Marine Pollution Bulletin 56 (2008) 1680–1695

Contents lists available at ScienceDirect

Marine Pollution Bulletin

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

Review

The response of benthic macrofauna to anthropogenic stress in Narragansett Bay, Rhode Island: A review of human stressors and assessment of community conditions

Christopher J. Calabretta *, Candace A. Oviatt

Graduate School of Oceanography, University of Rhode Island, South Ferry Road, Narragansett, Rhode Island 02882, United States

ARTICLE INFO

Keywords:
Benthic macrofauna
Faunal succession
Diversity
Hypoxia
Heavy metals
Narragansett Bay

ABSTRACT

The present state of knowledge regarding the input of anthropogenic pollutants into Narragansett Bay, Rhode Island was reviewed and benthic infaunal communities present at four depositional environments within the upper Bay were characterized. Inter-station differences in species composition and abundance of these assemblages were examined in relation to established pollution gradients.

Using diversity curves and multivariate statistics, evidence of significant anthropogenic impact on the structure of benthic macrofaunal communities in Narragansett Bay was identified. The magnitude of this impact was greatest at stations closest to the Bay's urban centers, where exposure to multiple stressors had resulted in communities of opportunistic taxa which persisted in a state of low faunal diversity characteristic of early stages of species succession. As was expected based on historic models of faunal succession; the apparent maturity of benthic assemblages in Narragansett Bay increased along the north-south gradient of decreasing anthropogenic stress.

1. Introduction

Benthic invertebrates have become well established as useful bio-indicators of ecological quality in coastal and estuarine environments. Numerous studies have demonstrated that benthic macrofauna respond in a predictable and relatively rapid manner to a variety of natural and anthropogenic stress (e.g. Dauer, 1993; Tapp et al., 1993; Levin, 2000). Many characteristics of benthic community assemblages make them useful as bio-indicators. The most important of these characteristics relate to the exposure of organisms within this community to stress and the diversity of their response (Bilyard, 1987; Weisberg et al., 1997). Benthic macrofauna are relatively sedentary and cannot avoid deteriorating conditions within the water and sediment columns. Also, benthic communities typically consist of a variety of species that exhibit a wide range of physiological tolerances for stress, feeding modes, and trophic interactions (Weisberg et al., 1997; Levin, 2000; Rosenberg, 2001).

Models of faunal succession developed by Pearson and Rosenberg (1978) and Rhoads et al. (1978) describe predictable changes in the structure of benthic assemblages with spatial or temporal distance from a disturbance. These models have been repeatedly tested and appear to be universally applicable for most physical, chemical, or biological disturbances in sub-littoral, soft-bottom habitats (Rhoads and Germano, 1986; Heip, 1995; Rosenberg et al., 2004). A complete discussion of benthic faunal succession can be found in reviews by Pearson and Rosenberg (1978), Rhoads and Germano (1982) and Rhoads and Boyer (1982).

In general, according to the Pearson and Rosenberg (1978) and Rhoads et al. (1978) models, immediately following a disturbance or close to a pollution source the first species encountered will be small and few in number. As the distance (in space or time) from a disturbance increases the number of organisms will increase to a peak, where the benthic assemblage is dominated by a few, highly abundant, opportunistic (*r*-selected) species. These pioneering species tend to be small tube-dwelling polychaetes that feed at the sediment surface, are short lived, mature rapidly and have high reproductive output. Following this abundance peak, and with further distance from the disturbance, there will be an increase in both the number of species present within the community (species richness) and the relative abundance of individuals among species (evenness). At the same time there will be a decline in the overall faunal abundance to the steady state level typical of "normal" conditions. Ultimately, the mature benthic community is dominated by large, deep-dwelling, equilibrium (*K*-selected) species that feed at depth, have a long lifespan and low fecundity. Early and late stages of faunal succession are not mutually exclusive. For example, there are cases where a disturbance only involves near-surface sediments and pioneering and equilibrium

* Corresponding author. Tel.: +1 401 874 6656; fax: +1 401 874 6613.
E-mail address: chrisc@gso.uri.edu (C.J. Calabretta).

0025-326X/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.marpolbul.2008.07.012

species may coexist in the same sediment (Rhoads and Boyer, 1982).

Quantitative analysis of the benthic communities within Narragansett Bay, Rhode Island dates back to the early 1950's, however, problems encountered when comparing data obtained using different collection methods and sieve sizes have made it difficult to combine the available data in order to assess the effects of anthropogenic stress on Narragansett Bay's benthic assemblages over large temporal and spatial scales (Frithsen, 1989). With few exceptions, historic benthic data sets for the bay have lacked standard methodology and were limited in their spatial coverage (Frithsen, 1989; Ellis, 2002). As a result, the overall understanding of human impact on the dynamics of benthic faunal assemblages in Narragansett Bay is limited when compared to the bay's pelagic communities.

In this paper, we will initially review the present state of knowledge regarding anthropogenic stressors associated with the water column and sediments of Narragansett Bay. We will then provide a characterization of benthic infaunal communities present at four depositional environments within the upper Narragansett Bay; examine inter-station differences in the structure (species composition and abundance) of these communities and attempt to relate these differences to established pollution gradients. In addition, this study will provide baseline data describing the state of the bay's benthic communities prior to the legislated reduction of nitrogen entering the bay through sewage treatment plant discharge.

1.1. Anthropogenic influence in Narragansett Bay, Rhode Island

Narragansett Bay is a well mixed coastal embayment and estuary complex with a small down-bay salinity gradient that ranges from 24‰ in the Providence River estuary to a maximum of about 32‰ at the mouth of the bay (Kremer and Nixon, 1978; Nixon et al., 1995). The upper Narragansett Bay has experienced a long history of water quality concerns dating back to around the turn of the nineteenth century and the start of the American industrial revolution. A thorough review of the industrialization and urbanization of the land adjacent to the head of the bay and its major freshwater tributaries can be found in Desbonnet and Lee (1991) and Nixon (1995).

There are currently five principal sources of pollution to Narragansett Bay: rivers, sewage treatment plants, seepage of wastewater from septic systems (ISDS), industry, and combined sewer overflows. The flux of pollutants into the bay has been and still remains highest at the head of the bay due to the abundance of point sources from adjacent urban areas. The flushing dynamics of Narragansett Bay are such that pollutants travel from the upper bay, through the lower bay and out into Rhode Island Sound; creating a down-bay gradient in the concentration of pollutants within both the water column and the sediments (Desbonnet and Lee, 1991; Valente et al., 1992).

More than 73% of the average total annual input of both nitrogen (TN) and phosphorus (TP) to Narragansett Bay arrives at the head of the bay via river and direct sewage treatment plant (STP) discharge into the Seekonk and Providence River estuaries and Mt. Hope Bay (Table 1, Fig. 1). A recent review of past and present nutrient data suggests that, while TP inputs have declined, the TN inputs to the bay from these sources has remained constant for at least the past two decades (Nixon et al., 2005). Nutrients within the water column decrease exponentially from a maximum in the Providence River and upper bay (annual average TN = l70 μM, TP = 5 μM) to a minimum in Rhode Island Sound (annual average TN = 12 μM, TP = 1 μM; Oviatt et al., 2002). Levels of primary production tend to mirror the gradient in nutrient concentrations with highest values of about 600 g C m^{-2} y^{-1} in the Providence River and lowest values of about 200 g C m^{-2} y^{-1} in the lower Narragansett Bay. The bay-wide mean primary production has been estimated to be 323 g C m^{-2} y^{-1} (Oviatt et al., 2002). Organic matter reaching the sediments of Narragansett Bay is actively remineralized and recycled and Nixon et al. (1986) estimates that only 1.7% of the TN and 2.6% of the TP entering the bay is retained in the system.

The majority of other toxic substances, such as heavy metals, PCBs, and petroleum hydrocarbons entering Narragansett Bay also arrive through the urbanized/industrially-impacted upper bay region. A first-order approximation of the metal inputs to Narragansett Bay was made by Nixon (1995) who found that, as with nutrients, the bulk of metals entering the bay arrive through river flow and direct STP discharge into the Seekonk and Providence river estuaries and Mt. Hope Bay (Table 1). The only exception to this is lead, where direct atmospheric deposition onto the surface of the bay contributed about 20% of this metal's total input, prior to the removal of lead from gasoline (Table 1). The Blackstone River provides an estimated 14 kg of the 26 kg of total polychlorinated biphenyls (PCBs) entering the bay each year, with an additional 6 kg arriving through the combined discharge of the Bucklin Point and the Fields Point STPs (Table 1). The Blackstone also dominates the fluvial transport of petroleum hydrocarbons to Narragansett Bay, providing almost 50% of the loadings (Table 1). A breakdown of total hydrocarbon loadings by STP is presently not available. However, a report listing the sources of the two forms of petroleum hydrocarbons indicates that at least 43% of petroleum hydrocarbons (PHCs) and 51% of polycyclic aromatic hydrocarbons (PAHs) enter the bay through direct STP discharge into the Seekonk and Providence river estuaries (Narragansett Bay Project, 1989).

The fraction of the total toxic material entering Narragansett Bay that ultimately reaches and is retained by the bay's sediments varies based on the material in question and largely depends upon the efficiency and speed with which each substance is carried to the bottom and the rate at which it is remobilized and returned to the water column (Nixon et al., 1986). For example Nixon et al. (1986) reports that while only 7% of the Mn and 16–29% of the Cd input is retained within the bay, 69–95% of the Cu and 80–100% of the Pb entering the bay is stored within the sediments instead of being carried offshore dissolved in the water column. An estimated 47% of petroleum hydrocarbons entering the bay are lost to the atmosphere through volatilization and respiration, with 26–67% retained in the sediments and 0–27% transported offshore (Nixon et al., 1986).

According to a study by King et al. (1995), the concentrations of heavy metals in the surface sediments of Narragansett Bay decrease exponentially from the upper bay to Rhode Island Sound. These authors found that the effects range-median (ERM) guidelines of Long et al. (1995) for copper, lead, zinc, nickel, silver, and cadmium were exceeded throughout the Seekonk and Providence river estuaries, suggesting an increased potential for toxic effects to biota. Further, while the effects range-low (ERL) guideline for copper was exceeded throughout most of the bay, concentrations of lead, zinc, chromium, nickel, silver, and cadmium exceeding the ERL were generally limited to areas north of Prudence Island (King et al., 1995). Similar to metals, the concentrations of PCBs, total petroleum hydrocarbons and PAHs in the surface sediments systematically decrease down-bay from the Seekonk, Providence and Taunton Rivers at the head of the bay (Hartmann, 2001; Hartmann et al., 2004,a). Total PCB concentration was highest (1760 ng/g dry wt.) in the surface sediments off Bucklin Point STP in the Seekonk River and ERM guidelines were widely exceeded above Conimicut Point, along the Taunton River, and in several of the coves off Greenwich Bay (Hartmann et al., 2004). Surface sediment