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Optimizing recovery of eutrophic estuaries: Impact of destratification and re-aeration on nutrient and dissolved oxygen dynamics

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A R T I C L E I N F O

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A B S T R A C T

Widespread and global efforts to improve degraded coastal ecosystems, especially those experiencing hypoxia, warrant a renewed focus on understanding and quantifying restoration trajectories. We describe a whole-ecosystem experiment to manipulate dissolved oxygen concentrations using large-scale destratification aeration that was used to document the biogeochemical response of a small estuary to changes in oxygen availability. The experiment was successful in creating oxic and anoxic bottom water conditions at a spatial scale much larger than that encompassed by the aerators. After a period of anoxic conditions, the return of oxygenated bottom water by destratification resulted in rapid decreases in sediment phosphate fluxes, uptake of nitrate and nitrite, and an increase in simulated denitrification rates. Bottom water nutrient concentrations responded near-simultaneously to these changes to benthic–pelagic fluxes. The rapidity with which the ecosystem responded to increases in bottom water oxygen confirms the critical role of dissolved oxygen concentrations in modulating nutrient cycling. This result also provides insight into the likely response of hypoxic and anoxic estuaries to remediation of oxygen deficits at the sediment–water interface.

1. Introduction

Hypoxia and anoxia (defined here as dissolved oxygen concentrations less than 63 μM and 16 μM, respectively) are widespread consequences of eutrophication in coastal areas, and can frequently be linked to nutrient loading from anthropogenic sources (Diaz and Rosenberg, 2008; Zhang et al., 2010). Much of restoration science in these ecosystems has hinged on the paradigm that reduced nutrient loading will decrease the frequency and extent of hypoxic conditions. However, reviews by Duarte et al. (2009) and Kemp et al. (2009) point to more nuanced responses of estuarine biogeochemistry to changed climate and nutrient conditions that may alter restoration trajectories. Whereas reduction of external nutrient loading is an essential prerequisite for remediation of culturally eutrophic basins, such efforts may be insufficient for restoration to a lower trophic state because of internal cycling of nutrients. The eutrophic state is often a highly stable, self-perpetuating condition once a critical threshed of external nutrient loading has occurred, especially in shallow water bodies (Scheffer, 1998; Søndergaard et al., 2001).

Regulatory frameworks intended to encourage restoration of coastal waters with changed oxygen conditions include the United States' total maximum daily load (TMDL) requirements, set out by the Clean Water Act which establishes target annual loading rates for a pollutant that is responsible for impaired waters. Actions taken within a TMDL context to remediate impaired basins strongly emphasize improvements within the watershed of the water body in question. In the case of coastal waters experiencing hypoxia, these TMDL values are set for N and P loads determined using historical data analysis and/or numerical models that assist in selecting the loading rate that has the highest likelihood of remediating cultural eutrophication. In Europe, stakeholders for estuarine systems like the Baltic Sea have endeavored to improve water quality conditions through multilateral agreements such as the Helsinki Convention, in this case setting "maximum allowable inputs" that are comparable to TMDL targets. This management approach to alleviating the symptoms of eutrophication has

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characteristics of an engineering perspective. Early ecosystem models and approaches (e.g., Kremer and Nixon, 1978) designed to identify controlling mechanisms and feedbacks were developed using the tenants of H.T. Odum's ecosystem science, one that incorporates thermodynamic constraints borrowed from electrical engineering (Odum, 1983). An emphasis of these models has been on dynamic simulation and empirically driven formulations.

In contrast, engineers working with wastewater treatment technology have a higher degree of operational control over the variables and configuration of a given wastewater treatment technology intended to reduce concentrations of carbon (C), N, or P in discharge effluent. The wastewater engineer also employs numerical models based on chemical engineering methodologies, to make design and operational decisions in response to a range of wastewater influent and target effluent discharge nutrient concentrations. These numerical exercises are typically reactors in series models employing a variety of biological, chemical, and physical unit process equations, for which design and operation exert a high degree of control over key variables to meet target effluent quality (Metcalf and Eddy, 2003; Kim et al., 2008). These methods more readily allow the engineer to consider optimization criteria for such processes as nitrification, denitrification, biochemical oxygen demand removal, and phosphorus removal. Although student engineers are commonly told that classic wastewater treatment methods are intensified versions of natural processes, it is also true that processes either unknown or unconfirmed in nature were first characterized in wastewater reactors through application of rigorous mass-balance models and microbiology investigations. Anammox and heterotrophic nitrification are recent notable examples (Robertson et al., 1988; Van de Graff et al., 1996).

There are parallels between a watershed and process reactor perspective of impaired estuaries. Numerical modeling and empirical work in support of TMDLs identifies controlling rate processes that determine water quality of an estuary. Many processes such as oxygen transfer and water chemistry are common intellectual territory of water quality and wastewater engineering. The differences arise from both practical considerations and approach. A necessary condition to remediate eutrophication in any water body is to reduce the loading responsible for eutrophication in the first place. The watershed TMDL approach is to establish loading reduction targets and means to meet those targets. In contrast, wastewater engineering largely deals with intensive transformation of polluted water in a series of reactors to a quality – often determined in a TMDL process – acceptable for discharge to a water body. In contrast to a TMDL approach, applying engineering methods to impaired basins in situ, with methods and process rationale analogous to wastewater reactors, has a long history of success in water quality and ecological remediation (Cooke, 2005; Cooke et al., 2005). This engineering method explicitly recognizes that the ecological stability of impaired basin water quality may impede realization of water quality goals set within a TMDL context, at least within the near to intermediate term. Thus, persistent impairments, such as sediment anoxia, may merit in situ remediation in some cases either to force a shift to a desirable alternative stable ecological state, thereafter sustained by an effective TMDL plan, or to maintain acceptable water quality until the long-term benefit of a TMDL plan is realized. However, there are few studies that have evaluated the ecosystem impacts of in situ engineering remediation, such as aeration, in estuaries.

In the summer of 2012, we were presented with a unique opportunity to explore an estuarine system from both a wastewater treatment and ecosystems perspective. Chesapeake Bay the largest estuary in North America, is also under a presidential executive order to implement TMDLs for N and P. Rock Creek, a sub-tributary of the Patapsco River in the northern portion of Chesapeake Bay is unusual in that its community chose in situ engineering solutions to reduce hypoxia and its negative effects in the early days of Bay management. In 1988, following the recommendation of the engineering company Dames and Moore (1988), an aeration system was installed that currently consists of 830 m of aeration pipes and 138 diffusers. The purpose of aeration is to destroy saline and thermal stratification that isolates bottom water from oxygen-rich surface water. The destratified water column is then responsive to tidal and wind energy that readily mixes oxygen-rich surface water to the bottom, thereby preventing anoxia. The installation cost for the aeration system in Rock Creek was $253,000 in 1988, with average annual electrical costs of $11,000 that have ranged from $6,350 to $14,000 between 2000 and 2010 (CH2M HILL, 2011b). Upgrade costs for tertiary treatment and N removal at wastewater treatment plants typically cost millions of dollars, yet impact an area larger than the 353 ha tributary studied here. Although aeration may appear to be a cost-effective solution in Rock Creek, it does nothing to address the other deleterious effects of nutrient loading and larger-scale aeration projects would likely be unsuccessful (Conley et al., 2009b). This relatively small, tidal estuary is heavily loaded with nutrients, resulting in extreme eutrophic characteristics. After over 20 years of continuous summer use, local government and stakeholders required scientific information to inform their decisions about possible repair, replacement, or removal of the large scale aerators. This place-based question also afforded a serendipitous experimental setting to explore how manipulating dissolved oxygen levels via control of the aerators might affect sediment and water column biogeochemistry.

The majority of studies describing the impact of depleted oxygen on nutrient biogeochemistry rely on time series, or datasets of sediment nutrient fluxes that use the natural gradient of water column conditions often characteristic of estuarine systems, where salinity, oxygen, and temperatures vary in space. Important questions have remained regarding the effects of destratification. In particular, the effect of sediment oxygen demand (SOD) on water quality and on nutrient dynamics with and without destratification needs detailed investigation. Here we present our effort to take advantage of a tributary scale experiment to evaluate whether aeration (a) impacts water column SOD and water quality and (b) affects nutrient fluxes and benthic–pelagic coupling processes. Borrowing from the engineering perspective, we consider how rate processes may act to optimize response of estuaries to changed oxygen or nutrient conditions using a combination of direct measurement and modeling techniques.

This study neither promotes nor denigrates destratification as a remediation measure in tidal estuaries. Instead, the aeration system here was leveraged as a whole ecosystem experiment, enabling manipulation of bottom water oxygen and providing an opportunity to measure system response to a simulated recovery that was designed to provide insights into the biogeochemistry that affects larger scale restoration efforts for hypoxic estuaries.

2. Methods

2.1. Study site

In order to evaluate the biogeochemical response of an impacted, hypoxic estuarine system to changes in bottom water oxygen concentrations, we experimentally manipulated the aeration system of Rock Creek. Rock Creek is a 353-ha tidal creek tributary to the Patapsco River in Anne Arundel County, Maryland (Fig. 1). The creek has experienced poor water quality for about 35 years. A large scale aeration system was installed in the creek by the Anne Arundel County Department of Public Works in October