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Multi-faceted monitoring of estuarine turbidity and particulate matter provenance: Case study from Salem Harbor, USA

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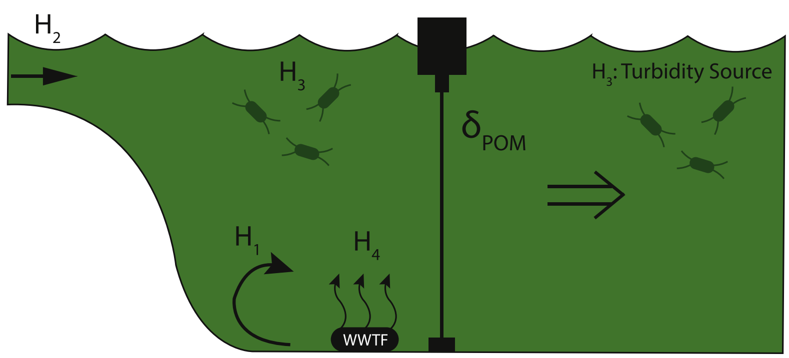
HIGHLIGHTS

- Estuarine turbidity examined through monitoring buoys and stable isotopes
- Provenance of particulates is complex and varies by location and time
- Weight of evidence reveals phytoplankton as dominant turbidity source
- Sediment resuspension and allochthonous input contribute to mixed suspended load
- Combined buoy, isotope, and meteorological approach robust for turbidity studies

GRAPHICAL ABSTRACT



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ABSTRACT

Turbidity is a water quality parameter that is known to adversely affect aquatic systems, however the causes of turbid water are often elusive. We present results of a study designed to constrain the source of particulate matter in a coastal embayment that has suffered from increased turbidity over past decades. Our approach utilized monitoring buoys to quantify turbidity at high temporal resolution complemented by geochemical isotope analysis of suspended sediment samples and meteorological data. Results reveal a complex system in which multiple sources are associated with particulate matter. Weight of evidence demonstrates that phytoplankton productivity in the water column, however, is the dominant source of particulate matter associated with elevated turbidity in Salem Harbor, Massachusetts. Allochthonous matter from the watershed was observed to mix into the pool of suspended particulate matter near river mouths, especially in spring and summer. Resuspension of harbor surface sediments likely provides additional particulates in the regions of boat moorings, especially during summer when recreational boats are attached to moorings. Our approach allows us to constrain the causes of turbidity events in this embayment, is helping with conservation efforts of environmental quality in the region, and can be used as a template for other locations.

1. Introduction

Turbidity, which is an optical property that quantifies light transmission though the water column, is a key water quality parameter due to its direct influence on the photosynthetic compensation depth. Specific

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ecologic effects of high turbidity, and associated suspended particulate matter, include light limitation of submerged aquatic vegetation such as eelgrass (Dennison et al., 1993; Moore et al., 1997; Nielsen et al., 2002; Olesen, 1996) and the associated reduced dissolved oxygen; increases in water temperature as particles suspended absorb and scatter sunlight (Paaijmans et al., 2008); various effects on pelagic and benthic invertebrates associated with clogging of filtration systems, burial, and substrate alteration (Wilber and Clarke, 2001; Zweig and Rabeni, 2001); and effects on fish through gill clogging and associated reduced resistance to disease, and stress to migrating, spawning, and developing fish eggs and larvae (Newcombe, 2003; Newcombe and Jensen, 1996; Wilber and Clarke, 2001).

A number of studies have identified major causal factors that may contribute to elevated turbidities in coastal waters. Elevated turbidities are frequently attributable to resuspension of bottom sediments (Koch, 2001; Newell and Koch, 2004). Resuspension may occur by a number of mechanisms such as heavy wind, tidal currents, precipitation, and storm events over the water surface (Davis et al., 2004; Mitchell et al., 2003; Ogston et al., 2000; Uncles and Stephens, 1993), and the persistent shift of boat moorings (Hastings et al., 1995; Walker et al., 1989). Moreover, turbidity may also result from the suspension of allochthonous material flushed in from the watershed via storm water runoff and elevated stream discharges (Berto et al., 2013; Dalzell et al., 2005). Finally, numerous studies have found that elevated turbidities in coastal waters indirectly result from chronic nitrogen eutrophication, which leads to phytoplankton blooms that block light transmission through the water column (e.g. Cederwall and Elmgren, 1990; Kemp et al., 1983; Lapointe and Clark, 1992; Nixon, 1995). In order to address elevated turbidities in coastal systems, it is important to tease out the balance of different mechanisms that are forcing turbidity dynamics in a given system (Chen et al., 2005; Mitchell et al., 2003; Uncles and Stephens, 1993).

Turbidity has become a water quality parameter of concern in Salem Sound, Massachusetts (USA) over recent decades. This concern has led to funding from Massachusetts state agencies with the applied goal of constraining the dominant source of particulate matter in the coastal embayment so that a remediation strategy can be developed. Of note, *Zostera marina*, a species of submerged aquatic vegetation known for its importance in ecosystem services (Kemp et al., 2004; Heck et al., 1995), has experienced the largest decline in Salem Sound of any coastal region in Massachusetts since 1995 (Costello and Kenworthy, 2011). Over this time turbidity at the harbor mouth has increased, with Secchi depth measurements declining from 3.5 m in 1997 (Chase et al., 2002) to 3.2 m in 2010 - 2011 (unpublished data). Further, a station within inner Salem Harbor had an average Secchi depth value of 2.5 m in 2010–2011, demonstrating comparatively high turbidity within the inner harbor. Although not definitive, the connection in timing between turbidity increases and eelgrass declines warrant the further study of turbidity in Salem Harbor.

Various tools have been used by coastal oceanographers to determine the origin of particles that lead to turbid conditions in coastal embayments. Continuous turbidity sensors, automated sensors, and remotely sensed data have had success in generating time series of turbid conditions in various systems (Glasgow et al., 2004; Mitchell et al., 2003), however information on suspended particulate matter (SPM) provenance is often desired. Numerous studies have studied the role of nutrients and phytoplankton in coastal turbidity zones to better understand spatio-temporal dynamics of this potential driver for turbid conditions (Bužancic et al., in press; Carstensen et al., 2015; Llebot et al., 2011; Lugoli et al., 2012; Meler et al., 2016; Reed et al., 2016). In addition, modeling efforts have been used to better constrain forcings on phytoplankton for a particular system (Artigas et al., 2014). Although SPM consists of a mixture of organic and mineral particles, quantifiable proxies of the particulate organic matter (POM) fraction of the SPM has yielded robust constraints on the provenance of the particulates. Successful approaches have included the study of particulate organic carbon (POC) and nitrogen from elemental (Etcheber et al., 2007; Veyssy et al., 1999) and isotopic (Berto et al., 2013; Savoye et al., 2003) perspectives.

The objective of this study is to utilize a multi-faceted approach to constrain the causes of turbid estuarine conditions using monitoring buoys, stable isotopic analyses of SPM, and meteorological data. Specifically we addressed the causes of increased turbidity in Salem Harbor, an urban mesotidal coastal embayment north of Boston, Massachusetts, USA. As compared to more sophisticated automated sensors and remotely sensed data (e.g. Glasgow et al., 2004), this approach did not have large start up and maintenance costs, and it directly addressed the provenance of particulate matter in the water column.

The four hypotheses examined in this study are:

1. Elevated turbidities are associated with resuspension of seafloor surface sediments, caused by either a) shift in mooring chain position on the seafloor as wind events consisting of high velocities and shifts of prevailing direction occur, or b) tidal currents.
2. Elevated turbidities are caused by precipitation events and associated increases in storm water runoff and stream discharge, both of which transport allochthonous matter to the water body.
3. Elevated turbidities are caused by phytoplankton blooms.
4. Elevated turbidities are caused directly by turbid sewage effluent from a local wastewater treatment facility's (WWTF) discharge pipe.

2. Methods

2.1. Project Location

Salem Sound (Fig. 1) is a vertically mixed drowned river estuary with semi-diurnal tides (2.75 m range). It is approximately 24 km northeast of Boston, MA, is relatively large (35.6 km^2) and shallow

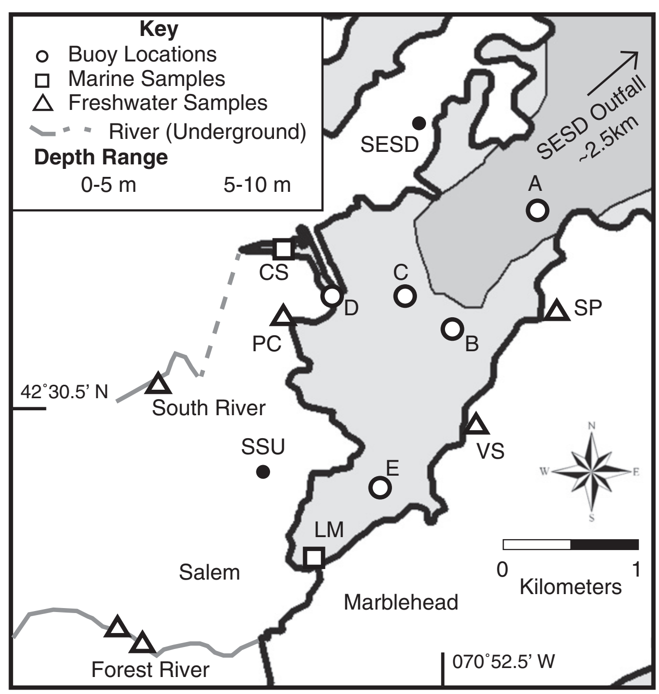

Fig. 1. Map of Salem Harbor with sampling locations noted (see Table 1 for location details). Buoy locations include control site (A), mooring sites (B and C), and river mouth sites (D and E). Marine samples were taken at buoy locations as well as at shoreline locations Congress Street (CS) and Lead Mills (LM). Freshwater river samples were from Forest ($n = 2$) and South Rivers and storm water outfalls at Palmer Cove (PC), Village Street (VS), and Stramski Park (SP). South Essex Sewerage District (SESD) effluent was sampled directly at the plant as labeled in the figure, and the effluent outfall pipe is located ~2.5 km northeast of Salem Harbor. Weather data recorded at Salem State University (SSU).