White Paper (b) Recent Literature on Nutrient Impacts in Water Bodies

As summarized in other white papers in this package, the role of nutrients in aquatic ecosystems is complex, and the addition of excess nutrients to a water body results in a host of effects, from the microbial level to the top predator level. Although researchers have a general idea of these relationships, based on a body of scientific literature that stretches back at least four decades, except for lakes, it is less common to find quantitative relationships between nutrient levels and specific nutrient impacts. In large part this is due to the differences between natural systems, where similar nutrient concentrations may not cause similar responses because of non-nutrient factors, such as flow, shading, sediment loads, etc. However, from the perspective of numeric nutrient criteria development, quantitative relationships are important because they can help relate a desired level of biological response (such as dissolved oxygen or chlorophyll a levels) to a specific nutrient level, and can be used over a geographic region or for a group of similar water bodies.

For this review we have focused on reporting information that is most pertinent to nutrient criteria development in California and that does not repeat the excellent and thorough reviews of the state of understanding that have been presented in the US EPA guidance documents for lakes and reservoirs (US EPA, 2000a), streams and rivers (US EPA 2000b), and estuaries (US EPA, 2001). This review is based on literature from the last 15 years where biotic effects of nutrients on streams, lakes, estuaries and coastal waters have been studied.

Streams and Rivers

In examining literature on nutrients in streams, we focused on studies where authors had reported relationships between nutrient levels and any biological impacts. In almost all instances the response that was defined quantitatively was that between nutrients and mean or maximum chlorophyll levels in periphyton. In Table 1 we present regressions between chlorophyll and nutrient concentrations from the literature. When several alternative expressions were presented by authors, we focused on those with the best fits (highest r^2 values). In several instances, authors presented data on nutrients and chlorophyll levels, but did not perform a regression. In these cases, we independently estimated best fits using simple and multiple linear regression on the published data. These are also presented in Table 1.

Most studies reported in Table 1 show a fairly strong correlation between observed mean and maximum chlorophyll concentrations and some nutrient species (most commonly one or more of the following: TP, TN, SRP, and TKN). In most cases, phosphorus or nitrogen species alone could explain the observed chlorophyll levels, and in some cases, both nitrogen and phosphorus were required to explain the observations. This compilation of studies shows that it is incorrect to make a simple generalizations that phosphorus is the primary limiting nutrient in freshwaters (as opposed to nitrogen being the primary limiting nutrient in marine waters). Further, it was noted by several authors

that chlorophyll concentrations are significantly impacted by the flow rate (Snelder *et al.* (2004), Biggs (2000), Biggs and Close (1989), Welch *et al.* (1988), Heiskary and Markus (2001)). Biggs (2000) explicitly considered flow in the regressions, where the effect of scour by flood flows is incorporated as a factor called days of accrual. Chlorophyll concentrations were positively correlated to days of accrual, and the inclusion of this factor in the regressions improved the quality of the fit. In one case, conductivity was better at explaining chlorophyll a levels in periphyton than any nutrient species, but this may be the consequence of a correlation between nutrients and conductivity (Chetelat *et al.*, 1999).

Dodds *et al.* (1997) used data on benthic chorophyll (mean and maximum), planktonic chlorophyll, and nutrients to classify streams as oligotrophic, mesotrophic, or eutrophic. These boundaries are shown in Table 2. Values presented in this table can be a starting point for development of criteria in California.

Other studies have focused on effects that do not fit the formats of Tables 1 and 2, but are nonetheless important from the perspective of nutrient criteria. Sabater *et al.* (2000) explored the connection between chlorophyll *a* concentrations and the surrounding riparian vegetation. They found that in logged reaches of the stream there are much higher concentrations of planktonic chlorophyll (246.7 mg/m^2 in the logged reach versus 46.2 mg/m^2 in the shaded reach) and that the density of algal mats is increased. These findings serve to reiterate the impact of riparian communities on instream conditions. Sosiak (2002) found that, following a decline of nutrient loads over a period of 16 years, there were accompanying declines in periphyton and macrophyte biomass. A study in San Joaquin River, California, a river draining an arid region, found that algae communities were strongly affected by nutrients as well as salinity levels, both of which originate in agricultural drainage.

There also exists a significant body of literature evaluating changes in algal communities in response to nutrients in streams as well as other water bodies (e.g., Hill *et al.*, 2000; Chetelat, *et al.*, 1999; Winter and Duthie, 2000). However, in most cases it is difficult to relate changes in particular algal species to impairment of use. There are some exceptions, as when a particular alga starts to dominate the community, or when it imparts an odor to the water, but in general we will not focus at this level of detail for nutrient criteria development.

Table 1. Correlations between chlorophyll, nutrients, and other factors.

Citation	Parameters	Regression analysis	Comments
Correlations obtained from literature sources:			
Basu and Pick, 1996	Chl *a* and TP	Log chl *a* = -0.26 + 0.73 log TP	$r^2 = 0.76$, p<0.001, n=31
Van Nieuwenhuyse and Jones, 1996	Chl *a* and TP	Log chl = -1.65 + 1.99 log TP – 0.28 (log TP)^2	S=0.32, R^2=0.67, n=292
Chetelat *et al.*, 1999	Chl a, TP	Log Chl a = 0.905 log TP + 0.49	r^2 = 0.56; Conductivity a bette explainer than TP (r^2 = 0.71)

Biggs, 2000 (from Snelder *et al.*, 2004)	Maximum Chl *a* and SIN	Log_{10} (maximum chl *a*) = 4.285 ($\log_{10}$ D_a) – 0.929 ($\log_{10}$ D_a)^2 + (0.504 $\log_{10}$ SIN) – 2.946	D_a = Days of accrual as determined from D_a = (1/*FRE*3) × 365.25 where FRE3 is the mean number of flood evens per year that exceed 3 times the median flow.
	Maximum Chl *a* and SRP	Log_{10} (maximum chl *a*) = 4.716 ($\log_{10}$ D_a) – 1.076 ($\log_{10}$ D_a)^2 + (0.494 $\log_{10}$ SIN) – 2.741	As above
Dodds *et al.*, 2002	Mean Chl *a*, TN, and TP	Log_{10} (mean Chl *a*) = 0.155 + 0.236 $\log_{10}$ TN + 0.443 lob_{10} TP	$r^2 = 0.40$ (Mean Chl *a* regressions were also reported for a USGS data set but had much lower r^2 values.)
	Maximum Chl *a*, TN, and TP	Log_{10} (max Chl *a*) = 0.714 + 0.372 $\log_{10}$ TN + 0.223 $\log_{10}$ TP	$r^2 = 0.31$
Winter and Duthie, 2000	Mean Chl a, TN, TP		Both the relationships between mean chl *a* and TN (r^2=0.33, *p*=0.04); and mean chl *a* and TP (r^2=0.17, *p*=0.16) are significant.

Correlations developed by us from data reported in studies:

Biggs, 2000	Chl a, SIN, SRP, Days accrual	Chl a= -4.309+1.495(SRP) +0.604 (DA))	r^2= 0.22, showed a marginal increased relationship with the addition of SIN
Heiskary and Markus, 2001	Max ChlT (Chl a + Pheo) and TP	Max Chl T = -19.815 + 0.632 (TP)	r^2=0.78, showed a marginal increased relationship with the addition of NO_3
	Max ChlT and TKN	Max Chl T = -86.109+144.539 (TKN)	r^2=0.85, same r^2 value whether or not TP was added
Welch, 2001	Max Chl a and NO_3+NO_2-N	Max Chl a = 48.928 + 0.238 NO_3+NO_2-N	r^2=0.26, showed no increased relationship with the addition of TP
Biggs and Close, 2001	Mean Chl a, TKN, and TP	Mean Chl a= 11.501+0.813 (TP)	r^2=0.19, showed a marginal increase with the addition of TKN

Table 2. Classification of streams into oligotrophic, mesotrophic, or eutrophic categories (Dodds *et al*, 1998).

Variable	Oligotrophic-Mesotrophic Boundary	Mesotrophic-Eutrophic Boundary	N
Mean Benthic Chl (mg/m^2)	20	70	286
Max Benthic Chl (mg/m^2)	60	200	176
Planktonic Chl (ug/l)	10	30	292
TN (ug/l)	700	1500	1070
TP (ug/l)	25	75	1366

Lakes and Reservoirs

Lakes and reservoirs are somewhat more amenable to development of correlations with nutrient chemistry because the complications arising from variable flow do not occur. For this reason, there have been comprehensive studies of nutrient-chlorophyll relationships for a much longer time, and nutrient chemistry data have been used to classify lakes into categories such as oligotrophic, mesotrophic, eutrophic (Vollenweider, 1968, and reproduced in Wetzel, 2001). Despite the age of the Vollenweider study, it is still accepted widely in the limnology literature. The US EPA Guidance Document (US EPA, 2000a) for lakes and reservoirs provides a comprehensive review of this literature, and will not be repeated here.

Although is generally considered that phosphorus is the main limiting nutrient in freshwaters, recent re-evaluation of large, global lake data sets shows that the relationship is not linear over large ranges, and that at moderately elevated phosphorus concentrations, lakes become nitrogen limited. The chlorophyll-phosphorus relationship is linear up to a point and then becomes flat due to nitrogen limitation (Prairie *et al*., 1989; McCauley *et al*., 1989). This is important information to consider in developing a predictive approach for criteria, although the model employed in our work method (BATHTUB) explicitly includes the possibility of both nitrogen and phosphorus limitation.

Other studies looking at changes in algal and zooplankton communities in response to nutrient loads, as discussed in the stream section above, are considered too detailed and limited in spatial coverage for broad application to nutrient criteria (e.g., Avalos-Perez *et al*., 1994; Balseira, *et al*., 1997; Cottingham, 1998; Koehler and Hoeg, 2000). However, some studies that use controlled experiments in lakes to evaluate the changes due to nutrient addition, particularly on upper trophic levels (e.g., Blanc and Margraf, 2002), may be useful to develop a scientific rationale for the linkage between lower trophic levels and beneficial uses.

Estuarine and Coastal Waters

Because estuaries and some coastal zones have complex flows, with tidal effects, and varying degrees of mixing of freshwater and saltwater flows, it is very difficult to make quantitative generalizations about nutrient conditions across estuaries. For this reason, it is thought that the criteria development for estuarine waters will have to be conducted on a case-by-case basis. Although the mechanisms of interaction are different in these

waters, the data needs will be broadly similar to that for stream and lake criteria development. The interactions of nutrients in estuaries and coastal waters as describe in the most current research is well-documented in the US EPA Guidance Document (US EPA, 2002). As this is a recent document, it covers most recent research reports, and the effort is not duplicated here. What follows is a general discussion highlighting aspects of interest to Pacific coast.

Generally, however, the following aspects of nutrient-related responses are apply everywhere. Excess nutrients, almost always nitrogen, allow the formation of algal blooms on the water surface during the warmest months of the year. As the algae in these blooms die and settle to the bottom, their decomposition consumes oxygen from the deeper layers. The depleted or lowered oxygen in these zones (anoxic or hypoxic zones) have adverse effects on all other biota. The likelihood of depleted oxygen in deeper waters is a function of the nutrient loading, the degree of mixing in the waters, and the degree of vertical stratification. Well-mixed, poorly stratified estuaries are less likely to have nutrient problems (Bricker *et al.*, 1999). Of the estuaries studied nationally for nutrient problems (Bricker *et al*., 1999), it was found that most of the estuaries likely to be nutrient-impaired were along the coasts of the Atlantic Ocean and the Gulf of Mexico (29 estuaries on the east coast compared to 6 on the west coast). The 6 estuaries with potential problems include: San Francisco Bay, Newport Bay, Tijuana Estuary, Elkhorn Slough, Tomales Bay, South Puget Sound, and Hood Canal.   The difference between the east and west coasts can be attributed to various reasons, related to the lower population density and runoff (and proportionally lower nutrient loads), lower temperatures, and lower atmospheric deposition of nitrogen.

Nutrient enrichment has also been associated with other infrequent problems, although, to date, most of these reported problems have been on the eastern US. One consequence of nutrient enrichment, that is much less understood than the formation of anoxic zones, is increased frequency of algal blooms with toxins (termed harmful algal blooms, or HABs). It is thought that HABs are more likely to occur in the presence of nutrient enrichment, but because these are somewhat unpredictable events, it is not known what other factors play a role and whether control of nutrient loads alone can reduce the problem. Yet another consequence of elevated nutrients is thought to be the presence of the toxic dinoflagellate *Pfiesteria piscicida. Pfiesteria*-like cells were positively correlated with phytoplankton biomass which was shown to be positively correlated to increased nutrient concentrations (Pinckney *et al.*, 2000).

References:

Avalos-Perez, E., J. DeCosta and K. Havens. 1994. The Effects of Nutrient Addition and Ph Manipulation in Bag Experiments on the Phytoplankton of a Small Acidic Lake in West Virginia, USA. Hydrobiologia. 291 (2): 93-103.
Balseira, E., B. Modenutti and C. Queimalinos. 1997. Nutrient Recycling and Shifts in N:P Ratio by Different Zooplankton Structures in a South Andes Lake. Journal of Plankton Research. 19 (7): 805-817.

Biggs, B. 2000. Eutrophication of Streams and Rivers: Dissolved Nutrient-Cholorphyll Relationships for Benthic Algae. Journal of the North American Benthological Society. 19 (1): 17-31.

Biggs, B. and M. Close. 1989. Periphyton Biomass Dynamics in Gravel Bed Rivers: The Relative Effects of Flows and Nutrients. Freshwater Biology. 22 209-231.

Blanc, T. and F. Margraf. 2002. Effects of Nutrient Enrichment on Channel Catfish Growth and Consumption in Mount Storm Lake, West Virginia. Lakes & Reservoirs: Research and Management. 7 (2): 109-123.

Bricker, S., C. Clement, D. Pirhalla, S. Orlando and D. Farrow. 1999. National Estuarine Eutrophication Assessment: Effects of Nutrient Enrichment in the Nation's Estuaries. NOAA, National Ocean Service, Special Projects Office and the National Centers for Coastal Ocean Science.

Chetelat, J., F. Pick, A. Morin and P. Hamilton. 1999. Periphyton Biomass and Community Composition in Rivers of Difference Nutrient Status. Canadian Journal of Fisheries and Aquatic Sciences. 56 (4): 560-569.

Cottingham, K., S. Carpenter and A. St. Amand. 1998. Responses of Epilimnetic Phytoplankton to Experimental Nutrient Enrichment in Three Small Seepage Lakes. Journal of Plankton Research. 20 (10): 1889-1914.

Dodds, W., V. Smith and B. Zander. 1997. Developing Nutrient Targets to Control Benthic Chlorophyll Levels in Streams: A Case Study of the Clark Fork River. Water Research. 31 (7): 1738-1750.

EPA Office of Water. 2001. Nutrient Criteria Technical Guidance Manual: Estuarine and Coastal Marine Waters. EPA-822-B-01-003.

EPA Office of Water and Office of Science and Technology. 2000a. Nutrient Criteria Technical Guidance Manual: Lakes and Reservoirs. EPA-822-B-00-001.

EPA Office of Water and Office of Science and Technology. 2000b. Nutrient Criteria Technical Guidane Manual: Rivers and Streams. EPA-822-B-00-002.

Heiskary, S. and H. Markus. 2001. Establishing Relationships among Nutrient Concentrations, Phytoplankton Abundance, and Biochemical Oxygen Demand in Minnesota, USA, Rivers. Lake and Reservoir Management. 17 (4): 251-262.

Hill, B., A. Herlihy, P. Kaufmann, R. Stevenson, F. McCormick and C. Burch Johnson. 2000. Use of Periphyton Assemblage Data as an Index of Biotic Integrity. Journal of the North American Benthological Society. 19 (1): 50-67.

Koehler, J. and S. Hoeg. 2000. Phytoplankton Selection in a River-Lake System During Two Decades of Changing Nutrient Supply. Hydrobiologia. 424 (1-3): 13-24.

McCauley, E., J. Downing and S. Watson. 1989. Sigmoid Relationships between Nutrients and Chlorophyll among Lakes. Canadian Journal of Fisheries and Aquatic Sciences. 46 1171-1175.

Pinckney, J., H. Paerl, E. Haugen and P. Tester. 2000. Responses of Phytoplankton and *Pfiesteria*-Like Dinoflagellate Zoospores to Nutrient Enrichment in the Neuse River Estuary, North Carolina, USA. Marine Ecology Progress Series. 192 65-78.

Prairie, Y., C. Duarte and J. Kalff. 1989. Unifying Nutrient - Chlorophyll Relationships in Lakes. Canadian Journal of Fisheries and Aquatic Sciences. 46 1176-1182.

Sabater, F., A. Butturini, E. Marti, I. Muñoz, A. Romani, J. Wray and S. Sabater. 2000. Effects of Riparian Vegetation Removal on Nutrient Retention in a Mediterranean Stream. Journal of the American Benthological Society. 19 (4): 609-620.

Snelder, T., B. Biggs and M. Weatherhead. 2004. Nutrient Concentration Criteria and Characterization of Patterns in Trophic State for Rivers in Heterogeneous Landscapes. Journal of the American Water Resources Association.

Sosiak, A. 2002. Long-Term Response of Periphyton and Macrophytes to Reduced Municipal Nutrient Loading to the Bow River (Alberta, Canada). Canadian Journal of Fisheries and Aquatic Sciences. 59 987-1001.

Vollenweider, R. 1968. Scientific Fundamentals of the Eutrophication of Lakes and Flowing Waters with Particular Reference to Nitrogen and Phosphorus. Oecd Report Das/Csi/68.27. OECD.

Welch, E., J. Jacoby, R. Horner and M. Seeley. 1988. Nuisance Biomass Levels of Periphytic Algae in Streams. Hydrobiologia. 157 161-168.

Wetzel, R. 2001. Limnology: Lake and River Ecosystems. 1006.

Winter, J. and H. Duthie. 2000. Epilithic Diatoms as Indicators of Stream Total N and Total P Concentration. Journal of the North American Benthological Society. 19 (1): 32-49.