

Long-Term Improvements in Water Quality Due to Sewage Abatement in the Lower Hudson River

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ABSTRACT: Long-term trends in dissolved oxygen (DO) and total coliform bacteria concentrations are used to evaluate the impact of almost 60 yr of sewage abatement and treatment in the lower Hudson River near New York City. Although some water pollution control plants have been in operation in the region since the 1930s, the most significant abatement of untreated sewage in the lower Hudson River has occurred since the late 1970s, when most of the existing plants were upgraded to secondary treatment, and additional plants were constructed. From at least 1922 through the early 1960s, average summer DO percent saturation varied between 35% and 50% in surface waters and 25% and 40% in bottom waters. Beginning in the late 1970s, DO concentrations generally increased through the 1980s and especially into the 1990s, coinciding with the upgrading of the $7.4 \text{ m}^3 \text{ s}^{-1}$ (170 million gallons per day, mgd) North River plant to secondary treatment in the spring of 1991. Average summer percent saturation in the early 1990s exceeded 80% in surface waters and 60% in bottom waters. In addition, summer DO minima have increased from less than 1.5 mg l^{-1} in the early 1970s to greater than 3.0 mg l^{-1} in the 1990s, and the duration of hypoxia during summer months has been reduced. Total coliforms also display strong declining trends from the 1970s into the 1990s, with declines attributed to plant upgrades, construction of two New York City plants (North River and Red Hook) in the mid 1980s, and improved operation of the sewer system.

Introduction

The Hudson-Raritan Estuary (Fig. 1) is a complex tidal system which has for many decades been subjected to an enormous loading of pollutants. Until recently this loading has included the discharge of millions of liters of untreated sanitary sewage. The components of untreated sewage which most adversely impact receiving waters include suspended solids, floatables, bacteria, organic carbon, nutrients, and toxicants (O'Connor 1990). These constituents are also present in varying degrees in water pollution control plant effluents, industrial effluents, combined sewer overflows (CSOs), urban runoff, riverine inputs, and atmospheric deposition.

This loading has in the past caused various use impairments to the system (O'Connor 1990; Suszowski 1990; Brosnan and O'Shea 1993). For example, pathogens from untreated sewage have been responsible for the closure of shellfish beds and beaches, and loadings of oxygen-demanding organic compounds have depressed dissolved oxygen levels. In response, pollution control efforts

have focused on treatment of sewage to remove pathogens and organic total suspended solids (TSS), which create a high biochemical oxygen demand (BOD) when consumed by bacteria in receiving waters (O'Connor 1990). More recently, eutrophication from excess nutrients has also contributed to depletion of summer oxygen concentrations in the outer areas of the estuary (Malone 1982), and controls on point and nonpoint sources of nutrients are currently being investigated (St. John 1990).

Although water pollution control plants have been in operation in the region since the 1930s, the most significant abatement of untreated sewage in the lower Hudson River has occurred since the late 1970s when most of the existing plants were upgraded to secondary treatment, and additional plants were constructed. Currently, the Hudson-Raritan Estuary receives approximately $115 \text{ m}^3 \text{ s}^{-1}$ (2.5 billion gallons per day, bgd) of municipal effluents, virtually all of which receive secondary treatment (Hydroqual, Inc. 1991).

Long-term decreases in loadings of several pollutants to the estuary are attributed to abatement of untreated municipal and industrial effluents, and to product bans. These pollutants include total organic carbon (Ayres et al. 1988); phosphorus

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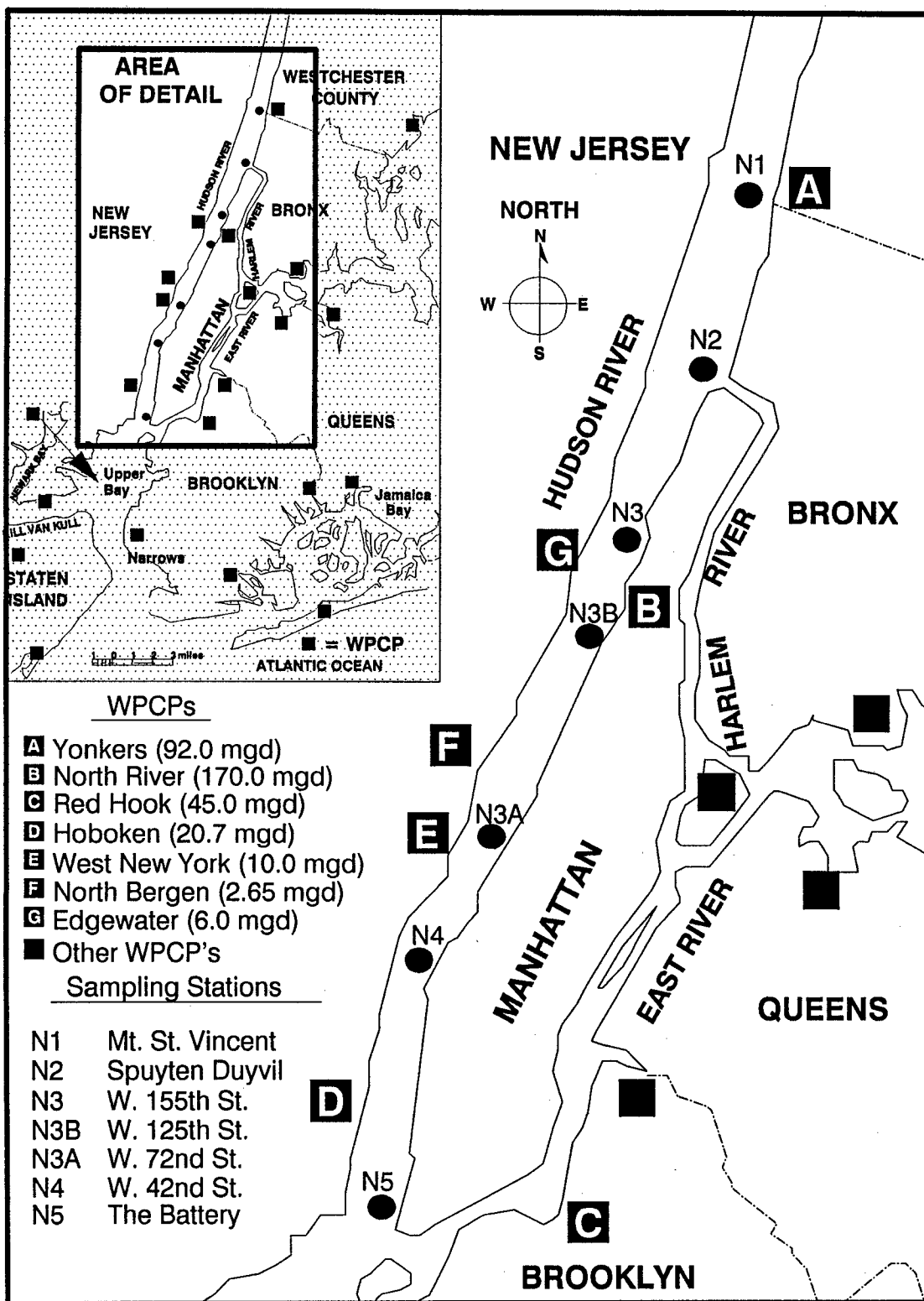


Fig. 1. The Hudson River and the Hudson-Raritan Estuary.

(Clark et al. 1992); cadmium, copper, lead, and mercury (Ayres and Rod 1986); and PCBs and the insecticides chlordane and p,p-DDD (Bopp and Simpson 1989).

This paper focuses on changes to dissolved oxygen (DO) and coliform bacteria in the lower Hudson River, in response to recent improvements in both sewage capture and treatment.

History of Sewage Abatement in the Hudson-Raritan Estuary

Wastewater collection and sewer construction in New York City began in 1696, with many of lower and central Manhattan's sewers constructed between 1830 and 1870 (O'Connor 1990). The first wastewater treatment facility in New York City was built in 1886 and consisted of floatable screening designed to protect bathing beaches on Coney Island. From the 1800s through the 1920s regional population growth and development exacerbated sewage disposal problems and further degraded water quality throughout the Hudson-Raritan Estuary. This degradation was associated with increased discharges of untreated sewage and industrial effluents, coupled with land use changes, physical modifications, and coastal habitat destruction (O'Connor 1990; Suszkowski 1990; Brosnan and O'Shea 1993).

In 1906, the Metropolitan Sewerage Commission of New York was created to study water pollution in the region and to formulate a plan to improve water quality (Metropolitan Sewerage Commission 1912). At this time around $26 \text{ m}^3 \text{ s}^{-1}$ (600 mgd) of untreated sewage was being discharged from New York City alone (Casper 1990). The Commission reported evidence of gross sewage pollution, including seas of floating garbage, within 15 miles of Manhattan. Increased discharges of raw sewage and industrial effluents, and habitat loss contributed to the decline of several regional fisheries by the 1930s (Pearce 1987; Studholme 1987, 1988).

Following a Master Plan from the Metropolitan Sewerage Commission, New York City began construction of modern facilities in the 1930s, starting with the Coney Island water pollution control plant in 1935, and three East River plants in 1938 (Brosnan and O'Shea 1993). Other local treatment facilities constructed around this same time included the North and South Yonkers plants in 1933, with a combined design capacity of $5.9 \text{ m}^3 \text{ s}^{-1}$ (130 mgd), and New Jersey's $3.0 \text{ m}^3 \text{ s}^{-1}$ (60 mgd) Passaic Valley plant which was constructed in 1924 and upgraded to $11 \text{ m}^3 \text{ s}^{-1}$ (250 mgd) in 1937 (Interstate Sanitation Commission 1969).

By 1952, a total of 11 water pollution control plants were in operation throughout New York City. During the late 1950s and 1960s seven of

these plants were enlarged to accommodate population shifts to the outer boroughs (unpublished NYCDEP 1992). In 1967, with the opening of New York City's largest plant, Newtown Creek on the East River, over $43.8 \text{ m}^3 \text{ s}^{-1}$ (1 bgd) of New York City sewage was receiving treatment. Using a New York City-developed process known as modified aeration, these plants achieved approximately a 60% reduction in biological oxygen demand (BOD) and total suspended solids (TSS) (unpublished NYCDEP 1992).

In 1972, the Federal Clean Water Act provided the first clear statutory mandates for levels of wastewater treatment and water quality standards. For water pollution control plants, the Clean Water Act mandated secondary treatment, defined as 85% removal of BOD and TSS. By 1980, 9 of the 12 New York City water pollution control plants and several other water pollution control plants in the region were upgraded to full secondary treatment. However, this upgrading postponed completion of New York City's last two water pollution control plants while they were redesigned (unpublished NYCDEP 1992). Consequently, despite significant upgrades to other New York City water pollution control plants, over $8.8 \text{ m}^3 \text{ s}^{-1}$ (200 mgd) of untreated sewage was still being discharged into the lower Hudson River from Manhattan, and into the Lower East River from Brooklyn during the mid 1980s.

In the 1980s, New York City constructed its two final plants. In spring of 1986, the North River water pollution control plant (Fig. 1) abated the discharge of over $7.4 \text{ m}^3 \text{ s}^{-1}$ (170 mgd) of raw sewage from 50 outfalls along the western shore of Manhattan into the Hudson River; secondary treatment was achieved in April 1991. The Red Hook water pollution control plant abated the discharge of $1.7 \text{ m}^3 \text{ s}^{-1}$ (40 mgd) of raw sewage from 33 outfalls along the northwestern shore of Brooklyn into the lower East River starting in spring of 1987; secondary treatment was achieved in May 1988. The addition of these two plants ensured treatment capacity of greater than 99.9% of New York City's dry-weather sewage. Presently, 13 of the city's 14 plants provide full secondary treatment. The Newtown Creek water pollution control plant upgrade is in the planning phase.

Study Location

REGIONAL HYDRODYNAMICS

The lower Hudson River is part of the Hudson-Raritan system (Fig. 1), which is a varied and complex coastal plain estuary. The system is dominated by a drowned river valley (the Hudson), with a network of tidal straits (Arthur Kill, Kill Van Kull, and the Harlem and East rivers), open and enclosed

TABLE 1. Pollutant loadings to the Hudson-Raritan Estuary (in percent)^a.

Parameter	Tributary	Municipal Effluents	Combined Sewer Overflow	Storm Water	Other ^b	Total Load
Flow	81	15	1	4	<0.5	765 m ³ s ⁻¹
Fecal Coliform	2	<0.1	89	9	<0.1	2.1 × 10 ¹⁶ d ⁻¹
BOD	16	58	19	5	2	5.7 × 10 ⁵ kg d ⁻¹
TSS	80	11	5	3	1	2.4 × 10 ⁶ kg d ⁻¹
Nitrogen	29	63	2	2	4	2.8 × 10 ⁵ kg d ⁻¹
Phosphorus	16	75	4	4	<0.5	2.3 × 10 ⁴ kg d ⁻¹

^a Modified from HydroQual ((1991) based on data from the late 1980s. Values across may not equal 100% due to round off.

^b Other = industrial discharges, landfill leachate, and direct atmospheric deposition combined.

bays (Raritan, Jamaica, and New York bays), tidal mud flats, and beaches. The estuary communicates with the Atlantic Ocean through The Race at the eastern end of Long Island Sound and through the mouth of Lower New York Bay at Sandy Hook (Swanson et al. 1982); the tidal pulse is semidiurnal throughout.

With an average flow of 683 m³ s⁻¹ at the Battery, the Hudson River constitutes approximately 87% of the total riverine flow into the estuary, draining 34,600 km² of a total watershed of 42,188 km² (Mueller et al. 1982). The 7-Day, 10-Year Low Flow (7Q10) for the Hudson-Raritan system has been estimated at 82 m³ s⁻¹, and the 100-yr flood flow is 5,760 m³ s⁻¹ (National Oceanographic and Atmospheric Administration 1985). The volume of water entering the coastal system during the flood tide (i.e., the tidal prism) is ~7.49 × 10⁹ m³; therefore, the volume of water introduced from the tributaries is small compared to the amount introduced from tidal action, and tides dominate the density-driven estuarine circulation (National Oceanographic and Atmospheric Administration 1985). Freshwater replacement times (the ratio of total equivalent volume of fresh water to freshwater discharge at the Battery) vary from less than 15 d during spring high river flows, to 45–60 d during summer low flow conditions (Clark et al. 1992). Water depths in the lower Hudson River range from 11 m to 21 m.

This network of varying freshwater inflows, tides, and tidal flows produces vertical density stratification in the Hudson River and Upper New York Bay, with seasonal and tidal variations in stratification. Average summer salinities in the lower Hudson River are typically 10–15 mg g⁻¹ (‰) in surface waters, and 15–25 mg g⁻¹ in bottom waters (Brosnan and O'Shea 1993). Temperature stratification is normally less than 2°C. Because the difference between surface and bottom salinities in the estuary is generally less than 10 mg g⁻¹, the estuary is classified as moderately stratified and partially mixed (National Oceanographic and Atmospheric Administration 1985; Clark et al. 1992).

POLLUTANT SOURCES

The Hudson-Raritan Estuary is subjected to a very large pollutant load, transported by various freshwater sources within its drainage basin. As indicated in Table 1, the significance of different sources varies by pollutant. For example, combined sewer overflow discharges contribute only 1% of flows but contain almost 90% of the current fecal coliform load to New York Harbor (HydroQual, Inc. 1991). Conversely, loadings for BOD, nitrogen, and phosphorus are dominated by water pollution control plants, while 80% of the TSS load is derived from the tributaries (Table 1).

Materials and Methods

As part of the New York Harbor Water Quality Survey, New York City Department of Environmental Protection personnel presently monitor 52 stations in the Hudson-Raritan Estuary for a variety of water quality indicators. In recent years water samples were collected from onboard the New York City Department of Environmental Protection's *HSV Osprey*. Seven stations are currently sampled along the lower Hudson River, extending from the Battery at the southern tip of Manhattan to the New York City Westchester County border approximately 26 km upstream (Fig. 1). Stations are located in the field by latitude-longitude and line-of-site from station descriptions (Brosnan and O'Shea 1993). Water samples are collected from surface waters (1 m below the water surface) and bottom waters (1 m above the sediment surface) using a 3.2-l Kemmerer sampler, or a 5.0-l Teflon-lined Niskin sampler.

New York City has been monitoring DO at various stations in New York Harbor including the Hudson River since 1909. The frequency of summer (June–September) sampling at these sites has varied overall from 5 times or less during 1909–1930 to 5 for 1931–1950; 6 to 9 for 1951–1970; 12 for 1970–1984; 8 to 10 from 1985 to 1989; and 9 to 11 for 1990–1993. In the initial years of the survey, DO was measured using a procedure some-

times called the Albert Levy Method, in which DO depended upon the absorption of oxygen by ferrous sulphate in the presence of an alkali. The amount of ferrous sulphate not acted upon by the oxygen was then determined by acidifying and titrating with potassium permanganate (Metropolitan Sewerage Commission 1912). This method was certified at that time to produce results identical to the more familiar Winkler method. Subsequently the azide modification of the Winkler method was used through 1984. From 1985 through 1987, YSI (Yellow Springs Instruments Inc.) meters were also often used. These DO meters were calibrated and re-checked two to three times each sampling day using the azide modification of the Winkler method (American Public Health Association et al. 1985). The Winkler method was once again used exclusively from 1988 through 1995. Duplicates were analyzed at one random station per day and reagents were changed at regular intervals.

Total coliforms have been monitored by New York City since 1954 using the multiple tube fermentation technique. For the 1972–1995 sampling period presented herein, coliform samples were collected from surface and bottom waters at each station approximately once every other week, for a total of 8–12 samples collected per station, per summer. Analysis of total coliform bacteria was begun onboard by aseptically inoculating five tubes of lauryl tryptose broth in three serial decimal dilution portions (American Public Health Association et al. 1985). The tubes were incubated immediately at 35°C, and subsequently transported to the laboratory for continued incubation. The presumptive test was followed by the confirmed test using brilliant green bile media. Data were reported as the most probable number of coliforms per 100 ml (MPN 100 ml⁻¹).

Coliform samples were analyzed at New York City Department of Environmental Protection's Special Project Laboratory at Wards Island, New York, which is certified by the New York State Environmental Laboratory Approval Program (ELAP). Daily quality control procedures were modeled after Standard Methods (American Public Health Association et al. 1985). Quality control charts and comparisons of Harbor Survey Program data with other monitoring programs are presented in Brosnan (1991) and Brosnan and O'Shea (1993).

Long-term linear trends in dissolved oxygen were determined by estimated linear trends with time by the OLS (ordinary least squares) regression method for each of the following dependent variables: DO bottom mean, DO bottom minimum, and DO surface mean. All linear trends were estimated by running the Statistical Analysis System

(SAS) procedure PROC REG. Levels of significance examined were $p < 0.1$ and $p < 0.05$. Pearson correlation coefficients were obtained from the SAS procedure PROC COR.

Durations of summertime DO depletion were calculated by linearly interpolating between DO field observations (typically 8–12 per summer) to provide DO values for intervening days, and then counting the number of days in that season which were less than a given concentration (Welsh et al. 1994).

Results and Discussion

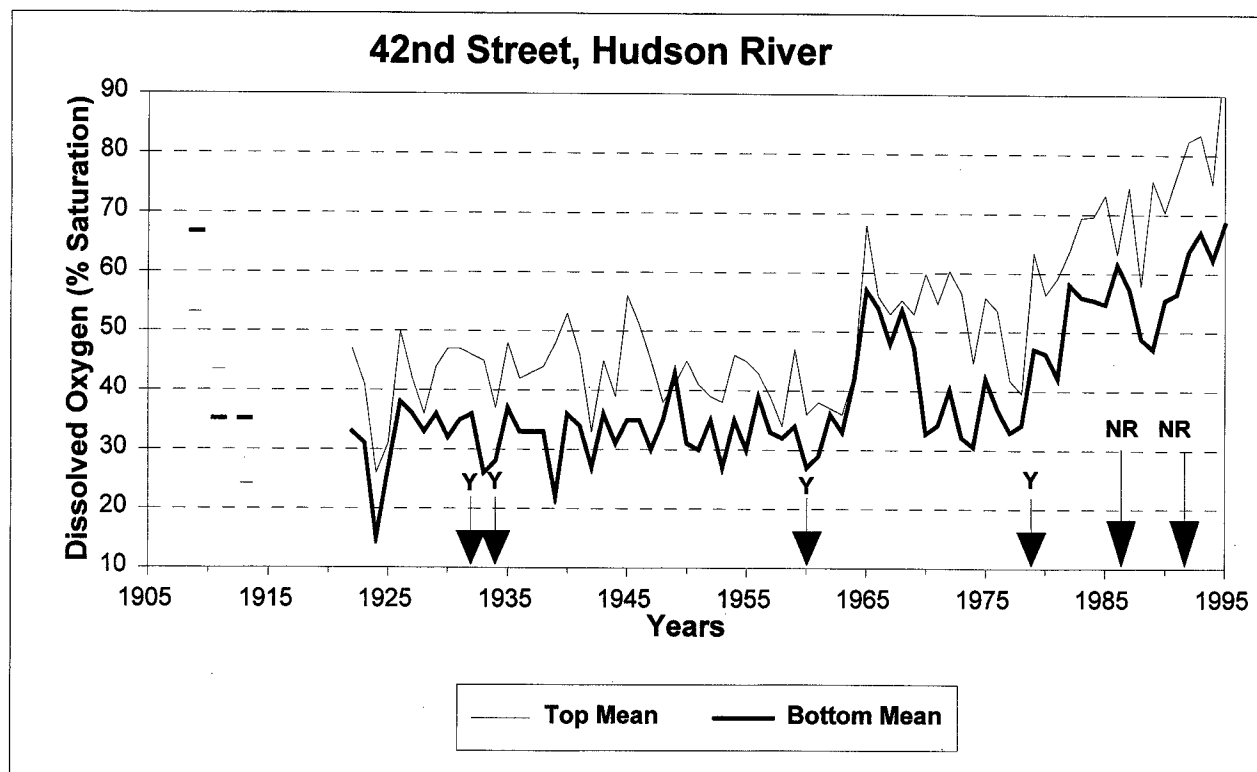
Together, DO and coliform bacteria represent two of the most readily interpretable indicators of anthropogenic impacts on aquatic environments. Dissolved oxygen is required for respiration by all aerobic forms of life. High BOD loads from sewage can deplete DO, causing hypoxia ($\text{DO} < 3 \text{ mg l}^{-1}$). Persistent hypoxic conditions are considered to be harmful to many aquatic organisms, causing a variety of sublethal effects, degradation of habitat, and in severe cases, mortality (Strieb 1993). Consequently, DO is one of the most universal indicators of overall water quality in aquatic systems.

Total coliform bacteria are measured by the Harbor Survey Program as nonconservative indicators of not disinfected or only partially disinfected, sewage-related pollution. New York State Water Quality Standards currently utilize total coliform and fecal coliform bacteria to indicate the presence of fecal contamination, and the potential presence of pathogenic bacteria, fungi, and viruses often associated with fecal pollution. Changes in DO and coliform concentrations over the years in the lower Hudson River are directly related to changes in water pollution control activities.

DISSOLVED OXYGEN (DO)

There is significant interannual variability in DO concentrations in the Hudson River. Year-to-year variability in the duration and severity of hypoxia are linked to variations in vertical density stratification, wind mixing, tidal and gravitational circulation, and especially the quality and quantity of water coming into the area (Diaz et al. 1992). While a detailed analysis of meteorological and hydrological impacts on DO in the Hudson River is beyond the scope of this paper, the following analysis does attempt to differentiate (where possible) variability attributable to anthropogenic versus natural effects.

Dissolved oxygen has been depressed in the lower Hudson River since at least the 1920s. Figure 2 depicts concentrations from 1909 to 1995 for the Hudson River at 42nd Street in Manhattan, which is 7.5 km upstream from the Battery (site N4, Fig.



*Dates of construction and significant upgrades to the Yonkers (Y) and North River (NR) water pollution control plants are also depicted

Fig. 2. Summer average dissolved oxygen in surface and bottom waters at Hudson River sampling station N4 (see Fig. 1 for location). Sampling period: 1909–1995, with intermittent sampling prior to 1922. Arrows along the x-axis show dates of construction and major upgrades for the Yonkers (Y) and North River (NR) water pollution control plants.

1). This site historically displays the lowest DO concentrations among the sites monitored in the lower Hudson River (Brosnan and O'Shea 1993). Following declines from 1909, which were also observed throughout the estuary (Brosnan and Stubin 1992), average summer DO percent saturation from the 1920s through the 1960s generally varied between 35% and 50% saturation in surface waters, and 25% and 40% in bottom waters (Fig. 2). Despite the construction of several water pollution control plants throughout the estuary since the 1930s, a clear impact on DO in the lower Hudson River was not observed during this period. This is in contrast to other regional waterways (e.g., the lower East River) where DO increases have been observed since the 1940s (Brosnan and Stubin 1992).

In the mid-to-late 1960s, the high and low DO periods roughly coincided with a dry, low flow period and a wet, high flow period, respectively (O'Connor 1990). During the mid-to-late 1970s DO concentrations decreased as many regional water pollution control plants were upgrading to secondary treatment and bypassing of raw sewage during construction was common (Parker and O'Reil-

ly 1991). Concentrations of DO generally rose through the 1980s and especially into the 1990s, such that summer surface averages are now typically greater than 90% saturation and bottom averages are greater than 60%. These DO improvements also coincide with declining coliform bacteria. For example, at sites along Manhattan a correlation analysis of 26 yr of fecal coliform and surface mean DO data indicate correlation coefficients ranging from -0.57 to -0.78 ($p < 0.05$). Recent sewage abatement efforts (see below) have also significantly reduced the loading of BOD. Elevated BOD is believed to be responsible for most of the depression of DO in the core area of the estuary, including the Hudson River (St. John 1990).

Other methods of analyzing hypoxia show similar trends. Minimum DO concentrations in the lower Hudson River routinely ranged from less than 1.5 mg l^{-1} to 2.0 mg l^{-1} during much of the mid 1970s (Fig. 3). Similarly, the relative duration of summer hypoxia was also greater during the mid 1970s, when durations of $\text{DO} < 3 \text{ mg l}^{-1}$ were estimated to occur for more than 50% of the summer (Fig. 4). Some years experienced concentra-

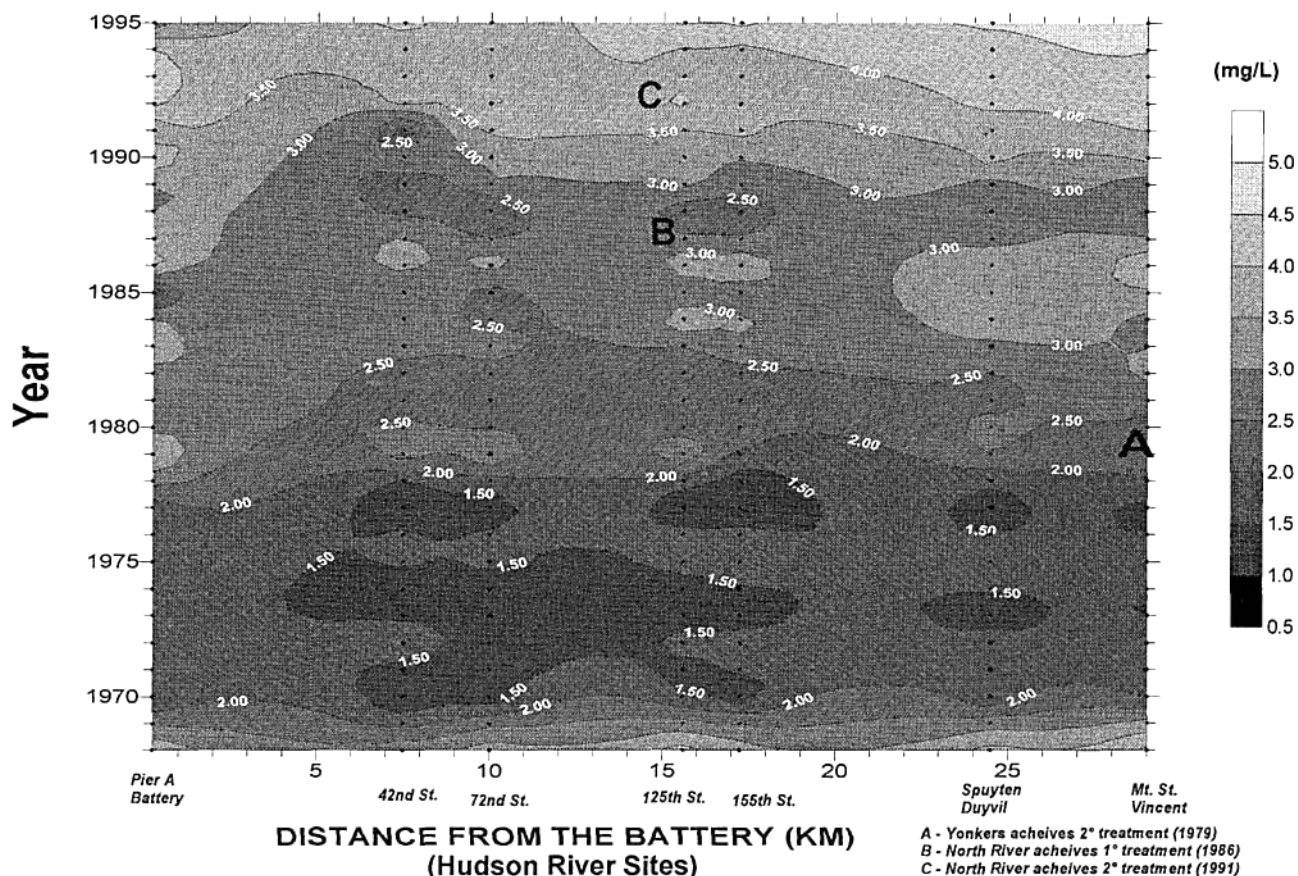


Fig. 3. Time-space contour plot of annual bottom minima DO for the Hudson River sampling stations (see Fig. 1 for locations). Dates of primary (1°) and secondary (2°) upgrades of water pollution control plants are shown on the right margin.

tions of less than 2 mg l^{-1} and even 1 mg l^{-1} for significant periods. By 1980, when many water pollution control plants in the region had achieved secondary treatment, minimum DOs of less than 2

mg l^{-1} were virtually eliminated and the duration of hypoxia was significantly reduced (Figs. 3 and 4).

With the start-up of primary treatment at the North River plant in 1986, approximately $26,000 \text{ kg d}^{-1}$ of BOD and $10,400 \text{ kg d}^{-1}$ of TSS were removed from Manhattan sewage loadings into the lower Hudson River. However, the impact of this removal was not immediately evident in terms of average percent DO saturation, DO minima, or duration of hypoxia (Figs. 2–4). In fact, conditions seemed to worsen for 1987–1989. Similar declines were also observed elsewhere in the estuary, particularly in areas exhibiting algae blooms and density stratification (Brosnan and Stubin 1992). This widespread concurrence of DO declines suggests a broad-scale meteorological, hydrological, or oceanographic effect. For example, some of the warmest air temperatures on record occurred in the late 1980s, with 1990 being the warmest summer in New York City since 1869 (Swanson et al. 1991). The years 1987–1989 were also notable for somewhat below-normal spring flows in the Hudson Riv-

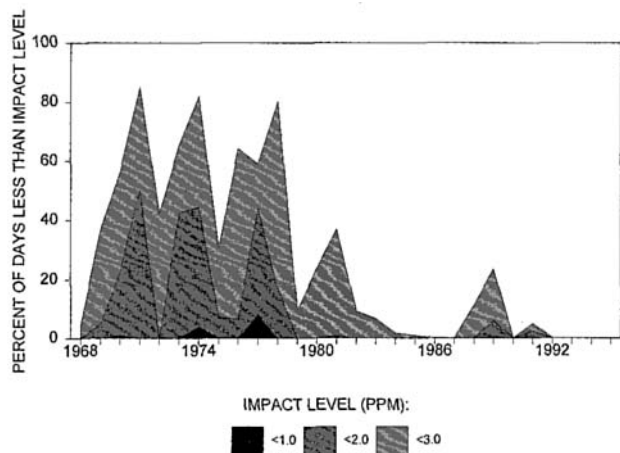


Fig. 4. Duration of summertime (June–September) hypoxia in the bottom waters of Hudson River sampling station N4 (see Fig. 1 for location).

TABLE 2. Long-term dissolved oxygen trend analysis: 1968–1995.

Station	DO Bottom Minimum		DO Bottom Mean		DO Surface Mean	
	Trend ^a	Slope ^b	Trend ^a	Slope ^b	Trend ^a	Slope ^b
N1	+	0.09	+	0.05	0	0.04
N2	+	0.09	+	0.06	+	0.06
N3	+	0.09	+	0.07	+	0.07
N3A	+	0.08	+	0.07	+	0.08
N3B	+	0.08	+	0.06	+	0.07
N4	+	0.08	+	0.08	+	0.10
N5	+	0.07	+	0.08	+	0.09

^a Trends evaluated at a significance level of $p < 0.05$. “+” = significant increasing trend, “0” = no significant trend.

^b Units = $\text{mg DO l}^{-1} \text{ yr}^{-1}$.

er, the well-publicized floatable washups on New Jersey (1987) and Long Island (1988) beaches, and the mass die-off (1988) of dolphins along several mid-Atlantic coastal states.

When North River achieved secondary treatment in 1991, an additional 60,000 kg of BOD and 33,000 kg of TSS were removed from the effluent discharged daily into the Hudson River. This represents the removal of approximately 10% and 1% of the BOD and TSS load, respectively, to the entire Hudson-Raritan Estuary in the late 1980s (Table 1). In addition, in 1989, $1.46 \text{ m}^3 \text{ s}^{-1}$ (33.3 mgd) of flow discharged from two New Jersey water pollution control plants into the Hudson River was diverted to the Passaic Valley water pollution control plants, which discharges to upper New York Bay approximately 5 km below the Battery (Interstate Sanitation Commission 1990). However, once again improvements were not readily apparent, and conditions were worse than the year before. Note however, that the summer of 1991 had a record-setting 39 d greater than 90°F (Brosnan and O’Shea 1993). In addition, although local rainfall was slightly above average during the summer of 1991, the spring and especially the summer flow of the Hudson River were low, with summer flows at their lowest since at least 1970 (National Oceanographic and Atmospheric Administration 1991; United States Geological Survey 1993). Higher local rainfall increases the BOD loading from combined sewer overflows and stormwater, while low river flows reduce the flushing rate, thus promoting oxygen depletion. Conditions improved considerably in 1992 and 1993 with minimum DOs exceeding 3.5 mg l^{-1} (Fig. 3). Regression analyses conducted on the 1968–1995 dataset (Table 2) confirm that the improving trends observed are statistically significant. Average rates of improvement over the 27-yr-period ranged from 0.05–0.08 $\text{mg DO l}^{-1} \text{ yr}^{-1}$ for mean bottom DOs and 0.04–0.10 $\text{mg DO l}^{-1} \text{ yr}^{-1}$ for mean surface DOs. An earlier regression analysis of the shorter 1968–1989

dataset by Keller et al. (1991) also detected significant improving trends at several sites in the Hudson.

TOTAL COLIFORMS

Total coliform data from 1972 to 1995 further highlight the recent improvements in water quality reflected in the DO data. Coliform standards are set by New York State to protect designated “best-uses” of each water in the state. Currently, the New York State Department of Environmental Conservation Best-Use classifications for the waterways surrounding Manhattan are “I” (i.e., secondary contact, e.g., fishing), while the Hudson River directly north of Manhattan is classified as “SB” for primary contact such as bathing. The total coliform standards associated with these classifications are included on Fig. 5. Note that true assessment of compliance with New York State Water Quality Standards for total coliform requires the testing of five or more samples per month. Since the Harbor Survey Program typically tests each site only two or three times per month (for a total of 8–12 times per summer), a true determination of compliance is not possible. Instead a seasonal compliance can only be inferred by comparing seasonal geometric mean data to the appropriate monthly numeric standard.

As depicted in Fig. 5, in 1972 most of the waterways surrounding Manhattan had total coliform concentrations greater than 10,000 MPN 100 ml^{-1} , indicating significant raw sewage contamination. Only a small area north of Manhattan met the secondary contact standard, possibly as a result of treatment at the $2.7 \text{ m}^3 \text{ s}^{-1}$ (61 mgd) Yonkers water pollution control plant (Fig. 1), coupled with dilution from upstream.

By 1985, a decade of plant upgrades and expansions had occurred, as mandated by the 1972 Clean Water Act. Locally, these were the Yonkers water pollution control plant, which achieved secondary treatment in 1979 (Interstate Sanitation Commission 1983), and 9 of the 12 New York City water pollution control plants, including 3 of the 4 East River plants. In addition, by 1973 chlorine was in use at all New York City water pollution control plants for effluent disinfection (Ayres and Rod 1986). All of these actions resulted in attainment of higher water quality to the north, south, and east of Manhattan (Fig. 5). However, although improvements were recorded, waters off of Manhattan still remained significantly polluted from raw sewage discharges through 1985.

After the opening of New York City’s last two water pollution control plants in 1986 (North River) and 1987 (Red Hook), total coliform concen-

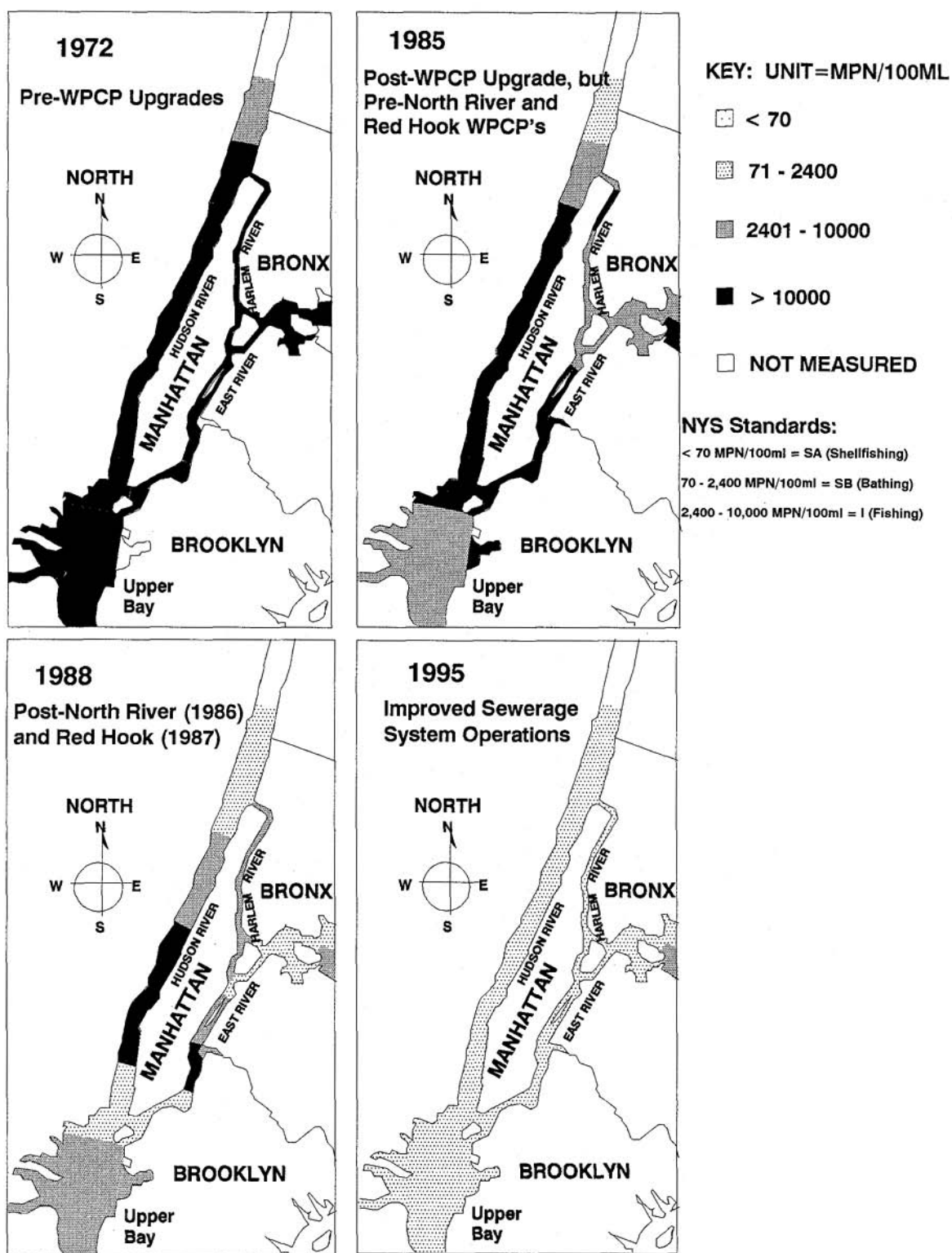


Fig. 5. Summer average total coliform bacteria concentrations for surface waters of the Hudson River, East River, and upper New York Bay from 1972 to 1995. Shadings represent changes in estimated compliance with New York State standards during periods of sewage abatement.

trations decreased in the Hudson River by 72%, and in the East River by 49% (Brosnan 1991). Similarly, fecal coliforms declined by 78% in the Hudson River and 63% in the East River. Larger areas were now in compliance with secondary and primary contact standards, although concentrations off of mid-Manhattan indicated that significant contamination remained (Fig. 5). This contamination was presumably from remaining uncontrolled sources of unintercepted sewage such as illegal connections and bypassing from failures in regional sewer systems. The area off of southern Manhattan (station N4) has historically had the worst water quality for both DO and coliforms (Figs. 3 and 5).

The trends in coliform reductions observed from 1968 to 1988 continued to be observed through 1995, both in the Hudson River and estuary-wide (Fig. 5). For example, from 1989 to 1995 average total and fecal coliform concentrations in surface waters of the Hudson River declined by over 50% at all seven stations. In contrast to earlier coliform declines, which are largely attributed to construction and upgrading of water pollution control plants, these recent improvements are attributed to the impact of several recent New York City water pollution control programs. These programs have focused on the abatement of the remaining sources of untreated sewage, and therefore coliforms, to New York Harbor. Current New York City abatement measures include increased surveillance and maintenance of the entire sewage distribution system, including abatement of illegal connections, reduced raw sewage bypassing, and increased capture of combined sewage during rain events. These combined efforts have abated $0.19 \text{ m}^3 \text{ s}^{-1}$ (4.51 mgd) of untreated sewage city-wide from 1989 to 1995, and improved sanitary water quality conditions throughout the estuary (Fig. 5). In combination with the opening of the Red Hook and North River water pollution control plants, these actions have led to the re-opening of beaches and the lifting of bathing advisories in lower New York Bay (Brosnan and O'Shea 1993).

Conclusions

Water quality conditions in the lower Hudson River have improved markedly as a result of the increased capture and treatment of municipal sewage. While sewage abatement has increased throughout the estuary since the 1930s, the most significant improvements for the lower Hudson River have been observed in the past two decades, and especially in the last 5 yr. This improvement is reflected in increases in surface and bottom dissolved oxygen concentrations, reduction of the

spatial and temporal extent of severe hypoxia, and order of magnitude declines in total coliform bacteria.

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