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Use of flow-normalization to evaluate nutrient concentration and flux changes in Lake Champlain tributaries, 1990–2009

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ABSTRACT

The U.S. Geological Survey evaluated 20 years of total phosphorus (P) and total nitrogen (N) concentration data for 18 Lake Champlain tributaries using a new statistical method based on weighted regressions to estimate daily concentration and flux histories based on discharge, season, and trend as explanatory variables. The use of all the streamflow discharge values for a given date in the record, in a process called "flow-normalization", removed the year-to-year variation due to streamflow and generated a smooth time series from which trends were calculated. This approach to data analysis can be of great value to evaluations of the success of restoration efforts because it filters out the large random fluctuations in the flux that are due to the temporal variability in streamflow. Results for the full 20 years of record showed a mixture of upward and downward trends for concentrations and yields of P and N. When the record was broken into two 10-year periods, for many tributaries, the more recent period showed a reversal in N from upward to downward trends and a similar reversal or reduction in magnitude of upward trends for P. Some measures of P and N concentrations and yields appear to be related to intensity of agricultural activities, point-source loads of P, or population density. Total flow-normalized P flux aggregated from the monitored tributaries showed a decrease of 30 metric tons per year from 1991 to 2009, which is about 15% of the targeted reduction established by the operational management plan for the Lake Champlain Basin.

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Introduction

Nutrients in many streams in the United States and worldwide have increased throughout the 20th century as a result of increasing inputs from agricultural and urban sources (Dubrovsky et al., 2010; World Resources Institute, 2011). Elevated nutrient concentrations can lead to eutrophication or hypoxia of streams, lakes, and estuaries. Research generally attributes increasing nutrient concentrations to changes in climate (Park et al., 2010; Shrestha et al., 2011) or demographic factors including land-use alterations (Duh et al., 2008; Shi et al., 2010). Reducing nutrient loadings from wastewater treatment facilities and implementing BMPs that target specific types of land use are the typical means for mitigating excess nutrient enrichment in surface water (Bechmann et al., 2008; Dowd et al., 2008; Marsden and Mackay, 2001).

The Lake Champlain watershed in Vermont, New York, and Quebec is a 21,326 km^2 drainage area (Fig. 1) that has received attention in recent decades because parts of the Lake have become eutrophic with seasonal nuisance and potentially toxic algal blooms (Lake Champlain Steering Committee, 2003). Efforts to reduce phosphorus (P) began with the 1978 ban in Vermont on P in laundry detergents (Van Benschoten and Smeltzer, 1981), which had the goal of reducing the approximately 50% of estimated P load to Lake Champlain from point sources (Bogdan, 1978). By 2008, the contribution from point sources had been reduced to approximately 5% of the total load to the Lake, but challenging reductions in nonpoint sources have been much slower and algal blooms are still occurring (Lake Champlain Basin Program, 2011a). Efforts to reduce P inputs from point and nonpoint sources to the Lake are costly: approximately \$151 million for upgrades to wastewater-treatment facilities have been spent in Vermont, New York, and Quebec and about \$115 million have been spent within the two States on efforts to reduce P from nonpoint sources (Smeltzer et al., 2009). The P reduction goals for the Lake were established as numeric concentration criteria ranging from 0.010 to 0.025 mg/L for 13 lake segments in a 1993 Water Quality Agreement between New York, Quebec, and Vermont (Lake Champlain Phosphorus Management Task Force, 1993) and as a targeted basinwide load reduction of 192 mt/yr (Lake Champlain Management Conference, 1996) revised in 2003 to 202 mt/yr (Lake Champlain Steering Committee, 2003). It has been difficult to evaluate progress towards these reduction goals for the Lake (and for other important eutrophic water bodies such as Chesapeake Bay, the Gulf of Mexico, or the Great Lakes) because of the substantial

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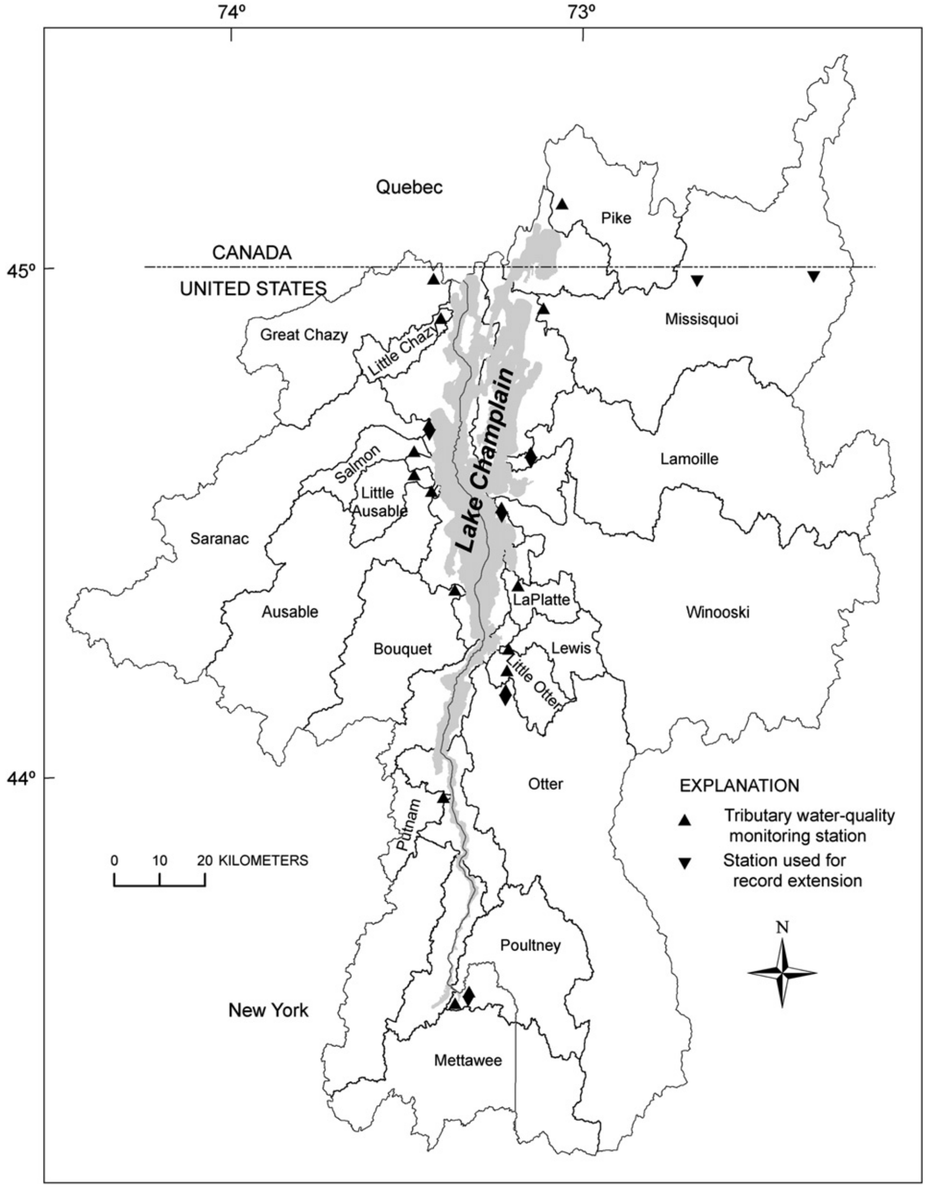

Fig. 1. Lake Champlain Basin showing tributary boundaries and streamgage and water-quality monitoring stations.

temporal variability in nutrient fluxes that are associated with the temporal variability in inflows. This new method of data analysis can be very useful in these kinds of evaluation efforts and is demonstrated here for Lake Champlain.

An extensive set of water-quality data have been collected since 1990 on 18 Lake Champlain tributaries by the Vermont Department of Environmental Conservation, New York State Department of Environmental Conservation long-term monitoring program (LTMP) for the primary purpose of detecting long-term environmental change in the Lake and its watershed (Vermont Department of Environmental Conservation and New York State Department of Environmental Conservation, 1998). These data have been collected using consistent methods in the field and the laboratory and provide a rich dataset for assessing progress towards meeting P reduction goals. Accompanying streamflow data have been collected by the US Geological Survey and Quebec Ministry of the Environment from all 18 tributaries.

Time-series plots of individual or averaged observed concentrations and loads are a typical initial step for analysis of water-quality data. However, plotting raw data does not provide a comprehensive assessment of the effectiveness of policies and remedial actions aimed at reducing P because the interpretation of chemical data for lotic water is confounded by climate-driven streamflow quantities. Chemical concentrations and loads that are mathematically adjusted to remove the effect of streamflow are less variable than unadjusted values and have increased power to detect trends. The ability to "filter out" the influence of wet and dry years has been one of the greatest impediments to meaningful analysis of water quality trends. To assess the progress of control measures in a watershed, the analyst must be able to separate out changes resulting from deliberate policy actions and changes brought about by random variations in flow conditions driven by the weather (Sprague et al., 2011).

A number of statistical methods have been developed that provide some kind of flow adjustment to concentration data for the purpose of identifying long-term trends (Alley, 1988; Harned et al., 1981; Hirsch et al., 1991). Conventional methods to evaluate trends in long-term water-quality datasets have provided information on the magnitude and direction or absence of trend, but impose methodological constraints on the analysis, such as requiring the same form of concentration-discharge relationship over the entire period of record and fitting a single linear or quadratic time-trend model over

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