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Changes in water quality following opening and closure of a bar-built estuary (Pescadero, California)

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ABSTRACT

Bar-built estuaries are coastal environments characterized by the partial closure of the estuary's mouth with a sandbar barrier for extended periods (closed state). Through natural events (rainfall) or anthropogenic influences, the sandbar is breached, reopening the estuary to the ocean. The transition from closed to open state often leads to extensive physical and chemical changes in the estuarine conditions, as water mixing and sediment resuspension are increased, which could result in the oxidation of sediment acid-volatile sulfides (AVS). We followed monthly changes in water's and sediment geochemical characteristics at thirty-two sites spanning the Pescadero Estuary over a one-year period. We showed that the transition from closed to open state leads to significant decreases in aqueous pH to circumneutral values and significant increases in aqueous hydrogen sulfide and iron concentrations to 10.6 μM and 59.1 μM, respectively, due to sediment AVS oxidation following sediment resuspension. Aqueous hydrogen sulfide concentrations observed in both closed and open states were significantly higher than the recommended thresholds for aquatic life. Moreover, mildly acidic water conditions in the open state were lower than the recommended limits for aquatic life. Our spatial analysis further highlighted that some parts of the estuary were more vulnerable to decreased water quality. Indeed, high sediment AVS contents (19–24 mmol kg^{-1}) were observed year-round at the River Confluence and Butano Creek regions, which implies a high potential for severe water acidification and metal release when the estuary transitions from closed to open state.

1. Introduction

Bar-built estuaries, also called temporarily open/closed estuaries (TOCEs), are dynamic coastal environments located between marine and freshwater sources (Chapman and Wang, 2001; Hu et al., 2004). Unlike permanently open estuaries that are connected to the ocean all year long, bar-built estuaries experience a closed state, in which they are separated from the ocean for extended periods by a sandbar barrier. Through high rainfall and wave events or artificial means to restore connectivity, the sandbar is breached, leading to the open state (Becker et al., 2009). TOCEs are ubiquitous, representing about 18% of the North American coastline (Barnes, 1980), 45–50% of estuaries in southern Australia (Griffiths and West, 1999; Roy et al., 2001), and 70% of estuaries in South Africa (Whitfield et al., 2012; Whitfield et al., 2008).

In recent decades, fish mortalities have been observed in bar-built estuaries around the world (Becker et al., 2009; Sloan, 2006; Whitfield, 2005; Whitfield et al., 2008; Wong et al., 2010), with many directly linked to biogeochemical (e.g., deoxygenation) events spared by physical (e.g., rainfall and flooding) events. Regular fish and invertebrate kills have occurred in several of California's bar-built estuaries, including the Pescadero Estuary (Largier et al., 2015; Sloan, 2006), Rodeo Lagoon (Martin et al., 2007), and San Gregorio Lagoon (Atkinson, 2010), where imperiled salmonid fish have been among the killed organisms (Sloan, 2006). Fish mortalities are often associated with the transition from closed to open state, and their extents are positively correlated with the length of the closed state, as observed in California (Sloan, 2006; Smith, 2009) and in Australia (Becker et al., 2009; Gladstone et al., 2006; Whitfield et al., 2008).

Fish kills are repeatedly linked to hypoxia and/or anoxia (< 5 mg L^{-1} dissolved oxygen), high hydrogen sulfide concentrations (> 50 μM), acidification (pH < 6.5), increased nutrient loadings, and elevated dissolved metal concentrations in estuarine waters (Bagarinao and Lantin-Olaguer, 1998; Becker et al., 2009; Luther et al., 2004; Thronson and Quigg, 2008; Wong et al., 2010). Hydrogen sulfide influences water and sediment conditions in three ways, acting as a (1) direct toxic pollutant, (2) detoxification agent *via* metal precipitation, and (3) indirect agent of deoxygenation, acidification, and metal

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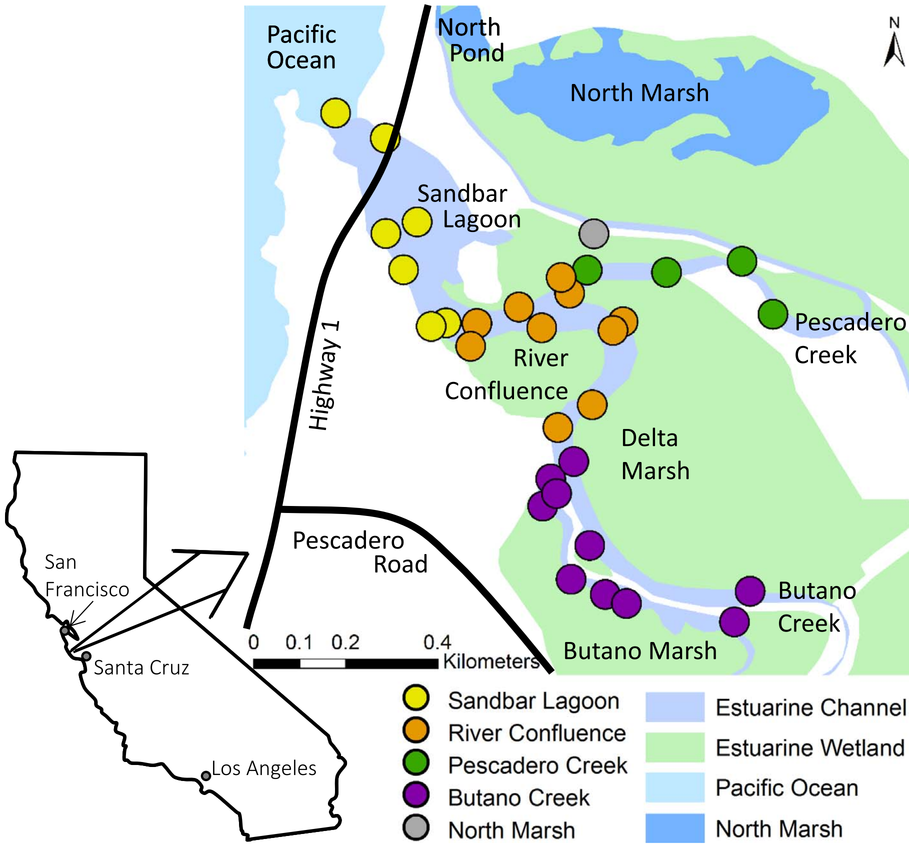

Fig. 1. Location of the Pescadero Estuary in California and of the thirty-two littoral sites sampled for water and sediment in 2014–2015. With the exception of the site adjacent to the North Marsh (gray), sites were separated into four segments, as represented by the Sandbar Lagoon sites (yellow), the River Confluence sites (orange), the Pescadero Creek sites (green), and the Butano Creek sites (purple). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

dissolution upon oxidation (Chapman and Wang, 2001). Water temperature is also a major contributor to habitat quality for estuarine species, in which higher values (> 22 °C) result in lower dissolved oxygen (DO) concentrations (< 9 mg L^{-1}) (Wong et al., 2010), therefore indirectly affecting fish survival. In addition to poor geochemical conditions in water, kills in Australian waters may also be attributed to suspended or fine particles that clog fish gills (Whitfield, 2005).

Among the California TOCEs affected by fish mortality events, Pescadero Estuary (Fig. 1) has been afflicted by reoccurring, near-annual kill events of federally-endangered steelhead trout since 1995, occurring in the transition from closed to open state (Sloan, 2006). Although not unique to the Pescadero Estuary or to California, these kill events have been more regular in Pescadero than in nearby estuaries on the California Coast. Recent studies on the physical, biological, and geochemical interactions in the Pescadero Estuary have focused on understanding its hydrodynamic interactions (Williams and Stacey, 2015), sediment geomorphology (Clarke et al., 2014), and geochemistry, with a focus on arsenic (Bostick et al., 2004) and sulfur cycling (Richards and Pallud, 2016). DO concentrations throughout the main Pescadero channels range from normoxic (> 5 mg L^{-1}) to hypoxic (3–5 mg L^{-1}) and anoxic (< 3 mg L^{-1}) levels, with higher values near the air/water interface (Jankovitz, 2014). Furthermore, aqueous hydrogen sulfide concentrations range up to 45 μM, and water pH values are mildly acidic to moderately alkaline in the main channels of the estuary (Jankovitz, 2015; Jankovitz, 2014; Richards and Pallud, 2016). Sediments in the Pescadero Estuary have a high potential for the production of metal sulfides under reducing conditions (Richards and Pallud, 2016). The disturbance of such sulfide-rich sediments can occur with natural precipitation and flood events (Sammut et al., 1996; Wilson et al., 1999) or anthropogenic influences (dredging, manual reopening) (Powell and Martens, 2005). Suggested to drive fish kills at Pescadero (Largier et al., 2015; Sloan, 2006), these disturbances can induce sulfide mobilization from sediment to water, re-oxidation, and dissolution (Powell and Martens, 2005; Wong et al., 2010), potentially leading to deoxygenation, acidification, and metal toxification of estuarine waters, as observed in other coastal and floodplain sediments (Burton et al., 2006a; Eyre et al., 2006; Wong et al., 2010).

This study investigates the monthly evolution in water and sediment geochemical conditions over a one year period in thirty-two littoral sites spanning the bar-built Pescadero Estuary. Our results illustrate that the transition from closed to open state is the critical step leading to poor water conditions, specifically decreased pH and increased aqueous hydrogen sulfide and iron concentrations. These results also show that the River Confluence and Butano Creek regions are chemically more unstable than other parts of the estuary due to higher AVS contents that render them highly susceptible to worsening conditions in the open state.

2. Material and methods

2.1. Field site

The Pescadero Estuary is a macrotidal and intertidal bar-built estuary located along the Pacific Coast in California, USA (Fig. 1). The Mediterranean hydroclimate at Pescadero is characterized by an mean annual rainfall of 73.5 cm with a pronounced colder wet season extending from November to April and warmer dry season from May to October (U.S. Climate Data, 2016). The source of the Pescadero Estuary freshwater derives from its two tributaries, the Pescadero Creek and the Butano Creek (Fig. 1) through stream inflow rates of 0.34 $m^3 s^{-1}$ and 0.17 $m^3 s^{-1}$, respectively (Sloan, 2006). The water column is shallow (< 3 m) at high tide and salinity-stratified (Williams and Stacey, 2015). Pescadero sediment encompasses a variety of textures ranging from silt loams to sandy loams (Richards and Pallud, 2016).

Pescadero is closed for 3 to 10 months per year, beginning in spring or summer months and has opened up to four times per year since 1985,