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Chloride and total phosphorus budgets for Green Bay, Lake Michigan

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ABSTRACT

Green Bay is an elongated freshwater embayment located in northwestern Lake Michigan. Due to its short residence time, the lower bay is heavily influenced by the Fox River's large nutrient load. The inner bay is classified as hypereutrophic and a well-defined trophic gradient is observed moving away from the Fox River towards Lake Michigan, where the bay is nearly oligotrophic. Recent chloride and total phosphorus loading estimates were used to update a chloride and total phosphorus mass-balance model for the bay for 1994–2008. The chloride model provided a means to estimate turbulent eddy diffusion within the bay and exhibited excellent agreement with observed data. The total phosphorus model agreement with observed data was generally good, with the exception of a large deviation in lower Green Bay during 1999–2004. The model was used to estimate the internal loadings necessary to account for the deviation in phosphorus concentrations. The source of the unexpected increase remains unclear, but we speculate significant internal loading due to wind-driven sediment resuspension and hypoxia-induced phosphorus diffusion was significant. These models allow needed reductions to be identified and sourced and also indicate the role internal loading may play in the Green Bay phosphorus budget.

Introduction

Lower Green Bay and the Fox River are listed as one of the 41 Areas of Concern (AOC) in the Great Lakes by the International Joint Commission (IJC). Eutrophication, or undesirable algal growth due to excessive nutrients, is identified as one of its primary beneficial use impairments (Wisconsin Department of Natural Resources (WDNR), 1993). A strong trophic gradient is observed along the major axis of the bay, ranging from hypereutrophic in the AOC to oligomesotrophic near Lake Michigan (Auer and Canale, 1986). The Fox River is the most important tributary in Green Bay, providing ~70% of the phosphorus load (Klump et al., 1997) which causes the observed trophic gradient.

Phosphorus is commonly the limiting nutrient throughout the Great Lakes, and is the principal factor determining eutrophication in many embayments (Millard and Sager, 1994). The Great Lakes Water Quality Agreement (GLWQA) established target loads for total phosphorus (TP) in each lake to minimize the problems associated with eutrophication, but does not set a target for Green Bay (GLWQA, 1972, 1978). The Pollution from Land Use Activities Reference Group (PLUARG) developed the groundwork to monitor and report TP loading to the Great Lakes, and it has been the basis for estimation since (Pollution from Land Use Activities Reference Group, PLUARG, 1978) Although formal reporting has ceased since 1991 (Dolan and McGunagle, 2005), comprehensive load estimates were conducted as part of the Lake Michigan Mass Balance Study (LMMBS) in 1994–1995 (U.S. Environmental Protection Agency, USEPA, 1997).

In addition to tracking the progress of pollution control measures, updated mass loadings, coupled with the existing historical data, are a necessary component for many water quality models used for management purposes and developing total maximum daily loads, or TMDLs (Chapra, 2003). Due to a lack of consistent load estimates, recent mass balance models for Green Bay have been scarce and have mainly been based on data from the 1980s (e.g., Martin et al. 1995; Klump et al., 1997). The goal of this project was to use chloride (Cl) loadings to Green Bay in conjunction with recent TP loadings (Dolan and Chapra, 2012) to develop an updated Cl and TP budget for Green Bay that can be used to explore the effects of management strategies in Green Bay.

Background on Green Bay

As depicted in Fig. 1, Green Bay is an elongated embayment, oriented in a NNE–SSW direction (Bertrand et al., 1976). Located in northwestern Lake Michigan, it is the largest freshwater embayment in the Great Lakes (Klump et al., 1997) with a length of 193 km and an average width of 22 km (Mortimer, 1979). The southern end of Green Bay has a mean depth of approximately 10 m (Klump et al., 1997), and the northern

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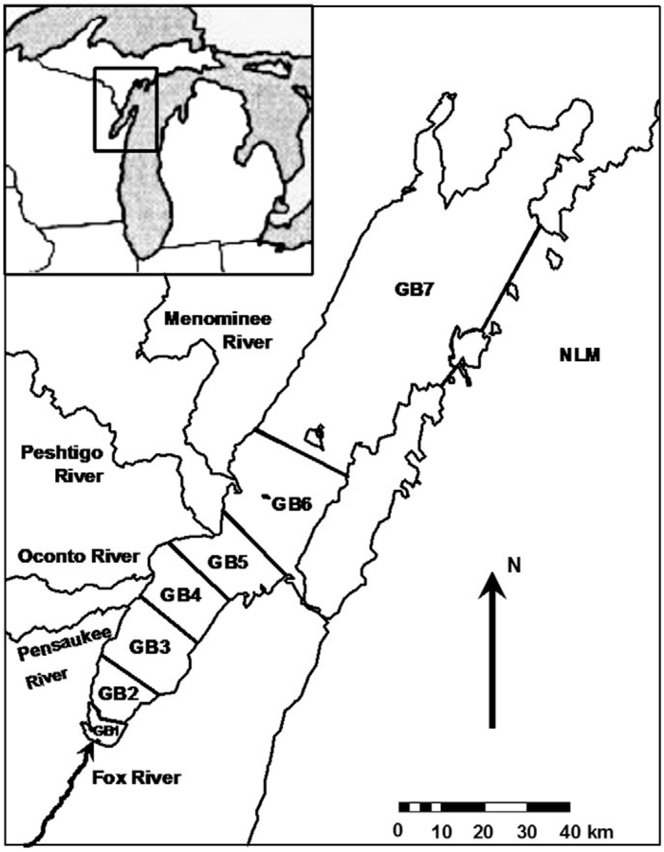

Fig. 1. Model segmentation (GB1–GB7) of Green Bay. NLM refers to northern Lake Michigan. Major inflowing rivers are shown.

end is deeper with average depths generally greater than 20 m and a maximum depth of 54 m (Miller and Saylor, 1985). While Green Bay's volume (~70 km^3) and surface area (4212 km^2) are relatively small in comparison to the main lake (Ahrnsbrak, 1971), its watershed area (42,000 km^2) constitutes about one-third of the Lake Michigan drainage basin (Bertrand et al., 1976). The Green Bay-Lake Michigan interface is open, only being separated by a series of islands (Bertrand et al., 1976). Four main channels connect through the islands (Fig. 1), three of which are at least 30 m deep and range from 2 to 7 km wide (Miller and Saylor, 1985).

Eleven tributaries flow into Green Bay (Bertrand et al., 1976). Of these, the Fox, Oconto, Peshtigo, Menominee, and Escanaba Rivers are the most important (Bertrand et al., 1976). The Fox River, which enters at the bay's south end, is the main source of pollution and nutrients to Green Bay, due to its highly industrialized lower basin and large surrounding areas of agriculture (Bertrand et al., 1976). A well-defined trophic gradient is observed, particularly within the first 10 km from the mouth of the Fox River, and has been well studied (Ahrnsbrak, 1971; Auer and Canale, 1986; Lathrop et al., 1990; Modlin and Beeton, 1970). The IJC designated a portion of Green Bay as an AOC due to its degraded water quality. This area consists of the inner bay stretching south to the De Pere Dam from Point au Sable in the east and Long Tail Point in the west (WDNR, 1993). The Remedial Action Plan indicated phosphorus load reductions as a high priority (WDNR, 1993).

Methods

Model framework

Green Bay can be generally treated as an elongated one-dimensional, vertically and laterally well-mixed embayment with an advective inlet from the Fox River and an advective/diffusive boundary condition with Lake Michigan. This type of system can be divided into a series of well-mixed volumes (Chapra and Dolan, 2012; Chapra and Sonzogni, 1979; Klump et al., 1997; Lesht et al., 1991). A mass balance for TP can be written generally for a given volume, *i*, as

$$V_i\frac{dc_i}{dt} = W_i + Q_{i-1,i}\left(\alpha_{i-1,i}c_{i-1} + \beta_{i-1,i}c_i\right) - Q_{i,i+1}\left(\alpha_{i,i+1}c_i + \beta_{i,i+1}c_{i+1}\right) + E'_{i-1,i}(c_{i-1} - c_i) + E'_{i,i+1}(c_{i+1} - c_i) - v_{s,i}A_{s,i}c_i \tag{1}$$

where the subscript i denotes the volume for which the mass balance is written, V = volume (km^3), c = concentration (mg/L for chloride or μgTP/L), t = time (yr), W = basin mass loading rate (kMTA $=10^3$ metric tonnes per annum for Cl and MTA = metric tonnes per annum for TP), Q = advective flow (km^3/yr), α and β = weighting coefficients where $\alpha = 1 - \beta$, E' = bulk horizontal mixing coefficient (km^3/yr), v_s = net apparent settling velocity (km/yr), and A_s = volume's bottom sediment surface area (km^2) across which TP is permanently lost from the system (Chapra and Dolan, 2012). Also note that by setting $v_s = 0$, Eq. (1) applies to any conservative substance such as Cl. Given the initial conditions, time-variable solutions for Eq. (1) can be generated numerically with a 4th-order Runge–Kutta method which tends to minimize the temporal component of numerical diffusion (Chapra, 2011).

The dimensionless weighting factors, α and β where $\beta = 1 - \alpha$, are used to approximate the concentration at the interface of the open boundary between given segments, *i*, by using linear interpolation as calculated by

$$\alpha_{i-1,i} = \frac{\Delta x_i}{\Delta x_{i-1} + \Delta x_i} \tag{2}$$

where Δx_i and Δx_{i-1} = the lengths (km) of the volumes of the segment and its upstream counterpart, respectively (Chapra and Reckhow, 1983). The spatial component of numerical diffusion is minimized by this approach, which centers the advective terms, creating a second-order accurate solution (Chapra, 1997).

The bulk horizontal mixing coefficient is related to more fundamental parameters by

$$E'_{i-1,i} = \frac{E_{i-1,i}A_{c,i-1,i}}{\ell_{i-1,i}} \tag{3}$$

where E = horizontal eddy diffusion coefficient (km^2/yr), A_c = interface cross-sectional area (km^2), and ℓ = mixing length (km) (Chapra, 1979).

The mixing length, ℓ, is defined as the length of the zone defining the gradient between adjacent volumes (Chapra, 1997). In the case of a continuous gradient, as occurs in Green Bay, the mixing length can be defined as the average of the lengths of adjacent volumes

$$\ell_{i-1,i} = \frac{\Delta x_{i-1} + \Delta x_i}{2}. \tag{4}$$

It is important to note that the application of this model is intended to predict the annual average concentrations and ignores short term phenomena (e.g. seiche effects) and seasonal variability. As a result, annual averages were used for the model parameters and mass loadings, consistent with previous studies (Chapra, 1977; Chapra and Sonzogni, 1979; Lesht et al., 1991; O'Connor and Mueller, 1970; Sonzogni et al., 1983).

Segmentation

Green Bay has been segmented along the major axis (Fig. 1) with segments corresponding to the Lower Green Bay AOC, previous models (Auer and Canale, 1986; Martin et al., 1995) and the locations of Green