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Physicochemical characteristics of a southern Lake Michigan river plume

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ABSTRACT

Riverine inputs are a major source of nutrients to the Laurentian Great Lakes and have important effects on nearshore biological processes, where mixing between river and lake water leads to formation of heterogeneous river plumes. We examined the physical and chemical characteristics of the St. Joseph River plume in southern Lake Michigan between May and October 2011, and in October 2012, June 2013 and April 2014. Specific electric conductivity and stable isotopes of water were used to quantify the fraction of river water (FRW) at sampling sites in Lake Michigan. Both tracers predicted similar patterns of FRW among sites; however, there was a systematic offset between the two methods, and specific electric conductivity method under-predicted the FRW by ~5%. We observed a distinct, seasonally varying river plume, with plume size correlated with flow rate of St. Joseph River. Within the plume, sediments and nutrients were non-conservative and exhibited significant and seasonally varying losses that we attribute to settling of particle-bound nutrients and/or nutrients in particulate phase below the plume. The characteristics and the spatiotemporal heterogeneity of the river plume documented here may have important implications for the nearshore biogeochemistry of the Great Lakes and for understanding the roles of these features in ecological processes in nearshore areas.

Introduction

Rivers and streams are a major source of nutrients and sediment to the Laurentian Great Lakes and many other large lacustrine systems. The mixing of river water with lake water results in the formation of river plumes, which are heterogeneous environments relatively enriched in nutrients and suspended sediments compared to the lake. Similar to oceanic river plumes, which are highly productive, act as a sink for sediments and pollutants, and have important ecological effects (Grimes, 2001; Grimes and Finucane, 1991; Peterson, 2003), freshwater river plumes can also be zones of high productivity and planktonic concentration (Johengen et al., 2008; Lohrenz et al., 2004; Vanderploeg et al., 2007) offering survival and growth advantages to many different fish species (Grimes and Kingsford, 1996; Jude and Pappas, 1992). Freshwater plumes have also been shown to play an important role in biogeochemical cycling of nutrients (Hecky et al., 2004; Howell et al., 2012; Morrice et al., 2004, 2009; Steinman et al., 2009).

Lacking the salinity gradients of their oceanic counterparts, freshwater plumes are generally characterized by distinct chemical and thermal properties, with potential implications for the physiochemical and biochemical processes occurring within the plumes (Stephens and Minor, 2010). Unlike oceanic plumes, which have been examined from ecological, chemical and physical perspectives in great detail, relatively few studies have examined freshwater plumes and river mouth zones within the Great Lakes (Larson et al., 2013, 2016; Marko et al., 2013; Tan et al., 2016). In their recent review, Larson et al. (2013) highlighted several critical knowledge gaps related to the understanding of these systems, including a lack of understanding of the impact of these zones on lake ecosystems.

Accurate delineation of freshwater plumes are challenging due to lack of salinity gradient between the mixing waters. Due to their conservative behavior, stable isotopes of water (SIW) and specific electric conductivity (SEC) have previously been used to quantify mixing between different freshwater sources (Klaus and McDonnell, 2013; Laudon and Slaymaker, 1997; Matsubayashi et al., 1993; McDonnell et al., 1991) and show potential promise for characterizing freshwater river plumes. In general, they are thought to provide robust and accurate estimates of the relative contribution of sources. However, few studies have used

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both tracers in combination or directly compared the results they produce. In many systems, river and lake water have distinct isotope ratios ($\delta^{18}O$ and δ^2H) and SEC due to differences in the residence time of water and dissolved ion concentrations in these systems. Here, we use such differences to estimate fractional contributions of lake and river water at one river mouth in Lake Michigan and compare results obtained with the two tracer types to inform their future application in freshwater plume studies.

River plumes may form an active interaction zone between nutrient and sediment rich (river) and poor (lake) environments. Within plumes, riverine inputs are transformed by biogeochemical processes (Krieger et al., 1992; Morrice et al., 2004), buried by sedimentation, or remobilized (e.g., through storm-induced resuspension). These active interactions in turn affect lake biogeochemical cycles and ecosystems and, in general, are not well understood for the Great Lakes (Larson et al., 2013). To improve our understanding for one such system within Lake Michigan we determined the fate of nutrients and sediments in the St. Joseph River plume by comparing the observed concentrations with those expected assuming conservative mixing between lake and river water. We characterized nutrient transport to and through the plume environment, to identify processes that may govern the fate of nutrients delivered to the plumes and their ultimate influence on near-shore lake ecological processes.

Methods

Watershed characteristics

The St. Joseph River has a catchment area of >12,000 km^2 and an annual average discharge of 97 m^3/s (USGS streamflow-gaging station 014101500 at Niles, Michigan). The watershed is home to >1.5 million people living in 15 counties that span the watershed. St. Joseph River is the third largest rivers flowing into Lake Michigan. Excluding the water category, land use in the watershed, is dominated by agriculture (69%), followed by developed (20%) and forest (11%, source: 2006 National land cover database), while bedrock is composed mainly of siliciclastic rocks (shale and sandstone).

Site description and sampling protocol

The St. Joseph River – Lake Michigan system (SJS) was sampled 1–3 times per month from May 2011 to October 2011 during non-windy and calm days between 10 AM to 6 PM (see Electronic Supplementary Material (ESM) Table S1 for wind velocity and direction during sampling events). The sampling scheme for each survey included six sites, one site near the mouth of the river and five sites in the lake near the river mouth. The lake sites were symmetrically distributed; with 1 site situated directly offshore of the river mouth (~ 1 km from the river site) and 2 pairs of sites to the right and left of the river mouth (positioned ~500 m and 1000 m alongshore from the river mouth along the ~10 m depth contour, Fig. 1). Subsequently, the river mouth site will be referred as the "river" site and the sites in the lake will be referred as "open water" sites.

The sampling protocol at each site included measuring SEC, temperature (T) and dissolved oxygen (DO) for the entire water column. We also measured transparency with a Secchi disk at each site. In addition, depth integrated water samples were collected from the top 1 m of the water column using a rigid tube sampler, then transferred to a 5 L Nalgene bottles and immediately stored on ice. Water samples were later analyzed in the lab for their stable isotopic composition ($\delta^{18}O$ and δ^2H), total phosphorus (TP), soluble reactive phosphorus (SRP), total nitrogen (TN), total suspended solids (TSS) and chlorophyll a using protocols specified below. All parameters were measured on most samples, but on a few occasions, some sites were not sampled at all or were sampled incompletely due to logistical constraints.

Targeted plume surveys

In addition to the temporal sampling described above, we also conducted extensive spatial sampling in October 2012, June 2013 and April 2014 to map the extent of the plume in detail under contrasting seasonal conditions. We sampled 22 sites in October 2012 (fall), 30 sites in June 2013 (summer) and 35 sites in April 2014 (spring). The number of sites sampled and spatial pattern of the surveys was determined by visual observation at the time of sampling to provide

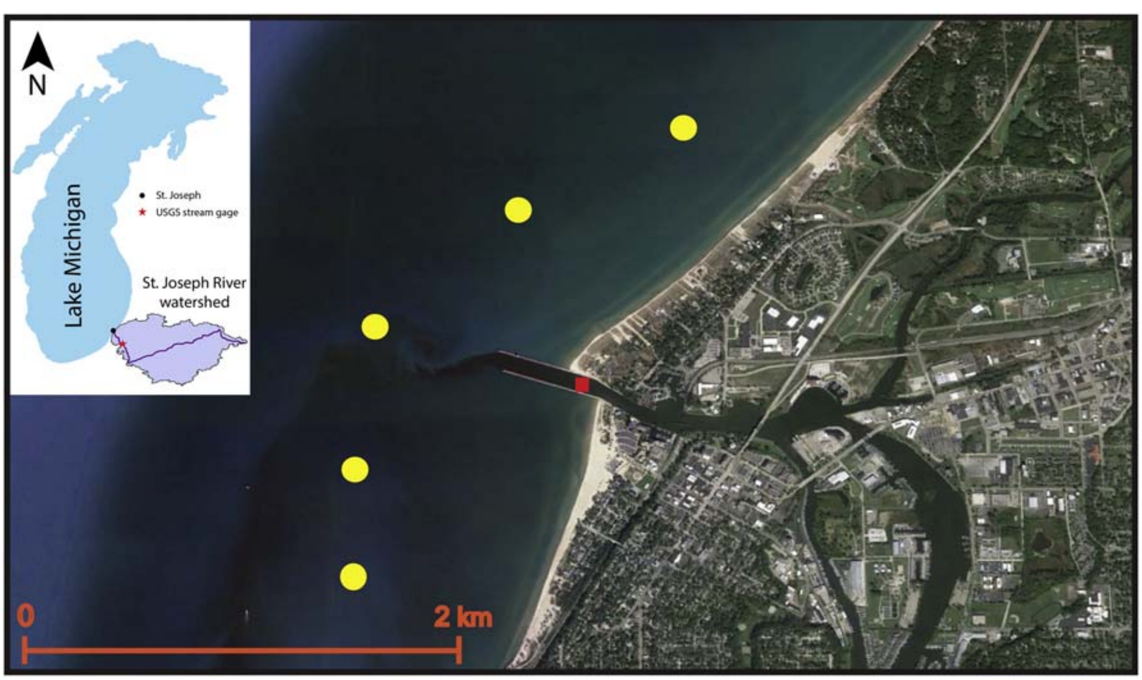

Fig. 1. St. Joseph river mouth zone, showing the location of open water (yellow circle) and river (red square) sites sampled in the lake and the river during the 2011 surveys (Map data: Google Earth). Inset: Map showing approximate location of St. Joseph River within Lake Michigan. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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