Estuarine, Coastal and Shelf Science 212 (2018) 11–22

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

journal homepage: www.elsevier.com/locate/ecss

Four decades of water quality change in the upper San Francisco Estuary

Marcus W. Beck[a,*], Thomas W. Jabusch[b], Philip R. Trowbridge[c], David B. Senn[c]

[a] Southern California Coastal Water Research Project, 3535 Harbor Blvd, Suite 110, Costa Mesa, CA, 92626, USA
[b] Sacramenta-San Joaquin Delta Conservancy, 1450 Halyard Drive, Suite 6, West Sacramento, CA, 95691, USA
[c] San Francisco Estuary Institute, 4911 Central Ave, Richmond, CA, 94804, USA

ARTICLE INFO

Keywords:
Estuary
Nitrogen
Sacramento - San Joaquin delta
Trend analysis
Weighted regression

ABSTRACT

Quantitative descriptions of chemical, physical, and biological characteristics of estuaries are critical for developing an ecological understanding of drivers of change. Historical trends and relationships between key species of dissolved inorganic nitrogen (ammonium, nitrate/nitrite, total) from the Delta region of the San Francisco Estuary were modelled with an estuarine adaptation of the Weighted Regressions on Time, Discharge, and Season (WRTDS). Analysis of flow-normalized data revealed trends that were different from those in the observed time-series. Flow-normalized data exhibited changes in magnitude and even reversal of trends relative to the observed data. Modelled trends demonstrated that nutrient concentrations were on average higher in the last twenty years relative to the earlier periods of observation, although concentrations have been slowly declining since the mid-1990s and early 2000s. We further describe mechanisms of change with two case studies that evaluated 1) downstream changes in nitrogen following upgrades at a wastewater treatment plant, and 2) interactions between biological invaders, chlorophyll, macro-nutrients (nitrogen and silica), and flow in Suisun Bay. WRTDS results for ammonium trends showed a distinct signal as a result of upstream wastewater treatment plant upgrades, with specific reductions observed in the winter months during low-flow conditions. Results for Suisun Bay showed that chlorophyll *a* production in early years was directly stimulated by flow, whereas the relationship with flow in later years was indirect and influenced by grazing pressure. Although these trends and potential causes of change have been described in the literature, results from WRTDS provided an approach to test alternative hypotheses of spatiotemporal drivers of nutrient dynamics in the Delta.

1. Introduction

Understanding drivers of water quality change in estuaries depends on accurate descriptions of source inputs. The Sacramento - San Joaquin River Delta (hereafter ‘Delta’) is a mosaic of inflows in the upper San Francisco Estuary (SFE) that receives and processes nutrient inputs from primarily urban sources, in addition to agricultural sources (Jassby and Cloern, 2000; Jassby et al., 2002; Jassby, 2008). Although water quality conditions in the SFE symptomatic of eutrophication have historically been infrequent, recent responses to stressors suggests that ecosystem condition may be changing from past norms. Changes in phytoplankton biomass and composition, water clarity changes from sediment alteration, increases in harmful cyanobacterial blooms (*Microcystis aeruginosa*), increases in non-native macrophytes, and periodic events of low dissolved oxygen have been a recent concern for management of the Delta (Lehman et al., 2005; Santos et al., 2009; Hestir et al., 2013; Lehman et al., 2015; Dahm et al., 2016; ASC, 2017). Although these changes are linked to drivers at different spatial and temporal scales, describing inputs from the Delta is critical to understand downstream effects.

Rates of primary production in coastal habitats are often defined by nutrient concentrations, although a simple relationship between enrichment and water quality changes can be difficult to determine (Cloern, 2001). Nutrient concentrations are generally non-limiting for phytoplankton growth in the upper SFE, whereas light availability is the primary limiting factor preventing accumulation of phytoplankton biomass (Cole and Cloern, 1984; Alpine and Cloern, 1988). Grazing pressure from pelagic fishes and benthic invertebrates can also reduce phytoplankton during periods of growth (Nichols, 1985; Jassby, 2008; Kimmerer and Thompson, 2014). Moreover, changes in flow management practices compounded with climate variation have altered flushing rates and turbidity as key factors that moderate phytoplankton growth in the system (Alpine and Cloern, 1992; Lehman, 2000; Wright and Schoellhamer, 2004; Canuel et al., 2009). Glibert et al. (2014) attributed recent phytoplankton blooms in Suisun Bay to a drought, during which residence times and nitrification rates increased.

* Corresponding author.
E-mail address: marcusb@sccwrp.org (M.W. Beck).

https://doi.org/10.1016/j.ecss.2018.06.021
Received 3 February 2018; Received in revised form 4 May 2018; Accepted 19 June 2018
Available online 25 June 2018

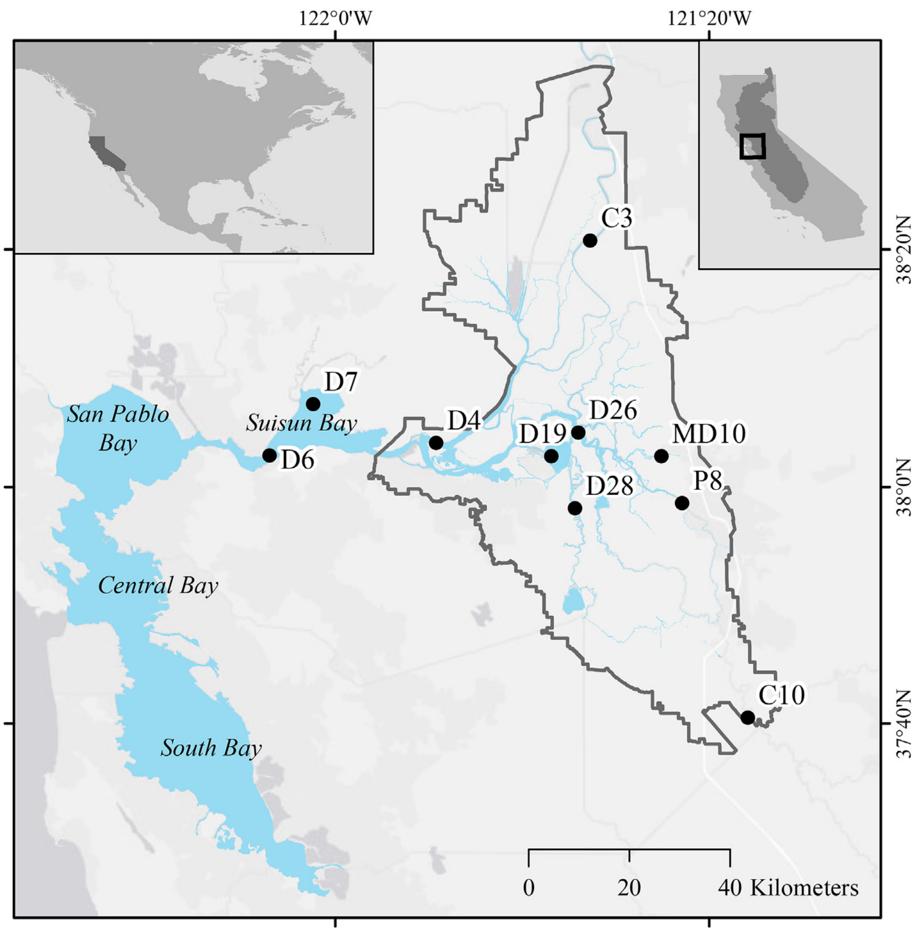

Fig. 1. The San Francisco Estuary and Delta region with monitoring stations used for analysis. The Delta drains the combined watersheds of the Sacramento and San Joaquin rivers (dark grey region in top right inset). The grey outline is the legal boundary of the Delta. All data were obtained from the Interagency Ecological Program website (http://water.ca.gov/bdma/meta/Discrete/data.cfm, IEP (2013)). See tab:stdescrp for station descriptions.

Speciation changes in the dominant forms of nitrogen confound a direct interpretation of links with phytoplankton blooms and the relationships between nutrients and primary production in the upper estuary are not completely understood. Although phytoplankton concentrations have been relatively consistent in recent years in Suisun Bay, biomass trends in the Delta are mixed (Jassby, 2008; ASC, 2017). Descriptions of nitrogen trends over several decades could be used to better understand long-term and more recent changes, particularly in the context of primary production and physical drivers of change (Dahm et al., 2016).

Long-term monitoring data are powerful sources of information that can facilitate descriptions of water quality change. A comprehensive water quality monitoring program has been in place in the upper SFE for several decades (Fig. 1, IEP, 2013). Although these data have been used extensively (e.g., Lehman, 1992; Jassby, 2008; Glibert, 2010), water quality trends covering the full spatial and temporal coverage of the Delta have not been systematically evaluated. Quantitative descriptions of nutrient dynamics are challenging given multiple sources and the volume of water that is exchanged with natural and anthropogenic processes. An evaluation using mass-balance models to describe nutrient dynamics in the Delta demonstrated that the majority of ammonium entering the system during the summer is nitrified or assimilated, whereas a considerable percentage of total nitrogen load to the Delta is exported (Novick et al., 2015). Seasonal and annual changes in the delivery of water inflows and water exports directly from the system can also obscure trends (Jassby and Cloern, 2000; Jassby, 2008). It is important to consider these variable effects to characterize different trends in nitrogen forms.

Formal methods for trend analysis are required to describe water quality changes that vary by space and time. As a practical approach for water quality evaluation, trend analysis of ecosystem response indicators often focuses on tracking the change in concentrations or loads of nutrients over many years. Response indicators can vary naturally with changing flow conditions and may also reflect long-term effects of management or policy changes. Similarly, nutrient trends that vary with hydrologic loading can vary as a function of utilization rates by primary producers or decomposition processes (Sakamoto and Tanaka, 1989; Schultz and Urban, 2008; Harding et al., 2016). Concentration of chlorophyll *a* (chl-*a*) as a measure of phytoplankton response to nutrient inputs can follow seasonal patterns with cyclical variation in temperature and light changes throughout each year, whereas annual trends can follow long-term variation in nutrient inputs to the system (Cloern, 1996; Cloern and Jassby, 2010). Describing the relationship of a water quality variable as changing (chemodynamic) or invariant (chemostatic) with flow can isolate components, such as nutrient inputs, for a more direct assessment of causal factors (Wan et al., 2017).

The Weighted Regressions on Time, Discharge, and Season (WRTDS) approach was developed in this context and has been used to characterize decadal trends in river systems (Hirsch et al., 2010; Sprague et al., 2011; Medalie et al., 2012; Hirsch and De Cicco, 2014; Pellerin et al., 2014; Zhang et al., 2016). The WRTDS method has more recently been adapted for trend analysis in tidal waters, with a limited focus on chl-*a* trends in Tampa Bay (Beck and Hagy III, 2015) and the Patuxent River Estuary (Beck and Murphy, 2017). Although the WRTDS method has been effectively applied to describe changes in freshwater systems, use in tidally influenced systems has not been as extensive. Application of WRTDS to describe trends in estuaries could reveal new insights given the disproportionate effects of physical drivers, such as flow inputs and tidal exchange, on water quality. The effects of biological drivers may also be more apparent because hydrological effects can be removed by WRTDS. As such, application of WRTDS models for trend analysis could facilitate a broader discussion on the need to focus beyond nutrients to develop integrated plans for water quality