Assessing environmental response and recovery of a Great Lakes watershed using a multiproxy paleolimnological approach

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Sediment geochemistry and diatom biostratigraphy can be used to identify stressor-response relationships in aquatic ecosystems for improved regional management strategies.

Aquatic ecosystems in the Great Lakes region of North America have been significantly altered since Euro-American settlement in the late 1700s. Human activities contributing to environmental degradation initially included population increase, land use change, and dramatic industrialization (Alexander, 2006). An understanding of the state of modern aquatic ecosystems can be gleaned from reconstructing the environmental history of the region. Integrating historical records with high-resolution paleolimnological data is an effective way to capture stressor-response relationships and evaluate human influence. These relationships facilitate an understanding of comprehensive aquatic ecosystem response, and are useful for developing predictive tools for future anthropogenic influences. Having such tools is critical for developing sustainable management strategies, and can be used directly by decision makers at the regional scale.

Impacts in the Laurentian Great Lakes Region

A sediment core from Muskegon Lake, Michigan, USA, was analyzed for multiple proxies to assess the system's response and recovery to human activity, with particular attention to ecosystem recovery since the introduction of environmental legislation in the United States (e.g., Clean Air and Clean Water Acts). Muskegon Lake is a 16.91 km^2 inland water body located in the Laurentian Great Lakes region (86°18' W, 43°14'N) (Parsons et al., 2004). Its mean depth is 7 m with a maximum depth of 23 m. Muskegon Lake itself is the end point of a drowned river mouth system that connects the Muskegon River Watershed to the coastal zone of Lake Michigan through a navigation channel (Steinman et al., 2008). This proximity to the Great Lakes and general ecological setting make it an important fishery, though invasive species, habitat loss and degradation continue to be factors of concern (Lake Michigan Lakewide Management Plan, 2004).

Muskegon Lake has a history of intense anthropogenic activity since the early 1800s (summarized in Fig. 1). During the lumber peak in the 1880s, the city of Muskegon had more than 47 sawmills. Following the depletion of lumber resources, Muskegon developed an industrial base, with oil and chemical industries being prominent (Alexander, 2006). In the mid-1900s, foundries, metal finishing plants, a paper mill and petrochemical storage facilities were built on the shore of Muskegon Lake (Steinman et al., 2008). Expansion of heavy industry and shipping in 1960s and 1970s contributed to over 100 000 m^3/day of wastewater discharged from industrial and municipal sources into the lake until a tertiary Waste Water Treatment Plant (WWTP) was installed in 1973 (Freedman et al., 1979; Steinman et al., 2008). Currently, there are eight abandoned hazardous waste sites (USEPA Superfund sites) in the region and fish consumption advisories have been issued due to significant levels of PCB (Polychlorinated biphenyls) and mercury.

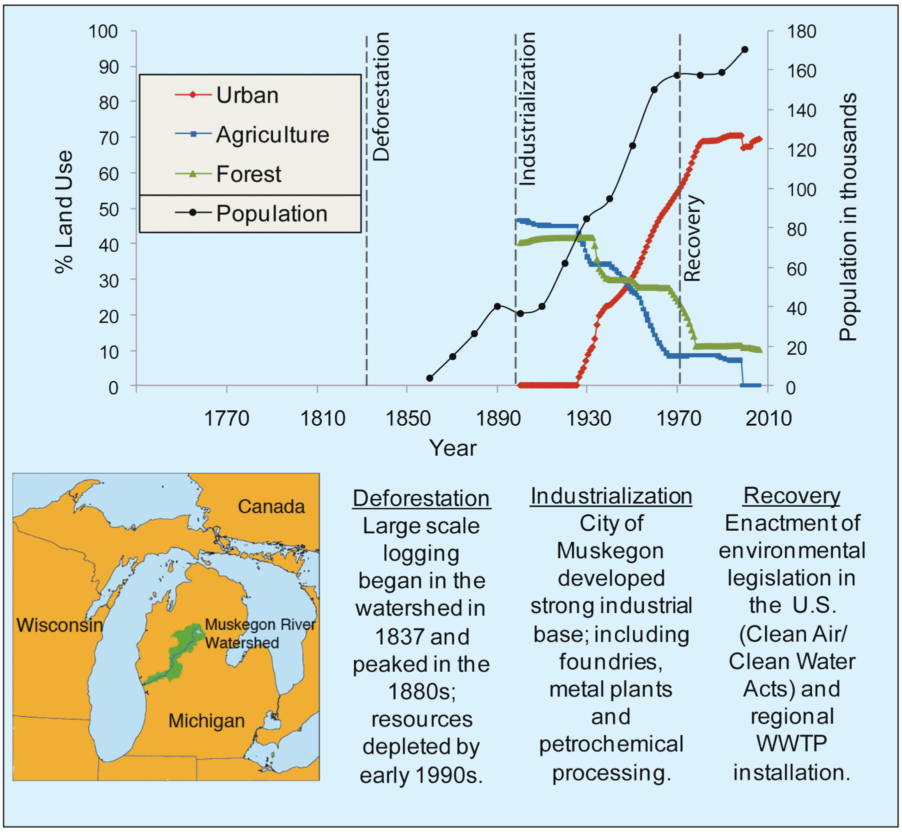

Figure 1: Trends of land use change since 1900 (Ray and Pijanowski, 2010) for the Muskegon River Watershed (location green on map inset), population data for Muskegon county since 1860 (US Census) and regional scale human impacts since Euro-American settlement. WWTP = Wastewater Treatment Plant.

Environmental response to regional impacts

Analyses of geochemical data from the sediment core showed suites of elements that corresponded to the source of the sediment, including terrestrial in wash, primary productivity, redox sensitive and anthropogenic related material (Long et al., 2010; Yohn et al., 2002). Elements influenced by terrestrial processes (e.g., Al, K, Ti and Mg) reflected drowned river mouth conditions of Muskegon Lake, and recorded deforestation-induced erosion in the late 1800s. Productivity related elements (e.g., P and Ca) indicated changes with nutrient inputs to the lake (presumably related land use change). Redox sensitive elements (e.g., Fe and Mn) were important for interpreting the redox state of the system. Elements associated with anthropogenic activity (e.g., Cr, Pb and Sn) had similar profiles, which closely track the history of human activity (see Fig. 2A), though concentration peaks for individual elements varied by specific industrial activity. For example, driven in part by policy mandates (e.g., discontinued use of leaded gasoline) Pb decreased to ~60 ppm in modern sediment from a peak of ~325 ppm, reflecting significant recovery from peak concentrations of anthropogenic elements. However, the Pb values did not return to the pre-disturbance Pb concentration of ~11 ppm. The geochemical reference condition was evaluated using sediment concentration profiles of the anthropogenic proxy group, which best indicates the pre-Euro/American settlement conditions. Results show that modern concentrations of anthropogenic elements have not decreased to the historical geochemical reference condition (e.g., Pb).

Biological change in Muskegon Lake, inferred from fossil diatoms, suggests that the pre-settlement community structure is markedly different from that of modern assemblages. Figure 2 includes specific diatom biostratigraphic changes that correspond to the timeline of various human stressors, including water chemistry changes resulting from agricultural development, industrialization and urbanization of the watershed. For example, taxa indicating high nutrient conditions (e.g., *Stephanodiscus* spp.) have peak abundances dated between 1930s and 1970s when nutrient inputs were increasing due to agriculture and urbanization. Moreover, productivity regimes in the lake, reconstructed from diatom habitat structure, identified a significant shift from planktonic- to benthic-dominated productivity in the top 25 cm of the core; this shift is dated to after the installation of the WWTP in 1973. Much of the water quality improvements in the past 30 years, reported by Freedman et al. (1979) and Steinman et al. (2008), and also noted in Figure 2, are presumably attributed to the WWTP installation. Decreases in lake-wide averages of total phosphorus and soluble reactive phosphorus at the water surface range from 68 to 27 µg/L and from 20 to 5 µg/L, respectively from 1972 to 2005. In addition, average chlorophyll-a concentrations have declined by 19 µg/L over this period, while Secchi disk depths (a measure for water transparency) have increased from 1.5 to 2.2 m (Freedman et al., 1979; Steinman et al., 2008). This partial recovery corresponds to the shift in dominant habitat of primary productivity, as the relative abundance of planktonic dominated taxa at the bottom of the core (i.e., in pre-settlement times) is between 56 and 77%, peaks at 88% in 24 cm depth (dated to 1970 at the peak of cultural eutrophication), and then quickly decreases to 26-37% in the top 8 cm of the core. The productivity shift in the top 8 cm (benthic taxa become 54-64% dominant) may also be influenced by the invasion of *Dreissena polymorpha* (zebra mussel).

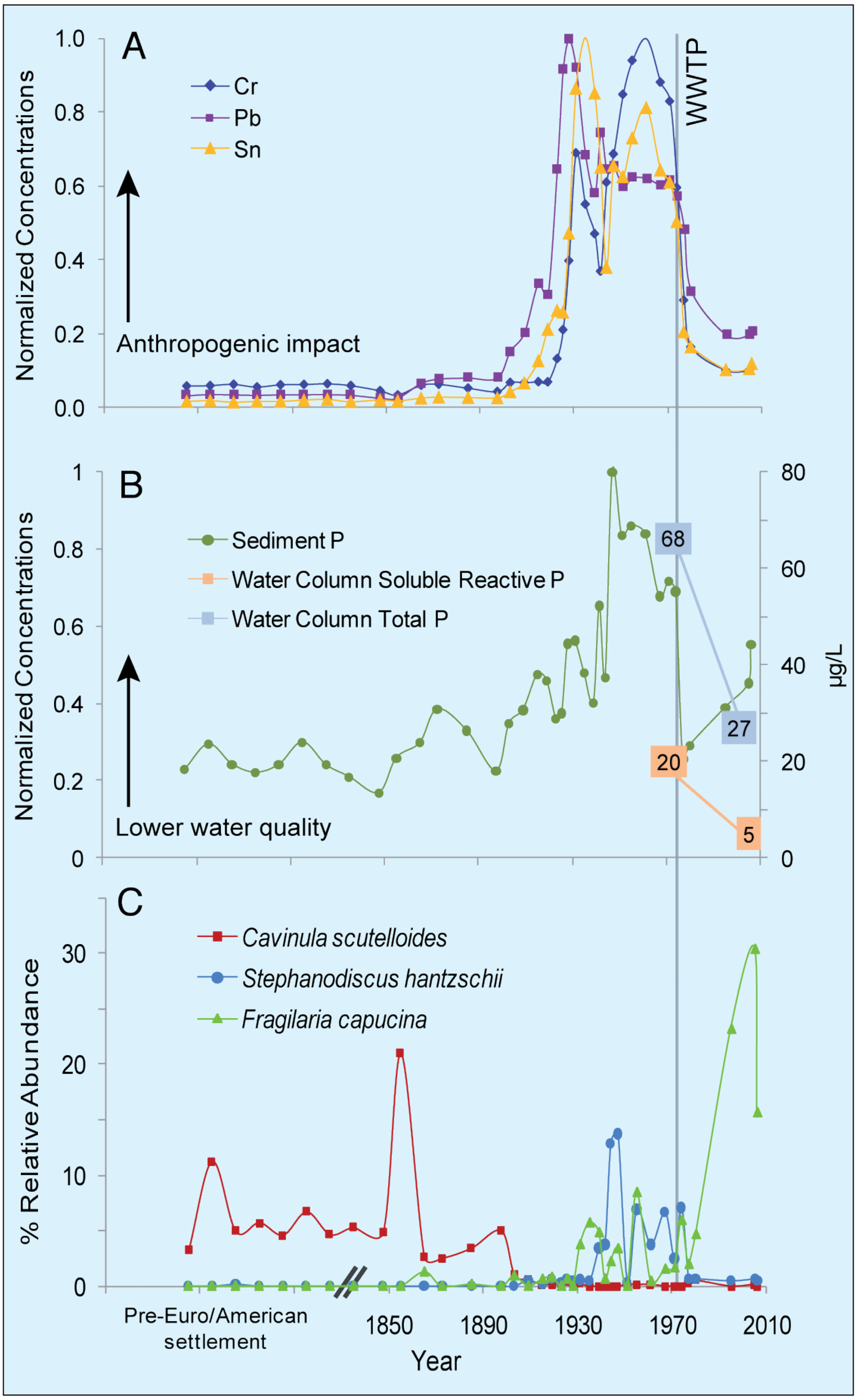

*Figure 2: **A**) Profiles of select anthropogenic elements with concentrations normalized to highest concentration of each element, **B**) Normalized sediment phosphorus (P) profile (as a measure of water quality) with measured concentrations of water column soluble reactive P and water column total P from 1972 and 2005 (Freedman et al., 1979; Steinman et al., 2008), and **C**) Relative abundances of select fossil diatoms indicative of water quality changes.*

This study identified causal agents at the regional scale directly linked to human activities such as deforestation, agriculture, industry and urbanization with an integration of geochemical and biological data inferred from fossil diatoms. Overall, the state of the lake system has dramatically improved as the result of environmental management efforts, and this study can be used as an indicator for the response of the larger Lake Michigan that it feeds into (Wolin and Stoermer, 2005). However, recent proxy trends (e.g., sediment P) do not indicate that the system has stabilized, suggesting that modern stressors such as climate variability (Long et al., 2010; Magnuson et al., 1997), invasive species (Lougheed and Stevenson 2004; Steinman et al., 2008) and further land use alterations (Ray and Pijanowski 2010; Pijanowski et al., 2007; Tang et al., 2005) whose influence remain uncertain, are likely to influence system recovery.

Recovery challenges and recommendations

Efforts to manage the watershed have reduced the loading of metals and nutrients, improving the ecological health of Muskegon Lake as evidenced by geochemistry and diatom biostratigraphy. The current geochemical conditions demonstrate significant recovery from high concentrations of anthropogenic elements and the fossil diatom record from this core suggests that efforts to reduce nutrient loading have been successful. Despite improvements, these data indicate that the system is still changing in response to human impacts at the regional watershed scale, suggesting that management strategies also need to target non-point source inputs. As such, it is recommended that modern remediation targets consider the legacy and overprint of multiple stressors, as well as be aware of emerging stressors that could further alter ecological dynamics in the larger Great Lakes Region.

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For full references please consult:
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Landslides in São Paulo, Brazil: An integrated historical perspective

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The growing severity of floods and landslides in the state of São Paulo, Brazil, is related to rapid environmental changes, such as urbanization, deforestation and settlement in hazardous areas, rather than to natural events, and unless more sustainable land-use practices are adopted the impact of these (un)natural disasters might become more severe.

The Problem

The Emergency Events Database (EM-DAT, www.emdat.be/), an international database of disasters maintained by the Centre for Research on the Epidemiology of Disasters (CRED), states that during the period from 1948 to 2010 Brazil was hit by 146 disasters related to precipitation (storms, floods and mass movements) that caused 8627 deaths and affected nearly 3 million people. Approximately 75% of these calamitous episodes have occurred in the last three decades (1980 to 2010) (EM-DAT, 2010). These figures are probably underestimated (Marcelino et al., 2006; Nunes, 2009) but are consistent with other studies that have demonstrated an upward trend in the severity of disasters triggered by precipitation. It has drawn attention to the question of how strongly this dramatic trend is connected to societal changes, with an ever-growing vulnerability to weather and climate episodes (Kunkel et al., 1999; Changnon et al., 2000;

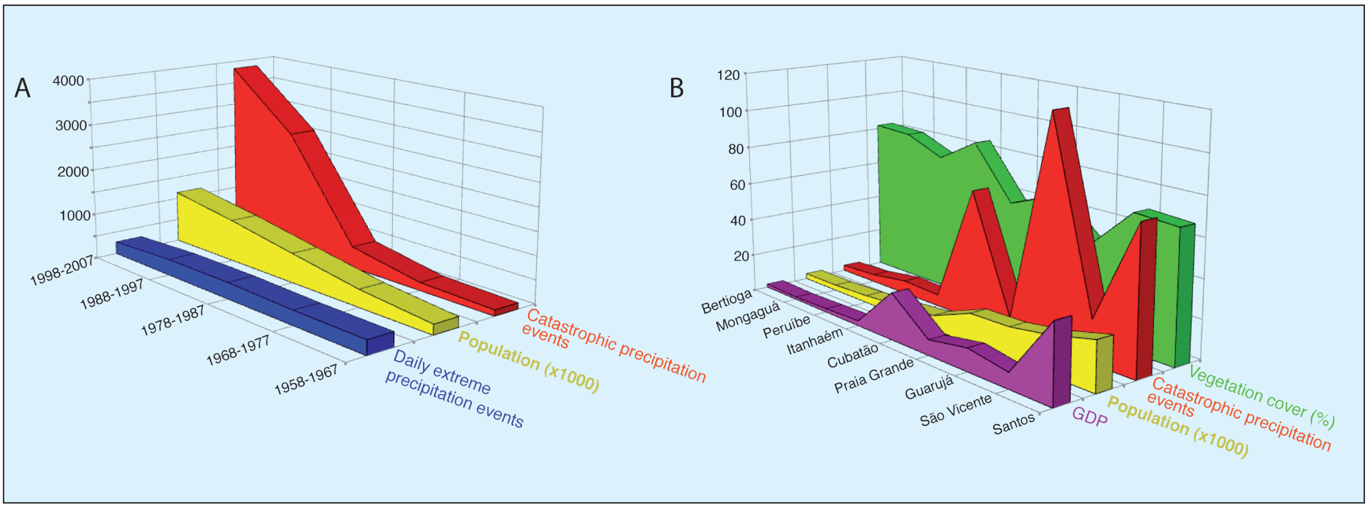

*Figure 1: **A**) Number of catastrophic events caused by precipitation (red) compared with population (yellow) and daily extreme precipitation episodes (blue) in Campinas, Brazil, for 5 decades (1958-1967 to 1998-2007). **B**) Comparison between Gross Domestic Product (GDP, purple, 2009), population (yellow, 2010), percentage of remaining vegetation (green, 2010) and survey (partially completed) of catastrophic events triggered by precipitation (red) from 1928 to 2009, for 9 municipalities of the Metropolitan Region of Baixada São Paulo, Brazil. Higher number of catastrophic events is related to higher deforestation, and lower GDP to lower rates of deforestation.*