Environmental monitoring and enforcement at animal feeding operations: The effects on surface water quality

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Abstract

The Clean Water Act has historically regulated point source dischargers through its permitting program, the National Pollutant Discharge Elimination (NPDES). To deter noncompliance with NPDES permits, EPA and authorized state agencies administer interventions, such as inspections and monetary penalties, at regulated operations. Agricultural and other nonpoint sources have typically been exempted from such permits and their associated regulatory interventions. But recently, EPA updated the NPDES program to require permits for certain animal feeding operations (AFO) that produce large amounts of manure in concentrated geographies and have the potential to contribute to surface waterbody impairments. In this paper, we contribute to the literature on the effectiveness of regulatory interventions and examine the efficacy of NPDES monitoring and enforcement at permitted AFOs in the US. Unlike point sources, permitted AFOs typically do not have numeric discharge limits and they contribute to surface waterbody pollution through nonpoint source runoff, rather than direct effluent discharge. We therefore examine the efficacy of regulatory interventions at AFOs in improving environmental (manure) management by studying their impacts on surface water quality. Our analysis leverages within-AFO variation in experiences with regulatory interventions (inspections, informal enforcement actions, and monetary penalties) and the upstream and downstream nature of the US stream and river network to identify the effects of regulatory interventions on downstream concentrations of total phosphorus and ammonia. We find that NPDES monitoring and enforcement at regulated AFOs result in decreases in downstream concentrations of total phosphorus and ammonia. Specifically, the more "severe" inspections (e.g., federal rather than state) lead to larger downstream decreases in concentrations of both pollutants. We also find that the threat of regulatory interventions, i.e., general deterrence, leads to larger water quality improvements than the interventions themselves, i.e., specific deterrence. Collectively, our results suggest that the recent public investments into monitoring and enforcement at AFOs produce water quality benefits.

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Introduction

Animal agriculture in the US has changed considerably over the past 50 years. Rather than consisting of small, individual farms, the industry has concentrated, with most production occurring on large operations and feedlots that operate in confined spaces (Sneeringer 2009; Raff and Meyer 2022). These "animal feeding operations" (AFO), which concentrate large amounts of manure nutrients in small geographic spaces, pose surface water quality concerns (Kellog et al. 2007). Because of prohibitive manure shipping costs, AFOs store their untreated manure onsite and spread it onto nearby agricultural fields. Onsite, manure can leach into groundwater or seep out of unlined pits. Many states also allow for AFOs to directly discharge liquid manure to waterbodies, especially during heavy precipitation events. When spreading manure, the surrounding land is often unable to assimilate the large amount of excess nutrients present in the manure, so the excess nutrients run off as nonpoint source pollution during precipitation and snowmelt events. Indeed, recent studies identify a causal relationship between AFO exposure and degraded nearby surface water quality (Raff and Meyer 2022; Meyer et al. 2024).

Because of the surface water quality impacts and concentrated nature of AFOs, they have historically been regulated differently than other agricultural operations. The Clean Water Act (CWA) effectively ignores nonpoint sources, the category under which most agriculture falls, instead focusing on point sources through its National Pollutant Discharge Elimination System (NPDES) program. As part of the program, point sources must obtain NPDES discharge permits, which regulate effluent discharges from the facilities. Large AFOs with over 1,000 animal units onsite that discharge to surface waterbodies, called concentrated animal feeding operations (CAFO), are considered point sources and have been required to obtain NPDES permits since 1976 (EPA 2003). In 2003 and 2008, EPA updated its CAFO rules to require NPDES permits for all

CAFOs, even if they do not directly discharge to surface waterbodies. The updated rules also require NPDES permits for all AFOs (regardless of size) that directly discharge to surface waterbodies. Importantly, some state agencies consider manure spreading as discharging while others do not, so there is heterogeneity in permitting requirements of AFOs by state (GAO 2003). When updating the CAFO rules in 2003 and 2008, EPA cited a lack of monitoring and enforcement, i.e., regulatory interventions, in the industry as a cause of persistent water pollution and a catalyst for the rule updates (EPA 2003). Further, EPA created its National Enforcement Initiative for inspecting and controlling AFOs in 2011 (EPA 2011), so evaluating the efficacy of regulatory interventions at AFOs is important. In this paper, we therefore examine the effectiveness of NPDES monitoring and enforcement at AFOs regulated under the NPDES program by studying their impacts on surface water quality.

We add to several literatures with this work. First, many studies examine the external costs of AFOs, but few focus on the regulatory environment of the industry. Chen et al (2019) and Yu et al. (2021) estimate the effects of the imposition of the updated CAFO rules on water quality and AFO waste management practices, respectively. Ours is the first study to examine the effectiveness of NPDES monitoring and enforcement at AFOs at improving surface water quality. Second, we add to a large literature that examines the effects of environmental monitoring and enforcement on environmental management (Raff and Earnhart 2019) and regulatory compliance (Gray and Shimshack 2011). Finally, we add to a growing literature in environmental and natural resource economics that uses the US stream and river network and surface water quality data to assess the impacts of nonpoint source pollution on surface water quality (Keiser and Shapiro 2019; Paudel and Crago 2021; Raff and Meyer 2022; Skidmore et al. 2023; Hsieh and Gramig 2023; Meyer et al. 2024). Although the CWA considers regulated AFOs as point sources, few operations discharge effluent directly to surface waterbodies outside of extreme precipitation events. However, AFOs spread their manure onto fields, which can then run off as nonpoint source pollution; the effects of environmental monitoring and enforcement on these nonpoint source discharges have not been studied.

To develop our contributions, we first combine data on NPDES permitted AFOs from EPA's Environmental Compliance History Online (ECHO) database with surface water data from the Water Quality Portal (WQP) [surface water quality] and the Watershed Boundary Dataset (WBD) and the National Hydrography Dataset (NHD) [geospatial surface water framework]. We then leverage within-AFO variation in exposure to NPDES monitoring and enforcement to estimate the impacts of these regulatory interventions on surface water quality. Like recent work looking at surface water quality outcomes (e.g., Keiser and Shapiro 2019; Taylor and Druckenmiller 2022), we use the US stream and river network to estimate the differences between average total phosphorus (TP) and ammonia concentrations upstream and downstream of each NPDES regulated AFO. This within-estimator uses upstream pollutant concentrations as a natural counterfactual for downstream pollutant concentrations, allowing us to control for local factors that impact surface water quality, e.g., land use, slope, better than a watershed approach.

Estimation results show that, nearly across the board, regulatory interventions at AFOs decrease downstream surface waterbody concentrations of TP and ammonia. We highlight three key results. First, the more "severe" inspections—federal inspections—have a statistically significant and practically larger effect on TP and ammonia concentrations downstream of NPDES regulated AFOs than do state inspections. Second, the general "threat" of a regulatory intervention (general deterrence, which occurs at other AFOs like one's own) has a larger impact on downstream TP and ammonia concentrations than inspections that occur at the facility itself (specific deterrence). Third, the primary estimation results are robust to using an alternative HUC12-level approach, suggesting that manure management practices impacted by regulatory interventions are local to the geolocation of the AFO.

The rest of this paper proceeds as follows. The second section describes the background necessary to understand the context of our study. The third section describes our data. The fourth section presents the econometric framework. The fifth section discusses the estimation results. And the final section concludes.

Background

This section describes the specifics of AFOs and water pollution stemming from these operations. We also discuss the regulatory environment surrounding AFOs, including the use of monitoring and enforcement to deter noncompliance with environmental regulations.

The trend in livestock agriculture toward larger and more confined operations poses surface water concerns because of the amount of manure produced in concentrated geographic spaces.[1] Dependent on AFO-level storage and handling processes, the excess manure can enter waterbodies primarily in one of two ways. First, when operators store manure onsite within insecure or unlined surface "lagoons" (Hribrar 2010) [hog and dairy operations], in large piles, or under buildings or tarps (poultry operations), the manure can leach into groundwater or leak from piles and lagoons, especially during precipitation events. Second, when operators spread manure onto nearby farmland at agronomically inappropriate rates and/or times, e.g., on frozen ground, without plant cover (Osterberg and Wallinga 2004; Hu et al. 2017) [even with certified nutrient management plans], the ground cannot absorb the excessive nutrients from the manure (EPA 2001; Kellogg et al. 2014;

[1] As a specific example, an average dairy farm with 1,200 dairy cows can produce nearly 30,500 tons of manure per year. This amount of untreated manure is roughly equivalent to the amount of annual human sanitary waste produced by a US city with 46,000 people (GAO 2008).

Gollehon et al. 2016). Under these settings, precipitation events and melting snow carry the manure to surface waterbodies. This runoff represents a form of nonpoint source pollution.

Regardless of these threats to surface water quality, environmental protection policies only lightly control water pollution stemming from AFOs. At the federal level, the CWA imposes no restrictions on nonpoint source pollution such as manure runoff. Instead, the CWA provides grants for nonpoint source pollution protection of watersheds through Section 319 funds. Section 319 grants encourage sources of nonpoint source pollution to adopt Best Management Practices (BMP) through cost-share incentives. In addition, the CWA establishes Total Maximum Daily Loads (TMDL) for nutrient loadings into surface waterbodies that fail to meet their ambient water quality standards. While TMDLs recognize the role of nonpoint source pollution, they provide no actionable legal stipulations for nonpoint pollution sources. And at the state level, regulatory agencies display considerable heterogeneity in the regulation of nonpoint source pollution. For example, in Wisconsin, all agricultural operators are subject to broad nonpoint source policies, which include the adoption of a nutrient management plan. At the other end of the spectrum, the US Government Accountability Office (GAO) estimates that zero of Idaho's estimated 365 CAFOs have NPDES permits, meaning that they are subject to minimal regulation. Even with regulatory requirements, nonpoint source pollution remains difficult to regulate. Most states focus on incentives designed to spur adoption of BMPs through cost-share programs akin to CWA Section 319 funds.

Although most AFOs face no federally imposed restrictions, EPA updated in 2003 the permitting program of the CWA, the NPDES program, to require certain AFOs and all CAFOs to obtain permits to operate and to develop nutrient management plans to control manure and nonpoint source pollution from their operations (Sneeringer and Key 2011; Chen et al. 2019).[2] Under

[2] The permit requirements of the 2003 EPA rule consider spreading manure on fields as discharge events and extend to all "large" CAFOs, which are those with over 1,000 animal units.

the revised NPDES stipulations, permitted AFOs and CAFOs are considered point source dischargers, which face discharge limits (which are not necessarily identified numerically) (EPA 2004).

The EPA and individual states with "primacy" administer the NPDES program; this includes 47 of the 50 US states.[3] (EPA grants a state primacy if the state's environmental protection agency can demonstrate the regulatory capacity to implement the provisions of the NPDES program.) As the first step towards reducing discharges under the NPDES program, EPA and authorized state agencies issue permits to regulated operations. These permits impose effluent limits on wastewater discharges for most permittees. The effluent limits are generally positive for point source dischargers. However, effluent limits imposed on discharges from manure stored onsite of AFOs are zero. In contrast, NPDES permits impose no effluent limits on manure spread onto farmland. Thus, regulation of AFOs under the NPDES program generally relies on narrative permit requirements (e.g., manure handling processes, certain direct discharge stipulations) and the application of nutrient management plans.

To deter noncompliance with imposed effluent limits and other NPDES permit requirements, EPA and authorized state agencies regularly conduct inspections at permitted AFOs and irregularly take enforcement actions against noncompliant AFOs. Inspections vary in their coverage. Some inspections represent nothing more than a simple assessment of paperwork. Alternatively, inspections can scrutinize all aspects of an AFO's operation, demanding hours of on-site evaluation. Enforcement actions also vary. Informal enforcement actions include warning letters and simple notices of violation that do not require any court involvement. In contrast, formal enforcement actions (e.g., monetary penalties or fines) involve administrative or civil courts and can

[3] Only Massachusetts, New Hampshire, and New Mexico are not authorized to implement the NPDES program.

impose administrative, civil, or even criminal penalties, including incarceration. Our study examines the effects of these regulatory interventions—inspections and enforcement actions—on surface water quality as evidence of their effects on manure and wastewater management (i.e., environmental management) at permitted AFOs.[4]

Regardless of the regulatory environment, the control of wastewater discharges and nonpoint source pollution from AFOs likely remains insufficient. First, all AFOs are considered "minor" dischargers (EPA 2020), which are less likely to face discharge limits. Consistent with the weaker imposition of discharge limits, minor dischargers are less likely to self-report their discharges (Raff and Earnhart 2019). Indeed, self-reported discharge measurements from AFOs are virtually non-existent in EPA's Integrated Compliance Information System (ICIS) database (EPA 2020). Consequently, agencies struggle to determine the NPDES compliance status of AFOs, undermining agencies' abilities to ensure compliance with NPDES requirements. Second, states considerably differ in their regulation of discharges from AFOs. Many states, such as North Carolina and Arkansas, do not permit large numbers of AFOs. This pattern likely stems from state-level differences in NPDES implementation and the definition of potential dischargers among states (GAO 2003), as well as regulatory avoidance by large AFOs (Sneeringer and Key 2011), which likely differs across states. Third, NPDES permits do not necessarily regulate the amount of manure from AFOs that is spread onto fields. Thus, NPDES permits for AFOs need not reduce the nonpoint source pollution stemming from manure applied to fields. Finally, nutrient management plans are often insufficient for the control of animal waste produced at AFOs, especially given high levels of soil phosphorus present in many states containing AFOs. Collectively then, NPDES

[4] In addition to the federal CWA requirements, states can also implement policies to reduce nonpoint source pollution from AFOs. For example, several Midwestern states have implemented legislation that governs agricultural water quality performance standards for agricultural operators.

monitoring and enforcement at AFOs represent opportunities to improve environmental disamenities stemming from these operations.

Some features shape the interpretation of the results from our analysis of AFOs, surface water quality, and the role of regulatory interventions. First, interventions are designed to deter noncompliance with discharge limits. In the absence of these limits, interventions need not prompt AFOs to improve their manure management. Second, agencies surely struggle to conduct an effective intervention strategy when they lack complete information on compliance status. Third, agencies can only conduct regulatory interventions against permitted AFOs. Thus, our analysis cannot assess the effects on surface water quality associated with unpermitted AFOs. Fourth, the impact of interventions is weaker when NPDES permits do not shape the spreading of manure on fields. Fifth, regulatory interventions may prove insufficient for improving AFO nutrient management in a setting where most nutrient management plans are insufficient, representing a social norm that impedes progress. The noted features also represent shortcomings that undermine the effectiveness of the regulation of pollution from AFOs. For these reasons and others, water pollution associated with AFOs remains a large concern for policymakers.

Data

In this section, we describe the data that we use for our empirical analysis. First, we describe our data sources. Then, we outline the construction of the panel dataset. Finally, we provide statistical summaries.

Sources

We gather data from several sources. First, we use EPA's ECHO database to gather AFO-level data on NPDES program details.[5] Specifically, ECHO contains information regarding each AFO's

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[5] https://echo.epa.gov/tools/data-downloads/icis-npdes-download-summary.

history of NPDES monitoring and enforcement and various operation-level characteristics such as permit issuance and re-issuance dates, geolocation, and standard industrial classification (SIC) code. Several ECHO tables are necessary for our analysis. First, the ECHO database contains entries for each permitted AFO in the US, for the duration of its active permit status, which include aspects of each operation and its permit ("FACILITIES", "PERMITS", and "SICS" tables). For example, a single ECHO permit record contains the AFO name, a unique NPDES identifier for that operation, and the issuance and expiration dates of the individual permit (typically a five-year period). The record also contains a variable indicating if the permit is expired, terminated, or active. We use these tables to create the universe of NPDES permitted AFOs in the US (Figure 1). Second, we use ECHO's monitoring and enforcement data for AFOs regulated under the NPDES program ("INSPECTIONS", "INFORMAL ENFORCEMENTS ACTIONS", and "FORMAL ENFORCEMENT ACTIONS" tables). The monitoring and enforcement data consist of records of interventions that regulators use to deter noncompliance with the NPDES program. For each type of regulatory intervention, ECHO contains a unique entry for the type of action at each AFO for a specific date. There exist several types of inspections, such as compliance evaluation and sampling inspections. For our analysis, we combine all inspection types into a single measure, which we distinguish between federal (i.e., EPA-led) and state (i.e., state environmental protection agency-led) inspections. Enforcement data consist of informal enforcement actions (i.e., warning letters) and monetary penalties. Although both states and EPA can issue warning letters and levy monetary penalties, federal enforcement actions at AFOs are extremely rare. For our analysis sample and during our sample period, only one AFO received a federal informal enforcement action and zero AFOs received federal monetary penalties. We therefore focus our analysis of enforcement actions on those led by state environmental protection agencies.

Next, we collect surface water quality data from the WQP. The WQP provides data for many recent studies in environmental and natural resource economics that study surface water quality and nonpoint source pollution (Keiser and Shapiro 2019; Paudel and Crago 2021; Raff and Meyer 2022; Skidmore et al. 2023; Hsieh and Gramig 2023; Meyer et al. 2024). The National Water Quality Council aggregates data from the US Geological Survey (USGS) National Water Information System (NWIS), EPA Storage and Retrieval (STORET), and USGS Biodata to provide in the WQP. These water quality sources contain measurements of the presence (i.e., concentration) of various water quality pollutants and indicators along with the exact location and timing of the monitoring. The WQP comprises measurements taken by governmental agencies, university researchers, and citizen scientists and volunteers. For our analysis, we use as our primary outcome TP and ammonia concentrations because they are the water pollutants most likely impacted by the storage and handling of manure from livestock operations (EPA 2002; Raff and Meyer 2022). We also collect other pollutant measurements for placebo tests. We collect water quality data for all surface waterbodies, eliminating observations from man-made structures, e.g., wastewater ponds, wells, ditches. For our primary analysis, we restrict the sample to streams, rivers, and lakes because we wish to use the US stream and river network to identify water quality monitoring locations upstream and downstream of NPDES permitted AFOs (e.g., Keiser and Shapiro 2019; Behrer et al. 2021). However, we also estimate a watershed-level specification (HUC12) where we use all surface waterbody readings in the US. Figure 2 shows the locations of TP and ammonia water quality monitoring in the US. The monitoring data contain some zero, non-detect, and very high readings. We transform zero and non-detected measurements to 1/2 of the smallest value in the sample, like previous studies (e.g., Keiser and Shapiro 2019; Meyer et al. 2024).[6] For outliers at

[6] Meyer et al. (2024) discuss several alternative transformations and analysis techniques when dealing with zero and non-detected measurements; the authors also show why the technique used is likely unimportant

the right tail of the distribution, we winsorize readings at the 99% level.

There exists a concern that water quality samplers may gather data on certain days, such as those following precipitation events, which would bias our analysis. However, this concern is unlikely to affect the present analysis, as Raff and Meyer (2022) show that sampling timing is not endogenous to precipitation. We nevertheless avoid overweighting more frequently monitored locations and smooth daily noise in the data by aggregating surface water quality readings to the monthly level. For our primary analysis sample, we average all readings along stream reaches that are within 20 km upstream and downstream of NPDES permitted AFOs.

Finally, we gather information on watershed boundaries and the US stream and river network from the WBD and the NHD, respectively. These datasets are national geospatial surface water frameworks that EPA and USGS developed together. The WBD contains data on watershed and catchment boundaries, allowing us to place AFOs and water quality monitoring locations in the appropriate HUC region (HUC12). The NHD provides information about the US streamflow network at the stream reach level for all streams, rivers, and lakes in the contiguous US. As the primary unit of analysis important for our purposes, the NHD delineates stream and river segments at the "stream reach" level. A stream reach is a section of each waterbody, typically one to five km in length depending on if it is part of the mainstem or a tributary. The NHD provides information on, among other things, the type of waterbody, its streamflow direction, its outlet, the type of stream reach (e.g., mainstem or tributary), and flow. Importantly, we use the streamflow network to navigate upstream and downstream from NPDES permitted AFOs and water quality monitoring stream reaches.

Construction of analysis sample

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in our setting. Regardless, our results are robust to several alternative substituted values and to an alternative random effects Tobit model that retains non-detect information.

To develop our analysis sample, we first wish to identify the appropriate temporal scale for our analysis. ECHO aggregates permit, monitoring, and enforcement data from all US states and several territories. Data quality and accuracy of the ECHO database have historically been problematic, for several reasons. First, different states have historically used different database management systems, so aggregation has proven difficult (Grant and Grooms 2017; Raff 2023). Second, state-level reporting of NPDES enforcement and compliance data has historically relied on voluntary reporting, most often via paper forms.[7] And third, reporting for permitted operations other than major point source dischargers has been inadequate. AFOs in particular pose a reporting problem because they are permitted most often under "general" permits, where a single permit covers many operations in a state; reporting of NPDES monitoring and enforcement at such operations is not required for many states. As a result of the data discrepancies between state and federal regulators, EPA has recently established protocols to harmonize data between itself and the states. Most important, EPA established in 2015 the "eReporting rule".[8] The rule requires that states and other regulatory authorities share permit, monitoring, and enforcement action data with EPA via its electronic reporting system, rather than through paper transmittal. The likely benefits of the rule are clear; more accurate and timely data reported and available through a single electronic system. Also important, as of 2014, all states with NPDES primacy use the same database management system (ICIS-NPDES). We use this institutional context and recent data quality improvements and select as our analysis period 2016 to 2022.

Next, we gather from ECHO permit data for all NPDES permitted AFOs in the US between 2016 and 2022. We then match to each permitted record ECHO's monitoring (state and federal

[7] There exist anecdotes of state environmental protection agencies with storage rooms full of outdated NPDES reporting forms.
[8] https://www.epa.gov/compliance/npdes-ereporting.

inspections) and enforcement action (state-administered informal enforcement actions and monetary penalties) data. As noted, we eliminate bias and smooth noise in the surface water quality data by aggregating measures to the monthly level; we do the same with the regulatory intervention data. We therefore have a monthly, AFO-level panel that includes measures of monitoring and enforcement. For inspections, our panel contains the count of state and federal inspections in each month. And for enforcement actions, the panel contains the number of state-administered informal enforcement actions and the value of state-administered monetary penalties at the monthly level. The monthly regulatory intervention counts and values are the basis for our primary regressors, which we describe in detail in the following section.

We next turn to the surface water data. To create our outcome measure, we match all water quality monitoring locations from the WQP (Figure 2) to their associated HUC12 in the WBD and stream reach in the NHD. Concurrently, we match each NPDES permitted AFO in the US (Figure 1) to its associated HUC12 and nearest stream reach. For our primary analysis sample, we use the interconnected nature of the NHD's stream and river network to aggregate average upstream and downstream TP and ammonia concentrations within 20 km of each AFO. Our unit of analysis is the 20-km aggregated stream reach-month level, with one analysis sample for each pollutant. In simple terms, for each month where there is at least one water quality sample within 20 km of a NPDES permitted AFO, either upstream or downstream via the NHD's stream and river network, there is a unique observation for that AFO and stream reach direction. As an alternative analysis sample, we aggregate surface water quality readings to produce a HUC12-month average (this is like most prior work using WQP data, e.g., Paudel and Crago 2021; Raff and Meyer 2022; Skidmore et al. 2023).

Finally, we combine the monitoring and enforcement measures—in specific and general deterrence form—with the surface water quality measures to create two final analysis samples. The analysis samples, one for TP and one for ammonia, are at the AFO-month level, with observations for surface water quality both upstream and downstream of each NPDES permitted AFO.[9] In addition, we create an analysis sample that is at the HUC12-month level that includes all water quality samples in the US, regardless of their proximity to NPDES regulated AFOs. Our final analysis samples are unbalanced panels from 2016 to 2022.

Statistical summaries

The final analysis sample for TP contains 55,631 observations and the final ammonia analysis sample contains 52,883 observations. Table 1 displays summary statistics for the final analysis samples, which contain all NPDES permitted AFOs in the US and average water quality readings that are within 20 km upstream or downstream (via the stream and river network) of those AFOs. Average surface waterbody concentrations of both TP and ammonia are relatively high, likely because of the presence of high values in some states. As expected, average TP concentrations downstream of AFOs are higher than those upstream of AFOs, suggesting that AFOs contribute to higher concentrations of TP in surface waterbodies. Curiously, the opposite is true of ammonia concentrations.

AFOs are subject to many more state inspections than federal inspections. For each analysis sample, the specific deterrence state inspection measures are nearly 50 times higher than the federal inspection measures. And the maximum number of times that the state inspects a single AFO within a 12-month period during our sample is five, while the maximum value for federal inspections is two. These relative values are expected, as states are the primary regulators of smaller and general permitted operations such as AFOs, while the federal regulators typically concern

[9] By design, the upstream and downstream monitoring and enforcement measures are the same for each AFO. Given our empirical strategy (described below), the upstream measures become effectively zero.

themselves with major polluters. The same is true of inspections in general deterrence form, which represent the general "threat" of receiving an intervention. Here, AFOs in both analysis samples face a regulatory environment where the threat of a state inspection is much higher than the threat of a federal inspection. Enforcement actions in general deterrence form are also infrequent. Compared to prior studies that examine similar monitoring and enforcement measures (e.g., Raff and Earnhart 2018), the threat of enforcement at NPDES permitted AFOs is low. Again, this is likely the case because of the relatively small scale of these polluters. Compared to a major discharger such as a large municipal wastewater treatment plant or a chemical manufacturing plant, AFOs directly discharge much less pollutants to surface waterbodies. Unlike prior work, however, we focus our analysis of enforcement actions on those administered by the states. Comparatively, the monetary penalty measures are more frequent than those of previous studies, but of a lesser magnitude. We hypothesize that the magnitude of monetary penalties will have an important impact in our estimation. Finally, we note the significant variation in the primary regression measures, which strengthens our identification.

Econometric framework

In this section, we describe our econometric framework and identification strategy. Briefly, we identify the effects of NPDES monitoring and enforcement at AFOs on surface water quality by leveraging within-AFO experiences with regulatory interventions over time and the upstream and downstream nature of the US stream and river network. This section first discusses the primary regressors and identification strategy. Then, we present our empirical model specifications.

Primary regressors and identification

Like previous studies examining environmental monitoring and enforcement, we wish to develop collective measures of regulatory exposure that incorporate a lag, which allows operations time to respond to the interventions and change their environmental management strategies (Gray and Shimshack 2011). Also consistent with the literature, we assume that operations respond to regulatory interventions based on their own recent experiences with regulatory interventions and the experiences with regulatory interventions of other, similar operations. We therefore measure NPDES monitoring and enforcement in two forms. First, specific deterrence measures regulatory interventions that occur at the facility itself (Earnhart and Friesen 2014; Raff and Earnhart 2019). Informal enforcement actions and monetary penalties stem from acts of noncompliance, so we do not examine enforcement actions in specific deterrence form because they are endogenous to operation-level environmental management practices. However, inspections are plausibly exogenous to environmental management because the NPDES program requires them periodically, i.e., with no specific or regular schedule (EPA 2004). Previous studies have examined the exogeneity of NPDES inspections when studying environmental management outcomes in depth (Raff and Earnhart 2022). Second, general deterrence measures regulatory interventions that occur at operations like one's self, i.e., general deterrence measures the "threat" of regulatory interventions (Cohen 2000; Gray and Shimshack 2011; Raff and Earnhart 2018). Clearly, general deterrence measures are exogenous to operation-level environmental management because general deterrence occurs at other operations.

We develop our primary regression measures of NPDES monitoring and enforcement in the following ways. For specific deterrence, we create, at the monthly level, a count of inspections (state and federal inspections separately) that each AFO experiences in the previous 12 months. We create our measures of general deterrence, also at the monthly level, by considering the level of regulatory interventions that occurs within the same state or EPA region (regardless of if the AFOs are in our final analysis samples). The state inspection general deterrence measure is the quotient of the count of NPDES inspections in the preceding 12 months at other AFOs in the same state divided by the count of NPDES permitted AFOs operating in that state (less the AFO itself) and in that month. For federal inspections in general deterrence form, we create a similar measure, where the numerator is the number of EPA inspections at other AFOs in the same EPA region and the denominator is the count of NPDES permitted AFOs operating in that same region (less the AFO itself). We create the enforcement action general deterrence measures analogously to the state inspection measures, but the numerators are the count of informal enforcement actions and sum of monetary penalties in the state in the preceding 12 months, again divided by the count of operating AFOs in that state in that month.

To estimate the effects of NPDES monitoring and enforcement at AFOs on surface water quality, we consider as our primary regressors the following intervention measures: inspections, informal enforcement actions, and formal enforcement actions, i.e., fines. In a preliminary estimation strategy, we combine sets of measures into a single regressor, like Raff and Earnhart (2020). We use as regressors inspections (both federal and state) in specific deterrence form, inspections (both federal and state) in general deterrence form, and enforcement actions (state-administered informal enforcement actions and monetary penalties) in general deterrence form. Then, for our primary specification, we examine the heterogeneity of the overall impacts by the specific type of monitoring and enforcement action. We divide each measure between state and federal actions, informal enforcement actions and monetary penalties, and specific and general deterrence. Our main specification therefore considers a total of six primary regressors. We denote inspections as vectors that contain both specific and general deterrence measures; $\boldsymbol{STINSP}$ represents state inspections and $\boldsymbol{FDINSP}$ represents federal inspections. And for enforcement actions, we denote the primary regression measures as $INFEA$ (informal enforcement actions) and $FINE$ (monetary penalties).

Our primary identification strategy leverages within-AFO variation in the experiences of AFOs with NPDES inspections and enforcement actions. We also use the US stream and river network to examine surface water quality impacts. Our identification strategy considers as "treated" the collection of water quality monitoring locations within 20 km (via the stream and river network) downstream of each NPDES permitted AFO. We denote these sections of the stream and river network $DOWN$. Control water quality monitoring locations, then, are the collection of locations within 20 km upstream of each AFO. We therefore use a variant of the upstream-downstream difference-in-differences within-estimator (Keiser and Shapiro 2019; Taylor and Druckenmiller 2022) that treats unaffected upstream surface water quality as a natural counterfactual to affected downstream surface water quality. Clearly, if NPDES monitoring and enforcement improve environmental management at AFOs, as is the purpose of these actions, this improves downstream surface water quality. Importantly, the same improvements will have no impact on water quality directly upstream of the AFO. We therefore leverage variation in the extent of NPDES monitoring and enforcement at AFOs within a 40 km stretch of streams, rivers, and lakes to identify our effects of interest. The use of a within-estimator allows us to control for time-invariant factors that impact surface water quality near each AFO, such as the flow of the waterbody or topological factors. For our analysis, we construct primary regression measures that are interactions between the NPDES monitoring and enforcement measures and the downstream indicator.

We also estimate a specification at the HUC12 level. The primary avenue for AFOs to impact surface water quality is through the spreading of manure onto nearby agricultural fields. As a result, the upstream-downstream identification may understate (or overstate) the true impact of each AFO on surface water quality, because the operations' manure may runoff into other surface waterbodies that are not necessarily the closest (Meyer et al. 2024).[10] The HUC12-level specification averages all TP and ammonia concentrations and each regulatory intervention measure within each sub-watershed, providing a HUC12-month level picture of the surface water quality and regulatory environment in these areas. For this specification, we identify the effects based on within-HUC12 level variation in NPDES monitoring and enforcement at regulated AFOs.

Empirical model specifications

We estimate the following specification to identify the effects of NPDES monitoring and enforcement on AFOs on downstream surface water quality:

$$ln(Y_{ihmt}) = (\boldsymbol{DOWN_i} \times \boldsymbol{STINSP_{imt-1}})'\boldsymbol{\beta_1} + (\boldsymbol{DOWN_i} \times \boldsymbol{FDINSP_{imt-1}})'\boldsymbol{\beta_2} + \beta_3(DOWN_i \times INFEA_{imt-1}) + \beta_4(DOWN_i \times FINE_{imt-1}) + \delta_i + \rho_h + \mu_m + \sigma_t + \varepsilon_{ihmt}\ , \quad (1)$$

where the outcome, $ln(Y_{ihmt})$, is the log-transformed average surface waterbody concentration of TP or ammonia (mg/L) within 20 km (upstream or downstream) of NPDES regulated AFO i in HUC12 h in month m of year t. $DOWN_i$ is a dummy indicating stream reach segments downstream of a NPDES permitted AFO. By interacting our primary regressors with the $DOWN_i$ dummy, we identify those stream reach segments that are "treated" by NPDES monitoring and enforcement at AFOs, using upstream stream reaches as a natural counterfactual. β_1 through β_4 are the coefficients of interest and represent the effects of state and federal inspections in specific and general deterrence form and state-administered informal enforcement actions and monetary penalties in general deterrence form on average downstream surface waterbody concentrations of TP and ammonia. If

[10] We note, however, that because of prohibitive shipping costs, nearly all manure from livestock is spread within 1-3 km from the geolocation of the operation itself (Ali et al. 2012; MN Dept. of Ag. 2017; Meyer et al. 2024). So, any bias of the upstream-downstream methodology is likely minimal.

NPDES monitoring and enforcement at AFOs improves environmental management at these regulated operations, then we expect the β_1 through β_4 coefficients to be negative. Next, δ_i captures AFO fixed effects. AFO fixed effects control for time-invariant characteristics of each AFO, such as its relative size and commodity type (i.e., animal). Because of the upstream-downstream nature of our analysis, δ_i also control for time-invariant characteristics that impact surface water quality surrounding each AFO, such as its location in the watershed or other topological factors. Next, ρ_h are HUC12 fixed effects, which control for time-invariant factors specific to each AFO's sub-watershed. We also control for temporal trends in surface water quality, such as seasonality or nationwide regulatory policies, with month (μ_m) and year (σ_t) fixed effects. Finally, ε_{ihmt} is the exogenous error term. We cluster standard errors at the AFO level.

To consider manure spreading that may occur outside of the immediate geolocation of each AFO, we also estimate the following HUC12-level specification:

$$ln(Y_{hmt}) = \boldsymbol{STINSP'_{hmt-1}\beta_1} + \boldsymbol{FDINSP'_{hmt-1}\beta_2} + \beta_3 INFEA_{hmt-1} + \beta_4 FINE_{hmt-1} + \rho_h + \mu_m + \sigma_t + \varepsilon_{hmt}\ , \qquad (2)$$

where all notation is identical to that in equation (1).[11] Here, there is no $DOWN_i$ interaction because we consider all waterbodies in each HUC12 as potentially "treated" by NPDES monitoring and enforcement at AFOs.

Estimation results

In this section, we present our estimation results, including economic impacts.

[11] For this specification, we include all surface water monitoring locations and readings, regardless of their proximity via the US stream and river network to NPDES permitted AFOs.

Table 2 presents the results for our preliminary estimation where we combine the primary regressors into three forms. We briefly discuss these results and present the results for the heterogeneity analysis in more depth below. Table 2 results show that there is no significant impact on downstream TP or ammonia concentrations because of inspections in specific deterrence form. In fact, three of the four results are positive, yet estimated imprecisely. In general deterrence form, however, all four columns of Table 2 show that the threat of inspections significantly decreases the average concentration of TP and ammonia directly downstream of NPDES permitted AFOs, which suggests that the threat of an inspection is more effective than receiving the inspection itself. Previous work suggests that regulated entities may feel that the "storm has passed" after receiving an inspection, so they do not improve their subsequent environmental management. Alternatively, the cooperative nature of state inspections, and compliance assistance inspections in particular, may lead to less impactful interventions (Raff and Earnhart 2018). For enforcement actions in general deterrence forms, there is a consistent negative effect on TP and ammonia concentrations in downstream surface waterbodies, although the effect for ammonia is estimated imprecisely. These results suggest that the threat of state-administered enforcement at AFOs is a meaningful deterrent.

Next, Table 3 tabulates the results for the primary estimation strategy, which examines the heterogeneity of results by specific regulatory intervention, in six forms. We include in this table results for several specifications and analysis samples to assess the robustness of our primary results. The first and fifth columns include the most basic set of fixed effects, which include AFO, month, year, and HUC12 fixed effects. Columns 2 and 6 add year-by-HUC12 fixed effects, which control for yearly variation in factors at the HUC12 level, such as general land uses. Columns 3, 4, 7, and 8 provide results for changes in analysis sample. The experiences with NPDES monitoring and enforcement for AFOs that are subject to varying levels of regulatory interventions at their own operation likely differ. Here, we eliminate from the analysis sample all AFOs that did not experience any state or federal inspections in specific deterrence form during our sample period, as they may be poor control AFOs.[12] Columns 3 and 7 provide estimation results for this analysis. Finally, columns 4 and 8 tabulate results for the HUC12-level analysis.

In general, results across all specifications and analysis techniques are qualitatively and quantitatively similar. Most notably, Table 3 shows that NPDES monitoring and enforcement at AFOs, in both specific and general deterrence form, decrease concentrations of TP and ammonia directly downstream of the operations. The lone exception—state inspections in specific deterrence form—shows an imprecisely estimated positive relationship between regulatory interventions and downstream ammonia concentrations. As mentioned, this unexpected result may be the result of operators feeling that state regulators will not intervene upon the AFOs again or that the state inspections prove too cooperative to have any meaningful deterrent effect. Next, Table 3 results show that, for inspections, the more "severe" regulatory interventions—federal inspections (instead of state inspections)—have the largest effect on downstream surface water quality. Coefficient estimates for federal inspections in specific and general deterrence form are much larger than those for state inspections. These results likely stem from the differing purposes of state and federal inspections. State agencies most often use inspections for compliance assistance while federal regulators use inspections to provide evidence for future enforcement (Earnhart 2004; Raff and Earnhart 2019). Here, the gravitas of the federal regulator proves important. Informal enforcement actions and monetary penalties also significantly decrease downstream concentrations of TP

[12] In our analysis sample, the threat of monitoring and enforcement (general deterrence) is much higher than the actual experience of monitoring and enforcement (specific deterrence). Over 95% of AFOs in our sample experience greater than zero measures of general deterrence for each of the measures, while roughly 50% of the analysis sample never experiences an inspection.

and ammonia, although differently. For TP concentrations, informal enforcement actions have a statistically significant and larger impact. While for downstream ammonia concentrations, monetary penalties have a statistically significant and larger impact, perhaps resulting from different water quality monitoring locations for each pollutant surrounding NPDES regulated AFOs. Regardless, the threat of enforcement actions from the state regulator leads NPDES regulated AFOs to improve their environmental management, which decreases downstream surface water pollution. Finally, the HUC12-level results are like those using the upstream and downstream specification, providing evidence that AFOs impact waterbodies very near their operation.

Economic impacts

In this sub-section, we assess the economic importance of the results. We highlight the statistically significant results from our primary estimation strategy: the upstream-downstream analysis with HUC12-by-year fixed effects (column 2 of Table 3 for TP concentrations and column 6 of Table 3 for ammonia concentrations). Because the average AFO is exposed to low levels of NPDES monitoring and enforcement, we discuss the economic impacts in terms of standard deviations. As discussed, nearly all regulatory interventions at AFOs improve surface water quality downstream of NPDES permitted AFOs. For those interventions that are statistically significant, the effects on downstream surface water concentrations of TP and ammonia are exclusively negative, meaning that NPDES monitoring and enforcement at AFOs improve surface water quality. We first discuss the economic impacts for TP concentrations. First, a one standard deviation increase in state inspections in general deterrence form (0.0319 inspections) decreases downstream TP concentrations by over 2.5%.[13] Based on the average downstream TP concentration in this sample (0.347 mg/L), a one standard deviation increase in state inspection related general deterrence decreases

[13] We interpret the economic impacts in the following way because we log-transform the outcome: $\exp(\beta * SD) - 1 = \%$ change in the outcome.

average downstream TP concentrations by 0.0087 mg/L. For federal inspections in general deterrence form, an increase of one standard deviation (0.000764 inspections) leads to a decrease in downstream TP concentrations of roughly 2.3%, or 0.008 mg/L based on the sample mean. Finally for the TP sample, state-administered informal enforcement actions in general deterrence form also significantly decrease downstream TP concentrations. Increasing this regulatory intervention measure by one standard deviation (0.0129 actions) decreases downstream TP concentrations by over 4.2% (0.015 mg/L based on the sample mean).

Next, we discuss the economic impacts for the ammonia sample, which are generally larger than the economic impacts of the TP sample. First, federal inspections in specific deterrence form improve downstream surface water quality. Increasing federal inspections in specific deterrence form by one standard deviation (0.0701 inspections) decreases downstream ammonia concentrations by roughly 4.6%, or 0.0066 mg/L based on the sample mean of 0.143 mg/L. Next, like TP concentrations, state inspections in general deterrence form improve downstream surface water concentrations of ammonia. A one standard deviation increase in state inspections in general deterrence form (0.0345 inspections) decreases ammonia concentrations downstream of NPDES permitted AFOs by nearly 55% (0.078 mg/L based on the sample mean). Finally, a one standard deviation increase in state-administered monetary penalties ($36.65) leads to a decrease in downstream ammonia concentrations of 11.2%, or 0.016 mg/L based on the sample mean.

Conclusion

The changing structure of the US livestock industry has led to concerns that larger and more concentrated operations pose a threat to surface water quality. Indeed, EPA and state environmental protection agencies have recently implemented more stringent water quality regulations on these operations. However, for any regulation to be effective, there must be monitoring and enforcement to ensure compliance (or at least deter noncompliance). EPA has shown that monitoring and enforcement of AFOs is a priority issue. But no study exists that examines the monitoring and enforcement of the NPDES program at AFOs, or of the efficacy of such actions. This study shows that, in general, the regulatory interventions produce water quality improvements downstream from NPDES regulated AFOs. Specifically, we find that the more "severe" inspections (federal rather than state) and the general threat of regulatory intervention (general rather specific deterrence) prove the most efficacious. Collectively, our study shows that the recent investments into NPDES monitoring and enforcement at regulated AFOs yield surface water quality improvements.

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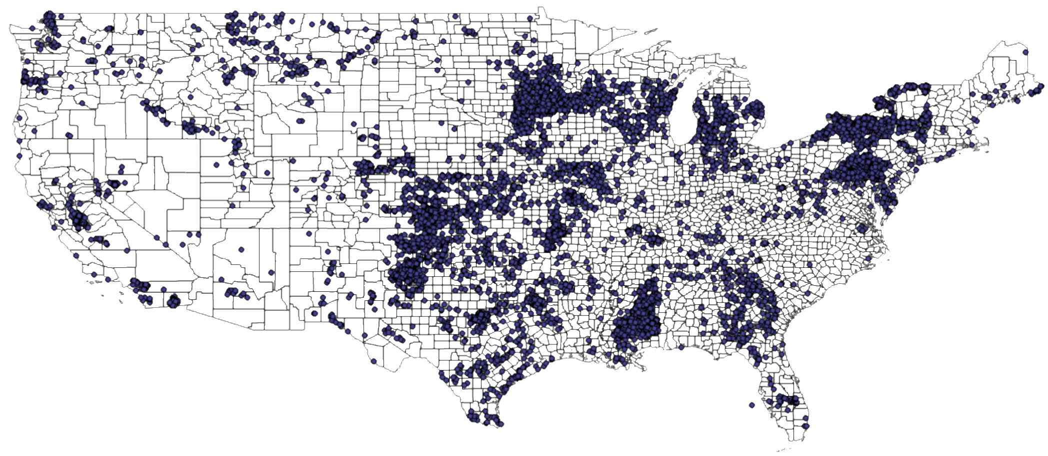

Figure 1. Locations of NPDES permitted AFOs in the US.
Notes: Dots represent the geolocation of each NPDES permitted AFO in the US, as provided in EPA's ECHO database.

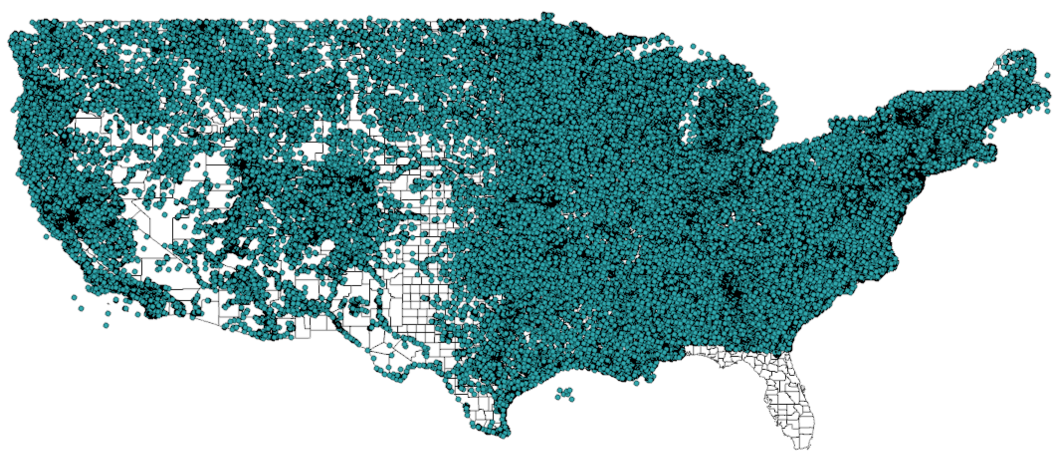

Figure 2. TP and ammonia water quality monitoring locations in the US.
Notes: Dots represent the geolocation of each TP and ammonia water quality monitoring location in the US. Florida data unavailable through the WQP.

Table 1. Summary statistics for final analysis samples

Variable	Mean	SD	Min	Max
Panel A. Total phosphorus				
Upstream pollutant concentration (mg/L)	0.245	0.409	2.92e-7	2.630
Downstream pollutant concentration (mg/L)	0.347	0.428	2.92e-7	2.630
State inspections, specific deterrence	0.192	0.514	0	5
Federal inspections, specific deterrence	0.00399	0.0630	0	1
State inspections, general deterrence	0.0146	0.0319	0	0.667
Federal inspections, general deterrence	0.000187	0.000764	0	0.0462
Informal enforcement actions, general deterrence	0.00353	0.0129	0	0.667
Monetary penalties ($), general deterrence	2.941	31.29	0	1,508
Observations		55,631		
Panel B. Ammonia				
Upstream pollutant concentration (mg/L)	0.273	0.416	4.5e-10	1.800
Downstream pollutant concentration (mg/L)	0.143	0.280	4.5e-10	1.800
State inspections, specific deterrence	0.179	0.498	0	5
Federal inspections, specific deterrence	0.00429	0.0701	0	2
State inspections, general deterrence	0.0152	0.0345	0	0.667
Federal inspections, general deterrence	0.000139	0.000716	0	0.0162
Informal enforcement actions, general deterrence	0.00308	0.0129	0	0.667
Monetary penalties ($), general deterrence	3.013	36.65	0	1,231
Observations		52,883		

Notes: Summary statistics are at the AFO-month level, for 2016-2022, and represent observations in the final analysis samples. Upstream and downstream pollutant concentration measurements are the monthly average of each pollutant 20 km upstream and downstream of a NPDES regulated AFO.

Table 2. Effect of NPDES monitoring and enforcement at AFOs on surface water nutrient concentrations

	Total phosphorus		Ammonia	
Variable	(1)	(2)	(3)	(4)
Panel A. Specific deterrence				
Inspections	0.0134	-0.00478	0.0604	0.0708
	(0.0118)	(0.0116)	(0.0677)	(0.0661)
Panel B. General deterrence				
Inspections	-0.696***	-0.822***	-17.20***	-15.57***
	(0.165)	(0.186)	(1.705)	(1.709)
Enforcement actions	-0.0191***	-0.0256***	-0.0213	-0.0299
	(0.00570)	(0.00658)	(0.0258)	(0.0243)
Operation FE	X	X	X	X
Month FE	X	X	X	X
Year FE	X		X	
HUC12 FE	X	X	X	X
HUC12#Year FE		X		X
Observations	55,631	55,631	52,883	52,883

Notes: *** p<0.01, ** p<0.05, * p<0.1. Robust standard errors are in parentheses and are clustered at the AFO level. For each column, the outcome is the log-transformed monthly average of TP or ammonia concentrations 20 km upstream or downstream of a NPDES permitted AFO. Inspections in specific deterrence form represent the count of state and federal inspections at a specific AFO in the preceding 12 months. Inspections in general deterrence form represent the sum of the state inspection general deterrence measure and the federal inspection general deterrence measure described in the main text. Enforcement actions in general deterrence form represent the sum of the standardized measures of state-administered informal enforcement actions (count) and monetary penalties (Raff and Earnhart 2020).

Table 3. Effect of NPDES monitoring and enforcement at AFOs on surface water nutrient concentrations, by specific regulatory action

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Panel A. Specific deterrence								
State inspections	0.0180	-0.00120	-0.00217	-0.00299	0.0851	0.0920	0.104	0.0342
	(0.0120)	(0.0121)	(0.0131)	(0.00840)	(0.0684)	(0.0664)	(0.0737)	(0.0340)
Federal inspections	-0.137	-0.126	-0.132	-0.0862	-0.933**	-0.647*	-0.779**	-0.868**
	(0.0929)	(0.113)	(0.120)	(0.0879)	(0.365)	(0.348)	(0.385)	(0.424)
Panel B. General deterrence								
State inspections	-0.657***	-0.788***	-1.114***	-1.023***	-17.47***	-15.81***	-23.78***	-10.32***
	(0.165)	(0.187)	(0.202)	(0.263)	(1.708)	(1.700)	(2.079)	(2.328)
Federal inspections	-33.79**	-30.30***	-52.59***	-27.29**	0.128	-46.06	-102.4*	-120.5**
	(6.577)	(6.874)	(9.816)	(11.98)	(29.56)	(31.05)	(59.51)	(54.40)
Informal enforcement actions	-2.418***	-3.221**	-2.223***	-1.546*	-1.277	-2.331	-0.383	-4.478
	(0.693)	(0.707)	(0.846)	(0.886)	(3.250)	(3.023)	(3.497)	(3.996)
Monetary penalties (000$)	-0.0321	-0.0282	-0.0380	-0.0334	-3.070***	-2.920***	-4.350	-2.790**
	(0.102)	(0.0797)	(0.264)	(0.107)	(1.010)	(0.935)	(0.425)	(1.140)
Operation FE	X	X	X		X	X	X	
Month FE	X	X	X	X	X		X	X
Year FE	X				X			
HUC12 FE	X				X	X		
HUC12#Year FE		X	X	X			X	X
Unit of analysis	AFO	AFO	AFO	HUC12	AFO	AFO	AFO	HUC12
Observations	55,631	55,631	21,971	21,170	52,883	52,883	19,062	15,505

Notes: *** p<0.01, ** p<0.05, * p<0.1. Robust standard errors are in parentheses and are clustered at the unit of analysis level. For columns 1-3 and 5-7, the outcome is the log-transformed monthly average of TP or ammonia concentrations 20 km upstream or downstream of a NPDES permitted AFO. For columns 4 and 8, the outcome is the average monthly TP and ammonia concentration at the HUC12 level. Columns 3 and 6 present results where we limit the analysis sample to only those AFOs with at least one state or federal inspection during the sample period.