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

Louis Chua
Cornell University

Ecologically conscious watershed management is not a new concept. It presents numerous benefits but also incurs economic costs. This study posits that NYC presents an exemplary case for which other metropolitan areas can adopt in establishing a symbiotic relationship with its hinterlands. Both creating efficient allocation of scare resources and reducing overall anthropogenic impact on the biota. In comparing the effectiveness of capital investments in water infrastructure in seven upstate New York (NY) watersheds from 1962-1998, this paper uses a quasi-experimental regional approach to explore the benefits and trade-offs of water infrastructure capital investments and policy decisions. Thereby allowing for a more mutually beneficial and sustainable urban-rural relationship to develop.

EXECUTIVE SUMMARY

Approximately half of the water quality metrics studied in NYC's watersheds saw on average, an unequivocal trend improvement for the entire study period of 1962 to 1998 - BOD (Biological Oxygen Demand) fell by $\sim 3\%$, Total Coliforms by $\sim 9 - 19\%$, and TSS (Total Suspended Solids) by $\sim 3 - 7\%$. Overall, increased developed land-use in the NYC's watershed was correlated with poorer water quality metrics, this is despite drawing most of the capital investments. This is indicative that either capital investments in dense metropolitan areas have been insufficient or ineffective. Meanwhile, *grey* infrastructure capital investments from the CWA (Clean Water Act) appear most effective in tackling Fecal Coliform and Turbidity, although its effects likely waned drastically after 1993.

Utilizing remote sensing data of land-use changes across 1974-1998, this study finds that although the joint effects of land-use and capital investments on pollutant levels are strong, their individual effects vary widely depending on the location (West or East of Hudson watersheds) and the water quality metric in question. This study builds the case for a regional approach. One that identifies water pollutants priorities according to the cost effectiveness but also the needs and land-use of each locale. Practically, I contend that pollution regulation and the appropriate mechanism of capital investments be targeted both at the watershed and regional level; dependent on the predominant and growing land-use trends. Depending on the pollutant, land-use effects generally produced stronger positive and negative effects in West of Hudson watersheds compared to the East of Hudson watershed. Pollutant trends were also shown to have significant differences after accounting for large scale regulatory milestones - the CWA of 1972, and EPA's first issuance of a FAD (Filtration Avoidance Determination) to NYC in 1993. The latter, involving an added regulatory pressure, and precipitated a strong coordinated push towards watershed land-use management.

Within the watersheds, capital investments in *water resources* and *water utilities* (CBO 2018) (henceforth *green* or *grey respectively*) appeared most effective for two pollutants- TSS and BOD. TSS was likely least affected by land-use changes and responded most positively to *grey* infrastructure capital investments. Meanwhile, *green* infrastructure capital investments were correlated with positive outcomes/ reduction in BOD. In the case of BOD, the benefits of the investments were likely channeled through increases in semi-developed land-use and appeared more effective after 1993.

Crucially, this study also considers past reports by NYS DOH and DEC, NYC DEP, draws from important findings in the last NYC Watershed Economic Impact Assessment Report commissioned in 2008 (DDCG 2009) and includes discussions and extensions on how such a regional watershed management framework combined with an enlightened pes approach may alleviate larger issues related to the urban-rural divide.

MOTIVATIONS AND BACKGROUND

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 or 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)[1]. 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)[2], not to mention preservation of biodiversity, and air pollution control to name a few. Each can have a PES (Payment for Ecosystem Services) program attached, as long as there exists detailed information on which service a given forest[3] 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,[4] while its benefits are easily quantifiable and accounted for[5].

This study aims to set the foundations for the accurate comparisons of water filtration ES[6] (Ecosystem Services) 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, Ashton, and Gentry 2013). After exploring supply options, the city focused supply expansion efforts on the nearby Croton River, but by the 20thcentury 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, Ashton, and Gentry 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[7] resulted in forest loss, high impervious surface coverage and associated run-off and water quality concerns[8] (Wilder and Kiviat 2008). The Catskills and Delaware watersheds[9] however did not experience the same development pressures as the Croton watersheds likely due to its distance from the city. (See **Land-use changes** in both West and East of Hudson watersheds from 1974-2012 in **Chapter 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, Ashton, and Gentry 2013). The SDWA (Safe Drinking Water Act) is the federal law regulating both anthropogenic and naturally occurring contaminants in US drinking water systems (EPA 2010). 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 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, Ashton, and Gentry 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 drinking watersheds was approved (EPA 1989). In 1993, EPA issued a 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, Ashton, and Gentry 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, Ashton, and Gentry 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 LAP[10] (Land Acquisition Program); 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 2011). The first two can reasonably be classified as *green* water infrastructure investments, while the third would be considered *grey* water infrastructure investments[11] henceforth.

DEFINITIONS AND DATA

Both water quality and CWA grant data were derived directly from (Keiser and Shapiro 2018)'s study. Specifically, 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 NWIS. While CWA grant data was obtained by clipping from the CWNS- a panel description of the country's WWTP (Wastewater Treatment Plant), 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 O&M (Operations and Maintenance). 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 annual trends in spending taken from (CBO 2018)[12].

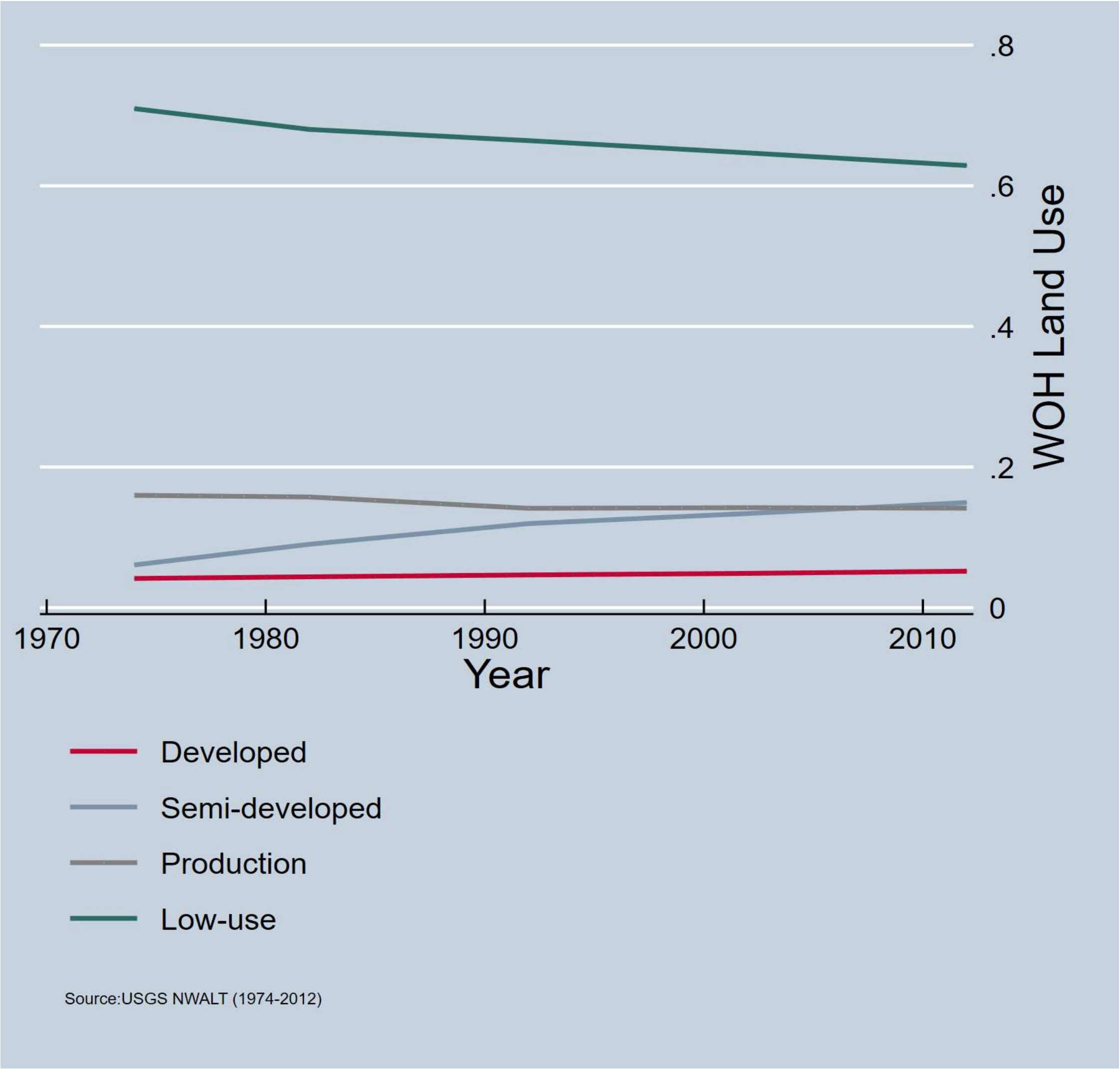
Land Use

Land-use raster data were obtained from USGS' 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 were matched to the larger 8-digit HUC watersheds given by the US Geological Survey (USGS). 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. 3.1** and **3.2** below.

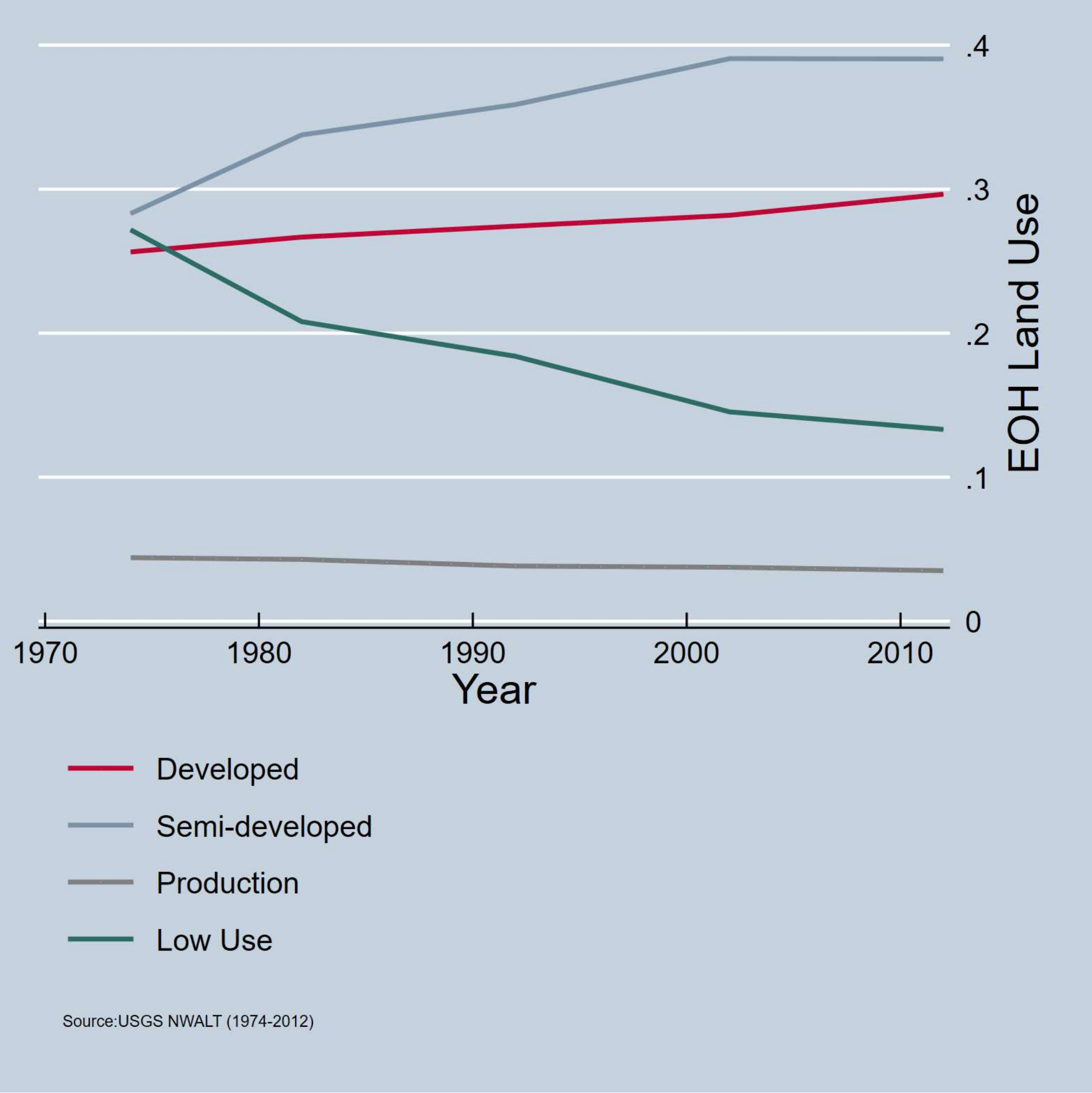
- **Developed**: The built environment- settings where residences, employment, and recreation predominate.
- **Semi-Developed**: The "near-built" environment- settings that are in close proximity to Developed lands and (or) are partially used for the same purposes.
- **Production**: Settings in which 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; that is, there is no evidence of regular human usage.

FIGURE 1
WEST OF HUDSON LAND-USE CHANGE



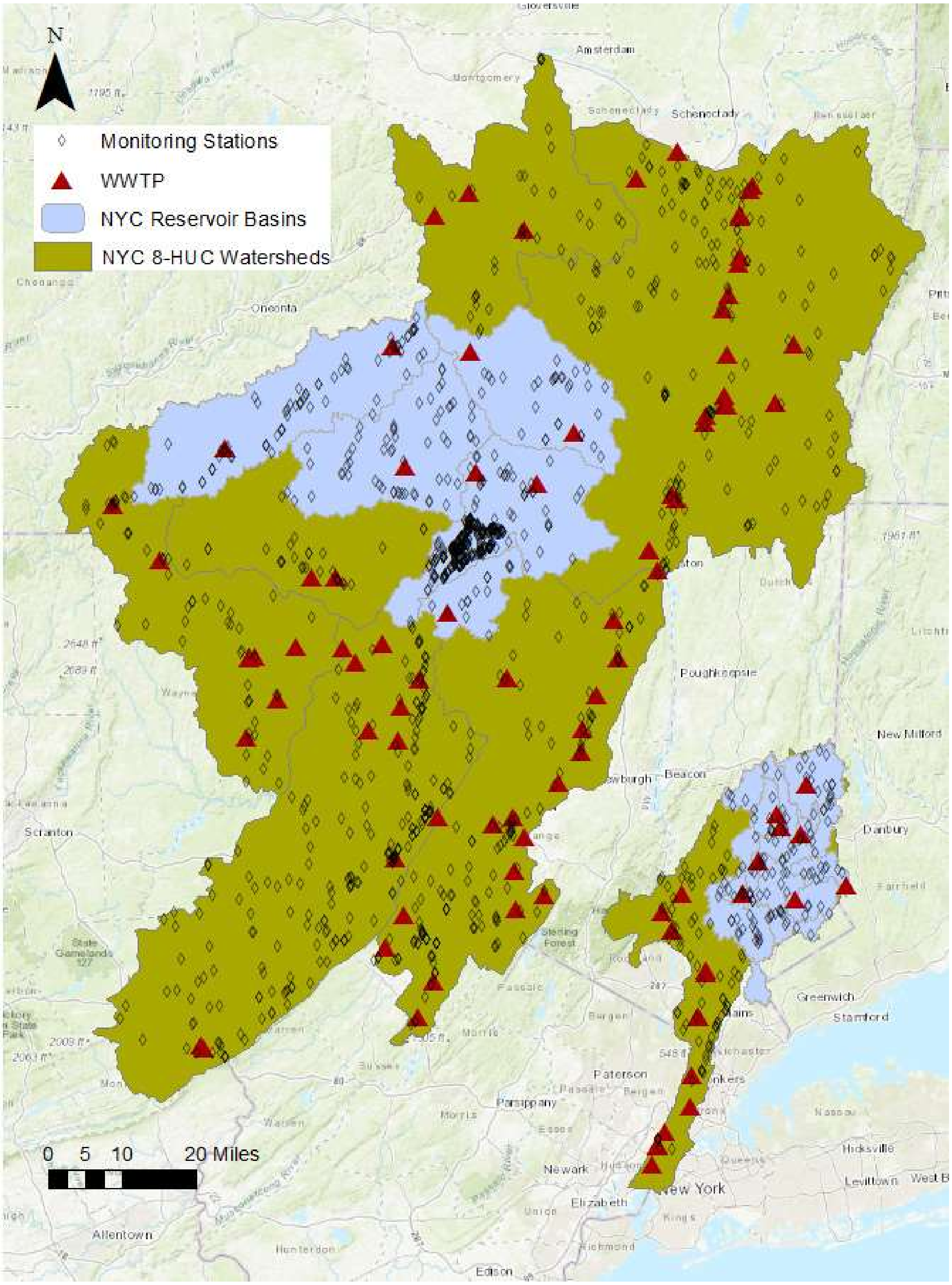
Source:USGS NWALT (1974-2012)

FIGURE 2
EAST OF HUDSON LAND-USE CHANGE



Source:USGS NWALT (1974-2012)

FIGURE 3
MAP OF STUDY AREA



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 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 (Keiser and Shapiro 2018; CBO 2018).

At the state and 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 8-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 more complex WTP (Willingness-to-Pay) approaches determined through capitalized real estate prices.

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*[13] 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[14]. 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 experiment parameters (see **Extensions** 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. Pollutant 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 for each 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

$$P_{iwy} = \beta T_{iy} + \gamma L_{wy} + \rho F_{wy} + \sigma_w + \varepsilon_{iwy} + \theta d_{72,93} \tag{1}$$

The variable P_{iwy} is the aggregated water quality metric, for metric 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 [first] were run. A first run of the fixed effects model only included the annual trend variable, T_{iy}. All water quality metrics, except for DOD[15], underwent a logarithmic transformation which addressed issues of heteroskedasticity. Post-transformation residuals by watershed year largely approached the condition $E(\varepsilon_{iwy}|w, y) = 0$ (See **Appendix A** for residual plots and annual trend plots).

$$P_{iwy} = \beta T_{iy} + \sigma_w + \varepsilon_{iwy} \tag{2}$$

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

$$P_{iwy} = \beta T_{iy} + \rho F_{wy} + \sigma_w + \varepsilon_{iwy} \tag{3}$$

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

$$P_{iwy} = \beta T_{iy} + \gamma L_{wy} + \rho F_{wy} + \sigma_w + \varepsilon_{iwy} \tag{4}$$

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.

$$P_{iwy} = \beta T_{iy} + \gamma L_{wy} + \rho F_{wy} + \sigma_w + \varepsilon_{iwy} + \theta d_{72} \tag{5}$$

$$P_{i,west,y} = \beta T_{iy} + \gamma L_{west,y} + \rho F_{west,y} + \sigma_{west} + \varepsilon_{i,west,y} + \theta d_{72} \tag{6}$$

RESULTS

General Findings

(Keiser and Shapiro 2018)'s study showed that improvements in all six water quality metrics were more rapid in the Northeast EPA census region compared to the rest of continental US[16]. However, this study finds that NYC's watersheds[17] have statistically significant improvements for only three[18] 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[19].

This panel study finds that aggregating water quality 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[20]. 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 that developed land-use was negatively correlated to production land-use, and/ or that there were 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. 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 (See **Fig 3.2**).

TABLE 1
FUNDING & LAND-USE CROSS-CORRELATION TABLE[CORRTABLE]

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[21].

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[22], hence making it less suitable a measure for this kind of modelling, or that 3) *green* capital investments[23] 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),[24] 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 1993 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 for turbidity, 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 (DOH 2017; DePalma 2006).

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 preceding 1972 or after 1993, the overall picture for water quality metrics divided by the discrete time periods was mixed. It would be ideal to reassess the watersheds given consistent pollutant readings for at least 10 years after 1993, as the implementation of capital investments or policy may have temporal lagged effects.

Water quality 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 limitation in the dependent variables thereby forced the analysis to be at a larger than desired geographic extent (8 digit HUC watersheds). Another avenue for deriving consistent, unbiased water quality data could be through multispectral raster data that moving forward could track chlorophyll levels in large water bodies (i.e. lakes) as proxies for water quality.

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 the 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)[25]. 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 Metrics and Land-Use Change

Unlike (Rahm et al. 2013) metric for *Violations*, the six pollutants used in this study do not cover *Nitrogen* violations, such as ammonia, nitrite or nitrate, and *Phosphorus*- key pollutants in NYC watersheds[26]. Should good pollutant 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[27]. 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[28]. Broadly speaking, due to the seasonal nature of water quality and susceptibility of measures to large storm-water events[29], 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 checklist of data points that can be further incorporated into the model- water quality measures[30], 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[31] (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.

Discussions

Valuation of ES

In (Haase et al. 2014) review of UES (Urban Ecosystem Services), most studies employed either revealed preferences[32], hedonic pricing[33], or contingent valuation[34] methods. Importantly, a majority of case studies valued ES without detecting temporal changes, and studies across cities or neighborhoods are almost entirely missing (Haase et al. 2014), militating a need for more of such panel studies for each ES. (Keiser and Shapiro 2018)'s study is unprecedented precisely because it utilizes both hedonic pricing and a granular panel dataset over almost four decades.

Ecosystems deliver multiple services and can involve trade-offs that increase the provisioning of one service while reducing the provisioning of another. For example, carbon sequestration through afforestation or forest protection may enhance timber production but reduce water (Haase et al. 2014). Beyond water filtration ES, my approach can also be applied to other ES of similar SPUs (Service Provision Units) in conservation and nature areas. Holistically, one can begin to examine the cross functional relationships of both; ES within SPUs and ES across SPUs, thereby improving the understanding of trade-offs and synergies across a temporal scale.

Holistic Economic Impacts

Regulation in the form of long-term industrial policy, can move rural economies and communities away from resource extraction industries- that may be lucrative in the short term but are inherently very volatile and destabilizing, not to mention result in serious long term ecological damage such as contamination of groundwater. Jeremy Grantham, chief investment strategist at the Boston-based investment firm, GMO, commented that half of the companies involved in the US oil fracking industry have little free cash flow, making them highly dependent on debt that carries large credit spreads over presumably safer debt options (Rajan 2020).

A recent New York Watershed Economic Impact Assessment Report conducted in 2008, using rudimentary Input-Output (IO) modelling[35], was very comprehensive in analyzing the potential shocks to employment and the productive output in watershed communities from the effects of watershed management policies, specifically *green* water infrastructure[36] (DDCG 2009). However the report, commissioned by the Delaware County Board of Supervisors and the Delaware County Chamber of Commerce, severely underestimated the benefits of the 'green' economy,[37] or the volatility inherent in natural extraction industries on which many of these regional economies currently depend. For example, DEP's 2009 Impact Assessment of Natural Gas Production found that Hydraulic fracturing, or fracking- a process where pressurized fluid is injected into deep horizontally bored holes to facilitate extraction of natural gas- was associated with the movement of natural gas and contaminants into acquifers or surface water bodies (DEP 2009). In addition, their IO models very likely overestimated the jobs and income provided by the resource extraction and manufacturing industries, while insufficiently accounting for severe economic and ecological downside risks[38]. One of the key assumptions of a static IO model is that prices are fixed and the economy is closed to foreign trade. With the importance of international trade, and counting on the recent (volatile) track record of commodity and energy markets[39], even the most ardent optimistic may have to admit that this is a dangerous assumption.

Where to Green?

(Alcott, Ashton, and Gentry 2013) cites a number of different tools useful for deciding locations to apply *green* or *grey* water infrastructure. (WPPS 2011) provides a useful example, utilizing a matrix that serves as an optimization tool for balancing public health, economic, social, and environmental concerns in the application of 'environmental' and 'engineered' solutions.

A robust tool for aggregating quantitative and qualitative inputs into a multi-criteria decision making framework is Analytical Hierarchy Process (AHP) (Saaty 1987)- a non-Bayesian approach that is particularly useful precisely because it does not assume a-priori theoretical framework, but allows decision makers to input overall key criteria, and ranks each actors' subjective pairwise trade-offs[40] to determine the best (policy or market) solution. It also possesses a built-in safeguard which assesses respondents' *consistency* in making discrete pairwise decisions of preferences. An example is (Srdevic, Blagojevic, and Srdevic 2011) use of AHP in determining loan applications for irrigation equipment in Serbia. This author has also developed a Python-based[41] AHP model linked to this study which can be accessed online here.

How to Green?

Upon deciding that *green* water infrastructure improvements are necessary in a locale, there are numerous BMP and WIP that provide detailed implementation guidelines. The Chesapeake Bay community is a notable example- providing a very methodical and scientific approach; from assessing local hydrology, topology, soil properties and scoring specific lands for planting suitability, to actionable guidance for planting (Swan 2012). The prevalence of remote sensing data also make changes in land-use easier to measure and track over time in different watersheds.

Who Pays?

Globally, in Costa Rica, the government has been involved in a scheme to help users such as hydropower companies pay farmers to maintain forest cover in watersheds, while in Quito, Ecuador, water companies are helping to pay for the management of protected areas that are the source for much of the capital's drinking water (Dudley and Stolton 2003). The main services of interest are usually hydrological benefits, including controlling the timing and volume of water flows and protecting water quality, reducing sedimentation, and preventing floods and landslides; biodiversity conservation; carbon sequestration; and, in some cases also scenic beauty (Dudley and Stolton 2003).

(Venkataramanan et al. 2020)'s global survey of WTP for g*reen* infrastructure on the whole described four contingent valuation studies that reported different WTPs. On the higher end, a study from Flanders, Belgium reported mean WTP as an acceptable increase in water bills of US\$55/year for a recurrent 20 year payment (Chen, Tung, and Li 2017). The other three studies were on the lower end, from US\$11.3/year for public spaces in Hong Kong, China (Chui and Ngai 2016), to US\$22.5/year to protect an urban forest in Kumasi, Ghana (Dumenu 2013) to US\$28 – 30/year for a recreational water park in Lombardy, Italy.

Within the US, a similarly blended approach can be trialed. Both private and public finance can be catalysts, and play a central role in accelerating a shift in paradigm. Although the finance world is gradually warming to physical risks posed by climate change (Schulten et al. 2019), it is by any measure a long way from accurately pricing ES or the loss of ES (NBIM 2019). Municipal bonds co-issued by urban-rural regions can be a useful instrument to ensure that their efforts (in this case of watershed protection) are sustainable- channeling capital into watershed communities for investments that require large outlays, and perhaps even contribute to revitalization. One can also imagine a case where local businesses may instead of paying for water be offered an option to buy water bonds that effectively pay for preservation of forests, getting paid dividends from recreation, tourism, higher land values in preserved land. For metropolitan areas and urban communities, such arrangements can also be a hedge against physical climate risks posed by sea level rise, floods, and droughts that affect water and sewer utilities. A recent collaborative report from Hauser Center for Non-profit organizations at Harvard University and the Initiative for Responsible Investment asserted that key performance indicators (KPIs) can play a vital role in any sustainability disclosure scheme. KPIs are most useful when they are specific to industry subsectors, and can be performance based (quantitative), or based on management policies and business processes (qualitative) (Lydenberg, Rogers, and Wood 2010). This is certainly applicable in the provision of clean water, where bonds that support sustainable and resilient means of providing clean water would fetch higher prices and a lower borrowing costs.

Within NYC, lessons can be learnt from a phosphorus trading pilot program conducted by the NYC DEP in the Croton watershed from 1997 to 2007 (Kane 2007). It was not extended largely due to reasons of; poor demand, high administrative burden; applicants finding it difficult and time-consuming to identify approvable offsets; and (yet again) a lack of capacity for monitoring and verification of reliable offsets at the time (Kane 2007). Therefore, for a payment or trading scheme to work, preconditions such as reliable and consistent testing[42], and a streamlined IT architecture- such as digital approval platform- must be in place.

(Alcott, Ashton, and Gentry 2013) also suggests that NYC DEP could provide incentives, for example, by providing a revolving fund for low-interest loans to lower the pressure for up-front investments before offset payments begin. It could utilize the (EPA 2007)'s Water Quality Trading Toolkit and other sources to take advantage of new trading schemes.

CONCLUSION

Although attempts have been made at the national level to assess the effectiveness of watershed management, varying levels of regional anthropogenic impact (and temporal trends), differences in climate, topology, and hydrologic regime necessitates a more granular study of watersheds and their abilities to provide water filtration ES. A watershed and regional approach to testing and assessment enables a more optimal allocation of public and market-based funding. This in turn informs better policy and planning decisions at the regional level.

As well as foreshadowing a workable example of a sustainable symbiotic urban and rural relationship, held together by ES and PES, the NYC watershed case study provides an attractive middle ground- advocating for a system that reaps the agglomeration benefits of population density while still preserving, or re-wilding large swathes of watersheds surrounding a city or a network of cities.

Although the NYC watershed management case study is driven largely by public health objectives; I am hopeful that scaling this approach and testing it in other locations will narrow the gulf between seemingly disparate fields of Environmental Health and Human Health into a united concept of Planetary (One) Health. Furthermore, with the right PES program in place, we might just find a way to reinvigorate municipalities suffering from chronic funding shortages, out-migration, ageing populations, and ailing regional industries and infrastructure.

ACKNOWLEDGEMENTS

I would like to thank an incredible cast of academics in helping me create this work; foremost of all, David Keiser for his utmost patience in dealing with my incessant badgering for data; to Rebecca Schneider for being an encouraging mentor in the early stages of my research and suggesting the NYC watershed in particular; to both Brian Rahm and Steven Pacenka for putting up with my less than ideal understanding of New York's hydrology issues, and entertaining what can only be described as a highly unorthodox approach to tackling them; to Iwan Azis for his ideas about AHP and ANP; to Peter Woodbury for his contributions on green infrastructure; to my special committee member Ivan Rudik for his invaluable network and contribution of resources, recommendations and methodological guidance; and lastly to my chair Kieran Donaghy an ever present voice of reason, for his network, experience and always maintaining a firm but empathetic drumbeat in my march for truth.

ENDNOTES

[1] One major reason why it has proved so difficult to halt and reverse global forest loss is that those who manage forests typically receive little or no compensation for the services that these forests generate for others and hence have little incentive to conserve them. Recognition of this has encouraged the development of systems in which land users are paid for the environmental services that they generate through their management. The central principles of the pes approach are that those who provide environmental services should be compensated for doing so and that those who receive the services should pay for their provision. From our perspective here, this means that if particular management systems are needed in watersheds to maintain the quantity or quality of water supply downstream, the users – like drinking water or hydropower companies – should pay for these (Dudley and Stolton 2003)

[2] Loss of forests has been blamed for everything from flooding to aridity and for catastrophic losses to water quality. Although according to (Dudley and Stolton 2003), there is a much more sporadic link between forests and the **quantity** of water available, and a variable link between forests depending on type and age and the constancy of flow; a review of 94 catchment experiments concluded that the establishment of forest cover on sparsely vegetated land decreases water yield, due to higher evapo-transpiration. To drive home the need for a regional and considered approach, they go on to add that what forests provide therefore depends to a large extent on individual conditions, species, age, soil types, climate, management regimes and needs from the catchment, and that information for policy makers remains scarce and models for predicting responses in individual catchments are at best approximate (Dudley and Stolton 2003).

[3] Or any natural spu. According to (Kremen 2005), SPUs are segments of a component of populations, species, functional groups, food webs, or habitat types that collectively provide the service in a given area.

[4] Having dispersed, complex long term effects that are ecological in nature, and less well understood and quantifiable

[5] Water filtration and purification services is one example that can be understood in this way.

[6] es are the subset of ecological functions (physical, chemical, and biological processes) that are directly relevant or beneficial to human well-being. (De Groot, Wilson, and Boumans 2002)

[7] What will fall within the East of Hudson watershed in this study.

[8] Measures of Phosphorus showed that the Croton watershed was more 'water limited' than the Catskill-Delaware watersheds (DEC 2000).

[9] Broadly referred to as the West of Hudson Watersheds in this paper.

[10] Includes land in fee simple, conservation and agriculture easements.

[11] See **Chapter 3.1** for more detailed definitions of both types of infrastructure.

[12] The proportion of *green* capital investments were obtained by matching CBO's proportion of spending allocated to *Water Resources*, while *grey* capital investments were obtained by matching CBO's proportion of spending allocated to *Water Utilities*. CBO terms spending in *Water Resources* to include water containment systems (dams, levees, reservoirs, and watersheds) and sources of freshwater (lakes and rivers) while *Water Utilities* to include water supply and wastewater treatment facilities. Note that this study is

essentially disaggregating CWA investments to simulate the spatial and temporal distribution of green and grey infrastructure investments

[13] The term *point source* means any discernible, confined and discrete conveyance, including but not limited to any pipe, ditch, channel, tunnel, conduit, well, discrete fissure, container, rolling stock, concentrated animal feeding operation, or vessel or other floating craft, from which pollutants are or may be discharged. This term does not include agricultural storm water discharges and return flows from irrigated agriculture that are currently classified as *non-point source* pollution. (EPA, n.d.)

[14] That presumably had a stronger effect on *non-point source* pollution.

[15] DOD was already calculated as a percentage and as such any transformation would complicate subsequent inference. In any case, its residual plot displayed acceptable variation about 0.

[16] (Keiser and Shapiro 2018) also finds that the Northeast has significantly lower cost-effectiveness, which occurs in part because grants there are estimated to decrease pollution less (NYC's watersheds have already better water quality by most measures), and that the share of pollution readings are also far lower compared to other census regions.

[17] But at the extent of HUC watersheds.

[18] BOD, Total Coliforms, and TSS.

[19] Future analysis using monthly fixed effects may shed more light on true DOD trends, since warmer summer temperatures and low flows may have especially detrimental effects on DOD.

[20] Tying in neatly with (DEP 2019)'s report that recommended monitoring priority be measures of total phosphorus, fecal coliform bacteria, and turbidity in NYC's watersheds.

[21] Since production land-use is negatively correlated with the growth in developed land-use, although not as strongly negatively correlated as semi-developed and production land-use, it is perhaps surprising that both had similar signed effects on DOD.

[22] This is can be a result of higher frequency of storm-water events and its strong effects on DOD levels, which are in turn exacerbated by dense areas with high proportion of impervious surface, levees, dams, or by climate change.

[23] It was weakly significant in the West of Hudson watersheds.

[24] which are not linked to capital investments

[25] One could otherwise predict funding cycles for WWTPs, since most are expected to have a useful life of 50 years, but mechanical and electrical components have a useful life of 15-25 years.

[26] Phosphorous being one of the highest profile pollutants in NYC water supply system due to its ability to cause algal blooms, leading to eutrophication. This in turn can have negative impacts on water quality through different means- 1) increased turbidity from algal material, increased organic carbon that can form dbp, and adversely affect dissolved oxygen levels (NRC 2000). DBPs, including trihalomethane and haloacetic acid are considered carcinogenic (Pereira 2009; EPA 2010), being the most harmful to humans.

[27] Although the Croton watershed- East of Hudson- has proportionally more urban and industrial land-use leading to far more toxic compounds and hazardous waste, both West and East of Hudson watersheds use pesticides on a regular basis (NRC 2000).

[28] Best studied during low flow conditions.

[29] tss is especially prone to large storm-water events.

[30] Broken down into Physical, Chemical, and Biological

[31] The phosphorus-restricted basin assessment for 2018 concluded that no Delaware or Catskill reservoir basin was phosphorus-restricted. With the exception of Boyd's Corners, all Croton System reservoir basins continued to have phosphorus-restricted status.

[32] To derive UES values based on secondary markets.

[33] Utilizing market prices; estimating values usually capitalized in real estate prices.

[34] Using stated preferences collected using survey methods, which may better capture subjective preferences better.

[35] A closed Leontief model economy.

[36] Such as LAP, and land easements.

[37] Assuming traditional definitions that include accommodation services, tourism, recreation, and conservation, without valuations of ES, or other reveal preferences such as those capitalized in real estate prices.

[38] To test this particular assertion, a similar IO model as the one prescribed in (DDCG 2009) would have to be replicated at various time intervals, for example every five years, to draw a more accurate picture of overall economic impacts.

[39] With the global surge in mercantilism and political instability.

[40] Stochastic approaches can be used if the number of actors exceed ~40- for example in population of watershed communities and NYC representative actors.

[41] Pairwise comparisons are inputted using excel files, as such little coding experience is required for operationalization.

[42] Which can be decentralized to citizen science groups, or watershed communities through testing kits, or the use of remote testing sites managed by watershed communities.

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APPENDIX A

Pollutant Trends

BOD

FIGURE 4
BOD RESIDUALS & ANNUAL TREND (FIXED EFFECTS)

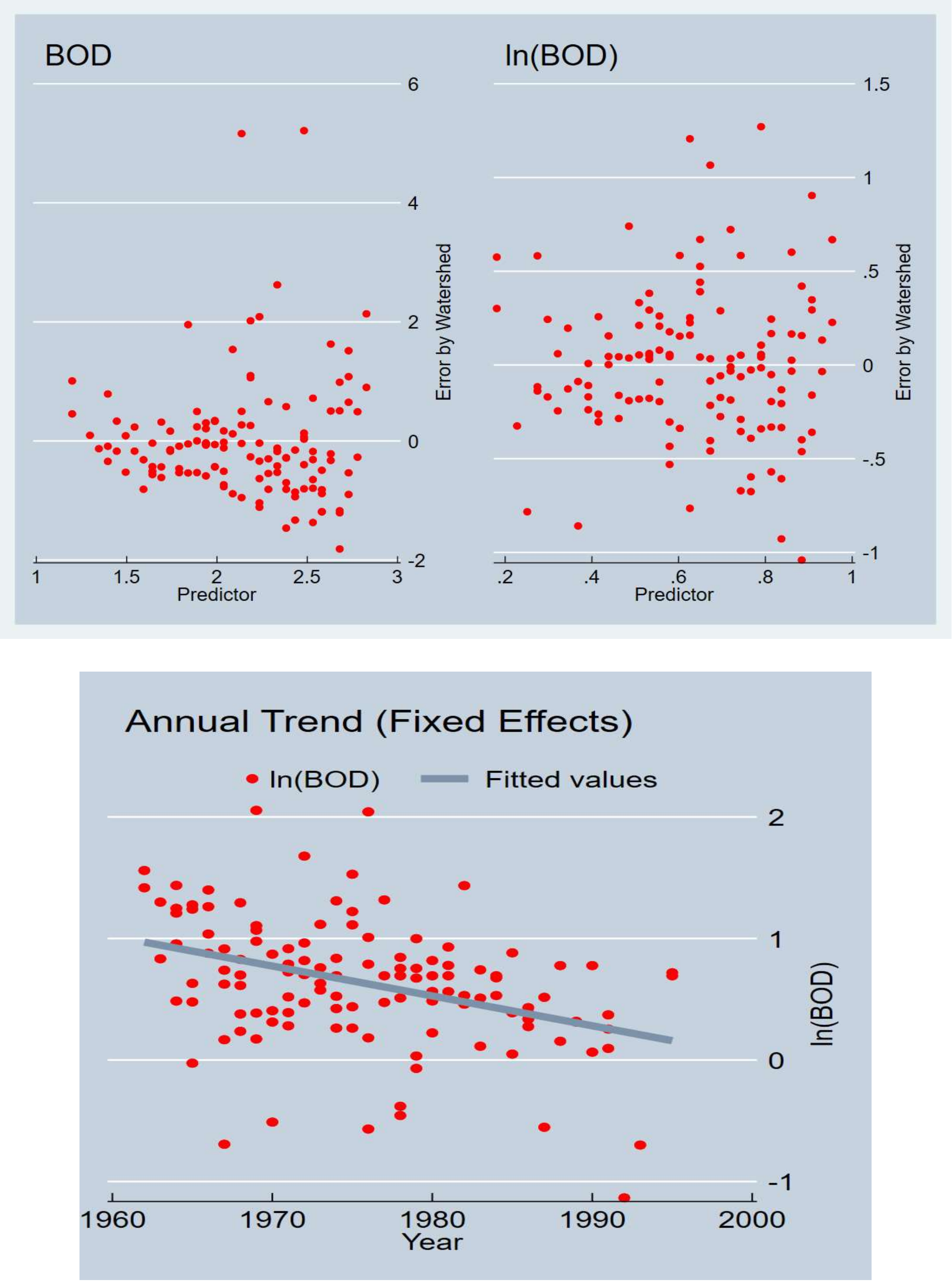
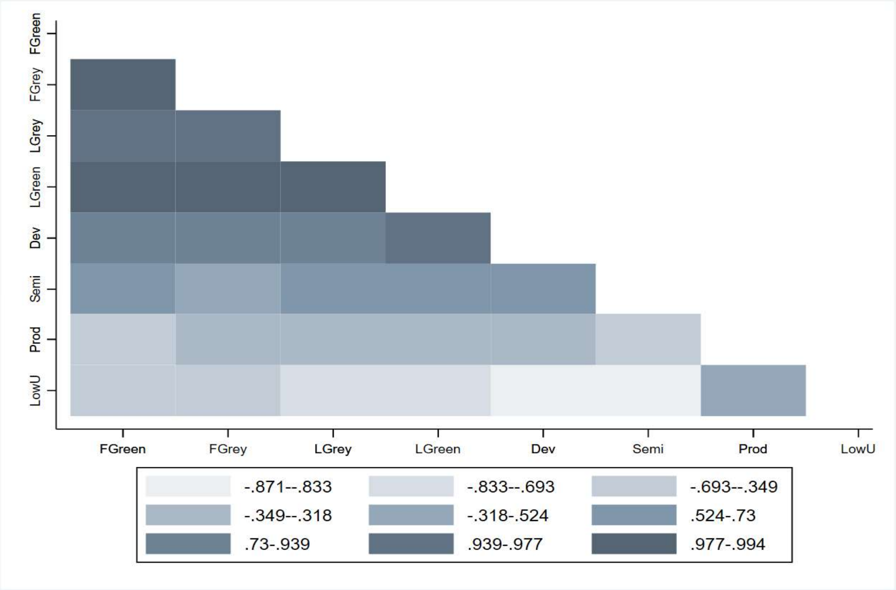
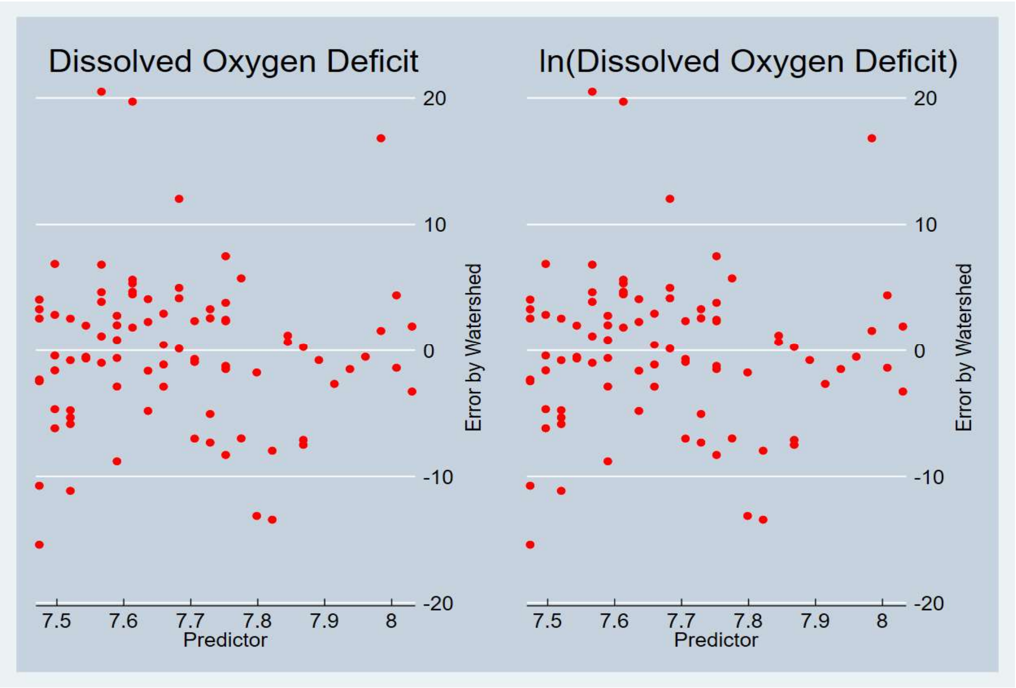


FIGURE 5
CORRELATION MATRIX (BOD)



Dissolved Oxygen Deficit

FIGURE 6
DISSOLVED OXYGEN DEFICIT RESIDUALS & ANNUAL TREND (FIXED EFFECTS)



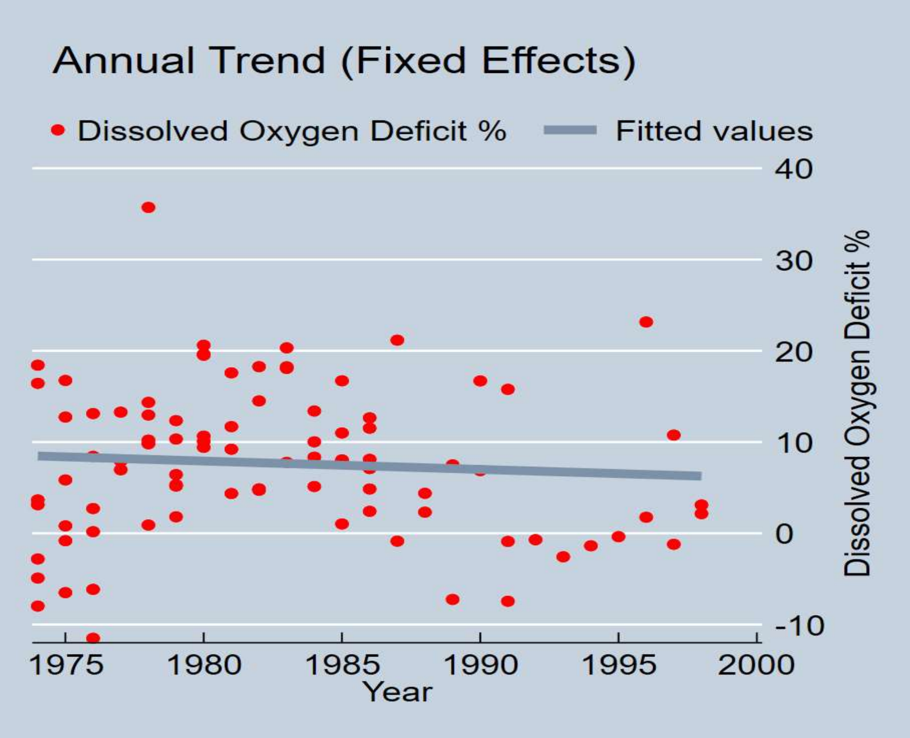
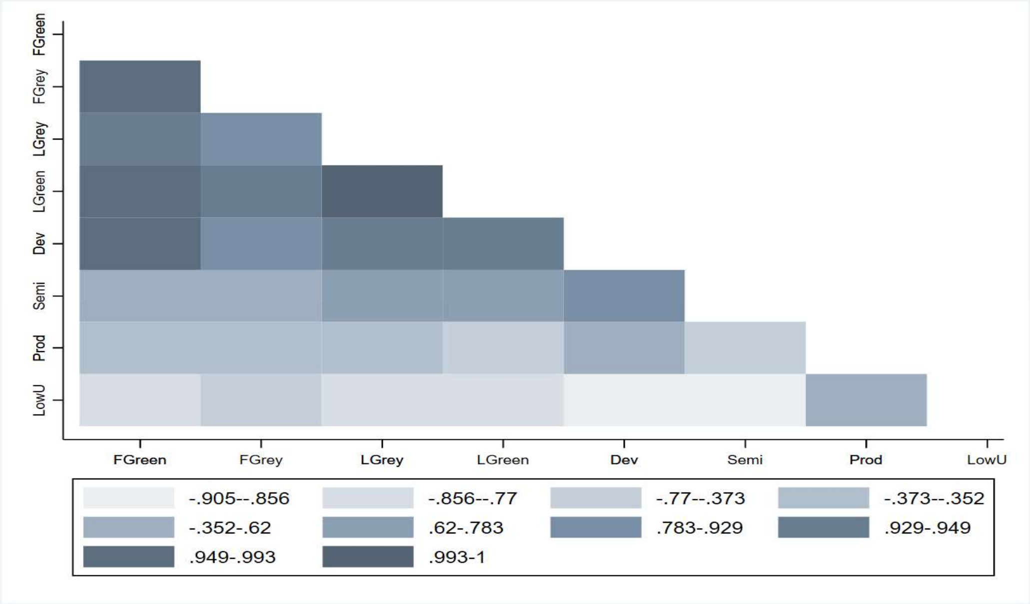


FIGURE 7
CORRELATION MATRIX (DOD)



Fecal Coliform

FIGURE 8
FECAL COLIFORM RESIDUALS & ANNUAL TREND (FIXED EFFECTS)

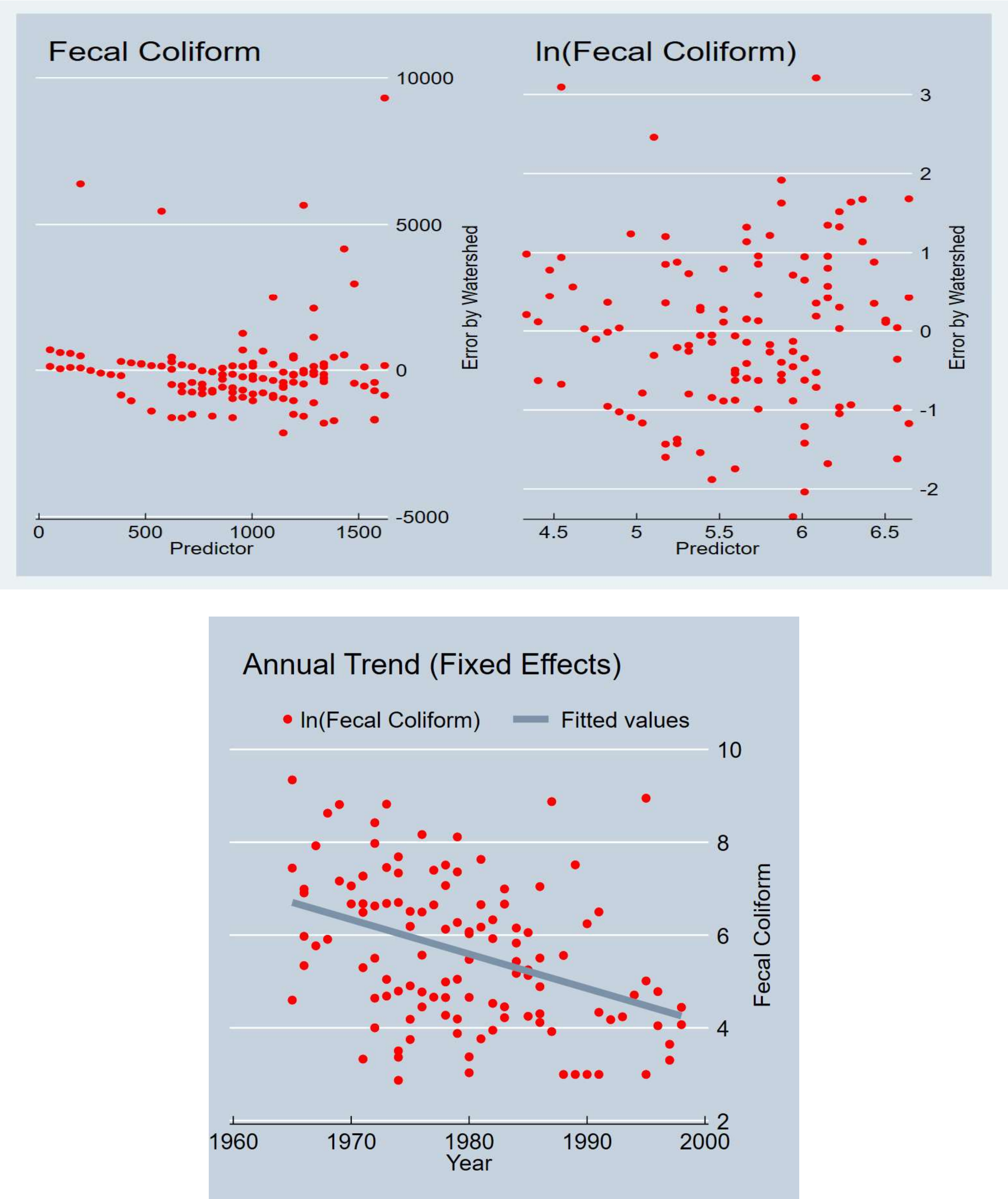
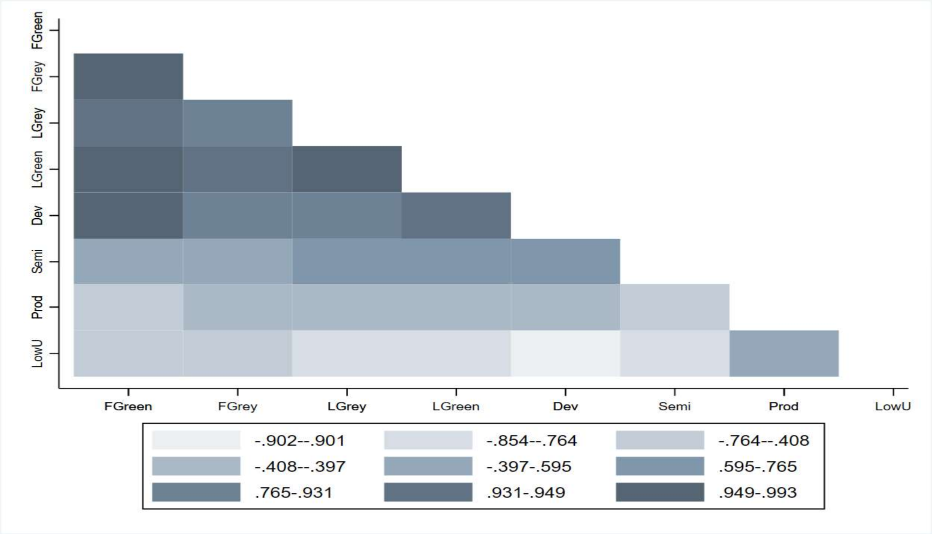
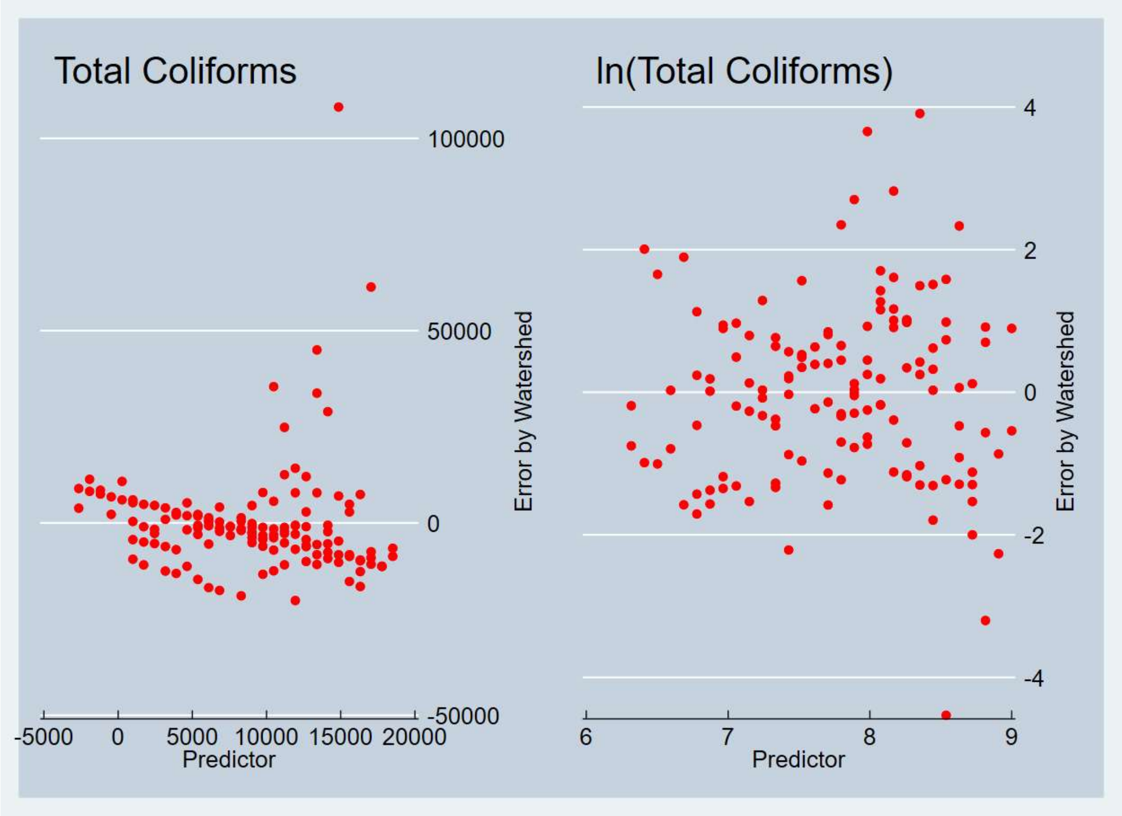


FIGURE 9
CORRELATION MATRIX (FECAL COLIFORM)



Total Coliforms

FIGURE 10
TOTAL COLIFORMS RESIDUALS & ANNUAL TREND (FIXED EFFECTS)



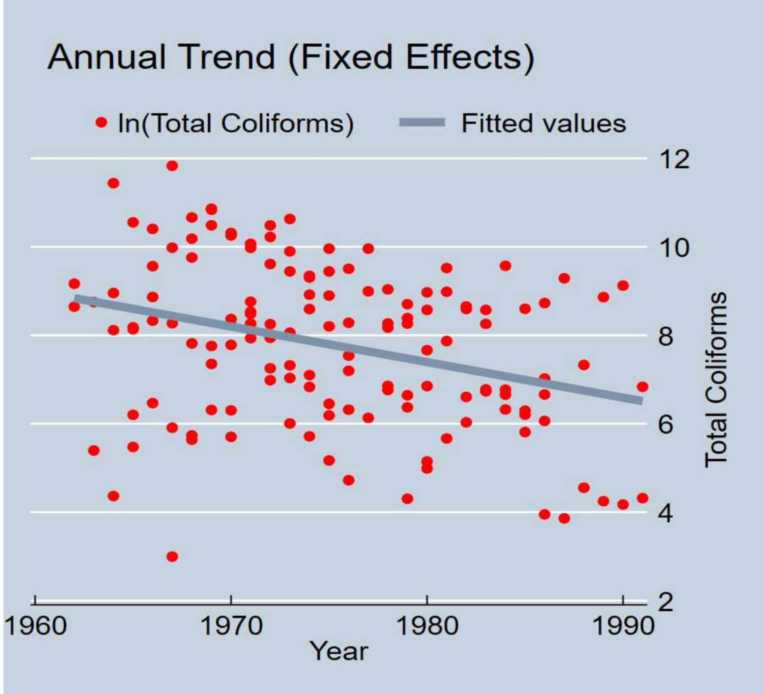
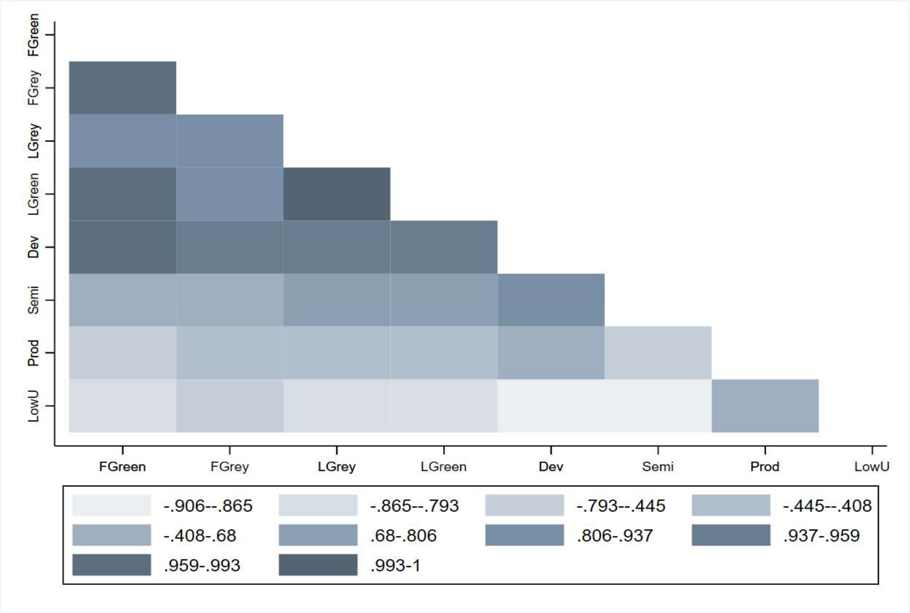


FIGURE 11
CORRELATION MATRIX (TOTAL COLIFORMS)



Total Suspended Solids

FIGURE 12
TOTAL SUSPENDED SOLIDS RESIDUALS & ANNUAL TREND (FIXED EFFECTS)

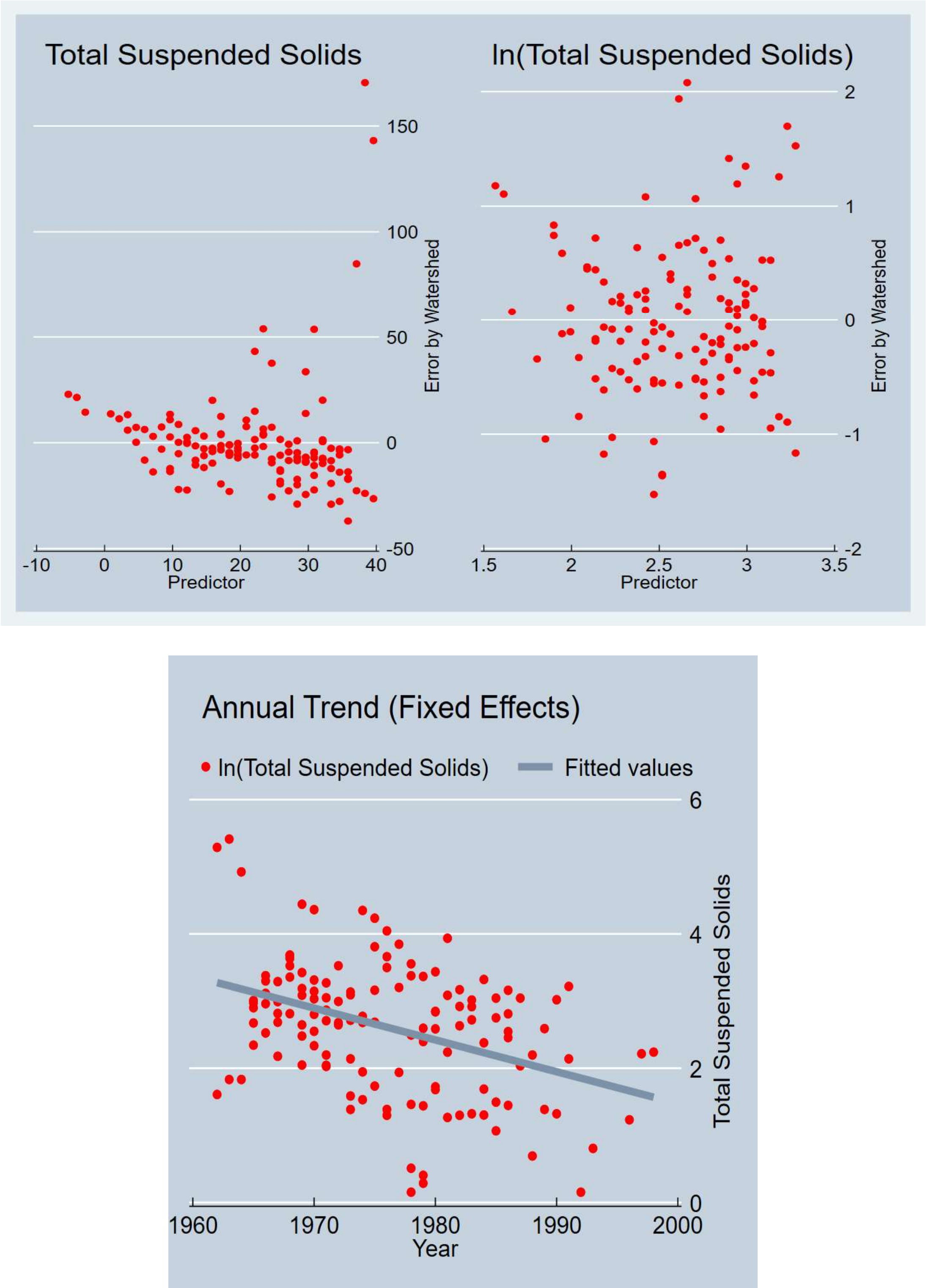
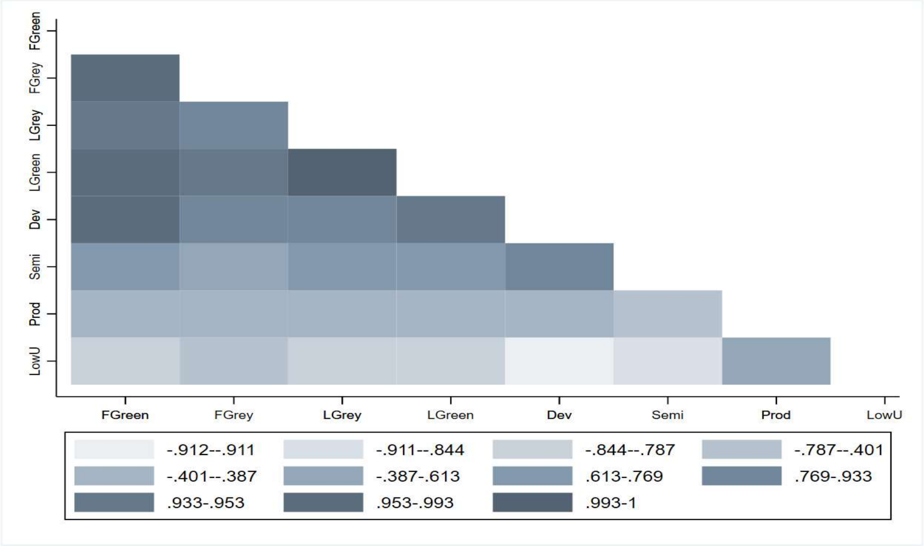
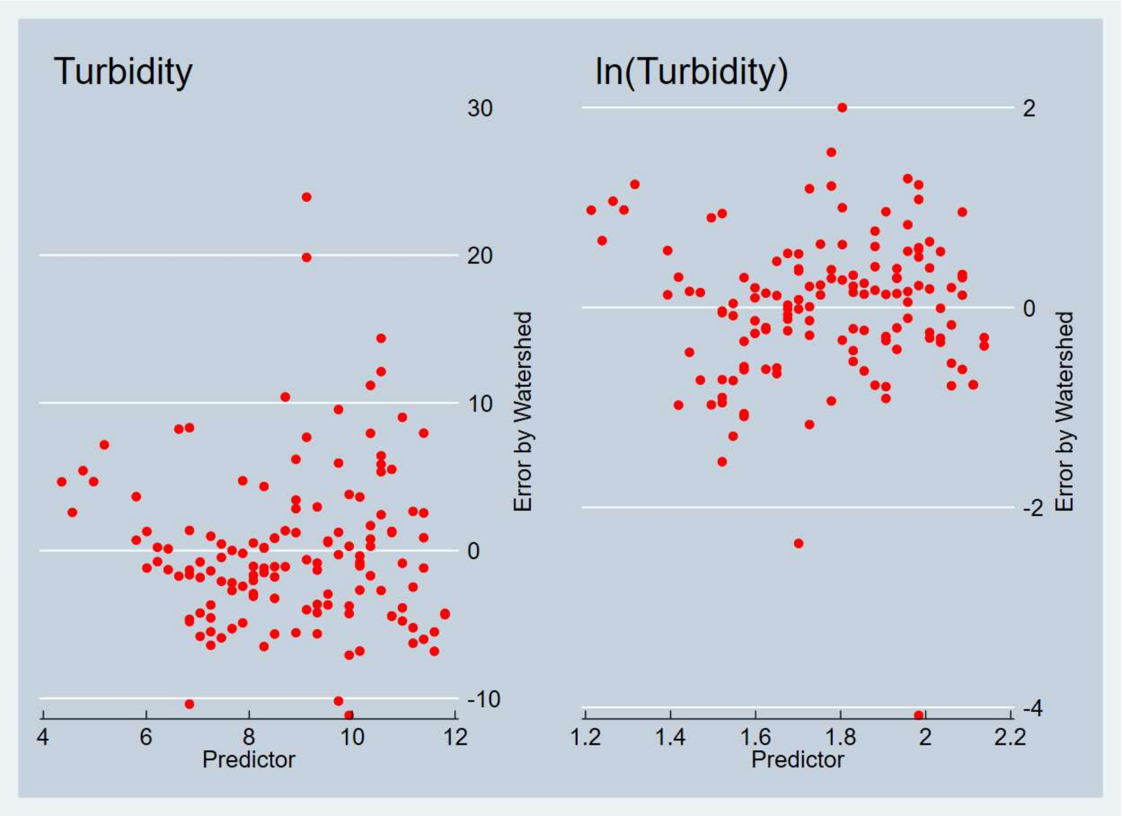


FIGURE 13
CORRELATION MATRIX (TSS)



Turbidity

FIGURE 14
TURBIDITY RESIDUALS & ANNUAL TREND (FIXED EFFECTS)



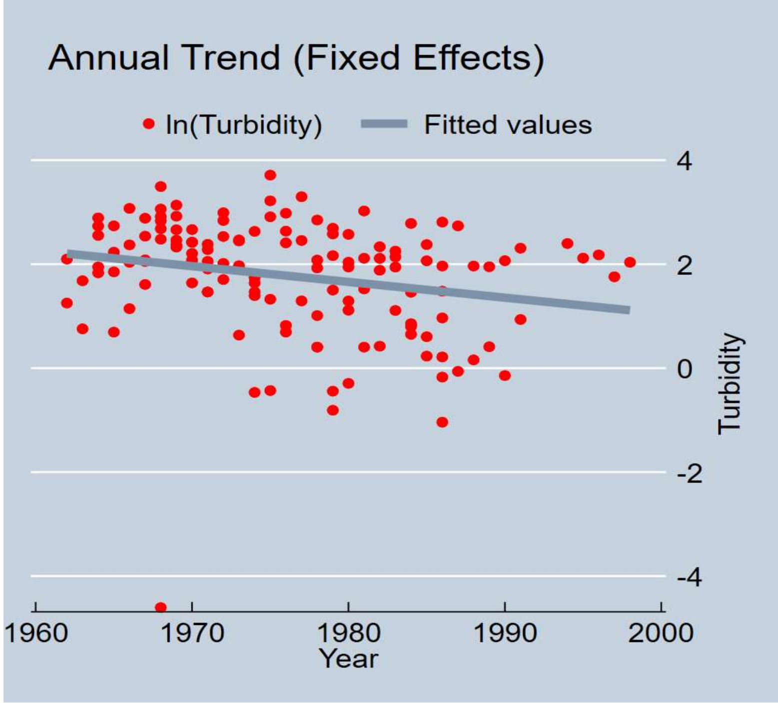
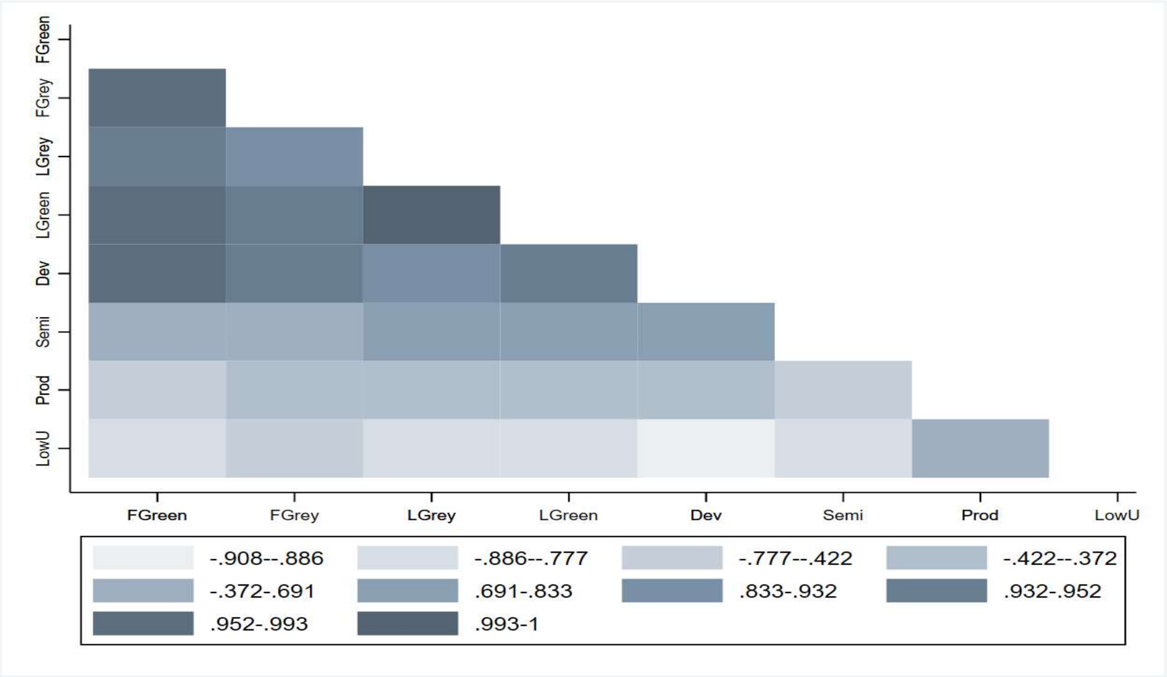


FIGURE 15
CORRELATION MATRIX (TURBIDITY)



APPENDIX B

Regression Outputs – All Watersheds
Pollutant Trends With Funding Controls

TABLE 2
BOD MG/L[TAB 1]

Year	-0.0201	-0.0233	-0.0274	-0.0256
	(0.00370)	(0.00398)	(0.00623)	(0.00410)
Fed Green		-35.27	-35.94	-34.76
		(17.40)	(17.43)	(17.22)
Fed Grey		5.098	4.539	5.641
		(2.667)	(2.746)	(2.651)
Local Green		3.130	8.280	1.571
		(25.08)	(25.80)	(24.83)
Local Grey		-19.07	-17.32	-26.04
		(59.47)	(59.55)	(58.94)
pre-1972			-0.0959	
			(0.111)	
pre-1993				-0.429
				(0.206)
Observations	168	168	168	168
R^2	0.156	0.221	0.225	0.242

TABLE 3
DISSOLVED OXYGEN DEFICIT (DOD)%[TAB 1]

Year	-0.00796	-0.00756	-0.157
	(0.107)	(0.116)	(0.141)
Fed Green		-274.7	-314.4
		(757.1)	(749.4)
Fed Grey		-5.206	4.423
		(152.9)	(151.4)
Local Green		400.5	377.6
		(1613.5)	(1596.5)
Local Grey		-760.6	-612.5
		(2060.6)	(2040.4)
pre-1993			-5.290
			(2.901)
Observations	120	120	120
R^2	0.000	0.004	0.034

TABLE 4
FECAL COLIFORM MPN[TAB 1]

Year	-0.0621	-0.0487	-0.0338	-0.0664
	(0.0103)	(0.0109)	(0.0136)	(0.0126)
Fed Green		15.18	13.52	9.823
		(37.05)	(36.79)	(36.39)
Fed Grey		3.477	6.144	4.886
		(5.361)	(5.525)	(5.284)
Local Green		-42.74	-68.87	-44.73
		(63.69)	(64.87)	(62.46)
Local Grey		-132.8	-114.0	-119.9
		(88.11)	(88.09)	(86.55)
pre-1972			0.520	
			(0.289)	
pre-1993				-0.935
				(0.354)
Observations	162	162	162	162
R^2	0.192	0.255	0.271	0.288

TABLE 5
TOTAL COLIFORMS MPN/100ML[TAB 1]

Year	-0.102	-0.0954	-0.110
	(0.0142)	(0.0155)	(0.0250)
Fed Green		-50.85	-51.81
		(46.88)	(46.97)
Fed Grey		9.977	9.053
		(6.822)	(6.951)
Local Green		79.69	93.94
		(80.44)	(82.92)
Local Grey		-283.1	-288.4
		(111.1)	(111.5)
pre-1972			-0.272
			(0.375)
Observations	153	153	153
R^2	0.262	0.301	0.304

TABLE 6
TOTAL SUSPENDED SOLIDS (TSS) MG/[TAB 1]

Year	-0.0451	-0.0462	-0.0338	-0.0517
	(0.00613)	(0.00657)	(0.0100)	(0.00701)
Fed Green		-43.31	-38.87	-46.21
		(39.19)	(39.09)	(38.80)
Fed Grey		7.652	8.152	8.229
		(4.974)	(4.958)	(4.929)
Local Green		38.04	9.066	35.11
		(60.36)	(62.63)	(59.73)
Local Grey		-96.44	-72.49	-92.36
		(81.76)	(82.66)	(80.91)
pre-1972			0.291	
			(0.179)	
pre-1993				-0.699
				(0.332)
Observations	171	171	171	171
R^2	0.249	0.262	0.274	0.282

TABLE 7
TURBIDITY NTU [TAB 1]

Year	-0.0230	-0.0215	-0.0205	-0.0320
	(0.00758)	(0.00807)	(0.0127)	(0.00837)
Fed Green		17.83	18.18	10.89
		(48.94)	(49.20)	(47.43)
Fed Grey		5.097	5.137	6.366
		(6.210)	(6.240)	(6.024)
Local Green		12.55	10.35	16.57
		(75.41)	(78.54)	(73.03)
Local Grey		-52.15	-50.33	-50.64
		(102.1)	(103.9)	(98.90)
pre-1972			0.0232	
			(0.223)	
pre-1993				-1.406
				(0.404)
Observations	179	179	179	179
R^2	0.051	0.065	0.065	0.129

TABLE 8
BOD MG/L[TAB 1]

Year	-0.0203	-0.0312	-0.0298
	(0.00634)	(0.0150)	(0.0151)
Fed Green		-27.85	-22.57
		(57.61)	(57.91)
Fed Grey		3.351	2.002
		(10.45)	(10.56)
Local Green		-7.439	-5.540
		(95.66)	(95.74)
Local Grey		-133.2	-154.4
		(153.2)	(154.9)
Developed		186.7	213.6
		(85.90)	(90.50)
Semi-developed		-15.55	-17.35
		(7.106)	(7.360)
Production		-12.38	-13.84
		(6.792)	(6.970)
pre-1993			0.148
			(0.156)
Observations	105	105	105
R^2	0.095	0.165	0.173

TABLE 9
DISSOLVED OXYGEN DEFICIT (DOD) % [TAB 1]

Year	-0.00796	0.444
	(0.107)	(0.200)
Fed Green		-135.8
		(697.6)
Fed Grey		-82.14
		(141.9)
Local Green		1130.4
		(1498.2)
Local Grey		-2720.4
		(1948.5)
Developed		2085.6
		(1049.5)
Semi-developed		-221.7
		(96.63)
Production		460.7
		(145.8)
Observations	120	120
R^2	0.000	0.187

TABLE 10
FECAL COLIFORM MPN/100ML [TAB 1]

Year	-0.0193	-0.00823	-0.00823	-0.0414
	(0.0144)	(0.0268)	(0.0268)	(0.0291)
Fed Green		106.9	106.9	90.88
		(89.98)	(89.98)	(87.78)
Fed Grey		-1.667	-1.667	3.389
		(18.31)	(18.31)	(17.93)
Local Green		-189.8	-189.8	-211.2
		(193.2)	(193.2)	(188.2)
Local Grey		129.9	129.9	237.5
		(251.4)	(251.4)	(248.1)
Developed		-101.5	-101.5	-224.8
		(134.9)	(134.9)	(139.6)
Semi-developed		-0.487	-0.487	11.62
		(12.52)	(12.52)	(13.04)
Production		-54.00	-54.00	-54.22
		(15.55)	(15.55)	(15.13)
pre-1993				-0.884
				(0.340)
Observations	118	118	118	118
R^2	0.016	0.315	0.315	0.358

TABLE 11
TOTAL COLIFORMS MPN/100ML [TAB 1]

Year	-0.147	-0.123
	(0.0226)	(0.0575)
Fed Green		44.22
		(95.52)
Fed Grey		8.545
		(20.41)
Local Green		169.6
		(198.7)
Local Grey		-63.52
		(294.6)
Developed		-262.7
		(273.4)
Semi-developed		5.399
		(20.26)
Production		-70.64
		(20.38)
Observations	89	89
R^2	0.343	0.505

TABLE 12
TOTAL SUSPENDED SOLIDS (TSS) MG/L [TAB 1]

Year	-0.0386	-0.0572	-0.0505
	(0.0114)	(0.0259)	(0.0267)
Fed Green		18.75	26.61
		(66.24)	(66.64)
Fed Grey		-12.34	-14.69
		(13.49)	(13.67)
Local Green		101.3	102.1
		(142.3)	(142.2)
Local Grey		-387.0	-425.9
		(185.1)	(188.7)
Developed		433.5	490.2
		(102.2)	(115.8)
Semi-developed		-39.32	-43.25
		(9.257)	(9.996)
Production		-27.35	-24.54
		(13.98)	(14.23)
pre-1993			0.343
			(0.329)
Observations	109	109	109
R^2	0.103	0.276	0.285

TABLE 13
TURBIDITY NTU [TAB 1]

Year	-0.0105	0.0264	-0.0270
	(0.0121)	(0.0191)	(0.0214)
Fed Green		14.96	24.66
		(68.19)	(62.78)
Fed Grey		-2.162	-5.561
		(14.46)	(13.33)
Local Green		27.27	15.33
		(142.4)	(131.0)
Local Grey		-57.23	-100.7
		(208.1)	(191.7)
Developed		-2.503	119.7
		(181.8)	(169.6)
Semi-developed		-21.31	-23.84
		(13.67)	(12.59)
Production		-49.65	-53.93
		(14.40)	(13.28)
pre-1993			-1.455
			(0.336)
Observations	113	113	113
R^2	0.007	0.284	0.400

APPENDIX C
REGRESSION OUTPUTS-WEST OF HUDSON WATERSHEDS

Pollutant Trends With Funding Controls

TABLE 14
BOD MG/L [TAB 1]

Year	-0.0223	-0.0294	-0.0335	-0.0307
	(0.00375)	(0.00681)	(0.00973)	(0.00676)
Fed Green		23.51	18.02	-2.150
		(147.5)	(148.2)	(146.5)
Fed Grey		19.02	13.96	23.47
		(21.36)	(23.08)	(21.25)
Local Green		-57.46	-4.719	-131.4
		(262.1)	(277.7)	(261.8)
Local Grey		349.3	312.9	339.2
		(451.9)	(457.2)	(447.1)
pre-1972			-0.0865	
			(0.148)	
pre_fad				-0.455
				(0.226)
Observations	151	151	151	151
R^2	0.197	0.210	0.211	0.232

TABLE 15
DISSOLVED OXYGEN DEFICIT (DOD) % [TAB 1]

Year	-0.00844	0.271	0.0601
	(0.113)	(0.171)	(0.204)
Fed Green		5888.4	4393.0
		(7188.7)	(7147.2)
Fed Grey		1036.6	1401.1
		(1408.9)	(1405.7)
Local Green		-14553.8	-16596.0
		(8941.4)	(8901.5)
Local Grey		21631.9	27068.5
		(16598.2)	(16659.1)
pre_fad			-5.628
			(3.057)
Observations	107	107	107
R^2	0.000	0.098	0.129

TABLE 16
FECAL COLIFORM MPN/100ML % [TAB 1]

Year	-0.0536	-0.0875	-0.0753	-0.118
	(0.0107)	(0.0198)	(0.0216)	(0.0220)
Fed Green		-55.62	-57.67	-212.0
		(379.1)	(377.8)	(373.4)
Fed Grey		-80.17	-40.74	-45.78
		(57.04)	(63.56)	(56.88)
Local Green		-431.3	-799.7	-721.4
		(704.8)	(750.9)	(694.1)
Local Grey		2033.0	2568.9	2593.7
		(1207.0)	(1263.3)	(1192.3)
pre-1972			0.548	
			(0.395)	
pre-1993				-1.080
				(0.383)
Observations	140	140	140	140
R^2	0.158	0.220	0.231	0.265

TABLE 17
TOTAL COLIFORMS MPN/100ML % [TAB 1]

Year	-0.0962	-0.141	-0.194
	(0.0154)	(0.0294)	(0.0422)
Fed Green		-418.1	-526.5
		(490.1)	(490.0)
Fed Grey		79.94	50.48
		(74.65)	(75.93)
Local Green		1308.9	1878.3
		(864.5)	(917.6)
Local Grey		-742.3	-965.2
		(1510.5)	(1503.3)
pre-1972			-0.842
			(0.483)
Observations	131	131	131
R^2	0.240	0.269	0.287

TABLE 18
TOTAL SUSPENDED SOLIDS MG/L% [TAB 1]

Year	-0.0452	-0.0618	-0.0482	-0.0675
	(0.00654)	(0.0117)	(0.0161)	(0.0120)
Fed Green		-163.4	-146.6	-203.1
		(256.0)	(255.9)	(254.6)
Fed Grey		24.92	41.51	36.06
		(37.21)	(39.53)	(37.36)
Local Green		516.2	322.6	403.7
		(452.4)	(478.3)	(452.4)
Local Grey		-186.8	-70.19	-108.9
		(788.0)	(792.3)	(782.2)
pre-1972			0.284	
			(0.231)	
pre-1993				-0.675
				(0.361)
Observations	152	152	152	152
R^2	0.248	0.267	0.275	0.285

TABLE 19
TURBIDITY NTU % [TAB 1]

Year	-0.0225	-0.00967	-0.0273
	(0.00803)	(0.0123)	(0.0134)
Fed Green		188.7	95.23
		(312.4)	(306.0)
Fed Grey		-16.71	9.137
		(44.21)	(43.94)
Local Green		842.8	843.2
		(558.3)	(544.0)
Local Grey		-1492.7	-1263.8
		(961.3)	(939.9)
pre-1993			-1.304
			(0.437)
Observations	160	160	160
R^2	0.049	0.082	0.135

TABLE 20
BOD MG/L [TAB 1]

Year	-0.0197	-0.0312	-0.0308
	(0.00653)	(0.0158)	(0.0157)
Fed Green		-436.5	-515.3
		(371.2)	(371.5)
Fed Grey		72.84	87.43
		(76.66)	(76.60)
Local Green		613.5	538.7
		(487.4)	(485.7)
Local Grey		-1063.1	-1003.1
		(895.4)	(888.7)
Developed		202.9	158.6
		(95.77)	(99.16)
Semi-developed		-17.57	-14.63
		(7.947)	(8.105)
Production		-10.29	-10.59
		(11.46)	(11.36)
pre-1993			-0.339
			(0.219)
Observations	97	97	97
R^2	0.092	0.177	0.201

TABLE 21
DISSOLVED OXYGEN DEFICIT (DOD) %[TAB 1]

Year	-0.00844	0.446	0.442
	(0.113)	(0.204)	(0.234)
Fed Green		4148.4	4132.4
		(6647.1)	(6700.8)
Fed Grey		1304.2	1308.2
		(1337.9)	(1350.5)
Local Green		-13355.2	-13379.9
		(8626.0)	(8705.1)
Local Grey		41177.2	41225.8
		(15767.3)	(15921.6)
Developed		2900.2	2885.6
		(1213.6)	(1297.6)
Semi-developed		-352.2	-350.9
		(107.8)	(115.8)
Production		586.1	585.1
		(213.0)	(216.0)
pre-1993			-0.103
			(3.133)
Observations	107	107	107
R^2	0.000	0.282	0.282

TABLE 22
FECAL COLIFORM MPN/100ML[TAB 1]

Year	-0.00557	-0.00878	-0.0477
	(0.0134)	(0.0279)	(0.0305)
Fed Green		831.6	527.8
		(844.5)	(823.0)
Fed Grey		-48.82	14.51
		(173.9)	(169.6)
Local Green		-1282.8	-1687.8
		(1114.1)	(1086.0)
Local Grey		2356.2	2877.1
		(2051.1)	(1990.0)
Developed		-72.38	-175.8
		(157.6)	(156.8)
Semi-developed		-2.866	8.129
		(14.19)	(14.28)
Production		-52.85	-59.22
		(26.10)	(25.31)
pre-1993			-0.966
			(0.351)
Observations	105	105	105
R^2	0.002	0.160	0.225

TABLE 23
TOTAL COLIFORMS MPN/100ML[TAB 1]

Year	-0.127	-0.153	-0.153
	(0.0237)	(0.0644)	(0.0644)
Fed Green		-341.3	-341.3
		(953.1)	(953.1)
Fed Grey		29.09	29.09
		(192.1)	(192.1)
Local Green		-67.54	-67.54
		(1209.8)	(1209.8)
Local Grey		2478.8	2478.8
		(2250.9)	(2250.9)
Developed		-176.2	-176.2
		(378.9)	(378.9)
Semi-developed		-8.028	-8.028
		(26.88)	(26.88)
Production		-35.17	-35.17
		(30.61)	(30.61)
pre-1972			0
			(.)
Observations	76	76	76
R^2	0.292	0.449	0.449

TABLE 24
TOTAL SUSPENDED SOLIDS MG/L[TAB 1]

Year	-0.0346	-0.0655	-0.0684
	(0.0122)	(0.0275)	(0.0268)
Fed Green		-1056.0	-1041.8
		(659.9)	(640.8)
Fed Grey		210.2	208.5
		(133.0)	(129.1)
Local Green		264.0	290.1
		(857.7)	(832.9)
Local Grey		118.5	12.16
		(1565.5)	(1520.6)
Developed		529.4	853.7
		(125.0)	(179.8)
Semi-developed		-51.20	-73.94
		(10.78)	(14.01)
Production		-18.42	-11.32
		(21.23)	(20.81)
pre_fad			1.391
			(0.569)
Observations	96	96	96
R^2	0.083	0.299	0.347

TABLE 25
TURBIDITY NTU[TAB 1]

Year	-0.0225	0.0315	-0.0216
	(0.00803)	(0.0205)	(0.0235)
Fed Green		89.71	-89.79
		(684.1)	(637.1)
Fed Grey		-10.25	37.25
		(137.1)	(127.9)
Local Green		853.2	555.9
		(866.4)	(808.3)
Local Grey		-1592.3	-1090.5
		(1577.8)	(1471.0)
Developed		-206.0	0.0591
		(234.6)	(224.4)
Semi-developed		-4.998	-14.84
		(17.42)	(16.38)
Production		-54.01	-57.88
		(21.72)	(20.19)
pre-1993			-1.377
			(0.359)
Observations	160	100	100
R^2	0.049	0.276	0.383

ACRONYMS

BMP	Best Management Practices.
BOD	Biochemical Oxygen Demand.
CWA	Clean Water Act.
CWNS	Clean Watershed Needs Survey.
DBPs	Disinfection By-Products.
DEC	Department of Environmental Conservation.
DEP	Department of Environmental Protection.
DOD	Dissolved Oxygen Deficit.
DOH	Department of Health.
ES	Ecosystem Services.
FAD	Filtration Avoidance Determination.
HUC	Hydrologic Unit Code.
LAP	Land Acquisition Program.
NWALT U.S.	Conterminous Wall-to-Wall Anthropogenic Land-use Trends.
NWIS	National Water Information System.
O&M	Operations and Maintenance.
PES	Payment for Ecosystem Services.
SDWA	Safe Drinking Water Act.
SPU	Service Providing Unit.
TSS	Total Suspended Solids.
UES	Urban Ecosystem Services.
WIP	Watershed Implementation Plans.
WTP	Willingness-To-Pay.
WWTP	Wastewater Treatment Plant.