# Abatement cost pass-through of water pollution regulation: Evidence from sewer utility bills and Wisconsin's phosphorus rule[*]

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**Abstract**

In this paper, we estimate the abatement cost pass-through of Wisconsin's "phosphorus rule", which created the most stringent water quality standards for phosphorous in the country. We examine how compliance with the rule affects real billing rates at sewer utilities in Wisconsin, providing the first empirical estimates of pass-through from a water pollution regulation. We find that compliance with the phosphorous rule increases the average real sewer utility bill in our sample by 8-11%. We also examine the implementation of Wisconsin's water pollution offset trading program and how it differentially impacts pass-through in this setting. Real sewer utility rates increase by 14.6% for utilities that comply with the phosphorus rule with a treatment technology upgrade, as compared to 6.4% for utilities that comply with the rule through water pollution offset trading. Overall, our results suggest that pass-through of the phosphorus rule is between 72% and 88% for affected sewer utilities.

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## 1. Introduction

Since 1972, the US has collectively spent more than $1 trillion on water pollution abatement (Keiser and Shapiro 2019). Despite these considerable expenditures, the economic literature on air pollution control is much larger than that of water pollution control, in part because of identification concerns. Specifically, program evaluations of water quality regulations are challenging because water quality regulation is often uniform across space, obfuscating efforts to identify effects in regulated versus unregulated areas (Keiser and Shapiro 2019). An important question therefore remains unanswered in the economics literature: how do these considerable water pollution abatement expenditures in the US affect consumers, i.e., pass-through? The concept of pass-through is important, because it identifies how increased input costs from environmental regulation ultimately affect output prices, and hence, consumer welfare. The extant literature provides evidence that electric utilities, which are subject to stringent air pollution regulations, pass through large proportions of their compliance costs to consumers in the form of higher electricity prices (Sijm et al. 2006; Fabra and Reguant 2014; Hintermann 2016; Krumholz 2019). Importantly, sewer (i.e., wastewater) utilities that incur sizable water pollution abatement costs because of environmental regulation are nearly always local monopolies, suggesting that pass-through could be even larger for water pollution abatement than for air pollution abatement.

In this paper, we address the pass-through of water pollution regulation by studying how water pollution abatement expenditures affect consumers via their real sewer utility bills, relative to the counterfactual outcome without the regulation. We overcome the identification issues present when studying most water pollution regulations by focusing our analysis on Wisconsin. In 2010, Wisconsin revised its water quality rules for phosphorus to adopt the most stringent standards in the country, collectively known as Wisconsin's "phosphorus rule." Wisconsin's implementation of the rule rolled out across point sources, such as wastewater treatment plants, in the state according to exogenous National Pollutant Discharge Elimination System (NPDES) permit reissuance dates, providing a natural experiment that allows us to identify the effects of stringent water pollution regulations on our outcome of interest. We exploit this natural experiment to answer two primary research questions. First, we identify the effects of the phosphorus rule on residential sewer utility billing rates and estimate the extent of compliance cost pass-through. Second, Wisconsin's phosphorus rule allows point sources to comply with the rule by either upgrading their wastewater treatment technology to expensive tertiary filtration systems or engaging in water pollution offset trading. We therefore extend the analysis to estimate the cost-effectiveness of Wisconsin's water pollution offset trading program relative to a technological compliance option. Does Wisconsin's water pollution offset trading program empirically reduce abatement costs? And, if so, is there heterogeneity in the pass-through of Wisconsin's phosphorus rule by compliance option?

Some background on water pollution offset trading and Wisconsin's phosphorus rule elucidates why the pass-through of the rule may be heterogenous. Economists have long endorsed market-based trading programs as cost-effective pollution control instruments, both in theory and in practice. And policymakers laud as successes among historical air pollution control policies well-known examples, such as the US Acid Rain Program for trading sulfur dioxide emissions (Goulder 2013; Schmalensee and Stavins 2013). The analogous water pollution control policies, which governmental agencies, environmental organizations, and agricultural associations promote (e.g., EPA 2019), typically allow for point sources to trade water pollution (i.e., discharge) offsets with agricultural or other nonpoint sources.[1] The intuition behind these policies is clear; point sources avoid the high marginal costs of technological pollution abatement by paying nonpoint sources to implement practices that reduce pollution elsewhere in the watershed.[2] In theory then, water pollution offset trading is more cost-effective than command-and-control technological standards. However, and despite the existence of several water pollution offset trading programs in the US, few trades occur in practice.[3]

In addition to representing a useful setting to identify the effects of water pollution regulation on our outcome of interest, Wisconsin also provides a good setting to study water pollution offset trading. Wisconsin's Department of Natural Resources (WDNR) administers a

[1] Although policymakers often conflate them, there are two distinct types of pollution trading markets. First are cap-and-trade markets (like the Acid Rain Program), where there exists an authoritative emission or discharge "cap" for the entire market. Participants in these programs then trade pollution allowances – that collectively equal the cap – with other market participants. Second, offset markets consist of regulated entities purchasing pollution "offsets", typically from non-regulated entities. Total emissions or discharges in these markets are not capped, so the individual permits of regulated entities determine the overall stringency of the market. Trading programs for water pollution control generally take the form of offset markets. For this reason, we refer to these programs for water quality as "water pollution offset trading".

[2] The practices typically consist of agricultural "best management practices", such as the installation of cover crops or riparian buffers, and are much cheaper per unit of phosphorus abated than the installation of wastewater treatment technology at the point source.

[3] The inherent right to pollute given to nonpoint sources, the localized and uncertain nature of water pollution, and high transaction costs all contribute to this lack of trades (Fisher-Vanden and Olmstead 2013).

program that comparatively facilitates many trades because of the stringency of the state's phosphorus rule. The regulation resulted in point sources experiencing large changes in their permitted phosphorus discharge limits, from 1.0 mg/L to 0.075 mg/L. As a result of the sizable increase in costs to comply with their discharge limits via treatment technology upgrade, many point sources now trade phosphorus credits with other, usually nonpoint, sources.[4]

Several studies catalog water pollution offset trading programs throughout the US, but do not focus on their efficacy (e.g., Woodward et al. 2002; Morgan and Wolverton 2008; Shortle et al. 2021). There exist some ex ante studies that model agricultural and environmental systems to predict the effects of these programs.[5] However, few papers conduct ex post program evaluations of water pollution offset trading programs, because the programs are relatively new and transaction costs in these markets are high (Newburn and Woodward 2012). As a result, many programs do not have enough existing trades to conduct empirical analyses. Ex post evaluations are generally limited to describing the geographic pattern of trades (Saby et al. 2021), the best management practices (BMP) that nonpoint sources use to generate credits (Newburn and Woodward 2012), bidding behavior (Newburn and Woodward 2012), market response to baseline stringency (Ribaudo et al. 2014), social context and farmer participation (Breetz et al. 2005), and transaction costs (Fang et al. 2005; Newburn and Woodward 2012; Deboe and Stephenson 2016). In general, there exists a sizable gap in the literature on the ex post performance of water pollution offset trading programs relative to alternatives.

This paper adds to the literature in two main ways. First, we provide the first evaluation of the pass-through of water pollution regulation. Previous work examines pass-through in other contexts, primarily studying how taxes and regulatory policy (e.g., air pollution regulation) affect end user prices in different markets. These studies examine, for example, pass-through of gasoline taxes (Marion and Muehlegger 2011), carbon prices (Fabra and Reguant 2014), fuel costs and CO2

[4] The Clean Water Act, which state environmental protection agencies primarily administer, allows for states to establish trading markets for individual point sources to use to comply with their discharge permits. Wisconsin is one such state that administers a water pollution trading program.

[5] For example, Fleming et al. (2020) use an integrated assessment model to predict likely effects of Maryland's proposed water pollution offset trading program. The authors focus on the behavioral response of farmers, finding that the trading program would likely decrease the effectiveness of the existing conservation subsidy programs. Rabotyagov et al. (2014) compare trading programs with command-and-control and performance standards. The authors simulate the policies in an agricultural watershed in Iowa and find trading programs would produce cost-effective outcomes for nitrogen abatement, although the simulations suggest that trading programs may not attain the regulated abatement requirement. Ghosh et al. (2011) simulate the effects of baseline requirements in the Conestoga watershed in Pennsylvania and find that such requirements can discourage trades.

regulation (Miller et al. 2017), New Source Review lawsuits (Krumholz 2019), and taxes on sugar-sweetened beverages (Cawley et al. 2021). Second, we quantify potential cost savings of a water pollution offset trading program, for facilities both regulated under the program and end users serviced by these facilities, relative to counterfactual policy options. The extant literature lacks empirical evidence on the cost-effectiveness of these trading programs, at least in part because of the relative low frequency of transactions.

To develop our contributions, we use three primary data sources. First, we gather permit information for each point source discharger in Wisconsin from EPA's Environmental Compliance History Online (ECHO) database. From this permit information, we identify when Wisconsin's phosphorus rule regulates each facility. Important for our setting, the NPDES permit process results in temporal variation of each point source's permit reissuance, which helps us to overcome the identification issues present in previous analyses of water pollution regulation (Keiser and Shapiro 2019). Second, we obtain compliance option and water pollution offset trading plans that point sources regulated under the phosphorus rule submit to WDNR. We scrape these plans to first determine each facility's compliance option (water pollution offset trading or treatment technology upgrade). We then use the third- and fourth-year plans to gather descriptive information about the trades that occur as part of Wisconsin's water pollution offset trading program. Third, we gather longitudinal sewer utility billing rates through a repeated survey of sewer utilities in Wisconsin; we normalize these rates to 2020$.

Then, we use a difference-in-differences (DD) research design to estimate the pass-through of Wisconsin's phosphorus rule to municipal sewer utility customers. For our analysis, we compare changes in real sewer utility billing rates for customers serviced by municipal sewer utilities that are treated by, i.e., subject to, Wisconsin's phosphorus rule with changes for those serviced by control group sewer utilities that are not subject to the phosphorus rule. Treatment in our setting is therefore determined primarily by exogenous temporal variation in each municipal source's NPDES permit reissuance date. We also examine treatment effect heterogeneity along several dimensions including facility size, number of customers served, and median income of the surrounding municipality. Finally, we examine the water pollution offset trading program in the state. We estimate the cost savings for point sources that participate in water pollution offset trading to comply with the phosphorus rule instead of upgrading to tertiary treatment technology. We also provide a descriptive analysis of WDNR's trading program, including the costs of trades, their locations, and the types of point sources that participate in the program. Most importantly, we estimate the heterogeneity in the pass-through of the phosphorus rule by compliance option.

Using our baseline specification, we find that Wisconsin's phosphorus rule increases the average real sewer utility billing rate in the state by roughly 10%. This value represents an annual increase of $48.85 for the average sewer utility customer in our sample. Our estimates imply that sewer utilities pass through around 74% of the compliance costs of Wisconsin's phosphorus rule. Our heterogeneity analysis suggests that the estimated treatment effects are primarily the result of larger, more urban sewer utilities that service customers with higher incomes passing through costs, rather than smaller, rural utilities with lower income customers. These results support the argument that there is political pressure to keep sewer utility billing rates low, especially for lower income individuals where rate increases are likely regressive. Further, phosphorus rule compliance costs are directly linked to facility size, so larger facilities have higher costs, which they pass through to end users at a higher rate.

Consistent with economic theory, we find that WDNR's water pollution offset trading program presents a cost-effective form of water pollution abatement in the state. The average annual abatement costs for point sources in our sample to comply with the rule via tertiary treatment technology upgrade are roughly $372,000. However, for facilities that comply with the standards by participating in WDNR's water pollution offset trading program, the average abatement costs are $93,800 per year. Therefore, water pollution offset trading throughout the state provides compliance cost savings of $17.5 million per year over treatment technology upgrades, while theoretically delivering the same or better water quality improvements.

Finally, we find that there exists considerable heterogeneity in the pass-through of Wisconsin's phosphorus rule depending on the compliance option of each sewer utility. The phosphorus rule increases real billing rates for sewer utilities that upgrade their treatment technology to comply by 14.6%, whereas the rule only increases rates by 6.4% for utilities that comply with the rule via water pollution offset trading. Our results suggest that compliance through water pollution offset trading saves the average Wisconsin sewer utility customer approximately $40 per year. We find pass-through of 72% for sewer utilities that comply with the phosphorus rule via water pollution offset trading and 88% for utilities that comply by upgrading their treatment technology.

The rest of this paper proceeds as follows. Section 2 provides background information on

Wisconsin's phosphorus rule and sewer utilities in the state. Section 3 provides an analysis of how phosphorus rule compliance costs affect sewer utility billing rates and estimates the extent of pass-through to customer bills. Section 4 describes water pollution offset trading in the US, provides a descriptive analysis of the implementation of Wisconsin's trading program, and investigates heterogeneity in the effects of the phosphorus rule on sewer utility rates based on compliance option. Finally, Section 5 concludes.

## 2. Background

In this section, we provide the necessary background information for our study. First, we describe the statutory framework of Wisconsin's phosphorus rule. Then, we provide information about point source compliance with the rule, including compliance options, requirements, and schedules. Finally, we describe the background of municipal sewer utilities in Wisconsin, including their regulation.

### 2.1. Statutory framework of Wisconsin's phosphorus rule

In 2010, Wisconsin revised its phosphorus water quality rules to make them much tighter, effectively creating the most stringent phosphorus standards in the country.[6] Administrative code NR102 (Water Quality Standards for Wisconsin Surface Waters or the "phosphorus rule") establishes a set of water quality standards and administrative code NR217 (Effluent Standards and Limitations for Phosphorus) establishes discharge limits, schedules of compliance, and alternative compliance options such as water pollution offset trading.[7]

NR102 specifies total phosphorus criteria as follows: 0.1 mg/L (small number of codified rivers), 0.075 mg/L (streams and all other rivers), 0.015-0.04 mg/L (lakes and reservoirs), 0.007 (Lake Michigan), and 0.005 (Lake Superior) (WDNR 2020). NR217 specifies six types of total phosphorus limits: technology based effluent limits (TBEL), water quality-based effluent limits (WQBEL), total maximum daily load limits (TMDL derived), interim limits, s.217.14 mass limits, and adaptive management interim limits (WDNR 2020). Of these limits, TBELs and WQBELs are the relevant limits for understanding the context of our study. TBELs have been in place since 1993. Their intent is to require a minimum level of wastewater treatment for point source dischargers of phosphorus (industrial dischargers of more than 60 pounds of total phosphorus per

[6] The rules became effective on December 1, 2010.
[7] The CWA grants states the authority to establish these alternative compliance options.

month or municipal dischargers[8] of more than 150 pounds of total phosphorus per month). Most state environmental protection agencies, including WDNR, typically set TBELs at 1.0 mg/L and point sources can attain them with secondary, or biological, treatment technology. In contrast, a WQBEL is based on the quality of the waterbody receiving the discharge. Wisconsin statute requires a WQBEL any time a point source discharger has the potential to cause total phosphorus concentrations to exceed NR102 criteria in the receiving or downstream waterbody (WDNR 2020). Whenever the receiving waterbody has a total phosphorus concentration exceeding the relevant NR102 criterion, WDNR sets the WQBEL at the level of the applicable total phosphorus criterion.

### 2.2. Complying with Wisconsin's phosphorus rule

Because of Wisconsin's 2010 phosphorus regulations, many point sources in the state experienced drastic changes in their total phosphorus discharge limit from 1.0 mg/L to 0.075 mg/L. These point sources discharge to streams and rivers that do not meet the relevant NR102 criterion and WDNR consequently considers them impaired.

In general, NR217 provides three options for point source dischargers to comply with the new total phosphorus effluent limits. The first option is to upgrade their wastewater treatment technology. WDNR (2020) considers limits less than 0.3 mg/L as "stringent" limits that require tertiary, or filtration, treatment technology to attain.[9] The second compliance option is through water pollution offset trading. Here, point sources offset their pollutant load by reducing phosphorus pollution elsewhere in the watershed. The third option is through adaptive management, which is like water pollution offset trading in that it allows a point source to reduce phosphorus pollution elsewhere in the watershed. As part of adaptive management, the permitted point source must work with other point and nonpoint sources to reduce the total phosphorus load and demonstrate improvement in water quality.[10] Point sources that comply with the phosphorus rule via adaptive management are subject to interim total phosphorus limits (0.6 mg/L in the first

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[8] The NPDES program distinguishes between industrial and municipal dischargers. Industrial dischargers are typically those that produce a marketable product, while municipal dischargers are typically publicly or investor owned wastewater treatment plants.

[9] Before the change in standards, point sources could comply with TBELs using only secondary, or biological, treatment technology or through chemical phosphorus removal. To comply with the new WQBEL, point sources must use tertiary treatment technology, which are filtration systems. These systems provide additional chemical and filtering treatment, primarily using sand or some other catalyst to remove phosphates and nitrates from the wastewater. We discuss the costs of tertiary treatment technology upgrades at facilities in our sample below.

[10] An adaptive management plan is generally only an option if the nonpoint source contribution to the total phosphorus load is greater than 50%.

permit term and 0.5 mg/L in the second-fourth terms).[11] We collectively refer to water pollution offset trading and adaptive management as water pollution offset trading. In rare cases, point source dischargers may request an individual variance if all compliance options are too costly and would result in an economic hardship for an industry or community. EPA must grant approval for WDNR to authorize a variance.

As part of the statutes and the administration of the state's NPDES program, WDNR gives point sources a relatively flexible compliance schedule. First, WDNR requires facility level reports three years following the first NPDES permit reissuance of each facility that faces a total phosphorus WQBEL after the promulgation of the 2010 laws. (For example, consider a NPDES permit holder whose active permit, at the time of the 2010 phosphorus rule, expired on April 1, 2012. As part of its new NPDES permit, WDNR would require that the facility develop a third-year report by April 1, 2015.) The third-year report, also called the preliminary compliance alternatives plan, outlines the potential options for the point source to comply with the phosphorus rule. These plans, which environmental engineering consultants generally produce, contain a list of the facility's phosphorus rule compliance options and their associated costs. For example, a single compliance alternatives plan can include cost estimates for water pollution offset trading,[12] treatment technology upgrades, plans for a new discharge location, plans to combine with another point source (i.e., regionalization), or any other option that allows the point source to comply with the phosphorus rule. Many of these plans also contain a compliance option recommendation, based almost exclusively on the least cost compliance option.

The final compliance alternatives plan, also known as the fourth-year-report, is due four years after the first NPDES permit reissuance following the promulgation of the 2010 phosphorus rule. For point sources that comply with the phosphorus rule through water pollution offset trading, the fourth-year reports lay out the facility's chosen path for compliance. For these facilities, WDNR refers to the fourth-year report as the water pollution offset trading or adaptive management plan. The report contains the full, final plan for complying with Wisconsin's

[11] Complying with these interim adaptive management limits could require capital investments for some facilities (WDNR 2020). NR217 allows firms to combine capital upgrades or process optimization with water pollution offset trading or adaptive management to achieve the necessary phosphorus effluent reductions. However, the only way to meet the 0.075 mg/L criterion using solely a technological solution is with the installation of a costly tertiary filtration system.

[12] Oftentimes, these plans include the types of trades available, their locations, and their costs. However, some compliance alternative plans include only an average cost of each pound of phosphorus reduced through trading.

phosphorous rule through the water pollution offset trading option, which includes the necessary total phosphorus load reductions, trading partners, locations and types of trades, e.g., agricultural BMPs, and the applicable trading ratios and offset credits.[13] For facilities that comply via tertiary treatment technology upgrade, the fourth-year reports must include a final engineering design report and facility plan. Finally, five years after the first NPDES permit reissuance following the promulgation of the 2010 phosphorus rule, WDNR reissues the next permit for the second term following rule promulgation. This second term permit contains the approved compliance schedule.

### 2.3. Municipal sewer utilities in Wisconsin

The Public Service Commission of Wisconsin (PSCW) regulates all water utilities (i.e., those providing drinking water) in the state. However, under Wisconsin statute, municipal sewer systems do not fall within the definition of public utility (Wis. Statute § 196.015). Therefore, the PSCW does not regulate sewer utility rates; sewer utilities set their own rates and self-determine rules, service quality, and plant additions/upgrades (PSCW 2021).[14] In Wisconsin, there are more than 600 sewer utilities. Importantly, of the roughly 600 sewer utilities in the state, nearly all are publicly owned municipal facilities, rather than investor owned.[15] As a result, the facilities that we examine are not profit maximizing companies. Sewer utilities in Wisconsin are therefore responsible only for wastewater treatment, not to generate profits or provide return on investment for shareholders.

## 3. The effect of Wisconsin's phosphorus rule on sewer utility customers

Given these institutional details on Wisconsin's phosphorus rule, we next turn to our analysis of the compliance cost pass-through of the rule, by estimating how it affects real sewer utility billing rates. We focus our analysis on municipal source (rather than industrial source) dischargers and real sewer utility billing rates for several reasons. First, product prices for industrial source dischargers in Wisconsin are highly regulated, e.g., dairy markets, or in disparate markets, e.g., plastics manufacturing, aquaponics, so isolating the effects of the phosphorus rule on output prices

[13] WDNR is very flexible in the types of offset practices that it approves as part of the program. If the trades provide additionality and result in the required reduction in pollutant loadings to surface waterbodies (as measured by WDNR's integrated assessment model), WDNR approves of the trade. Table 4 contains a list of the practices that WDNR has approved as part of the program.

[14] Two sewer utilities in Wisconsin have voluntarily elected to combine water and sewer operations into a single public utility (Tigerton and Shawano); these are the only two sewer systems currently regulated by the PSC. We therefore eliminate these sewer utilities from our final analysis sample.

[15] The only investor owned water utility in Wisconsin is Superior Water, Power, and Light Company. We do not include this sewer utility in our final analysis sample.

is more difficult in these markets. Second, no single source contains historical output price data for industrial source dischargers. Third, the price of municipal sewer services is largely dependent on treatment costs. The price of final outputs for industrial sources depends on several, more difficult to quantify, factors, namely input costs. As a result, we can better isolate the effect of phosphorus rule compliance on product prices for municipal, rather than industrial, point sources.

### 3.1 Data

To construct our analysis sample, we first gather NPDES permit data for all municipal point sources in Wisconsin from 2001 to 2019. Importantly, EPA's ECHO database contains the effective and expiration dates of each municipal source's NPDES permit. The ECHO data also include information about each facility, such as its size and major/minor status. From the permit dates and the NR102 and NR217 statutory language, we identify the treated group. We define the treatment date as five years after the first post-December 1, 2010 permit reissuance, consistent with the date in which treatment facilities fully understand expected compliance costs and have approved compliance plans. Next, we gather compliance option (water pollution offset trading or treatment technology upgrade) and water pollution offset trading information from the third- and fourth-year reports, respectively, that point sources regulated under the phosphorus rule submit to WDNR. These plans therefore identify the treated group, i.e., the municipal sources that eventually must comply with the phosphorus rule.

As our final data source, we obtain propriety data on sewer utility billing rates from MSA Professional Services. In Wisconsin, some sewer utilities list their user rates on their websites, but in general, there is no publicly available data source that comprehensively tracks sewer utility rates in the state. Every three years, MSA surveys all sewer utilities in Wisconsin to inquire about rate information. In addition, MSA asks respondents questions about other utility and facility level information, such as treatment technology presence, plant capacity, sludge processing methods, and the number of customers that the utility serves.[16] Sewer utilities report their current rates as well as the date that the sewer rate last changed. We use this information to create an annual time series of sewer rates for each utility in the database.[17] Sewer utility billing rates typically have fixed and variable (volume based) components. Some sewer utilities use only fixed charges with

[16] From MSA, we obtain survey data from 2001, 2004, 2007, 2010, 2013, 2016, and 2019.

[17] Based on conversations with MSA personnel, it would be extremely uncommon for sewer utilities to change rates more than one time in a three-year period. We are therefore confident that we accurately measure annual sewer rates using the MSA data.

no volume charge and some use only volume charges with no fixed component. Furthermore, sewer utilities can bill at different frequencies (monthly, quarterly, semi-monthly, or annually). We therefore use MSA's standardized annual rates, which they calculate for a "typical" residential household using 55,000 gallons of water per year. We focus our analysis of sewer utility billing rates on residential, rather than industrial or commercial, users and normalize all rates to real 2020$.

We then match all sewer utilities from the MSA dataset to their corresponding NPDES permits. For facilities "treated" by the phosphorus rule (based on the quality of the waterbody receiving their discharges and their NPDES permit reissuance date), we also merge the relevant information from their third- and fourth-year reports submitted to WDNR. As such, we build an annual balanced panel of surveyed municipal sewer utilities, covering the time-period of 2001-2019.

Finally, we present sample summary statistics. Table 1 presents the statistical summaries for the entire sample. In our analysis sample, the average real annual sewer utility billing charge (55,000 gallons) for all utilities is $474.28. Roughly 8% of observations come from facilities in the treatment group.

### 3.2. Empirical approach

To identify the causal effect of Wisconsin's phosphorus rule on residential sewer utility billing rates, we use a DD research design. We estimate the following two-way fixed effects (TWFE) regression specification:

$$ln(Y_{ict}) = \beta Comply_{ict} + \delta_i + \mu_t + \varepsilon_{ict}, \quad (1)$$

where $ln(Y_{icdmt})$ represents the log-transformed annual sewer utility billing rate, normalized to 2020$, for municipal point source $i$ located in county $c$ in year $t$. Here, we log transform the outcome for two reasons: 1) to normalize the wide ranging and leftward skewed distribution of the outcome and 2) to facilitate interpretation of the independent variables in percentage terms, which is more appropriate than levels for heterogeneous municipal sources. Next, $Comply_{ict}$ is the DD indicator, which identifies treated time periods for the treatment group—municipal sources that must comply with the phosphorus rule because they discharge to a waterbody that does not meet the relevant NR102 criterion and are five or more years past their post-December 1, 2010 NPDES permit reissuance date.[18] $\beta$ is therefore the coefficient of interest and represents the effect of

[18] Our treatment does not necessarily indicate that the municipal source has installed tertiary treatment technology or

phosphorus rule compliance on real municipal sewer utility billing rates for the treated group. In our primary specification, the control group consists of three groups of sewer utilities: 1) those that must eventually comply with the phosphorus rule but have not yet reached five years after their post-December 1, 2010 NPDES permit reissuance date, 2) those that comply with the phosphorus rule through an individual variance, and 3) those that are not subject to the phosphorus rule at all (now or in the future), because the waterbody receiving the point source's discharges meets the relevant NR102 criterion and WDNR therefore does not consider it impaired.[19] It is possible, however, that sewer utilities in groups 2) and 3) are not good comparisons for treated facilities, because they are not subject to high compliance costs (of water pollution offset trading or treatment technology upgrade) or they are located in areas with acceptable water quality. As a result, we also estimate a specification where we exclude groups 2) and 3) from the analysis sample. For this specification, we therefore identify the effects of treatment based only on timing, because every sewer utility in the sample will eventually be treated. Next, $\delta_i$ represents facility fixed effects, which control for time invariant characteristics of each sewer utility, such as sewer utility class. Facility fixed effects also control for the time invariant characteristics of the facility's watershed, such as its location in the watershed (e.g., at the top or bottom) or the number of river and stream miles surrounding the facility (which are important factors for facilitating water pollution offset trades). We capture common trends in sewer utility billing rates with year fixed effects, $\mu_t$. Finally, $\varepsilon_{ict}$ is the exogenous error term. We cluster standard errors at the facility level, which is the level of identifying variation.

When estimating TWFE specifications such as ours, $\beta$ above represents the DD coefficient. Assuming several conditions, such as plausibly exogenous treatment assignment, researchers traditionally consider the $\beta$ coefficient to identify a causal relationship between the treatment and the outcome for the treated group. However, recent work demonstrates that TWFE regressions may not recover causal parameters of interest when there are more than two time periods and units are treated at different times. This empirical setting can particularly lead to bias when there are heterogeneous treatment effects across units or when treatment effects are dynamic (de

begun offset trading as of that date, only that they have begun their new permit requiring compliance and are fully aware of their estimated compliance costs. Ours is a reasonable treatment definition, as sewer utility billing rate changes can occur based on expected changes in costs of service provision.

[19] Of course, these facilities may eventually be treated by the phosphorus rule if the quality of the receiving waterbody deteriorates over time.

Chaisemartin and D'Haultfoeuille 2020; Borusyak et al. 2021; Callaway and Sant'Anna 2021; Goodman-Bacon 2021; Sun and Abraham 2021; Roth et al. 2022). Roth et al. (2022) review several related classes of alternative estimators. One class, which resembles the proposal of Borusyak et al. (2021), is sometimes termed an imputation estimator.[20] Appropriate for applications such as ours, where treatment is an absorbing state so that once a unit is treated it remains treated for the duration of the panel, the imputation estimators use a two-step process. In the first step, one fits a TWFE regression on not-yet-treated units and time periods. Then, in a second step, one predicts never-treated counterfactual outcomes, which the researcher uses to infer treatment effects for each unit, and then aggregates to produce average parameter estimates. In addition to estimating equation (1), we also employ this two-stage process to account for potential bias in our TWFE estimates. Specifically, we follow the methods of Gardner (2021).[21]

### 3.3. Primary estimation results

Table 2 presents the results for the estimation of equation (1). We provide in Table 2 several sets of estimation results, to assess the robustness of our primary results. The first column contains results from our baseline estimation of equation (1). The second column presents estimation results where we identify treatment based only on timing. Here, we exclude from the control group sewer utilities that comply with Wisconsin's phosphorus rule via an individual variance and sewer utilities that are never subject to the phosphorus rule. The third column contains results for a specification that includes year-by-county fixed effects, which control for potential differential political trends or trends in other unobserved characteristics of each municipal sewer utility's county that could affect real sewer utility billing rates. Finally, the fourth column presents results from the Gardner (2021) two-stage DD approach.

Estimation results for all specifications are quantitatively and qualitatively similar. The value of the $\beta$ coefficient lies between 0.0756 and 0.106 for all specifications. These values suggest that complying with the phosphorus rule increases real sewer utility billing rates by 8-11% as compared to municipal sources that have not yet faced more stringent phosphorus standards.[22] In the baseline specification, this increase is approximately 10.3%. To put this value into context, the average annual real sewer utility billing rate in our analysis sample is $474.28 per customer.

[20] Roth et al. (2022) group together proposals by Borusyak et al. (2021), Gardner (2021), Liu et al (2021), and Wooldridge (2021) into this class of imputation estimators.
[21] The "did2s" Stata package (Butts 2021) implements the methods of Gardner (2021).
[22] We calculate all relevant marginal effects in percentage terms as $\exp(\hat{\beta})$-1.

Therefore, the average municipal sewer utility affected by the phosphorus rule increases its real rates by $48.85 per customer per year compared to those municipal sources that are not bound by the revised phosphorus standards.

In our setting, the potential bias of the standard TWFE estimate is likely lower than in many generalized DD settings. As described in Roth's (2022) recent review of the literature, the standard TWFE estimator produces biased estimates primarily when different units are treated at different times and there is heterogeneity in treatment effects over time.[23] However, treatment in our setting is largely lumped toward the latter portion of our sample. No municipal sewer utilities are treated until at least five years after the promulgation of Wisconsin's phosphorus rule on December 1, 2010. As a result, our empirical framework more closely resembles a 2x2 fixed effects model than a setting where treatment occurs throughout the panel. Our TWFE and Gardner two-stage DD estimation results, which are nearly identical, confirm this structure. When discussing our estimation results, we therefore focus on the TWFE estimates from our baseline specification.

Our estimation results present evidence that the costs of compliance for strict total phosphorus limits in Wisconsin are at least partially passed through to end users in the form of higher real sewer utility billing rates. We next examine the incidence of the pass-through of these compliance costs by simulating additional sewer utility revenues from phosphorus rule compliance and comparing these to the estimated annual compliance costs (either trading costs or abatement technology costs) reported on the third- and fourth-year reports. It is preferable to use these utility-specific costs rather than a statewide average because phosphorus rule compliance costs, for both the treatment technology upgrade and water pollution offset trading options, are different for each facility. The abatement technology costs depend largely on the size of the facility, while the water pollution offset trading costs depend on the required number of offset practices and the specific types of practices implemented.[24]

Specifically, we estimate incidence using the following procedure. First, we use the estimated marginal effect from our baseline regression, which we show above to be 10.3%. We then multiply this estimated marginal effect by the average pre-treatment real sewer utility bill at

[23] This bias relates to the insight in Goodman-Bacon (2021) that negative weighting of 2x2 treatment effects arises when already-treated units serve as controls. It is this negative weighting that can bias the TWFE estimate away from the true treatment effect of interest.

[24] As examples, streambank stabilization projects and the installation of cover crops have largely different costs for the municipal source. In this way, the compliance costs are not like a set tax, which much of the incidence literature examines.

each treated facility in our sample to find the estimated per customer dollar value of the increase in sewer utility rate. Next, we multiply this estimated dollar increase in the average sewer utility bill by the number of customers at each treated facility to find the total additional residential revenue collected at each sewer utility. Then, we divide the estimated additional annual revenue by the estimated annual compliance costs of the phosphorus rule and multiply by 100 to convert to a percentage. From this distribution, we find that the median facility passes through approximately 74% of the additional compliance costs from the phosphorus rule to customer sewer utility bills.

Previous work finds that stringent air pollution regulation results in pass-through of compliance costs to electric utility customers of between 60% and 100% (Sijm et al. 2006; Fabra and Reguant 2014; Hintermann 2016; Krumholz 2019). Our estimate of the pass-through of Wisconsin's phosphorus rule is in the range of these values, but toward the lower end. While 74% pass-through is substantial, it may be surprising that the value is less than 100%, especially considering the unregulated nature of sewer utilities in Wisconsin and the relatively inelastic demand of residential sewer utility users. We interpret this value in several ways. First, the average cost of a treatment technology upgrade is based on engineering estimates calculated before construction has begun. It is possible that some sewer utilities do not completely factor in the costs of compliance until they actually incur the costs or their ex ante estimates are low. In addition, treatment technology upgrades take several years to complete and sewer utilities often pay for the upgrades via loans with long time horizons. Complete rate adjustments may roll out slowly over time, rather than all at once after an initial compliance plan date.[25] Second, previous research suggests that there exists some inefficiency in the operations of Wisconsin sewer utilities prior to the 2010 phosphorus rule. Aubert and Reynaud (2005) find that the average Wisconsin sewer utility from 1998 to 2000 had costs that were 13% higher than the cost of a fully efficient sewer utility on the cost frontier. It is therefore possible that sewer utilities partially offset increased treatment technology costs with improved efficiency elsewhere. Finally, discussions with MSA personnel and PSCW employees suggest that sewer utilities are apprehensive to raise rates for political concerns, so they may limit how fast they pass through phosphorus rule compliance costs

[25] Alternatively, a staggered rate increase rollout may be preferable for sewer utility managers who are concerned with public reaction to rate increases. Unfortunately, the post period of our observational data is unable to witness these behaviors.

to consumers.

**3.4. Event study**

We also re-estimate equation (1) using an event study specification. One of our key identifying assumptions is that of parallel trends in the outcome between the treatment and control groups. Although this assumption is fundamentally untestable, we present an event study to primarily examine the pre-treatment trends in the outcomes between the two groups. Differences in these trends before treatment cast doubt on our identification. Additionally, the event study allows us to examine how the average effects presented in Table 2 change over time in the post-treatment period.

Figure 1 provides estimation results for the event study. Most importantly, Figure 1 presents empirical evidence supporting the parallel trends assumption and our identification. The figure shows no evidence of pre-treatment trends in real sewer utility billing rates between municipal sewer utilities that are subject to the phosphorus rule and those that are not subject to the rule; the pre-treatment differences in the outcomes between the groups are close to zero and statistically insignificant. In the post-treatment period, the event study shows that the treatment effects that we identify do not occur right away, but rather after two or more years. As before, we interpret these increasing post-treatment effects to suggest that municipal sewer utilities likely increase their real rates once they begin to accrue the necessary phosphorus rule compliance costs, rather than when the utilities become aware of impending costs.

**3.5. Robustness and heterogeneous treatment effects**

In this subsection, we assess the robustness of our results to changes in model specification and examine treatment effect heterogeneity. First, we re-estimate equation (1) using a falsified treatment dummy. Here, we change our treatment measure to indicate lagged phosphorus rule compliance, where we falsify the date that treatment begins to each facility's last active permit before Wisconsin's phosphorus rule went into effect in 2010. We examine this specification to further assess the causal nature of our estimated effects. Clearly, sewer utilities would not have changed their billing rates to comply with the phosphorus rule before the statutes existed. Therefore, the presence of falsified treatment effects likely implies that our model is misspecified. Column 1 of Table 3 presents results for this re-estimation of equation (1). As expected, the falsified treatment effects are precisely zero and statistically insignificant, which lends further support to our identification. As a second robustness check, we re-estimate equation (1) using a daily, rather than yearly, panel. Although most sewer utilities set their rates as of January 1 each year, it is possible for utilities to adjust their rates in the middle of the year. MSA survey data contain the effective date of each sewer utility billing rate. Additionally, ECHO's NPDES permit dates are also at the daily level. Like for our yearly sample, we create a balanced from 2001 to 2019, but now at the daily level. This new analysis sample allows treatment status to change mid-year. Column 2 of Table 3 presents results that are nearly identical to those of our primary specification. We therefore conclude that results are robust to the temporal unit of our analysis sample.

Next, we examine treatment effect heterogeneity along three dimensions: 1) facility size, 2) population of the surrounding municipality, and 3) median income of the surrounding municipality. For each case, we re-estimate equation (1), where we interact the heterogeneous element with our primary definition of treatment.

First, we examine heterogeneous treatment effects by the design capacity (size) of each sewer utility, measured in millions of gallons per day (MGD). The third column of Table 3 presents results for this estimation. The median facility size in our sample is 0.18 MGD, so the primary coefficient approximately represents the effects of complying with the phosphorus rule on real sewer utility billing rates for the smaller facilities in our sample. Therefore, for facilities with low design capacity, the pass-through effect is on the smaller range of those values presented in Table 2 for the full analysis sample. The interaction between the treatment dummy and the facility size measure is significant and positive, meaning that the larger sewer utilities pass through their phosphorus rule compliance costs to end users at a higher rate than the smaller utilities. However, the magnitude of the differential effect is small. Adding one million gallons per day increases the marginal effect by only 0.2%. But the differences become noticeable when looking at increasingly larger facilities. To put these marginal effects into greater context, consider a specific example for a large facility whose design capacity is 10 MGD. For this facility, the marginal effect considerably changes ($\hat{\beta}$=0.0822) and is statistically significant (p=0.004). These results suggest that treatment effects are heterogeneous along size, but primarily on the righthand side of the size distribution. We hypothesize that these heterogeneous treatment effects are the result of two forces. First is political pressure. Although Wisconsin does not regulate sewer systems as public utilities, there is still strong political pressure to keep rates down, especially considering the relatively inelastic demand of sewer utility services. Additionally, smaller sewer utilities typically service small, rural municipalities, where incomes are lower. As a result, sewer utility rate increases at smaller facilities are more regressive. Larger facilities therefore have a greater ability to pass through the costs of water pollution regulation than smaller facilities, because the increase in sewer utility bills for customers is typically a smaller percentage of their overall budget. Second, the costs of complying with Wisconsin's phosphorus rule are directly related to the size of the facility. For facilities that comply with the rule using either option, but particularly those that comply via treatment technology upgrade, the abatement costs are much higher for large sewer systems. To afford such expensive abatement options, larger facilities therefore need to pass through costs to sewer utility users more than smaller facilities.

Next, we examine treatment effect heterogeneity by the population of the surrounding municipality. The exercise here is like that of examining treatment effect heterogeneity by the design capacity of the facility, but we now focus on the size of the sewer utility as measured by the number of customers it services. Column 4 of Table 3 shows the results for this heterogeneity analysis. As before, we find heterogeneous treatment effects along this dimension. Increasing municipality population by 10,000 residents increases the estimated marginal effect by approximately 0.62%. Our results therefore suggest that pass-through is higher for larger sewer utilities (by customers served). The treatment effect heterogeneity that we find along this dimension likely occurs because of reasons like those listed above. Urban sewer utilities that service many customers face less political pressure to keep rates down and their phosphorus rule compliance costs are much higher than rural sewer utilities that service few customers. Therefore, sewer utilities that service more customers pass through phosphorus rule compliance costs at a higher rate than utilities that service few customers.

Finally, the fifth column of Table 3 presents heterogeneous treatment effects by real median income of the surrounding municipality (in 2020$). For our analysis, we interact the primary DD indicator with a dummy that indicates if the median income of the municipality serviced by the sewer utility is less than the median value for this measure in our sample ($59,941). Estimation results show that sewer utilities serving above median income municipalities increase real sewer utility billing rates by approximately 13.9% when they are treated by the phosphorus rule. Interestingly, the treatment effect is significantly smaller for sewer utilities serving below median income municipalities. The estimated marginal effect for below-median income municipalities declines to approximately 3.8%. These results further confirm that political pressure to not raise sewer utility rates because of their regressive nature in lower income, rural areas leads to less pass-through in these areas than in higher income, urban areas.

## 4. Water pollution offset trading in the US and Wisconsin

Given our finding that Wisconsin's phosphorus rule significantly increases real sewer utility billing rates, the next important question is whether the estimated rate increases differ by compliance option. Namely, we are interested in whether water pollution offset trading programs, which decrease compliance costs for point sources relative to installing new treatment technology at these utilities, also empirically deliver theoretical savings to sewer utility customers. In this section, we therefore first discuss water pollution offset trading programs in the US, while summarizing the associated challenges of these programs documented in the literature to date.[26] We then provide more information about Wisconsin's water pollution offset trading program in the context of the phosphorus rule, including a descriptive analysis of the program. Finally, we empirically test for heterogeneity in the pass-through of the phosphorus rule between treatment technology upgrade and water pollution offset trading compliance options.

### 4.1. Water pollution offset trading in the US

The Clean Water Act (CWA) requires states to regulate point sources by issuing permits that correspond with effluent limits set by the NPDES program. These limits vary by pollutant and depend on available wastewater treatment technologies. According to the CWA, states must develop water quality standards and assess surface waterbodies within their borders. Many waterbodies do not meet ambient water quality standards for their designated use(s), largely due to nonpoint source agricultural and urban runoff. Section 303(d) of the CWA requires states to list specific waterbody segments that do not meet their designated use(s) as impaired. States must then develop Total Maximum Daily Loads (TMDLs) for waters on the 303(d) "impaired list". A TMDL determines the maximum amount of a pollutant that a waterbody can assimilate without violating water quality standards. TMDLs allocate the allowable load among point sources, nonpoint sources, and a margin of safety.

As noted by Fisher-Vanden and Olmstead (2013), "in almost all water quality trading programs established in the United States, the regulatory driver has been the establishment (or

[26] Fisher-Vanden and Olmstead (2013) provide a detailed overview of water pollution offset trading programs and the related literature. We base much of this section on their review. Stephenson and Shabman (2017) and Shortle (2021) also provide recent reviews of water pollution offset trading programs and the associated literature.

anticipated establishment) of a [TMDL].” TMDLs must inventory point and nonpoint pollution sources. While TMDLs are the impetus for water pollution offset trading programs throughout much of the US, the CWA also allows individual states to establish trading programs that can help point sources achieve compliance with their NPDES permit. As a result, water pollution offset trading can occur in both impaired and unimpaired watersheds.

Although point sources face discharge limits through the NDPES permitting process, water pollution from agricultural sources is largely exempt from CWA regulations. Therefore, regulators have realized that programs to reduce agricultural runoff are important for achieving any substantial improvements in water quality (Olmstead 2010; Fisher-Vanden and Olmstead 2013). Moreover, marginal abatement costs for nonpoint sources are typically low compared to those for point sources.[27] Thus, the largest scope for water pollution offset trading is between point sources with high marginal abatement costs and the largely unregulated nonpoint sources.

In 2003, EPA finalized its water pollution offset trading policy (EPA 2003), although it had been working on draft frameworks since the 1990s (Fisher-Vanden and Olmstead 2013). Fisher-Vanden and Olmstead (2013) highlight two important aspects of the 2003 EPA water pollution offset trading policy: 1) if a TMDL has been created, all trading must occur within the watershed or defined area of the TMDL and 2) the policy generally supports trading of nutrients and sediment, but trading other pollutants needs prior approval. Trading is intended to facilitate a source’s effort to attain additional restrictions from the TMDL.

Although growing, water pollution offset trading programs are relatively new and limited in number. Fisher-Vanden and Olmstead (2013) describe 21 active and pilot programs; 18 of the 21 listed trading programs are in the US. Stephenson and Shabman (2017) and Shortle et al. (2021) list 26 active trading programs in the US, while Selman et al. (2009) identify nearly 60 active trading or offset programs using a wider definition of qualifying programs. Most of these trading programs have a rather small number of market participants. In summary, trading markets are less common and thinner than is optimal.

Fisher-Vanden and Olmstead (2013) identify two classes of factors limiting the success of water pollution offset trading programs. The first class of challenges relates to spatial issues inherent in water pollution. Unlike uniformly mixed air pollutants, damages from water pollution

[27] There are some exceptions. For example, Stephenson et al. (2010) discuss the comparatively high marginal abatement costs for nonpoint sources of nitrogen in Virginia.

are often heterogeneous based on the discharging location and are more likely to result in pollution "hotspots", making water pollution a more localized problem than air pollution (Doyle et al. 2014).[28] This problem has technical and theoretical solutions such as spatial trading ratios, where policymakers establish exchange rates to reflect varying damages across reductions in different locations (Rodriguez 2000; Fisher-Vanden and Olmstead 2013).[29] A perhaps more fundamental spatial challenge is that water pollution offset trading must occur within a watershed or area defined by a TMDL. This spatial requirement means that many watersheds are limited to few potential trading partners and the scope of efficiency gains is smaller than with a larger geographic area. The second class of challenges relates to the de facto exclusion of agricultural nonpoint sources from CWA regulations. This implicit right to pollute limits the extent of water quality improvements possible through trading since point sources have become relatively small contributors to the overall pollutant load (Fisher-Vanden and Olmstead 2013).

Another related spatial challenge is modeling and monitoring pollution reductions from nonpoint sources; there is significant uncertainty in the effectiveness of abatement practices from these sources. Difficulties in establishing baseline pollution levels for nonpoint sources raise concerns about the additionality of credited pollution reductions (Ribaudo and Savage 2014; Ribaudo et al. 2014; Shortle et al. 2021).

Multiple case studies document the institutional challenges of water pollution offset trading programs.[30] Woodward (2003) examines the factors that impeded trades in the Lake Dillon Reservoir in Colorado. Jarvie and Solomon (1998) review similar difficulties in the earliest example of water pollution trading in Wisconsin's Fox River program. One barrier cited in these case studies is high transaction costs. DeBoe and Stephenson (2016) quantify transaction costs for a trading program in Virginia and find relatively low costs for land conversion projects but predict high costs for an expanded program that allows credits for agricultural BMPs.

### 4.2 Wisconsin's water pollution offset trading program

Next, we discuss the implementation of WDNR's water pollution offset trading program. As

[28] Of course, water pollution can also pose a problem on a larger scale, as evidenced by nutrient pollution throughout the Midwest contributing to the dead zone in the Gulf of Mexico.

[29] Spatial restrictions on trade exist in other markets as well, such as in North Carolina under the US flue-cured tobacco program (Rucker et al. 1995); these restrictions result in similar problems as those of water quality markets.

[30] For two example programs that generated comparatively higher amounts of trading, see Fang et al. (2005) and Newburn and Woodward (2012). A related experimental literature also considers design issues of water quality markets (e.g., Suter et al. 2013; Jones and Vossler 2014).

discussed, although EPA and many state environmental protection agencies promote water pollution offset trading programs to cost-effectively improve water quality (e.g., EPA 2019), there exist few programs in the US where trades occur, for many reasons, e.g., high transaction costs. However, Wisconsin's adoption of strict total phosphorus WQBEL presents point sources in the state with a better opportunity to participate in such programs because the cost of traditional compliance options is prohibitive (tertiary treatment technology upgrade) or the compliance options are ineffective at meeting a WQBEL (chemical treatment). As such, our examination of the Wisconsin program enables us to analyze observational data on the program that do not exist in other contexts.

We scrape from the facility level third- and fourth-year reports descriptive information on WDNR's water pollution offset trading program. From the third-year (and some fourth-year) reports, we collect the compliance option cost data, particularly for the tertiary treatment technology upgrade option. From the fourth-year reports, we collect information on the offset practices that nonpoint sources implement as part of the program. Finally, we receive directly from WDNR a list of the facilities whose final compliance option is a tertiary treatment technology upgrade.

In the state, 63 water pollution offset trading or adaptive management agreements are part of the program; Figure 2 maps the location of the point sources engaged in these agreements. (These facilities include all facilities that participate in trading, not just the municipal sewer utilities in our primary analysis sample.) Table 4 provides an overview of the practices that affected point sources use to offset total phosphorus discharges as part of WDNR's program. Panel A presents agricultural practices, which point sources typically use as the low marginal abatement cost practices as part of trading programs. Panel A shows that point sources trade offsets as part of the program using many agricultural practices. Most common is the conversion of farmland to permanent vegetative cover (i.e., grassland); this practice is a part of roughly a third of the trades that occur as part of Wisconsin's program. The frequency with which point sources participate in the conversion of farmland to permanent vegetative cover is likely a result of the sizable ex ante total phosphorus loading reductions achieved through this practice. As a result, the acreage requirements for large decreases in total phosphorus loadings when using permanent vegetative cover are low. Point sources can therefore achieve sizable offsets with minimal trades or cropland conversion. Point sources also frequently pay for the use of vegetative buffers/filter strips and cover crops to offset their discharges as part of the program. As Panel A of Table 4 shows, the land requirements for these BMPs are higher than for permanent vegetative cover, because the former practices do not prevent runoff as well as the latter.

Panel B of Table 4 presents information on the urban or other practices that point sources use to offset their total phosphorus discharges as part of the program. Most popular are streambank stabilization practices, followed by stormwater management at the point source. We hypothesize that streambank stabilization practices are common because of the ease and availability of implementing the practice. Although not all point sources that must comply with Wisconsin's phosphorus rule can participate in agricultural offset practices (e.g., urban point sources), many can stabilize streambanks because streams and rivers are ubiquitous in Wisconsin. However, streambank stabilization practices can be costly, so it is possible that point sources do not engage in this practice in favor of others.

Next, Table 5 provides summaries of the key components of the WDNR program's offset agreements. Of the nonpoint source offset agreements, nearly 70% represent water pollution offset trading, while the remaining 30% are adaptive managements plans. Perhaps most important for the point sources, the compliance costs of water pollution offset trading, compared to a tertiary treatment technology upgrade, are low. For the average facility that complies with the phosphorus rule through water pollution offset trading, the yearly cost of the practices is $93,800. For these same facilities, the average yearly cost of compliance via a tertiary treatment technology upgrade is $372,000.[31] Therefore, the program results in cost savings for point sources that comply with Wisconsin's phosphorus rule through water pollution offset trading (rather than through a tertiary treatment technology upgrade) of roughly $17.5 million annually throughout the state.

In addition, WDNR's program requires that any water pollution offset trading plan must result in water quality improvements. The expected total phosphorus discharge reductions and offset credits represent this potential water quality improvement. The average water pollution offset trading agreement within the program results in an ex ante decrease of 1,101 pounds of total phosphorus discharges from nonpoint sources. For these decreases, the average point source earns 456 pounds of offset credits, which is the amount that the point source must decrease its pollutant

[31] In their guide to water pollution offset trading, WDNR recommends beginning the negotiations for nonpoint source offsets using the Environmental Quality Improvement Program prices plus some additional costs for legal and administrative work. We therefore estimate compliance costs as 150% of the 2020 EQIP price for each practice. For treatment technology upgrade costs, we use the engineering estimates from the third-year reports.

load by to comply with the rule. These values represent an average trading ratio of 2.4:1.[32] Table 5 also presents descriptive information about the point sources that engage in water pollution offset trading through WDNR's program. EPA classifies 30% of the participants in the program as major facilities, which is how EPA distinguishes NPDES permitted facilities by size and polluting impact.[33] Additionally, nearly 75% of the point sources that engage in water pollution offset trading are municipal dischargers, likely because all municipal sources have total phosphorus discharges and limits, while many industrial dischargers in the state do not.

Finally, Table 6 presents similar descriptive information about the municipal sewer utilities that must comply with the phosphorus rule through water pollution offset trading or treatment technology upgrade. These facilities therefore represent those that are part of our sewer utility billing rate analysis sample and are treated at some point during the sample period. Of these facilities, 42% participate in water pollution offset trading, 26% in participate in adaptive management, and the remaining 44% achieve compliance with the phosphorus rule via a tertiary treatment technology upgrade. For this sample, the average annual water pollution offset trading cost is $125,000 and the average annual treatment technology upgrade cost is $461,000. The cost savings of offset trading relative to treatment technology upgrade are therefore higher for sewer utilities in our sample than for all point sources that participate in trading through WDNR's program. This difference suggests that municipal sewer utilities can save more money through trading that other point sources.

### 4.3. Heterogeneity by compliance option

In this subsection, we examine the effect of municipal source dischargers' phosphorus rule compliance option on real sewer utility billing rates. As described, Wisconsin's phosphorus rule imposes sizable costs on point sources that discharge to waterbodies with poor ambient water quality. To meet the stringent standards, point sources subject to the rule must upgrade to tertiary wastewater treatment technology, which we show above to cost roughly $461,000 per year for the average sewer utility in our primary analysis sample. Alternatively, point sources subject to the

[32] The average trading ratio for the individual offset agreements is lower than 2.4:1. However, many point sources engage in trading by purchasing offsets from practices that are greater than their required total phosphorus discharge decreases, most often to account for uncertainty in the amount of reductions from the nonpoint source practices or to bank the credits for future trading with other point sources.

[33] EPA determines major status using a points ranking, with points assigned based on toxic pollution potential, flow type, conventional pollutant load, public health impact, and water quality impact. EPA then classifies any discharger (municipal or industrial) as a major facility if they have more than 80 total points.

phosphorus rule can participate in water pollution offset trading to comply, at lower cost. Our descriptive discussion of Wisconsin's program shows that water pollution offset trading can save point sources hundreds of thousands of dollars per year. We are therefore interested in the extent to which the point sources in our sample differentially pass through these costs to end users.

To examine differential impacts, we modify equation (1) to allow for heterogeneous effects of the two primary phosphorus rule compliance options. In this second specification, we interact an indicator for water pollution offset trading facility, $Offset_i$, with our treatment dummy:

$$ln(Y_{ict}) = \beta Comply_{ict} + \gamma Comply_{ict} \times Offset_i + \delta_i + \mu_t + \varepsilon_{ict}, \quad (2)$$

where all notation follows equation (1). We again cluster standard errors at the sewer utility level.

Table 7 presents results for the estimation of equation (2). As before, estimation results are quantitatively and qualitatively similar for each regression specification and analysis sample. The results in Table 7 suggest heterogeneity in the pass-through of Wisconsin's phosphorus rule along the compliance option dimension. Focusing on our baseline specification, Column 1 shows that, for facilities complying with Wisconsin's phosphorus rule with a tertiary treatment technology upgrade, compliance with the rule increases real sewer utility billing rates by 14.6%. Also evident from column 1, the magnitude of the effect for facilities complying with the rule via water quality offset trading is substantially smaller. The linear combination of the main effect of phosphorus rule compliance and the interaction between phosphorus rule compliance and the water quality offset indicator is 0.0620 (p=0.071). Therefore, we estimate that the phosphorus rule increases real sewer utility billing rates for facilities participating in the water pollution offset trading program by 6.4%, relative to a counterfactual scenario without the more stringent phosphorus rules. Recall that the average annual real sewer utility bill in our sample is $474.28 per customer. Our results suggest that complying with the phosphorus rule via a treatment technology upgrade increases the average annual sewer utility bill by $69.24, whereas complying with the rule via water pollution offset trading increases the average bill by $30.35. This differential represents sizable cost savings for customers of sewer utilities that comply with the phosphorus rule via water pollution offset trading as compared to the technological upgrade option.

Finally, we make the analogous calculations to those from subsection 3.3., where we estimate the extent of pass-through in these markets. We find that the median sewer utility in our sample that complies with the phosphorus rule via treatment technology upgrade passes through approximately 88% of its compliance costs to the sewer utility bills of its customers. Likewise, the median sewer utility in our sample that complies with the phosphorus rule with water pollution offset trading passes through approximately 72% of its phosphorus rule compliance costs. The higher cost pass-through of compliance via treatment technology upgrade is intuitive. Upgrading to tertiary treatment technology is much more expensive than water pollution offset trading. As a result, sewer utilities that comply with the rule via trading are more likely than utilities that comply via treatment technology upgrade to be able to cover some or all of the costs of trades through measures other than rate increases. For utilities that upgrade their treatment technology to comply with the rule, such large expenses leave little room for capital acquisition other than through rate increases.

Collectively, we find that municipal sewer utilities in Wisconsin pass through most of their phosphorus rule compliance costs to customers by increasing real sewer utility billing rates, regardless of the compliance option. Our findings therefore imply that savings generated from water pollution offset trading programs translate to proportional savings for sewer utility end users.

**5. Conclusion**

In this paper, we provide the first ex post program evaluation of the pass-through of water pollution regulation. We focus on the effects of Wisconsin's phosphorus rule. In 2010, Wisconsin revised its water quality regulations to make total phosphorus discharge limits at regulated point sources much more stringent. Upon renewing their NPDES permits, point source dischargers were faced with either upgrading their treatment technology to tertiary filtration systems or engaging in water pollution offset trading to comply with the revised regulations. However, only a portion of point source dischargers are up for permit reissuance each year, which provides a natural experiment to identify the effects of the regulation, which is not the case for most water pollution control policy. We use a DD framework to identify the increases in real sewer utility billing rates for customers of utilities who are treated with phosphorus rule compliance. We find that Wisconsin's phosphorus rule increases real sewer utility billing rates by over 10% for those utilities subject to the rule. Analyzing estimated compliance costs from plans submitted to the state environmental protection agency, these billing rate increases suggest that sewer utilities pass through 74% of the compliance costs of the rule to customers.

We then investigate Wisconsin's water pollution offset trading program to determine if it presents a cost-effective option for complying with stringent water pollution regulation. Consistent with the theory of tradable permits, our descriptive analysis of the program finds substantial cost savings from water pollution offset trading as compared to the command-and-control technological solution. In total, point sources in Wisconsin that comply with the phosphorus rule via water pollution offset trading save $17.5 million annually in compliance costs compared to the counterfactual of upgrading to tertiary treatment technology. These cost savings serve as the motivation to then examine the differential in the pass-through effects between sewer utilities that comply with the phosphorus rule through water pollution offset trading and those that comply by upgrading their treatment technology. We find that these cost savings affect end users of municipal sewer utilities as well. The average real sewer utility bill increases by only 6.4% for users serviced by utilities that comply with the phosphorus rule via water pollution offset trading, which is considerably less than the 14.6% increase experienced by customers serviced by utilities that comply by upgrading to tertiary treatment technology. These increases in real sewer utility bills equate to 72% and 88% pass-through, respectively, for the two compliance options.

Our results are important from a policy perspective. There do not exist evaluations of the pass-through of water pollution regulations, yet these values are important to identify from a welfare perspective, especially when considering markets with relatively inelastic demand and the potential for regressive rate increases. Our results can also help shed light on the efficiency of Wisconsin's phosphorus rule and other water quality regulations like it that aim to further control point source discharges. As mentioned, the marginal costs of point source pollution control now outweigh the marginal benefits (Olmstead 2010; Fischer-Vanden and Olmstead 2013). We show that, in Wisconsin, mandating extremely stringent point source discharge limits results in considerable compliance costs for point sources. And these costs are not simply borne by the point sources themselves but are passed through to sewer utility customers. If the overall water quality impacts of decreased pollutant loadings from point sources because of these tighter limits are low, which previous work suggests is likely, then Wisconsin's phosphorus rule may be net benefit negative. Future work should examine the benefits of the policy to fully assess the rule.

However, Wisconsin's water pollution offset trading program and its brokering of many trades may present an important opportunity. Economists and environmental protection agencies have long advocated for market-based approaches to water pollution control to improve water quality at lower costs to society. In practice, these market-based programs have experienced limited success. A primary reason for the limited implementation is uncertainty regarding the effectiveness of the programs, both in terms of cost savings and environmental effectiveness. With this paper, we demonstrate that real world cost savings of trading programs can be substantial relative to technological solutions and that these savings have welfare impacts. However, much work is still needed to estimate the water quality impacts of trading programs. Future program evaluations to assess water quality outcomes are essential for understanding the overall efficacy of the programs. Furthermore, resolving this scientific uncertainty could help make adoption of the programs more widespread.

Lastly, although we find substantial cost savings and less pass-through of these costs because of water pollution offset trading in Wisconsin, there is reason to believe that the effect in other settings could be larger than what we estimate. Wisconsin enacted its phosphorus rule in 2010 and sewer utilities received multiple years to implement their compliance options, as described in the compliance schedules. Our treatment date corresponds to the mandated compliance date for affected sewer utilities, but the installation of treatment technology can take years. As a result, much of what we estimate is the early response to this regulation. We still need further research to determine the effects in the longer-term horizon once sewer utilities fully realize costs.

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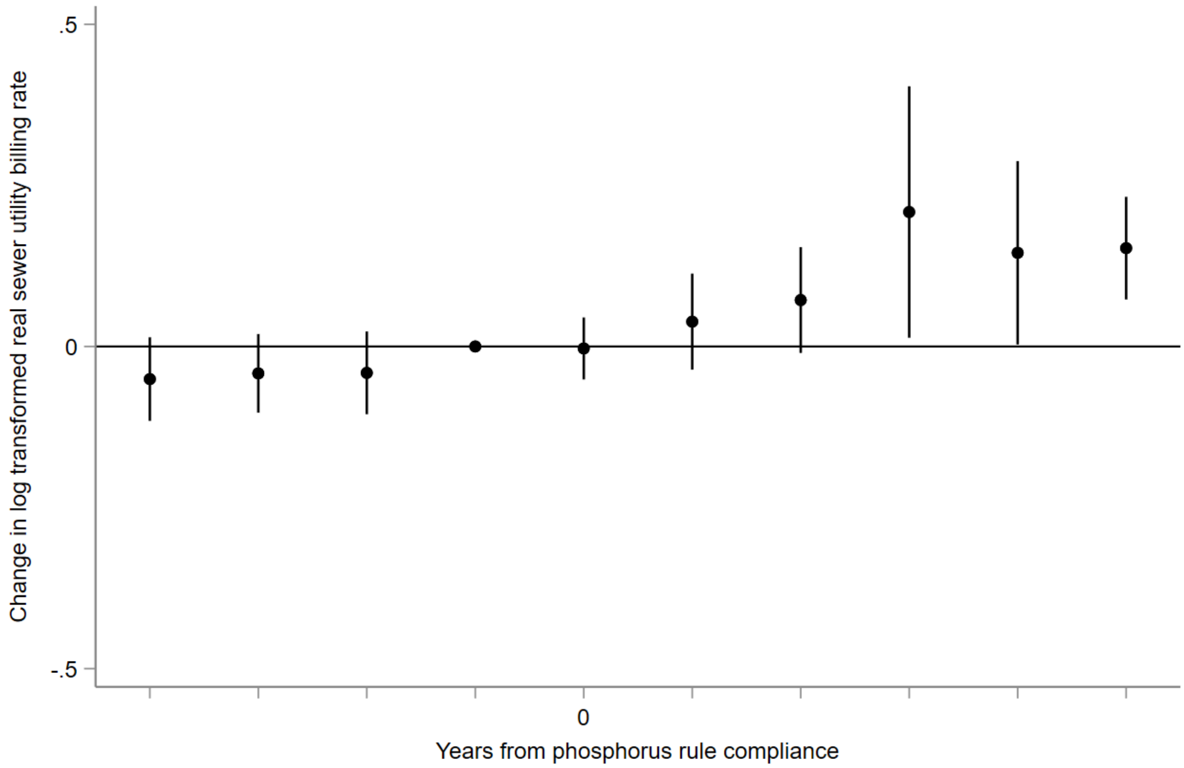


**Figure 1. Effect of Wisconsin's phosphorus rule on real sewer utility billing rates, event study.**

*Notes*: Results are the point estimates from the estimation of an event study of equation (1). Standard errors are clustered at the sewer utility level and produce 95% confidence intervals, which are included. Dependent variable is annual log-transformed real sewer utility billing rate for 55,000 gallons of use. Years from phosphorus rule compliance indicates years from the date of NPDES permit reissuance five years after the first post-December 1, 2010 permit reissuance.

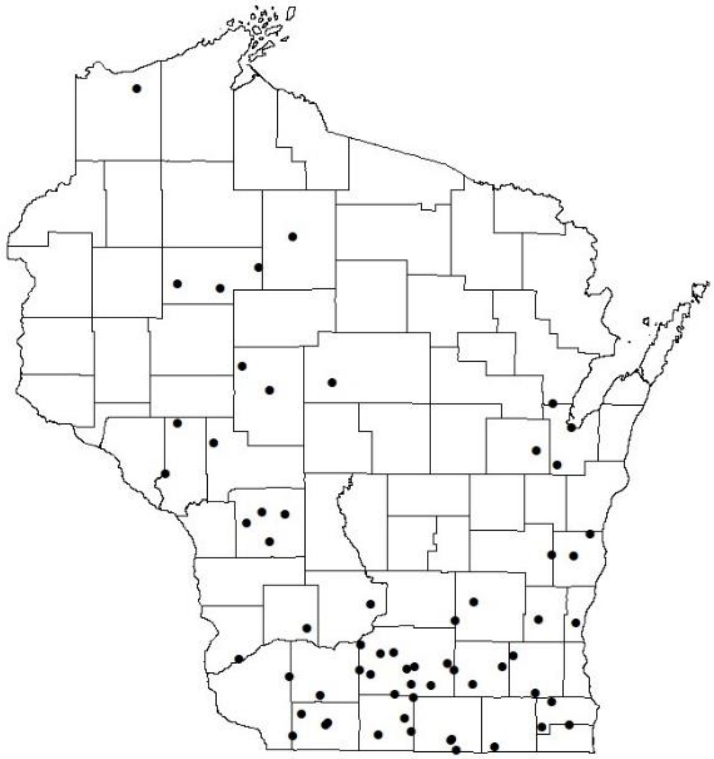

**Figure 2. Location of point sources that participate in water pollution offset trading in Wisconsin.**
*Notes*: Locations identify the municipal and industrial point source dischargers in Wisconsin that engage in offset trading or adaptive management through WDNR to comply with the phosphorus rule.

**Table 1. Summary statistics for phosphorus rule pass-through analysis sample**

| Variable | Mean | SD |
|---|---|---|
| Billing rate (55,000 gallons/year) | 474.28 | 235.63 |
| Treated sewer utility | 0.0785 | 0.269 |
| Facilities that comply via abatement technology upgrade | 0.0222 | 0.147 |
| Facilities that comply via offset trading | 0.0563 | 0.231 |
| Customers | 2043.8 | 7196.3 |
| Facility capacity (MGD) | 1.289 | 4.346 |
| Daily flow (MGD) | 0.677 | 2.378 |
| Observations | 12,825 | |

*Notes*: Summary statistics are at the facility-year level and for the final analysis sample. Costs are normalized to 2020$.

**Table 2. Effect of Wisconsin's phosphorus rule on real sewer utility billing rates**

| Variable | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| Comply | 0.0983*** | 0.106*** | 0.0756** | 0.105*** |
| | (0.0315) | (0.0346) | (0.0373) | (0.0313) |
| Facility FE | X | X | X | |
| Year FE | X | X | | |
| Year#county FE | | | X | |
| Gardner two-stage DD | | | | X |
| Observations | 12,825 | 7,136 | 12,825 | 12,825 |

*Notes*: Each column presents regression results from a separate specification of equation (1), where the outcome is annual log-transformed real sewer utility billing rate for 55,000 gallons of use. Column 2 presents results where facilities that comply with the phosphorus rule via an individual variance or facilities never subject to the phosphorus rule are eliminated from the analysis sample. Column 4 presents results from the Gardner (2021) two-stage DD estimator. Comply is the treatment dummy, which indicates facilities that are five or more years after the first post-December 1, 2010 permit reissuance. Robust standard errors are in parentheses and are clustered at the facility level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

**Table 3. Effect of phosphorus rule on real sewer utility billing rates, robustness and heterogeneous treatment effects.**

| Variable | (1) | (2) | (3) | (4) | (5) |
|---|---|---|---|---|---|
| Comply | | 0.0930*** | 0.0613* | 0.0856** | 0.130*** |
| | | (0.0295) | (0.0347) | (0.0341) | (0.0397) |
| × facility size (MGD) | | | 0.00210*** | | |
| | | | (0.000757) | | |
| × population (tens of thousands) | | | | 0.00619*** | |
| | | | | (0.00171) | |
| × below median income | | | | | -0.0932* |
| | | | | | (0.0515) |
| Comply (falsified) | -0.00413 | | | | |
| | (0.00975) | | | | |
| Facility FE | X | X | X | X | X |
| Year FE | X | X | X | X | X |
| Observations | 7,425 | 4,683,825 | 9,709 | 12,825 | 12,825 |

*Notes*: Each column presents regression results from a separate specification of equation (1), where the outcome is annual log-transformed real sewer utility billing rate for 55,000 gallons of use. Column 1 presents results where we falsify treatment timing. Column 2 presents results where the analysis sample is a balanced daily, rather than yearly, panel. Columns 3-5 present heterogeneous treatment effects. Comply is the treatment dummy, which indicates facilities that are five or more years after the first post-December 1, 2010 permit reissuance. Robust standard errors are in parentheses and are clustered at the facility level. *** p<0.01, ** p<0.05, * p<0.1.

**Table 4. Nonpoint source offset practices implemented in Wisconsin as part of WDNR's water pollution offset trading program.**

| Practice | Aggregate usage | Number of trades |
|---|---|---|
| *Panel A. Agricultural practices* | | |
| Cover crops | 6,152 acres | 10 |
| Farmstead improvement/barnyard runoff control | --- | 6 |
| Grassed waterways | 2,731 feet | 2 |
| No till | 777 acres | 4 |
| Nutrient management plan | --- | 4 |
| Permanent vegetative cover | 3,948 acres | 23 |
| Vegetative buffers/filter strips | 11,755 feet | 11 |
| *Panel B. Urban and other practices* | | |
| Lake dredging | --- | 2 |
| Leaf collection (street sweeping) | --- | 1 |
| Point-to-point trading | --- | 3 |
| Stormwater management | --- | 5 |
| Streambank stabilization | 72,577 feet | 25 |
| Wet detention ponds | --- | 2 |
| Wetland restoration | --- | 1 |

*Notes*: Practice represents the nonpoint source offset management practice that point source dischargers use to offset their total phosphorus discharges through trading as part of WDNR's program. Aggregate usage represents the total units of trades of the practice throughout the state that are part of the program. Number of trades represents the total count of trades of the practice that are part of the program. The sum of this count does not equal the number of facilities that participate in water pollution offset trading in the state because many facility plans contain multiple trades to reach the point source's required pollution offsets. Additionally, adaptive management plans can be approved with unspecified "agricultural BMPs" as the practice.

**Table 5. Summary of water pollution offset trading practices and point source dischargers.**

| Variable | Mean | SD |
|---|---|---|
| *Panel A. Offset policy* | | |
| Water quality trading | 0.698 | 0.463 |
| Trade cost (000$/year) | 93.8 | 130 |
| Treatment technology upgrade cost (000$/year) | 372 | 874 |
| Phosphorus reductions | 1,101 | 1,786 |
| Offset credits | 456 | 579 |
| Observations | 63 | |
| *Panel B. Point source* | | |
| Major | 0.300 | 0.462 |
| Facility size (MGD) | 3.16 | 9.97 |
| Municipal discharger | 0.746 | 0.439 |
| Observations | 63 | |

*Notes*: Summary statistics are at the facility level and for the point source dischargers that engage in offset trading or adaptive management through WDNR's trading program to comply with the phosphorus rule. Costs are normalized to 2020$. Trade costs represent engineering estimates or 150% of the 2020 EQIP prices for the offset practice used to achieve the required total phosphorus loading reductions. Treatment technology upgrade costs represent engineering estimates for the facility to upgrade to a tertiary filtration system based on facility size and current wastewater treatment technology.

**Table 6. Statistical summaries for phosphorus rule compliance sample.**

| Variable | Mean | SD |
|---|---|---|
| Water pollution offset trading | 0.415 | 0.497 |
| Adaptive management | 0.302 | 0.43 |
| Treatment technology upgrade | 0.283 | 0.454 |
| Trade cost (000$/year) | 125 | 148 |
| Treatment technology upgrade cost (000$/year) | 455 | 949 |
| Major | 0.491 | 0.505 |
| Facility size (MGD) | 4.26 | 10.9 |
| Observations | 53 | |

*Notes*: Summary statistics are at the facility level and for the municipal sewer utilities that are eventually treated in our sewer utility billing rate analysis sample. Costs are normalized to 2020$. Trade costs are only for those facilities that participate in water pollution offset trading to comply with the phosphorus rule. Treatment technology upgrade costs represent engineering estimates for the facility to upgrade to a tertiary filtration system based on facility size and current wastewater treatment technology. We calculate summaries of treatment technology costs for all facilities subject to the rule, regardless of their final compliance option.

**Table 7. Effect of phosphorus rule on real sewer utility billing rates, heterogeneity by compliance option**

| Variable | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| Comply | 0.136*** | 0.135*** | 0.116** | 0.150*** |
| | (0.0472) | (0.0482) | (0.0579 | (0.0435) |
| Comply × offset | -0.0743 | -0.0647 | -0.0812 | -0.0876* |
| | (0.0571) | (0.0607) | (0.0710) | (0.0504) |
| Comply + (Comply × offset) | 0.0620* | 0.0703* | 0.0352 | 0.0622** |
| | (0.0343) | (0.0399) | (0.0456) | (0.0282) |
| Facility FE | X | X | X | |
| Year FE | X | X | | |
| Year#county FE | | | X | |
| Gardner two-stage DD | | | | X |
| Observations | 12,825 | 7,136 | 12,825 | 12,825 |

*Notes*: Each column presents regression results from a separate specification of equation (2), where the outcome is annual log-transformed real sewer utility billing rate for 55,000 gallons of use. Column 2 presents results where facilities that comply with the phosphorus rule via an individual variance or facilities never subject to the phosphorus rule are eliminated from the analysis sample. Column 4 presents results from the Gardner (2021) two-stage DD estimator. Comply is the treatment dummy, which indicates facilities that are five or more years after the first post-December 1, 2010 permit reissuance. Offset is a dummy indicating a facility who complies with the phosphorus rule via water pollution offset trading. Robust standard errors are in parentheses and are clustered at the facility level. *** p<0.01, ** p<0.05, * p<0.1.