or significance of potential reductions cannot be estimated with the above models because they were developed for lakes rather than rivers/reservoirs. However, this may be important as the adaptive management elements of the TMDL are implemented over time.

Fisheries

Balancing the use of reservoirs and lakes for recreation, such as swimming and boating, with fishing purposes has recently gained greater exposure. In the Fall 2001 North American Lakes and Reservoir Management quarterly publication, ***Lakeline***, fisheries scientists John Ney and Michael Maceina highlighted the effect of nutrient reductions on fisheries. Appendix A includes tables and figures from various articles that have examined the relationship between total phosphorus or chl *a* and a number of metrics related to fish population.

Large reductions in fish populations have been documented for reservoirs with reduced nutrient inputs (Axler et al. 1988, Ney 1996). It has also been documented that overall fish yields can increase to chl *a* levels as high as 100 μg/L (Figure A-2, Ogelsby 1977). The conclusion that fish standing stock or biomass increases with greater nutrient and chl *a* levels is further supported by a study of Appalachian reservoirs by Ney et al. (1990). In this study, greater total phosphorus (up to 80 μg/L) was significantly correlated with greater fish standing stock (Figure A-3, Ney et al. 1990).

Fish biomass can also affect the effort required to catch sportfish by anglers and by electrofishing. For example, Tables A-1 and A-2 (Maceina 2001) show that total fish biomass was greater in Alabama reservoirs with higher chl *a* and the hours required to catch a large bass (electrofishing) was less. Maceina (2001) also evaluated the effect of phosphorus reductions on fishing success in West Point Reservoir. It was noted that the weight of fish caught declined and the effort to catch a bass >2.27 kilograms (kg) increased from 100-200 to 500 hours. A study of tournament catch data from 27 Alabama reservoirs (Hendricks et al. 1995) showed that the average weight of black bass caught during tournaments increased with an increase in chl *a* (Figure A-4, Hendricks et al. 1995). Although it appears in Figure A-4 that the weight of bass caught levels off at chl *a* concentrations between 15 and 20 μg/L, this same study also indicated that the hours required to catch a bass >2.27 kg continued to decrease at levels higher than 25 μg/L.

It can not be assumed that a decrease in trophic state will reduce the proportion of rough fish to sport fish. Bayne et al. (1994) showed that the percent composition of sport fish was largely the same in eutrophic and oligotrophic Alabama reservoirs but the total weight of sportfish was greater in the eutrophic reservoirs (chl *a* = 10.3-27.3 μg/L in the eutrophic reservoirs). In this same study, the number of black bass caught by electrofishing was significantly less (25 fish/hour) in the less eutrophic reservoir (chl *a* = 10.3 μg/L) compared to catch rates (40 fish/hour) in the most eutrophic reservoir (chl *a* = 27.3 μg/L). Largemouth bass catch rates were also greater in the most eutrophic reservoir although the difference was not statistically significant. Jones and Hoyer (1982) found that in Midwestern lakes and reservoirs sportfish harvest increased to chl *a* levels >60 μg/L (Figure A-5, Jones and Hoyer 1982).

The decomposition of phytoplankton can have a measurable effect on dissolved oxygen and fisheries in lakes and reservoirs. In Cannonsville Reservoir, New York, a high concentration of phytoplankton at the metalimnion was correlated with lowered dissolved oxygen from August to early October (Effler et al. 1998). The relationship between phosphorus, phytoplankton, dissolved oxygen, and the ultimate effect each of these has on fisheries, however, is complex. Phosphorus reduction can reduce phytoplankton growth and hence potentially improve dissolved oxygen levels. Lower phosphorus can also affect a fishery and cause competition between warm and coolwater fish species. Ney et al. (1990) observed that phosphorus reduction in Smith Mountain Lake (Virginia) reduced food availability and increased the habitat of coolwater fishes by increasing dissolved oxygen. However, lower primary productivity led the coolwater species to forage in habitat traditionally dominated by warmwater species, leading to the potential for direct competition.

Chlorophyll Standards

State Approaches

This discussion primarily is derived from a document of the North American Lake Management Society (NALMS 1992) on the approaches states have taken to develop lake eutrophication standards. A total of eight approaches were addressed in this document:

1) User survey (Vermont)
2) Ecoregion and attainable trophic state approach (Minnesota)
3) Nuisance phytoplankton growth approach (Oregon)
4) Nutrient enriched waters (Virginia)
5) Nondegradation approach (Maine)
6) Nutrient sensitive waters (North Carolina)
7) Biological approach (Tennessee Valley Authority)
8) Water use based approach (British Columbia)

Most lake eutrophication control efforts have been focused on the development of phosphorus criteria to limit primary productivity or biological degradation. Vermont used user survey response data to develop a site-specific phosphorus criteria for Lake Champlain. Criteria for Virginia, Tennessee Valley Authority and Maine are narrative and action to reduce nutrient loading is triggered by evidence of nutrient enrichment or degradation of biological life. British Columbia does not have a chl *a* criterion but has a total phosphorus criterion for lakes.

Oregon has chl *a* ***guidance values*** for stratified lakes (10 μg/L), and for other lakes including reservoirs (15 μg/L) "to identify water bodies where phytoplankton may impair the recognized beneficial uses." When these guidance values are exceeded, a number of actions are triggered including additional study, identification of the possible causes and impacts on beneficial uses, and evaluation of strategies to attain compliance where technically and economically feasible. The Oregon rule recognizes that if the chl *a* value is exceeded, "new or additional discharge loading from point sources (may be approved) provided that the beneficial uses would not be significantly impaired." We requested and ODEQ provided background information on the 1988 rule that established the chl *a* guidance values. Several important and relevant conclusions from this Oregon process include (ODEQ 1986):

- Recognition of water body-specific conditions: "Just as plant growth is dependent upon a variety of environmental factors…so is the resultant or potential impact."
- Derivation of chl *a* guidance levels for rivers, reservoirs, unstratified lakes and estuaries: The document recognizes that it is appropriate to have a higher guidance level for these water bodies than stratified lakes. The level selected (i.e., 15 μg/L), however, was not based on scientific literature information (which was deemed to be limited at the time), but rather a more semi-quantitative analysis of information on chl *a* levels in selected Oregon water bodies in relation to indications of other water quality concerns such as pH and dissolved oxygen. The document further notes: "…excessive growth as indicated by chlorophyll a concentrations may occur in many eastern Oregon streams but the other related water quality problems were not apparent as suggested by the accompanying data…This pattern merits further study as suggested by the course of

> action in the standard. A higher standard for eastern Oregon water may be warranted but further study is needed."

The North Carolina chl *a* standards were developed using extensive state-wide monitoring data and a consensus of expert opinion (WRRI 2001, Weiss and Kuenzler 1976). North Carolina's chl *a* standard is 40 µg/L for lakes, reservoirs, and slow moving waters designated not as trout waters and 15 µg/L for trout waters. A single exceedance of the standard is not considered a violation. The expert committee that developed the standard considered it a "good indication of when problems with over-enrichment were imminent or possible" (WRRI 2001).

Overall, the approach of most states has been narrative or lake-specific with "trigger" chl *a* values that require additional study to determine the cause of elevated chl *a* values and the identification of potential solutions.

Chl *a* criteria have not been promulgated in Minnesota (Steven Heiskary 2001, pers. comm.) but future criteria will be used in conjunction with the State's TMDL program to identify impaired waters. Minnesota's ecoregion approach will be used to set criteria that are used to trigger TMDL action.

How Chl *a* Standards or Guidance Values are Expressed

Chl *a* criteria or guidance levels tend to be measured as average (mean) concentrations or trigger levels to further evaluate conditions. Average values may not take into account extreme (nuisance) conditions, although criteria (chl *a* or phosphorus) based on average values are often set to minimize these extreme values.

Oregon's chl *a* guidance values are measured as an average (of at least 3 samples) over three consecutive months. The three-month average was chosen based on the following discussion (ODEQ 1986):

> "A three month average was suggested to represent more typical conditions and to reduce the influence of short-term bloom conditions. In addition, much research has focused either on spring or summer conditions which would be included in a three month average. Peak growth as well as peak recreational use typically occur in summer months which are included in this three month average. Given the variability in growing and water use seasons statewide, a three month average allows for flexibility to address local conditions."

The North Carolina chl *a* standards do not have an explicit averaging period specified (e.g., instantaneous versus growing season average). According to a recent newsletter that explains the genesis of the standard, the "… standard does not specify when exceedances of the 40 µg/L level are to be considered a violation of the standard…the Environmental Management Commission has not enforced single exceedances of the 40 µg/L concentration, as it might with other standards…it has used the chl *a* number as an indicator of when to expect water quality problems…" (WRRI 2001).

Chl *a* criteria in Minnesota will likely be developed as summer mean values (Heiskary and Walker 1988, Heiskary per. comm. 2001). A mean chl *a* value will be used to ensure that a particular threshold value (e.g. nuisance) is not exceeded more than "x" times or percent during the summer. Once the threshold chl *a* value is identified, and an acceptable frequency of exceedance, the mean chl *a* criterion can be calculated from a statistical analysis (i.e., mean and standard deviation) of monitoring data. Professional judgement is often used to determine an acceptable frequency of nuisance chl *a* levels. For Lake Pepin (a run-of-river reservoir), Minnesota-Wisconsin, the ***mean*** summer chl *a* goal was set at 30 µg/L. This goal was set as a mean value to minimize the frequency of algal blooms that can be defined as nuisance (chl *a* >40 µg/L) or severe nuisance (chl *a* >60 µg/L).

This approach is similar to that proposed by Walker (1985) and used by Raschke (1995) to develop a proposed 25 µg/L chl *a* criterion for aesthetic and recreational purposes in the southeastern United States. Walmsey (1984) classified chl *a* levels into four groups according to the presence of surface blooms and other symptoms of eutrophication. The four chl *a* classes included:

1) 0-10 µg/L, no problems encountered
2) 10-20 µg/L, algal scums evident
3) 20-30 µg/L, nuisance conditions encountered
4) >30 µg/L, severe nuisance conditions encountered

Heiskary and Walker (1995) defined "nuisance" as >40 µg/L and "severe nuisance" as >60 µg/L chl *a* for Lake Pepin. Because the level of chl *a* that will be considered nuisance or severe nuisance will differ for water bodies, regions, and states, it may be necessary to define these threshold chl *a* levels before using the methods of Walker (1985) and Raschke (1995) to develop chl *a* criteria for specific rivers or reservoirs with adequate monitoring data.

Summary

The reduction of phosphorus loading and hence chl *a* levels for the purpose of aesthetics or protection of the "swimmable" designated use can clearly have an adverse effect on reservoir fisheries. However, the results of this literature review suggest that is possible to maintain a healthy fisheries resource as well as protect the human beneficial uses.

User surveys are one way to establish what levels of chl *a* are considered acceptable to the public with regard to the "swimmable" designated use. In this process nuisance chl *a* levels are identified, then a mean chl *a* criterion is chosen so that the nuisance chl *a* level is not exceeded more than "x" percent of the time during the summer. Professional judgement is used to identify how often the chosen nuisance chl *a* level can be exceeded during the summer. Nuisance levels identified in this review ranged from 20-30 µg/L chl *a* (Rashke 1995, Walmsey 1984) to >40 µg/L for Lake Pepin (Heisakry and Walker 1995). Table 1 suggests that recreational uses can be adversely affected when the frequency of nuisance algal levels exceeds 25 percent.

There is ample evidence that sportfish yield increases when chl *a* is increased from <10 µg/L to just below 30 µg/L and in one study yield increased through 60 µg/L (Jones and Hoyer 1982). An increase in yield has been largely associated with an increase in angler success in catching large bass (e.g., Table A-2, Maceina 2001). Hence, the primary question is what lower level of chl *a* will support an acceptable reservoir fishery. A case study presented by

Maceina (2001) showed that mean chl *a* reduction from >40 µg/L chl *a* to 10-20 µg/L resulting from phosphorus reductions in West Point Reservoir, Georgia, corresponded with decreased weight of, and increased effort (100-200 to 500 hours) to catch, bass greater than 2.27 kg. Hendricks (1995) noted a similar result. Interpreting from a graph in Hendricks (1995), the hours needed to catch a bass greater 2.27 kg was approximately 125 to 250 at 25 µg/L chl *a*.

Overall, chl *a* levels <20 µg/L have been shown to significantly reduce yield and the sport fishery value of a reservoir and chl *a* levels as high as 60 µg/L have been shown to increase sportfish yield. Levels of chl *a* considered nuisance, or non-swimmable, range from 20 to >40 µg/L, but this has been found to be highly subjective depending on human perceptions and their expectations and experience.

Recommendations and Implications

The ***mean*** chl *a* target should be >20 µg/L and <60 µg/L to avoid adverse effects on the existing fishery. The preferred target to prevent recreational use impairment should be in between these two extremes. The two factors that appear to be key in determining an appropriate recreational chl *a* target is the definition of "nuisance" conditions and the frequency of these conditions. The definition of nuisance condition should be determined for a given water body based on outreach to representative users. Once these conditions have been defined, the frequency of chl *a* concentrations should be evaluated to determine an appropriate average target concentration that will result in an acceptable frequency of exceedances based on site-specific chl *a* data.

Given that a well-designed and executed user survey could not be accomplished within the timeframe available to complete the first phase of the SR-HC TMDL, it may be appropriate that the chl *a* criterion developed for Lake Pepin, a run-of-river reservoir, be used as an interim recreational use target. This target would be a "nuisance threshold" of 40 µg/L, which is also consistent with North Carolina's standard for non-trout waters.

Our analyses of Upstream Snake River reach chl *a* data (see Figure A-6) suggests strong similarity with the Lake Pepin case, i.e., that a growing season ***mean*** of 30 µg/L would prevent individual bloom values from exceeding 40 µg/L (the user-survey established Lake Pepin nuisance level) more than 25 percent of the time. The mean chl *a* value for May through September for this reach is about 30 µg/L based on 1995 through 2000 data. Thus, if Snake River users have similar perceptions of chl *a* levels as those for Lake Pepin, the Snake River would be in or very near to the "fully supporting-threatened" category. One potential limitation of this analysis is whether the 1995 through 2000 chl *a* data are representative of the range of hydrologic and other conditions that affect algae blooms in this river reach. Although these years do not capture a critical drought period, the maximum chl *a* values (i.e., up to 118 µg/L) are greater than the values shown for a bloom survey during the 1992 drought (see Figure 3.2.3. of the IDEQ October 5, 2001 Nutrient Loading Analysis).

The type of analysis shown in Figure A-6 can also be used to evaluate a range of potential "nuisance level" selections for the Snake River and the mean values needed to protect against those levels for any desired exceedance percentage. For example, if one were to be more conservative than the Lake Pepin users, and select a nuisance level of 35 µg/L at the same acceptable exceedance frequency of 25 percent, the growing season mean chl *a* target would be about 25 µg/L. Note that derivation of Figure A-6 assumed a normal distribution, but could be readily modified for a log-normal (or other) distribution, as appropriate.

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