Marine Pollution Bulletin 129 (2018) 70–80

Contents lists available at ScienceDirect

Marine Pollution Bulletin

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

A multi-indicator approach for identifying shoreline sewage pollution hotspots adjacent to coral reefs

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ARTICLE INFO

Keywords:
Fecal indicator bacteria
Hawai'i
Macroalgae
Nutrients
Pollution score
Stable nitrogen isotopes

ABSTRACT

Sewage pollution is contributing to the global decline of coral reefs. Identifying locations where it is entering waters near reefs is therefore a management priority. Our study documented shoreline sewage pollution hotspots in a coastal community with a fringing coral reef (Puakō, Hawai'i) using dye tracer studies, sewage indicator measurements, and a pollution scoring tool. Sewage reached shoreline waters within 9 h to 3 d. Fecal indicator bacteria concentrations were high and variable, and $\delta^{15}N$ macroalgal values were indicative of sewage at many stations. Shoreline nutrient concentrations were two times higher than those in upland groundwater. Pollution hotspots were identified with a scoring tool using three sewage indicators. It confirmed known locations of sewage pollution from dye tracer studies. Our study highlights the need for a multi-indicator approach and scoring tool to identify sewage pollution hotspots. This approach will be useful for other coastal communities grappling with sewage pollution.

1. Introduction

With > 50% of the world's population living within coastal areas, sewage pollution has become a growing global problem that is largely unrecognized. Untreated sewage from cesspools and septic tanks is a concern for human and environmental health in rural areas (Lapointe et al., 1990; Paul et al., 2000; Whittier and El-Kadi, 2014). Sewage pollution is a complex environmental problem because it is a cocktail containing elevated and potentially hazardous levels of pathogens, hydrocarbons, nutrients, toxins, organic and inorganic compounds, and endocrine disruptors (Wear and Vega Thurber, 2015). For example, human exposure to sewage can result in skin and urinary tract infections, hepatitis, and gastroenteritis (Pinto, 1999). Annually, there are over 120 million gastroenteritis cases worldwide associated with sewage contaminated waters (Shuval, 2003). In addition, sewage pollution can have detrimental effects on coastal ecosystems (Wear and Vega Thurber, 2015). Coral reefs, which are one of the most economically valuable and biologically diverse ecosystems in the world, are steadily declining from multiple stressors including sewage pollution (Wear and Vega Thurber, 2015). Sewage pollution has been linked with increased coral disease prevalence and severity (Sutherland et al., 2010; Redding et al., 2013; Yoshioka et al., 2016). White pox disease in Caribbean corals is one well documented example where a human pathogen is found in sewage, *Serratia marcescens*, was shown to cause the disease (Sutherland et al., 2010), although this relationship is disputed (Lesser and Jarett, 2014). Nutrient enrichments associated with sewage can stimulate benthic algal growth, resulting in a benthic phase shift from coral-to macroalgal-dominated reefs (Hunter and Evans, 1995; Lapointe et al., 2005). These nutrients also alter coral growth rates, species distribution and abundance, and coral community diversity (Pastorok and Bilyard, 1985; Parsons et al., 2008).

As the human population and associated coastal development continues to grow, monitoring water quality for sewage pollution is essential. Dye tracer studies provide irrefutable evidence that sewage from on-site sewage disposal systems (OSDS; i.e., cesspool, septic tanks) and treatment plants is entering and contaminating water bodies (Yates, 1985; HDOH, 1984; Glenn et al., 2013). These studies reveal hydrogeologic features connecting these treatment systems to

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https://doi.org/10.1016/j.marpolbul.2018.02.005
Received 28 April 2017; Received in revised form 1 February 2018; Accepted 2 February 2018

nearshore waters, and are used to calculate pollution transit times, flow rates, and dilution within aquifers. However, dye tracer studies are laborious with hourly, daily, and in some instances, monthly sample collections. They also occur at one location at a time, and thus, provide limited geographical information on where sewage is entering into the ocean. Hence, they are only generally conducted when it is suspected that sewage is entering the ocean from a specific site.

In contrast, measurements of fecal indicator bacteria (FIB) are a more widely used to detect sewage than dye tracer studies, and they serve as a proxy for assessing human health risks (Cabelli, 1983; Prüss, 1998). *Enterococcus* spp. is monitored in marine recreational waters by the United States Environmental Protection Agency (USEPA) and state health agencies. In tropical locations like Hawai'i, a secondary indicator, *Clostridium perfringens*, is also assessed (Fujioka et al., 1997; Fujioka et al., 2015). Unlike *Enterococcus* spp., *C. perfringens* is an anaerobic, spore-forming bacterium that does not multiply in coastal waters, nor grows in tropical soils (Hardina and Fujioka, 1991; Fung et al., 2007). Hence, it is thought to more accurately detect sewage pollution than *Enterococcus* spp. (Fujioka and Shizumura, 1985; Hardina and Fujioka, 1991; Fujioka et al., 1997).

Measurements of stable nitrogen (N) isotopic composition ($\delta^{15}N$) in macroalgal tissues is another method employed to detect sewage pollution in coastal waters (Umezawa et al., 2002; Savage, 2005; Lin et al., 2007; Dailer et al., 2012; Wiegner et al., 2016). Macroalgae minimally discriminate between ^{14}N and ^{15}N. Therefore, they have similar isotopic compositions relative to their N sources (Savage, 2005). Sewage, in particular, has a very distinct stable N isotopic composition compared to other N sources, i.e., fertilizers, soils, groundwater, and ocean water (*reviewed in* Wiegner et al., 2016), and thus, has been successfully used to identify locations of shoreline sewage pollution (Umezawa et al., 2002; Savage, 2005; Lin et al., 2007; Dailer et al., 2010; Dailer et al., 2012).

Nutrient concentrations are also commonly used to assess water quality. It has been shown that nutrient concentrations are significantly higher nearshore with known sewage pollution (Lapointe et al., 1990; Nelson et al., 2015). However, measuring nutrients at the shoreline alone as a sewage indicator is not informative enough for management actions because of their numerous non-sewage watershed sources. Mixing plots of nutrient concentrations and salinity, a tool commonly used for examining mixing behavior and determining nutrient sources (freshwater vs. ocean) (Officer, 1979), may be useful for identifying locations where sewage is entering coastal waters and increasing nutrient concentrations.

Due to spatial and temporal variability associated with different sewage indicators, assessing pollution from a single one can be misleading. For example, authorities are more likely to post beach advisories when using *Enterococcus* spp. rather than *C. perfringens* (Shibata et al., 2004). In addition to FIB, $\delta^{15}N$ in macroalgal tissues can be highly variable due to N inputs from different sources with differing N isotopic compositions (Ochoa-Izaguirre and Soto-Jiménez, 2015). Hence, it is imperative to measure multiple sewage indicators to determine spatial and temporal pollution patterns particularly when concerned with both human and ecosystem health. However, few studies have done this to date, with most only measuring two indicators simultaneously because methods are difficult, expensive, and time consuming (Knee et al., 2008a; Baker et al., 2010; Moynihan et al., 2012; Yoshioka et al., 2016).

Hawai'i is an ideal location to develop a multiple sewage indicator approach as its coastal waters and coral reefs have been impacted by sewage pollution for decades (Pastorok and Bilyard, 1985; Whittier and El-Kadi, 2014). Presently, cesspools are the primary source of sewage pollution in rural areas, which comprise most of the state and are the location where the healthiest coral reefs are found. Hawai'i uses cesspools more widely than any other state (USEPA, 2013), and has only recently banned the installment of new ones (HDOH Administrative Rules-Title 11, HAR, 2016). Cesspools are particularly concerning in Hawai'i where many of the homes are in close proximity to the water on highly porous substrate. As of 2014, there were over 110,000 OSDS in Hawai'i State. On Hawai'i Island alone, there are nearly 59,000 OSDS, with 49,000 being classified as cesspools (Whittier and El-Kadi, 2014). A high-risk area where OSDS are likely impacting nearshore waters on Hawai'i Island is Puakō (Whittier and El-Kadi, 2014). Puakō is a coastal community that is home to some of the richest, most diverse reefs in the state (Hayes et al., 1982). However, coral coverage has decreased from 80% in 1975 to 33% in 2010 (Minton et al., 2012), with concurrent decreases in fish abundance (49%–69%), and increases in turf and macroalgal cover (38%) (HDAR, 2013). Declining coral health and elevated disease prevalence and severity have also been documented (Couch et al., 2014; Yoshioka et al., 2016). While sewage pollution is thought to be one of the culprits contributing to these ecosystem changes, the link between these conditions and the presence of sewage has not been made.

The goal of this study was to develop a multiple sewage indicator approach to more accurately detect the presence of sewage in Puakō's nearshore waters. More specifically, we aimed to: 1) determine whether OSDS were hydrologically connected with coastal waters, 2) measure three sewage indicators including: FIB, $\delta^{15}N$ in macroalgal tissue, and nutrients along the shoreline, 3) identify locations of shoreline sewage pollution using mixing plots, and 4) pinpoint sewage pollution hotspots by developing a sewage pollution score.

2. Materials and methods

2.1. Site description

This study was conducted along the Puakō coastline in the South Kohala region of Hawai'i Island (Fig. 1), which is primarily comprised of basalt from the Mauna Loa Volcano. Annual rainfall ranges from 250 to 750 mm and infiltration of rainwater into the aquifer is high due to the permeable substratum. Average submarine groundwater discharge (SGD) at the shoreline ranges from 2083 to 2730 $L\,m^{-1}\,h^{-1}$ (Paytan et al., 2006).

Puakō is a residential community along a 3.5 km stretch of coastline with 207 lots, of which 163 have homes. The population is growing at a rate of 6.9% per year (Minton et al., 2012). At Puakō, 47 homes have cesspools and 139 have conventional septic tanks with leach fields (Schott, 2010). The entire coastline is accessible to the public and is frequently used for recreational activities such as fishing, surfing, SCUBA diving, and snorkeling. Presently, there is one development upslope of Puakō, Waikoloa Village, which has 2000 homes, with 1587 having OSDS; the remainder are connected to the sewer line (per. comm. Hawai'i Water Supply).

2.2. Dye tracer studies

Dye tracer studies were conducted to determine the hydraulic connectivity between OSDS at four oceanfront homes. Studies were conducted along the southern portion of Puakō's coastline where nearshore waters are relatively fresh. Three homes had cesspools, and one had a fractured aerobic treatment unit (ATU) tank (a type of OSDS that utilizes an aeration process). Two of the four homes were occupied during the studies. At each home, the closest point where dye could be delivered to the OSDS was identified. Fluorescein, a non-toxic organic dye was used for the studies. It has a strong fluorescence and detection levels as low as 1 ppb (Gaspar, 1987; Reich et al., 2001). For our studies, 500–1000 g of high purity fluorescein dye (Amresco Fluorescein Sodium Salt) was injected over ~10 h. Each hour, 50 or 100 g of dye were mixed with 20 L of tap water and slowly added to the OSDS. Additional tap water was added throughout the day and its volume recorded to calculate an initial dye concentration.

To sample for the presence of dye at the shoreline, five to six stations were identified in front of each home and adjacent properties