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Combined Sewer Overflows (CSOs) Impact on Water Quality and Environmental Ecosystem in the Harlem River

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Abstract

The Harlem River, a 9.3-mile channel that flows from the Hudson River to the East River, has experienced decades of industrial abuse and remains gritty and industrial. During heavy rains, the pipes discharge raw sewage into the river through combined sewer overflows (CSOs) that can contain bacteria and cause illness. Water samples were collected from CSO discharge point and several adjacent sites along the river in the Bronx side close to River Park Towers at Richman Plaza and Manhattan side at Wards Island. Nutrients, bacteria, polychlorinated biphenyls (PCBs), and fish consumption safety have been analyzed. Results showed that phosphorus, ammonia concentration as well as fecal coliform, E.Coli, enterococcus levels increased significantly during heavy rainstorms. Ammonia concentration was up to 2.725 mg/L during tropical storm Arthur on July 2, 2014 and rainstorm in May 2013, and soluble reactive phosphorus (SRP) or orthophosphate was up to 0.197 mg/L during heavy thunderstorm in April 2011; both nutrients were exceeded EPA regulation for ammonia (0.23 mg/L) and phosphate (0.033 mg/L) for New York City (NYC) waters. The colonies of fecal coliform were more than 5 million MPN/100ml (most probable number per 100 ml) during tropical storm Arthur in July 2014 and heavy rainstorm in April 2014, and fecal coliform was more than 10,000 MPN/100ml during storm in July and November 2013; E.Coli reached more than 5000 MPN/100ml during tropical storm Arthur and storm in May 2013; enterococcus reached more than 10,000 MPN/100ml during tropical storm Arthur and heavy rainstorm in April 2014. These bacteria (pathogen) levels in the Harlem River were significantly higher than EPA standards (fecal coliform: 200 MPN/100ml, E.Coli: 126 MPN/100ml, enterococcus: 104 MPN/100ml), especially during rainstorm/tropical storm. Of particular significance, nutrients and bacteria were analyzed before and after Hurricane Sandy devastated NYC in late October 2012; results determined that bacteria and ammonia concentrations increased after this monumental storm, elucidating the environmental impact of large storm events. PCB 11 (3,3'-dichlorobiphenyl,

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$C_{12}H_8Cl_2$), the high molecular weight (MW), an indicator of raw sewer and storm water runoff in the NYC harbor waters, is the major polychlorinated biphenyls (PCBs) in the Harlem River. PCBs are carcinogenic, which could bioaccumulate via food chain from fish and seafood, endangering public health. Oyster farming has been used to purify water and improve water quality in the river. CSOs and storm water runoff have degraded water quality and been threatening environmental ecosystem and public health. This research will help local communities understand CSO impact on nutrients, bacteria, PCBs contamination and fish consumption safety, and make contributions on CSOs reduction as well as improve water quality and environmental ecosystem in the Harlem River.

Keywords

CSOs, Ammonia, Phosphate, Fecal Coliform, E.Coli, Enterococcus, PCBs, Fish Consumption Safety

1. Introduction

Combined sewer overflow (CSO) water is a mixture of urban runoff and municipal wastewater; is discharged into rivers and canals during heavy rainfall; releases dissolved contaminants, particulate organic matter loads, oxygen consumption, bacteria and viruses, causing fish death and health risks [1] [2]. CSO under wet weather and permanent dry weather impacts the river quality spatially and temporally [1]. In frequent-rainfall regions, CSO causes contaminations frequently, which was weather and climate dependent [3]. In dry weather, a combined sewerage system theoretically only collects municipal waste [3]. In wet weather, wastewater is mixed with urban runoff water, and sometimes the sewer systems could not transport all the wastewater to reach the waste water treatment plant (WWTP) or the wastewater capacity exceeds the WWTP treatment capacity. In this situation, CSOs occur, resulting in untreated sewer (raw sewer) discharge into urban river systems, such as the sewer discharge into the Harlem River in the Bronx side during storm [4]. CSOs and sanitary sewers are often a significant source of unsafe levels of pathogens in urban areas that endangers swimming, fishing and other recreation uses [5].

CSOs regularly caused strong oxygen depletion in the river, endangering the fish population and water quality [1] [6]. CSO impacts the river ecology and water quality; high load of organic matter (OM) brought by untreated wastewater causes oxygen depletion; the reduction of photosynthetic primary production increases turbidity; plus metal and organic pollutants' concentrations increase; nutrient levels increase and bacteria increase [4]. Total SS, biological oxygen demand (BOD_5), NH_4 or total Kjedal nitrogen (TKN), nitrates and total phosphorus concentrations were considered as basic parameters of CSOs test [7]. The CSOs effects on contaminants load include: oxygen demand (BOD, COD and NH_4^+), nutrients (N and P), toxic substances (NH_3, heavy metals, microcontaminants), hygiene (fecal coliform, E.Coli, enterococcus bacteria), and physical parameters (temperature, suspended solids, flow, EC, pH, DO, redox etc.) [3]. When the CSO exceeded the capacity of waste water treatment plant, the discharge receiving river may be contaminated severely [3]. Industry, agriculture and domestic sewage are three major sources of phosphorus pollution in aquatic environment [8] [9]. Some of the high nutrient levels (nitrogen and phosphorus) were found in downstream urban rivers close to WWTP facility [10]. Toxic contamination, pathogens and wetland loss are primary environmental concerns in the NY/NJ Harbor system. Untreated sewage particularly contributed by CSOs during rains has been threatening water quality in NY/NJ Harbor [11].

The combined sewage system in NYC carries both storm water and sanitary wastewater in the same pipe to WWTP in dry weather, where it is treated before being discharged into local waterways. During wet weather conditions, when there is heavy rainfall, water volume exceeds the pipe capacity, and the excess is discharged into rivers and streams directly without treatment. This is called CSOs as mentioned above. Over 90% of the pollution in NYC's waterways is from this runoff [2] [12]. The CSOs can contaminate water and degrade water quality; can carry bacteria and viruses; and cause diseases [2]. During wet weather, discharge points along the Harlem River may discharge rainwater mixed with untreated sewage that contains bacteria and can cause illness. There is a warning sign about the safety at the Wet Weather Discharge Point: "This outfall may discharge rainwater mixed with untreated sewage during or following rainfall and can contain bacteria that can cause illness";

"If you see a discharge during dry weather, please call 311 or contact NYS DEC office". In summer, sewer overflow discharges a large amount of nutrients, including P, N, ammonia, pathogens (fecal coliform, E.Coli, and enterococcus) and other pollutants into the river. These pollutants can stay in the river for nearly half month before flowing into the Atlantic Ocean.

Determining the nutrients and pollutants level is important to help reduce water contamination and improve water quality in the Harlem River. Phytoremediation with water hyacinth, a floating aquatic plant, native to tropical America, has been used to remove total phosphorous (TP) and ammonia nitrogen (NH_3-N) [9] [13]. However, water hyacinth had been planted in the Harlem River and Harlem Meer (lake) in Central Park, which could not be able to survive or remove nutrients due to different hydro-climatic conditions. Oysters farming had been used to filter the NYC river water; they absorbed the contaminants and improved water quality in the Harlem River and the Bronx River. The Bronx oysters have the ability to filter pollutants and anchor a marine ecosystem with their craggy reefs [14].

Polychlorinated biphenyls (PCBs) have historically been a pollution problem in the Hudson River and the Harlem River—tributary of the Hudson River. Sources of PCBs in the Harlem River are from the upper Hudson River general electric (GE) plants located at Fort Edward and Hudson Falls [15]-[17]; as well as from Harlem River local sources including storm water runoff, CSOs, and wastewater effluents [18]. PCBs from the upper Hudson River are dominated by lower molecular weight (MW) congeners including low MW Aroclor 1254 by GE as well as dechlorination of PCBs in the sediments [18]. In the Harlem River and NY/NJ Harbor, high MW PCBs sources are dominated by storm water runoff and CSOs mostly PCB 11 that is a non-Aroclor congener and is an indicator of storm water, CSOs and wastewater [18]-[20]. PCBs affect human health through the food chain or by individual exposure, such as swimming. PCBs that are bioaccumulated through the food chain from fish and seafood, such as striped bass, American eel etc. can cause cancer in animals. PCBs also can cause non-cancer health effects such as reduced ability to fight infections, low birth weights, and learning problems [21].

Striped bass caught in the Hudson River had been banned from commercial in 1970's because PCB's concentration is more than EPA regulated level of 2 ppm (parts per million). After 1980's, striped bass was back to commercial after PCB levels lower than 2 ppm [22]. GE was fined by EPA for 6 million dollars for dredging out the polluted sediments [23], and the project has been on-going since 2006 [24]. The New York State Department of Health (NYS DOH) 2002-2003 Health Advisories for Chemicals in Sport Fish and Game listed fish consumption advisories for the Harlem River, especially for women under 50 years old and children under 15 years old (**Table 1**) [25]. The major concern was for fish containing PCBs, including the American eel, striped bass, and blue fish [26].

The Harlem River, a tributary of the Hudson River, receives pollutants from the Hudson River; therefore the pollutants including mercury and PCBs flow into the Harlem River. Mercury, PCBs, as well as low levels of radioactive material have historically been found in the Harlem River system. PCBs contamination of fish is a primary concern for both the Hudson River and Harlem River water bodies [27]. Pollutants from the East River flow into the Harlem River, as well [28]. Even though water quality parameters do not exceed NYC DEP standards, the Harlem River received substantial pollutants from urban runoff, including storm water runoff and CSOs. There are around 50 Harlem River CSOs sources, which are greater than those of the Hudson and the Bronx Rivers [29]. Water in the Harlem River is turbid because high suspended solid content and high concentrations

Table 1. Advice of fish consumption caught in the Harlem River [25].

fish	Men over 15 and Women over 50	Women under 50 & Children under 15	Chemicals of Concern
Blue Crab Meat	Up to 4 meals/month (6 Crabs per Meal)	Don't Eat	PCBs, Cadmium
Crab or Lobster Tomalley (Hepatopancreas, Mustard) and Cooking Liquid	Don't Eat	Don't Eat	PCBs, Cadmium, Dioxin
Channel Catfish, Gizzard Shad, White Catfish	Don't Eat	Don't Eat	PCBs
Atlantic Needlefish, Bluefish, Carp, Goldfish, Rainbow Smelt, Striped Bass, White Perch	Up to 1 meal/month	Don't Eat	PCBs
All Other Fish	Up to 4 meals/month	Don't Eat	PCBs

of nutrients that potentially lead to nutrient enrichment [30].

The Federal Clean Water Act limits the amount of ammonia that can be discharged into wastewater treatment plant effluents to 1 mg/L. Many municipalities use bacteria to remove ammonia from water by nitrification/denitrification. Some municipalities retain breakpoint chlorination to remove ammonia from wastewater effluents [31]. The US EPA suggested a criterion concentration of P of maximum of 0.015 mg/L in reservoirs [32]. The national background P concentration was 0.042 mg/L [10]. The highest TP concentrations were in streams in urban and agricultural areas (in US), and the median concentration (0.25 mg/L or 250 μg/L) was around 6 times greater than background concentrations (0.042 mg/L or 42 μg/L). In urban area, P sources were runoff from golf courses, residential lawns, construction sites, sewage overflow (treated wastewater effluent), and septic-system drainage. In agricultural area, P sources were associated with fertilizers and manure intensive applications [10]. EPA's criterion of nutrient for ecoregion of P is 0.033 mg/L or 33 μg/L [33]. US EPA ammonia criterion is 0.23 mg/L (230 μg/L) [34]. NYS DEC suggested using EPA's chronic value of DO-4.8 mg/L for NYC waters. EPA recommends that DO for Class I marine water is never less than 4.0 mg/L; the aquatic life survival DO value is never less than 2.3 mg/L [34]. EPA standards of bacteria levels in NYC waters: fecal coliform < 200 MPN/100ml (most probable number per 100 ml), E.Coli < 126 MPN/100ml, and enterococcus < 104 MPN/100ml [35]. EPA standard of turbidity for NY/NJ waters is 0.25 - 5.25 FAU/NTU [33] [36].

The Harlem River has been used as a major resource for water recreation throughout its history [29]. Currently there is limited accessibility to the Harlem River for community enjoyment, and the Harlem River watershed has been highly urbanized. Water quality has been degraded by CSOs as point-source pollution and storm water runoff and activates from the Hudson/East River as nonpoint sources of pollution [28]. Untreated sewage contributes to decrease in usability and water quality, as increased fecal coliform and enterococci levels, decreased dissolved oxygen and increased nutrient levels. There are basic water quality parameters and enterococcus levels on Riverkeeper website [37] [38]; however the data are limited and some pollutants levels (such as turbidity and enterococcus) were underestimated. Nutrient and bacteria levels in the Harlem River on USGS website [28] were underestimated. This research has aimed to provide more updated and accurate bacteria, supplement nutrients and water quality data; provide solid references and comparison to existed data to EPA, NYC DEP, NYC DEP, USGS, Urban Divers Ecology Center (UDEC), Bronx Council for Environmental Quality (BCEQ), Bronx River Alliance, and Riverkeepers; help improve water quality, community accessibility, water recreation and ecology restoration of the Harlem River. This research has been conducted since 2011 to present: collected water samples and analyzed EC, pH, ammonia, phosphate, turbidity, fecal coliform, E.Coli, enterococcus and PCBs; estimated the levels if exceeded EPA regulated concentration in NYC waters; determined CSOs impact on water contamination; kept communities aware of fish consumption safety.

2. Material and Methods

2.1. Study Area

The Harlem River (**Figure 1**), a 9.3-mile channel that flows from the Hudson River to the East River, has been experienced decades of industrial abuse and remains gritty and industrial. "In the Bronx side, major highways and train tracks cut the public off from the water on the Bronx side, and the pipes that discharge raw sewage during heavy rains dot both shores [39]." The Harlem River is classified by New York State Department of Environmental Conservation (NYS DEC) as a Class I saline surface water for secondary contact recreation and fishing [30], swimming as primary contact is not safe in the river [28].

The Harlem River is part of Hudson River estuary system. It is a navigable tidal straight that divides the island of Manhattan from the Bronx. The Harlem River flows between the Hudson River and the East River, separating the boroughs of Manhattan and the Bronx [40]. It connects two larger water bodies, stretching from the Hudson River to the intersection of the East River at Randall's Island, at approximately 125th Street in Manhattan [40]. Currents fluctuate dramatically in the Harlem River because of the ebb and flow of the tides. Tides affect pollutants, silt, and suspended sediments transported in the water. Tides make it particularly difficult to navigate in the northern portion of the waterway in the Harlem River [40]. Wards Island WWTP is the only WWTP serves the Harlem River. Precipitation, increased water use and WWTP failure caused CSOs discharge into the Harlem River [28].

Over the past century, the Harlem River watershed has become highly urbanized with 90 percent of the waterway constrained by infrastructure, and there is limited accessibility to the Harlem River for community [28].

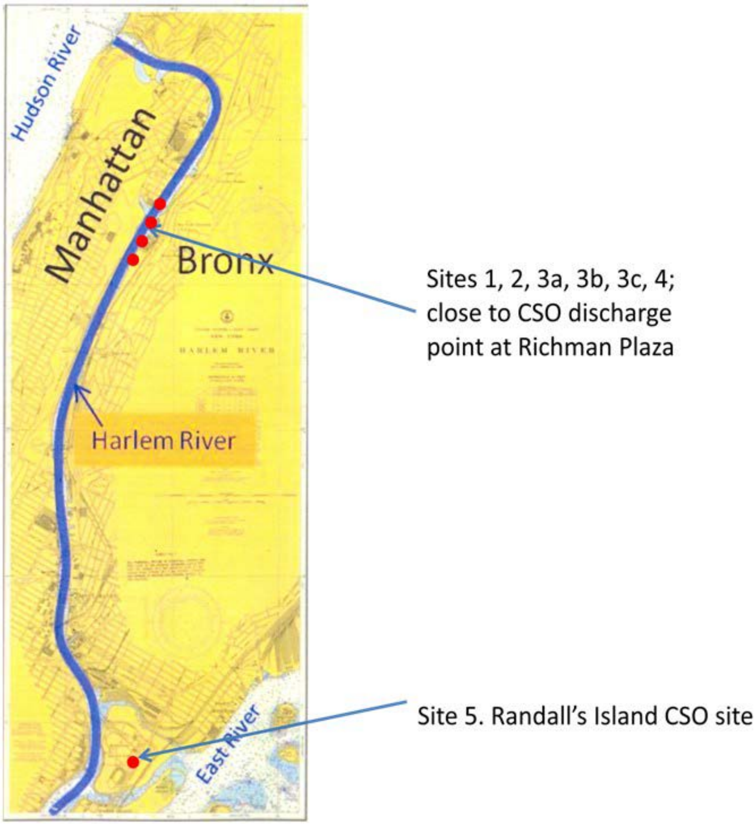

Figure 1. Harlem River study area and sampling sites (map source: USGS, 2012).

The Harlem River became highly industrialized as urban sprawl continued and local economy grew. Historically swimming, boating and fishing were activities of the Harlem River. South Bronx Officials are trying to turn an industrial area between 149th and 138th Streets into a waterfront district, making both sides of the river accessible to the public [41]. During rainstorm, there are more than 50 CSOs that discharge untreated sewage and runoff from impervious surface to the Harlem River [28]. NYC DEP and NYS DEC made effort to divert some of the rainwater from reaching CSOs in order to reduce the untreated sewage load to the local waterway, which is aim to help ecological restoration of the Harlem River [28]. CSO discharge of untreated sewage during precipitation events contributes pollutants that degrade water quality and impact aquatic life and enjoyment by residents. Tidal current carried pollutants from the Hudson River and East River and effluent from sewage retreatment plant [28].

2.2. CSOs Water Sampling

Water samples were collected from the CSO discharge point located at River Park Towers in Richman Plaza beside Roberto Clemente State Park, which is the major sampling site. Other sites are: beside Harlem River Ecology Center (HREC), CSOs tank, CSOs overflow, beach below the High Bridge and CSO discharge point at Randal's Island (**Table 2**). Most sites other than Randal's Island site are located in the Bronx section of the River. Water samples were transported to Bronx Community College (BCC) Chemistry Laboratory and Lehman College Environmental Laboratory and analyzed EC, pH, ammonia, turbidity and bacteria immediately; stored at 4˚C for further experimental analysis.

2.3. Bacteria Analysis

Water samples were filtered through 0.45 µm sterilized membrane, then transfer the membrane to the selective agar plates for fecal coliform, E.Coli, and enterococcus; incubate at 37˚C for 24 h and count the colonies as MPN/100ml.

Table 2. Water sampling sites' locations and coordinates in the Harlem River.

Site#	Name	Location	Latitude	Longitude
1	HREC	Water front beside HREC office at 10 Richman Plaza	40˚51'04.62"N	73˚55'26.13"W
2	Beside HREC	Below the fence, water front beside UDEC office at 10 Richman Plaza	40˚51'04.38"N	73˚55'26.29"W
3	CSO	CSO wet weather discharge point	40˚51'02.42"N	73˚55'27.00"W
3a	CSO surface	Beside CSO discharge site pipes, surface water site	40˚51'02.42"N	73˚55'27.00"W
3b	CSO downstream	50 yards south downstream of CSO discharge site		
3c	CSO tank	The tank of CSOs discharged to the pipes	40˚51'02.42"N	73˚55'27.00"W
4	Beach	Beach below high bridge	40˚50'32.50"N	73˚55'46.18"W
5	Randall's Island site 1	Close to CSO discharged point	40˚48'06.95"N	73˚55'31.98"W
Hudson	Hudson River	125th St. along the Hudson River close to North River WWTP raw sewer spill (7/20/11) location	40˚49'11.75"N	73˚57'37.36"W

Harlem River: sites 1, 2, 3, 3a, 3b, 3c, 4 and 5. Hudson River: North River WWTP raw sewer spill site at 125th St.

2.4. Ammonia

Filtered water samples were analyzed by Nessler reagent method for ammonia (NH_3-N), using the HACH Program #25 on the HACH 4000 spectrophotometer [31] [42].

2.5. Phosphate (Soluble Reactive Phosphorus)

Filtered water samples were analyzed automated ascorbic acid method [43], by Shimazu UV-2501PC probe spectrophotometer at wavelength 880 nm.

2.6. Turbidity

Turbidity was measured by HACH 4000 spectrophotometer [42], recorded as FAU. Use 10 ml deionized distilled water as blank and zero, then place 10 ml water sample into the glass cell and record turbidity data [31] [42].

2.7. PCBs

The water samples were extracted by methylene chloride (dichloromethane-DCM): 100 ml water sample mixed with 100 ml DCM, shaking well in a separation funnel, get DCM extraction with a beaker with sodium sulfate (Na_2SO_4 as drying agent), then concentrate the extraction in a rotavapor to 5 ml, filter with pipette (cotton and silica gel), reconstitute with isooctane to keep the same matrix as the standard of PCB 11: 3,3'-dichlorobiphenyl (BZ#11) (100 µg/ml) and matrix is isooctane (2,2,4-trimethylpentane). Then analyze by high resolution gas chromatography/mass spectrometry (HRGC/MS) at BCC Chemistry Department [44] [45]. In order to get strong signal, water sample was concentrated before extraction, and spike with non-Aroclor congener PCB 11/Aroclor 1242/1254 standards.

3. Results and Discussion

3.1. EC, pH, DO

EC and pH is considerable stable among different sites in different weather conditions (**Table 3**). Average pH was 7.22 in water samples collected in 2014, 7.26 in 2013, and 7.52 in 2011, which were lower than average pH in the Bronx River 7.8 for water samples collected in 2006 and 2007 [46]-[48]. Average EC for water samples collected in the Harlem River in 2011 and 2013 was 2271 µs/cm, which was significantly higher than EC in the Bronx River freshwater section (756 µs/cm in 2006; 741 µs/cm in 2007); which was lower than the EC in the Bronx River saline estuary sites at Sound View Park (34,900 µs/cm in 2006; 31,600 µs/cm in 2007) [46]-[48]. The EC maximum in 2014 was 1794 µs/cm on July 28, 2014; however during heavy rainstorm on April 30 2014 EC decreased to 19.22 µs/cm and dilution could cause the low EC (EC and pH were not available in some of the data in 2014 due to instrument usage limitation). Harlem River was a mixing with fresh and saline water, therefore the EC was higher than freshwater, and lower than estuary in the Bronx River. The New York/New Jersey (NY/NJ) Harbor is rated good for DO concentrations, with 62% of the estuary are rated good for this component

Table 3. Water quality data of the Harlem River from 2011-2014.

Date	Weather	Site	pH	EC µs/cm	Fecal coliform	E.Coli	Enterococcus
4/22/14	Afternoon showers	3a	6.63	825.5	2500	10	54
4/30/14	Heavy rain	3	7.06	19.22	5 million	500	10,000
7/2/14	Tropical storm Arthur	3			>5 million	>5000	10,000
7/14/14	Rainstorm afternoon	3a			millions	1000 - 2000	2000 - 2500
7/24/14	Rain night before	3a			1100	136	335
7/29/14	Sunny	3a	7.67	1797	80 - 100	44	160
3/30/13	Cloudy storm	3c	7.55	1878			
5/1/13	Sunny	3c	7.40	3070	400	18	35
5/8/13	Rainstorm	3c	7.23		millions	>5000	>500
5/9/13	Rainstorm	3c	7.28		<millions	<5000	<500
5/23/13	Thunderstorm	3c	7.02		>5000	>2000	>2000
7/8/13	Sunny	5. RI1	7.10	1942	>5 millions	>5000	100
7/12/13	Showers	3c	7.02	1644	10,000	300	820
10/4/13	Drizzle	3c	7.28		200	5	42
10/7/13	Showers	3c	7.29		7500	220	600
11/1/13	Rain	3c	7.41		>10,000	500	>5000
3/10/11	Rain, windy	1	7.5		100	20	
3/17/11	Sunny	2	7.7		>1000	100	2
3/24/11	Day after rain	1	7.5	2820	800 - 1000	0	6
4/7/11	Rain morning	2					
4/7/11	Rain morning	3c			>2000	>1000	800
4/28/11	Thunderstorm	3			millions	thousands	0
4/28/11	Thunderstorm	3a			thousands	hundreds	0
4/28/11	Thunderstorm	3b					
5/5/11	Sun mix clouds	3a					
5/5/11	Sun mix clouds	4	6.7		hundreds	100	20
5/12/11	Cloudy	3a					
5/12/11	Cloudy	4	7.52				
7/13/11		3a					
7/13/11		4					
7/25/11		3a					hundreds
7/25/11		3c			>thousands	hundreds	thousands
7/25/11		H-NR					thousands
9/28/11		3a					
7/18/12		3a					
9/18/13		3a					
10/24/12	Before Sandy	3a				100	
11/1/12	After Sandy	3a	7.33			>100	
11/8/12	After Nor'easter	3a					

5. RI1: Randall's Island site 1; H-NR: Hudson River site close to North River WWTP raw sewer spill at 125th St.

indicator and none of the area rated poor [11]. The DO ranged from 4.65 (59%) to 7.52 (66.9%) mg/L in 2011; average DO in the Harlem River was 6.21 mg/L or 63.6% (water collected in 2011; no DO data in 2012,2013 and part of the data in 2014 due to funding limitation and instrument shortage); which has similar range compared to USGS data for surface water 2 to 9 mg/L in a 5-year increments and average is higher than USGS data 4 mg/L [28]. However, during tropical storm Arthur on 7/2/2014, the DO was 4.0 mg/L (49%) at beginning of the heavy thunderstorm and then dropped down to 2.9 mg/L (35%) as the tropical storm getting heavier. It indicated that DO in the CSOs decreased significantly during heavy tropical storm, which was lower than USGS average DO of 4 mg/L [28] and EPA standard that DO for Class I marine water is never-less-than 4.0 mg/L [34]. It was lower than DO minimum 48% at Harlem River-Washington Bridge data [38].

3.2. Bacteria—Fecal Coliform, E.Coli, and Enterococcus

Fecal coliform, E.Coli, enterococcus levels increased significantly during heavy rains (**Table 3**). Fecal coliform was more than 5 million MPN/100ml in CSOs at CSO discharge point (site 3) during tropical storm Arthur on July 2, 2014. It reached 5 million MPN/100ml during heavy rainstorm on April 30, 2014 at site 3 as well as on July 8, 2013 at Randall's Island site 1 (close to CSO discharge point). Fecal coliform reaches millions (uncountable colonies) MPN/100ml during rain storm on July 14, 2014; May 8 - 9, 2013 at site 3a (surface water close to the CSO discharge point), and April 28, 2011 at site 3 CSO discharge point; more than 10,000 MPN/100ml in heavy rain in July and November 2013; far exceeded EPA standard of 200 MPN/100ml. Summer average fecal coliform ranged from 40 to 2500 MPN/100ml among the data 1909 to 2009 [28], this research indicated that much higher level of fecal coliform in the Harlem River during spring and summer especially during heavy rainstorms at CSO discharge points along the river.

E.Coli was more than thousands, 5000, 1000, 500 MPN/100ml during heavy rains as well (EPA standard is 126/100ml). E.Coli was more than 5000 MPN/100ml duringtropical storm Arthur on July 2, 2014 and rainstorm on May 8, 2013, and reached thousands MPN/100ml on April 28, 2011 during heavy thunderstorm. E.Coli appeared high level >5000 MPN/100ml on July 8, 2013, a dry day at Randall's Island site 1 where close to CSO discharge point and Wards Island WWTP. There was an increase of pathogens (used no-selective plate, could not distinguish bacteria type) after Hurricane Sandy (>100 MPN/100ml) compared to before Sandy (100 MPN/100ml).

Enterococcus, an indicator of raw sewer, reached 10,000 MPN/100ml during tropical storm Arthur on July 2, 2014 and heavy rainstorm on April 30, 2014; which was nearly twice as the maximum of Riverkeeper's data of 5635 MPN/100ml on 7/14/2008 at Harlem River-Willis Ave. Bridge [38] (**Table 4**). Enterococcus maximum levels in 2014 on Riverkeeper's website was 148 MPN/100ml on 5/12/2014 at Harlem River-Washington Bridge station, and 109 MPN/100ml on 5/12/2014 at Harlem River-Willis Ave. Bridge station (**Table 4**). Riverkeeper published data was short of tropical storm and heavy rainstorm data in 2014 [38], and it could underestimate the maximum enterococcus levels in the Harlem River. Enterococcus reached 5000 MPN/100ml during heavy rainstorm in Nov 1, 2013; >2000 MPN/100ml during thunderstorm on May 23, 2013; reached 800 MPN/100ml on April 7, 2011 during rains, and 500 MPN/100ml during storm on May 8 - 9, 2013. Enterococcus could reach significantly high levels during heavy tropical storm/rainstorms. CSOs discharged raw sewer during rainstorm resulted in increased enterococcus level exceeded EPA standard of 104 MPN/100ml [35], which might cause illness threatening public health and environmental ecosystem in the river. Compared to river keeper's count in 2013 on their website (**Table 3** and **Table 4**), the maximum of Harlem River-Willis Ave. Bridge was 173 MPN/100ml on 8/14/13 and the maximum of Harlem River-Washington Bridge was 1670 MPN/100ml on 08/14/2013, both were unacceptable, exceeded the sample thresholds (111 MPN/100ml) [37] [38]. Enterococcus count from CSOs discharge point research site close to River Park Towers at Richman Plaza, close by Roberto Clemente State Park, maximum was >5000 MPN/100ml on 11/1/2013, significantly higher than Willis Ave and Washington Bridge data from Riverkeeper record in 2013 and similar to historical high record in 2008 of 5635 MPN/100ml at Harlem River-Willis Ave. Bridge and higher than record in 2013 of 1670 MPN/100ml at Harlem River-Washington Bridge (**Table 3** and **Table 4**) [37] [38]. Enterococcus level was more than 2000 MPN/100ml on May 23, 2013 during heavy thunderstorm in the Harlem River, which was more than river keeper's data of 1670 MPN/100ml on August 14, 2013 during rainstorm at Harlem River-Washington Bridge. Enterococcus level reached 820 MPN/100ml in rainstorm on July 12, 2013; which was lower than river keeper's data in summer storm on August 14, 2013 (1670 MPN/100ml) at Harlem River-Washington Bridge.

In 2011, enterococcus reached thousands MPN/100ml on 7/25/2011, which was more than enterococcus in the Hudson River. This collection was five days after a catastrophic fire that destroyed one wastewater tank of North River wastewater treatment plant (WWTP) resulting in raw sewer spilled 125 million gallons per day to the Hudson River. Enterococcus level in the Harlem River (>thousands MPN/100ml) was higher than this raw sewer spill site on the Hudson (thousands MPN/100ml). This maximum reading in 2011 that more than thousands MPN/100ml was significantly higher than Riverkeeper's data of maximum in 2011 (Harlem River-Willis

Table 4. Riverkeeper's enterococcus data (MPN/100ml) [38].

Date	Willis Ave. Bridge	Date	Washington Bridge
7/7/14	<10	7/7/14	108
5/12/2014	109	5/12/14	148
8/14/13	173	8/14/13	1670
8/16/11	565	10/10/12	132
5/16/11	448	5/16/11	121
10/12/11	487	10/12/10	816
7/28/09	399	7/14/08	231
6/5/09	512	4/18/07	244
7/14/08	5635	10/18/06	1467
6/24/08	160	7/11/07	238
4/18/07	356	4/18/07	274
11/10/06	310		
10/18/06	263		

Date	North River WWTP	Date	Gowanus Canal	Date	Newtown Creek-Metropolitan Ave. Bridge
7/17/13	723	8/14/13	364	8/14/13	4352
10/10/12	2098	11/8/12	>24,196	11/8/12	1095
9/10/13	2987	10/10/12	259	10/10/12	446
8/13/12	521	7/16/12	241	7/16/12	414
10/21/11	794	5/16/11	>24,196	5/15/12	146
8/16/11	201	10/10/10	>24,196	10/21/00	2300
6/27/11	262	8/17/10	4884	8/16/11	613
7/14/08	147	6/10/10	882	5/16/11	1063
4/18/07	236	6/19/09	160	10/12/10	>24,196
		5/29/09	17,329	8/17/10	3873
		7/23/08	5790	10/29/09	>24,196
		5/16/08	>24,196	6/22/09	880
				6/18/09	>24,196
				6/5/09	977
				9/26/08	>24,196
				8/19/08	223
				7/23/08	>24,196
				7/14/08	>24,196
				7/2/08	159
				6/24/18	268

All the selected data >111 MPN, not acceptable, all under wet weather condition; WWTP: Waste Water Treatment Plant; data source: www.riverkeeper.org; http://www.riverkeeper.org/water-quality/locations/nyc-hudson-bergen/harlem-river-willis-ave-bridge/; http://www.riverkeeper.org/water-quality/locations/nyc-hudson-bergen/harlem-river-washington-bridge/; http://www.riverkeeper.org/water-quality/locations/nyc-hudson-bergen/north-river-stp/; http://www.riverkeeper.org/water-quality/locations/nyc-hudson-bergen/gowanus-canal/; http://www.riverkeeper.org/water-quality/locations/nyc-hudson-bergen/newtown-creek-metropolitan-ave-bridge/.

Ave. Bridge: 565 MPN/100ml; Washington Bridge: 121 MPN/100ml). Riverkeeper's data (**Table 4**) showed that North River WWTP's maximum of enterococcus was 2987 on 9/10/13; Gowanus Canal—maximum was >24,196 on 5/16/11, 10/10/11 and 5/16/08; Newtown Creek Metropolitan Ave. Bridge maximum—>24,196 on 10/12/10, 6/18/09, 9/26/08, 7/23/08 and 7/14/08 [37] [38]. All these unacceptable conditions appeared on wet weather conditions indicated the CSOs discharged raw sewer during wet weather conditions and increased bacteria levels, which was potentially cause illness and harmful to public health.

3.3. Ammonia

Ammonia concentrations increased significantly during heavy rainstorm especially from April to October when water temperature is warmer. Ammonia concentration reached 2.725 mg/L during tropical storm Arthur on July 2, 2014 as well as heavy rain storm on May 8, 2013; 2.555 mg/L and 2.536 mg/L during two storms on October 2013; 2.293 mg/L on a dry day on May 1, 2013; 2.273 mg/L during morning rain on June 5, 2014; 1.848 mg/L during heavy rainstorm on Nov 1, 2013 (**Figure 2**). In most of the data, ammonia concentrations were significantly exceeded EPA criteria for region 2 NYC water of 0.23 mg/L [34]. The average NH_3-N (ammonia) concentration in 2013 data was 1.32 mg/L, which was higher than average in 2012 (1.02 mg/L) and 2011 (0.831 mg/L). In 2012, before Hurricane Sandy on October 24, ammonia concentration was 0.516 mg/L, increased to 0.653 mg/L 3 days after Sandy on November 1, and 0.665 mg/L one day after Nor'easter snowstorm on November 8, 2012 (**Figure 3**). CSOs during extreme super storm such as Sandy increased ammonia levels in the river. On April 28, 2011 during heavy thunderstorm, ammonia concentration was 1.449 mg/L; the maximum ammonia in 2011 was 2.205 mg/L on July 13 2011 (**Figure 4**). On July 25, 2011, five days after North River WWTP raw sewage spill, ammonia was tested in the Harlem River and the Hudson River; ammonia in the Harlem River site 3a was 1.214 mg/L and 3c was 1.326 mg/L (**Figure 4**); which were around twice of ammonia in the Hudson River (0.627 mg/L). Results showed that ammonia increased significantly during rainstorms/tropical storms.

3.4. Phosphate (SRP)

Similar as ammonia, phosphate (ortho-phosphate or soluble reactive phosphorus—SRP) reached 0.181 mg/L that was the highest in 2013 during rain storm Oct 7th, followed by 0.176 mg/L during rain on Oct 4th, 0.173 mg/L during rain storm on May 8, 0.172 mg/L on Nov 1st during heavy rain storm (**Figure 5**); phosphate concentration reached 0.197 mg/L during tropical storm April 28, 2011 (**Figure 6**). Phosphate and ammonia (**Figures 2-6**) showed that ammonia and phosphates shared the same pattern that significantly increasing concentrations during heavy rains. In 2011, the peak concentration of SRP appeared during the heavy thunderstorm on April 28, 2011 in the CSOs of 0.197 mg/L (**Figure 6**). Average SRP in 2013 was 0.145 mg/L and is higher the SRP in 2011 of 0.102 mg/L; which was more than (similar to) twice of SRP average in the Bronx River (0.067 mg/L in 2006; 0.068 mg/L in 2007) [46] [47]. Phosphate level was largely above EPA standard of 0.033 mg/L [33], and P levels were increased significantly during storms. Ortho-phosphate concentrations were from 0.0001 to 0.0015

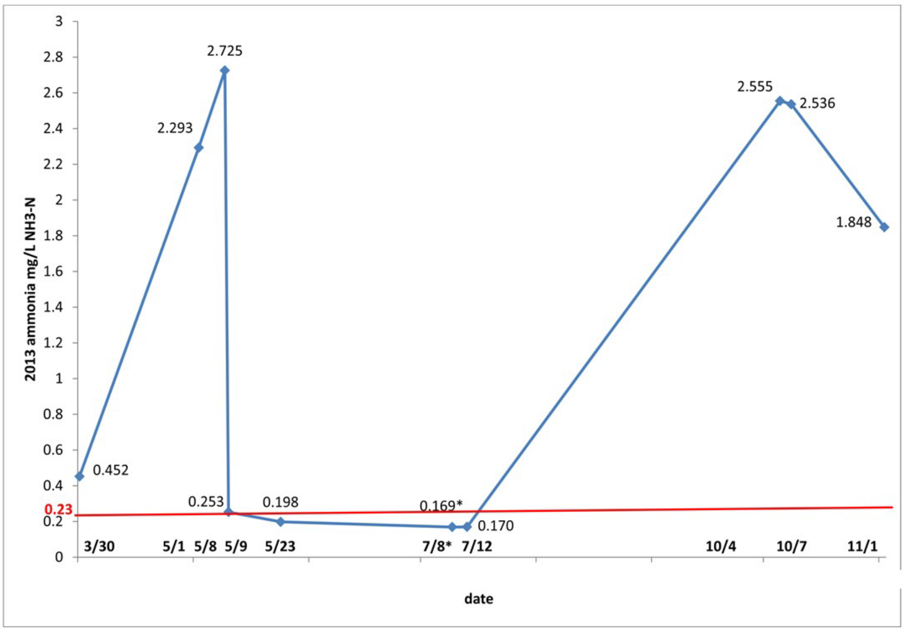

Figure 2. 2013 Ammonia in the Harlem River water. 2013: Water sampling at site 3a, other than * site at site 5 Randall's Island close to CSO discharge point.

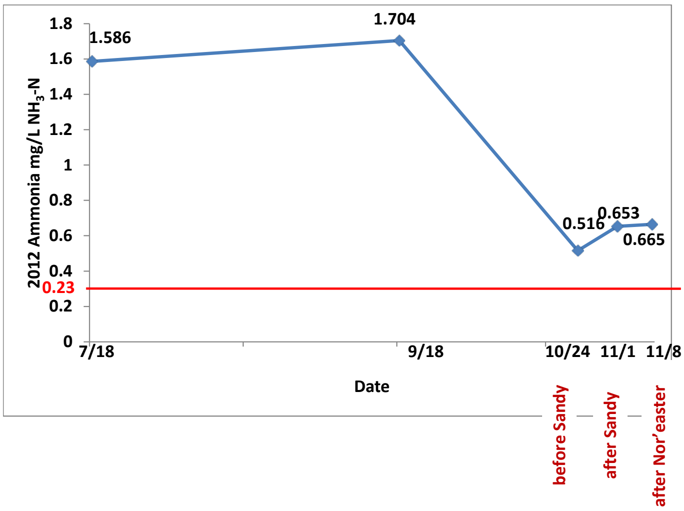

Figure 3. 2012 Ammonia in the Harlem River water. 2012: water sampling at site 3a.

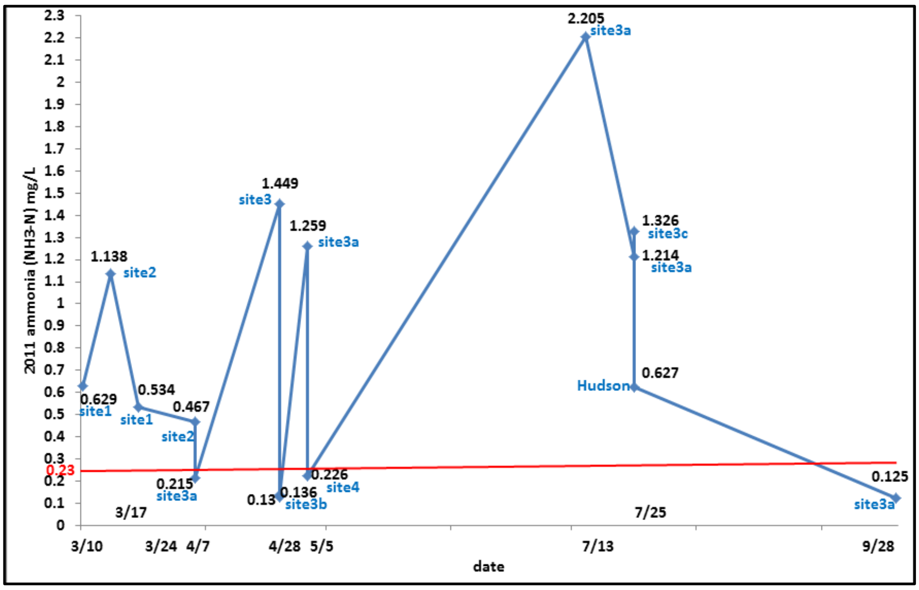

Figure 4. 2011 Ammonia in water samples collected from the Harlem River (water sampling on different sites). 2011: water sampling at sites 1, 2, 3, 3a, 3b, 3c, 4, and Hudson River North River WWTP raw sewer spill site.

mg/L (or 0.1 - 0.15 μg/L) from USGS's 5-year seasonal data [28]; which were significantly lower than our data; therefore it is important to report and publish updated phosphate level in the Harlem River. Total P (TP) and organic P (OP) was tested on limited water samples collected in 2011; the TP maximum was 3.115 mg/L during April 28 heavy thunderstorm at CSO discharge point site 3, followed by 0.624 on March 17 at site 2, and 0.581 at site 4 on May 5; average TP was 0.531 mg/L which was higher than average TP in the Bronx River (0.438 mg/L in 2006 and 0.089 mg/L in 2007) [46] [47]. Organic P average was 0.428 mg/L, which was higher than average OP in the Bronx River as well (0.372 mg/L in 2006; 0.021 mg/L in 2007) [46] [47]; OP maximum was 2.919 mg/L during heavy thunderstorm on April 28 2011. OP could potentially be hydrolyzed to SRP becoming bioavailable P (BAP), and the enzymatically hydrolysable P (EHP); which have impact on water quality [46]-[51]. Phosphorus (P) is a major nutrient for plant growth, and is a primary limiting nutrient in rivers and streams [50] [52]-[54]. Excessive P results in eutrophication of freshwater systems, in turn, excessive algal growth/toxic algal blooms, oxygen depletion, and water quality degradation [46]-[51] [55] [56].

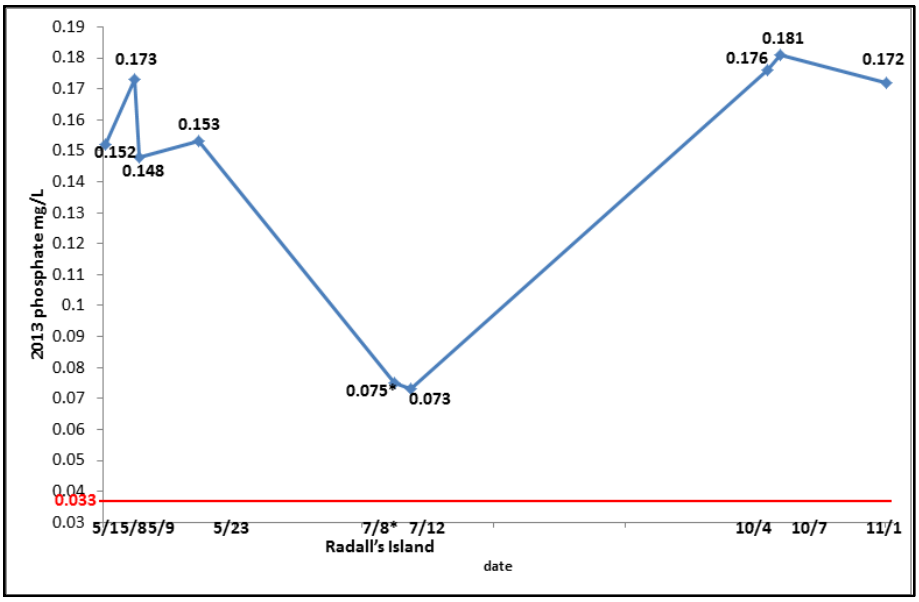

Figure 5. 2013 phosphate in water samples collected from the Harlem River. 2013: Water sampling at 3a, other than * site at site 5 Randall's Island close to CSO discharge point.

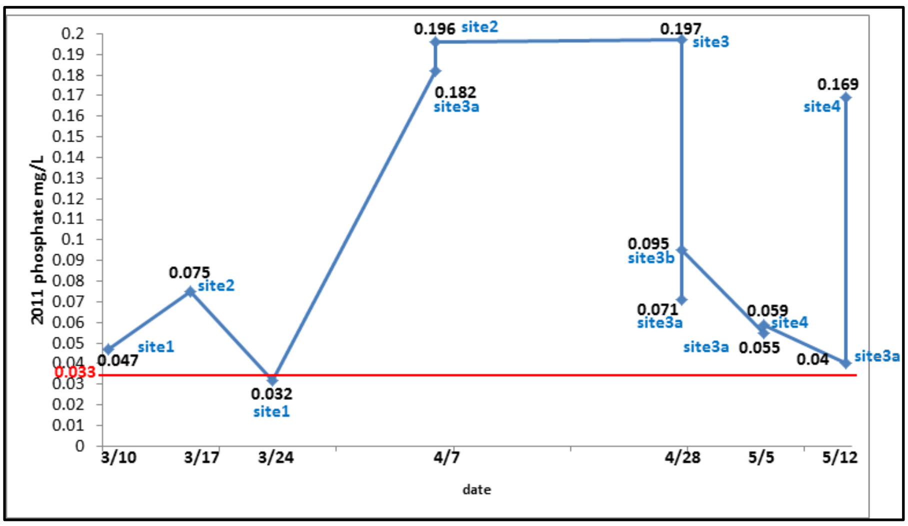

Figure 6. 2011 phosphate in water samples collected in the Harlem River. 2011: water sampling at sites 1, 2, 3, 3a, 3b, 3c, 4.

3.5. Turbidity

The turbidity in CSOs collected during tropical storm Arthur on July 2 2014 was 882 FAU, which was the maximum during data from 2011-2014. Results showed that CSOs during tropical storm Arthur increased nutrients (ammonia), bacteria and turbidity significantly. Turbidity was 112 FAU during heavy rainstorm on April 30, 2014. In 2013, turbidity was highest of 107 FAU during the showers on July 12 (**Figure 7**). The dilution factors could decrease turbidity during and after rainstorm. In 2012, turbidity increased from 4 FAU to 48 FAU after Hurricane Sandy (**Figure 8**). Rainstorm and Hurricane Sandy stirred the water increasing turbidity in the Harlem River. In 2011, turbidity peaked at the heavy thunderstorm on April 28, 2011 of 245 FAU (**Figure 9**), and at site 4 where the waters were muddy of 232 FAU on a sunny day; which were higher than Riverkeeper's data maximum (9/14/2011) of 198 FAU at Willis Ave. Bridge and 183 FAU at Washington Bridge [37] [38]. Turbidity also could be affect by surrounding suspended sediment environment, such as the muddy sediments at

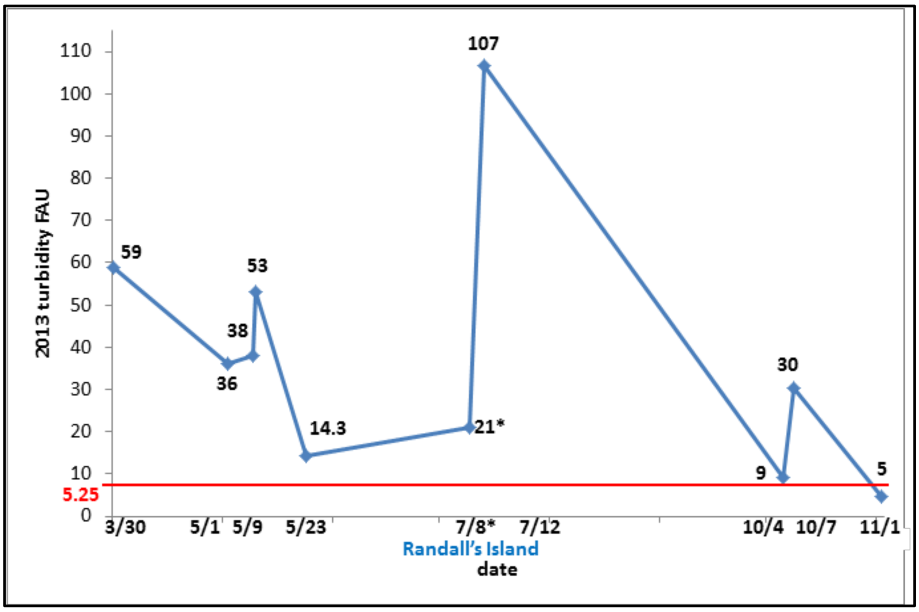

Figure 7. 2013 turbidity in water samples collected from the Harlem River. 2013: water sampling at site 3a, other than 7/8/12 site at site 5 Randall's Island close to CSO discharge point.

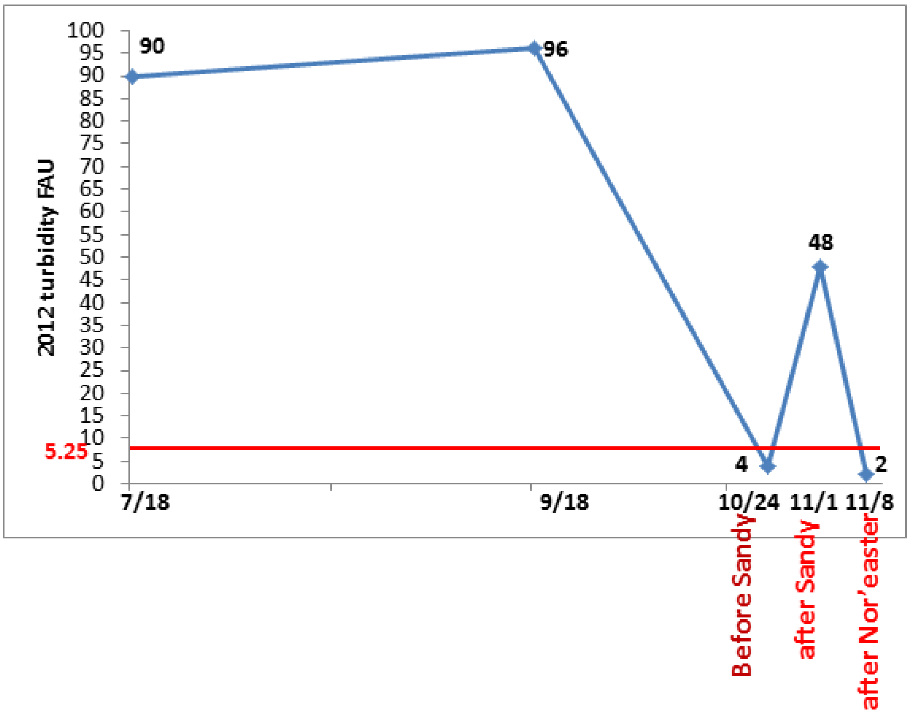

Figure 8. 2012 turbidity in water samples collected from the Harlem River. 2012: water sampling at site 3a.

site 4. Overall turbidity levels (**Figures 7-9**) were significantly higher than EPA standard: 0.25 - 5.25 FAU [33] [36]. On the heavy rainstorm on April 28, 2011, ammonia, phosphate, turbidity, E.Coli and fecal coliform reached the highest level during the year of 2011; however, no enterococcus found during that storm that is uncommon.

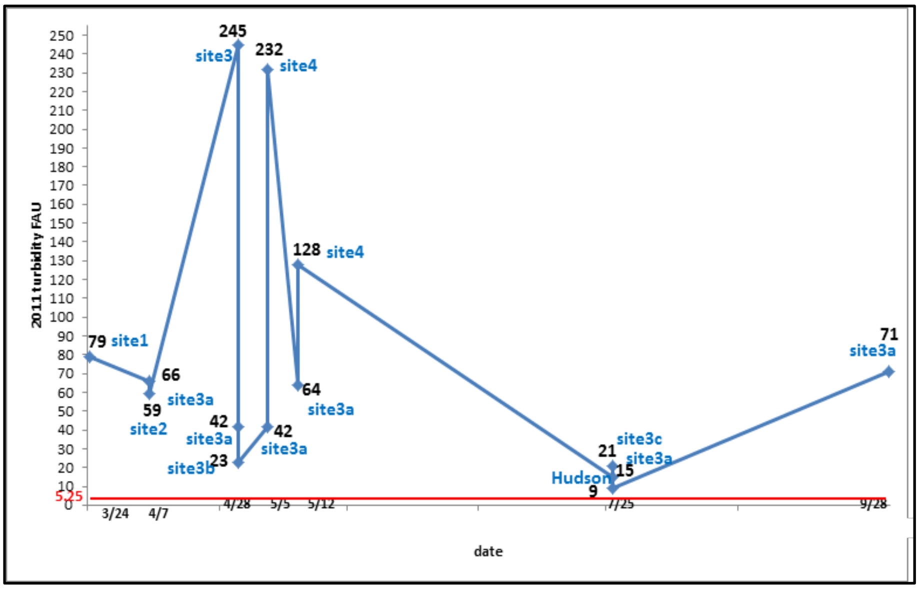

Figure 9. 2011 Turbidity in water samples collected from the Harlem River. 2011: water sampling at sites 1, 2, 3, 3a, 3b, 3c, 4, and Hudson River North River WWTP raw sewage spill site.

3.6. PCBs

3,3'-Dichlorobiphenyl (BZ#11) was the primary interest of the PCB analysis. The peak from GC/MS analysis in concentrated water samples appeared to be PCB 11. Spiked water sample showed the same peaks of 3,3'-dichlorobiphenyl. However, further experimental analysis was needed. From the results, there are different chemicals found in river water samples, such as 1,1-dibromodifluoroethylene, acetic acid, (3,4-dichlorophenoxy). The concentrations of PCBs in river waters usually considered as low, not easy to detect and could below detect limit. Spiking technique had been used on this research. PCBs concentrations in the Harlem River were below the detection limits. It is ongoing to try other techniques for PCBs identification.

3.7. Reduce CSOs

Wetland can be constructed to capture storm water, and remove pollutants from storm water runoff (Harlem River renaissance, 2014). Green infrastructure such as green walls, green corridor could be built for storm water retention and treatment [57]. An ultra-light weight green roof plant growth medium, which has higher adsorption than regular soil, has been used as a biogeochemical reactor to breakdown dioxins and PCBs [58]. Meanwhile, wetland and green infrastructure could help improve the waterfront access, improve the community activity along the river [59]. Green roof and green wall have been built in the Bronx to help storm water capture; storm water treatment and CSO reduction on the Bronx River [58]. The bio-composting system has been used on green roof in Manhattan to reduce storm water runoff and CSOs [60].

4. Future Perspective of the Research

If funding is available, water quality parameters will be tested in more locations from Spuyten Duyvil-Metro North Hudson line station where the Hudson River joins to its tributary, to Wards Island where the Harlem River joins to the East River. Spatial and temporal variations will be analyzed. DO will be tested for each water sample collection continuously. PCBs analysis is on-going. There is no guarantee to detect any PCB above detection limits in water samples; however PCBs identification is possible with different techniques. Water samples will be further concentrated for non-Aroclor congener PCB 11 and Aroclor 1242/1254 analysis, and spiking techniques will be used. Sediment samples will be collected for nutrients and PCBs analysis. Undergraduate students from BCC and Lehman College, CUNY will be involved in this water quality research as part of environmental science courses.

5. Conclusion

This research analyzed impact of CSOs on water quality as well as environmental ecosystem and public health in the Harlem River. Phosphate, ammonia, fecal coliform, E.Coli enterococcus levels increased during rainstorms. Enterococcus levels were higher than Riverkeeper's record. Ammonia maximum was 2.725 mg/L, and far exceeded EPA level of 0.23 mg/L; phosphate maximum was 0.196 mg/L significantly higher than EPA standard which is 0.033 mg/L; turbidity maximum was 245 FAU in 2011, almost 50 times that of EPA standard of 0.25 - 5.25 FAU. Fecal coliform, E.Coli, and enterococcus exceeded EPA regulated levels (200, 126, 104 MPN/100ml). Nutrients and bacteria levels were significantly higher than USGS data record. Turbidity and enterococcus data showed higher levels compared to Riverkeeper's data. PCBs (PCB 11) were below detection limit, and future analysis was expected. CSOs discharge in the Harlem River during rainstorms increased nutrient and bacteria levels, degraded water quality, threatened fish consumption safety, which is a critical issue in NYC waters. It is hoped that any solution could help improve water quality, and make the Harlem River swimmable and fishable again in the future.

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