The Geochemical Record of Cultural Eutrophication in Sediments of Beseck Lake and Lake Waramaug, Connecticut: Implications for Nutrient Cycling and Remediation Efforts

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Principle Investigator: Timothy Ku, Wesleyan University

Problem and Research Objectives

Anthropogenic activities have dramatically altered the biogeochemical cycles of carbon, sulfur, nitrogen, and phosphorous in nearly every major aquatic ecosystem on Earth (Smith, 2003). Cultural eutrophication is the process whereby human activity increases the amount of nutrients, primarily nitrogen and phosphorous, entering an aquatic ecosystem causing excessive biological growth. The accelerated production of autochthonous organic matter results in anoxic conditions within the water column, thereby changing the community structure of aquatic ecosystems and degrading the recreational and retail value of the surrounding land. Eutrophication is a widespread environmental problem as it accounts for ~50% of impaired lake area and 60% of impaired river reaches in the U.S. (U.S. EPA, 1996). In Connecticut, prior to the mid-1800s the land was mostly forested, but increases in agriculture, urban, and residential land areas contributed to the eutrophication of several Connecticut lakes by the 1930s (Deevey, 1940; Bell, 1985). Progressive eutrophication associated with land-use changes continued in many Connecticut lakes as average Secchi disk depths decreased by 1.2m and total phosphorous concentrations doubled from the late 1930s to the early 1990s (Siver et al., 1996). During approximately the same time, mean estimated total phosphorous (eTP) and mean estimated total nitrogen (eTN) concentrations increased from 15 and 374 μg/L to 25 and 450 μg/L, respectively (Field et al., 1996). These results, together with biological-based paleolimnology studies, clearly demonstrate that anthropogenic activities have accelerated the eutrophication process in many Connecticut lakes (Siver et al., 1999).

To reverse or decelerate cultural eutrophication, many regulatory agencies have implemented stringent laws intended to lower the delivery rate of nutrients into impacted water bodies such as the Chesapeake Bay, Lake Erie, and Lake Baldeggersee (Switzerland) (Lotter, 1998; Boesch, 2002). In Connecticut, the Long Island Sound study aims to reduce nutrient inputs delivered to Long Island Sound, but restoration or preservation of inland lakes is usually the responsibility of local governing agencies working in conjunction with the Connecticut Department of Environmental Protection (NYSDEC and CTDEP, 2000). This study focuses on two eutrophic Connecticut lakes that have been the focus of major remediation efforts, Lake Waramaug and Beseck Lake. Lake Waramaug experienced significant eutrophication from the 1950s through the 1980s and two hypolimnetic withdrawal systems were installed in 1983 to contain the phosphorous in the bottom waters of the lake. Since 1983, additional remediation efforts have included the installation of two in-lake layer aeration systems, the passing of new zoning regulations to limit soil and water runoff, and the stocking and seeding of fish and zooplankton to improve water quality (http://www.lakewaramaug.org). The Lake Waramaug Task Force (LWTF) is a non-profit organization of volunteers and scientists and together with Ecosystem Consulting Services, Inc. has continuously monitored the lake since 1977. During this time, the lake water clarity has improved and epilimnion phosphorous concentrations have declined (ECS data, pers. comm.). Beseck Lake is a manmade impoundment created by a dam in the mid 1800s and has experienced episodic eutrophic conditions from the 1970s to the 1990s, in part due to the addition of nutrients from failing septic systems (Canavan and Siver, 1995; Cinotti, 1997; Jacobs and O'Donnell, 2002). To decrease the flux of nutrients entering the lake, surrounding residences were converted from septic systems to a city sewer system. This transition was completed in 2002 and the Lake Beseck Association now helps maintain and monitor the lake water quality (R. Boyton, pers. comm.).

While these efforts to decelerate the eutrophication process have yielded positive results, future remediation policies must set realistic goals of water quality (chemical composition and biologic activity). By using historical data, time series data, or reference region data, regulatory agencies can determine pristine water quality conditions that are absent of the effects of human activity (Smith, 2003). Sediment cores collected from Beseck Lake and Lake Waramaug record the pre-anthropogenic lake conditions and the onset and remediation of cultural eutrophication. This project examines the history of these two lakes, which will help guide future remediation efforts in Beseck Lake and Lake Waramaug as well as in other worldwide lakes experiencing similar eutrophication problems.

Methodology

The three main objectives of this study are 1) determine the sedimentation rates of organic C, organic N, and detrital minerals, 2) determine the source of organic matter and detrital minerals, and 3) determine the paleoredox history of these lakes. Sediment push cores and freeze cores were collected using a pontoon boat. Linear sedimentation rates (LSR, cm/yr) and mass accumulation rates (MAR, $g/cm^2/yr$) were determined by ^{210}Pb, ^{137}Cs, and Hg and Pb methods (Appleby and Oldfield, 1992; Siver and Wozniak, 2001; Callender, 2004; Fitzgerald and Lambourg, 2004; Varekamp et al., 2005). Organic C and N concentrations were analyzed with an elemental analyzer. Major, minor, and trace element compositions were determined by digesting sediments in a HCl/ HNO_3/ HF/ $HClO_4$ solution followed by ICP and ICP-MS analyses. $\delta^{13}C$ and $\delta^{15}N$ organic matter measurements were performed at the Stable Isotope facility at Indiana University. Paleoredox indicators (DOP, $\delta^{34}S_{pyrite}$, and pyrite framboid size distributions) were analyzed using Fe-S methods and sediment phosphorus species (labile P, Al-P, organic P, and Fe-P) were determined by a sequential sediment extraction method (Canfield et al., 1986; Raiswell et al., 1994; Wilkin et al., 1996; 1997).

Principal Findings and Significance

Eight and seven sediment cores were collected from Lake Waramaug and Beseck Lake, respectively. Three sediment cores have been dated and represent 200 to 400 years of lake history. In Lake Waramaug, the Hg and Pb sediment concentrations increase at ~1900 A.D. due to fossil fuel use related to the Industrial Revolution and peak concentrations are found between 1950-1970 A.D. Compared to times before ~1900 A.D., Lake Waramuag experienced a period of higher C/N ratios shortly after 1900 A.D. that indicates a greater proportion of allochthonous organic matter being delivered from the surrounding watershed. This could be related to increased forest clearing, a major storm event, or a period of increased rainfall. The organic C, C/N, and $\delta^{15}N$ values (background 0.4‰) all indicate increasing cultural eutrophication throughout the 1900s and the highest organic matter $\delta^{15}N$ value of +3.1‰ occurring in the 1970s-1980s. The $\delta^{15}N$ values decrease from this peak time to values of +1.9‰ today and this is likely related to the remediation efforts of the Lake Waramaug Task Force, which significantly decreased the external nutrient inputs and implemented in-lake restoration solutions since the 1970s-1980s. This finding is significant because this represents one of the few cases where remediation results are documented by lake sediments. Sediment iron-sulfur paleoredox indicators show high spatial and temporal variability demonstrating that Fe-S-P cycling has been greatly altered by human pollution and remediation activities. In general, our data show that the oxic/anoxic interface has fluctuated significantly over the last ~70 years, which has caused the fraction of Fe-bound phosphorus to decrease in recent times. Additionally, sulfuric acid from acid rain sources appears to have increased the ratio of pyrite Fe to reactive Fe, which would further decrease the amount of reactive iron available to bind phosphorus. Due to the high variability of Fe-S-P chemistries between sediment cores, we have had to 210Pb-date more cores than anticipated to firmly establish sediment chronologies. This data is currently being collected and we anticipate that all data will be collected during the summer of 2009 and the first manuscript focusing on Lake Waramaug will be submitted for publication in August 2009.

In Beseck Lake, the sediments document the time from prior to the mid-1800s, when the lake water was raised by damming the outflow, to the last few years. Higher C/N ratios mark the older swamp sediments and increased cultural eutrophication results in greater concentrations of organic C, lower C/N ratios, and higher $\delta^{15}N$ values. Unlike Lake Waramaug, a decrease in $\delta^{15}N$ values is not observed, however, that signal may be lost due to moderate bioturbation of the bottom sediments. The sediment Fe-S-P chemistries do not show significant changes over time, but rather show clear correlations with current water column heights and average overlying dissolved oxygen concentrations. In shallow, oxic portions of the lake, there is low total phosphorus and most of the phosphorus is found in non-Fe phases. However, in the deeper, anoxic portions of the lake, there are higher total phosphorus concentrations with iron-phases comprising the most important P-binding phase. These results highlight the importance of iron and sulfur cycling to the available phosphorus budget and demonstrate that the dominant P-bearing phase may shift due to human activities.

Our findings will help the Lake Waramaug Task Force and Beseck Lake Association with future remediation decisions and provide the scientific community with a rare opportunity to compare recent sediment geochemistry with long-term, remediation efforts. We expect that future researchers will use the techniques and results from this study to examine other eutrophic water bodies, thereby making Beseck Lake and Lake Waramaug the model examples for this type of work.

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