chapter V

Chlorophyll *a* Criteria

BACKGROUND

Phytoplankton are small microscopic plants, or algae, drifting in the water column with the currents. They constitute a diverse group that contributes importantly to the base of the Chesapeake Bay's food web, linking nutrients and the energy of sunlight with small planktonic animals or zooplankton, forage fish, filter feeders such as oysters, bottom-dwelling worms and clams and fishes (Bay and Horowitz 1983; Tuttle et al. 1987; Malone et al. 1986; Heck 1987; Malone et al. 1988). The majority of the Chesapeake Bay's animals feed directly on phytoplankton or secondarily on the products of phytoplankton that support the 'microbial loop' (such as nonphotosynthetic flagellates, protozoa, bacteria and fungi), all of which support higher trophic levels. The Chesapeake Bay's 'carrying capacity' or its ability to support productive and diverse populations of flora and fauna, including highly valued species, depends largely on how well phytoplankton meet the nutritional needs both in quantity and quality of the various consumers.

SCOPE AND MAGNITUDE OF NUTRIENT ENRICHMENT IN CHESAPEAKE BAY

Problems caused by nutrient over-enrichment are perhaps the longest-standing water quality issues created by people (Vollenweider 1992). Early marine scientists considered nutrients as a resource, not a problem (Brandt 1901) and considered ways to fertilize coastal seas to increase fisheries production. However, this was before human populations and land use activities to support these bourgeoning populations had reached today's levels, especially since about the 1960s. The problem is especially challenging in the Chesapeake Bay ecosystem because the Bay ecosystem's variable dynamics produce large, natural fluctuations. Superimposed onto these natural changes are those caused by human disturbance, and nutrient enrichment is only one among many other pressures experienced by the Bay ecosystem (Breitburg

et al. 1999). The scientific challenge persists because human disturbance often is subtle, indirect and sometimes is confounded by natural changes (Cloern 1996) that are not yet understood enough for predictive purposes. Anthropogenic nutrient enrichment of rivers—which deliver much of their nutrient loads to estuaries and shelf waters—has resulted, in the U.S. in nitrogen fluctuations 5 to 14 times greater than natural rates (Jaworski et al. 1997). Phosphorus loading to estuarine systems has increased two- to sixfold since 1900 (Conley 2000).

Nutrient over-enrichment can cause ecological symptoms in the Chesapeake Bay that impair designated uses, as defined by the Clean Water Act. Nutrient enrichment and changes in important grazer populations such as oysters, menhaden, zooplankton and benthic macroinvertebrates have potentially altered the natural equilibrium between phytoplankton production and consumption in the last century (Kennedy and Breisch 1981; Boynton et al. 1982; Officer et al. 1984; Marshall and Lacouture 1986; Nixon et al. 1986; Gerritsen et al. 1988; Newell 1988; Verity 1987; Malone et al. 1991; Malone 1992; Gerritsen et al. 1994; Hartman and Brandt 1995; and Kemp et al.1997). Phytoplankton populations currently reach very high concentrations (Filardo and Dunstan 1985; Boynton et al. 1982; Sellner et al. 1986; Magnien et al. 1992; Malone 1992; Haas and Wetzel 1993; Lacouture et al. 1993; Harding 1994; Glibert et al. 2001) and high production rates during the spring and summer (Sellner et al. 1986; Magnien et al. 1992; Lacouture et al. 1993; Marshall and Nesius 1996; Sin et al. 1999). Phytoplankton communities also are capable of supporting several potentially toxic taxa (Seliger et al. 1975; Ho and Zubkoff 1979; Luckenbach et al. 1993; Lewitus et al. 1995; Marshall 1995; Glibert et al. 2001).

Excess, uneaten phytoplankton accumulate in the water column and contribute to reduced water clarity and summer oxygen depletion in bottom waters, ultimately stressing the food webs they support (Neilson and Cronin 1981; Boynton et al. 1982; Harding et al. 1986; Seliger et al. 1985; Fisher et al. 1988; Malone 1992). Nutrient enrichment had already affected underwater bay grass distributions throughout much of the Chesapeake Bay by the early 1960s (Flemer et al. 1983; Orth and Moore 1983) and deep-channel hypoxia and anoxia has been confirmed to have been initiated during the early 1970s (Hagy 2002). Local nutrient over-enrichment problems occurred earlier in some Bay tidal tributaries; massive blue-green algae blooms in the upper tidal freshwater Potomac River Estuary began during the 1950s (Jaworski et al. 1972), and Baltimore Harbor experienced a widening hypoxia problem well-established by the mid-1800s (Capper et al. 1983).

CHLOROPHYLL *A*: KEY INDICATOR OF PHYTOPLANKTON BIOMASS

Scientific interest and practical management needs required that the quantity of phytoplankton biomass in aquatic ecosystems be simply measured as an indicator of water quality and ecosystem health. It was discovered many decades ago that chlorophyll *a*, a ubiquitous photosynthetic pigment often associated with other pigments in freshwater and coastal marine phytoplankton, would serve as a useful indicator for

both the photosynthetic potential and biomass of phytoplankton (Flemer 1969a, 1969b). Thus, over the years, chlorophyll *a* has become a principal measure of the amount of phytoplankton present in a water body. Chlorophyll *a* also plays a direct role in reducing light penetration (Lorenzen 1972). Relatively rapid methods evolved to measure the concentration of chlorophyll *a* in discrete water samples and *in vivo* (Flemer 1969; U.S. EPA 1997). Methods have been developed to measure chlorophyll *a* using aerial surveillance techniques based on passive multispectral signals associated with phytoplankton (Harding 1992). As Harding and Perry (1997) wrote, "Chlorophyll *a* is a useful expression of phytoplankton biomass and is arguably the single most responsive indicator of N [nitrogen] and P [phosphorus] enrichment in this system [Chesapeake Bay]."

Compelling evidence indicates that reduced water clarity and low dissolved oxygen conditions improve when excess phytoplankton or blooms, measured as chlorophyll *a*, are substantially reduced (National Research Council 2001). Improvement in water clarity is a major issue for the recovery of the Bay's shallow-water underwater grasses (see Chapter IV); correcting the low dissolved oxygen problems that occur in the deeper waters of the mesohaline mainstem Chesapeake Bay and lower tidal tributaries has been a challenge to Chesapeake Bay restoration for decades (see Chapter III). High algal biomass present in small embayments may be associated with super-saturated dissolved oxygen conditions during the day and hypoxic to anoxic conditions during the early morning hours (D'Avanzo and Kremer 1994). Attaining the Chesapeake Bay dissolved oxygen and water clarity criteria will require reductions in chlorophyll *a* concentrations by reducing nutrient (yielding nutrient limitation) and sediment (resulting in light saturation) loadings.

In addition to the habitats described above that require chlorophyll *a* criteria, other locations in Chesapeake Bay tidal waters experience phytoplankton blooms that may not be directly associated with low dissolved oxygen and the shading of underwater bay grasses due to phytoplankton. Numerous small shallow-water embayments continue to experience inordinately high chlorophyll *a* concentrations. Some of these habitats may experience early-morning hypoxia or anoxia, while others may not have contained documented growth of underwater bay grasses before the baywide decline. In some parts of the Chesapeake Bay and its tidal tributaries, even reducing nutrient and sediment loadings to levels that would result in attaining the deep-water and deep-channel dissolved oxygen and shallow-water clarity criteria will not prevent harmful algal blooms or ensure the return of high quality food to open-water habitats. These areas include, but are not limited to, those without low oxygen conditions for hydrologic reasons (e.g., high mixing rates) and those in which reduced water clarity conditions are driven more by suspended sediments than by water-column algae. For these reasons, the EPA believes it is necessary to develop and adopt chlorophyll *a* criteria in addition to water clarity and dissolved oxygen criteria for the protection of Chesapeake Bay tidal waters.

CHESAPEAKE BAY CHLOROPHYLL *A* CRITERIA

This chapter presents the EPA's recommended narrative chlorophyll *a* criteria, along with supporting numeric concentrations and methodological approaches to addressing nutrient-enrichment impairments related to the overabundance of algal biomass measured as chlorophyll *a*. The EPA expects states to adopt narrative chlorophyll *a* criteria into their water quality standards for all Chesapeake Bay and tidal tributary waters. The EPA strongly encourages states to develop and adopt site-specific numerical chlorophyll *a* criteria for tidal waters where algal-related impairments are expected to persist even after the Chesapeake Bay dissolved oxygen and water clarity criteria have been attained.

The narrative chlorophyll *a* criteria in Table V-1, derived in part through a review of other states' chlorophyll *a* water quality standards (Appendix D), are recommended for encompassing the full array of possible impairments, all of which may not manifest themselves within a particular water body at any one time. The site-specific nature of impairments caused by the overabundance of algal biomass supports state adoption of the EPA-recommended narrative criteria, with application of site-specific numeric criteria for localized waters addressing local algal-related impairments.

Because of the regional and site-specific nature of algal-related water quality impairments, baywide numerical criteria have not been published here. Therefore, the chlorophyll *a* concentrations tabulated in this document are not numerical EPA criteria. Along with the documented methodologies, the tabulated chlorophyll *a* concentrations are provided as a synthesis of the best available technical information for the states consideration and use in their development and adoption of more regional and site-specific numerical chlorophyll *a* criteria. States can use this information in deriving numerical translators for their narrative criteria, and use these for their narrative criteria, target chlorophyll *a* concentrations in concert with narrative criteria.

Several different approaches were evaluated to develop relationships among chlorophyll *a* concentrations and tidal-water designated uses. The states also should consider the strengths and limitations of each approach, as well as other available scientific and technical information, when deriving site-specific numerical chlorophyll *a* criteria or numerical translators for their narrative criteria.

Table V-1. Recommended Chesapeake Bay chlorophyll *a* narrative criteria.

Concentrations of chlorophyll *a* in free-floating microscopic aquatic plants (algae) shall not exceed levels that result in ecologically undesirable consequences—such as reduced water clarity, low dissolved oxygen, food supply imbalances, proliferation of species deemed potentially harmful to aquatic life or humans or aesthetically objectionable conditions—or otherwise render tidal waters unsuitable for designated uses.

SUPPORTING TECHNICAL INFORMATION AND METHODOLOGIES

Algae play a unique role at the base of the aquatic food web. The size and composition of the phytoplankton community strike a delicate balance between supporting a balanced, productive ecosystem and fueling severe impairments of water quality and natural ecological relationships. Given that an overabundance or a shift in species composition can yield diverse negative ecological consequences, the supporting chlorophyll *a* concentrations and methodologies have been structured to characterize an array of ecological conditions. They are based on decades of historical observations; scientific findings published in the international, peer-reviewed literature; field and laboratory experiments; historic Chesapeake Bay water quality data; and extensive Chesapeake Bay-specific research, monitoring and modeling.

CONTEXT FOR THE NARRATIVE CHESAPEAKE BAY CHLOROPHYLL *A* CRITERIA

To interpret the narrative chlorophyll *a* criteria that will protect the designated uses of the Chesapeake Bay and its tributaries, various ecological conditions must be considered and different water quality impairments should be addressed. Table V-2 presents various water quality conditions along the continuum of trophic status or ecological conditions, framing the connections between algal growth and productivity, the various ecological and water quality consequences and, ultimately, designated uses for Chesapeake Bay tidal waters.

An *oligotrophic* status indicates conditions that are not signficantly affected by nutrient and sediment enrichment, typically characterized with low nutrient/low organic matter input or production. Under *mesotrophic* conditions, a water body is nutrient-enriched but still functions adequately without the enhanced production of algae having an adverse impact on the aquatic food web. When a water body reaches *eutrophic* conditions, excess production of algae can lead to low dissolved oxygen conditions, reduced water clarity, harmful algal blooms and other ecological impairments that reflect alterations of the aquatic food web. Aquatic systems that have become so overloaded with nutrients that they are unable to assimulate available nutrients are characterized as *hyper-* or *highly eutrophic*.

Estuarine scientists and managers have borrowed from the field of limnology such terms as oligotrophic, mesotrophic, eutrophic and hypereutrophic to reflect a range in symptoms of nutrient over-enrichment. The reality is that there is no scientific consensus on exactly what these terms mean for nutrient enrichment in estuaries. In the case of the Chesapeake Bay, Table V-2 establishes an ecosystem trophic status classification scheme useful for setting the context for the narrative Chesapeake Bay chlorophyll *a* criteria (see Table V-1) and supporting technical information and methodologies.

Table V-2. Trophic status, water quality, phytoplankton community and ecological function along a trophic continuum.

Trophic Status	Oligotrophic	Mesotrophic	Eutrophic	Highly Eutrophic
	Near-pristine conditions; not significantly affected by nutrient enrichment	Experiencing some level of nutrient enrichment but still functioning adequately with an enhancement of productivity and without large impact on the structure of the food web	Significantly impacted by nutrient enrichment, excess primary production leading to dissolved oxygen, harmful algal blooms and other problems; food web structure significantly altered	Aquatic system so overloaded with nutrients those nutrients cannot be assimilated by the system and therefore nutrients are exported to adjacent waters; all the effects listed for eutrophic, but even more extreme
Status in Chesapeake Bay Waters	No examples of oligotrophic conditions currently in Chesapeake Bay waters	Occasionally found in some areas of the Chesapeake Bay and its tidal tributaries	Many areas in the Chesapeake Bay and its tidal tributaries are currently characterized as eutrophic	Areas in the tidal waters where very large load reductions are required to improve water quality; Back River in Maryland is an example
Ecological Functions	• Strong trophic coupling and nutrient recycling processes (ecosystem is efficient); • No undesirable algal blooms; •Algal growth often is nutrient-limited, with little accumulation of inorganic nitrogen or phosphorus; • Habitat goals for bay grasses, phytoplankton, zooplankton, water-column fishes and bottom organisms met in all places; • Food pathways to fish and higher trophic levels dominate	• Trophic coupling and nutrient recycling processes; • A few undesirable algal blooms; •Algal growth often is nutrient-limited, with little accumulation of inorganic nitrogen or phosphorus, and light-saturated; • Habitat goals for bay grasses, phytoplankton, zooplankton, water column fishes and bottom organisms met in most places; • Food pathways to fish and higher trophic levels dominate	• Sporadic trophic decoupling; • Algal growth frequently limited by light, not nutrients; nutrient saturation occurs with significant accumulations of inorganic nitrogen and phosphorus; • Transport of nutrients downstream; • More frequent undesirable algal blooms; • Organic matter buildup in bottom waters leading towards anoxia/hypoxia; • Phytoplankton biomass is a frequent cause of water clarity impairment; •Bay grasses stressed by reduced water clarity due to algal shading in the water column and epiphytic algae growth on leaf surfaces	• Persistent, significant trophic decoupling (inefficient ecosystem); • Nutrient saturation /light limitation of algae growth with significant accumulations of nitrogen and phosphorus; • Significant transport of nutrients downstream; • More frequent undesirable algal blooms; • Significant organic matter buildup in bottom waters leading towards anoxia/hypoxia; • Phytoplankton biomass is a major cause of water clarity impairment; •Bay grasses decline or are lost due to turbidity in water column and epiphytic algal growth on leaf surfaces; • Food pathways to bacteria (microbial loop) dominate
Bay Criteria Attainment	Meets all water clarity and dissolved oxygen criteria	Meets water clarity and dissolved oxygen criteria most of the time	Often does not meet water clarity and dissolved oxygen criteria infrequently	Never meets water clarity and dissolved oxygen criteria

The analogy equating *oligotrophic* with *pristine* is somewhat forced, because even before European contact, the Chesapeake Bay probably was never poor in nutrients (in the sense of an oligotrophic lake, for example, where likely a small watershed and a relatively impervious geology supplied very low nutrient loads). Proximity to terrestrial nutrient inputs, long residence times for nutrient recycling and generally shallow (8 meters average depth) conditions allowing fairly significant benthic-pelagic coupling are all factors that would prevent the Chesapeake Bay from ever being truly oligotrophic.

So, in a relative sense, the Chesapeake Bay might have been considered *mesotrophic* during these earlier times and became eutrophic as changes in land uses resulted in increased nutrient supplies. This is based on a definition of *eutrophic* as having excess algae, leading to the observed more frequent, persistent and intense periods of low to no dissolved oxygen and substantial reductions in water clarity. Tidal waters surrounded by intensely developed lands have become *hyper-eutrophic*. In a reference condition context, if a majority of Chesapeake Bay tidal waters are considered eutrophic now, a management goal might be to reduce nutrient loadings and, therefore, chlorophyll *a* concentrations, to achieve a more mesotrophic condition, in contrast to the present eutrophic to hypereutrophic situations.

CHLOROPHYLL *A* CONCENTRATIONS CHARACTERISTIC OF VARIOUS ECOLOGICAL CONDITIONS

Described and documented below are the chlorophyll *a* concentrations characteristic of various ecological conditions within Chesapeake Bay tidal-water habitats.

Historical Chlorophyll a Concentrations

Chlorophyll *a* concentrations that historically reflected a more balanced Bay ecosystem were quantified through reviews and evaluations of 1950s through 2000 data (Harding 1994; Harding and Perry 1997; Olson 2002). The chlorophyll *a* concentrations derived through this detailed analysis of historically observed concentrations are characteristic of a mesotrophic estuarine system.

1950s to 1990s Concentration Trends. Harding and Perry (1997) documented significantly increasing trends in chlorophyll *a* concentrations during the past several decades in the Chesapeake Bay mainstem. Surface mixed-layer concentrations increased five- to tenfold in the higher salinity mesohaline and polyhaline regions, with 1.5- to twofold increases observed in the tidal-fresh to oligohaline regions of the Bay. During this 50-year period, they documented three major patterns in freshwater flow to the Chesapeake Bay: a long period of low river flows during the 1960s, followed by a series of high flow years throughout most of the 1970s, with a mix of river flow levels in the following two decades, and the extreme droughts (1989) and near-record river flows (1993, 1994) reported toward the end of the data record. Harding and Perry (1997) applied an autoregressive moving-average procedure to

explain possible chlorophyll *a* concentrations over time strictly on the basis of observed freshwater inflow, salinity and temperature. When compared with observed concentration trends over decades, the significant increases in chlorophyll *a* could not be accounted for strictly by the variability of freshwater flow, salinity and temperature. The resulting trends could be explained by increased nutrient enrichment of the estuarine ecosystem.

Taking into account the effects of variable annual river flows, chlorophyll *a* concentrations were shown to respond to changes in nutrient loadings over the period of record. These historically observed chlorophyll *a* concentrations were more representative of mesotrophic conditions.

In oligohaline to tidal-fresh reaches of the Chesapeake Bay mainstem (regions V and VI, respectively), Harding and Perry (1997) documented an increasing trend in chlorophyll *a* concentrations from the 1950s to the 1970s, followed closely by a decreasing trend that has carried through into the 1990s (Table V-3; Figure V-1). The decreasing trends are likely due to significant decreases in phosphorus loadings to the Bay, resulting from widespread upgrades in wastewater treatment for phosphorus. Bans on phosphates in detergents also were enacted in states surrounding the Bay during the mid- to late 1980s. The phytoplankton in lower salinity systems where phosphorus has been limited have responded positively, and this has led to lower chlorophyll *a* concentrations, whereas comparable reductions in nitrogen loads have not yet been achieved, limiting opportunities for reduced phytoplankton biomass in the higher salinity regions of the mainstem Bay.

In the 1950s, recognizing limitations in the temporal and spatial coverage of the available data, regional mean chlorophyll *a* concentrations were 3.19 and 2.51 μg liter^{-1}in the tidal-fresh to low- salinity regions between the Susquehanna Flats and the Bay Bridge and between the Bay Bridge and the South River, respectively (regions VI and V, respectively, Harding and Perry 1997; see Figure V-1). Concentrations peaked at 15.59 μg liter^{-1} (1960s) and 13.12 μg liter^{-1} (1970s) in these two regions, respectively, and were recorded as regional means of 5.57 μg liter^{-1} and 10.86 μg liter^{-1}during the 1985-1994 period.

In the higher salinity mesohaline regions—Region IV-South River down to the Patuxent River and Region III-Patuxent River south to the Rappahannock River—chlorophyll *a* concentrations increased 1.5- to twofold from the 1950s through the mid-1990s (Figure V-1; Harding and Perry 1997). Regional mean chlorophyll *a* concentrations ranged from 4.33 μg liter^{-1} in the 1950s up to 8.20 μg liter^{-1} for the period of 1985- 1994 in the mainstem Bay between the South and Patuxent rivers. At the same time, regional mean chlorophyll *a* concentrations were 3.58 μg liter^{-1}and 8.03 μg liter^{-1}, respectively, in the mainstem Bay between the Patuxent and Rappahannock rivers.

Harding and Perry (1997) reported the largest trends in the polyhaline regions of the mainstem Bay, where chlorophyll *a* concentrations increased five- to tenfold in nearly 50 years. In the mainstem Bay from the Rappahannock River down to

Table V-3. Chesapeake Bay mainstem surface chlorophyll a concentration (μg liter^{-1}) annual means for 1950 to 1994.

Time Period	Region	Chlorophyll *a* Annual Mean	Number of Observations	Percent Difference[1]
1950-1959	I	0.46	41	-
	II	1.21	18	-
	III	3.58	108	-
	IV	4.33	7	-
	V	3.19	15	-
	VI	2.51	18	-
1960-1969	I	1.89	8	310
	II	2.61	9	115
	III	7.09	28	98
	IV	7.48	58	73
	V	7.79	97	144
	VI	15.59	295	521
1970-1979	I	4.39	101	853
	II	6.89	31	468
	III	7.95	100	122
	IV	7.29	206	68
	V	13.12	324	311
	VI	12.90	845	414
1985-1994	I	5.49	1862	1093
	II	7.40	2350	510
	III	8.03	1261	124
	IV	8.20	1022	89
	V	10.86	1164	240
	VI	5.57	1005	122

[1] Percent difference of annual mean chlorophyll *a* concentration for each region is based upon a comparison with the corresponding chlorophyll *a* concentration in 1950-1959.

Source: Harding and Perry 1997.

Mobjack Bay (Region II; Figure V-1), regional chlorophyll *a* concentrations averaged 1.21 μg liter^{-1} in the 1950s, but increased to 7.40 μg liter^{-1} from 1985 to 1994. The regional mean chlorophyll *a* concentration of 0.46 μg liter^{-1}observed in the 1950s increased tenfold through the 1990s to 5.57 μg liter^{-1}in the mainstem Bay from Mobjack Bay to the mouth of the Bay.

Benchmark Levels Derived from Analysis of the CBP Water-Quality Database. Evaluating a similar time period of data using different methodologies,

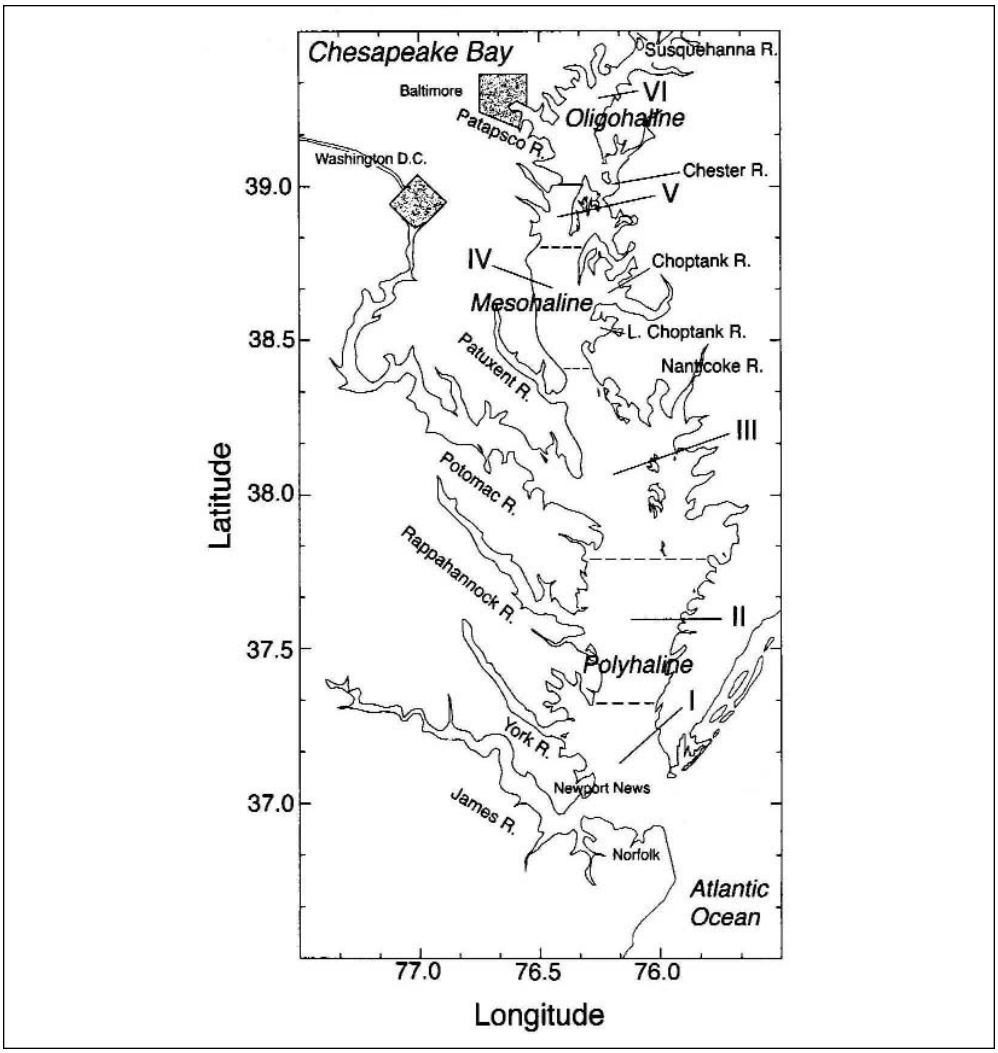

Figure V-1. The Chesapeake Bay showing locations of the six regions chosen to represent major salinity provinces of the estuary, the principal rivers draining into the Chesapeake Bay and major metropolitan areas.
Source: Harding and Perry 1997.

Olson (2002) reported a series of benchmark concentrations for chlorophyll *a* as well as for nitrogen, phosphorus and total suspended solids. Benchmark concentrations, derived from a 1985 to 1990 benchmark data set, were applied to the entire 1950s through late 1990s data set (Table V-4). Tabular summaries of decadal spring, summer and annual median chlorophyll *a* concentrations across five decades are documented in Appendix E, tables E-1 and E-2. Table V-5 summarizes the results of these reviews and evaluations of the extensive historical and recent chlorophyll *a* concentration data records.

Strengths and Limitations. Consideration of the historical chlorophyll *a* concentrations reflecting a more balanced, mesotrophic Chesapeake Bay ecosystem must be tempered by a recognition of the limited spatial and temporal coverage of

Table V-4. Historical chlorophyll *a* concentrations (μg liter^{-1}) derived through applying relative status benchmark data.

Season	Salinity Zone	Chlorophyll *a* Median	Chlorophyll *a* Mean	Chlorophyll *a* 90th Percentile	Number of Observations
Annual	Tidal-Fresh	3.1	4.2	10.2	972
	Oligohaline	4.7	6.0	10.8	910
	Mesohaline	7.3	7.2	10.9	4192
	Polyhaline	4.4	4.3	7.0	1132
Spring	Tidal-Fresh	3.1	3.7	4.2	488
	Oligohaline	5.1	5.9	9.8	279
	Mesohaline	6.9	7.2	11.0	708
	Polyhaline	3.4	4.1	12.9	91
Summer	Tidal-Fresh	7.3	7.0	8.7	423
	Oligohaline	8.0	7.6	10.8	566
	Mesohaline	8.4	7.9	11.1	1677
	Polyhaline	4.3	3.7	6.0	341

Sources: Olson 2002.

Table V-5. Summary of historical Chesapeake Bay chlorophyll *a* concentrations (μg liter^{-1}).

Salinity Regime	Harding and Perry (1997)-1950s Chesapeake Bay Mainstem Annual Mean Concentrations	Olson (2002)-1950s Chesapeake Bay and Tidal Tributaries Spring/Summer/ Annual Mean Concentrations	Olson (2002)–Relative Status Spring/Summer/ Annual Benchmark Concentrations
Tidal-fresh	2.51	1.1 / 1.1 / -	3.7 / 7.0 / 4.2
Oligohaline	2.51-3.19	2.3 / 2.0 / 3.1	5.9 / 7.6 / 6.0
Mesohaline	3.58-4.33	3.7 / 4.4 / 3.1	7.2 / 7.2 / 7.9
Polyhaline	0.46-1.21	3.9 / - / 3.2	4.1 / 3.7 / 4.3

Sources: Harding and Perry 1997; Olson 2002.

the available data for the 1950s and 1960s, as well as the different living resource communities present in the Bay's tidal habitats more than 50 years ago. The data limitations of the 1950s and 1960s data are particularly of concern in the lower portion of the Chesapeake Bay. The large reduction in filter-feeder (e.g., oysters, menhaden) populations has reduced the capacity of the Chesapeake Bay's living resources to assimilate nutrient loads and to maintain lower chlorophyll *a* concentrations. Thus, the changes in living resources may have affected chlorophyll *a*

concentrations as much as or more than the reverse. It should be noted that temporal trends alone do not demonstrate causal relations between chlorophyll *a* concentrations and specific ecological conditions.

Literature Values Related to Trophic Status

Several influential scientific papers, synthesizing data from many different aquatic systems, describe conditions that were judged to reflect the trophic status of different water bodies (e.g., Wetzel 2001; Ryding and Rast 1989; Smith 1998). Chlorophyll *a* is the principal parameter quantified in these literature reviews. The information is drawn from a diversity of systems across the spectrum of healthy (oligotrophic) to severely stressed (eutrophic) water bodies.

Several papers in the literature synthesize data from many aquatic systems and focus on conditions that reflect different trophic states of water bodies. R. G. Wetzel's *Limnology* presents a table of phytoplankton-related trophic states based on hundreds of studies in freshwater systems (Wetzel 2001). His text defines eutrophic systems as having the same four dominant phytoplankton species as those currently found in most of the Chesapeake Bay system's tidal-fresh or oligohaline habitats and chlorophyll *a* concentrations greater than 10 μg liter^{-1}. A system is defined as eutrophic when it has: 1) very high productivity but mostly occurring in the lower trophic levels (e.g., algae, bacteria); 2) a simplified structure of biological components; and 3) reduced ability to withstand severe stresses and return to pre-stress conditions. In a eutrophic condition, "excessive inputs commonly seem to exceed the capacity of the ecosystem to be balanced, but in reality the systems are out of equilibrium only with respect to the freshwater chemical and biotic characteristics desired by man for specific purposes" (Wetzel 2001). Mesotrophic freshwater systems are defined by Wetzel (2001) as having chlorophyll *a* concentrations in the range of 2-15 μg liter^{-1} (Table V-6).

Table V-6. Summary of aquatic system trophic status as characterized by mean chlorophyll *a* concentrations (μg liter^{-1}).

Aquatic System	Trophic Status	Wetzel (2001)	Ryding and Rast (1989)	Smith et al. (1999)	Molvaer et al. (1997)	Novotny and Olem (1994)
Fresh-water	Eutrophic	>10	6.7-31	9-25	-	>10
	Mesotrophic	2-15	3-7.4	3.5-9	-	4-10
	Oligotrophic	0.3-3	0.8-3.4	<3.5	-	<4
Marine	Eutrophic	-	-	3-5	>7	-
	Mesotrophic	-	-	1-3	2-7	-
	Oligotrophic	-	-	<1	<2	-

Sources: Molvaer et al. 1997, Novotny and Olem 1994, Ryding and Rast 1989, Smith et al 1999, Wetzel 2001.

Ryding and Rast (1989) also deal with characteristics of eutrophication in lakes, based on surveys of hundreds of temperate lakes globally. In Table 4.2, they give the following boundary values for mean and peak chlorophyll *a* values (μg liter^{-1}), as follows:

	Mean range	Peak Range
Oligotrophic	0.8-3.4	2.6-7.6
Mesotrophic	3.0-7.4	8.9-29
Eutrophic	6.7-31	16.9-107

The peak range is for occasional blooms, and the mean ranges are those for annual geometric means, with outliers removed (see Table 4.2 in Ryding and Rast 1989). The ranges overlap slightly, and in fact the authors recommend using multiple parameters, including total phosphorus, total nitrogen, chlorophyll *a* and Secchi depth to classify the lakes. Using their criteria, much of the Chesapeake Bay would clearly be classified as 'eutrophic.'

In a review of lake and marine systems, Smith et al. (1999) equated mesotrophic status in lake systems to mean chlorophyll *a* concentrations ranging from 3.5 to 9 μg liter^{-1}. A chlorophyll *a* concentration range of 1 to 3 μg liter^{-1} was equated with mesotrophic status in marine systems (assumed here to be principally polyhaline in terms of salinity). Smith et al. (1999) also published values characteristic of hyper-eutrophic lake (>25 μg liter^{-1}) and marine systems (>5 μg liter^{-1}) .

The Norwegian Environmental Protection Agency has constructed a system for classifying estuaries and coastal waters with respect to water quality and eutrophication using five classes of water quality (Molvaer et al. 1997). For salinities above 20 ppt, chlorophyll *a* concentrations below 2 μg liter^{-1} are considered Class I or 'very good,' whereas concentrations above 20 μg liter^{-1}are classified as "very bad" or Class V waters. Sweden has adopted similar chlorophyll *a* water quality standards for its estuarine (1.3 to 2.0 μg liter^{-1}) and marine (1.0 to 1.5 μg liter^{-1}) waters that reflect the lower end of these concentration ranges (Sweden Environmental Protection Agency 2002).

Strengths and Limitations. The trophic classifications should be used with caution since the majority of the scientific literature-based values were developed for lake, coastal or marine systems, not temperate, partially mixed estuaries such as the Chesapeake Bay. In particular, marine ecosystems should not be considered directly comparable to polyhaline estuarine areas. The polyhaline areas of the Chesapeake Bay are in much closer proximity to land-based freshwater and nutrient inputs. Therefore, they should be expected to have higher nutrient concentrations and associated chlorophyll *a* concentrations than marine systems.

Trophic classifications are useful, general ecological concepts. However waters classified strictly by chlorophyll *a* concentrations may or may not experience all or any of the ecological conditions characteristic of that category (see Table V-2).

Phytoplankton Growth-Limiting Water Quality Conditions and Related Chlorophyll *a* Concentrations

Biological communities found in pristine or minimally affected habitats provide essential information on how restoration efforts might improve ecosystem structures and functions. They also serve as references for measuring restoration progress. Chesapeake Bay water quality and phytoplankton data collected at Chesapeake Bay Program phytoplankton monitoring stations between 1984 and 2001 were analyzed to identify reference phytoplankton communities for Chesapeake tidal waters. The seasonal and salinity-specific reference communities were used to quantify chlorophyll *a* concentrations in the least-impaired water quality conditions currently found in the Chesapeake Bay.

For the purposes of deriving the reference communities, least-impaired water quality conditions were defined as the co-occurrence of high light penetration, low dissolved inorganic nitrogen and low dissolved inorganic phosphorus concentrations. Low dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (PO_4) concentrations are below the threshold concentrations shown to limit phytoplankton growth in Chesapeake Bay waters (Fisher et al. 1999), whereas high light penetrations are the Secchi depth values identified by the Relative Status, or benchmark, method as 'good' (Olson 2002). The high light penetration levels are approximately the same as those necessary for restoring underwater bay grasses (Batiuk et at. 2000). Thresholds for DIN, PO_4 and Secchi depth for spring and summer across four salinity zones (tidal-fresh, oligohaline, mesohaline and polyhaline) were applied to the 1984 through 2001 Chesapeake Bay water quality monitoring database to bin the data records into six water quality categories. Reference communities were derived from the least impaired water quality categories found in each season-salinity regime.

Water quality conditions that met all three reference criteria ('better'/'best') between 1984 and 2001 occurred in 1.6 percent (spring) and 5.8 percent (summer) of the mesohaline biomonitoring samples, and 21.1 percent (spring) and 10.4 percent (summer) of the polyhaline water quality monitoring samples, so reference communities could be characterized directly from the data. Water quality conditions that met all the reference criteria rarely occurred in tidal-fresh and oligohaline salinities. In these cases, the 'mixed better light' category (see Appendix F for definition) was used as a surrogate, since values of most phytoplankton parameters (e.g., chlorophyll *a*, biomass, pheophytin and species composition) in this category closely resembled those in 'better'/'best' in mesohaline and polyhaline waters. For the spring mesohaline reference community, 'better'/'best' data were augmented with 'mixed better light' data to increase the number of data records. Chlorophyll *a* concentrations

observed in the phytoplankton reference communities are shown in Table V-7. The water quality binning method and identification of the phytoplankton reference communities are described in more detail in Appendix F.

It is important to realize that the chlorophyll *a* concentrations in Table V-7 reflect phytoplankton reference communities in the absence of robust grazer populations. There are no undisturbed sites in the Chesapeake Bay with a full complement of natural grazers. Harvesting and disease have significantly decreased Chesapeake oyster abundances (Newell 1988). Menhaden populations have declined to approximately 5 percent of 1970s levels (data from the Maryland Department of Natural Resources). Comparisons of historic and contemporary populations of mesozooplankton and benthos indicate that declines may also have occurred in these grazers. Median chlorophyll *a* concentrations in the reference communities are significantly lower than those in impaired waters, and algal blooms are absent. Reference community chlorophyll *a* concentrations are slightly higher than historic Chesapeake Bay concentrations and are typical of mesotrophic conditions. They indicate the chlorophyll *a* concentrations that could be attained in the present-day Chesapeake Bay with significant nutrient and sediment reductions, in the absence of robust populations of grazers. If key grazer populations are at least partially restored to historical levels, it is possible that the phytoplankton reference community chlorophyll *a* concentrations will approach 1950s levels (see Table V-3).

Table V-7. Chlorophyll *a* concentrations in the salinity- and season-based Chesapeake phytoplankton reference communities (μg liter^{-1}). The median and range (5%–95%) are shown. Reference community values are derived from samples with the least improved water quality conditions in the 1984–2001 Chesapeake Bay Program phytoplankton and water quality monitoring station data.

Salinity Regime	Spring	Summer
Tidal-Fresh	4.3 (1.0 - 13.5)	8.6 (3.2 - 15.9)
Oligohaline	9.6 (2.4 - 24.3)	6.0 (2.5 - 25.2)
Mesohaline	5.6 (2.2 - 24.6)	7.1 (4.4 - 14.0)
Polyhaline	2.9 (1.1 - 6.7)	4.4 (1.7 - 8.7)

Source: Chesapeake Bay Water Quality and Phytoplakton Monitoring Programs Databases. http://www.chesapeakebay.net/data

Strengths and Limitations. It is important to realize that these values were selected from samples subject with least-improved water quality, and they came from a larger data set obtained from generally nutrient- and sediment-enriched Chesapeake Bay. Under better water quality conditions (lower annual nutrient load-

ings, more zooplankton grazing and better trophic coupling), these chlorophyll *a* values might be even lower than those obtained under low current nutrient loadings due to the carryover of nutrients from previous high load conditions.

The phytoplankton reference community approach does not demonstrate any direct relationship between chlorophyll *a* concentrations and designated use impairments. However, this method does provide solid insights into how chlorophyll *a* concentrations will likely respond in estuarine systems as water quality improves, leading to more nutrient-limited, light saturated conditions.

Chlorophyll *a* concentrations do not always show a high correlation with algal biomass because after a bloom, some species of nonchlorophyll-bearing phytoplankton can feed on organic material (Livingston 2001).

Research Needs. Further analysis of the Chesapeake Bay monitoring databases could help determine if nitrogen, phosphorus or suspended sediment reductions or a combination thereof will be most effective in minimizing the occurrence of harmful algal blooms.

Chlorophyll *a* Concentrations Characteristic of Potentially Harmful Algal Blooms

The scientific literature indicates that certain phytoplankton community taxonomic groups produce poor quality food and even toxins that impair the animals that feed on them (Roelke et al. 1999; Roelke 2000). Phytoplankton assemblages can become dominated by poor quality food taxonomic groups to an extent that the overall food quality of that phytoplankton assemblage becomes significantly reduced. Chlorophyll *a* concentrations were identified that corresponded to an increased probability that potentially harmful algal taxa would exceed specific impairment thresholds.

Several of the more than 700 phytoplankton species in the Chesapeake Bay are known to be harmful to consumers. Approximately 2 percent of these species have shown evidence of producing toxins (Marshall 1996). Some species, however, form blooms and can dominate the community at particular locations during specific times of the year. Some of these species are even capable of producing toxins.

The dinoflagellates, *Prorocentrum minimum* and *Cochlodinium heterolobatum*, which commonly bloom in spring and summer, respectively, in certain mesohaline areas of the estuary, have been shown to harm various life stages of the Eastern oyster, *Crassostrea virginica* (Ho and Zubkoff, 1979; Luckenbach et al. 1993; Wickfors and Smolowitz 1995). The dinoflagellate *Karlodinium micrum* has been associated with numerous fish kills in the Chesapeake Bay (Goshorn et al. 2003). In tidal-fresh regions, a colonial cyanophyte, *Microcystis aeruginosa*, forms surface blooms that cover the upper reaches of certain Bay tributaries for miles during the summer. This species has been documented to affect zooplankton communities under bloom conditions (Lampert 1981; Fulton and Paerl 1988).

The occurrence of harmful algal blooms is a complex, incompletely-understood phenomenon. Many harmful blooms cannot effectively be predicted or modeled at this time, and the physical, chemical and biological controls on many such blooms are not known. Nutrient concentrations or loads are only one of many environmental parameters that can potentially affect harmful algal blooms. For example, some harmful blooms may respond more to nutrient ratios than absolute concentrations, or may be regulated by top-down controls (e.g., grazer dynamics) more than by nutrient availability. This section represents a valuable compilation of information, focusing on several Chesapeake Bay species that have been observed to correlate with chlorophyll *a* concentrations. As illustrated below using the four previously cited species, the likelihood of bloom conditions being produced by some harmful or nuisance algal species tends to be associated with elevated chlorophyll *a* levels. Future monitoring and research is expected to provide more insight into the practicality and methodology for managing blooms of these and other species.

Microcystis aeruginosa. A substantial body of literature deals with the negative effects of toxic cyanobacteria on the feeding, growth, behavior and survival of micro- and mesozooplankton. Numerous studies have documented the avoidance of ingestion of toxic and nontoxic strains of *Microcystis aeruginosa* by specific taxa of zooplankton (Clarke 1978; Lampert 1981; Gilbert and Bogdan 1984; Fulton and Paerl 1987, 1988; DeMott and Moxter 1991) while others indicate physiological and behavioral problems associated with its ingestion (Lampert 1981, 1982; Nizan et al. 1986; Fulton and Paerl 1987; DeMott et al. 1991; Henning et al. 1991).

From laboratory studies, 10,000 cells milliliter^{-1} was determined to be the threshold above which zooplankton communities can be adversely altered by the poor food quality, large particle size of the colonies, increased density of particles in the water column or directly by the toxin (Lampert 1981; Fulton and Paerl 1987; Smith and Gilbert 1995). (See Appendix G for more detailed descriptions of the determination of the effects threshold.)

Upon matching the chlorophyll *a* concentrations to samples containing *M. aeruginosa*, normalized frequency distribution plots were constructed for *M. aeruginosa* bloom frequency and the frequency of both bloom and non-bloom abundances versus chlorophyll *a* concentrations (figures V-2 and V-3, respectively). Chlorophyll *a* concentrations <15 μg liter^{-1} characterize *M. aeruginosa* concentrations less <10,000 cells milliliter^{-1} (Figure V-2). Increasing concentrations of chlorophyll *a* above 15 μg liter^{-1} leads to increasing frequencies of bloom samples > 10,000 cells milliliter^{-1} (Figure V-3).

Colonies of *M. aeruginosa* vary in their cell counts but colony counts provide an additional measure of bloom conditions (Figure V-4). The ratio of cells per colony is approximately 17:1, providing an estimate of 588 colonies containing 10,000 cells as a translation to threshold levels for zooplankton community impacts.

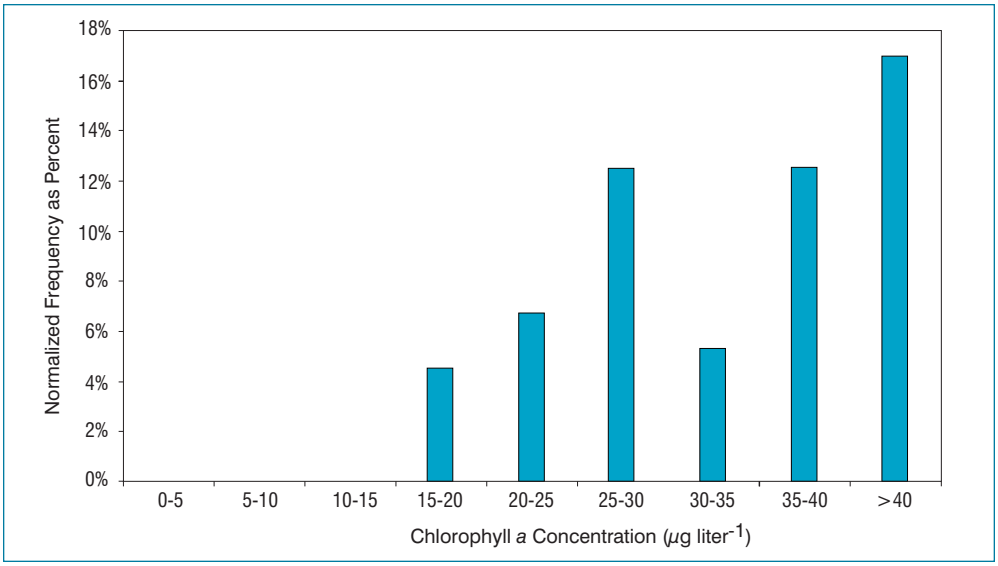

Figure V-2. Normalized frequency of *Microcystis aeruginosa* abundances above-threshold (i.e., >10,000 cells milliliter^{-1}) versus summer tidal fresh chlorophyll *a* concentration. The number of above-threshold *Microcystis aeruginosa* abundances in each chlorophyll *a* interval is divided by the total number of phytoplankton records in that interval. For summer tidal fresh, there were 16 above-threshold occurrences in a total of 266 samples.

Source: Chesapeake Bay Phytoplankton Monitoring Program Database.
http://www.chesapeakebay.net/data

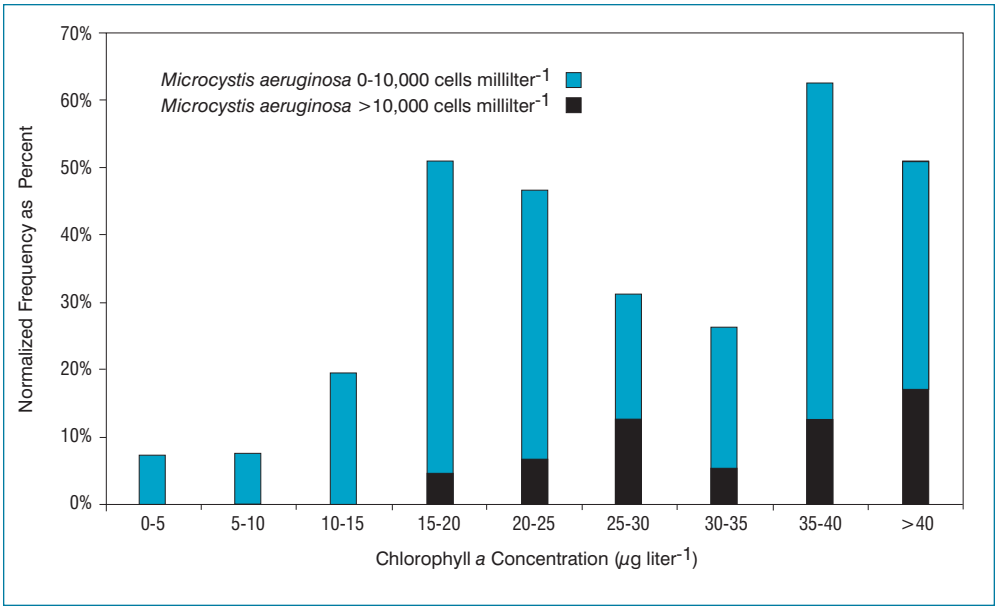

Figure V-3. Normalized frequency of above- and below-threshold *Microcystis aeruginosa* abundances versus summer tidal fresh chlorophyll *a* concentration. The number of above- and below-threshold *Microcystis aeruginosa* abundances in each chlorophyll interval is divided by the total number of phytoplankton records in that interval. For summer tidal fresh, there were 62 total occurrences of *Microcystis aeruginosa* in a total of 266 samples. The increasing trend in total occurrences of *Microcystis aeruginosa* identify it as an indicator species of eutrophication.

Source: Chesapeake Bay Phytoplankton Monitoring Program Database.
http://www.chesapeakebay.net/data

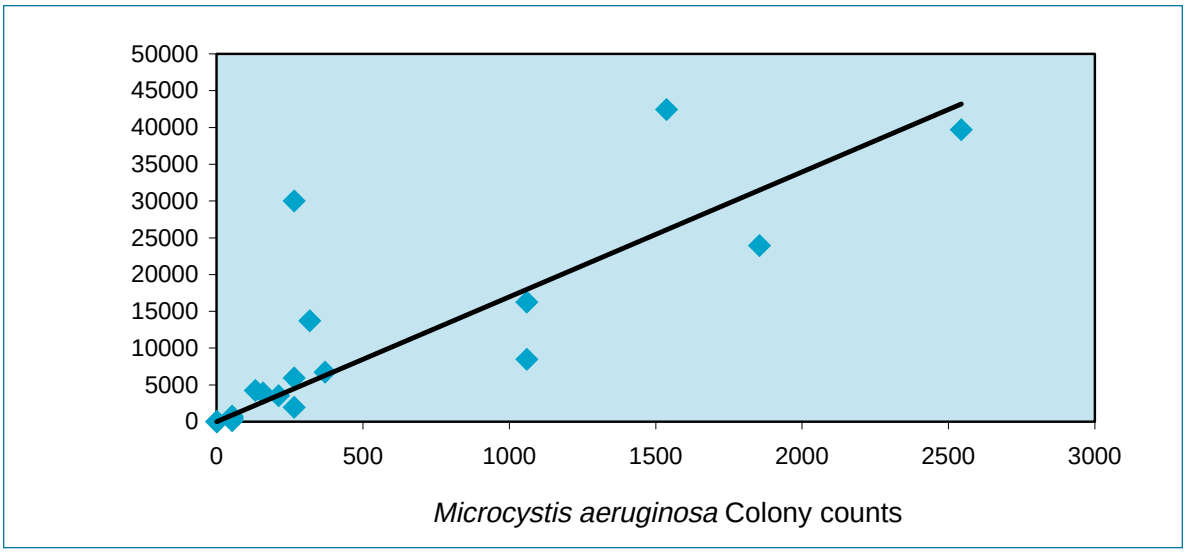

Figure V-4. Relationship of *Microcystis aeruginosa* colony counts versus cell counts. Cell counts=16.97 x colony counts; r2=0.66; n=20.

Source: Maryland Department of Natural Resources unpublished data.

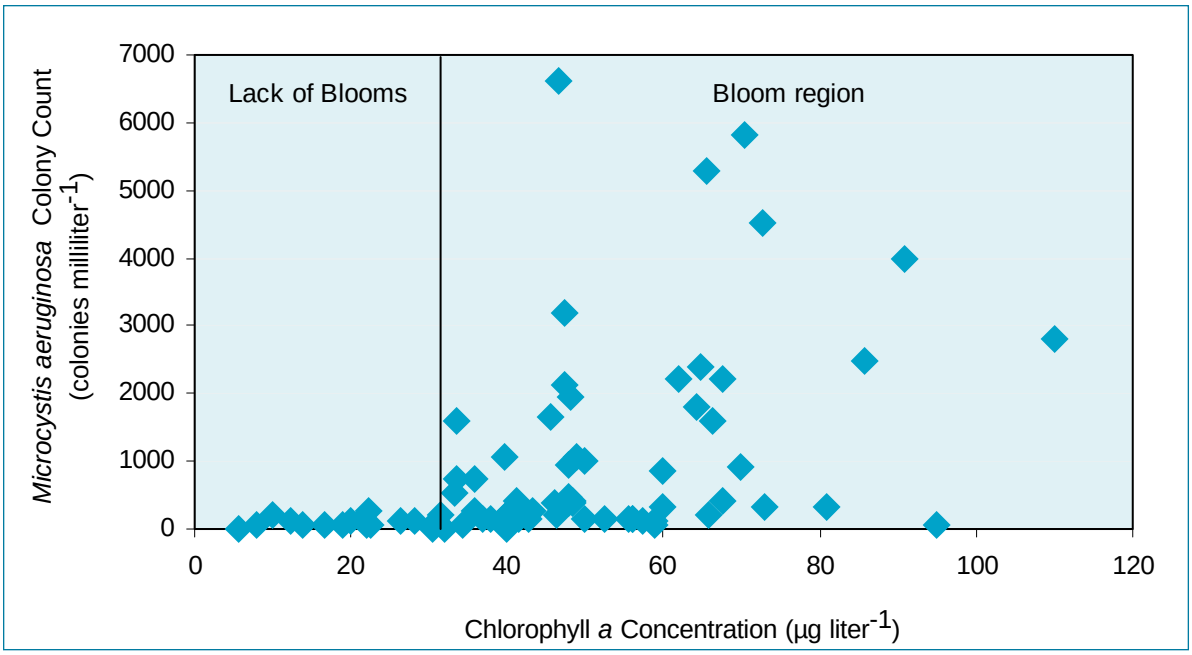

Figure V-5. *Microcystis aeruginosa* colony counts versus a gradient of chlorophyll *a* concentrations illustrating the boundary between bloom and non-bloom conditions.

Source: Maryland Department of Natural Resources unpublished data.

M. aeruginosa counts were made from water samples collected by the Maryland Department of Natural Resources through a separate water quality monitoring program from the tidal-fresh and oligohaline waters of Maryland's Chesapeake Bay. Between 1985 and 2000, *M. aeruginosa* colony counts showed low concentrations (<588 colonies milliliter^{-1}) and low variance between 0-33 μg liter^{-1} chlorophyll *a* (Figure V-5). Beyond 33 μg liter^{-1} chlorophyll *a*, the variance of colony counts increases significantly and counts exceeding the 588 colonies milliliter^{-1} threshold increase to 42 percent beyond 33 μg liter^{-1} chlorophyll *a*, providing a threshold and probability for potentially harmful blooms of this cyanobacteria with respect to chlorophyll *a* measures. The chlorophyll *a* range of 15-33 μg liter^{-1} provides a threshold region between levels that protect against *M. aeruginosa* blooms versus conditions with a high likelihood for blooms.

One of the primary locations for *M. aeruginosa* blooms in the Chesapeake Bay estuary is the tidal-fresh Potomac River. Extensive blooms of *M. aeruginosa* were documented over the period of 1965-1983, before the initiation of the coordinated Chesapeake Bay monitoring program. During the period of 1965-1974, summer chlorophyll *a* concentrations in the vicinity of Indian Head (near monitoring station TF2.3) were typically above 50 μg liter^{-1} and often exceeded 100 μg liter^{-1} in the surface layer (Pheiffer 1975). During the same period, cyanobacteria blooms were extensive in this portion of the river in summer, although there are very few data reflecting cell densities. Total cyanobacteria densities ranged from 20,000–120,000 cells milliliter^{-1} in the summer of 1971 near Possum Point (Simmons et al. 1974).

In 1983, a massive bloom of *M. aeruginosa* was documented in this portion of the Potomac River (mile 12 - mile 46) (Thomann et al. 1985). Chlorophyll *a* concentrations averaged over 200 μg liter^{-1} for the Indian Head area in August 1983. Again, little species composition data is documented for this bloom.

With the initiation of the Chesapeake Bay phytoplankton monitoring program in August 1984, a steady flow of phytoplankton species composition and chlorophyll *a* data was recorded for a station in the tidal-fresh Potomac River near Indian Head (TF2.3). Figure V-6 summarizes these data for *M. aeruginosa* during the summer months of 1985–2002. The data show that the threshold is rarely exceeded during this period after 1988, but one can assume that during the severe blooms of the 1970s and early 1980s, this threshold may have been surpassed on a regular basis. The fact remains that this taxon is an impairment to zooplankton assemblages above a specific threshold and this threshold density has been surpassed on a number of occasions in the tidal-fresh Potomac River during the past several decades.

Strengths and Limitations. The strength of this line of evidence for establishing a chlorophyll *a* threshold for the tidal-fresh and oligohaline regions of the estuary lies in the evidence provided in the many laboratory and field studies that indicate adverse affects on zooplankton populations caused by cyanobacteria in general and, more specifically, by *M. aeruginosa*. *M. aeruginosa* has been found in many of the tidal-fresh locations sampled as part of the Chesapeake Bay water quality

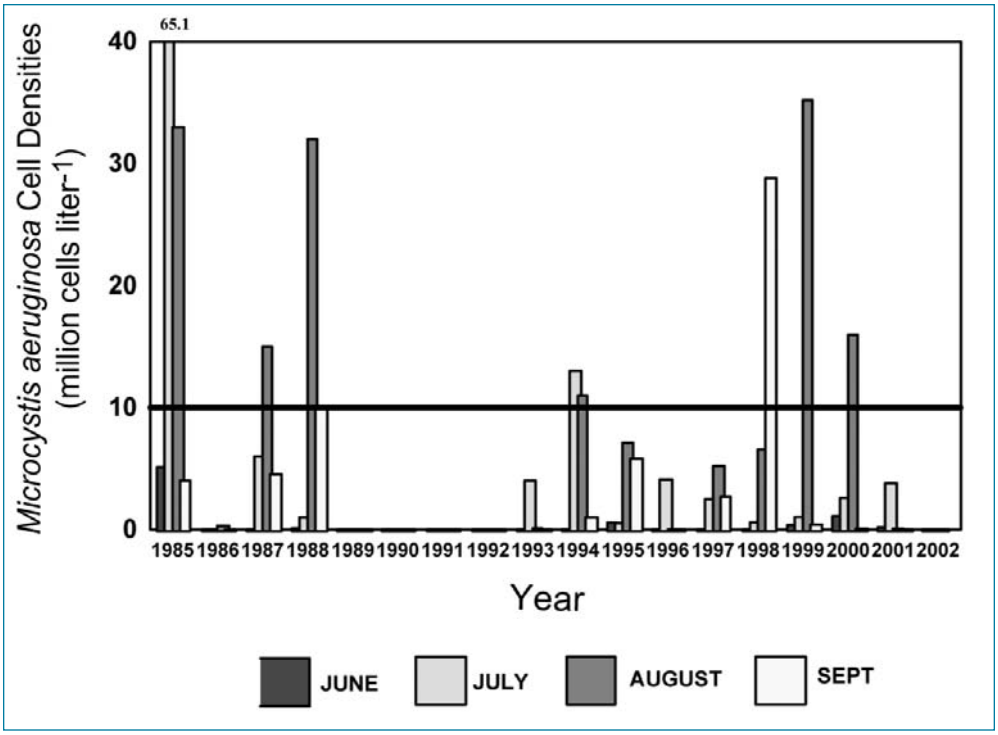

Figure V-6. Mean summer *Microcystis aeruginosa* cell densities from 1985–2002 from the surface mixed layer of the Potomac River tidal fresh phytoplankton monitoring station TF2.3.

Source: Chesapeake Bay Phytoplankton Monitoring Program Database. http://www.chesapeakebay.net/data

monitoring program, implying that this 'indicator' species is ubiquitous to this particular tidal-fresh habitat during the summer under certain hydrodynamic conditions and with a given set of nutrient requirements.

Numerous field studies have documented changes in zooplankton community structure associated with blooms of cyanobacteria in general (Infante and Riehl 1984; Orcutt and Pace 1984; Threlkeld 1986; Burns et al. 1989; Gilbert 1990; Fulton and Jones 1991). These studies most frequently cite the inability of many zooplankton taxa in using cyanobacteria as a nutritive food source. Therefore, it can reasonably be stated that high chlorophyll *a* concentrations in tidal-fresh and oligohaline regions of the Chesapeake Bay estuary in summer often are associated with high densities of cyanobacteria, which can adversely alter the zooplankton community structure in these areas.

Colony counts have a lower variance than, and a positive relationship to, *M. aeruginosa* cell counts, providing a robust indicator to describe bloom conditions. Both data sets in these analyses independently define a relatively narrow range of conditions that separate the bloom from non-bloom regions of the chlorophyll *a* gradient based on threshhold level effects on living resources of 10,000 cells milliliter^{-1}.

The threshold value for the cell density that affects zooplankton populations was derived from two laboratory studies citing impairment thresholds at very different cell densities (see Appendix G). A third study has been identified that documented negative effects on zooplankton at *M. aeruginosa* cell densities of 50,000 cells milliliter^{-1}, which is an intermediate value compared to the two previously cited studies (Smith and Gilbert 1995).

Some of the detrimental effect of *M. aeruginosa* on zooplankton assemblages is related to the toxin content of a particular strain of this cyanobacterium (one reason that the threshold density of the two laboratory studies is so different). The toxin content of the strains of *M. aeruginosa* found in the Chesapeake Bay has not been determined, which forced the extrapolation of the threshold for this document to be chosen as a midpoint between the thresholds of the two laboratory studies.

Colony counts are not interchangeable with cell counts, since the variance increases as the counts increase. The risks have been stated based on a threshold for zooplankton effects using an abundance of cells, while the risks to toxin production or toxic effects are less well understood in relation to cell or colony concentrations.

Research Needs. Two obvious research studies would strengthen this line of evidence. The first would be to assess the toxin content in the populations of *M. aeruginosa* found in various tidal-fresh regions of the Chesapeake Bay. The second would be to use some strains of the cyanobacterium in specific laboratory experiments that studied effects on zooplankton feeding, reproduction and survival at specific cell densities and associated chlorophyll *a* concentrations.

The estimate of colony counts as a threshold can be refined using the conversion with cell counts through results of the Chesapeake Bay phytoplankton monitoring program. Additional work is needed to correlate the concentration data with levels associated with detrimental levels of microcystin toxins in the ecosystem. Spatial and temporal resolution of *M. aeruginosa* levels in relation to cell and colony concentration would provide valuable information for any reassessment of the density driven thresholds being proposed.

Prorocentrum minimum. *P. minimum* effects may be a function of bloom density or toxicity. In Japan in 1942, *P. minimum* was attributed as the cause of a shellfish poisoning in Japan in which 114 people died (Nagazima 1965, 1968). *P. minimum* isolated from a 1998 bloom in the Choptank River and subsequently grown in the laboratory was found to be toxic to scallops (G. H. Wickfors, personal communication). Blooms of *P. minimum* in the source intake waters to Virginia and Maryland oyster hatcheries were suspected to have caused oyster larvae mortality at the two hatcheries in 1998 (Mark Luckenbach and Don Merritt, personal communication). There has been no documented case of shellfish toxicity or mortality as a result of the 1998 *P. minimum* bloom in the Chesapeake Bay, but clearly the potential exists for toxic repercussions to shellfish and other organisms as a result of this bloom.

The *P. minimum* density of 3,000 cells milliliter^{-1} was chosen as a threshold for the chlorophyll *a* criteria analysis based on laboratory analyses (Wickfors and Smolowitz 1995; Luckenbach et al. 1993; see Appendix G). When the threshold is applied to Chesapeake Bay phytoplankton monitoring program data, the normalized frequency distribution of chlorophyll *a* concentrations associated with bloom densities (>3,000 cells milliliter^{-1}) illustrates that concentrations > 5 μg liter^{-1} can generate densities that may impair the survival of various life stages of oysters (Figure V-7). The likelihood of bloom level events tends to increase with increasing chlorophyll *a* concentrations (Figure V-8).

When the threshold is applied to Chesapeake Bay phytoplankton monitoring program data, the normalized frequency distribution of chlorophyll *a* concentrations associated with the *P. minimum* bloom densities (greater than 3,000 milliliter^{-1}) indicates a large increase at chlorophyll *a* concentrations of 25 to 30 μg liter^{-1} (Figure V-9). More than 19 percent of samples containing *P. minimum* in mesohaline waters in spring are characterized by densities that exceed the threshold whereby oyster life stages are impaired and fall within the chlorophyll *a* range of 25 to 30 μg liter^{-1}. In addition, more than 70 percent of the above-threshold data for *P. minimum* occur at chlorophyll *a* concentrations greater than 25 μg liter^{-1} (Figure V-10). These normalized frequency distributions thus indicate that chlorophyll *a* concentrations of greater than 25 μg liter^{-1} in spring in mesohaline waters often are associated with densities of *P. minimum* that may impair the survival of various life stages of oysters.

In an analysis of a separate Maryland Department of Natural Resources database from 1985-2000, a probability analysis illustrated that no blooms of *P. minimum* occurred at or below chlorophyll *a* concentrations of 4 μg liter^{-1} (Figure V-11). This analysis of an independent data set complements the previously described Chesapeake Bay Phytoplankton Monitoring Program database analysis confirming the low target chlorophyl *a* concentration needed to eliminate conditions for blooms of *P. minimum* in the mesohaline Chesapeake Bay. Figure V-11 shows that as the chlorophyll *a* concentration increases, the probability of detecting a *P minimum* bloom level above the 3,000 cells milliliter^{-1} threshold in a sample increases in a non-linear fashion. The possibility increases rapidly at first above 4 μg liter^{-1} and then slows as the maximum potential detection of 11 percent of samples is reached at high chlorophyll *a* concentrations. Maximum bloom probability was 11 percent in the spring, or 1 in every 9 samples when conditions are optimal. Protecting against the conditions for 50 percent of maximum bloom potential occurred at approximately 25-30 μg liter^{-1} (Figure V-11).

Currently, the impairment thresholds are usually reached in spring in mesohaline waters, but *P. minimum* commonly occurs in both spring and summer in oligohaline, mesohaline and polyhaline habitats.

Strengths and Limitations. *P. minimum* blooms occur in many mesohaline portions of the estuary. The appearance of the major bloom events in these areas occur on regular seasonal basis. Therefore this would be a useful indicator species to monitor.

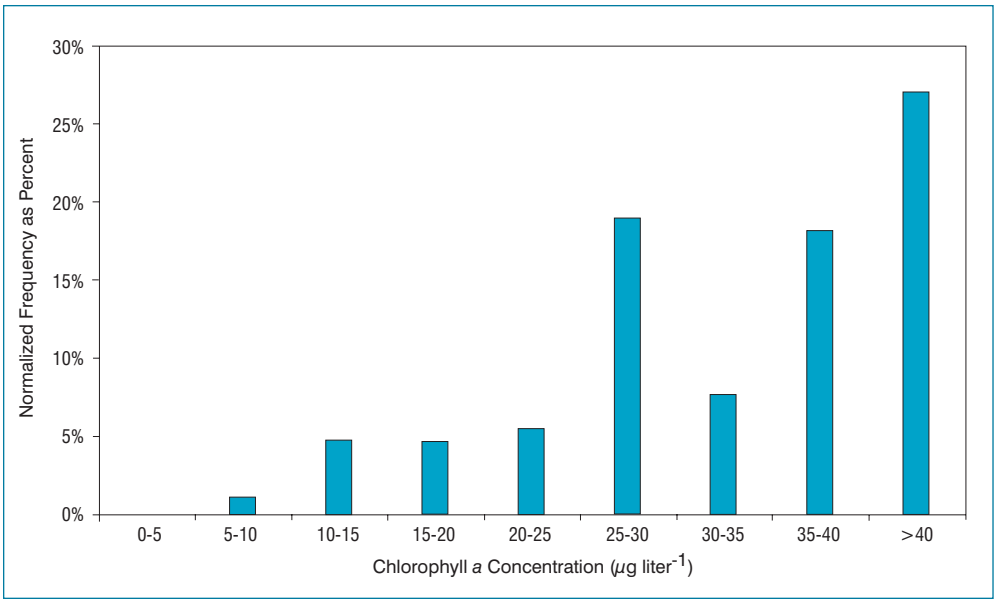

Figure V-7. Normalized frequency of *Microcystis aeruginosa* abundances above-threshold (i.e., >3,000 cells milliliter^{-1}) versus spring mesohaline Chesapeake Bay and tidal tributary chlorophyll *a* concentration. The number of above-threshold *Prorocentrum minimum* abundances in each chlorophyll *a* interval is divided by the total number of phytoplankton records in that interval. For spring mesohaline stations, there were 35 above-threshold occurrences out of a total of 648 sampling records.

Source: Chesapeake Bay Phytoplankton Monitoring Program Database. http://www.chesapeakebay.net/data

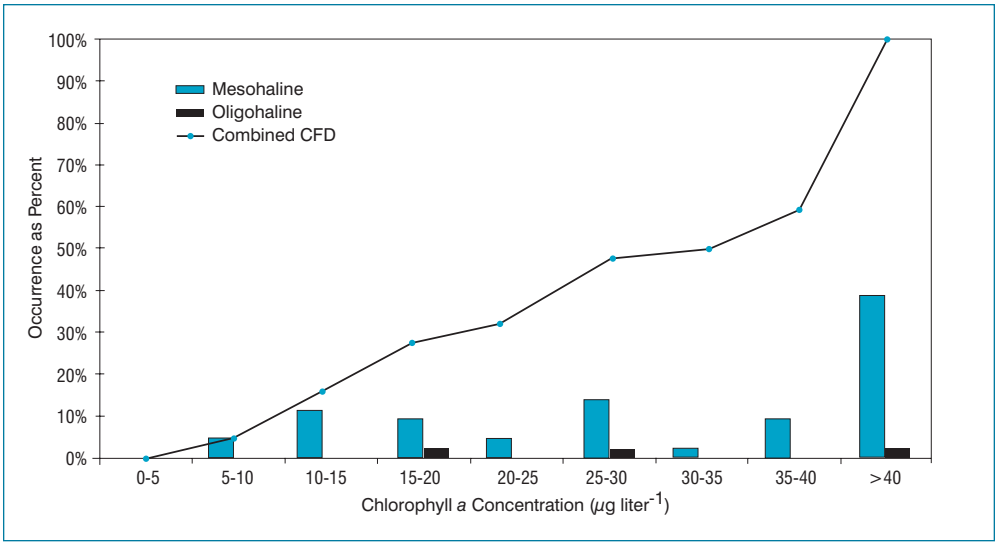

Figure V-8. All occurrences of *Prorocentrum minimum* abundances above threshold versus combined spring and summer, mesohaline and oligohaline Chesapeake Bay and tidal tributary chlorophyll *a* concentration. The number of above threshold *Prorocentrum minimum* densities in each chlorophyll *a* interval is divided by the total number of above-threshold densities (n=44).

Source: Chesapeake Bay Phytoplankton Monitoring Program Database. http://www.chesapeakebay.net/data

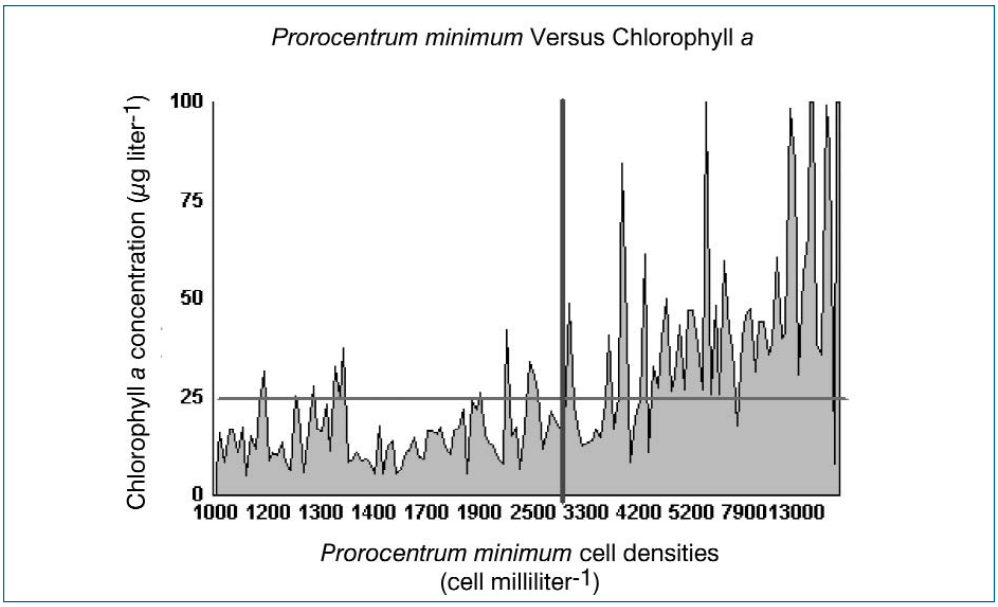

Figure V-9. *Prorocentrum minimum* cell densities and associated chlorophyll *a* concentrations in the Chesapeake Bay, 1985-2000. Cell density threshold associated with impacts on the oyster community is indicated by the vertical black line at 3,000 cells milliliter^{-1}.

Source: Chesapeake Bay Phytoplankton Monitoring Program Database. http://www.chesapeakebay.net/data

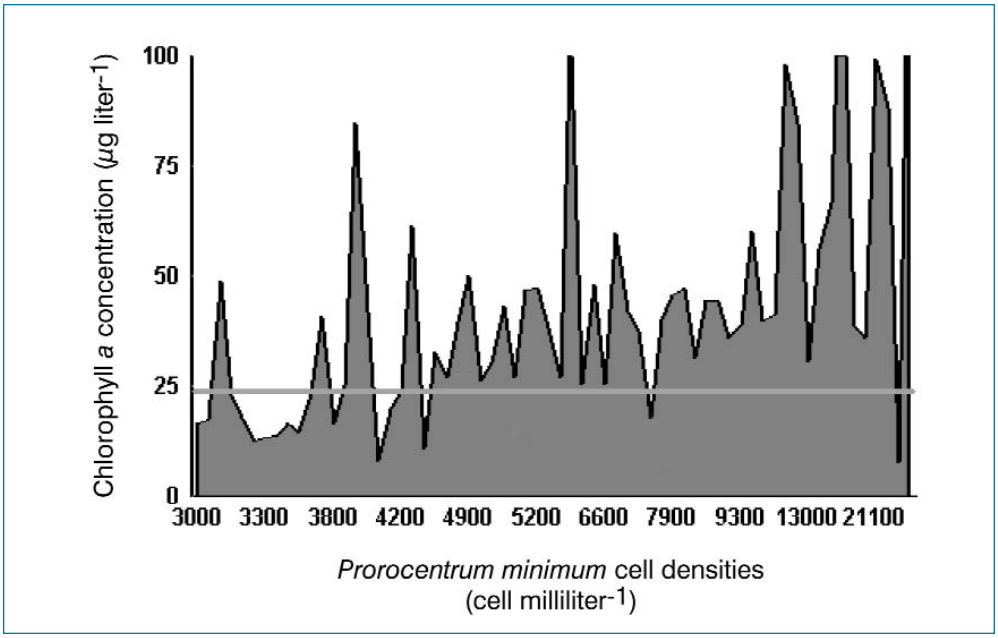

Figure V-10. Enlarged version of Figure V-9 focused on the *Prorocentrum minimum* cell densities and associated chlorophyll *a* concentrations above the 3,000 cells milliliter^{-1} threshold. Over 73 percent of the 64 observed chlorophyll *a* concentrations are greater than 25 µg milliliter^{-1}.

Source: Chesapeake Bay Phytoplankton Monitoring Program Database. http://www.chesapeakebay.net/data

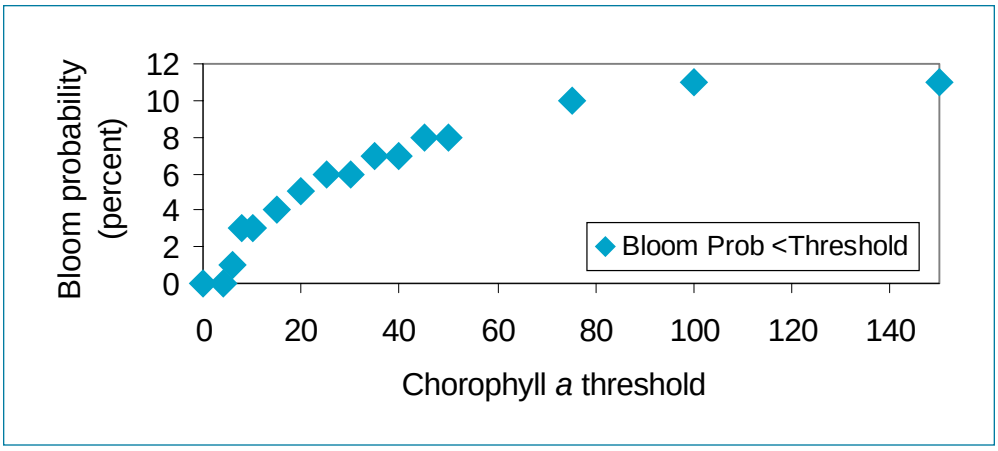

Figure V-11. Spring (March-May) *Prorocentrum minimum* bloom probability, 1985–2002, measured as a percent of the samples exceeding the 3,000 cells milliliter^{-1} threshold plotted against each sample's measured chlorophyll *a* concentration.

Source: Chesapeake Bay Phytoplankton Monitoring Program Database. http://www.chesapeakebay.net/data

This taxon's effects are fairly well-documented, although the toxin content of different strains seems to be variable. The consumer organism that has been tested, *Crassostrea virginica*, the Eastern oyster, is important economically and ecologically as a filter-feeder. The associated chlorophyll *a* threshold is well-defined based upon the historic data from the Chesapeake Bay water quality monitoring program. Both data sets used in these analyses independently defined a relatively narrow range of conditions that separate the bloom from non-bloom regions of the chlorophyll *a* gradient.

Toxin content of different strains of *P. minimum* varies. Although widespread anecdotal evidence suggests that oyster larvae are negatively affected by blooms of *P. minimum* in the Chesapeake Bay, no direct evidence supports this hypothesis. The value chosen as a threshold for impairment is extrapolated from several laboratory studies and does not pertain directly to the strains of *P. minimum* found in the Chesapeake Bay.

Research Needs. Clearly it is necessary to determine the toxin content and conditions conducive to toxin production of the Chesapeake Bay *P. minimum* strain. In addition, grazing studies using water from different bloom sites or cultures isolated from various bloom sites in the Bay would provide pertinent information on the potential effects of this dinoflagellate on oyster larvae and other filter-feeding organisms. These studies thus would be aimed at determining not only a threshold for cell densities but also an associated range of chlorophyll *a* concentrations.

Links between toxicity and density deserve further work as well as a determination of the frequency with which toxic strains of *P. minimum* occur in the Chesapeake

Bay. Defining density relationships to light field requirements is likely to be a fertile area of analysis with this species, since its distribution coincides with spring growth of underwater bay grass beds in the mesohaline portion of the Chesapeake Bay.

Additional studies also are needed to determine if adverse effects of *P. minimum* occur in mixed algal diets. Finally, research is needed to determine effective management strategies for *P. minimum*. This will require a better understanding of the physical, biological and chemical controls on blooms of this taxon.

Cochlodinium heterolobatum. This species forms intense blooms in warm months at the mouth of the York River and in the lower Chesapeake Bay (Mackiernan 1968; Zubkoff and Warriner 1975; Zubkoff et al. 1979; Marshall 1995). The bloom appears to begin at the mouth of the York River and is dispersed into the lower Chesapeake Bay from this point of origin and has been documented to affect ~ 215 km^2 in this part of the estuary (Marshall 1995). In this bloom area, cell densities were generally >1,000 cells $milliliter^{-1}$. Laboratory studies indicated a threshold concentration of ~ 500 cells $milliliter^{-1}$ resulted in mortality of oyster larvae (Ho and Zubkoff 1979). Further analysis of these data published by Zubkoff et al. (1979) yielded a chlorophyll *a* concentration of approximately 50 μg $liter^{-1}$ at the threshold concentration of 500 cells $milliliter^{-1}$.

Karlodinium micrum. *K. micrum*, synonymous with *Gyrodinium galatheanum* Braarud and *Gymnodinium micrum*, and historically reported as *Gyrodinium estuariale* in Maryland, is a common and widespread estuarine dinoflagellate in the Chesapeake Bay. Recent work by Deeds et al. (2002) has demonstrated that Maryland isolates of the dinoflagellate produced toxins with hemolytic, cytotoxic and ichthyotoxic properties. Initial studies indicate *K. micrum* may produce sufficient toxin to result in fish mortality in the field at cell densities of 10,000 to 30,000 cells $milliliter^{-1}$ and above (Deeds et al. 2002; Goshorn et al. 2003).

K. micrum is present year-round in the water column of the Chesapeake Bay. Peak monthly average abundances occur between April and September, favoring mesohaline salinities and elevated concentrations showing a preferred temperature of 21.5-27.5°C (Goshorn et al. 2003). Between 1985 and 2002, there were 1,312 samples from approximately 7,000 collected from Maryland's Chesapeake Bay that contained *K. micrum*. Mean density of the cell counts when present was 589 cells $milliliter^{-1}$, with nine samples (0.7 percent) exceeding the potential lethal threshold of 10,000 cells $milliliter^{-1}$ (Goshorn et al. 2003).

A historical review of a fish kill database maintained by the Maryland Department of the Environment showed eight events where kills were associated with the presence of potential acutely lethal concentrations of *K. micrum* (Goshorn et al. 2003). Cell concentrations in these near-shore creek environments not sampled in routine monitoring provided a range in concentrations from 10,270 to 322,968 cells $milliliter^{-1}$. Deeds et al (2002) however, also report on fish kills in aquaculture ponds on the lower Eastern Shore of Maryland that implicate *K. micrum* in fish kill events

with densities > 10,000 cells milliliter^{-1}. Kempton et al. (2002) related *K. micrum* to a South Carolina fish kill in a brackish water retention pond with evidence of toxicity and concentrations of 64,000-68,000 cells milliliter^{-1}. Nielsen (1993) showed that juvenile cod exposed to 100,000 cells milliliter^{-1} of *K. micrum* resulted in death within 2 days.

A subset of the *K. micrum* (n=684) database had chlorophyll *a*-associated data. *K. micrum* was more likely to exceed 2,000 cells milliliter^{-1} when chlorophyll *a* concentrations exceeded 10 µg liter^{-1} in open-water habitat (Figure V-12). One count exceeded the 10,000 cells milliliter^{-1} boundary and the associated chlorophyll *a* was 75 µg liter^{-1}. Kempton et al. (2002) found chlorophyll *a* concentrations of 117 µg liter^{-1} in association with acutely lethal concentrations (64,000-68,000 cells milliliter^{-1}) of *K. micrum* at the South Carolina fish kill site. Variance in *K. micrum* cell counts increases with increasing chlorophyll *a* measures suggesting the risk of acutely toxic levels coincidentally increasing with the rise in chlorophyll *a* out to 75 µg liter^{-1}. However, the present Maryland data set does not presently demonstrate a clear threshold level for chlorophyll *a* with acutely toxic boundary conditions of *K. micrum* densities.

Strengths and Limitations. *K. micrum* represents an abundant, relatively easy to identify potential harmful algal bloom species in the Chesapeake Bay. Maryland isolates from fish kill events have generated toxicity at many levels from cytotoxicity to hepatotoxicity and ichthyotoxicity. Lab results demonstrated acutely lethal levels of *K. micrum*. The aquatic life impairment associated with fish kills is clear.

Sublethal effects are essentially unknown. Concentration alone does not imply toxicity but co-occurring conditions that induce disintegration of the cells may be needed

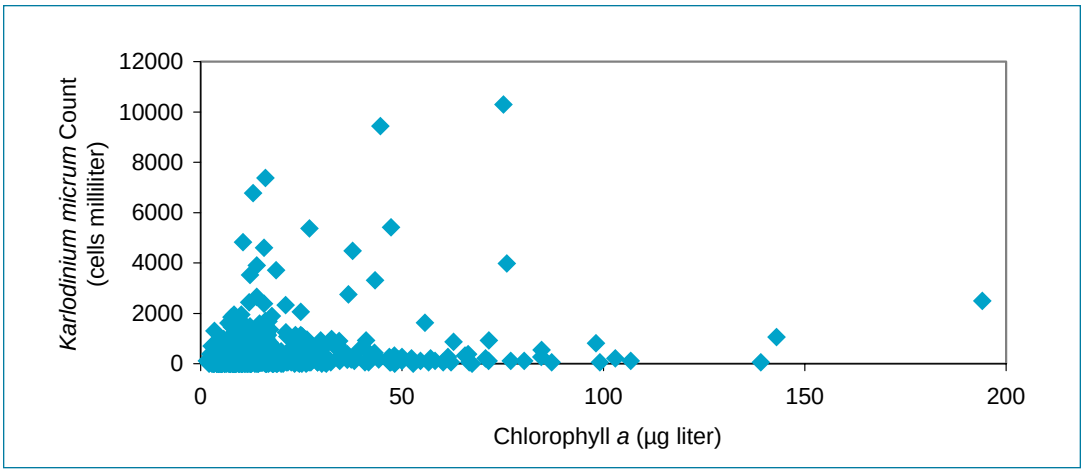

Figure V-12. *Karlodinium micrum* cell counts versus chlorophyll *a* concentrations in the Maryland portions of the Chesapeake Bay. A total of 684 samples are illustrated.

Source: Maryland Department of Natural Resources unpublished data.

in order for the toxins to be released (Deeds et al. 2002). The habitats where fish kills have been most commonly associated with potentially lethal densities of *K. micrum* are shallow-water and near-shore habitats, and small tributary systems (Goshorn et al. 2003), aquaculture facilities (Deeds et al. 2002) and brackish retention ponds (Kempton et al. 2002). To date, these habitats are not typical of areas routinely sampled by water quality monitoring programs of the Chesapeake Bay. Thus far, while the risk of acutely lethal concentrations increases with increasing chlorophyll *a*, only two instances are noted with chlorophyll *a* data at 75 μg liter^{-1} (this chapter), 117 μg liter^{-1} (Kempton et al. 2002) and > 10,000 cells milliliter^{-1}. Although the probability of elevated densities is higher when chlorophyll *a* exceeds 10 μg liter^{-1}, above this concentration there is no strong correlation between cell density and chlorophyll *a* concentration.

Research Needs. More detailed knowledge of the relationship between densities above the acute threshold boundary and chlorophyll *a* levels is needed from near-shore monitoring and fish kill responses to refine the critical range of chlorophyll *a* levels that we should avoid in managing for reducing levels of harmful algal blooms in the Chesapeake Bay. The sublethal effects of *K. micrum* on the environment is in an obvious area for further study. Understanding toxin concentration relationships of *K. micrum* under field conditions that result in cell disintegration enhancing the likelihood of toxin interaction with living resources also needs additional research. And it is necessary to better understand the physical, chemical and biological processes that control *K. micrum* blooms in order to develop even more effective management strategies.

CHLOROPHYLL *A* CONCENTRATIONS CHARACTERISTIC OF TROPHIC-BASED CONDITIONS

Table V-8 categorizes, by trophic status, chlorophyll *a* concentrations that characterize desired (oligotrophic and mesotrophic) and stressed (eutrophic) ecological conditions in Chesapeake Bay open-water tidal habitats. These concentrations were drawn from scientific literature values related to trophic status, historically observed concentrations in the Chesapeake Bay and those characteristic of reference phytoplankton communities versus potentially harmful algal blooms.

Chlorophyll *a* concentrations characteristic of oligohaline conditions published by Ryding and Rast (1989), Wetzel (2001), Smith et al. (1999), Molvaer et al. (1997) and Novotny and Olem (1994) are listed first in Table V-8 in each salinity-regime specific row under the heading 'oligohaline conditions.' Seasonal mean chlorophyll *a* concentrations derived from Olson's analysis (2002) of the 1950s Chesapeake Bay mainstem chlorophyll *a* conditions using the same historical data set as Harding and Perry (1997) are listed next in each 'oligohaline conditions' salinity-regime specific row.

Mesotrophic conditions expressed as ranges of chlorophyll *a* concentrations characterized in the scientific literature by several authors (Ryding and Rast 1989; Wetzel

Table V-8. Summary of chlorophyll *a* concentrations reflecting trophic-based water quality, phytoplankton community and ecological conditions.

Salinity Regime	Chlorophyll *a* Concentrations (μg liter^{-1})					
	Oligotrophic Conditions		Mesotrophic Conditions		Eutrophic Conditions	
	Average or General Range	Peak Range	Average or General Range	Peak Range	Average or General Range	Peak Range
Spring (March - May)						
Tidal-Fresh	0.8 - 3.4[a] 0.3 - 3[b] <3.5[c] <4[e] 1.1[f]	2.6 - 7.6[a]	3.0 - 7.4[a] 2 - 15[b] 3.5 - 9[c] 4-10[e] 4.3[g] 15[i]	8.9 - 29[a] 13.5[g]	6.7 - 31[a] 10-500[b] 9-25[c] >10[e] 6.7[h]	16.9 - 107[a] 42.9[h] <33[i]
Oligohaline	2.3[f]		9.6[g] 15[i]	24.3[g]	5.0[h]	29.8[h] <33[i]
Mesohaline	3.7[f]		5.6[g] 5[j]	24.6[g]	11.1[h]	44.9[h] <25-30[j]
Polyhaline	<1[c] <2[d] 3.9[f]		1-3[c] 2 - 7[d] 2.9[g] 5[j]	6.7[g]	3-5[c] >7[d] 9.1[h]	18.0[h] <25-30[j]
Summer (July - September)						
Tidal-Fresh	0.8 - 3.4[a] 0.3 - 3[b] <4[e] 1.1[f]	2.6 - 7.6[a]	3.0 - 7.4[a] 2 - 15[b] 3.5 - 9[c] 4-10[e] 8.6[g]	8.9 - 29[a] 15.9[g] 15[i]	6.7 - 31[a] 10-500[b] >10[e] 25.3[h]	16.9 - 107[a] 62.1[h] 33[i]
Oligohaline	2.0[f]		6.0[g]	25.2[g] 15[i]	17.1[h]	60.5[h] 33[i]
Mesohaline	4.4[f]		7.1[g] 5[j]	14[g]	12.2[h]	52.5[h] <25-30[j]
Polyhaline	<1[c] <2[d]		1 - 3[c] 2 - 7[d] 4.4[g] 5[j]	8.7[g]	3-5[c] >7[d] 6.1[h]	25.8[h] <25-30[j]

[a]Ryding and Rast, 1989; [b]Wetzel, 2001; [c]Smith, 1998; [d]Molvaer et al., 1997; [e]Novotny and Olem, 1994; [f]Olson 2002; [g]Table V-7 this chapter; [h]Appendix F, Figure F-3 this volume; [i]*Microcystis aeruginosa* section this chapter; [j]*Prorocentrum minimum* section this chapter.

2001; Smith et al. 1999 and Novotny and Olem 1994) are listed first in each salinity-regime specific row first in Table V-8 under the 'mesotrophic conditions' column heading. The trophic status data shows a narrow range of chlorophyll *a* concentrations that characterize mesotrophic aquatic ecosystems (Table V-8). For freshwater areas, seasonal average chlorophyll *a* concentrations in mesotrophic systems should fall in the range of 2 to 15 μg liter^{-1} with a mean around 7 μg liter^{-1}. In high-salinity marine ecosystems, mesotrophic status is characterized by seasonal average chlorophyll *a* concentrations from 1 to 7 μg liter^{-1} with a mean around 3 μg liter^{-1}

The paired general and peak values that follow are the median and 95th percentile concentrations of chlorophyll *a* in waters supportive of the phytoplankton reference community. These chlorophyll *a* concentrations reflect conditions in which water clarity is sufficient for healthy algae and bay grasses growth and the concentrations of one or both of the critical nutrients are low enough to limit excess algal growth (e.g., 'best,' 'better' and sometimes the 'mixed better light' categories). The range of chlorophyll *a* concentrations that follow in the mesotrophic conditions' peak range column are those characteristic of algal communities not containing cell densities of *Microcystis aeruginosa* and *Prorocentrum minimum* exceeding thresholds above which adversely impact zooplankton and oyster communities, respectively.

The spring and summer chlorophyll *a* concentrations characterizing each of these salinity-based phytoplankton reference communities provide the most direct water quality measures of a more balanced phytoplankton assemblage (see Table V-7). Chlorophyll *a* concentrations characteristic of the phytoplankton reference communities, which straddle the boundary between mesotrophic and eutrophic (Table V-8) conditions, are higher than those observed in the 1950s (see Table V-5) which reflect oligotrophic conditions.

Ryding and Rast (1989); Wetzel (2001); Smith et al. (1999); Molvaer et al. (1997) and Novotny and Olem (1994) have all published ranges of chlorophyll *a* concentrations characterizing eutrophic conditions listed first in Table V-8 under the 'eutrophic conditions' in each salinity regime specific row. The paired general and peak range values listed next in each row are the median and 95th percentile concentrations, respectively, of chlorophyll *a* in waters categorized as 'poor' during the process for characterizing the reference phytoplankton communities (Appendix F, Figure F-1). These chlorophyll *a* concentrations reflect water quality conditions in which both critical nutrients (nitrogen and phosphorus) exceed the empirically determined growth-limiting thresholds for algae, and water clarity is not sufficient for healthy algae or underwater bay grasses growth. The range of chlorophyll *a* concentrations that follow in the eutrophic conditions' peak range column are those characteristic of harmful algal blooms exceeding cell density thresholds derived from literature-based values for *M. aeruginosa* and *P. minimum*.

Trends in chlorophyll *a* concentrations observed over the past fifty years indicate that water quality in many tidal habitats of the Chesapeake Bay has changed from oligotrophic-mesotrophic to eutrophic and even highly eutrophic. Chlorophyll *a*

concentrations in the highly saline waters at the mouth of the Chesapeake Bay were characteristic of oligotrophic marine conditions in the 1950s (<2 μg liter^{-1}). They now reflect mesotrophic conditions, with a mean concentration of 5.6 μg liter^{-1} and maxima exceeding 18 μg liter^{-1}. Chlorophyll *a* concentrations in the middle and upper Chesapeake Bay mainstem were indicative of mesotrophic conditions during the 1950s, with mean concentrations well below 7 μg liter^{-1}. They now reflect eutrophic conditions, with mean chlorophyll *a* concentrations above 7 μg liter^{-1} in mid-Bay waters and above 10 μg liter^{-1} in the tidal-fresh, upper Chesapeake Bay waters. Peak concentrations often exceed 30 μg liter^{-1}.

Eutrophic conditions also characterize all the major Bay tidal tributaries. Smaller, urbanized watershed tidal tributaries with poor flushing, such as the Back River, experience highly eutrophic conditions. Excessive nutrient and sediment loadings are the cause of the shift towards eutrophic conditions in the Chesapeake Bay's tidal waters. The results are more deep-water habitats prone to anoxia, further losses of underwater bay grasses and more extensive harmful algal blooms.

Decisions on what chlorophyll *a* value should be applied to protect a designated use against a specific impairment should be made at local or regional water-body scales. More specific implementation procedures and guidelines are provided in Chapter VI.

CHLOROPHYLL *A* CONCENTRATIONS PROTECTIVE AGAINST WATER QUALITY IMPAIRMENTS

Contributions to Reduced Light Levels

Phytoplankton attenuate or reduce the amount of light reaching the leaves of bay grasses by absorbing or scattering the light (see Chapter IV). Additional reductions in light occur at the leaf surface, as the remaining light must pass through algal epiphytes and suspended solids settled there (see Appendix J). Chesapeake Bay scientists have developed a diagnostic tool to calculate the relative contributions of chlorophyll *a* versus total suspended solids to reducing light penetration through the water column (Batiuk et al. 2000; Gallegos 2001).

Water-Column Diagnostic Tool. Water-column attenuation of light measured by the light attenuation coefficient K_d can be divided into contributions from four sources: water, dissolved organic matter (color), chlorophyll *a* and total suspended solids. The basic relationships can be expressed in a series of simple equations, which were combined to produce the equation for the percent water-column diagnostic tool (Gallegos 2001). The resulting equation calculates linear combinations of chlorophyll *a* and total suspended solids concentrations that just meet the percent light-through-water (PLW) criteria for a particular water-column depth at any site or season in the Chesapeake Bay and its tidal tributaries. This diagnostic tool can also be used to consider management options for improving water quality conditions when the water clarity criteria are not currently met (see Chapter VII).

Derived Chlorophyll *a* Concentrations. A finite yet significant number of possible chlorophyll *a* concentrations exist that support attainment of the percent light-through-water criteria, depending on the ambient total suspended solids concentration and water-column application depth. For the purpose of deriving chlorophyll *a* criteria applicable across a wide array of tidal habitats, total suspended solids concentrations were assumed to range from 5 to 20 mg liter-1 (Table V-9). The

Table V-9. Chlorophyll a concentrations (μg liter^{-1}) that reflect attainment of the Chesapeake Bay water clarity criteria given a range of total suspended solids concentrations and shallow-water application depths. Areas in gray indicate exceedance of the water clarity criteria.

Total Suspended Solids (mg liter^{-1})	Tidal-Fresh and Oligohaline			Mesohaline and Polyhaline		
	Water-Column Depth (meters)					
	0.5 m	1 m	2 m	0.5 m	1 m	2 m
5	199	71	9	122	34	
10	171	43		95	8	
15	144	16		68		
20	116			42		

water-column application depths were set at 0.5, 1 and 2 meters to reflect the range of shallow-water designated use boundary depths (U.S. EPA 2003).

Chlorophyll *a* concentrations of 16 μg liter^{-1}(tidal-fresh and oligohaline) and 8 μg liter^{-1} (mesohaline and polyhaline) were identified as protective against negative water clarity effects. Values were selected as they corresponded with total suspended solids concentrations in the range of 10-15 mg liter^{-1}, which were previously identified as habitat requirements for underwater bay grasses (Batiuk et al. 1992; Dennison et al. 1993; Stevenson et al. 1993) and the 1-meter shallow-water application depth (mid-depth between 0.5 and 2 meters; U.S. EPA 2003).

Strengths and Limitations. The assignment of water clarity criteria application depths and the selection of appropriate total suspended solids ambient concentration assumptions should be made on a Chesapeake Bay Program segment by segment basis. These values will vary on temporal and spatial scales. In some regions, chlorophyll *a*/algal biomass is a negligible component of the total light attenuation, compared with non-algal solids. In such regions, chlorophyll *a* reductions would not be expected to significantly improve water clarity.

Contribution to Low Dissolved Oxygen Conditions

Algae that are not consumed by zooplankton, oysters and fish becomes fuel, through its breakdown by the microbial community, for reducing dissolved oxygen levels. Seasonal chlorophyll *a* concentrations (e.g., algal biomass) that lead to desired

dissolved oxygen conditions can be estimated using the Chesapeake Bay water quality model.

The Chesapeake Bay watershed model and the 13,000-cell version of the Chesapeake Bay water quality model can be used to determine the seasonal average chlorophyll *a* concentrations associated with estimated nutrient and sediment reductions needed to attain the Chesapeake Bay dissolved oxygen criteria.

The model-simulated chlorophyll *a* levels were extracted from the nutrient and sediment loading reduction allocation scenario which attained the Chesapeake Bay dissolved oxygen criteria across all designated uses and tidal waters. The simulated chlorophyll *a* concentrations were compiled for spring (March-May) and summer (July-September) by salinity regime—tidal-fresh, oligohaline, mesohaline and polyhaline. The seasonal mean chlorophyll *a* concentration for each season and salinity regime combination was then calculated (Table V-10). See Chapter VI for details on how the Chesapeake Bay water quality model and Chesapeake Bay water quality monitoring results have been integrated for assessing criteria attainment under various management scenarios in support of setting loading allocations.

Strengths and Limitations. Like the water clarity criteria, the chlorophyll *a* concentrations that are needed to attain the dissolved oxygen criteria are expected to vary over temporal and spatial scales. Table V-10 shows the general relationship between chlorophyll *a* concentrations and attainment of the dissolved oxygen criteria. Depending on their location in the Chesapeake Bay system and hydrologic and hydrodynamic factors, individual segments or tributaries may exceed these concentrations without experiencing dissolved oxygen-related impairments.

Table V-10. Model-simulated seasonal mean and salinity regime-specific chlorophyll *a* concentrations (μg liter^{-1}) estimated to characterize conditions supporting attainment of the Chesapeake Bay dissolved oxygen criteria.

Season	Tidal-Fresh	Oligohaline	Mesohaline	Polyhaline
Spring	4	5	6	5
Summer	12	7	5	4

METHODOLOGIES FOR DERIVING WATERBODY-SPECIFIC CHLOROPHYLL *A* CRITERIA

Water Clarity Impairment-Based Methodology

Regional and segment-specific chlorophyll *a* criteria can be derived to protect against water clarity impairments by applying the water-column diagnostic tool described previously. When applied to local and regional tidal waters, more site-specific assumptions about existing or anticipated ambient total suspended solids

concentrations and the shallow-water bay grasses designated use boundary depths can be factored into the derivation of the chlorophyll *a* criteria.

Dissolved Oxygen Impairment-Based Methodology

Region-specific chlorophyll *a* concentrations can be derived by applying the Chesapeake Bay water quality model and analyzing the segment-specific results. Confidence in the derived chlorophyll *a* criteria can be increased by focusing on those Chesapeake Bay Program segments that are the principal contributors to low dissolved oxygen conditions due to an excess production of unconsumed algae.

Nuisance Bloom-Based Methodology

Regional and segment-specific chlorophyll *a* targets can be derived using studies—either user perception surveys or algal condition assessments—to identify chlorophyll *a* concentrations that protect against nuisance blooms.

User Perception Surveys. User perception surveys can be conducted to rate a user's satisfaction with a water body's color, clarity and overall appearance. Surveys have been successfully applied in lake settings by several states, including Vermont and Minnesota. User perception surveys require careful design and their form depends on the type of water body and its uses. All such studies should include certain elements:

1. Surveys should be conducted in conjunction with water quality and phytoplankton monitoring to allow correlation of user perceptions with ambient conditions.
2. Commercial and recreational users should be targeted for the survey.
3. Questions should be worded to avoid bias.
4. Questions should focus on present, specific conditions rather than on general perceptions of the Chesapeake Bay's water quality.
5. Surveys should be conducted under a variety of water quality and sky conditions, and under a range of chlorophyll *a* and clarity conditions.
6. Surveys should be conducted in conjunction with objective, scientific assessments of algal conditions in the water body, as described below.

Vermont and Minnesota used lake user surveys to identify specific total phosphorus, chlorophyll *a* or Secchi disk values at which algal nuisances and impairment of recreation were perceived by the public (Heiskary and Walker 1988; Smeltzer and Heiskary 1990; North American Lake Management Society 1992). Using the results of a survey on physical appearance and recreation potential, Smeltzer and Heiskary (1990) defined the statistical relationships between eutrophication-related water

quality variables (Secchi and chlorophyll *a*) and user perceptions of lake quality in Minnesota and Vermont.

In Minnesota, surveyors calibrated user response by determining Secchi depth and chlorophyll *a* levels that correspond to perceived nuisance conditions or impairment of water uses. A nonparametric procedure was used to cross-tabulate the water quality measurements against the user categories. Results showed a distinct contrast between observations of 'definite algae' and 'high algae' for chlorophyll *a* measurements. Also, 'impaired swimming' and 'no swimming' ratings generally had chlorophyll *a* levels exceeding 20-40 μg liter^{-1} (Heiskary and Walker 1988). In Minnesota some distinct ecoregional patterns in user perception emerged, whereby expectations were much greater in the deeper lakes of the northern forested region (similar to Vermont) as compared to the shallow prairie lakes of southern Minnesota.

The final steps necessary for setting chlorophyll *a* criteria include specifying the nuisance criterion (e.g., extreme chlorophyll *a* >30 μg liter^{-1}) or recreation potential and the acceptable risk level (i.e., probability that nuisance condition will be encountered 1 percent). Although Minnesota has not yet adopted total phosphorus or chlorophyll *a* criteria into water quality standards, the state used the methodology as a basis for setting lake management goals for total phosphorus. The various chlorophyll *a* and Secchi depth thresholds can be related to total phosphorus based on empirical relationships (e.g., total phosphorus and frequency of various levels of chlorophyll *a*) as noted in Heiskary and Walker (1988).

Algal Condition Assessments. Algal condition assessments involve qualitative descriptions and ordinal ratings of algal conditions by monitoring personnel. These constitute the 'scientific' version of the user perception survey. Qualitative information to be recorded includes the presence or absence of floating algae, its color, odor, etc. As with user perception surveys, algal condition assessment should be performed in conjunction with water quality and phytoplankton monitoring. It is highly recommended that states develop and apply standard indices for use with algal condition assessments. For example, Table V-11 provides an example developed for coastal waters in Oregon.

Algal condition assessments should be conducted by trained scientists or technicians. The more highly trained the personnel, the more detailed information can be collected on the size, texture and density of blooms. States that decide to pursue this approach should consider adding algal assessments to their existing Chesapeake Bay and tidal tributary monitoring programs. Ideally, user perception surveys and algal condition assessments would be conducted in tandem. However, algal condition assessments will have some utility for setting chlorophyll *a* targets independent of user perception surveys. It is expected that surveys and assessments would result in different chlorophyll *a* targets for different salinity regimes. For example, bright-green algae that form surface scums (e.g., *M. aeruginosa*) in some tidal freshwater segments might be more perceptible at lower chlorophyll *a* concentrations than brownish, more dispersed blooms.

Table V-11. Example of an algal condition index.

Algal Index Value	Category	Description
0	Clear	Conditions vary from no algae to small populations visible to the naked eye.
1	Present	Some algae visible to the naked eye but present at low to medium levels.
2	Visible	Algae sufficiently concentrated that filaments or balls of algae are visible to the naked eye. May be scattered streaks of algae on water surface.
3	Scattered Surface Blooms	Surface mats of algae scattered. May be more abundant in localized areas if winds are calm. Some odor problems.
4	Extensive Surface Blooms	Large portions of the water surface covered by mats of algae. Windy conditions may temporarily eliminate mats, but they will quickly redevelop as winds become calm. Odor problems in localized areas.

Source: Coastnet, 1996, *Sampling Procedures: A Manual for Estuary Monitoring*, prepared for the Coastnet Water quality Monitoring Project administered by the Oregon State University Extension Sea Grant Program, http://secchi.hmsc.orst.edu/coastnet/manual/index.html.

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