CONSERVATION-INDUCED WASTEWATER FLOW REDUCTIONS IMPROVE NITROGEN REMOVAL: EVIDENCE FROM NEW YORK CITY

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ABSTRACT: Water resources are under increasing pressure to meet potable supply needs while sustaining aquatic ecosystems and fisheries. Growing populations and enforcement of the Total Maximum Daily Load provisions of the Clean Water Act present public water and wastewater utilities with costly options to meet potable water demands and reduce pollutant discharges into receiving waters. This paper documents that New York City’s comprehensive water conservation program – designed to extend the city’s safe yield of potable water—has also resulted in reduced nitrogen discharges from the city’s water pollution control plants during a period of population increases. This paper demonstrates and quantifies the effects that wastewater inflow volume reductions have on increased nitrogen removal, controlling for plant process changes. Conservation programs have saved the city billions of dollars in delayed or avoided capital improvements to both water and wastewater treatment plants, and have enabled the city to meet interim effluent discharge standards.

(KEY TERMS: water quality economics; wastewater treatment; nutrient removal; water conservation; point source pollution.)


INTRODUCTION

Large metropolitan regions face increasing pressures to meet growing demands for potable water supplies and to reduce pollutant loads from municipal water pollution control plants (WPCPs). The environmental impact and financial cost of developing and treating new water sources and improving wastewater treatment to meet national and state water quality standards suggest that comprehensive water conservation policies will play an increasing role in water management strategies. In this paper, we document an additional benefit of water conservation strategies in enabling additional nitrogen removal in WPCPs.

New York City’s history illustrates the challenges of meeting source-water and wastewater needs and the role of conservation measures in achieving these goals. Through the 19th and 20th Centuries, New York City tapped water supplies further and further from the city’s political boundaries to meet growing needs.
demand, including from as far as the Catskill Mountains and the headwaters of the Delaware River. Moreover, in 1988, in response to water quality studies for Long Island Sound and Jamaica Bay, the New York State Department of Environmental Conservation (NYSDEC) imposed State Pollution Discharge Elimination System (SPDES) permits on New York City, requiring reduced total nitrogen discharges (mass loadings) from WPCPs into the Upper East River and Jamaica Bay. The New York City Department of Environmental Protection (DEP) thus initiated a comprehensive water conservation program to preserve existing water supplies and meet interim water quality standards imposed by the SPDES permits.

The purpose of this paper is to demonstrate the relationship between the reduction in wastewater flows attributable to water conservation programs and improved nitrogen removal in New York’s wastewater treatment plants. As a result of conservation efforts, nitrogen removal efficiency was increased which allowed the city to meet interim effluent limits without costly plant retrofits. Conservation also delayed costly investments in additional water supply capacity.

Although conservation’s benefits in terms of source-water development have been well known, this paper documents the additional benefits of improved nitrogen removal efficiency in WPCPs, especially in those operating at or near full capacity. These additional environmental and fiscal benefits of conservation suggest that conservation programs may play an important role in enabling large metropolitan regions to meet water supply and water quality challenges.

This paper is organized as follows: the next section describes the history and development of wastewater treatment in New York City, as well as the development of discharge permits and the conservation programs undertaken. We then follow with a development of the hypotheses concerning conservation and nitrogen removal, along with descriptive data of inflow and effluent characteristics in WPCPs. The next section presents our data and the statistical model, along with empirical results. Following, we provide some estimates of the magnitude of nitrogen removal from conservation efforts which could be utilized in policy decisions.

WATER SUPPLY, WASTEWATER, AND CONSERVATION IN NEW YORK CITY

Water supply challenges for New York City have resulted in extensive source-water development far from the city’s borders. As early as 1830, city water supplies included the Croton River in Westchester County. By the early 1900s, water sources in the Catskill Mountains were utilized and in the 1930s, the city began the development of sources in the Delaware River watershed. Conflicts with New Jersey and other downstream states over withdrawals from the Delaware River watershed led to litigation and a U.S. Supreme Court Consent Decree in 1931, amended in 1954 (283 U.S. 805 and 347 U.S. 996). The 1931 decree allowed New York City to divert 440 mgd (1666 mld). The 1954 decree permitted annual diversions of, on average, 800 mgd (3028 mld), conditioned upon compensatory releases of stored water during low-flow periods on the Delaware River. However, the drought of the 1960s revealed that available storage capacity was insufficient to meet the required diversion and compensatory release flows (Featherstone, 1996).

New York City’s surface water supply is provided by three systems (Croton, Catskill and Delaware), with 19 reservoirs and three controlled lakes, contained in a 1972 square mile (5107 km$^2$) watershed extending 125 miles (201 km) northeast of the city and providing 1.2 bgd (4542 mld) (DEP, 2003).

Wastewater treatment in New York City is provided by 14 WPCPs, 11 of which were constructed prior to 1956 (Finance Authority, 2003). Continued increases in water usage from the 1950s through the 1980s required additions to WPCP capacity that could barely keep pace with increased wastewater flows. By 1985, a number of plants (Ward’s Island, Newtown Creek, North River and Coney Island) were approaching or operating above design capacity (DEP, 2002). Figure 1 shows a map of the location of the 14 WPCPs with their respective service areas or sewer-sheds.

In 1988, State Pollution Discharge Elimination System permits (SPDES) required the reduction of total nitrogen discharges (mass loadings) into the Upper East River and Jamaica Bay in an effort to reduce anoxic conditions in those water bodies because of elevated nutrient levels (NYSDEC, 2000). The WPCPs which discharge into the Upper East River, as shown in Figure 1, are Ward’s Island, Bowery Bay, Hunt’s Point and Tallman Island. Jamaica Bay, Coney Island, 26th Ward and Rockaway discharge into Jamaica Bay.

Faced with potential water supply shortages, costly development of new water sources, overburdened WPCPs, more stringent water quality standards, and city fiscal stress, the DEP initiated a comprehensive water conservation program in the mid-1980s. We believe that the costs of implementing water conservation, while significant, were less than the costs of developing new water supplies and significantly
retrofitting WPCPs. While detailed engineering cost estimates of new water supplies and wastewater treatment plants retrofits are not available, the evidence presented here is suggestive of significant cost savings. In terms of water supply, detailed cost estimates are unavailable because New York has not constructed any new reservoirs in 40 years. Water conservation was determined to be the most cost-effective approach because construction of new reservoirs would have been prohibitively expensive and politically impossible. Even if politically feasible, legal challenges, land acquisition and construction cost for reservoirs in upstate New York or New Jersey would be in the billions of dollars. Water conservation has also reduced the need for extended use of the Croton reservoir system, which delayed construction of a new water filtration plant for the Croton supply system.

In terms of cost savings in wastewater treatment, we demonstrate that conservation allowed New York to meet interim discharge standards, thus delaying capital expenditures for retrofits and reducing the costs of future upgrades. Specifically, in its 1998 Nitrogen Control Feasibility Plan (DEP, 1998), cost estimates were developed for DEP to retrofit and upgrade all wastewater treatment plans to meet interim and final total maximum daily load (TMDL) permit requirements for nitrogen removal. The 1988 SPDES permits established interim limits on nitrogen discharges of 73,900 pounds (33,520 kg) per day for the Upper East River and 45,300 pounds (20,547 kg) per day in Jamaica Bay. The permit limits for the year 2014 were set at 39,800 pounds (18,030 kg) per day for the Upper East River, with final TMDL requirements to be decided in 2017 based on plant performance.

In order to comply with these interim discharge limits, the DEP and its consultants assumed that plants would need initially to reduce nitrogen discharge concentrations to 9 mg/l. The plan further assumed that nitrogen effluent concentrations of 4 mg/l would need to be reached to meet the final TMDL requirements. Although the SPDES permits are total discharge (mass loadings) permits, the DEP developed concentration targets based on assumptions of wastewater flows in its 1998 Water Demand and Wastewater Flow Projections analysis (DEP, 1998). These 1998 flow projections were based on assumed higher levels of wastewater flows and did not include projections of flow reductions attributable to conservation.

DEP cost estimates to meet interim permit discharge limits (based on assumed 9 mg/l concentration) were US$924 million and cost estimates to meet final permit discharge limits (assuming 4 mg/l concentrations) were $22.7 billion (DEP, 1998). As a result of the experience with water conservation, DEP has revised their current cost estimates to meet final TMDL requirements down to $2.4 billion (DEP, 2006). These 2006 preliminary cost estimates are based on upgrading 13 of the City’s 14 WPCPs. The cost reductions are associated with effluent concentrations of between 7.5 and 9 mg/l, rather than the 4 mg/l previously assumed. Water conservation can thus allow for cost savings in meeting nitrogen discharge limits because effluent concentrations can be higher while still meeting aggregate discharge limits.

The difference in projected costs, while only representing projected and not programmed costs, is quite significant in comparison to conservation. The three primary conservation programs are the leak detection program ($600,000 annually), the universal metering program ($225 million), and the toilet rebate program ($270 million). Although the programs were implemented throughout New York City, DEP officials specifically targeted water conservation efforts in the sewersheds whose WPCPs discharge into the Upper East River. DEP officials believed that reduced wastewater flows to those Upper East River treatment plants operating near full capacity would also provide improvements in nitrogen removal.

In the mid-1980s, the City began an aggressive leak detection and repair program. The program instituted the inspection of over 23 mft (7 million meters) of water mains every three years. Detected
leaks decreased by 90% from 1987 to 1989. Water loss to leaks declined from over 4600 gpd/1000 ft of pipe (57,000 lpd/1000 m of pipe) to 500 gpd/1000 ft of pipe (6200 lpd/1000 m of pipe), an 89% reduction. The DEP estimates that leak detection saved 11 mgd (41 mld) in 1996 alone (DEP, 2002).

Until 1989, DEP charged most consumers a flat fee for their water usage rather than a rate based on actual water usage. Flat fees for water provide no incentives for efficient usage. In 1989, DEP initiated a Universal Metering Program. From 1989 to 2001 the Universal Metering Program installed 20,000 water meters each year in residences, with billing based on actual usage. DEP credits the Universal Metering Program with savings of up to 200 mgd (757 mld) (DEP, 2002).

DEP's toilet-rebate incentive program promoted the installation of low-flow (1.6 gallons or 6 liters per flush) toilets. The program was responsible for the installation of 1.34 million low-flow toilets between 1994-1996, which accounted for water use reductions of at least 90 mgd (340 mld) (DEP, 2002). In monitored apartment buildings, new toilets reduced water consumption by 29% (Endreny, 2002). DEP also hired contractors for leak inspections and building water audits. From 1993 to 2001, leak inspection teams visited 400,000 dwelling units, resulting in estimated water reductions of 11 mgd (41 mld) (DEP, 2002). Further, in cooperation with the New York City Housing Authority, toilets and showerheads were replaced in 100,000 units. Toilet rebates and residential leak detection efforts, though city-wide, were targeted in areas discharging to the Upper East River.

The combined effect of New York's comprehensive water conservation program has been reductions in water consumption during a time of growing population (Roberts, 2006). Figure 2 shows New York's average yearly water consumption in million gallons and million liters per day from 1990 to 2003. In 1990, the average consumption was over 1424 mgd (5390 mld), and by 2003 it had been reduced to 1094 mgd (4141 mld). This represents a decline in total water usage by 23.2%. According to U.S. Census figures, the population of New York between 1990 and 2003 increased 580,333 or 7.9% (U.S. Census Bureau, 2000). Thus, average per capita water consumption dropped from 194.4 gpd (736 lpd) in 1990 to 138.4 gpd (524 lpd) in 2003, a 28.8% decline in per capita water consumption.

Historically, New York City had no good end-user data on water usage. Black and Veatch, Inc. (2003) estimated water usage by category for the year 2001. Of the 1,198 mgd (4,535 mld) usage, residential accounted for 817 mgd (3092 mld) or 68%. Nonresidential usage constituted 204 mgd (772 mld), or 17%. The remaining 177 mgd (670 mld) was unaccounted for. Large declines in industrial water consumption occurred in the 1960s, long before water conservation programs. Current industrial uses, including breweries and garment industries, are generally low water users, and thus industrial water use has remained relatively constant during the conservation period (W. Liebold, New York City DEP, September 2005, personal communication). The declines in water usage over the time period are thus mostly attributable to conservation efforts.

Figure 2 also demonstrates that average daily water consumption levels since 1997 have consistently been below safe-yield amounts. Safe yield is defined as the amount of water available should the drought of record (1963-1965) recur. The safe yield of surface water as shown in Figure 2 is 1,290 mgd (4,883 mld) (Endreny, 2002). One of the purposes of the conservation programs was to improve the dependability of water supplies in drought periods.

Most water usage in New York City is sanitary usage. Industrial and power usage is about 20 mgd (76 mld) (Black and Veatch, 2003) and water-cooled air conditioning may account for a similar volume of water, but has not been estimated. Because most water usage is sanitary usage, reduced water consumption should result in reduced wastewater flows. In fact, as a result of water conservation programs in general, and particularly the toilet rebate program (removal of old toilets with low-flow new toilets), the volume of wastewater flows to WPCPs dropped significantly. In 1992, New York's 14 WPCPs received an average of 1538 mgd (5822 mld) in wastewater. By 2003, they received an average of 1321 mgd (5001 mld), a reduction of 14.1%. Table 1 documents the reduction in flows to all 14 WPCPs over this time period. As Table 1 also indicates, four plants were operating on average above 90% of design capacity in

![FIGURE 2. New York's Average Yearly Water Consumption in Million Gallons and Million Liters per Day From 1990 to 2003.](image-url)
In the late 1980s, the Long Island Sound Study revealed extended periods of hypoxia (less than 5 mg/L dissolved oxygen) in the bottom waters of the Sound. In 1989, more than 500 square miles (1294 km²) of the Sound’s bottom waters experienced dissolved oxygen levels below 3 mg/L. Nitrogen was determined to be the limiting nutrient, and nitrogen discharges from the city’s WPCPs were determined to be a significant contributor to eutrophication of the Sound (NYSDEC, 2000). Additionally, the Jamaica Bay Combined Sewer Overflow Water Quality Study identified the need for nitrogen reductions in effluent discharges into Jamaica Bay. As a result, the New York State Department of Environmental Conservation imposed SPDES permitting requirements limiting total nitrogen discharges into the Upper East River and Jamaica Bay.

SPDES permits established preliminary aggregate limits on nitrogen discharges of 73,900 pounds (33,520 kg) per day for the Upper East River and 45,300 pounds (20,547 kg) per day in Jamaica Bay. DEP was required to investigate nitrogen removal
technologies to meet process efficiency and nitrogen effluent limitations. Pilot studies of new nitrogen removal strategies were required, and total allowable nitrogen discharges were to be reduced when the pilot studies were finished (NTAC, 1999). While these feasibility studies were being conducted, the city was implementing the comprehensive water conservation program.

Nitrogen removal poses significant challenges for New York’s WPCPs because of their size, age, and physical limitations. The treatment facilities have been designed to provide secondary treatment while operating at minimum hydraulic retention time (HRT) in the aeration basins. Most of the plants have been designed with little automation or automatic process control. Plants are generally on land-restricted sites with little or no room available for expansion and any plant expansion is met with strong political opposition.

While water conservation has reduced flows to the WPCPs, the concentrations and total loading of nitrogen in the influent has remained constant or increased as populations increased within sewersheds. Thus, reductions in the total mass of nitrogen discharged by WPCPs should be the result of improved plant efficiency rather than a reduction of total nitrogen influent because conservation does not reduce the amount of nitrogen entering the WPCPs. Figure 4 demonstrates the reductions in total nitrogen effluent loads for the Upper East River, while Figure 5 demonstrates the reductions in nitrogen effluent in Jamaica Bay. Both Figures 4 and 5 show a 12-month rolling average of nitrogen loadings, as well as the permitted discharge amounts. Figure 4 demonstrates that monthly discharges from the WPCPs into the Upper East River have been consistently below the maximum and average permitted amounts since 1998, except for a brief spike during the wet-season spring of 2003. Figure 5 illustrates that nitrogen discharges into Jamaica Bay have consistently been below maximum permitted amounts since 1993 and below the 12-month rolling average permitted amounts since 2000.

Reduced wastewater inflow volumes, constant or increasing influent nitrogen amounts and decreased nitrogen discharge together mean that treatment plants must have increased nitrogen removal efficiency. In order to suggest that the improvement in nitrogen removal was largely due to conservation rather than process changes or plant retrofits, this section will discuss the possible mechanism between reduced flows and nitrogen removal. As well, we will describe any process or structural changes undertaken at the plants. The next section will then utilize statistical techniques on actual plant data to try to control for plant retrofit and influent characteristics so as to separate out the independent effect of flow reductions on nitrogen removal.

Reduced wastewater flows affect nitrogen removal in two ways. First, reduced flows allow for increased HRT in volume-limited aeration basins. Secondly, mixed liquor suspended solids (MLSS) concentrations in aeration basins can be increased while maintaining consistent solids loadings to the final clarifiers. The resulting increase in mean cell residence time in aeration basins results in improved nitrogen removal (NTAC, 1999). The clarifiers can then carry a higher MLSS concentration and thus a higher solids retention time (J. Barnard, Black and Veatch, Inc., October 2004, personal communication). Further, at WPCPs where basic biological nutrient removal (BNR) was implemented, lower flow volumes allow for a reduction in the return activated sludge rate thus resulting in increased sludge mass in the first
aerobic and two anaerobic zones. This increases sludge retention time while enabling higher MLSS in the final aerobic zone (J. Barnard, October 2004, personal communication). Thus, in plants operating at or near capacity and without any process changes or retrofits, reduced flows can improve plant performance. In plants with retrofits or process changes, conservation-induced flow reductions can enhance the effectiveness of these changes.

In 1997 and 1998, DEP implemented basic BNR retrofits at all four Upper East River plants (Ward’s Island, Hunt’s Point, Tallman Island and Bowery Bay) and at only one Jamaica Bay plant (26th Ward) (DEP, 1998). The DEP refers to these BNR retrofits as “Basic Step Feed BNR” to distinguish them from full-scale BNR retrofits. The retrofits at these five plants consisted of providing baffles to create anoxic zones in some of the aeration tanks, adding mechanical mixers for these zones as well as froth control systems. These changes enabled DEP to begin nitrogen removal while evaluating treatment and process options. However, many of the Basic BNR retrofits experienced process difficulties (such as frothing and inadequate aeration) and were periodically discontinued throughout the time period of this study. The 1998 Nitrogen Control Feasibility Plan (DEP, 1998) provides details on these changes and problems for each plant, including procurement problems, equipment failures and process upsets. In general, process changes were minimal, extremely problematic, and frequently discontinued. It is likely that some of these process changes explain improved nitrogen removal, a fact we attempt to account for in the statistical results in the next section.

Ward’s Island implemented Basic Step Feed BNR in one new aerator in December 1997, representing only 10% of its capacity. Hunt’s Point implemented Basic Step Feed BNR in January 1998, Tallman Island in April 1997 and Bowery Bay in July 1998. Each of these three plants has had periodic froth control problems (DEP 2001), and the Hunt’s Point retrofits were discontinued in October 1998. At the 26th Ward plant, Basic Step Feed BNR was implemented in April 2000 and Separate Centrate Treatment was implemented in March 1998. The 26th Ward thus constituted the most significant attempt at nitrogen removal at any of the WPCPs (DEP, 1998). The statistical analysis in the next section will control for these plant retrofits with dummy variables for the appropriate time periods.

The different approaches taken at various plants, while not representing a laboratory controlled experiment, do provide a somewhat “natural experiment” to test the relationship between conservation and nitrogen removal. The four Upper East River plants, subject to permit limitations, were targeted by DEP for water conservation efforts but only limited BNR retrofits. In contrast, nitrogen removal efforts in Jamaica Bay were focused on more significant plant changes at 26th Ward, including Separate Centrate Treatment, and did not include targeted conservation.

Recalling again Table 1, wastewater flows to WPCPs aggregated by receiving water body illustrate the targeted nature of conservation programs during the study period. Upper East River plants saw aggregate wastewater inflow reductions of 18% from 1992 to 2003. Inflows to Jamaica Bay plants – which were not targeted for conservation – actually increased by 1%. Yet, both Jamaica Bay and the Upper East River saw decreased nitrogen effluent discharges, suggesting that both process improvements and conservation can improve nitrogen removal.

In 2005, after the time period of this study, the DEP began construction of full-scale upgrades for the plants discharging to the Upper East River and Jamaica Bay. The upgrades are scheduled to be completed around 2014. A full-scale BNR upgrade differs considerably from the “Basic” retrofit in that it provides all facilities needed to maximize the capability of the step-feed BNR system to remove nitrogen (DEP, 2001). This includes a general modernization of plant equipment, extensive process changes, and significant increases in plant capacity.

DATA AND STATISTICAL ANALYSIS

In this section, we utilize a statistical model to explain the relationship between flow reductions and nitrogen effluent, based on actual plant performance data. For this analysis, the authors acquired from New York City DEP detailed monthly operations data on the 10 WPCPs which discharge into the Upper and Lower East Rivers and Jamaica Bay. Data include monthly average dry-weather wastewater inflow volumes, nitrogen discharges (mass loadings of nitrogen), and influent nitrogen amounts. Data are available from July 1993 to March 2004 for most plants, with detailed data from Lower East River plants (Newton Creek and Red Hook) only available after July 1996.

Because New York operates combined sewer systems (CSOs), it is important in this analysis to use dry-weather flow data. For each month, DEP determined days which were unaffected by storm events and measured flow at the same time on those days. Flows for dry-weather days were aggregated and averaged to estimate average monthly dry-weather wastewater inflows.

One complication to the analysis of New York City data is that many WPCPs import sludge. Accurate
records of dates and amounts of sludge delivery to the various plants is not available, thus accounting for some of the uncertainty in nitrogen removal measures. The regression results below do not attempt to account for or control for sludge importation because we do not have adequate data. If anything, the lack of statistical controls for sludge importation biases the results against our hypothesis that reduced wastewater volumes are significantly related to nitrogen discharge reductions.

Based on the understanding of the wastewater treatment process and the discussion above, the statistical model relating inflows to nitrogen removal should include control of all factors that are known to affect removal efficiency. Conceptually, our model is that nitrogen effluent amounts should be a function of wastewater flows, inflow nitrogen amounts, temperature, and process changes. In equation form, we thus estimate a regression of the form

\[
\text{Nitrogen Effluent} = \text{Intercept} + \text{Inflow Volume} + \text{Nitrogen Influent} + \text{Temperature}.
\]

The dependent variable, nitrogen effluent, is provided by the variable TN (total nitrogen), measured as monthly average pounds per day. The authors used total nitrogen effluent loadings rather than concentrations because the SPDES permits are aggregate limits on mass loadings of nitrogen discharge. Inflow Volumes are measured as average dry-weather inflow volumes, in million gallons per day (mgd). Data on the nitrogen content of influent are given by the variable TKN (total Kjeldahl nitrogen), also measured as monthly average pounds per day. Average monthly temperature data were acquired from the National Climate Data Center, measured at Central Park (NOAA, 2005). Thus, data for each plant are monthly average data, where each observation in the sample is one plant for one month, and includes data on average monthly discharges, inflow volumes, inflow nitrogen amounts, and temperature. We estimate a separate regression equation for each of the 10 plants.

In order to control for the effect on nitrogen removal of the process changes and retrofits described above, we create a dummy variable for each plant-month observation, with a value of “0” if no retrofits had been undertaken, and a value of “1” if a retrofit had been undertaken. For example, Ward’s Island implemented Basic Step Feed BNR in one aerator in December 1997, so all months before December 1997 for Ward’s Island are coded with a “0” while all months after are coded with a “1.”

Multiple regression analysis is a statistical technique used to explain variations in a dependent variable (in this case nitrogen effluent amounts) by means of a number of independent or explanatory variables. Regression techniques allow for the determination of the marginal effect of one explanatory variable on changes in the variable of interest, while holding constant the effects of all other explanatory variables. The interpretation of a regression coefficient, therefore, is the impact of a one-unit change of the explanatory variable on the dependent variable, holding all other variables constant.

The key result of interest in these regressions is the estimated coefficient on dry-weather inflow. The hypothesis being tested is that reductions in flow should lead to reductions in effluent loadings, controlling for the effects of influent nitrogen loadings, temperature and process retrofits. The hypothesized relationship, statistically, is that inflow volumes and effluent loadings should move in the same direction (reductions in one are associated with reductions in the other), which would result in a positive regression coefficient. Thus, if the estimated regression coefficient on flow is statistically significant and positive, that would provide evidence that, controlling for other known influences, reduced wastewater flows caused reductions in nitrogen effluent. We further expect that the coefficients on TKN influent should be positive, indicating that increased nitrogen influent is associated with increased nitrogen discharges. And, we hypothesize that the coefficient on temperature should be negative, in that nitrogen removal is more efficient at higher temperatures.

Because the data come from a consistent time series of observations at each plant, we introduce two statistical techniques to control for the effects of time on the analysis. First, for each plant regression, we include a time-trend variable as an explanatory variable. A time-trend variable would test for some change in nitrogen effluent which is correlated with time but not accounted for by other variables. A negative coefficient on the time-trend variable could represent some factor which has changed over time, but which is unobserved in our other variables. For example, a negative coefficient could represent plant learning over time or minor process changes by plant managers in response to nitrogen limits. A regression with a positive time-trend variable indicates that nitrogen discharges increased over time outside of the other explanatory variables. The three plants with positive time-trend variables all discharge to Jamaica Bay, which suggests some consistent, yet unexplained relationship.

The second statistical correction for time is required because the error terms in the regression model are autocorrelated (correlated across time). Although standard regression coefficients in the presence of autocorrelated residuals are still unbiased, they may not be the most efficient estimates. Durbin-Watson test
statistics indicated the presence of autocorrelated residuals. We control for this by means of estimating the regression equation with auto-regressive moving-average (ARMA) errors of order (1,1). Full specification tests and details of the estimation procedure are available from the authors. After correcting for autocorrelation in the error terms and utilization of a time-trend variable, the remaining coefficient estimates are robust.

For each coefficient, statistical significance is reported with the "p-value." Statistical significance is based on a "t-test" of the hypothesis that the coefficient is zero, which would indicate no relationship between the independent variable and dependent variable (effluent loadings). The authors report the probability value ("p-value") of this statistical significance test for ease of interpretation. Standard statistical practice holds that p-values less than 0.05 are statistically significant at the 5% level. Intuitively, this means that if one repeated the analysis on 100 separate samples, one would get the same results at least 95% of the time.

Table 2 presents the regression results for the six plants which did not experience any basic retrofits or known process changes. The coefficient on flow is statistically significant and the correct sign (positive) in four out of the six plants – Newton Creek, Red Hook, Coney Island and Rockaway – providing evidence that reduced flows were associated with reduced nitrogen effluent. In the two plants which did not see a statistically significant relationship (Jamaica and Hunt’s Point), there are a number of possible explanations. In the Jamaica Bay plant, not targeted for conservation, total flows actually increased over the time period. As well, there does not appear to be much fluctuation in flow volumes in any consistent manner in Jamaica, as flows decreased and then increased.

If the greatest reductions in nitrogen are shown in the plants at or near design capacity, then the fact that Hunt’s Point started the period at only 71% of design capacity might explain the insignificant coefficient. However, Red Hook started at 63% of capacity but showed a statistically significant parameter on inflow volumes. The more likely explanation in Hunt’s Point is some form of plant learning or process changes associated with the discontinued retrofit efforts. Recall from above that basic BNR retrofits were conducted at Hunt’s Point only from January 1998 to October 1998, when they were discontinued.

Table 3 presents the regression results for the four plants which experienced retrofits. In order to control for plant retrofits, we create a dummy variable equal to 0 for months before the retrofit, and equal to 1 for months after the retrofit. We first conducted a “Chow test” to determine whether the dummy variable for plant retrofits should be used alone (as an intercept
Looking at Table 3 results, we see that the coefficient on flow is significant and positive for Bowery Bay and Tallman Island, indicating that wastewater flow reductions were associated with increased nitrogen removal. Moreover, in both of those plants, the interaction terms (a negative coefficient on the flow interaction term in Bowery Bay and a positive coefficient on the TKN interaction term in Tallman Island) indicate that the BNR retrofits at those plants were associated with reduced nitrogen removal and therefore decreased plant efficiency relative to before the retrofits. A close examination of the specific plants’ experience as detailed in the Nitrogen Control Action Plan indicates significant process upsets and frothing control problems in these plants, along with periodic discontinuance of basic BNR retrofits.

Ward’s Island shows a negative coefficient on the flow variable, which indicates that over the time period of the study, flow reductions were associated with increases in nitrogen discharge. However, the coefficient on the interaction term with the BNR retrofits is significant and positive, indicating that BNR retrofits and water conservation had a synergistic effect on nitrogen removal. In fact, the size of the coefficient relative to that on flow would be supportive of the hypothesis that flow reductions improved nitrogen removal.

The 26th Ward plant provides an interesting case, as none of the flow variables or BNR dummy variables or interaction terms or time-trend variables are statistically significant. As with the explanation of the Jamaica Bay plant above, the most likely explanation for these insignificant results is the fact that inflows into 26th Ward actually increased during the overall time period, while fluctuating up and down. Thus, there may not be enough statistical variation in flows to produce statistically significant results. Another explanation may be that the BNR retrofits improved plant

### Table 3: Regression Results, 4 WPCPs With Retrofits.

<table>
<thead>
<tr>
<th>Explanatory Variable</th>
<th>Bowery Bay Coefficient</th>
<th>Bowery Bay p-Value</th>
<th>Tallman Island Coefficient</th>
<th>Tallman Island p-Value</th>
<th>Ward's Island Coefficient</th>
<th>Ward's Island p-Value</th>
<th>26th Ward Coefficient</th>
<th>26th Ward p-Value</th>
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<td>0.0020**</td>
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<td>Interaction: BNR dummy with Inflow</td>
<td>-61.8551</td>
<td>0.0721*</td>
<td>-8.6916</td>
<td>0.6999</td>
<td>46.4117</td>
<td>0.0927**</td>
<td>24.8620</td>
<td>0.5160</td>
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<td>Time trend</td>
<td>4.6635</td>
<td>0.6075</td>
<td>-8.6280</td>
<td>0.0001**</td>
<td>-20.5195</td>
<td>0.0856**</td>
<td>8.3508</td>
<td>0.2026</td>
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<tr>
<td>ARMA parameter</td>
<td>0.5187</td>
<td>0.0000**</td>
<td>0.4847</td>
<td>0.0000**</td>
<td>0.7216</td>
<td>0.0000**</td>
<td>0.6116</td>
<td>0.0000**</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.9504</td>
<td>0.9456</td>
<td>0.9871</td>
<td>0.9849</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes: Dependent variable: TN (total nitrogen).
p-Values are computed based on a heteroskedastic-consistent variance matrix.
**Indicates statistically significantly different from zero at 5% level; * indicates at 10% level.
performance just enough to handle the increased inflow, but not enough to show a statistically significant reduction in nitrogen.

PREDICTING NITROGEN REDUCTIONS FROM WATER CONSERVATION

The 10 WPCPs in New York City studied in this paper differ significantly in terms of size and design. The results of this analysis, therefore, can be used to make some reasonable predictions about the nitrogen discharge effects of water conservation in other locations. Plant engineers or policy analysts may be faced with the task of predicting the effects of water conservation on nitrogen removal or in calculating cost-benefit or cost-effectiveness analyses of the gains from water conservation. To the extent that plants in other locations are similar in size and process to any particular plant in New York, then specific regression results from that plant could be utilized. However, in this section, we combine the results from all 10 plants to provide a "universal" estimate of the effects of water conservation on nitrogen removal.

In order to produce predictive numbers for the relationship between flow reductions and nitrogen removal, we need to control for plant size. For each plant, we first use the plant-specific regression equation to calculate predicted (or "fitted") TN effluent amounts as a function of variations in inflow volumes, holding all other values fixed at their mean. For each plant, our predicted TN effluent amounts are compared to actual flow levels. To standardize this relationship, we convert each actual flow volume into flow as a percentage of plant capacity by dividing by plant capacity. To standardize TN effluent amounts, one could divide predicted amounts by average or median TN effluent amounts, to get an approximation of average TN reductions. However, given that most TMDL permitting regimes are based on maximum effluent loadings, we divide each predicted TN amount by the maximum predicted TN amount for each plant, to represent predicted TN as a function of maximum TN effluent. Thus, the data will allow us to relate flows as a percentage of plant capacity to TN levels as a function of maximum predicted TN effluent.

Our data now consist of 1,200 observations of flow as a percentage of plant capacity and predicted TN as a percentage of maximum plant TN effluent. When plotted, even these fitted data exhibit significant variation because of the wide variation in plant types of plant processes. Because we are interested in predicting TN effluent as a function of inflow volume, we regress flows on TN loads. A 7th-degree polynomial regression provides the best fit of the data, with an adjusted $R^2$ of 0.15. Full regression results and specifications are available from the authors upon request. Because of the reasonably low predictive value of this equation, the confidence intervals on predicted nitrogen reductions may seem relatively large. The fitted regression line along with the 95% confidence intervals around the estimates are shown in Figure 6 below. Figure 6 demonstrates that, holding all other factors constant, TN effluent decreases as wastewater inflows decrease.

Although Figure 6 illustrates the average relationship between wastewater flows and nitrogen effluent, the ability to predict decreases in nitrogen effluent as a function of conservation requires estimation of the
marginal effects. Therefore, Figure 7 shows the same data as Figure 6, only this time representing the percent decrease in nitrogen effluent expected for a 1% reduction in wastewater flow volumes, as a function of plant capacity. The way to read Figure 7 is to identify existing plant capacity (for example 95%) and read the vertical axis as representing the percent decrease in nitrogen for a 1% decrease in inflow volumes (in this case 2.1%). Figure 7 demonstrates that the largest marginal reductions in nitrogen effluent occur up to about 88% of plant capacity. For ease of calculation, Table 4 below presents the data from Figure 7 in tabular form for 5% increments. The full data are available from the authors upon request.

Using the values from Figure 7 and Table 4 on Ward’s Island illustrates the utility of these calculations. Recall from Table 1 that, in 1992, Ward’s Island was operating at 95% of capacity, while in 2003, it was operating at 70% of capacity. Figure 7 would predict a 14.2% reduction in maximum nitrogen effluent for this reduction in inflow volumes. In fact, maximum TN discharges (measured on the monthly average basis) decreased 15.4% from 1992 to 2003.

### CONCLUSIONS

Nitrogen discharges from New York City’s WPCPs discharging to the Upper East River and Jamaica Bay have contributed to degraded water quality and triggered regulatory action under the SPDES permit system. SPDES permits for the Upper East River and Jamaica Bay are aggregate limits on mass loading of nitrogen discharges. Meeting water quality permit requirements through technical and process improvements has proven costly, time-consuming, and technically challenging in many older plants. The results in this paper demonstrate that water conservation programs are associated with reductions in nitrogen discharge and have therefore enabled the city to meet interim effluent limits. Water conservation programs have deferred expensive water supply and wastewater treatment capital costs, and have provided the city with time to investigate and experiment with alternative nitrogen removal strategies. Furthermore, water conservation efforts will allow the city to meet future TMDL requirements at higher effluent concentrations, thus providing additional significant cost savings. The Nitrogen Technical Advisory Committee, established to monitor the City’s compliance with legal consent decrees and permits, has determined that the targeted water conservation programs in the Hunt’s Point and Ward’s Island WPCP sewersheds, when later combined with full-scale step-feed BNR retrofits, will allow the city to meet future SPDES effluent limits at lower costs (NTAC, 1999).

One additional benefit of the conservation-induced wastewater flow reductions has been the increased ability of WPCPs to treat stormwater before discharge into receiving water bodies. Like many older cities, New York operates CSOs. When WPCPs are operating at or near design capacity, additional stormwater flow bypasses plants and is discharged directly into water bodies without treatment. The DEP has determined that the combination of water conservation measures and capital improvements has increased the percent of stormwater overflows captured and treated at WPCPs from 18% in 1991 to 72% in 2004 (DEP, 2004).

As a matter of policy, the Nitrogen Technical Advisory Committee (NTAC), a panel of national experts organized to advise DEP on nitrogen removal strategies, recommends that when SPDES permits are renewed, the DEP should continue permits based on mass of nitrogen discharged rather than nitrogen concentration limits. These recommendations are based on the assertion that WPCP capacity ratings that are based on flow provide disincentives to exploring water conservation as a tool to reduce nitrogen discharges. Under the current rating system, WPCP upgrades and retrofits are targeted at design capacity flows, thus requiring capital investments to meet conditions that conservation can delay or even prevent, and do not account for the benefits to nitrogen removal of increased HRT resulting from reduced wastewater flows (NTAC, 1999).

States across the nation are developing TMDL plans for impaired watersheds under requirements of the Clean Water Act. Nutrient outputs from WPCPs are a significant cause of water quality impairment in many watersheds. Frequently, costly plant upgrades are the only available option to meet nutrient reductions required under state and federal permits and regulations. Analysis of New York City’s WPCPs shows that water conservation can assist

### TABLE 4. Predicted Percent Reduction in Nitrogen Effluent for a 1-Percent Reduction in Inflow Volumes (as a percent of plant capacity).

<table>
<thead>
<tr>
<th>Plant Capacity (%)</th>
<th>Nitrogen Reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1.03</td>
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<tr>
<td>95</td>
<td>2.10</td>
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<tr>
<td>90</td>
<td>0.79</td>
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<tr>
<td>85</td>
<td>-0.16</td>
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<td>75</td>
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<td>70</td>
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<td>65</td>
<td>1.21</td>
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<tr>
<td>60</td>
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</table>
wastewater utilities to meet discharge limits (especially those based on mass nutrient loadings) with cost savings compared to plant expansion or retrofits. For metropolitan regions that draw supplies from ground-water sources, water conservation could also improve base flows in streams and rivers. Recalculation of improved base flows due to conservation should be taken into consideration in the calculation of drought-flows on which many TMDLs are calculated.

Comprehensive water conservation programs provide numerous economic and environmental benefits for large or growing metropolitan regions. Reductions in water consumption improve the stability and dependability of water supplies, may save consumers money, and may reduce or delay costly infrastructure development for new sources. This paper has demonstrated an additional benefit of conservation programs. Conservation-induced reductions in wastewater flows to treatment plants improve the efficiency of plants in removing nitrogen, and this paper has provided quantitative estimates of the magnitude of this relationship. A challenging fiscal environment for water and wastewater infrastructure capital expenditures, combined with increasingly stringent water quality regulations would suggest that water conservation programs should be an important component in any metropolitan water resources management and planning effort.

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