# INVESTIGATING THE INFLUENCE OF SEDIMENT RESUSPENSION ON THE BACTERIAL WATER QUALITY OF THE HARLEM RIVER

A Final Report of the Tibor T. Polgar Fellowship Program

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# ABSTRACT

Understanding temporal changes in the concentration of fecal indicator bacteria (FIB) at public access points is a high priority for water-quality managers. In 2017, a study was conducted by the United States Geological Survey (USGS) on the Harlem River (New York City, New York) to better understand the mechanisms causing elevated FIB concentrations. While precipitation was one important mechanism, the study identified sediment resuspension as a mechanism linked to the exceedance of allowable FIB concentrations during periods of dry weather. This study built upon the prior USGS finding and investigated the influence of sediment resuspension from boat wake disturbances on the total suspended solids (TSS) and bacterial water quality of the Harlem River. Samples were taken before and after boat wake events from a shoreline dock at Roberto Clemente State Park on the Harlem River. Enterococci values were orders of magnitude higher in benthic sediment than in the undisturbed water when compared on a per mass basis (100 ml water and 100 g sediment), suggesting that sediment could act as a source of FIB contamination if large quantities of sediment became suspended in the water column. Although TSS was found to increase significantly after boat wakes, the levels of FIB at this site did not change significantly.

## TABLE OF CONTENTS

Abstract ........ VI-2

Table of Contents ........ VI-3

Lists of Figures and Tables ........ VI-4

Introduction ........ VI-5

Methods ........ VI-7

- Boat Wake Event Sampling ........ VI-7
- Sediment Fecal Bacterial Sampling ........ VI-8
- Sediment Sample Processing ........ VI-9
- Enterococci Analysis ........ VI-9
- Total Suspended Solids Analysis ........ VI-10
- Statistics ........ VI-11

Results ........ VI-11

- Enterococci Levels in Water and Sediment ........ VI-11
- Comparison “Before” and “After” Boat Wake Disturbances ........ VI-13

Discussion ........ VI-17

Acknowledgments ........ VI-21

References ........ VI-22

# LIST OF TABLES AND FIGURES

Figure 1 - Map of sampling locations ................................................................ VI-8

Figure 2 - Boxplots of enterococci MPN / 100 g of sediment comparing RCSP enterococci levels to two CSO impacted locations in inner Flushing Bay VI-12

Figure 3 - Boxplots of Enterococci MPN / 100 ml of water or per 100 g of dry sediment ........................................................................................ VI-13

Figure 4 - Graphs of the changes in Turbidity (FNU) and Surface elevation (ft) before and after boat wake events ...................................................................... VI-14

Figure 5 - A) Box plots of TSS “before” and “after” boat wake events at the RCSP Dock; and B) paired TSS measurements “before” and “after” boat wake events at the RCSP Dock ........................................................................................ VI- 15

Figure 6 - A) Boxplots of enterococci per 100 ml of water “before” and “after” boat wake events at the RCSP Dock; and B) paired measurements of enterococci per 100 ml of water “before” and “after” boat wake events at the RCSP Dock ........ VI- 16

Figure 7 - The observed change in enterococci from before and after boat wake events can be compared to the expected increase that is calculated from the observed change in TSS (mg/L) and the concentration of enterococci per mg of sediment at the site ........................................................................................ VI-17

# INTRODUCTION

For over a century, water quality managers have utilized cultivation-based enumeration of fecal indicator bacteria (FIB) as the primary method of assessing bacteriological water quality and the associated risk to public health (LeClerc et al. 2001). Prior studies have demonstrated correlations in many urban waterways between elevated FIB concentrations and the presence of fecal pathogens (Byappanahalli et al. 2012; Touron et al. 2007; Zhang et al. 2016; Steele et al. 2018). The cultivation-based FIB commonly used to assess fecal contamination by water quality managers are *Escherichia coli* and enterococci. The highest concentrations of fecal bacteria in urban waterways typically occur after precipitation and are often attributed to stormwater discharges contaminated with fecal waste from human or animal sources (e.g., Sercu et al. 2009; Steele et al. 2018) or a mixture of stormwater and untreated sewage from combined sewer overflows (CSOs) (e.g., Young et al. 2013).

FIB monitoring data can be utilized to create predictive statistical models that link meteorological conditions with fecal contamination in urban waterways (Farnham and Lall 2015). Predictive models allow water quality managers to develop high FIB concentration warning systems that can be adjusted to various guidelines and used to manage human exposure to fecal pollution in waterways. However, some common assumptions about the fate and transport of FIB outside of the gut and associated pathways of pathogen exposure are often oversimplified, leading to complexities in interpreting monitoring data and modeling the distribution and abundance of FIB in the environment (O’Mullan et al. 2017). One of the common over-simplifications of the extra-enteric ecology of FIB and fecal pathogens is that FIB are entirely free-living

(O’Mullan et al. 2017).

A study of the Lower Hudson River Estuary demonstrated that approximately 50 percent of water column FIB were particle-associated, and FIB concentrations were found to be correlated with turbidity (Suter et al. 2011). FIB in this environment were also found to have significantly higher concentrations at nearshore sites compared to mid-channel sites, likely in part due to resuspension of sediment particles containing FIB in the shallow near-shore environments.  Particle association of enterococci, relative to free-living enterococci, has been shown to accelerate dark (e.g. at depth or at night) growth rates, decrease mortality when exposed to sunlight, and increase sinking rates (Myers and Juhl 2020). The sediment acts as a reservoir for FIB, making resuspension of FIB into the water column possible (Jamieson et al. 2005; Smith et al. 2008; O’Mullan et al. 2019). These studies have concluded that particle association can alter FIB persistence and concentration in urban waterways and that resuspension may be one mechanism to explain elevated FIB concentrations occurring during dry weather at some sites (Cho et al. 2010; O’Mullan et al. 2019; Myers and Juhl 2020).

In 2019, the U.S Geological Survey conducted a fecal indicator study on the Harlem River at locations with current or planned shoreline access. Preliminary results suggested that sediment resuspension contributed to elevated FIB concentrations during dry weather. Boat wakes were predicted to be one mechanism of this resuspension that may be relevant to understanding FIB and total suspended solids (TSS) concentrations. Although still understudied, boat wake disturbances of sediment have been previously associated with water quality degradation in other systems (Pettibone et al. 1996; Gabel et al. 2017).  In this study, the hypothesis was tested that sediment resuspension from boat wake disturbances is a cause of high FIB and TSS concentrations during dry weather in the nearshore coastal environment at Roberto Clemente State Park (RCSP) on the Harlem River.

## METHODS

### Boat Wake Event Sampling

Samples were collected from two adjacent locations at RCSP along the Harlem River: the USGS Monitoring Station on the waterfront bulkhead and at the public access floating dock adjacent to the USGS Monitoring Station (Figure 1). Sampling locations are also adjacent to a shallow sedimented cove that is the likely source of sediment resuspension following boat wake events. Water samples were taken at the USGS Monitoring Station, where sensor elevation is -6.5 ft below NAVD88, using a Masterflex Portable Sampler Pump. The streambed at this location has an elevation of -13.0 ft below NAVD88. Samples at the floating dock were taken from just below the water surface, directly into sterile sampling bottles. Samples for total suspended solids (TSS) were collected in 500 ml bottles, and enterococci samples were collected in 100 ml sterile IDEXX bottles. Water samples for TSS and enterococci were collected in pairs both before and after a boat wake event. “Before” samples were collected approximately ten minutes before a boat wake event to represent pre-disturbance water conditions, with no other boat disturbances occurring within 5 minutes before the sample was taken. “After” samples were collected approximately 5 minutes after a boat wake event to represent post-disturbance water conditions. It should be acknowledged that “after” conditions were visually observed to create patchy patterns of elevated turbidity, but the highest levels were not always located at the sampling sites. Collected samples were immediately labeled and put into a dark cooler with ice.

**Figure 1:** **Map of sampling locations. Google Earth Satellite image of sampling locations at Roberto Clemente State Park. The two sampling locations are labeled: USGS Monitoring Station and the public access dock. Locations occur between the Harlem River and a shallow sedimented cove.**

Sediment Fecal Bacterial Sampling

Six sediment samples were collected using a Ponar sediment sampler at locations around the public access dock and one in the cove parallel to the USGS Monitoring Station. The sediment sampler was lowered to the sediment bed for each sampling event, and a messenger weight was dropped to trigger collection. The sampler was then retrieved, carefully drained of excess water, and sediment was deposited into a large container without disturbing the top layers of the sample. Using sterile 50 ml polypropylene tubes, the top layer of the sediment (approximately 1 cm depth) was collected, labeled, and put into a dark cooler with ice for transport to the laboratory for processing within eight hours.

### Sediment Sample Processing

For each sediment sample, 10 grams wet weight was measured using an analytical balance. Weighed sediment was added to a container with 100 ml of a sterile sediment extraction buffer consisting of 0.1% sodium pyrophosphate and 0.1mM EDTA. The extraction slurry was then shaken at 200 revolutions per minute for 30 minutes (O'Mullan et al. 2019). The overlying extraction liquid was separated from the sediment using a sterile nitex mesh (10-micron pore size) and deposited into a sterile 50 ml tube. 10 ml of the extraction liquid was then subsampled from the tube and processed for enterococci analysis following the water protocol described below.

### Enterococci Analysis

Enterococci levels in both water and sediment samples were measured using the IDEXX Enterolert system within eight hours of collection. IDEXX Enterolert is a U.S EPA-approved method for the enumeration of enterococci in water (USEPA 2007). To process both water and sediment extraction liquid samples, 10 ml subsamples were added to a 100 ml bottle containing 90 ml of sterile water and a proprietary Defined Substrate Technology (DST) nutrient indicator and gently swirled (IDEXX 2021). For each set of water and sediment samples analyzed, a blank sample (negative control) of 100 ml sterile water mixed with the DST nutrient indicator was also processed. The resulting 100 ml solution was then added to a Quanti Tray 2000 and sealed with an IDEXX Quanti-Tray

Sealer. The sample was then incubated at 41 °C for 24 hours. After incubation, samples were viewed under UV light, and the blue fluorescing wells were enumerated. Fluorescent wells in the Enterolert tray are considered to be positive for the presence of species of *Enterococcus,* including *E. faecalis, E. faecium, E. avium, E. gallinarum, E. casseliflavis,* and *E. durans* (IDEXX 2021). The IDEXX most probable number (MPN) table was then used to quantify the total number of bacteria present in 100 ml of each sample. Water FIB samples were reported as MPN per 100 ml. Sediment sample microbial abundances were normalized per gram of sediment dry weight using dry weight/wet weight ratios. To determine sediment dry weight, wet samples were weighed and then were dried at 60 °C for 48 hours, at which time dry weight was recorded (O'Mullan et al. 2019). Dry weight/wet weight ratios and extraction liquid dilutions were used to calculate a final enterococci MPN value per 100 grams of sediment dry weight.

### Total Suspended Solids Analysis

Water samples' total suspended solids (TSS) levels were measured using Standard Method 2540d (ASTM International 2019). Water samples were thoroughly mixed by shaking through inversion, and 100 ml was measured out using a graduated cylinder. 50 ml at a time was filtered through a pre-weighed ProWeigh filter with a 1.5 µ pore size until all 100 ml was filtered through. Before removing the filter, the filtration rig was flushed with sterile water to suspend any solids stuck along the sides of the filtration rig, and that water was also passed through the filter. Filters were then placed inside the paired ProWeigh filter pan and into a drying oven set at 104 °C for at least one hour. Filters and pans were removed from the oven, and filters were weighed using an analytical balance to the nearest 0.001g. The initial weight of the pre-weighed filter was subtracted from the final weight, the value was then multiplied by 10, and TSS was recorded as mg TSS/L.

### Statistics

Non-parametric statistics were used to analyze the results from this study. This included Spearman’s coefficient for correlations, Mann-Whitney and Kruskal-Wallis tests for comparison of the central tendency among samples, and a one-tailed Wilcoxon matched pairs signed rank test for comparisons of FIB and TSS before and after boat wake disturbances where levels of FIB and TSS were expected to be higher after the disturbance. Statistics were calculated using the Prism (GraphPad; version 6) statistical analysis software.

## RESULTS

### Enterococci Levels in Water and Sediment

Enterococci levels in sediment samples (n=7) ranged from an MPN of $2.7 \times 10^4$ to $1.0 \times 10^5$ per 100g of sediment dry weight, with a median of $6.8 \times 10^4$. The levels observed at Roberto Clemente State Park were not significantly different (Kruskal-Wallis p=0.256) than sediment FIB levels observed in a previous study (O’Mullan et al. 2019) at two inner Flushing Bay sites from another CSO impacted waterway (Figure 2).

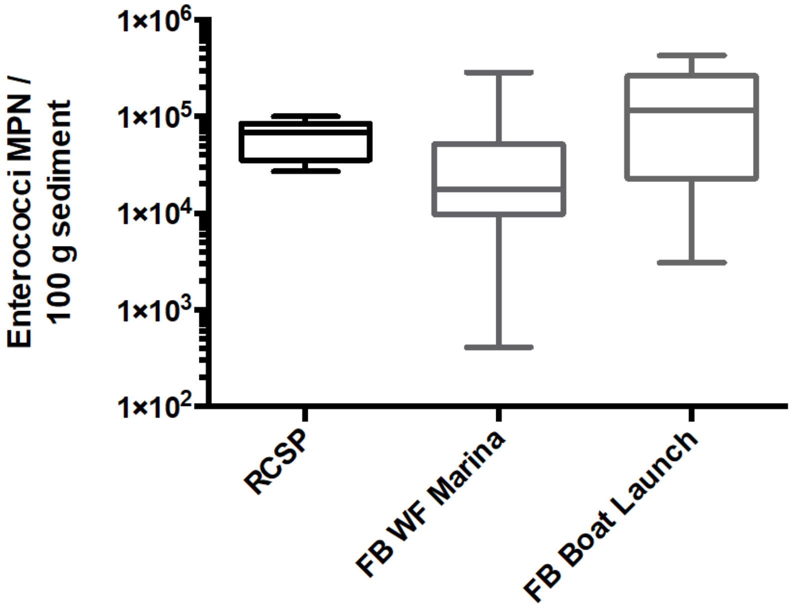

**Figure 2:** **Boxplots of enterococci MPN / 100 g of sediment comparing RCSP enterococci levels to two CSO impacted locations in inner Flushing Bay.**

Enterococci levels in sediment were orders of magnitude higher than in water samples collected pre-boat wake disturbance in dry weather, based on a per mass comparison (100 ml or g of water and 100 g sediment dry weight) (Figure 3). Enterococci levels in water samples ranged from an MPN below detection (>10/100ml) to 1.1 x $10^3$ per 100 ml of water, with a median level of 4.1x $10^1$ (n= 7 for sediment, n=29 for water).

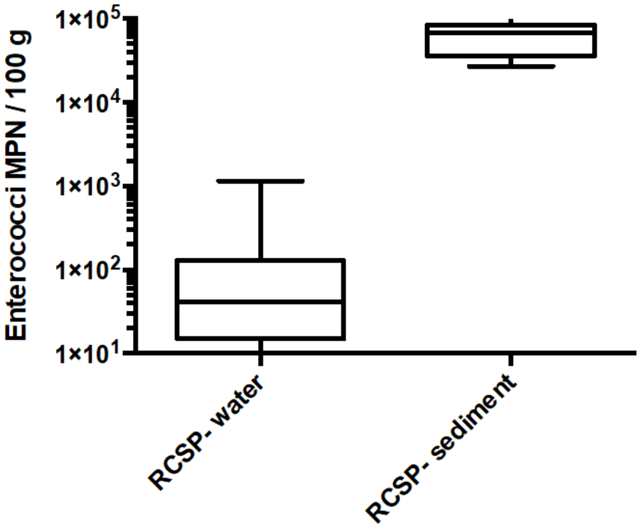

**Figure 3: Boxplots of Enterococci MPN / 100 ml of water or per 100 g of dry sediment. Water samples displayed are those collected pre-disturbance during dry weather.**

Comparison “Before” and “After” Boat Wake Disturbances

Surface elevation and turbidity data recorded at the RCSP-USGS Monitoring station were used to demonstrate the disturbance events caused by boat wakes when large vessels passed the station (Figure 4). Surface elevation of the water overall increased from the boat wake events, but most records displayed an increased variability, including a decrease in elevation followed by an increase consistent with the displacement of water by the vessel, creating a series of waves that pass by the station, consistent with visual observations. These surface elevation changes preceded a spike in turbidity that occurred as the waves interacted with the shoreline and river bottom creating sediment resuspension, but the exact timing and magnitude of this turbidity varied from event to event and was spatially patchy based on visual observations. Paired measurements of surface elevation and turbidity across these events were positively correlated (Spearman r = 0.390, p = 0.004), indicating that the creation of waves was associated with higher turbidity.

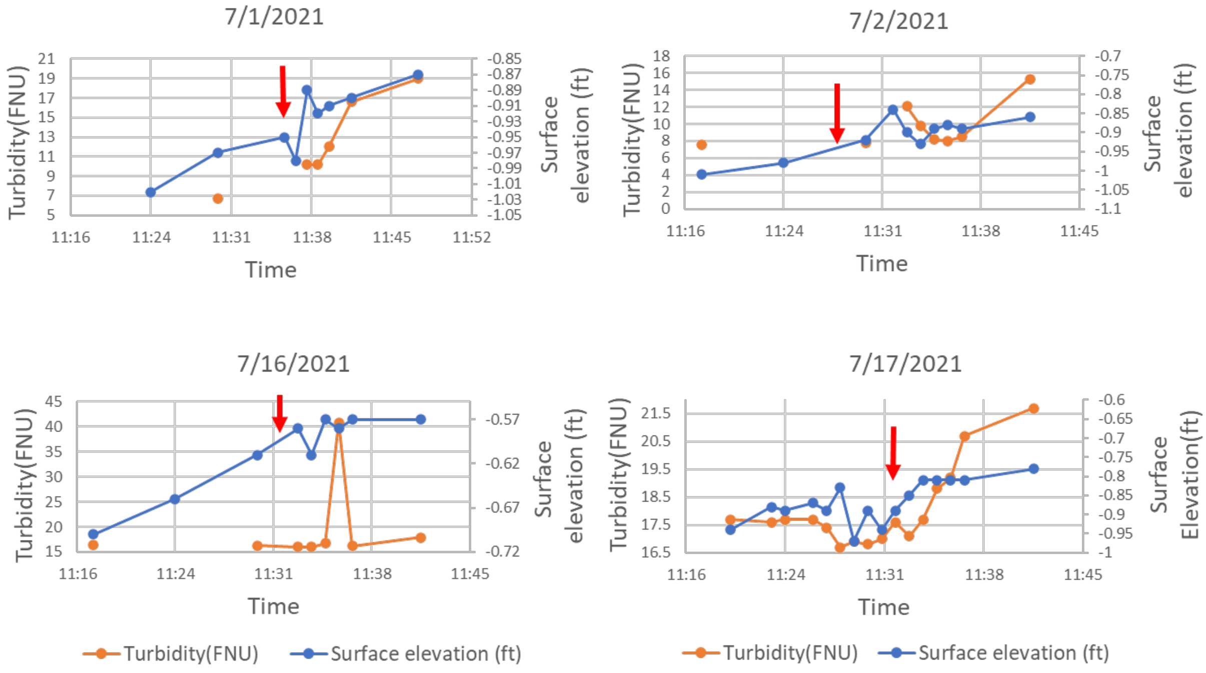

**Figure 4:** **Graphs of the changes in Turbidity (FNU) and Surface elevation (ft) before and after boat wake events. The vertical red arrows indicate the approximate time at which the boat passed the dock.**

Discrete grab samples for TSS were collected from the RCSP floating dock just before and after boat wake events, and TSS was found to be significantly greater after the boat wakes (Wilcoxon, p = 0.029; Figure 5). In contrast, paired enterococci samples collected from the floating dock before and after boat wake events were not significantly different (Wilcoxon, p = 0.267; Figure 6). The change in TSS in paired samples (TSS after – TSS before) at the dock ranged from -76 mg/L to +336 mg/L. Given the observed concentration range of enterococci in sediment at this site (MPN of 2.7 x $10^4$ to 1.0 x $10^5$ per 100 g of sediment) and the observed change in suspended sediment after boat wakes, the expected change in enterococci from this amount of suspended sediment would fall between an MPN of -3/100 ml and +34/100 ml. By comparison, the observed change in enterococci ranged from an MPN -231/100 ml to +496/100 ml, with a median of 0/100 ml.

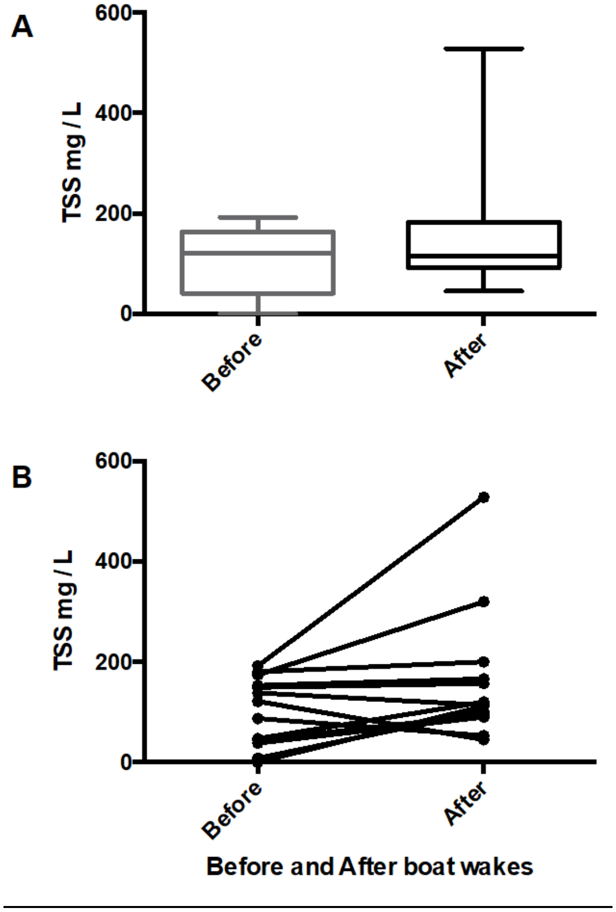

**Figure 5:** **A) Box plots of TSS "before" and "after" boat wake events at the RCSP Dock; and B) paired TSS measurements "before" and "after" boat wake events at the RCSP Dock.**

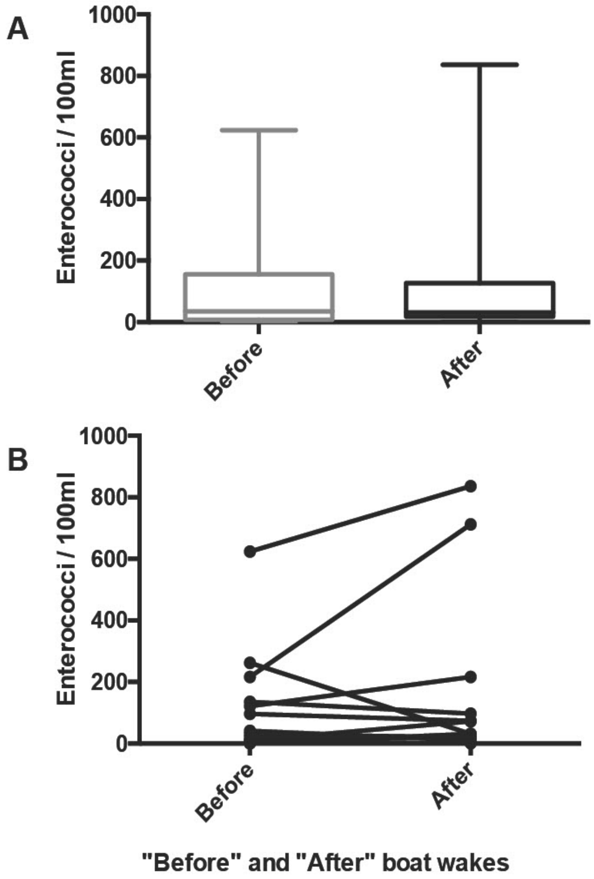

**Figure 6:** **A) Boxplots of enterococci per 100 ml of water "before" and "after" boat wake events at the RCSP Dock; and B) paired measurements of enterococci per 100 ml of water "before" and "after" boat wake events at the RCSP Dock.**

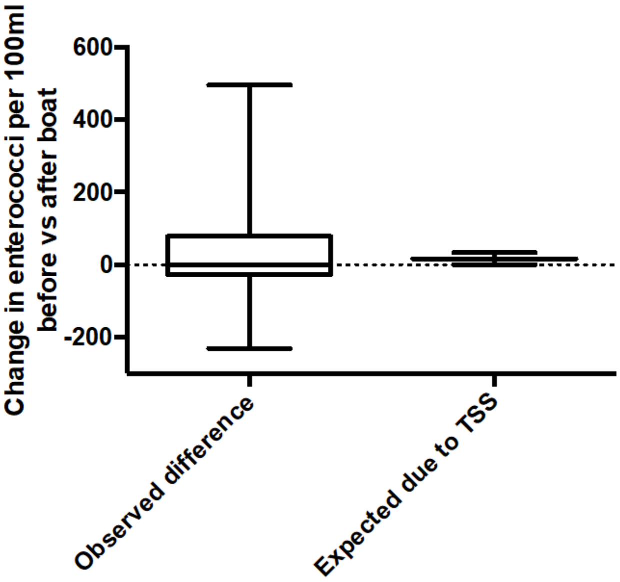

**Figure 7:** **The observed change in enterococci from before and after boat wake events can be compared to the expected increase that is calculated from the observed change in TSS (mg/L) and the concentration of enterococci per mg of sediment at the site.**

## DISCUSSION

The sediment FIB levels measured in this study are the first reported from the Harlem River. Although samples are limited in number and only spatially represent the area directly next to RCSP, the levels observed were within the range reported in Flushing Bay, another New York City CSO impacted waterway (O'Mullan et al. 2019). Harlem River sediment FIB values were at the upper range for those reported from other Hudson River estuarine environments. It should be noted that this study was primarily done in dry weather conditions and does not represent the full range of FIB concentration expected for water samples from the Harlem River. Although this study has only measured enterococci levels in the water column and sediment of the Harlem River, based upon other surveys of sediment in estuaries, the levels of enterococci would be expected to correlate with other fecal indicators, including *E. coli* and fecal associated potential pathogens (e.g., *Salmonella*, *Cryptosporidium*, *Giardia* and enteric viruses) (Perkins et al. 2014; Hassard et al. 2016; O'Mullan et al. 2019).

The levels of FIB in sediment from prior surveys and this study were significantly higher than the FIB levels in the overlying water column, providing evidence that sediment accumulates FIB from the water column and acts as an environmental reservoir. Once deposited into a sediment bed, particle-associated FIB have prolonged persistence relative to those in water (Korajkic et al. 2013; O'Mullan et al. 2017; Myers and Juhl 2020). This is the case, especially in sediment composed of high amounts of clay, silt, and fine sand, which are positively correlated with higher concentrations of organic matter (Korajkic et al. 2013; Perkins et al. 2014). Particle-associated FIB are not confined to the sediment reservoir and can be released back into the water through disturbance of the sediment bed (e.g. surface waves, storm-generated currents, and boat wake disturbance) (Pettibone et al. 1996; Valipour et al. 2017).

In combination with other factors, boat wakes are correlated to shoreline erosion and disturbance of bottom sediments in various water systems (Johnson 1994; Gabel et al. 2017). Boat wakes produced by commercial and recreational boat traffic have been found to induce sediment resuspension events, especially at the shoreline, due to the waves' grouped structure and steepness (Beachler and Hill 2003; Garel et al. 2008; Houser 2011). As a result of sediment resuspension, particle-associated FIB derived from the sediment reservoir can be a potential driver for elevated FIB levels in water during periods of dry weather.  Event-based data from the RCSP USGS monitoring station demonstrated sediment disturbances following boat wakes in the form of positive correlations between water surface elevation and turbidity levels. As a boat passes by the sampling location, waves are expected to be created, resulting in sediment bed disturbance of the shallow cove and adjacent shoreline. Boat wakes, as expected, induced a rise in surface elevation. Measures of turbidity and visual observations provided evidence that sediment resuspension occurred near the waterfront of RCSP following these disturbance events.

There are prior examples of boat wakes associated with sediment resuspension causing elevated FIB levels. A study in the Buffalo River, NY, found elevated levels of TSS and fecal coliform following the passage of large vessels (Pettibone et al. 1996). Similarly, in Dublin Port, Ireland, turbidity plumes caused by ship traffic had *E. coli* and enterococci levels up to 9 times higher than pre-disturbance conditions (Briciu-Burghina et al. 2014). Other types of disturbances (e.g., shoreline wading, stream velocity increases, breaking waves) have also been shown to cause sediment resuspension and associated degradation in water quality. A study in the Hudson River demonstrated an increase in FIB concentration following experimental sediment bed disturbances from a sampler entering the water (O’Mullan et al. 2019). During high discharge, periods of increased sheer velocity have been associated with mobilization of particle-associated FIB from sediment beds in streams (Smith et al. 2008; Cho et al. 2010). Turbulence from breaking waves in the surf zone of recreational beaches has been shown to cause elevated levels of both turbidity and FIB, helping to understand water quality degradation during dry weather (Halliday et al. 2014). These studies collectively demonstrate the potential importance of sediment disturbance events for understanding water quality in shallow systems. However, in this study, enterococci concentrations compared before and after boat wake disturbance events did not differ significantly in FIB concentration.

Visual observations during sampling noted patchy plumes of resuspended sediment that differed with each sampling event and highest turbidity levels did not always reach the sampling location, possibly providing an explanation for the variable “before” and “after” results. Previous studies have found that after sediment resuspension, the direction of net transport can be changed or reinforced based on the timing of the group of boat waves hitting the shoreline (Houser 2011). This factor creates variability in the conditions of each sampling event. Sampling occurred at a fixed location, not always capturing the maximum turbidity levels, whereas some prior studies specifically sampled in turbidity plumes flowing boat passage (e.g. Briciu-Burghina et al. 2014) and may account for the differing conclusions.

Although the sampling events all took place during dry weather, to limit other important factors contributing to FIB variability, this preliminary study captured only a small number (n = 14) of disturbances from large boat wake events that occurred under differing conditions. Given the small number of sampling events, complicating factors such as the combination of tidal depth, tidal direction, river velocity, and speed and size of the boat could not be controlled. The sedimented cove was also expected to vary in complex ways with the characteristics of the soft shoreline possibly amplifying waves differently than the nearby bulkhead and the composition (rocky vs. sedimented) of the shoreline interacting with waves changes at differing tidal heights or tidal directions. The results of this study did show that boat wake events can cause a significant increase in TSS by disturbing the sediment bed, and that sediment contained high levels of FIB, but these events did not cause a consistent or significant increase in FIB compared to the background dry weather FIB variability observed at this Harlem River site. There may still be need for management concern about the potential impacts of boat wake driven sediment resuspension events on water quality. However, data from this study suggests that the causes of elevated dry weather FIB levels beyond boat wake disturbances still require additional investigation.

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