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# Chain of eutrophication models for assessing the potential impact of nutrient enrichment on Choctawhatchee Bay, FL, USA

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**Abstract** Coastal eutrophication is a worldwide environmental concern, but especially so in Florida where there remains an inability to predict possible impacts on the chemical, physical, and biological features of the State's estuaries. An empirical approach developed for freshwater systems was used to examine the potential impact of suspected eutrophication on Choctawhatchee Bay, an estuary in northwestern Florida. Special attention was given to the hypothesized impact on submersed aquatic vegetation (SAV). A mass balance phosphorus-loading model accurately predicted phosphorus concentration within the bay. Similar to freshwater systems, significant empirical relationships were established between phosphorus and chlorophyll concentrations, and chlorophyll concentrations and water clarity as measured by using a Secchi disc. Secchi depth measurements were used to estimate the maximum depth of plant colonization and these predicted depths showed that the measured abundance of SAV in Choctawhatchee Bay was significantly less than the potential abundance, assuming light was the sole limiting factor to SAV distribution and abundance. The suspected eutrophication of Choctawhatchee Bay was not apparent using the chain of eutrophication models and was likely not a factor determining the distribution and abundance of SAV in the bay.

**Keywords** Estuaries, aquatic plants, nutrient loading, eutrophication, Secchi depth

## Introduction

For the last century, freshwater and coastal systems have reportedly suffered from the symptoms of nutrient enrichment (Carpenter et al. 1998, Lotze et al. 2006). During this time period, freshwater limnologists have defined lake trophic status as the ability of an aquatic system to maintain some level of organic matter and that the biological structure of the system is limited primarily by phosphorus and/or nitrogen (Naumann 1919, Hasler 1947, Hutchinson 1967). Additionally, increases in nutrient inputs to the system, the process of eutrophication, often resulted in an increase in trophic status. Over the last few decades, many of these freshwater concepts have been adopted by coastal scientists and used to manage estuarine systems (Steel 1974, Vollenweider 1992, Conley et al. 2000, Cloern 2001).

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With regard to freshwater systems, after large-scale whole-lake experiments confirmed that phosphorus was the primary limiting nutrient in many if not most lakes (Schindler 1975), multiple models (mechanistic and empirical) were developed to estimate phosphorus concentrations in lakes from annual loads adjusted for ranges in lake morphology and hydrology (Vollenweider 1976, Canfield and Bachmann 1981). Empirical models were also developed to predict chlorophyll concentrations from total phosphorus (Jones and Bachmann 1976, Canfield 1983), water clarity from chlorophyll concentrations (Carlson 1977, Canfield and Hodgson 1983) and the maximum depth of aquatic plant colonization from water clarity (Chambers and Kalff 1985). Finally, empirical models were successfully developed to assess changes in fish populations with lake trophic state (Oglesby 1977, Jones and Hoyer 1982). This chain of empirical models finally provided managers with a basis for estimating how changes in nutrient loading would potentially change the physical, chemical and biological properties of the targeted aquatic system. The general empirical approach has been very successful in eutrophication management for many lakes in both Europe and North America (OECD 1982, Cooke et al. 1993). With this success, the chain of eutrophication models rapidly spread to research and management of coastal systems (Rask et al. 1999, Conley et al. 2000, Nielsen et al. 2002).

Examining coastal eutrophication in 19 Finnish estuaries, Meeuwig et al. (2000) successfully used freshwater mass balance phosphorus loading models developed by Canfield and Bachmann (1981) to accurately predict phosphorus concentrations in the estuaries. These estimated phosphorus concentrations were then used with the phosphorus-chlorophyll models for predicting chlorophyll concentrations in the estuaries. The calculated concentrations differed from observed concentrations by only 28%. This type of modeling approach was also used successfully to help manage seagrass recovery in Tampa Bay, FL (Greening and Janicki 2006, Greening et al. 2011). Eutrophication of Tampa Bay caused an increase in chlorophyll, which in turn caused a significant decrease in water clarity that caused a tremendous decrease in the seagrass beds of the bay (over 7,600 ha loss from 1950 to 1982, Greening and Janicki 2006). After nitrogen load reductions and maintenance of chlorophyll target levels in Tampa Bay, seagrass coverage has increased 25% between 1982 and 2008. The Finnish and Tampa Bay successes, therefore, suggest that the chain of eutrophication models, first developed in freshwater systems, may be appropriately applied to estuaries, but the application of these models needs to be examined in other estuaries (Souchu et al. 2010).

Choctawhatchee Bay is a large estuary (approximately 350 $km^2$) in Northwest FL that has historically supported a diverse ecology that provides substantial economic and quality of life benefits to the residents of northwest Florida (NWFWMD 1996, Ruth and Handley 2002, Harper et al. 2006). The seagrass beds in Choctawhatchee Bay are considered extremely important because they support diverse populations of fish and invertebrates, including many recreational and commercial species (Larkum et al. 2007). Studies on the seagrass beds in Choctawhatchee Bay have been conducted periodically since 1940 (McNulty et al. 1972, USACE 1973, 1976) and Burch (1983) summarized these studies. Burch's (1983) interpretation of the available data suggested that the bay supported varying amounts of submersed vegetation, with declines evident in several localized areas since 1949. Burch further noted that this decline was less evident between 1972 and 1982, but Ruth and Handley (2002) pointed out that these studies were conducted with different methodologies, limited field verification and were really not comparable.

Reported declines in seagrass habitats have led the United States Environmental Protection Agency (USEPA) and the Florida Department of Environmental Protection (FLDEP), similar to governmental agencies around the world, to recommend establishment of nutrient criteria and total maximum daily loads of nutrients in the attempt to control eutrophication and enhance a specific biological component, especially the seagrasses, of the aquatic ecosystem. The objective of this study was to examine an empirical chain of eutrophication models at Choctawhatchee Bay and to determine if the current trophic status of the bay could be used to explain the reported decreases in seagrass coverage. Answering this question is important because controlling nutrients in this system has political and economic consequences for surrounding communities as well as communities outside the State of Florida because the main source of water input, the Choctawhatchee River, originates in Alabama. We, therefore, examined the following questions: 1) Can the mass balance phosphorus loading model developed by Canfield and Bachmann (1981) be used to accurately estimate phosphorus concentrations in Choctawhatchee Bay, 2) Is there a significant empirical relationship between nutrient concentrations (phosphorus or nitrogen) and chlorophyll concentrations in the bay, 3) Is chlorophyll concentration a significant driver of water clarity in the bay, and 4) Is water clarity limiting the seagrass coverage in the bay?

## Methods

**Study site description.** Choctawhatchee Bay is a large estuary in Okaloosa and Walton Counties, FL, with a length of approximately 50 kilometers (km), and a width varying between 2 and 10 km (Figure 1). The Choctawhatchee Bay watershed encompasses nearly 13,800 square kilometers ($km^2$) and spans portions of northwest FL and southern AL. The surface area of the bay is approximately 350 $km^2$. Water depths range from 0 to 13 meters (m), with a mean depth of approximately 3.8 m (B. Schaeffer, USGS, unpublished data). The bay has shallow shelf areas and relatively steep slopes that level out to average depths of 3 m in eastern portions and 8 m in western potions of the bay (Livingston 2010). The bay is aligned along an east-west axis, essentially the Latitude 30.43, with the Choctawhatchee River entering the bay at its eastern end.

The Choctawhatchee River provides approximately 90% of the freshwater input to the bay system, with secondary inflows from multiple bayous (11 bayous, 1 pass, and 1 harbor: NWFWMD 1996, Livingston 2010). A small but influential pass to the Gulf of Mexico (East Pass) is in the western region, immediately west of the City of Destin (Figure 1). Historically, marine waters entered the bay only through periodic breaks in the barrier islands that are located within what is now referred to as Destin Harbor (Hemming and Brown 2004). However, locals artificially opened Choctawhatchee Bay at the area now called East Pass in 1929 to alleviate flooding when there were heavy rains and the intermittent opening failed to open on its own. East Pass is now

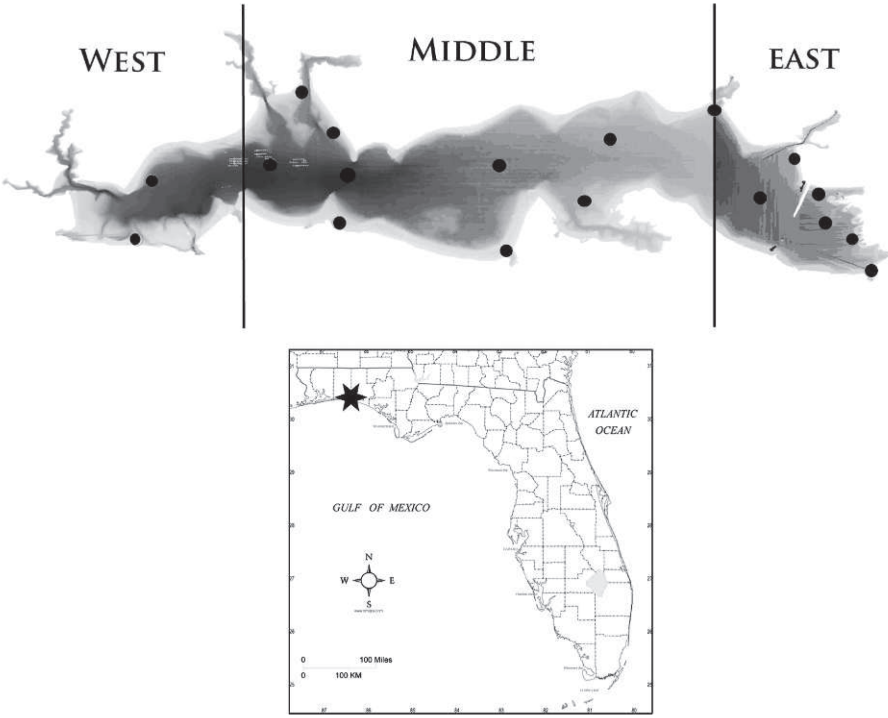


Figure 1. Bathymetric map of the study area (0.5-m gray scale), showing location of 18 sampling stations located in the main part of Choctawhatchee Bay, FL. The vertical lines represent seagrass bay areas: east, middle and west. Star shows location of bay in Florida.

maintained by the U.S. Army Corps of Engineers to provide a permanent pass to the Gulf of Mexico. With the opening of the bay, there was an introduction of a relatively small tidal fluctuation that ranges about 0.15 m (Ruth and Handley 2002). Opening of East Pass also resulted in increased salinity and the subsequent loss of freshwater marshes and aquatic plants yielding patchy seagrass beds (primarily *Halodule wrightii* with occasional *Rupia maritima*) throughout the bay (Ruth and Handley 2002, Livingston 2010). Choctawhatchee Bay is also connected in the east to West Bay of the St. Andrew Bay system in Panama City via the Gulf Intracoastal Waterway (GIWW) and in the west to East Bay in the Pensacola Bay system via Santa Rosa Sound (Blaylock 1983).

**Water chemistry.** The Choctawhatchee Basin Alliance (CBA) of Northwest Florida State College working with the University of Florida's Florida LAKEWATCH program conducted water quality monitoring at 18 deep-water stations throughout the bay between 2001 and 2011 (Figure 1). Florida LAKEWATCH is a volunteer monitoring program started in 1986 with the goal of collecting scientifically credible data throughout Florida and two studies have shown that the data collected by the volunteers are equivalent to that collected by professionals (Canfield et al. 2002, Hoyer et al. 2012). The goal was to sample each station monthly, but due to logistical problems some months were missed. However, 90% of the annual means for each station can be calculated with greater than eight months of sampling data.

The Choctawhatchee Bay volunteers collected monthly surface water samples at each station for nutrients (total phosphorus and total nitrogen), and chlorophyll following LAKEWATCH standard operation procedures (Canfield et al. 2002, Hoyer et al. 2012). On a quarterly basis, surface water was also collected for the analysis of true color (platinum-cobalt units, Pt-Co) following the procedures outlined in Canfield et al. (2002). Water transparency at each sampling location was measured by use of a Secchi disc. Volunteers also used a Hydrolab Quanta Water Quality Monitoring System provided by CBA to record surface salinity (ppt).

**Nutrient loading.** Between 2004 and 2011, CBA staff collected monthly Choctawhatchee River water samples from a station near Bruce, FL where the USGS measures daily discharge of the river. These samples were analyzed for total phosphorus and total nitrogen (Canfield et al. 2002, Hoyer et al. 2012) and used with discharge measurement to estimate the annual nutrient load to the Choctawhatchee Bay. Following the procedures of Meeuwig et al. (2000), we used a mass balance nutrient-loading model published by Canfield and Bachmann (1981) to estimate total phosphorus concentrations in the bay and compared those calculated values with actual measured concentrations. Their model is as follows:

$$TP = \frac{L}{z(\sigma + \rho)} \tag{1}$$

where TP is concentration of total phosphorus ($\mu g \cdot L^{-1}$), L is annual phosphorus loading per unit of the water body's surface area ($mg \cdot m^{-2} \cdot yr^{-1}$), z is mean depth (m), $\rho$ is hydraulic flushing rate ($yr^{-1}$), and $\sigma$ is phosphorus sedimentation rate ($yr^{-1}$). The phosphorus sedimentation rate is not measured, but calculated as follows:

$$\sigma = 0.129 \left(\frac{L}{z}\right)^{0.589} \tag{2}$$

A bathymetric map for Choctawhatchee Bay was created with 0.5 m contours using the NOAA's Digital Elevation Model (DEM) and this map was used to calculate surface area, mean depth and volume of the bay. The annual discharge estimated at the Bruce, FL USGS gauging station was divided by bay volume to calculate flushing rate. This estimate accounts for flushing Choctawhatchee River freshwater inputs but not from the smaller salt-water exchange due to tidal fluctuations.

**Seagrass.** While historical studies of seagrass in Choctawhatchee Bay have been conducted sporadically since the 1940s (McNulty et al 1972, Burch 1983), Ruth and Handley (2002) explained the difficulty each study encountered, thus making direct comparison with current data and accurate long-term trend analyses impossible. However, seagrass mapping conducted by USGS in 2003 using natural-color aerial photography at a 1:24,000 scale are comparable to data collected by CBA. Lazzarino and J. Terrell (unpublished data) using Landsat 5 TM imagery with extensive ground-truthing for 2009, 2010, and 2011. Lazzarino and Terrell estimated seagrass coverage in three different sections of the bay as follows: 1) Eastern Choctawhatchee Bay, which includes all areas east of W 86° 13′ 42.96″ to the Choctawhatchee River delta, 2) Middle Choctawhatchee Bay, the largest bay segment, covers the area west of W 86° 13′ 42.96 and east of W 86° 30′ 23.04″, and 3) Western Choctawhatchee Bay, which includes all areas west of W 86° 30′ 23.04″ to where Santa Rosa Sound begins (Figure 1). Lazzarino and Terrell then compared seagrass estimates from these three seagrass sections to the USGS survey in 2003. These measured seagrass area-coverages were compared to the surface area of each section of the bay above the calculated maximum depth of plant colonization (MDC) based on the bathymetric map (Dixon 2000) to determine if the actual plant coverage equaled the potential coverage assuming that light was the sole limiting factor determining plant coverage.

In the Tampa Bay seagrass restoration effort (Greening et al. 2011), the target maximum depth of seagrass colonization (Dixon 2000) was estimated at approximately 20% (20.5%) of the photosynthetically active radiation (PAR). Using this estimated percentage, but recognizing that

PAR requirements differ by species and location, the maximum depth of plant colonization (MDC) can be calculated based on the Lambert-Beer equation:

$$MDC = \frac{-\ln\left(\frac{I_z}{I_0}\right)}{K} \tag{3}$$

where $I_z$ is the light intensity at depth z, $I_0$ is the light intensity at the surface, ($I_z/I_0 = 0.2$) is the percentage of light at MDC of the submersed aquatic plant of interest and K is the light attenuation coefficient, which is generally measured with a light meter. No light meter readings were available for Choctawhatchee Bay, but K can be estimated using Secchi depth measurements by the following equation (Poole and Atkins 1929), which is used worldwide:

$$K = \frac{1.7}{SD} \tag{4}$$

where SD is Secchi depth (m) and 1.7 is a constant with no units. There is published support for the universality of this equation (Idso and Gilbert 1974, Bracchini et al. 2009) and dissension (Graham 1966, Padial and Thomaz 2008). Being cognizant of this debate, we calculated a K value for the three sections of Choctawhatchee Bay using annual average Secchi depth measurements for each individual section and Eq. 4 with the following range of constants bracketing the 1.7 published by Poole and Atkins (1929): 1.6, 1.8, and 2.0. The resultant K values were then used in Eq. 3 to estimate MDC depths for the three sections of Choctawhatchee Bay (east, middle and west) where submersed aquatic vegetation was mapped. Additionally, we used annual average Secchi depth measurement for each individual section and the Secchi depth versus MDC model published by Caffrey et al. (2007) to provide an additional estimate of MDC.

Data analyses were performed using the JMP statistical package (SAS 2000). Prior to analyses, data were Log10-transformed where needed to accommodate heteroscedasticity (Sokal and Rohlf 1981). Empirical models were developed using annual mean data from each station. All statements of significance are at $p < 0.05$.

## Results

**Water chemistry.** Annual water chemistry means were averaged by the three bay sections that were defined for seagrass mapping (east, middle and west, Figure 1) and for the bay as a whole (Table 1). All water chemistry variables showed a strong gradient moving from east (near Choctawhatchee River inputs) to the west (near the East Pass to the Gulf of Mexico). Salinity, Secchi depth and the ratio of nitrogen to phosphorus increased and total phosphorus, total nitrogen, color and chlorophyll decreased moving from east to west through the bay (Table 1). The whole bay grand mean nitrogen to phosphorus ratio (by mass) was 19.5 with no annual mean in any year throughout the bay being less than 10 (lowest annual mean 12.5) suggesting that Choctawhatchee Bay for most time periods is most likely phosphorus limited (Smith 1982, Hoyer et al. 2002).

There was a strong positive linear relationship between total phosphorus and chlorophyll concentrations (Figure 2a) with phosphorus accounting for 73% of the variance in chlorophyll concentrations of Choctawhatchee Bay. Total nitrogen also showed a positive relationship with chlorophyll, but only accounted for 59% of the variance in chlorophyll (Figure 2b). Further

Table 1. Surface water chemistry (TP is total phosphorus, TN is total nitrogen and CHL is chlorophyll) grand means calculated from annual means measured from monthly samples collected at 18 stations in Choctawhatchee Bay, FL between 2001 and 2011. Minimum and maximum annual means are listed in parentheses. The values are listed by three major sections of the bay and combined.

| Parameter | West | Middle | East | Combined |
|---|---|---|---|---|
| Salinity (ppt) | 21.4 (13.6–26.6) | 19.6 (7.8–27.4) | 10.9 (1.5–21.7) | 16.5 (1.5–27.5) |
| TP ($\mu g \cdot L^{-1}$) | 10.6 (8.9–14.2) | 13.1 (8.4–19.9) | 24.8 (16.5–42.9) | 17.3 (8.4–42.9) |
| TN ($\mu g \cdot L^{-1}$) | 227 (184–299) | 245 (169–371) | 397 (265–540) | 301 (169–540) |
| TN/TP | 22.9 (18.3–28.0) | 20.2 (12.5–28.3) | 17.6 (12.8–25.4) | 19.5 (12.5–28.3) |
| CHL ($\mu g \cdot L^{-1}$) | 2.9 (1.5–8.1) | 3.6 (1.6–9.4) | 8.6 (2.3–34.5) | 5.4 (1.5–34.5) |
| Secchi (m) | 3.0 (1.4–4.3) | 2.6 (0.7–4.7) | 1.1 (0.8–1.9) | 2.0 (0.7–4.7) |
| Color (Pt-Co) | 9 (5–17) | 11 (4–30) | 18 (7–35) | 13 (4–35) |

examination, using multivariate linear regression analyses with chlorophyll as the dependent variable and total phosphorus and total nitrogen as the independent variables, showed that after accounting for total phosphorus, total nitrogen did not account for additional significant variance in bay chlorophyll concentrations.

There was a significant negative linear relationship between Secchi depth and chlorophyll with chlorophyll accounting for 47% of the variance in measured Secchi depth (Figure 3a). Color, as expected, also showed a negative linear relationship with Secchi depth, but only accounted for 39% of the variance in Secchi depth (Figure 3b). Annual average color for each station ranged from 4 to 35 (Pt-Co units) and was significantly correlated to chlorophyll concentrations ($r = 0.57$ $p < 0.05$). Multivariate linear regression analyses with Secchi depth as the dependent variable and chlorophyll and color as the independent variables ($R^2 = 0.57$, $p < 0.05$), however, showed that after

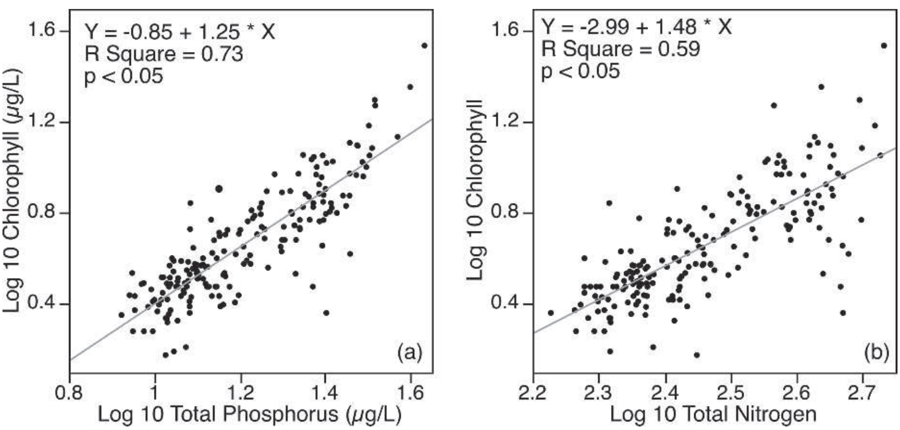


Figure 2. Relationships between both annual average total phosphorus (a, $\mu g \cdot L^{-1}$), annual average total nitrogen (b, μg/L) and chlorophyll ($\mu g \cdot L^{-1}$) concentrations for all 18 stations sampled in Choctawhatchee Bay between 2001 and 2011.

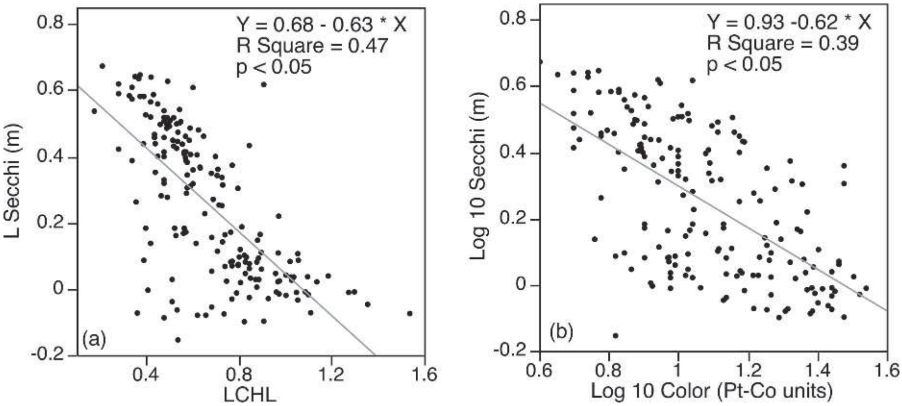


Figure 3. Relationships between both annual average total chlorophyll (a, $\mu g \cdot L^{-1}$), annual average color (b, Pt-Co units) and Secchi depth (m) for all 18 stations sampled in Choctawhatchee Bay between 2001 and 2011.

accounting for chlorophyll, color significantly accounted for only another 10% of the variance in Secchi depth.

**Nutrient loading.** The range in annual discharge from the Choctawhatchee River varied approximately 300% (22.1 to 90.3 $m^3 \times 10^8$, Table 2) while the range in annual average total phosphorus concentration in the river ranged only about 40% (21 to 38 $\mu g \cdot L^{-1}$). Additionally, there was not a significant correlation between discharge and annual average total phosphorus concentration in the river ($r = 0.30$, $p = 0.44$).

Comparing the predicted total phosphorus concentration to the measured annual average total phosphorus concentration, by individual section of the bay defined by the seagrass surveys, showed that the measured phosphorus concentration in the eastern section was always higher than the predicted concentration, and that predicted concentrations were always higher than measured in the middle and western sections. The predicted total phosphorus concentrations, however, compared well with the annual averages for the whole bay (Figure 4) with the absolute value of the percent difference averaging 11% and ranging from 1% to 27%, which is well within the calculated error listed by Canfield and Bachmann (1981) for their mass balance nutrient model.

**Seagrass.** There was a gradient in annual average water clarity with Secchi depth ranging from 0.9 m (2003) in the eastern section of Choctawhatchee Bay near the Choctawhatchee River to 2.6 m (2010) in the western section of the bay near the East Pass (Figure 1, Table 3). This gradient was also evident in the four different methods used to estimate the maximum depth of plant colonization with the shallowest estimates in the eastern section and the deepest in the western section.

The estimated potential area of the Choctawhatchee Bay in the western and middle sections that could support submersed aquatic vegetation (assuming light

Table 2. Annual discharge from the Choctawhatchee River measured at Bruce, FL, annual average total phosphorus (TP) concentrations measured in the river near Bruce and annual total phosphorus load to Choctawhatchee Bay measured between 2004 and 2011. Additionally, the calculated annual flushing rate (ρ) and sedimentation coefficient (σ) used with the mass balance nutrient-loading model published by Canfield and Bachmann (1981) to calculate the predicted phosphorus concentration in Choctawhatchee Bay. Mean depth (5.2 m) and volume ($42.48 \cdot m^3 \times 10^8$) of Choctawhatchee Bay used in the loading model were calculated from a bathymetric with 0.5-meter contours calculated using NOAA's Digital Elevation Model (DEM).

| Year | Mean River TP ($\mu g \cdot L^{-1}$) | Discharge ($m^3 \times 10^8$) | TP Load ($mg \cdot m^{-2} \cdot yr^{-1}$) | ρ ($yr^{-1}$) | σ ($yr^{-1}$) | Predicted TP ($\mu g \cdot L^{-1}$) |
|---|---|---|---|---|---|---|
| 2004 | 33.5 | 54.5 | 222.3 | 1.3 | 1.0 | 18.6 |
| 2005 | 26.6 | 69.2 | 224.2 | 1.6 | 1.0 | 16.3 |
| 2006 | 27.6 | 31.8 | 107.0 | 0.7 | 0.7 | 14.4 |
| 2007 | 30.7 | 30.6 | 114.4 | 0.7 | 0.7 | 15.4 |
| 2008 | 30.9 | 54.4 | 204.5 | 1.3 | 1.0 | 17.5 |
| 2009 | 37.6 | 90.3 | 413.6 | 2.1 | 1.4 | 22.4 |
| 2010 | 21.3 | 60.2 | 156.5 | 1.4 | 0.8 | 13.3 |
| 2011 | 28.9 | 22.1 | 77.7 | 0.5 | 0.6 | 13.7 |

was the only limiting factor) exceeded the actual estimated coverage of submersed aquatic vegetation by a factor of two for the most conservative estimate (k=2.0/SD, Table 4) and around five times with the most liberal estimate (MDC, Table 4). There was virtually no submersed aquatic vegetation in the eastern section of the bay (maximum of 2 ha) even though the potential area estimates, again assuming light to be limiting, showed there could be as little as 270 ha to as much as 1760 ha of submersed aquatic vegetation.

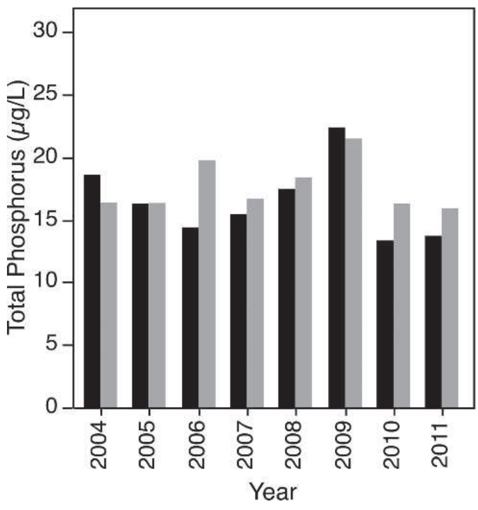


Figure 4. Comparison between predicted total phosphorus concentration (gray bars, $\mu g \cdot L^{-1}$) estimated with a mass balance phosphorus-loading model (Canfield and Bachmann 1981) and actual measured annual average total phosphorus concentration (black bars, $\mu g \cdot L^{-1}$) for Choctawhatchee Bay from 2004 to 2011.

Table 3. Annual average (2003, 2009, 2010, and 2011) Secchi depth values (SD) measured monthly in three sections of Choctawhatchee Bay (east, middle and west). The estimated depth (m) of light penetration to 20% of surface irradiation using light attenuation coefficients (k) calculated from the relation between Secchi depth and a range of k values (k=1.6/SD, k=1.8/SD and k=2.0/SD) calculated similar to that published by Poole and Atkins (1929: k=1.7/SD). The estimated depth of maximum plant colonization (MDC) calculated from the relation between Secchi depth and MDC published by Caffrey et al. (2007).

| Section | Year | SD (m) | k=1.6/SD | k=1.8/SD | k=2.0/SD | MDC |
|---|---|---|---|---|---|---|
| West | 2003 | 2.3 | 2.3 | 2.1 | 1.7 | 3.4 |
| West | 2009 | 2.3 | 2.4 | 2.1 | 1.7 | 3.4 |
| West | 2010 | 2.6 | 2.6 | 2.3 | 1.9 | 3.7 |
| West | 2011 | 2.6 | 2.6 | 2.4 | 1.9 | 3.7 |
| Middle | 2003 | 1.8 | 1.8 | 1.6 | 1.3 | 2.9 |
| Middle | 2009 | 2.1 | 2.1 | 1.9 | 1.5 | 3.2 |
| Middle | 2010 | 2.6 | 2.7 | 2.4 | 1.9 | 3.7 |
| Middle | 2011 | 3.1 | 3.1 | 2.8 | 2.3 | 4.1 |
| East | 2003 | 0.9 | 0.9 | 0.8 | 0.7 | 1.9 |
| East | 2009 | 1.0 | 1.1 | 0.9 | 0.8 | 2.1 |
| East | 2010 | 1.2 | 1.2 | 1.1 | 0.9 | 2.3 |
| East | 2011 | 1.3 | 1.3 | 1.1 | 0.9 | 2.3 |

## Discussion

Comparing the predicted total phosphorus concentration to the average of each individual plant survey section shows that the measured concentration in the western section next to East Pass is less than the predicted concentration, suggesting a flushing from the Gulf of Mexico that was not accounted for in

Table 4. Four years of estimated surface area (ha) of submersed aquatic vegetation (SAV) in Choctawhatchee Bay. Surface area (ha) of Choctawhatchee Bay above the depth of 20% surface irradiation when the light extinction coefficient is calculated using light attenuation coefficients (k) calculated from the relation between Secchi depth and a range of k values (k=1.6/SD, k=1.8/SD and k=2.0/SD) calculated similar to that published by Poole and Atkins (1929: k=1.7/SD). Surface area (ha) of Choctawhatchee Bay above the estimated depth of maximum plant colonization (MDC) calculated from the relation between Secchi depth and MDC published by Caffrey et al. (2007).

| Region | Year | SAV (ha) | k=1.6/SD | k=1.8/SD | k=2.0/SD | MDC |
|---|---|---|---|---|---|---|
| West | 2003 | 511 | 1280 | 1180 | 910 | 1810 |
| West | 2009 | 469 | 1340 | 1180 | 910 | 1810 |
| West | 2010 | 365 | 1425 | 1280 | 1060 | 1930 |
| West | 2011 | 190 | 1425 | 1340 | 1060 | 1930 |
| Middle | 2003 | 586 | 3050 | 2710 | 1920 | 4400 |
| Middle | 2009 | 1008 | 3460 | 3235 | 2485 | 4770 |
| Middle | 2010 | 1020 | 4170 | 3835 | 3235 | 5520 |
| Middle | 2011 | 1044 | 4620 | 4285 | 3685 | 6160 |
| East | 2003 | 2 | 370 | 320 | 270 | 1420 |
| East | 2009 | 2 | 570 | 370 | 320 | 1580 |
| East | 2010 | 0 | 727 | 570 | 370 | 1760 |
| East | 2011 | 0 | 860 | 570 | 370 | 1760 |

the model. When looking at the whole bay however, the mass balance total phosphorus-loading model developed using data from lakes and reservoirs (Canfield and Bachmann 1981) was generally successful in predicting the actual annual average total phosphorus concentrations for the entire Choctawhatchee Bay. However, all models have considerable error associated with them and all of the measured phosphorus concentrations were well within the 95% confidence interval of 31% to 288% reported by Canfield and Bachmann (1981). Others have also successfully used this mass balance-loading model to predict total phosphorus concentrations in estuaries in Canada (Meeuwig 1999) and Finland (Meeuwig et al. 2000). While Meeuwig et al. (2000) and others (Richardson and Jørgensen 1996) point out that there are differences in lakes and estuaries that may influence eutrophication factors, which include flushing rates, general water chemistry, morphometry, grazing rates, physical energy and others, it still seems that the four variables used in the Vollenweider mass balance model account for these differences and allow for accurate predictions of total phosphorus concentrations in estuarine systems.

Empirically estimating chlorophyll using total concentrations of phosphorus, rather than nitrogen, seems to be appropriate for Choctawhatchee Bay. The annual average total phosphorus concentrations accounted for a significant amount of the variance in annual average chlorophyll concentrations ($R^2 = 0.73$), and after accounting for this variance, total nitrogen did not account for significantly more variance in chlorophyll. This supports findings from several other systems around the world (Meeuwig et al. 2000, Hoyer et al. 2002, Smith 2003). Additionally, Murrell et al. (2002) used nutrient addition bioassays in Pensacola bay, FL (a bay approximately 60 km west of Choctawhatchee Bay) to show phosphorus limitation of phytoplankton growth. However, further studies by Juhl and Murrell (2008) showed that phytoplankton growth was nitrogen limited indicating the difficulty in determining actual nutrient limitation in estuarine systems. There is considerable debate in the literature on whether phosphorus or nitrogen is the limiting nutrient in estuarine systems (Downing 1997, Guildford and Hecky 2000, Howarth and Marino 2006), but the underlying premise of this debate is that the nutrient responsible for limiting algal biomass in estuarine systems is ultimately dependent on the ratio of nitrogen to phosphorus (N limitation when TN/TP by mass $< 10$). However, this ratio in individual systems can change both spatially and temporally (Juhl and Murrell 2008, Hartzell and Jordan 2012, Lui and Chen 2012). Whatever nutrient is actually limiting the physiological growth of algae in Choctawhatchee Bay, the 11 years of data presented for Choctawhatchee Bay strongly suggests that total phosphorus accounts for the majority of the variance in chlorophyll concentrations (the index of algal biomass) and agrees with the findings of Hoyer et al. (2002) who used data from 300 sites located in nearshore coastal water distributed around FL to show that phosphorus accounted for more variance in chlorophyll than did total nitrogen.

In Choctawhatchee Bay, changes in chlorophyll concentrations accounted for significant variance observed in water clarity as measured with a Secchi disk. Countless studies on freshwater systems have shown this relationship (Carlson 1977, Canfield and Bachmann 1981, Hoyer and Jones 1983) and it has also been confirmed for the coastal waters around the world (Cloern 2001, Hoyer et al. 2002, Nielsen et al. 2002). Chlorophyll concentrations, however, accounted for only 47% of the variance in Secchi depth measurements at Choctawhatchee Bay suggesting that an additional factor or factors are also impacting water clarity. Besides suspended algal cells (estimated with chlorophyll concentrations), organic and inorganic dissolved and suspended substances determine the optical properties of water (Kirk 1994, Padial and Thomaz 2008). Measurements of color are estimates of the dissolved organics that can impact the optical properties of water and the Choctawhatchee River discharges considerable colored water into the bay that produces a gradient from the river to the East Pass (Hoyer et al. 2013: Table 1). Color by itself accounted for 37% of the variance in Secchi depth. Therefore, when chlorophyll and color were used in a multivariate linear model they accounted for 57% of the variance in Secchi depth of the bay. We have no measurements of non-algal suspended solids, which probably accounts for additional variance in Secchi depth measurements in the bay, but it is still apparent that chlorophyll concentration can significantly impact the water clarity of Choctawhatchee Bay and thus the maximum depth of plant colonization.

Modeling the potential surface area of Choctawhatchee Bay that should sustain submersed aquatic plants, assuming light was the only limiting factor (light requirements can exceed the 20% value used in this paper; Dixon (2000) and unpublished data from St. Andrews Bay, FL indicate PAR requirements of 24% to 27%), showed that the actual measured plant coverages are significantly less than available light would indicate. Obviously factors other than chlorophyll and color that directly influence water clarity are limiting submersed aquatic plant abundances in the bay.

Many studies have documented the primary importance of light to the abundance and distribution of submersed aquatic plants in fresh and estuarine ecosystems (Hutchinson 1975, Chambers and Kalff 1985, Bach et al. 1998), but many additional factors impact the abundance and distribution of aquatic plants, including water pressure (Hutchinson 1975), substrate characteristics (Bachmann et al. 2001), waterfowl grazing (Weisner et al. 1997), changing salinities (Hoyer et al. 2004) and a multiple of physical, geological, and geochemical factors (Koch 2001). Data are not available to determine exactly what factors may be determining the abundance of submersed aquatic vegetation in the bay, but light seems not to be limiting.

Hoyer et al. (2013) showed that there is a great amount of spatial and temporal variance in the water chemistry of Choctawhatchee Bay and this variability is primarily driven by annual freshwater inputs to the bay. These large water chemistry changes, especially in salinity and color may also be the dominant factors determining the distribution of aquatic plants (species and abundance) in the bay, especially when considering the possible long-term impact of stochastic events like hurricanes or extremely high rainfall. However, we have not yet attempted to identify the factor/factors that are determining the distribution of submersed aquatic plants in Choctawhatchee Bay. Based on the available data, we suggest that light attenuation caused by chlorophyll is not the primary environmental factor limiting distribution and abundance of submersed aquatic plants. Therefore, nutrient enrichment may not be the cause of hypothesized decline in the plant abundance of the bay.

In conclusion, the chain of eutrophication models originally developed in freshwater systems can be used in the Choctawhatchee Bay estuary in the following ways: 1) mass balance phosphorus loading models can be used to predict the total phosphorus concentration in Choctawhatchee Bay, 2) phosphorus concentrations can be used to predict chlorophyll concentrations in the bay, 3) chlorophyll concentrations can be used to predict Secchi depth measurements and 4) Secchi depth values can be used to determine maximum depth of plant colonization, which can then be used to estimate the potential surface area that plants could colonize based on light being the limiting factor. While eutrophication has been shown to impact the abundance of aquatic plants in many estuaries due to light limitation caused by increased algal abundance (e.g., Tampa Bay), light does not appear to be limiting the abundance of aquatic plants in Choctawhatchee Bay. Thus, it is unlikely that eutrophication and related decreases in light penetration has caused any decrease in aquatic plant abundance in the bay. This conclusion could have been determined with only the modeling exercise that examined the potential surface area of the bay that would support aquatic vegetation based on Secchi depth measurements and comparing that to actual measured plant coverage. Understanding the entire chain of eutrophication models in the system, however, will help estuarine resource managers understand how changes in the watershed may impact the bay ecology and focus limited financial resources on solving “fixable” problems.

Meeuwig et al. (2000) suggested that the reason lake developed mass balance nutrient model worked in the Finnish estuaries could be that they have characteristics in-between lakes and estuaries. They are open systems with little tidal fluctuation and with little exchange to the Baltic water due to narrow openings caused by the complex coastal morphology and the presence of islands. Similarly, Choctawhatchee Bay has a small tidal exchange (a range of about 0.15 m, Ruth and Handley 2002) because of the narrow man-maintained opening to the Gulf of Mexico at East Pass and this may explain why the loading model worked well in Choctawhatchee Bay. As Souchu et al. (2010) suggested, the limnological modeling approach first developed in freshwater systems can be an appropriate management strategy for estuaries, but they need to be examined further in other estuaries, especially ones more open to the major oceans. However, Florida has both types of estuaries and they should become a focal point for coastal research in Florida using the chain of eutrophication models.

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## References

Bach SS, Borum J, Fortes MD, Duarte C. 1998. Species composition and plant performance of mixed seagrass beds along a siltation gradient at Cape Bolinao, The Philippines. Marine Ecology Progress Series 171:247–256.

Bachmann RW, Hoyer MV, Canfield DE Jr. 2001. Evaluation of recent limnological changes at Lake Apopka. Hydrobiologia 448:19–26.

Blaylock D. 1983. Choctawhatchee Bay: Analysis and interpretation of baseline environmental data. Technical Paper No. 29. Institute for Statistical and Mathematical Modeling, University of West Florida. Pensacola.

Bracchini LA, Dattilo M, Hull V, Loiselle SA, Tognazzi A, Rossi C. 2009. Modelling upwelling irradiance using Secchi disk depth in lake systems. Journal of Limnology 68:83–91.

Burch TA. 1983. Inventory of submerged vegetation in Choctawhatchee Bay, Florida. Northwest Florida Water Management District Water Resources Report, 83–86. Havana, FL.

Caffrey AJ, Hoyer MV, Canfield DE Jr. 2007. Factors affecting the maximum depth of colonization by submersed macrophytes in Florida lakes. Lake Reservoir Management 23:287–297.

Canfield DE Jr. 1983. Prediction of chlorophyll a concentrations in Florida lakes: The importance of phosphorus and nitrogen. Water Resources Bulletin 19:255–262.

Canfield DE Jr, Bachmann RW. 1981. Prediction of total phosphorus concentrations, chlorophyll a, and Secchi depth in natural and artificial lakes. Canadian Journal of Fisheries and Aquatic Sciences 38:414–423.

Canfield DE Jr, Hodgson LM. 1983. Prediction of Secchi disc depths in Florida lakes: impact of algal biomass and organic color. Hydrobiologia 99:51–60.

Canfield DE Jr, Brown CD, Bachmann RW, Hoyer MV. 2002. Volunteer lake monitoring: testing the reliability of data collected by the Florida LAKEWATCH program. Lake Reservoir Management 18:1–9.

Carlson RE. 1977. A trophic state index for lakes. Limnology and Oceanography 22:361–373.

Carpenter SR, Caraco NE, Correll DL, Howarth W, Sharpley AN, Smith VH. 1998. Non-Point pollution of surface waters with phosphorus and nitrogen. Ecological Applications 8:559–568.

Chambers PA, Kalff J. 1985. Depth distribution and biomass of submersed aquatic macrophyte communities in relation to Secchi depth. Canadian Journal of Fisheries and Aquatic Sciences 42:701–709.

Cloern JE. 2001. Our evolving conceptual model of the coastal eutrophication problem. Marine Ecology Progress Series 210:223–253.

Conley DJ, Kaas H, Møhlenberg F, Rasmussen B, Widlof J. 2000. Characteristics of Danish estuaries. Estuaries 23:820–837.

Cooke GD, Welch EB, Peterson SA, Newroth PR. 1993. Restoration and management of lakes and reservoirs. 2nd ed. CRC Press, Inc., Boca Raton.

Dixon LK. 2000. Establishing light requirements for seagrass *Thalssia testudinium*: An example from Tampa Bay, Florida. Pp. 9–31 *in* Bortone SA, ed. Seagrass: Monitoring, Ecology, Physiology, and Management. CRC Press, Inc., Boca Raton.

Downing JA. 1997. Marine nitratrogen:phosphorus stoichiometry and the global N:P cycle. Biogeochemistry 37:237–252.

Graham JJ. 1966. Secchi disk observations and extinctiction coefficients in central and eastern North Pacific Ocean. Limnology and Oceanography 11:184–190.

Greening HS, Janicki A. 2006. Toward reversal of eutrophic conditions in a subtropical estuary: water quality and seagrass response to nitrogen loading reductions in Tampa Bay, Florida, USA. Environmental Management 38:163–178.

Greening HS, Cross LM, Sherwood ET. 2011. A multiscale approach to seagrass recovery in Tampa Bay, Florida. Ecological Restoration 29:82–93.

Guildford SJ, Hecky RE. 2000. Total nitrogen, total phosphorus, and nutrient limitation in lakes and oceans: Is there a common relationship? Limnology and Oceanography 45:1213–1223.

Harper R, Morgan A, Morgan C. 2006. Economic Analysis of the Contribution of Choctawhatchee Bay to Okaloosa and Walton Counties. Haas Center for business research and economic development. University of West Florida, Pensacola. 61 pgs.

Hasler AD. 1947. Eutrophication of lakes by domestic drainage. Journal Ecology 28:383–395.

Hartzell JL, Jordon TE. 2012. Shifts in the relative availability of phosphorus and nitrogen along estuarine salinity gradients. Biogeochemistry 107:489–500.

Hemming JM, Brown JM. 2004. Sediment analysis in Choctawhatchee Bay. U.S. Fish and Wildlife Service. Publication No. PCFO-EC-04-01. Panama City.

Hoyer MV, Jones JR. 1983. Factors affecting the relation between phosphorus and chlorophyll a in midwestern reservoirs. Canadian Journal of Fisheries and Aquatic Sciences 40:192–199.

Hoyer MV, Frazer TK, Notestein SK. Canfield DE Jr. 2002. Nutrient, chlorophyll, and water clarity relationships in Florida's nearshore coastal waters with comparisons to freshwater lakes. Canadian Journal of Fisheries and Aquatic Sciences 59:1–8.

Hoyer MV, Frazer TK, Notestein SK. Canfield DE Jr. 2004. Vegetative characteristics of three low-lying Florida coastal rivers in relation to flow, light, salinity and nutrients. Hydrobiologia 528:31–43.

Hoyer MV, Wellendorf N, Frydenborg R, Bartlett D, Canfield DE Jr. 2012. A Comparison Between Professionally (Florida Department of Environmental Protection) and Volunteer (Florida LAKEWATCH) Collected Trophic State Chemistry Data in Florida. Lake Reservoir Management 28:277–281.

Hoyer MV, Terrell JB, Canfield DE Jr. 2013. Water Chemistry in Choctawhatchee Bay, Florida USA: Spatial and Temporal Considerations Based on Volunteer Collected Data. Florida Scientist 76: 453–466.

Howarth RW, Marino R. 2006. Nitrogen as the limiting nutrient for eutrophication in coastal marine ecosystems: Evolving views over three decades. Limnology and Oceanography 51:364–376.

Hutchinson GE. 1967. A treatise on limnology. Introduction to lake biology and the limnoplankton, Volume 2. John Wiley and Sons, New York.

Hutchinson GE. 1975. A treatise of limnology. Volume 3. Limnological botany. John Wiley and Son, Inc. New York.

Idso SB, Gilbert RG. 1974. On the universality of the Poole and Atkins Secchi disk-light extinction equation. Journal of Applied Ecology 11:399–401.

Jones JR, Bachmann RW. 1976. Predictions of phosphorus and chlorophyll levels in lakes. Research Journal of the Water Pollution Control Federation 48:2176–2182.

Jones JR, Hoyer MV. 1982. Sportfish harvest predicted by summer chlorophyll-a concentration in Midwest lakes and reservoirs. Transactions of the American Fisheries Society 111:176–179.

Juhl AR, Murrell MC. 2008. Nutrient limitation of phytoplankton growth and physiology in a subtropical estuary (Pensacola Bay, Florida). Bulletin of Marine Science 82:59–82.

Kirk JTO. 1994. Light and photosynthesis in aquatic ecosystems. Cambridge University Press, Cambridge.

Koch EW. 2001. Beyond light: Physical, geological, and geochemical parameters as possible submersed aquatic vegetation habitat requirements. Estuaries 24:1–17.

Larkum AWD, Orth RJ, Duarte CM, eds. 2007. Seagrasses: Biology, Ecology and Conservation. Springer, New York.

Livingston RJ. 2010. Choctawhatchee River–Bay system: A nutrient report for the Florida Department of Environmental Protection (FDEP). Tallahassee.

Lotze HK, Lenihan HS, Bourque BJ, Bradbury RH, Cooke RG, Kay MC, Kidwell SM, Kirby MX, Peterson CH, Jackson JBC. 2006. Depletion, degradation, and recovery potential of estuaries and coastal seas. Science 312:1806–1809.

Lui H, Chen CA. 2012. The nonlinear relationship between nutrient ratios and salinity in estuarine ecosystems: implications for management. Current Opinion in Environmental Sustainability 4:227–232.

McNulty K, Lindall W. Sykes J. 1972. Cooperative Gulf of Mexico estuarine inventory and study, Florida: Phase I, Area Description. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service.

Meeuwig JJ. 1999. Predicting coastal eutrophication from land use: an empirical approach to small non-stratified estuaries. Marine Ecology Progress Series 176:231–241.

Meeuwig JJ, Kauppila P, Pitkanen H. 2000. Predicting coastal eutrophication in the Baltic: a limnological approach. Canadian Journal of Fisheries and Aquatic Sciences 57:844–855.

Murrell MC, Stanley RS, Lores EM, DiDonato GT, Smith LM, Flemer DA. 2002. Evidence that phosphorus limits phytoplankton growth in a Gulf of Mexico estuary: Pensacola Bay, Florida, USA. Bulletin Marine Science 70:155–167.

Naumann E. 1919. Nagra synpunkter angaende limnoplankton okologi Med sarskild hansyn till fytoplanton. Svensk Botanisk Tidskrift 13:129–163.

Nielsen SL, Sand-Jendsen K, Borum J, Geertz-Hansen O. 2002. Phytoplankton, nutrients, and transparency in Danish coastal waters. Estuaries 25:930–937.

Northwest Florida Water Management District (NWFWMD). 1996. Choctawhatchee River and Bay system surface water improvement and management plan. Program Development Series 96-4. Havana, FL.

OECD. 1982. Eutrophication of waters: monitoring, assessment and control. Organization for Economic Cooperation and Development, Paris.

Oglesby RT. 1977. Relationships of fish yield to lake phytoplankton standing crop, production, and morphometric factors. Canadian Journal of Fisheries and Aquatic Sciences 34:2271–2279.

Padial AA, Thomaz SM. 2008. Prediction of the light attenuation coefficient through the Secchi disk depth: empirical modeling in two large neotropical ecosystems. Limnology 9:143–151.

Poole HH, Atkins WRG. 1929. Photo-electric measurement of submarine illumination through out one year. Journal of the Marine Biological Association of the United Kingdom 16:297–324.

Rask N, Pedersen SE, Jensen MH. 1999. Response to lowered nutrient discharges in coastal waters around the island of Funen, Denmark. Hydrobiologia 393:69–81.

Richardson K, Jørgensen BB. 1996. Eutrophication: definition, history and effects. Pp. 1–19 *in* Richardon K, Jorgenson BB, eds. Eutrophication in coastal marine ecosystems. American Geophysical Union as part of the Coastal and Estuarine Studies, Volume 52.

Ruth B, Handley LR. 2002. Choctawhatchee Bay *in* Handley L, Altsman LD, DeMay R, eds. Seagrass status and trends in the northern Gulf of Mexico: 1940–2002. U.S. Department of the Interior and U.S. Geological Survey, Scientific Investigations Report 2006-5287, U.S. Environmental Protection Agency 855-R-04-003. Reston, VA.

SAS. 2000. JMP Statistics and graphics guide. SAS Institute, Inc. Cary, NC.

Schindler DW. 1975. Whole-lake eutrophication experiments with phosphorus, nitrogen and carbon. Verhandlungen der Internationalen Vereinigung für Theoretische und Angewandte Limnologie 19:3221–3231.

Schaeffer B. 2010. Choctawhatchee Bay. A presentation to the Pensacola public workshop, February 10, 2010, in support of the development of numeric nutrient criteria in Florida estuaries and coastal waters. http://www.dep.state.fl.us/water/wqssp/nutrients/estuarine.htm. Accessed June 2012.

Smith VH. 1982. The nitrogen and phosphorus dependence of algae biomass in lakes: an empirical and theoretical analysis. Limnology and Oceanography 27:1101–1112.

Smith VH. 2003. Eutrophication of freshwater and coastal marine ecosystems: a global problem. Environmental Science and Pollution Research 10:126–139.

Souchu P, Bec B, Smith VH, Laugier T, Fiandrino A, Benau L, Orsoni V, Collos Y, Vaquer A. 2010. Patterns in nutrient limitation and chlorophyll a along an anthropogenic eutrophication gradient in French Mediterranean coastal lagoons. Canadian Journal of Fisheries and Aquatic Sciences 67:743–753.

Sokal RR, Rohlf FJ. 1981. The principles and practices of statistics in biological research, 2nd ed. W. H. Freeman and Co., San Francisco.

Steele JH. 1974. The structure of marine ecosystems. Harvard University Press, Cambridge.

U.S. Army Corps of Engineers (USACE). 1973. LaGrange Bayou maintenance dredging Walton County, Florida: Draft environmental impact study.

U.S. Army Corps of Engineers (USACE). 1976. Maintenance dredging of the Gulf Intracoastal Waterway from Pearl River, Louisiana, Mississippi to Apalachee Bay, Florida. Final Environmental Statement.

Vollenweider RA. 1976. Advances in defining critical loading levels of phosphorus in lake eutrophication. Memorie dell'Istituto italiano di idrobiologia dott. Marco de Marchi 33:53–83.

Vollenweider RA. 1992. Coastal marine eutrophication: principles and control. Pp. 1–20 *in* Vollenweider, RA, Marchetti R, Viviani R, eds. Marine coastal eutrophication. Elsevier, London.

Weisner SEB, Strand JA, Sandsten H. 1997. Mechanisms regulating abundance of submerged vegetation in shallow eutrophic lakes. Oecologia 109:592–599.

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