Regulating Non-Point Source Pollution:

Evidence from the Municipal Separate Storm Sewer System Program

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Abstract

Nonpoint source pollution is one of the major contributors of water impairment in the United States. Command-and-control regulations have been the main policy tools in controlling nonpoint source pollution by setting pollution standards and enforcement mechanisms. The Clean Water Act provides a framework for regulating pollutants both point and nonpoint, through National Pollution Discharge Elimination Permits. A key component of this framework is the Municipal Separate Storm Sewer System program, which mandates municipal statistical and urbanized areas to obtain National Pollutant Discharge Elimination System permits and develop Storm Water Management Programs. This program aims to "improve the Nation's waterways by reducing the quantity of pollutants that stormwater picks up and carries into storm sewer systems during storm events" (U.S. EPA, 2016). This study employs a Regression Discontinuity Design, leveraging the population thresholds that trigger National Pollutant Discharge Elimination System permit requirements as a natural experiment to evaluate the effectiveness of the Municipal Separate Storm Sewer System program in enhancing water quality. This method allows for a robust assessment of the program's impact by comparing water quality outcomes between areas just above and below the population cutoffs for Municipal Separate Storm Sewer System regulation. We find that the program has improved water quality in regulated areas through reduced turbidity. Our analysis seeks to quantify the Municipal Separate Storm Sewer System program's contribution to water quality improvement and aims to inform future policy decisions regarding urban stormwater management and environmental protection. The findings of this study are expected to provide valuable insights into the efficacy of regulatory approaches in addressing urban water pollution and guide the optimization of environmental management strategies.

1. Introduction

Nonpoint source pollution (NPS) is the main type of pollutant affecting the quality of water bodies across the United States (Rotman & Hollis, 2022; US EPA, 2023). While agriculture is the main source of NPS in the US, urban pollution runoff from construction sites, parking lots, streets, and other sources contribute heavily to nonpoint source pollution particularly for sediment, heavy metals, phosphorus, and nitrogen (US EPA, 2020; Brett et al., 2005; Bannerman et al., 1993; Kasper & Jenkins, 2007).

NPS originates from many diffuse sources, which makes it challenging to regulate (Lombardo et al, 2000). Management of NPS is often accomplished through the use of command-and-control type regulations (Olmstead & Zheng, 2019), which mandate a certain type of technology or practice. In the case of the Clean Water Act, NPS is managed through the use of permits, called the National Pollutant Discharge Elimination System (NPDES) permits. The empirical evidence on the success of regulations for reducing NPS pollution is limited, due to the complex nature of NPS pollution. The Clean Water Act has been effective at reducing point source pollution, but the evidence of similar successful reduction of NPS pollution is not available. Additionally, land-use and environmental factors play a large role in the type of runoff, making targeted policies essential in management of NPS pollution (Keiser & Shapiro, 2019; Chang et al., 2013; Rissman & Carpenter, 2015).

In this paper, we study the effectiveness of the Municipal Separate Storm Sewer System (MS4) Phase II Policy in reducing nonpoint source water pollution. The MS4 policy is a critical component of the Clean Water Act and is the principal policy regulating urban stormwater runoff. The purpose of the MS4 policy is to reduce sediment and pollutant loads conveyed through storm sewer systems into local water bodies by requiring qualifying areas to obtain a National Pollutant Discharge Elimination System (NPDES) permit and develop Storm Water Management Programs to discharge runoff into local water bodies. The MS4 policy has been implemented in two phases. Initially, the Phase I policy went into effect in 1990 and regulated urbanized areas with a population of above 100,000, while the Phase II policy went into effect in 1999 regulating areas with populations of above 50,000. Despite the policy being in effect for more than 20 years, little is known about the effectiveness of the program in reducing urban water pollution runoff. Several previous studies have highlighted the issues that may negatively affect the success of the MS4 policy, such as the lack of funding or limited monitoring (Pitt et al., 2004; Rieck et al., 2022). However, the benefits of this policy in improving water quality have remained largely unevaluated.

To study the effectiveness of the MS4 policy, we use a regression discontinuity design, exploiting the ad hoc population threshold of the Phase II policy mandate. By comparing water quality in areas just above and below the threshold we can identify the change in water quality due to the policy. We measure water quality as turbidity, one of the major pollutant concentrations in stormwater runoff (Shen et al., 2018; Mallin et al., 2009; Al-Yaseri et al., 2012).

The major finding of our analysis is that the MS4 policy has been effective at reducing turbidity in regulated areas. Our analysis provides the first empirical evidence for the effectiveness of the command-and-control policies in improving municipal water quality. The level of turbidity is typically correlated with the level of viruses, parasites, bacteria, and other disease-causing organisms in water, so this reduction due to the MS4 policy leads to safer water conditions, particularly near urbanized areas where much of the population lives.

We contribute to the literature in three ways. First, the literature on the management of non-point source pollution mainly focuses on the management of agricultural pollutants and the use of subsidies in reducing NPS pollution (Cochard et al., 2005; Lichtenberg, 2019; Russell and Clark, 2006; Smith and Tomasi, 1995; Xepapadeas, 2011). Much of the literature on nonpoint source pollution uses modeling, simulation, and experiments to evaluate the role of agricultural best management practices to reduce runoff. These studies find that best management practices work best when implemented to target specific pollution sources in a certain watershed (Gharibdousti et al., 2019; Giri et al., 2012; Zimmerman et al., 2019; Xu et al., 2019). Cochard et al. (2005), Smith and Tomasi (1995), and Russell and Clark (2006) all evaluated different policy instruments addressing agricultural nonpoint source pollution. These studies find that, to effectively address nonpoint source pollution, a hybrid policy instruments will be necessary. Other studies use simulation methods to illustrate the heterogeneity of agricultural nonpoint source pollution, showing that land-use patterns, watershed characteristics, and behavior of polluters create varying pollution dynamics across regions (Arrueta et al., 2024; Wossink et al., 2001; Henri et al., 2020). Collectively the literature addresses agricultural nonpoint source pollution from different angles, but the findings highlight the need for region-specific management strategies. While agriculture is the primary emitter of NPS pollution, urban runoff, particularly during storms remains a significant contributor. With increased urbanization comes increased urban runoff, which makes understanding the effectiveness of urban NPS pollution all the more important. Furthermore, as most people live in or near cities, the improvement of water quality near urban areas is particularly important.

Second, we add to the related strand of literature studying the benefits and costs of the Clean Water Act components, evaluating a relatively unexplored aspect of the CWA (Flynn and Smith, 2022; Jerch, n.d.; Keiser and Shapiro, 2019; Lyon and Farrow, 1995). The analysis of the MS4 policy provides a more comprehensive overview of the CWA and strengthens understanding of its impact on urban water quality management. This study provides a comprehensive analysis of the impact of the MS4 program on urban stormwater management. By exploring the main policy addressing stormwater runoff, we gain a better understanding of effective management strategies. As the first in-depth analysis of the MS4 policy, we provide insights into the programs implementation, success, and implications for water quality management.

Third, there is an existing body of hydrology literature on urban water management that uses modeling approaches or primarily concentrates on assessing specific areas, such as a city, a catchment, or a public university (Keeley, 2007; Li et al., 2023; Pierce et al., 2021; Shree Dorestant et al., 2017). Other literature seeks to evaluate the policy in a qualitative nature. There has been no quantitative or empirical analysis of the impact that the MS4 policy has had on water quality in regulated areas, leaving a significant gap in the understanding of these policies (Dunn & Burchmore, 2007; Galavotti et al., 2004).

2. Background

2.1 Nonpoint Source Water Pollution

Water pollution comes from many different sources, such as agricultural production, industrial activities, wastewater, and urban development. Unlike point source pollution, which can be traced back to an identifiable source, nonpoint source (NPS) pollution comes from many sources in unknown quantities. This diffuse nature makes NPS pollution difficult to address. According to the EPA, nonpoint source pollution causes up to 40% of the United States' water bodies to fail to meet their designated uses (US EPA, 1988). Information asymmetry associated with nonpoint source pollution makes it difficult to regulate because regulators can only measure ambient pollution levels, and it is impossible to attribute any pollution to a particular polluter. (Xepapadeas, 2011). Andarge (2019) showed that in the case of the Mississippi River Basin, as the probability of polluters being known by the regulator decreases that the levels of nitrogen in the river increases. This incomplete information makes creating effective policies to address nonpoint source pollution challenging to design. Harrington et al. (1985) used a combination of theoretical analysis and practical observations to evaluate different policy options to address NPS pollution, such as voluntarism, command-and-control, and incentive-based, concluding that no single approach will likely be effective.

Much of the existing literature on NPS pollution addresses agricultural runoff and how effective related policies have been under varying circumstances (Dowd et al., 2008; Drevno, 2016; Jain and Singh, 2019; Larson et al., 1996; Wu and Ge, 2019). The main approach to curb agricultural runoff is to subsidize producers' adoption of conservation practices. The existing literature evaluating subsidies to reduce nonpoint source pollution uses experimental designs and policy analysis finding that without highly frequent monitoring subsidies are ineffective at reducing agricultural runoff (Lichtenberg, 2019; Shortle et al., 2012; Miao et al., 2016; Spraggon, 2004; Vossler et al., 2006). Proposed strategies to reduce agricultural runoff include input and ambient taxes (Segerson, 1999; Xepapadeas, 2011; Larson et al., 1996; Cochard et al., 2005), group fines (Spraggon, 2004; Cochard et al., 2005; Vossler et al., 2006), and water quality trading (Stephenson & Shabman, 2017; Fang et al., 2007; Saby et al., 2023, Lentz et al., 2014).

These strategies have been shown to reduce runoff from agricultural sources, but they rely on the ability to target a specific source, such as farmers or inputs. Agricultural runoff is addressed through conservation payments, and not regulated by environmental policies, such as the Clean Water Act. Urban and stormwater runoff, however, is subject to regulations under the Clean Water Act. Therefore, understanding the regulatory framework for different sources of pollutants is essential for effectively mitigating their impacts on water quality.

Urban runoff is becoming an increasing environmental concern. Urban development is projected to continue, increasing the amount of impervious cover and the resulting urban runoff (US EPA, 2015). Easton et al. (2007) evaluated the transport of phosphorus using hydrologic modeling, finding the highest levels of dissolved phosphorus in more densely urbanized areas, particularly near stormwater outflows. Additionally, they find that urban runoff varies from agricultural runoff both in the types of pollutants that are conveyed and the heterogeneity of these pollutants, so effective policies must consider the distinct sources of runoff. Qiu (2013) studied various best management practices to mitigate stormwater runoff and nonpoint source agricultural runoff and concluded that best management practices targeting agricultural nonpoint source pollution were more cost-effective in improving water quality than the best management practices for reducing stormwater runoff. Shrestha et al. (2022) evaluated the impact of land use cover changes on ecosystem degradation, finding a decrease in the value of ecosystem services as urban land use grows. In addition to improving water quality, stormwater management provides other social benefits, such as reduced flooding and improved aquatic environment. Ando et al. (2020) used willingness to pay and willingness to volunteer for stormwater management improvements to measure benefits of stormwater management, finding positive values for both willingness to pay and volunteer. This strand of literature highlights the importance of effective urban and stormwater management policies to adapt to the increasing load of urban pollutants.

2.2 Municipal Separate Storm Sewer System Policy Background

The Federal Water Pollution Control Act of 1948 was passed to address issues related to water quality. It was the first major federal law to address water pollution and had ambitious goals. Several of the act's primary goals include eliminating all pollutant discharge into navigable waters by 1985, limiting the release of toxic pollutants and providing financial support for public waste treatment facilities (Federal Water Pollution Control Act, 1948). The Federal Water Pollution Control Act was revised in 1972 and became known as the Clean Water Act (CWA). Most regulations in the CWA target point source pollution through the National Pollution Discharge Elimination System (NPDES) permitting program, though a few regulations attempt to address nonpoint source pollution, one of which is the Municipal Separate Storm Sewer System (MS4) Program. The CWA was amended in 1987 to include stormwater discharges, including municipal separate storm sewer systems (MS4s), which can convey both point and nonpoint source pollutants.

The MS4 regulation was implemented in two phases: Phase 1, which began in 1990, requires medium and large municipalities, cities, and counties with populations greater than 100,000 to obtain NPDES permits to discharge stormwater. Phase II of the program extended the regulation in 1999 and applies to urbanized areas with populations of 50,000 (Council et al., 2009). Additionally, Phase I requires permits for construction sites that disturb an area of five acres or more, while Phase II mandates permits for sites disturbing between one and five acres (National Research Council, 2009). Areas under the original 1990 Phase I ruling are "frozen", meaning any area regulated after 1990 is regulated under Phase II of the policy even if its population reaches 100,000 and the areas regulated under the original Phase I ruling never change (Leo et al., 2018).

The urban areas regulated under Phase II are, however, updated every 10 years with the release of the new decennial census population data.

The monitoring and administration of the MS4 policy varies by state. The EPA oversees permits for Idaho, Massachusetts, New Hampshire, New Mexico, and the District of Columbia, and the remaining 46 states have the authority to oversee their permits. Permittees in regulated areas under both Phase I and II programs must implement stormwater management Programs (SWMPs) that specifies the practices (BMPs) that will be implemented to reduce runoff. The minimum control measures for each phase of the program vary, but the goal of the SWMP under each phase is to minimize sewer system discharge into natural water bodies (Leo et al., 2018).

The MS4 program is the cornerstone policy to manage urban stormwater runoff. This program plays a crucial role in ensuring sustainable urban water management, particularly in reducing pollutants carried by stormwater into natural water bodies and minimizing the environmental impact of urbanization. Therefore, the successful implementation and continual improvement of the MS4 program are essential for preserving water quality in urban landscapes.

Under Phase II of the policy, regulated areas include urban areas with a population of 50,000 or more, some federally owned systems, such as military bases, hospitals, and prisons, and construction activity disturbing an acre or more. The policy allows two waiver options for qualifying areas. The first waiver applies to areas that are within an urban area of at least 50,000 people, but the system serves less than 1,000 people, the area is not a substantial contributor of pollutant loadings in a connected MS4, and does not discharge pollutants causing impairment in water bodies addressing total maximum daily loads. The second waiver applies to areas that are within an urban area of at least 50,000 people, but the system serves less than 1,000 people, an evaluation shows that stormwater controls are not needed, and the MS4 does not have the potential to exceed water quality standards. These waivers allow flexibility for smaller systems, while still maintaining stormwater control (US EPA, 2023b).

Regulated areas must implement a stormwater management program that reduces pollutant discharge by the “maximum extent practicable.” The stormwater management program must include six minimum control measures: public education and outreach; public participation/involvement; illicit discharge detection and elimination; construction site runoff control; post-construction runoff control; and pollution prevention/good housekeeping. For each of the minimum control measures, the MS4 must identify measurable goals and implement a selection of best management practices. Under Phase II regulated areas can apply for an individual or general permit. Under a general permit the MS4 submits a Notice of Intent under an existing permit and comply stormwater management program in the general permit. An individual permit requires the MS4 to submit their own permit application, along with the best management practices the area will implement, measurable goals, and other information required by the permit (US EPA, 2023c).

The policy requires annual reporting by the regulated MS4. The reports must include the implementation status of the stormwater management program, program changes, monitoring data, identification of water quality improvements, and other information required by the permitting authority. In addition to annual reports, the permitting authority uses audits and inspections to monitor compliance with the policy. While each state may vary in its approach, Section 309 of the Clean Water Act provides federal authority to fine the MS4 administrative penalties, civil penalties, or criminal penalties. These penalties range from $2,500 to $25,000 per day. The Clean Water Act also provides an avenue for citizens to file a civil suit against a person violating an effluent standard or an EPA administrator that has failed to enforce such standards.

By mandating stormwater management programs and best management practices, the MS4 policy attempts to mitigate the adverse effects of urbanization (The National Association of Clean Water Agencies, 2018).

The effectiveness of the MS4 policy in reducing water pollution in or near municipal areas has been questioned. Rieck et al. (2022) found that challenges facing implementation and limited financial resources of small municipalities regulated under the MS4 program are inhibiting these areas' ability to comply with the Phase II ruling, which impacts the policy's success. The National Research Council claims that the MS4 policy is not designed to adequately address stormwater runoff due to the lack of end-of-pipe monitoring and the self-monitoring aspects of the policy (Council et al., 2009). The most relevant analysis was performed by Pitt et al. (2004), whose goal is to provide a comprehensive stormwater database to guide future sampling and areas with limited data, in addition to providing a benchmark for future measures of stormwater quality data. Other literature seeks to evaluate the policy in a qualitative nature. There has been no quantitative or numerical analysis of the impact that the MS4 policy has had on water quality in regulated areas, leaving a significant gap in the understanding of these policies (Chiang, 2014; Dunn and Burchmore, 2007; Galavotti et al., 2012). This gap makes it challenging to identify areas for improvement or successful measures that could be implemented in areas suffering from water quality impairment.

3. Data

This study employs population data and water quality data from individual monitoring station locations. We also use spatial data on areas regulated under Phase I and Phase II of the program and those not regulated. This section describes data collection and integration for this analysis.

3.1 Population Data

Population data were collected for U.S. Census Bureau-defined urban areas based on the 1990, 2000, and 2010 Decennial Census. The two census definitions for urban areas are urban clusters and urbanized areas. Urban clusters are defined based on areas containing a population of between 2,500 and 50,000 people. An urbanized area contains over 50,000 people and "comprises one or more places—central place(s)—and the adjacent densely settled surrounding area—urban fringe—consisting of other places and nonplace territory" (US Census Bureau, 1994). These two groups allow us to evaluate areas that fall below and above the population threshold, capturing regulated and unregulated areas. Due to the ’freezing’ of the Phase I areas, we use areas regulated under Phase II as our treatment group and unregulated areas as our control group. Table 1 summarizes the number of regulated areas and total observations for each census year.

Regulated Areas

Year	Census Year	Phase I	Phase II	Total
1999	1990	228	NA	2,856
2000-2010	2000	228	443	2,856
2011-2020	2010	228	464	2,856

Table 1. The total number of urban areas that are regulated each year. Phase I areas are ’frozen’ based on the MS4 policy, therefore these areas never change.

These data were obtained from the Integrated Public Use Microdata Series National Historic Geographic Database (IPUMS NHGIS). This database provides population statistics with an area boundary standardized to a particular census year’s geography, which was 2010 for our analysis. This standardization is done by aggregating data from the smallest source units, like census blocks, and then reallocating this data to fit the geographic units defined by the 2010 Census (NHGIS, 2023; Schroeder, 2007). This standardization allows us to keep the geographic area being evaluated constant over time while the population is changing. This constant area helps to control for spatial variation and ensure that changes in water quality are more likely due to policy effects.

The dataset contains the year, population, latitude, longitude, county name, and state name. The data also includes a column of geographic information system (GIS) codes to match data tables with boundary files. Population data was used to determine the census classification of counties as municipal statistical areas (Phase I) and urbanized areas (Phase II). Each year in the analysis has between 400 and 500 areas regulated under Phase II of the MS4 policy. Table 2 represents summary statistics of each year's population data. The low population minimums reported for 1990 and 2000 are due to the standardization of the area boundaries based on the 2010 census. However, this is not a major concern for our analysis because areas with very low and very high populations will not affect the estimates as will be discussed in the Section 4.

Population Summary Statistics

Year	Minimum	Median	Average	Maximum	N
1990	4	6,520	66,590	16,411,693	2,934
2000	1	7,145	75,219	17,824,727	2,934
2010	2500	7,720	83,908	18,351,295	2,934

Table 2. Population summary statistics for urban and urbanized areas each decennial census year. 1990 and 2000 boundaries are standardized to 2010 boundaries. N is the total number of unique urban and urbanized areas.

3. 2 Water Quality Data

Water quality data was collected from the Water Quality Portal, which is supported by the Environmental Protection Agency, the United States Geological Survey, and the National Water Quality Monitoring Council. The Water Quality Portal is a comprehensive database that combines data from the National Water Information System collected by the United States Geological Survey the Agricultural Research Service’s Sustaining the Earth’s Watershed data, and Water Quality Exchange data (formerly called the STORET database) collected by the EPA. Water Quality Portal data provides a monitoring site identifier, monitoring site location, water quality measure, date of sample, and a column of Geographic Information Systems codes to match data tables with boundary files. Our analysis uses annual turbidity data from 1980 to 2022, but further research is needed to identify the most suitable measures of urban runoff. Figure 1 displays reported turbidity values for 1980 to 2022, reporting turbidity separately for treatment and control.

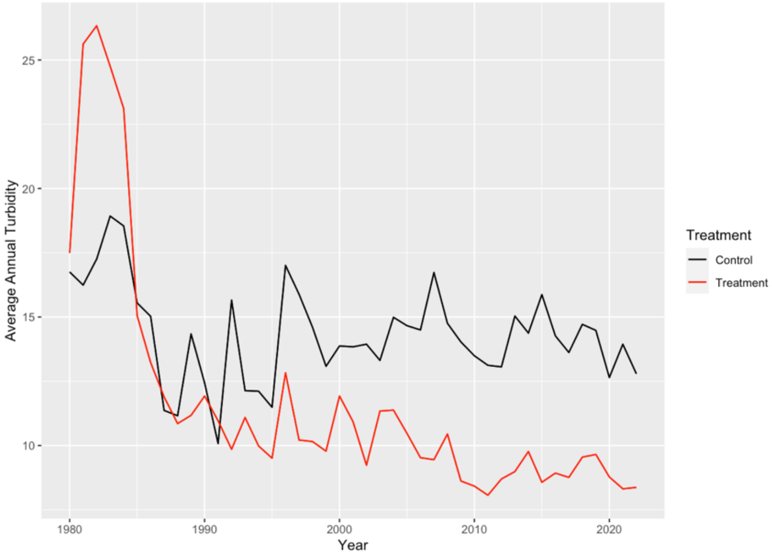

Figure 1. Average Turbidity Values from 1980 to 2022.

Average turbidity for each year by treatment and control areas.

To determine the most fitting parameters, we will evaluate the literature on urban water pollution and MS4 regulation. Figure 2 displays the distribution of stations that monitor turbidity across the United States. The size and intensity of the point vary based on the number of observations for that monitoring station, with the darker circles having the most observations. Table 3 provides the summary statistics for the reported turbidity levels. The average turbidity across the United States is about 11.5 nephelometric turbidity units (NTUs).

Turbidity Summary Statistics

Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
0.00	5.225	6.713	11.529	9.867	1000.000

Table 3. Summary statistics for annual turbidity for the United States reported from 1980 to 2022.

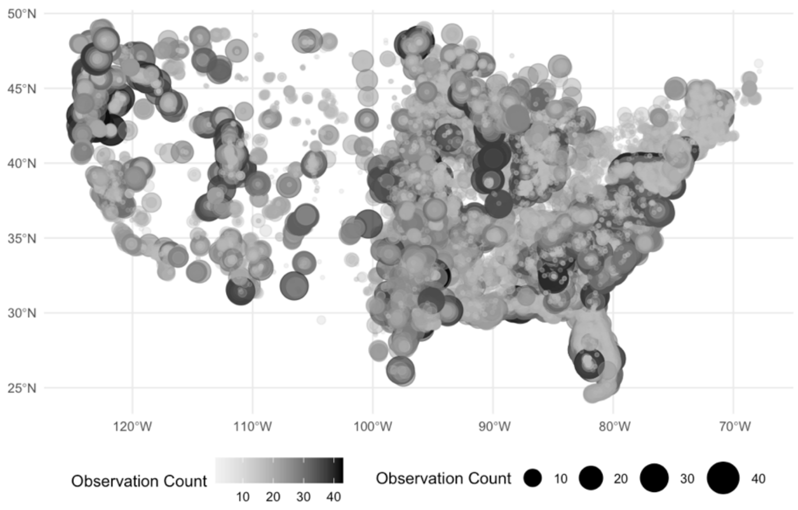

Figure 2. Water Quality Monitoring Sites

Distribution of water quality monitoring stations across the United States. The size and intensity of the circle vary based on the number of observations for the particular station.

3.3 Spatial Data

Spatial data for counties was collected from IPUMS NHGIS as shapefiles. Shapefiles contain multiple files that together describe geometric locations, represented as points, lines, or polygons, and their attributes. We obtain shapefiles for areas both within and outside the regulated areas. We then added a 5-mile buffer around each individual polygon inside the shapefile to ensure each monitoring station location was captured in the spatial file.

The shapefiles and the water quality reporting data from WQP were used to identify monitoring station locations that fall inside and outside of the areas regulated by the policy. This was done by overlaying the WQP water quality monitoring station data with the NHGIS shapefiles to identify the monitoring sites that lie within each shapefile using the latitude and longitude coordinates of the monitoring site using R. This overlay allows us to identify monitoring stations that are within regulated areas and those that are not, to compare the water quality in these areas.

Table 4 provides summary statistics for the turbidity data. We provide the number of monitoring stations per urban area, turbidity values per monitoring station, and turbidity values per urban area. We see the observations are very dispersed, with some monitoring stations and urban areas having only one observation in the turbidity data from 2000 to 2022, while other areas have thousands of observations. This could bias the results if the amount of reporting in an urban area is correlated with the level of water quality. If areas with high (low) water quality have a larger number of observations, then this could lead to an overestimation (underestimation) of policy impacts. This demonstrates a need to possibly weight the areas that have a small or large number of observations so that water quality in each area is represented proportionally to its actual state.

For the current analysis, we aggregate turbidity values per monitoring station and year to get an annual measure for each monitoring station.

Number of:	Minimum	First Quartile	Median	Mean	Third Quartile	Maximum
Turbidity Obs. per Station	1.00	1.00	1.00	3.035	3.00	24.00
Stations per UA	1.00	3.00	6.00	28.02	15.00	9,119.00
Turbidity Obs. per UA	1.00	5.00	17.00	84.03	52.00	14,843.00

Table 4. Summary statistics for the number of turbidity observations per monitoring station and urban area (UA) and the number of monitoring stations per urban area (UA). The distribution indicates a right skew in the distribution of the data.

4. Methodology

We exploit the exogenous treatment around the 50,000-population threshold under Phase II of the regulation using a regression discontinuity design (RDD). The population threshold of the policy serves as an exogenous cutoff, which creates the opportunity to isolate the effect of the MS4 program on water quality from other confounding factors. The RDD method assumes that areas with similar populations, those just under and above the threshold, are comparable in all aspects other than the regulation under the policy.

The treatment group will be cities that fall just above the MS4 threshold, with a population of 50,000 or more. The preliminary model is represented by equation 1, which is the most common specification of the RDD model[1].

$$y_{ilt} = \beta_0 + \beta_1 D_{it} + \beta_2 (x_{ilt} - c) + \beta_3 D_{it}(x_{ilt} - c) + zone \times year + \varepsilon \qquad (1)$$

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[1] To perform the RDD estimation we used the 'rdrobust' package in R. The default mechanism for selecting the optimal bandwidth in this package is by minimizing the mean squared error and applying triangular weights, which put more weight on the observations closest to the specified cutoff (Calonico and Calonico, 2023).

Where y_{ilt} is the water quality measure at monitoring station location i in urbanized area l, in year t. We restrict turbidity observations to post-1999 since this is when Phase II of the policy went into effect. D_{it} indicates whether a monitoring station location is in a regulated area under the MS4 Phase II program at time t. The variable x_{ilt} is the total population at time t for the urbanized area that monitoring station i is within, and c is the Phase II regulation population threshold of 50,000 people. *Zone* x *year* is a matrix of zone by year fixed effects. Zone is the Universal Transverse Mercator zone, which divides the United States into 6 zones, each of which is 6 degrees longitude wide (Langley, 1998), shown in Figure 3.

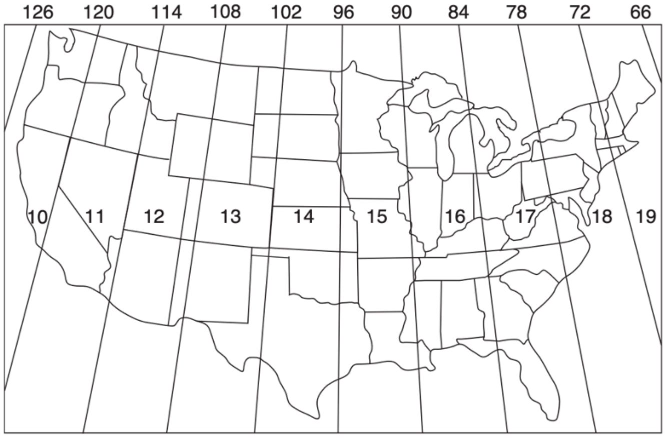

Figure 3. Universal Transverse Mercator Zones

Universal Transverse Mercator Zones divide the United States into 10 equal sections, each 6 degrees in longitude (U.S. Geological Survey, 2001).

A key assumption of RDD is that there can be no manipulation to gain or avoid treatment by units (individuals, organizations, regions, etc.). Since the treatment status for the policy is based on the Census population, we don't have concerns about sorting. Additionally, identification of the policy impacts can be difficult if multiple policies affecting water quality use the same population threshold, referred to as compound treatment. This is less of a worry in the United States where there are few policies based on a population threshold (Eggerset al., 2018; Hopkins, 2011).

Adding these fixed effects helps to control for temporal and spatial variations. We use zone by year to capture the different hydrologic and economic relationships for each region, as variations in annual land-use and regulatory environments can influence regional water quality. We will also add precipitation, temperature, land use changes, longitude, and latitude as control variables and watershed fixed effects. Precipitation and temperature variables help to control for changes in weather that are impacting turbidity, such as heavy rainfall, extreme temperatures, and rapid snow melt, which can influence runoff. Land-use changes are added as controls to try to capture changes in the natural landscape, such as an increase in urbanization or agricultural land, both of which influence the type and quantity of runoff. Finally, latitude and longitude are added as spatial controls to account for geographic variations.

In Panel A of Figure 4, we conduct a placebo test by plotting the residuals from a linear regression using average annual turbidity values from before policy implementation, 1980 to 1998, against population. This regression uses average annual turbidity as the outcome variable and latitude and longitude as controls with year, zone, and state fixed effects[2]. The figure shows, that when controlling for relevant variables, turbidity values are smooth across the threshold, showing that observed differences between regulated and unregulated areas after policy implementation are likely due to the policy. Panel B of Figure 4 plots the residuals from the same linear regression, but using data from 1999 to 2022, after Phase II of the policy was implemented. Panel B shows that after the implementation of Phase II, there is a discontinuity at the 50,000-population threshold, with a decrease in values on the right side of the population threshold. This indicates that the policy has had some effect on reducing turbidity.

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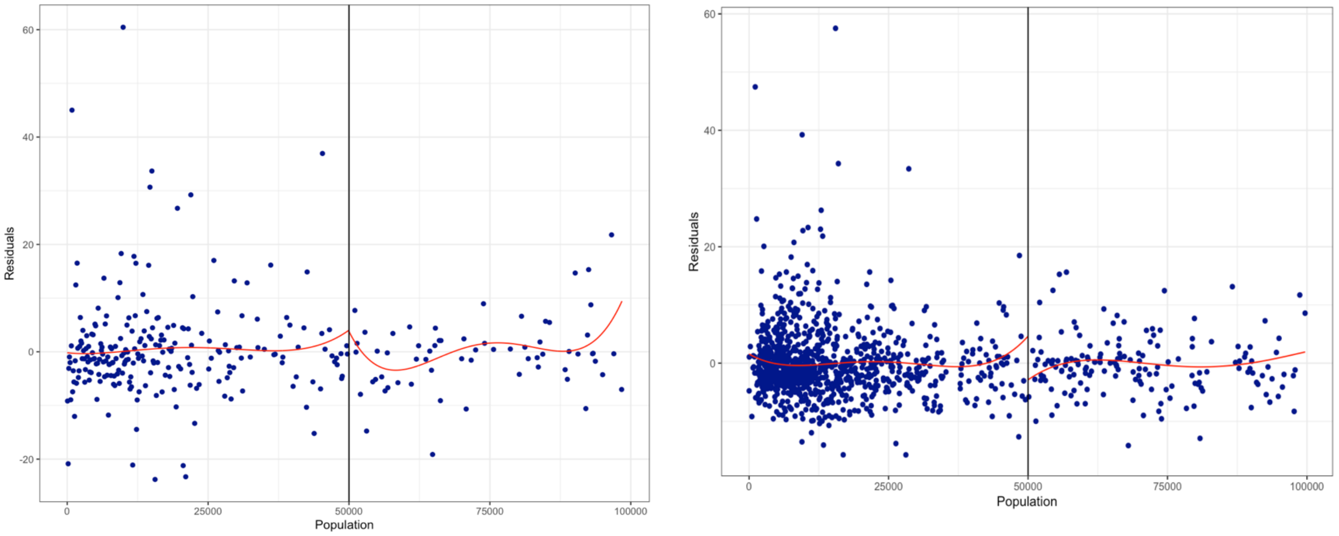
[2] $y_{ilt} = \beta_1 Latitude + \beta_2 Longitude + Zone + Year + State$



Panel A **Panel B**

Figure 4. Residuals from a linear regression plotted against population.

Panel A plots residuals from a linear regression with turbidity from 1980 to 1998 as the outcome variable as a placebo test. Panel B plots residuals from a linear regression with turbidity from 1999 to 2022 as the outcome variable to support regression discontinuity design as an identification strategy. Control variables for both regressions include latitude, longitude, and year, state, and zone fixed effects.

5. Results

We estimated the RDD model by using the default settings of the 'rdrobust' package in R, which selects the bandwidth by minimizing the MSE and then applies a triangular kernel. This method results in a bandwidth of 15,156.38, so the estimation uses areas with a population range from 34,543.62 to 65,156.38. The analysis used a total of 238,950 observations, with 87,395 below the threshold and 151,555 above the threshold.

The preliminary results of the RDD for turbidity are shown in Table 5. The bias-corrected RDD regression coefficient suggests that regulation under Phase II of the policy decreases averaged turbidity by about 3 NTUs. Average turbidity across the United States was about 11.5 NTUs during the evaluated time frame, 1980 to 2022. This is a reduction of roughly 26% of turbidity nationwide since the policy was implemented in 1999, showing the policy has been effective at reducing turbidity.

Regression Discontinuity Results

Method	Coefficient	Standard Error	z	Pr >z	[95% C.I.]
Conventional	-3.203	0.312	-10.282	0.00	[-3.814 , -2.593]
Bias-Corrected	-2.756	0.312	-8.845	0.00	[-3.366 , -2.145]
Robust	-2.756	0.367	-7.506	0.00	[-3.475 , -2.036]

Table 5. Regression discontinuity results using turbidity observations after the 1999 policy implementation as the outcome variable and 1990 population to identify the cutoff. The chosen bandwidth was 15,156.38 with 238,950 observations total.

To validate our findings, we will perform robustness tests to check bandwidth sensitivity and the sensitivity of our results when we use a different buffer distance. Additionally, we will use differences-in-regression-discontinuity design to compare the results from the regression discontinuity design. This will allow us to explore the heterogeneity of treatment, considering the policy is highly heterogeneous due to the majority of enforcement occurring at the state level.

6. Discussion

Based on our preliminary results, the MS4 policy has been successful at reducing stormwater impairment in regulated areas. Our analysis provides the first causal evidence of the effectiveness of an urban and NPS pollution regulation. In the next step, we will consider 1) other water quality variables; in addition to turbidity, the literature suggests common pollutants in stormwater include total suspended solids, biological and chemical oxygen demand, nitrogen, and phosphorus (Lee and Bang, 2000; Taebi and Droste, 2004; Taylor et al., 2005)); 2) the heterogeneity of the effectiveness across states: due to the heterogeneous nature of policy enforcement at the state level, we could identify different states implementing the MS4 policy more effectively and provide valuable insights into best practices and strategies that other states could adopt to enhance water quality and compliance with the MS4 program ; 3) consider a weighting method for areas that have extreme numbers of monitoring stations. This could provide valuable insights into best practices and strategies that other states could adopt to enhance water quality and compliance with the MS4 program.

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