From Grey to Green Filtration
Rethinking Urban-Rural divide in the Empire City Watershed

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The urban-rural divide characterizes much of the debate in modern day living and politics. Large segments of society have strong connections and identities that adhere to either one of the other along that divide. One may argue that it is chiefly brought about by differences in demography, lifestyle preferences, and industry. Globally, assuming such differences do not preternaturally disappear, even as urbanization accelerates (Ritchie and Roser, 2020), how can we harness those differences instead of succumbing to divisiveness? One of the ways to do so is to play to the strengths of both urban and rural communities. In choosing to locate their permanent residences, individuals have diverse predilections and priorities that may evolve depending on the phases of their lives and why not preserve diversity of living environments to better safeguard those choices? This author was inspired by the case study of NYC's relationship with its watershed communities and its management of this tenuous relationship. Although this urban-rural relationship developed organically over centuries, I contend that this relationship can be feasibly replicated in other geographies under similar conditions.

Why Go Green?

Rural communities almost by definition possess an abundance of nature areas and wildlife, and to varying levels of success spawn related industries with natural monopolies. Tourism, retail and accommodation services are sectors traditionally seen as alternative drivers of growth in certain rural areas. However, these sectors severely underestimate the rural areas' contribution to the preservation of regional biota and hydrology. Although gains may more effectively be capitalized in rising real estate prices in rural areas, these gains are by no means equitable, and can easily serve to compound urban-rural tensions by exacerbating housing stress. On the other hand, urban metropolitan areas draw individuals by their sheer ability to provide higher paying jobs and access to better networks, amenities, and services. Traditionally, macroeconomic national accounting measures heavily bias output in urban areas; while underestimating non-traditional outputs of rural areas that defy easy monetary quantification (Dudley and Stolton, 2003).

The co-benefits of ecological preservation are seemingly innumerable- there is a clear link between forests and the quality of water coming out of a catchment (Dudley and Stolton, 2003), not to mention preservation of biodiversity, and air pollution control to name a few. Each can have a Payment for Ecosystem (PES) program attached, as long as there exists detailed information on which service a given forest is providing, and to whom. Fundamentally, *green* infrastructure tends to have opportunity costs which are more clearly understood- in terms of forgone development and income, while benefits are poorly understood and priced. Grey infrastructure, on the other hand, can present hidden ecological opportunity costs, while its benefits are easily quantifiable and accounted for.This study aims to set the foundations for the accurate comparisons of water filtration Ecosystem Services (ES) provided by watersheds, through comparing the cost-effectiveness of capital investments in green and grey infrastructure over three time periods. In so doing, allow for objective allocation of scarce capital Rahm et al. (2013) among regions and watersheds, aid watershed scale analysis and decision making, and provide clear objectives for improving certain pollutant levels. Ideally, such an analysis of the historical cost effectiveness of capital investments in a watershed would complement a more forward-looking and detailed treatment like Rahm et al. (2013) composite scores, and goal-based watershed assessments. Furthermore, it is precisely creating comparative monetary values for such ES, that policy makers and businesses can better weigh costs and benefits before making investments and planning decisions.

The Empire City Watershed

The NYC drinking water supply system is the nation's largest unfiltered water supply, drawing its water from 1,972 square miles of upstate watersheds for its more than 8 million consumers downstate. At the end of the 18th century, NYC started looking upstream for fresh water sources in response to water contamination and destructive fires (Alcott et al., 2013). After exploring supply options, the city focused supply expansion efforts on the nearby Croton River, but by the 20th century demand was far outstripping supplies, and the city expanded into the Catskills and Delaware systems, more than 100 miles Northwest of the expanding metropolis (Alcott et al., 2013). The Catskill Water Supply System was completed in 1927, and the Delaware Water Supply System, in 1967 (NRC, 2000). By 2000, the enlarged Croton watershed area's permanent population had expanded to about 100,000 from 20,000 (in 1900), and due to its proximity to the city nearly 80% of the watershed was developed (Warne, 2010). Substantial development within the Croton area resulted in forest loss, high impervious surface coverage and associated run-off and water quality concerns (Wilder and Kiviat, 2008). The Catskills and Delaware watersheds however did not experience the same development pressures as the Croton watersheds likely due to its distance from the city. (SeeLand-use changesin both West and East of Hudson watersheds from 1974-2012inChapter 3). Today, the NYC water system comprises over 22 reservoir basins in total. Six of which lie West of Hudson (in Catskills and Delaware watersheds), and the other 16 lie East of Hudson (in the Croton watershed). In 2008, the Catskill-Delaware and Croton watersheds provided 50%, 40%, and 10% respectively, of the roughly 1.2 billion gallons of water consumed by NYC and upstate residents everyday (DOH,2008).

Regulatory Overview

NYC's drinking water although managed by the city, falls within a federal and state regulatory framework (Alcott et al., 2013). The Safe Drinking Water Act (SDWA) is the federal law regulating both anthropogenic and naturally occurring contaminants in US drinking water systems (EPA, 2010a). However, the actual implementation of water quality standards is delegated to states, localities, and water suppliers, while EPA oversees administration and compliance.

Within New York State, the Department of Health (DOH) is charged with implementing the SDWA, but the NYC DEP plays the primary role in structuring the programs that preserve NYC's watersheds (Warne, 2010). In the mid-1980s, when EPA asked Congress to pass an SDWA amendment that required filtration of all surface water sourcing systems, NYC resisted (Alcott et al., 2013). Having historically invested in and relied on consistently clean drinking water from the Catskills-Delaware and Croton watersheds, the cost of building new filtration plants seemed unreasonable (Appleton, 2002). NYC advocated for a less uniform application of EPA's filtration standards. After much deliberation, the final SDWA surface water treatment rule included a provision allowing filtration avoidance if two conditions were met- 1) compliance with water chemistry requirements, and 2) a long term plan for control and management of surface drinkingwatersheds was approved (EPA, 1989).

In 1993, EPA issued a Filtration Avoidance Determination (FAD) for the Catskill-Delaware system, contingent on 150 conditions, including critical upstream conservation requirements (EPA, 2000). Over and above securing the necessary funding, complexities related to land purchase contracts and water supply permits proved challenging for the planned land acquisition program, and by 1994, no land had been acquired (EPA, 2000). The regulatory framework and consequences precipitated a changing relationship between watershed communities and NYC authorities overseeing drinking water for its residents. This set into motion negotiations among city, state, upstate watershed communities, EPA, and environmental parties that culminated in the signing of a landmark NYC Memorandum of Agreement (MOA) on Jan 21, 1997 (Alcott et al., 2013). It stipulated land acquisition requirements, and created the NYC Watershed Protection and Partnership Council and corresponding watershed protection provisions and programs (EPA, 1997).

NYC Approach

A review of the West of Hudson watersheds revealed that the key barrier to effective regulation of water quality was the lack of public land ownership in the watersheds (Alcott et al., 2013). Furthermore, NYC determined that a watershed protection program would be far more cost effective compared to the expense of a new filtration plant to ensure sufficient compliance to water quality standards (NRC, 2000). This proved for all intention and purposes, a truly watershed moment; ushering an era focused on watershed management in NYC's water systems. Overall, the NYC DEP implements three source-water protection programs- 1) the Land Acquisition Program (LAP); 2) Watershed Protection and Partnership Programs that include watershed forestry, wetlands protection, stream management, waterfowl management, and agricultural pollution prevention planning and public outreach and education; and 3) capital programs that include sewer extensions, septic system rehabilitation and replacement, storm water retrofit, and wastewater treatment (WPPS, 2011b). The first two can reasonably be classified as *Green* water infrastructure investments, while the third would be considered *Grey* water infrastructure investments henceforth.

Definitions & Data

Both water quality and CWA grant data were derived directly from Keiser and Shapiro (2018)'s study. The water quality data was filtered from over 240,000 nation-wide pollution monitoring sites during the years 1962-2001 from three data repositories- Storet Legacy, Modern Storet and the National Water Information System (NWIS). While CWA grant data was obtained by clipping from the Clean Watershed Needs Survey (CWNS), a panel description of the country's Wastewater Treatment Plant (WWTP); and historical extract of the Grants Information and Control System describing each of 35,000 CWA grants the federal government gave cities.

Capital Investments

CWA capital investments are demarcated by federal, state or local, and Operations and Maintenance (O&M). Although O&M are most likely funded at the state and local level, this category of funding was dropped from my analysis for clarity; focusing narrowly on the capital investments clearly demarcated from Federal or State/Local sources. State or local investments will henceforth be referred to local capital investments. This step is crucial in subsequently estimating the annual grant investments dispensed for each year in each watershed. Cumulative grants was identified for each WWTP and aggregated by each of the seven watersheds in question. Subsequently, annual capital investments in each watershed were estimated using national trends in spending published by the Congressional Budget Office (CBO, 2018) from 1956-2017. Annual capital investments for each watershed were further subdivided into *green* or *grey* capital investments according to the trends in spending taken from CBO (2018).

Land Use

Land-use raster data were obtained from USGS' U.S. Conterminous Wall-to-Wall Anthropogenic Land-use Trends (NWALT) (Falcone, 2015). Due to the lack of readily available water quality data at a more granular NYC's reservoir basins scale, land-use data of larger 8 digit Hydrologic Unit Code (HUC) watersheds were used. Note that due to data limitations, the overall land area used in this study is 4.5 times larger than the actual NYC reservoir basins.

Although there is particular clustering of pollutant monitoring stations in the Neversink reservoir basin (See Figure 3.1 below for Map of the Study Area), for the most part WWTP and monitoring stations are fairly evenly distributed across the watersheds studied. The raster data were available at reasonably timed intervals- for the years 1974, 1982, 1992, 2002, and 2012. Land-use changes were linearly interpolated for each watershed, across the years where there was no data. Because most pollutant data spanned 1962-1998, the uneven overlap thereby excluded the analysis of land-use effects before 1974 and after 1998. The list below are definitions of land-use according to Falcone (2015). Note that in the original dataset, each type is further subdivided into up to seven sub-types of land-use. For the purposes of this study, four major types were used for analyzing NYC's watershed, with land-use types Conservation folded into the Low Use land-use type. Changes in land-use from 1974 - 2012, in both West of Hudson and East of Hudson watersheds are shown in Fig. 3.2 below.

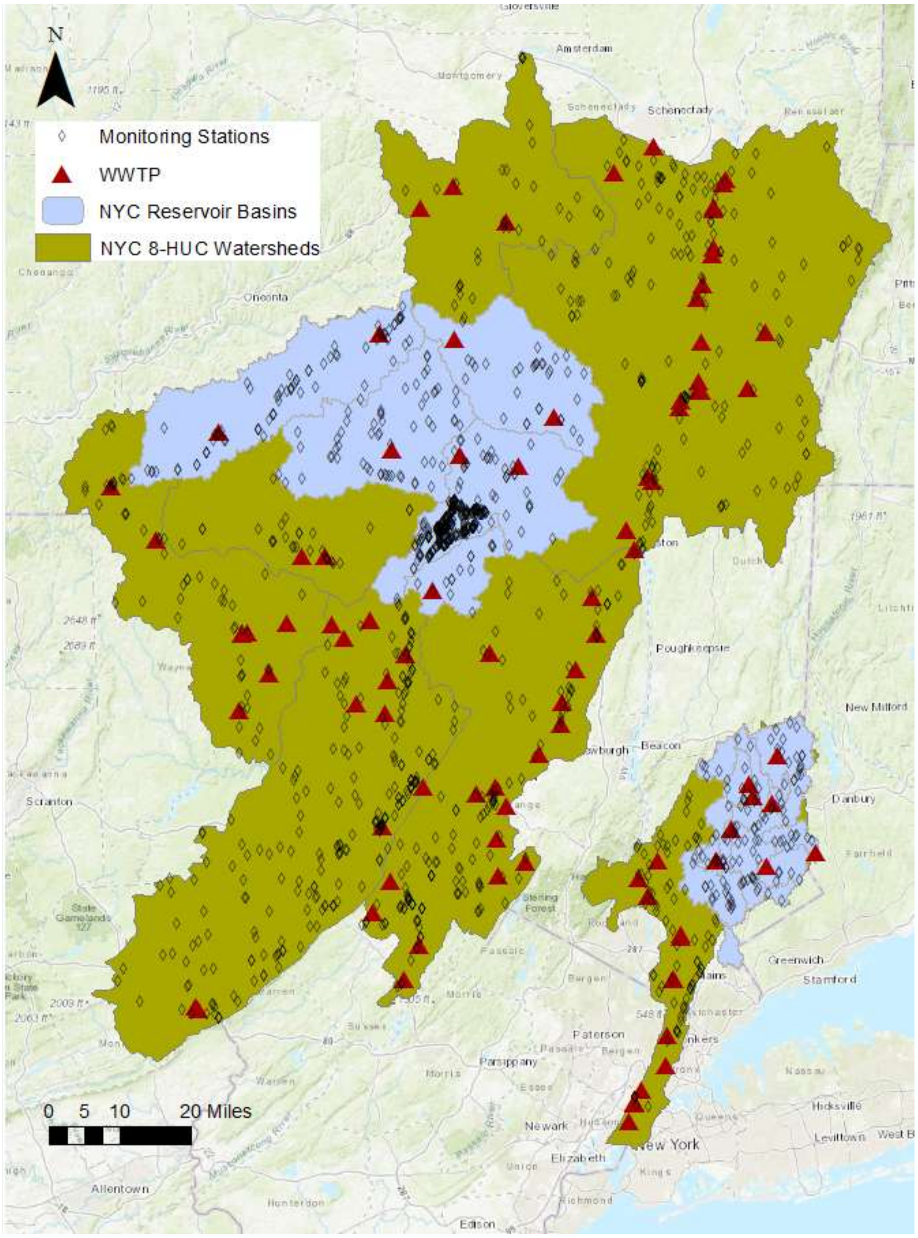

Figure 3.1: Map of the Study Area

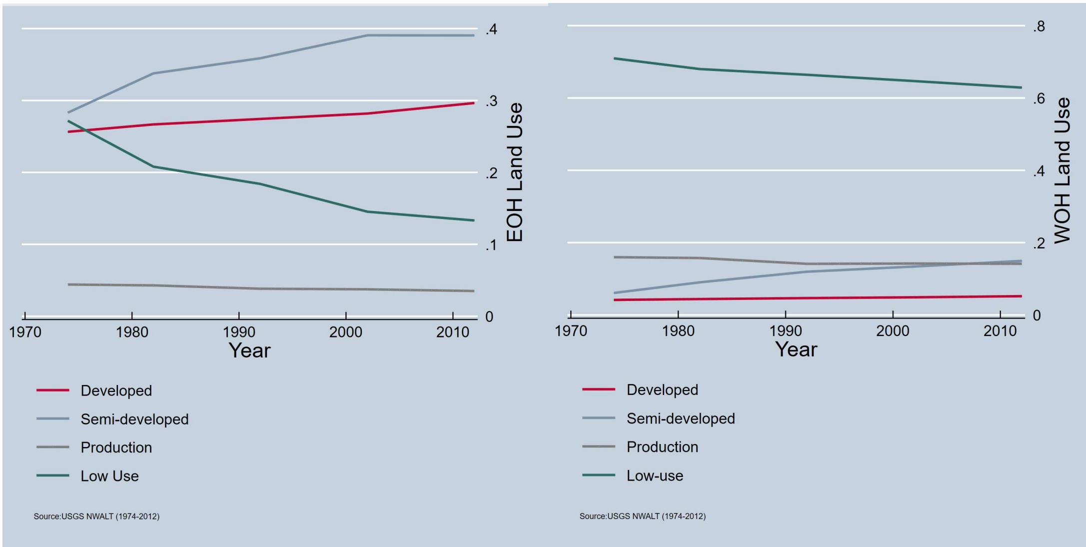

Figure 3.2: Land-use change

Land Use	**USGS (NWALT) Description**
Developed	The built environment- settings where residences, employment, and recreation predominate.
Semi-Developed	The “near-built” environment- settings that are in close proximity to Developed lands and (or) are partially used for the same purposes.
Production	Settings in which natural resources are produced (Agriculture) or removed (Mining and Timber).
Conservation	Land set aside for natural areas or wildlife protection.
Low Use	Land not discernible as being in any of the above categories; no evidence of regular human usage.

Methodology

By examining seven upstate New York (NY) 8-HUC watersheds that provide potable water to more than 8 million NYC residents over the course of 1962-1998, this study aims to investigate the comparative effects of capital investments from the Clean Water Act (CWA) and land-use change on six identified water pollutants- Biochemical Oxygen Deficit(BOD), Dissolved Oxygen Deficit(DOD), Fecal Coliform, Total Coliforms, Total Suspended Solids(TSS), and Turbidity. Utilizing a large panel dataset protects against unmeasured confounders unique to individual watersheds, but crucially does not guard against reverse causation. Additional understanding of the prevailing regulatory environment, as described in the *Background* section, was also folded into the sensitivity analysis for the model.

The Approach

Key regulatory milestones used for comparisons of cost-effectiveness are the enactment of the Clean Water Act (CWA) in 1972, and the issuance of NYC's first Filtration Avoidance Determination (FAD) in 1993. Introducing these milestones into the model allows an added dimension of temporal analysis of effectiveness. The 1972 U.S. Clean Water Act sought to restore and maintain the chemical, physical, and biological integrity of the Nation's waters. It had ambitious targets- to make all U.S. waters fishable and swimmable by 1983, to have zero water pollution discharge by 1985, and to prohibit discharge of toxic amounts of toxic pollutants (Keiser and Shapiro, 2018). The 1972 amendments to the Clean Water Act greatly expanded grants for the construction of municipal wastewater treatment facilities, and support for point source industrial abatement, on a scale unseen in previous laws (CBO, 2018, Keiser and Shapiro, 2018). At the local level, NYC's first FAD kick started a number of programs. The foundation of its watershed protection program being the Land Acquisition Program (LAP), alongside other programs which funded limiting land-use such as agriculture and conservation easements (Warne, 2007). Successfully protecting its upstate watersheds became instrumental to EPA's continued issuance of filtration avoidance to NYC.

Because this study primarily aggregated data at the HUC watershed level, it sacrifices a level of accuracy demonstrated in the (Keiser and Shapiro, 2018) study- by not deriving cost-effectiveness for each pollutant, in terms of stream length or river-mile made fishable or swimmable per year. However, my model is categorically simpler to replicate given the available data, and does not include aspects of Willingness-To-Pay (WTP) determined through capitalized real estate prices, thereby analyzing relative effectiveness of different pollution control investments.

Water Quality Measures

The spatially and temporally uneven nature of water quality testing across the US cannot be avoided even for an extended study period. As such, pollutant data at each monitoring station were linearly interpolated for intervening years where there were missing data, before aggregating by watershed year to be inputed into the panel.

Effects of Regulation

These two milestones (CWA and FAD) presented a unique opportunity for a longitudinal study on NYC's upstate watersheds and the consequences of strong regulatory oversight and large capital investments in both *green* and *grey* infrastructure at specific junctures in time. Broadly speaking, the CWA largely emphasized *grey* infrastructure by targeting point source water pollution, while *green* infrastructure featured prominently in NYC's watershed with the strong regulatory pressure in the form of term-based issuance of FADs. However, the Memorandum of Agreement (MoA) signed between NYC and upstate NY watershed communities in 1997 also catered for large sums of *grey* capital investments that could complicate the quasi-experimental parameters (see Extensions[1] for a full discussion of limitations and future data requirements that will address this issue).

Aggregation

Firstly, water quality monitoring stations and WWTP data were tagged to geographical locations and those which did not fall within the HUC watersheds were discarded. Water quality data and capital investment data were then appended to the remaining monitoring stations and WWTPs. Because waters may be tested multiple times in a year foreach pollutant, in constructing a panel data, the annual mean of multiple readings from each monitoring station was used and aggregated at the HUC watershed level. Cumulative capital investments for all WWTPs within each watershed were first decomposed by year and aggregated to respective watersheds.

Econometric Model

$$P_{iwy} = \beta T_{iy} + \gamma L_{wy} + \rho F_{wy} + \sigma_w + \varepsilon_{iwy} + \theta d_{72,93} \tag{4.1}$$

The variable P_{iwy} is the aggregated water quality measure, for measure i, measured in each watershed,w for year,y. The fixed effects σ_w control for all time-invariant determinants of water pollution specific to each watershed,w. T_{iy} is the year, and can be interpreted as annual trend for each pollutant, after accounting for watershed fixed effects, and capital investments F_{wy} and land-use L_{wy} covariates (where applicable). d_{72} and d_{93} are two separate dummy year variables- pre-1972, and pre-1993 that are individually included if data collected for a pollutant spans both sides of the dummy year variable. It therefore acts as a way to identify if pollutant levels were significantly different between two discrete time periods. The model assumes that the effects of additional funding and land-use are additive and constant, and that prior to 1968, watersheds have had similar variation and trends in water quality measures.

Sensitivity Analysis

For each measure of water quality, various combinations of the above equation 4.1were run. A first run of the fixed effects model only included the annual trend variable, T_{iy}. All water quality metrics, except for DOD, underwent a logarithmic transformation which addressed issues of heteroskedasticity. Post-transformation residuals by watershed year largely approached the condition $E(\varepsilon_{iwy}|w,y) = 0$.

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[1] Other discussions (apart from Data limitations) in the Extension are not included in this print to adhere to the 5,000 words limit.

$$P_{iwy} = \beta T_{iy} + \sigma_w + \varepsilon_{iwy} \tag{4.2}$$

A second run of the fixed effects model included capital investments data co-variate at each watershed by year, F_{wy}.

$$P_{iwy} = \beta T_{iy} + \rho F_{wy} + \sigma_w + \varepsilon_{iwy} \tag{4.3}$$

A third run then included annual land-use changes at each watersheds, L_{wy}, into the model.

$$P_{iwy} = \beta T_{iy} + \gamma L_{wy} + \rho F_{wy} + \sigma_w + \varepsilon_{iwy} \tag{4.4}$$

The final runs added either the pre-1972 or pre-1993 dummy year variable to the model. This process was then repeated for a subset watersheds located West of Hudson. A separate run was not conducted for the remaining singular East of Hudson watershed.

$$P_{iwy} = \beta T_{iy} + \gamma L_{wy} + \rho F_{wy} + \sigma_w + \varepsilon_{iwy} + \theta d_{72} \tag{4.5}$$

$$P_{i,west,y} = \beta T_{iy} + \gamma L_{west,y} + \rho F_{west,y} + \sigma_{west} + \varepsilon_{i,west,y} + \theta d_{72} \tag{4.6}$$

Results

General Findings

Keiser and Shapiro (2018)'s study showed that improvements in all six pollutant levels were more rapid in the Northeast EPA census region compared to the rest of continental US. However, this study finds that NYC's watersheds have statistically significant improvements for only three of the six pollutant levels studied- with improvements in these three measures similarly outstripping Keiser and Shapiro (2018) nationwide gains. This is indicative of heterogeneity across watersheds and regions within the large Northeast EPA census region. Crucially, Dissolved Oxygen Deficit (DOD) was one of the best performing metrics of the Northeast EPA census region in Keiser and Shapiro (2018), while this study showed no statistically significant improvement, instead DOD most likely suffered significant deterioration during the study period in NYC's watersheds.This panel study finds that aggregating pollutant metrics at the watershed level has generated results that are congruent with established scientific understanding of the types of land-use, and their effects on different water quality measures. One of the advantages of this model is that it can be readily operationalized to support an analysis of historical watershed level performance- presenting an elegant way to determine watershed health and effectiveness of investments and policy on pre-identified pollutants, all the while controlling for regional anthropogenic changes. Overall, developed land-use appeared to be bad for water quality measures, while semi-developed and production land-use in some cases correlated with positive outcomes of water quality measures. One reason could be tighter regulations and/or better septic systems in semi-developed and production land-uses.

Green infrastructure capital investments appear most suitable to address BOD, and DOD, and/or work particularly well in locations where semi-developed land-use predominate or are increasing. While *grey* infrastructure capital investments appear most effective for Coliforms, TSS, and Turbidity and/or work well in locations where production land-use predominate or are increasing. Developed land-use and capital investments in water infrastructure are positively correlated. Unsurprisingly, this is especially pronounced for areas that are densely developed, while less so with areas that are outside of metropolitan areas, as shown in the correlation Table 5.1 below. The fact that developed land-use is significantly correlated with poorer water quality even as capital investments are largely channeled there shows that current investment patterns in developed areas are ineffective or insufficient. Although production land-use appear to be somewhat negatively correlated with capital investments in water infrastructure, this is likely due to the strong inverse relationship between developed and production land-use- in that development largely encroaches upon primary production land-uses. This relationship is also likely stronger in the East of Hudson watershed (SeeFig 3.2).

Table 5.1: Funding & Land-use cross-correlation table

Variables	Fed green	Fed grey	Loc green	Loc grey	Dev	Semi
Fed green	1.000					
Fed grey	0.989	1.000				
Local green	0.970	0.970	1.000			
Local grey	0.994	0.985	0.988	1.000		
Dev cover	0.939	0.921	0.925	0.940	1.000	
Semi cover	0.524	0.509	0.568	0.548	0.730	1.000
Prod cover	-0.353	-0.346	-0.335	-0.345	-0.318	-0.457

Biochemical Oxygen Demand

From the results of the sensitivity analysis, major improvements in the level of BOD occurred before 1993, and in large part due to land-use changes. It is likely that federal *green* infrastructure capital investments, which were significantly correlated to reductions in BOD, were working through semi-developed land-use changes, while grey infrastructure capital investments appeared negatively correlated with BOD levels, essentially insufficient in stemming the significant polluting effects of increasing developed land-use. The West of Hudson watersheds also appear better at reducing BOD, compared to the East of Hudson watershed, likely due to far lower population density compared to the East of Hudson watershed.

Dissolved Oxygen Deficit (DOD)

The story for Dissolved oxygen deficits was very different, there was no statistically significant improvements in DOD levels for all the watersheds. In fact, after accounting for land-use change, it actually reported a large (~44%) deteriorating trend over the entire study period. Developed and production land-use were strongly correlated with negative outcomes of this pollutant, with its effects stronger in West of Hudson watersheds.Increasing semi-developed land-use was associated with positive effects on DOD. Likely explanations could be that 1) semi-developed areas have far more dispersed effects, and therefore have less impact on DOD; 2) that storm-water events introduce a great degree of noise into measures of DOD, hence making it less suitable a measure for this kind of modelling, or that 3) *green* capital investments are effectively working through semi-developed areas. Both discrete time interval dummy variables were however statistically insignificant, and were not informative about the interval at which DOD were worse.

Fecal Coliform

Although the improving trend in fecal coliform levels accelerated after 1972, after controlling for land-use change, there was overall no statistically significant improvements in the pollutant levels. A statistically significant deterioration after 1993 could explain the inconclusive results across the entire study period; as post-1993 deterioration nullified gains in the preceding years. Before the inclusion of land-use covariates, West of Hudson watersheds saw far stronger improvements compared to the

East of Hudson watershed, although it too became statistically insignificant upon the inclusion of land-use in the model. Crucially, improvements in fecal coliform levels were very strongly tied to production land-use for both West and East of Hudson watersheds. One explanation could be that *grey* infrastructure capital investments channeled into controlling point source effluent fecal coliforms were particularly effective, or that voluntary Non-Point Source (NPS) pollution controls such as farm Best Management Practices (BMP), have been particularly effective at combating levels of fecal coliform between 1972 and 1993.

Total Coliforms

Measures of total coliforms showed significant improvements over the study period, with the East of Hudson watershed somewhat outperforming West of Hudson watersheds. Although local *grey* infrastructure capital investments were statistically significant in reducing the pollutant levels, they became insignificant after including land-use covariates. Similar to the case for fecal coliform, production land-use showed a statistically significant positive relation with improvements in measures of total coliforms. These results indicate that all coliforms generally respond to the same measures, that *grey* infrastructure capital investments may be more suited to combating such pollutants, with its effects more pronounced in the East of Hudson watershed. Notably, of all the pollutants, total coliforms showed the best model fit ($R^2 \approx 0.5$) after including funding and land-use change covariates.

Total Suspended Solids (TSS)

TSS saw significantly strong improvements for all watersheds. With those improvements after 1993 significantly outstripping gains before, in the West of Hudson watersheds. In the East of Hudson watershed however, these improvements were statistically larger before 1993. Local *grey* infrastructure capital investments were statistically significant in reducing the pollutant levels in the East of Hudson watershed, while semi-developed land-use was again correlated with the reduction in pollutant levels, although this relation was not as strong as in West of Hudson watersheds. As in the case of DOD, semi-developed land-use are tied to positive outcomes of TSS, although this time *grey* infrastructure capital investments were also similarly significant in explaining reductions in the pollutant level. This is indicative that grey infrastructure capital investments work particularly well for TSS and its effectiveness maintains despite changes in land-use. Lastly, increases in developed land-use were detrimental to measures of TSS across all watersheds, although this was approximately two times more pronounced in the West of Hudson watersheds, indicating that more *grey* infrastructure capital investments may be needed there.

Turbidity

Overall, turbidity trends were mixed- with statistically significant improvements over the study period, but trend improvements becoming insignificant after the inclusion of land-use covariates. Results from sensitivity analyses indicate that infrastructure capital investments likely worked through land-use change in a substantially strong way. Sensitivity analysis of 1972 and 1993 dummy variables for both West and East of Hudson watersheds indicated that turbidity measures were sharply worse after 1993, with indications that overall improvements in turbidity across both West and East of

Hudson watersheds occurred during the intervening years of 1972- 1993. This is consistent with recent reports of Catskills watersheds struggling with poor turbidity measures (DePalma, 2006, DOH, 2017).

Turbidity generally appeared to be strongly tied to changes in land-use. For both watersheds, production land-use was significantly correlated to improvements in the levels of turbidity.

Extensions

Data

The existing model can be enriched substantially with better data on several fronts. In large part due to a shortage of water quality data either in the years preceding1972 or after 1993, the overall picture for pollution metrics divided by the discrete time periods was mixed. It would be ideal to reassess the watersheds given consistent water quality readings for at least 10 years after 1993, as the implementation of capital investments or policy may have temporal lagged effects. Water measures inherited from Keiser and Shapiro (2018) were tagged according to HUC watershed IDs, preventing any disaggregation of measures down to individual monitoring sites or NYC Reservoir Basins. This particularity in the dependent variables thereby forced the analysis to be at a larger than desired geographic extent (8 digit HUC watersheds).

Capital Investments

Access to actual *green* and *grey* capital investments and O&M data in NYC's watersheds at the reservoir basin level would be ideal. It can be inputted into the model instead of estimated values used here. *Grey* infrastructure capital investments may possess significant lagged effects- ~2-10 years after inception of grant, with EPA estimating that it took two to ten years after a grant was received for construction to finish (Keiser and Shapiro, 2018). In addition, a large proportion of grey infrastructure spending not included are recurring annual O&M costs, which would undermine its overall cost effectiveness, as such estimates of grey infrastructure capital investments in this study provide a lower bound approximation. Meanwhile, *green* infrastructure capital investments may have shorter lagged effects, future models may choose to apply appropriate lagged effects depending on the type and mechanism of capital investments. Separately, with a comprehensive panel database of level of WWTP treatment technology, one could introduce further controls for treatment technology available at each discrete time. Although prescribed by the CWA in 1972, not all WWTP had installed secondary treatment by 1977. In 1978, for example, nearly a third of all plants lacked secondary treatment, but by 1996, almost none did (Keiser and Shapiro, 2018). Therefore introducing such a covariate between 1978 and 1996, which falls squarely within the study period, should prove useful.

Water Quality Measures and Land-use Change

Unlike Rahm et al. (2013) metric for *violations*, the six water quality measures used in this study do not cover Nitrogen violations, such as ammonia, nitrite or nitrate, and Phosphorus- key pollutants in NYC watersheds. Should good data exist, future studies may wish to include Nitrogen and Phosphorus measures in the model specified, as they are important across both West and East of Hudson watersheds. Of all the water quality measures included in this study, DOD may be the least suited for aggregate watershed analysis due to its site specific reaeration and flow conditions. Broadly speaking, due to the seasonal nature of water quality and susceptibility of measures to large storm-water events, more granular panel data controlling for precipitation patterns, as well as both month and yearly fixed effects may prove informative. Even with limited resources, one could start by measuring water quality at Hillview Reservoir as a proxy for West of Hudson watersheds since it is the final stop for drinking water from the Catskill-Delaware System before it enters the NYC's distribution system; or at Kensico Reservoir, which is the terminal reservoir for the unfiltered Catskill-Delaware water supply, and is the last impoundment prior to entering the City's distribution system (DEP, 2019). For a comprehensive check-list of data points that can be further incorporated into the model- water quality measures, land-use changes, and weather data- DEP (2008) provides a good starting point. Watersheds often face challenges unique to its geography- for instance, problems with harmful phosphorus levels predominate in the Croton watershed reservoir basins (DEP, 2019)'s Watershed Water Quality Annual Report, and deserve priority in any study on the East of Hudson watershed. The NYC DEP's 2006 Long-Term Watershed Protection Program reported that when the LAP began in 1996, NYC owned about 3.5% of the land in the Catskills Delaware watershed (DEP, 2006), but as at 2019, NYC had acquired as part of LAP, 14.8% of the land area in the Catskills-Delaware watersheds (DEP and WLIS,2019). Incorporating water quality measures and land-use change spanning the time period of the LAP, as well as detailed LAP funding and program extent, would similarly complement this study and deepen the analysis of the efficacy of *green* water infrastructure capital investments in particular.

(4970 words)

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