Unintended Consequences of Sanitation Investment: Negative Externalities on Water Quality and Health in India

Kazuki Motohashi*

Click here for the most recent version

This version: November 10, 2023

Abstract

Developing countries have increased sanitation investment to improve child health. However, scaling up latrine construction can cause water pollution externalities that offset direct health benefits due to poor treatment of fecal sludge. I estimate these negative externalities of a sanitation policy in India that subsidized the construction of over 100 million latrines. Exploiting geographical variation in a soil characteristic that affects the feasibility of latrine construction, I find that the policy increases river pollution by 72%. While it reduces diarrheal mortality overall, this positive health effect is eliminated when upstream areas have lower capacities for treatment of fecal sludge.

JEL: I15, O13, Q53, Q56

Keywords: Sanitation, Water Quality, Health, Negative Externalities

---

* Hitotsubashi University, Hitotsubashi Institute for Advanced Study. Email: kazuki.motohashi@r.hit-u.ac.jp. I am grateful for guidance and advice from Ujjayant Chakravorty, Shinsuke Tanaka, and Marc Jeuland. For helpful comments, I thank Khushboo Aggarwal, Jenny Aker, Antonella Bancalari, Yuxian Chen, Jishnu Das, Kyle Emerick, Jun Goto, Raymond Guiteras, Cynthia Kinnan, Motohiro Kumagai, Takashi Kurosaki, Daniele Lantagne, Leslie Martin, Patricia Ritter, Adam Storeygard, Haruka Takayama, Takanao Tanaka, Kensuke Teshima, Duc Anh Tran, Zachary Wagner, Junichi Yamasaki, Akio Yamazaki, Hidefumi Yokoo, as well as seminar participants at Hitotsubashi University, Tufts University, Waseda University, JADE/GRIPS, SWELL, Osaka University, and conference participants at 2020 Young JADE Conference, 2021 SEEPS Camp, 2021 AERE Summer Conference, 2021 NEUDC Conference, 2022 JEA Spring Meeting, Camp Resources XXVIII, 2022 AMES Tokyo, AMIE 2nd Workshop in Applied Microeconomics, Fourth SANEM-World Bank North America Discussion Forum. This paper was awarded the 2022 Moriguchi Prize by the Institute of Social and Economic Research, Osaka University.

1 Introduction

The importance of sanitation investment for improving human health in developing countries is widely recognized by policymakers and researchers. Poor access to sanitation facilities and the associated practice of open defecation adversely affect child health by increasing the occurrence of diarrheal diseases. Worldwide, according to the WHO/UNICEF data, 688 million people practiced open defecation in 2016, which is estimated to have caused 432,000 deaths in that year (Prüss-Ustün et al., 2019). To address these issues, developing countries such as India and China have adopted a nationwide policy that provides significant subsidies for the construction of latrines.[1] Their policies intend to improve child health by reducing open defecation and exposure to fecal matter near human habitation. These direct health benefits have been well-documented as local impacts of latrine construction at the village level (Geruso and Spears, 2018; Cameron et al., 2021, 2022).

But little is known about the unintended negative externalities of latrine construction when scaled up as a nationwide policy, which can offset the direct health benefits. The constructed latrines accumulate a large volume of fecal sludge, which must be emptied periodically by vacuum trucks or by hand. The emptied fecal sludge should then be treated by wastewater treatment plants to disinfect the remaining active pathogens. However, due to insufficient infrastructure, the fecal sludge emptied from the growing number of latrines under the policy can be instead dumped into rivers, thus polluting them. These water pollution externalities may decrease the overall effectiveness of latrine construction in improving human health. In the extreme, latrine construction can, in fact, worsen health outcomes if water pollution externalities offset any direct positive effects from reduced open defecation.

Therefore, I examine such negative externalities of latrine construction on water quality and health in the context of India's nationwide sanitation policy, the Swachh Bharat Mission (SBM). Since its inception in 2014, the SBM has allocated about 6 billion USD to subsidize the construction of over 100 million latrines at the household level in rural India.[2] As the largest sanitation policy in the world, the SBM's impacts deserve careful examination. I use administrative panel datasets on the district-level number of latrines from 2012 to 2019 under the SBM and the water quality of 1,189 monitoring stations along rivers in 337 districts from 2007 to 2019 to examine the negative externality on water quality. I combine these with panel data on district-level diarrheal mortality estimates to examine the effect on health.

[1] Like the Indian government's Swachh Bharat Mission examined in this paper, the Chinese government's "Toilet Revolution" built and upgraded over 10 million rural toilets in 2018 to increase sanitary toilets with sealed and covered septic tanks.

[2] The types of latrines most commonly used in rural India are pit latrines and latrines with septic tanks. These are not connected to sewer pipes and accumulate fecal sludge. The disposal of fecal sludge from these latrines can result in water pollution externalities.

My analysis captures the differential effects of latrine construction relative to open defecation, which can also cause water pollution externalities. Open defecation, practiced before the latrine construction, generates small amounts of stool in a wide range of locations. These stools will be flushed into rivers only if it rains and if open defecation sites are close to rivers. On the other hand, constructed latrines concentrate a large volume of fecal sludge that may be dumped directly into rivers. Thus, the volume of fecal sludge that reaches rivers may increase after latrine construction.

To identify the causal effects of latrine construction on water quality and health, I adopt an instrumental variable (IV) design that exploits geographical variation in a soil characteristic that affects the feasibility of latrine construction under the SBM. Specifically, I use Available Water Capacity (AWC), a proxy for soil infiltration rate, interacted with a post-SBM indicator, as an instrument for the number of latrines.[3] This IV design is conceptually similar to the difference-in-differences design, where the reduced-form regression uses AWC as a treatment variable. Higher infiltration rates (lower AWC) increase the risk of groundwater contamination from the fecal sludge accumulated in latrines. To address this risk, an official technical guideline (CPHEEO, 2013), which became effective since the SBM's inception in 2014, requires either greater distances between latrines and wells or the addition of impervious materials inside latrines in areas with high infiltration rates. So, lower AWC increases the difficulty and cost of latrine construction after the SBM started in 2014. Indeed, I find that lower AWC is associated with a smaller increase in latrines during the post-SBM period in the first stage.

I also adopt an upstream-downstream specification that examines the effects of upstream latrine construction on downstream water quality and health. Dumped fecal sludge from latrines can flow downstream along rivers, causing water pollution externalities in downstream areas. I test these spillover effects in the modified IV design, where I use upstream AWC as an instrument for upstream latrine construction and examine its impacts on downstream outcomes. This upstream-downstream specification addresses the concern of exclusion restriction in the baseline IV design, especially for the health outcome. One potential violation could be that AWC, which measures soil quality, affects the health outcome by affecting agricultural output and income, which in turn affects the level of health investments. However, upstream AWC is not expected to affect the downstream health outcome through this income channel, as upstream AWC is unlikely to be associated with downstream agricultural output and income. Indeed, in the reduced-form event study regression, I find that upstream AWC does not have differential effects on water quality and health prior to the SBM policy

[3] Soil infiltration rate is the velocity or speed at which water enters the soil. Conversely, AWC is the amount of water that a soil can store that is available for use by plants.

(before the technical guideline on infiltration rates was published), supporting the validity of the exclusion restriction.[4]

My results show that latrine construction under the SBM degrades river water quality while improving health overall. I find that one additional latrine per square kilometer increases fecal coliform in rivers by 3%. The total effect of the SBM is estimated to be a 72% increase in river pollution. Moreover, I find that water pollution externalities spill over to downstream areas in the upstream-downstream specification. However, I find one additional upstream latrine construction per square kilometer reduces the downstream diarrheal post-neonatal mortality rate per 1,000 live births by 0.011, which is a 0.4% reduction from the pre-SBM period. The total effect of the SBM is estimated to be a 10% decrease in diarrheal mortality rate. This overall positive health effect suggests that the direct positive health effect that comes from the correlated increase in downstream latrine construction outweighs the water pollution externalities.

To identify the mechanism behind these negative externalities, I examine whether the effect of latrine construction on water quality vary by the level of complementary treatment of fecal sludge. Sufficient infrastructure to treat fecal sludge can prevent the dumping of fecal sludge, which is the main mechanism of the negative externalities. The most common such infrastructure takes the form of sewage treatment plants (STPs), which co-treat both urban sewer and rural fecal sludge in India. So, I compare the effects between areas with higher and lower treatment capacities of STPs than the median in the pre-SBM period. In both baseline and upstream-downstream specification, I find that the negative externality on water quality is eliminated in areas with higher treatment capacities.[5] Conversely, in areas with lower treatment capacities, the negative externality on water quality is found to be substantial, which suggests that the dumping of fecal sludge is the mechanism.

The same heterogeneity analysis by the treatment capacity of fecal sludge for the health outcome suggests that water pollution externalities offset direct positive health effects. I find that the total effect of the SBM is a 15% (42%) decrease in diarrheal mortality rate when upstream districts (states) have higher treatment capacities and water pollution externalities are found to be insignificant. However, the positive health effect is eliminated in cases of lower upstream treatment capacities, where water pollution externalities are significant. This difference in health effects between areas with higher and lower treatment capacities suggests that water pollution externalities counteract the direct positive health

[4] For the water quality outcome, I do not find differential effects of AWC prior to the SBM policy in either the baseline or the upstream-downstream specification. Therefore, I present results for both specifications for the water quality outcome, while I focus on the upstream-downstream results for the health outcome.

[5] This null result in areas with higher treatment capacities suggests a low probability that other mechanisms, e.g., the direct seepage of fecal matter from latrines into rivers, affect water quality.

effects, thereby reducing the overall effectiveness of latrine construction in improving human health.

A variety of tests corroborate my findings on the negative externalities of latrine construction. I find no effects on unrelated water quality indicators, such as water temperature and pH, nor on the prevalence of overweight in children aged 0-5. Second, my results are robust to an alternative difference-in-differences design, consideration of spillovers from neighboring districts, influence from urban areas, and a balanced panel, and an alternative mortality dataset.

My findings suggest that an enabling environment that includes effective treatment of fecal sludge can make sanitation policies more effective by mitigating water pollution externalities. The back-of-the-envelope cost-benefit analysis shows that the net mortality benefit (5.6 million USD) is about one-third of the subsidy cost of the SBM policy (16.9 million USD) at the district level. But complementing the latrine construction with sufficient sewage treatment plants would increase the mortality benefit significantly (by 7.4 million USD) with lower additional construction and operating costs of sewage treatment plants (4.5 million USD). More generally, my findings suggest the importance of promoting private goods together with complementary public service provisions to prevent potential negative externalities.

This paper makes three contributions. First, I contribute to the literature on the effects of sanitation interventions by revealing the negative externalities of latrine construction on the environment and health. Previous studies focused on the direct positive effects of sanitation interventions on child health and mortality (Duflo et al., 2015; Hammer and Spears, 2016; Geruso and Spears, 2018; Spears, 2018; Alsan and Goldin, 2019; Cameron et al., 2019, 2021; Flynn and Marcus, 2021; Cameron et al., 2022).[6] I complement these findings by showing that latrine construction additionally causes unintended water pollution externalities, which offset the direct positive health effects. The district-level analysis leveraging policy variation across hundreds of districts in India allows me to examine these externalities that extend beyond villages, which was not captured in most past studies relying on village-level field experiments. Moreover, this paper provides new evidence on the environmental and health effects of the SBM policy, which is the world's largest program of latrine construction.

Second, I contribute to the literature on the causes and effects of water pollution by pro-

[6] Past literature also showed the positive effects of such interventions on educational outcomes (Spears and Lamba, 2016; Adukia, 2017; Orgill-Meyer and Pattanayak, 2020), labor supply (Wang and Shen, 2022), and violence against women (Hossain et al., 2022). Another strand of literature examined the constraints behind latrine adoption, including financial constraints, inadequate information concerning the benefits of latrines and costs of open defecation (Pattanayak et al., 2009; Guiteras et al., 2015; Yishay et al., 2017; Lipscomb and Schechter, 2018), and religious and caste beliefs that discourage latrine use (Spears and Thorat, 2019; Adukia et al., 2021).

viding the first causal estimates of the effects of latrine construction on river water quality.[7] Previous literature has studied how water quality is affected by water quality regulations (Greenstone and Hanna, 2014; Keiser and Shapiro, 2019) and political boundaries (Kahn et al., 2015; Lipscomb and Mobarak, 2016; Motohashi and Toya, 2022). Another set of studies has investigated the effects of industrial and agricultural wastewater on health outcomes, including digestive cancer (Ebenstein, 2012), infant mortality (Brainerd and Menon, 2014; Do et al., 2018), and birth outcomes (Dias et al., 2023). This paper shows that latrine construction substantially increases river pollution (by 72% in the case of the SBM, which is a large effect) and that this increased domestic wastewater from latrines can offset positive health effects.

Third, more broadly, this paper advances the literature on the unintended negative effects of health policies in developing countries by showing that the negative effects due to the displacement of pollution sources can be minimized with sufficient complementary investment. Past literature documented how health policies unintentionally worsen health outcomes due to the reduction in complementary health behaviors (Bennett, 2012; Jeuland et al., 2021), switching to alternative unsafe health behaviors (Buchmann et al., 2019), and abandonment of and delays in project completion (Bancalari, 2020). This paper shows the unintended negative effects of health policies can also be caused by the displacement of pollution sources from open defecation sites to rivers where fecal sludge is dumped. I then show that these effects can be eliminated with sufficient complementary infrastructure for controlling pollution sources.

The rest of the paper is organized as follows. Section 2 describes the SBM and its potential effects on water quality and health. Sections 3 and 4 describe the data and empirical strategies. Section 5 presents the baseline results of the effects on water quality and health. Section 6 presents the heterogeneous effects of latrine construction. Section 7 concludes.

2 Background

2.1 Latrine Construction under Swachh Bharat Mission in India

To eliminate open defecation, the Indian government has subsidized the construction of over 100 million latrines in rural India under the Swachh Bharat Mission (SBM), the largest sanitation policy in the world.

[7] Public health literature has examined the association between pit latrines and groundwater quality based on a limited sample of a few hundred latrines (Graham and Polizzotto (2013) reviewed these studies). This paper estimates the causal effects of latrines on river water quality based on nationwide administrative data.

In India, a large number of people have historically practiced open defecation, which adversely affects child health by increasing the occurrence of diarrheal diseases. About 470 million people in India practiced open defecation in 2013, according to the WHO/UNICEF Joint Monitoring Programme. As such, India had the highest number of people practicing open defecation in the world, more than 10 times that of the country with the second-highest number, Nigeria, in 2013 (Appendix Figure C1).

To eliminate open defecation and improve human health, the Indian government has implemented a nationwide sanitation policy that subsidizes latrine construction, the SBM.[8] Since its inception in 2014, the SBM has set an ambitious goal of achieving universal latrine coverage by October 2nd, 2019, the 150th anniversary of Mahatma Gandhi's birth. To achieve this goal, the SBM significantly increased the amount of subsidy to about 145 USD (12,000 INR) per household. This subsidy covers most of the initial cost of basic latrines in rural India.

With this big push to construct latrines, the SBM has become the largest sanitation policy in the world, building over 100 million latrines in rural India by spending about 6 billion USD.[9] Latrine coverage dramatically increased from 39.2% in 2013 to almost 100% in 2019, according to the administrative database of the SBM (Figure 1). A recent government-commissioned survey also found that 85% of the rural population used toilets in 2019-2020, which suggests almost universal latrine coverage had been achieved under the SBM as shown in the administrative database (DDWS, 2020). As the largest sanitation policy in the world, the SBM's impacts on water quality and health deserve careful examination.

2.2 Negative Externality of Latrine Construction on Water Quality

The large-scale latrine construction under the SBM may cause a unintended negative externality on river water quality due to poor treatment of fecal sludge emptied from latrines.

Dumping fecal sludge emptied from latrines can cause river pollution. Latrines accumulate a large volume of fecal sludge, which must be emptied either by vacuum trucks or manually. The emptied fecal sludge should then be transported to and treated at the wastewater treatment plants to disinfect the remaining active pathogens.[10] However, due to

[8] Swachh Bharat Mission (SBM) is the most recent policy out of four consecutive sanitation policies at the central government level. Although state governments have primary responsibility for public health and sanitation, these central government-level policies were meant to influence the state-level sanitation policies through policy guidance and budget allocation.

[9] According to the actual expenditure shown in the annual budgets of the Indian government, the central government has spent about 6.37 billion USD (497 billion INR) from 2014 to 2019. The data source on the number of built latrines is the SBM website (`https://swachhbharatmission.gov.in/SBMCMS/about-us.htm`).

[10] Although the fecal sludge contained in pits degrades to some degree with time, pathogens can be

insufficient infrastructure, the emptied fecal sludge is instead frequently dumped into rivers, which can cause water pollution in rivers.[11]

My analysis captures the differential effects of latrine construction relative to open defecation, which can also cause the water pollution externality. Open defecation, practiced before the latrine construction, generates small amounts of stool in a wide range of locations. These stools decompose in sunlight and will be flushed into rivers only if it rains and if open defecation sites are close to rivers. On the other hand, latrines accumulate a large volume of fecal sludge that may be emptied and dumped directly into rivers. Thus, the volume of fecal sludge that reaches rivers may increase after latrine construction.

This paper argues that the water pollution externality of latrine construction is unintended, as evidenced by the absence of policy targets addressing the treatment of fecal sludge. Under the SBM, a village is declared and verified to be open defecation free based on a checklist of indicators including access to toilet facilities, 100% usage, fly-proofing, and safe septage disposal as per the SBM guideline (MDWS, 2018). In the safe septage disposal section, while the checklist stipulates that toilets should be connected to pits or septic tanks, it lacks specific guidance on how the emptied fecal sludge should be properly treated.

2.3 Negative Externality of Latrine Construction on Health

The latrine construction under the SBM may also result in a negative externality on health through increasing river pollution. Exposure to polluted water increases the risks of diarrheal diseases and mortality for people who uses river water in their daily lives.

These water pollution externalities of latrine construction may offset direct positive health effects from reduced open defecation. Latrine construction has direct positive effects on health by reducing open defecation and exposure to fecal matter near human habitation, while at the same time, latrine construction may indirectly cause negative externality on health due to increased river pollution. The magnitudes of both the direct positive health effects and the indirect negative externality determine the sign of the overall health effect. My analysis investigates this overall health effect in terms of diarrheal mortality. This tradeoff between water pollution externalities and direct positive health effects is formally presented in a conceptual framework in Appendix A.

present even after long-term storage. The primary objective of pit latrines is fecal containment rather than pathogen reduction (Orner et al., 2018).

[11] An ethnographic study on 32 truck operators that clean latrines showed that these operators practice illegal dumping, although this study focuses on urban areas in Bangalore, Karnataka (Prasad and Ray, 2019). Illegal dumping and associated water pollution have also been pointed out by news media.

2.4 Complementary Treatment of Fecal Sludge

The magnitude of negative externalities of latrine construction on water quality and health varies by the level of complementary treatment of fecal sludge. The adequate treatment of emptied fecal sludge prevents the dumping of fecal sludge, which is the main mechanism of the negative externalities of latrine construction.

In India, local governments are tasked with developing infrastructure that treats emptied fecal sludge, i.e., sewage treatment plants (STPs) and fecal sludge treatment plants (FSTPs). STPs are large-scale facilities that have been available in India for a long time. India had about 500 STPs in operation in 2015 (CPCB, 2015). STPs are typically designed to treat urban sewage, but they are also increasingly used to co-treat fecal sludge due to the under-utilization of STP capacities in India.[12] On the other hand, FSTPs are newly developed small-scale facilities for treating fecal sludge. FSTPs started operating in 2014, and there were only about only 30 FSTPs in operation at the end of 2019 (Rao et al., 2020).

I use geographical variation in STP capacity in the pre-SBM period to examine the heterogeneous effects on water quality and health.[13] The negative externality on water quality is expected to be substantial in areas with lower treatment capacities. Thus, in these areas, the negative externality on health is also expected to be larger, which suggests a smaller overall positive health effect. Conversely, I expect to find smaller water pollution externalities in areas with high treatment capacities, leading to a larger positive health effect. I develop a conceptual framework in Appendix A to derive these predictions on heterogenous effects, which are then tested in the empirical analysis.

3 Data

I combine administrative datasets on the water quality of rivers and latrines across India to examine the negative externality of latrine construction on water quality. I use district-level diarrheal mortality estimates as an additional outcome to examine the negative externality on health. I use Available Water Capacity (AWC) as an instrument for latrines. Moreover, I control for a district characteristic that might affect latrine construction and outcomes. All of these data are spatially matched based on the 2011 district-level boundary data.

[12] Although the data on the actual prevalence of co-treatment is not available, case studies are available for STPs in Panaji (Goa), Kanpur (Uttar Pradesh), and Chennai (Tamil Nadu). Also, policies and guidelines mentioning the co-treatments at STPs are available in multiple states, such as Punjab, Madhya Pradesh, Jharkhand, and Rajasthan (Gupta et al., 2018).

[13] I do not consider FSTP capacities because there were no FSTPs in the pre-SBM period.

3.1 Water Quality

This paper adopts two outcome variables: water quality and health. As a first outcome, I use detailed water quality data from 1,189 monitoring stations along rivers in India from 2007 to 2019 (Figure 2). The data is based on the National Water Quality Monitoring Programme (NWMP), managed by the Central Pollution Control Board (CPCB).[14]

Among multiple water quality indicators, I use fecal coliform as a main indicator because fecal coliform is a direct measurement of the fecal contamination caused by the fecal sludge emptied from latrines.[15] A higher value of fecal coliform means a higher level of fecal contamination. In the analysis, I use the average of maximum and minimum values of fecal coliform because mean values are only available up to 2014.[16] Lastly, since the distribution of fecal coliform is approximately log normal, I use the log of fecal coliform as a water quality outcome in the analysis.

3.2 Health

Another outcome variable is health. I use the diarrheal mortality rate estimates (per 1,000 live births) from 2000 to 2019, provided as 5-kilometer raster data by the Institute for Health Metrics and Evaluation (IHME, 2020a). This dataset includes estimates of diarrheal mortality in five age groups, i.e., early-neonatal (0-6 days), late-neonatal (7-27 days), post-neonatal (28 days - 1 year), ages 1-4, and under age 5. These estimates are constructed based on the geocoded datasets of multiple household surveys, including the India National Family Health Survey, the India District Level Household Survey, and the India Human Development Survey.[17] For the analysis, I compute the district-level mean of these estimates based on this raster data and district boundary data.

3.3 Latrines

The treatment variable is the number of latrines. I use the administrative data on the district-level number of household latrines from 2012 to 2019 in rural India, which are scraped from

[14] I additionally identify the basin of each monitoring station by using the GPS coordinates of monitoring stations and the "Watershed Map of India" of the ML Infomap.

[15] I do not use other common water quality indicators such as Biological Oxygen Demand (BOD) and Dissolved Oxygen (DO) because they capture the overall level of water contamination from various pollution sources, including agricultural and industrial wastewater.

[16] The correlation between mean values and average values of fecal coliform is 0.9973, which suggests that average values are good proxies of mean values.

[17] IHME (2020a) applies a Bayesian model-based geostatistical framework to 15 geocoded variables and 3 national-level time-varying variables to predict the posterior distributions of diarrheal mortality. One of the national-level time-varying variables is the percentage of the population with access to improved latrines, but my analysis controls for this in year fixed effects.

the database available on the SBM website. Based on this dataset, I compute the number of latrines per square kilometer as a normalized measure.[18]

One concern about this dataset is that the number of latrines may be systematically overestimated because the data are collected by the Indian government under the SBM policy, whose aim is to achieve universal latrine coverage. Due to this potential measurement error, my analysis could yield lower-bound estimates because the actual number of latrines could be lower than those in the administrative data. Adopting the IV design mitigates the concern of this potential measurement error.

3.4 Available Water Capacity

For the IV design, I use Available Water Capacity (AWC) as an instrument for the number of latrines. AWC is the amount of water that a soil can store that is available for use by plants. AWC represents a soil infiltration rate, i.e., the velocity or speed at which water enters the soil. Higher AWC is associated with a lower soil infiltration rate. The AWC data is available in the Harmonized World Soil Database v1.2 provided by the Food and Agriculture Organization of the United Nations (FAO). This database provides 30 arc-second raster data of AWC across the globe. I compute the district-level mean of AWC based on this raster data and district boundary data.

3.5 Other District Characteristic

I supplement the above information with further data to account for the district characteristic that might affect latrine construction, water quality, and health. Specifically, I use 0.25-degree raster data of precipitation from 2007 to 2019, provided by the India Meteorological Department (Pai et al., 2014). I aggregate daily raw data into annual data. Then, I construct the district-level mean of precipitation based on this raster data and district boundary data.

3.6 Data Matching and Sample Construction

To match water quality data with other data, I first use the 2011 district-level boundary data of the ML Infomap and the GPS coordinates of monitoring stations to identify the districts where monitoring stations are located. Then, I match water quality data with latrine data based on district names.[19] All other data are similarly matched to water quality and latrine

[18] I do not consider whether constructed latrines are used due to a lack of district-level panel data on latrine usage. Because the usage rate of constructed latrines can be lower than 100% in India, my estimates represent the lower bound of the effect of the increase in latrine usage.

[19] I deal with the changes in the district boundary by ensuring that all data are organized according to the 2011 boundary. Latrine data based on the 2019 boundary are aggregated to follow the 2011 boundary

data by following the 2011 district boundary.

After the data matching, I construct an unbalanced panel data of 1,189 water quality monitoring stations in 337 districts from 2007 to 2019.[20] In most analyses, I use data of 1,189 stations from 2012 because latrine data is only available from that year. When examining health effects, I focus on the same 337 districts used in the analysis of water quality. Specifically, I construct a balanced panel of 337 districts from 2012 to 2019. For the reduced-form event study analysis, I use a longer panel of water quality and health data spanning from 2007 to 2019.

Table 1 shows the summary statistics of the variables used for the baseline analysis.[21] Time-varying variables are shown separately for both pre-SBM and post-SBM periods.

4 Empirical Strategy

I empirically examine the effects of latrine construction under the SBM on river water quality and health. Estimates of ordinary least squares (OLS) might be biased due to reverse causality and omitted variables. For example, increase in diarrheal mortality rate may encourage latrine construction to address this health issue, leading to reverse causality. Moreover, spurious correlations may be caused by unobservables that affect both latrine construction and water quality. For example, unobserved persistent belief in open defecation may reduce the probability of latrine construction and affect water quality and health due to the associated practice of open defecation.

To estimate the causal effects of latrine construction, I adopt an IV design, which exploits geographical variation in a soil characteristic that affects the difficulty and cost of latrine construction under the SBM.

4.1 Instrumental Variable Design

In the IV design, I use geographical variation in Available Water Capacity (AWC), a proxy for the soil infiltration rate, interacted with a post-SBM indicator, as an instrument for latrine construction to examine the effects of latrine construction on water quality and health.

Higher soil infiltration rates (lower AWC) increase the risk of groundwater contamination from the fecal sludge accumulated in pit latrines, the widely adopted type in rural India.

by considering the district splits from 2011 to 2019.

[20] In the main specification, I use an unbalanced panel data of water quality to cover as many districts as possible to enhance the external validity. As a robustness check, I run the same analysis on a balanced panel in Section 5.3.

[21] Appendix Table D1 shows the summary statistics of the variables used in robustness checks.

Pit latrines consist of a hole, called a pit, that accumulates fecal sludge without a completely sealed wall. So, pathogens inside the fecal sludge can percolate into soils, potentially causing fecal contamination of groundwater sources such as wells.[22] The degree of this fecal contamination depends on the soil infiltration rates.

To address the risk of groundwater contamination, an official technical guideline (CPHEEO, 2013), which became effective since the SBM's inception in 2014, requires additional precautionary measures for latrine construction in areas with high infiltration rates (lower AWC). So, lower AWC increases the difficulty and cost of latrine construction after the SBM started in 2014. If the effective size (ES) of the soil is 0.2 mm or less, i.e., a lower infiltration rate (higher AWC), pits can be located at a minimum distance of 3 meters from water sources such as wells. However, for coarser soils with ES greater than 0.2 mm, i.e., a higher infiltration rate (lower AWC), the minimum distance must be greater than 3 meters. In cases where the requirement for minimum distance cannot be met, additional investments are mandated for latrine construction. Specifically, the bottom of the pits must be sealed off with impervious materials such as puddle clay and plastic sheeting, and a 500 mm thick envelope of fine sand of 0.2 mm effective size must surround the pit.[23] In short, higher infiltration rates (lower AWC) make it more difficult to find the space for latrines or increase the cost of their construction due to these additional investments after the SBM started in 2014.[24]

Therefore, I use AWC interacted with a post-SBM indicator as an instrument for the number of latrines. Figure 3 shows substantial variation in AWC across districts in India. In the first stage, an area with lower AWC, i.e., a higher infiltration rate, is expected to experience a smaller increase in the number of latrines. As expected, Column 2 of Tables 2 and 3 show that one mm/m decrease in AWC is associated with a smaller increase in the number of latrines per square kilometer by about 0.3. The F-statistics of the first stage regressions are relatively high (30.0 and 50.5 in Table 2 and 78.7 in Table 3).

In the analysis of the effect on water quality, I adopt the following two-stage least squares regressions, where regressions 1 and 2 are second stage and first stage regressions, respectively. This IV design is conceptually similar to the DID design, where the reduced-form

[22] This fecal contamination of groundwater sources is different from the river pollution that is caused by the dumping of fecal sludge emptied from latrines. The former is considered to motivate the IV design, while the latter is the effect I investigate in this paper.

[23] Noncompliance with these requirements in the technical guideline can weaken the first-stage relationship. I discuss the F-statistics of the first-stage relationship below, as well as show the confidence interval of the Anderson and Rubin (1949) test that is robust to the weak instrument in Section 5.

[24] This relationship applies not only to pit latrines but also to latrines with septic tanks, which are usually equipped with soak pits that treat septic tank effluent. Soak pits are subject to similar requirements that depend on soil infiltration rates to prevent groundwater contamination (CPHEEO, 2013).

regression in this IV design uses AWC as a continuous treatment variable.

$$Y_{i,d,t} = \alpha + \beta_{IV} Latrine_{d,t} + \gamma_1 Precip_{d,t} + \delta_i + \theta_t + \varepsilon_{i,t} \tag{1}$$

$$Latrine_{d,t} = \pi_1 + \pi_2 AWC_d \cdot Post_t + \pi_3 Precip_{d,t} + \delta_i + \theta_t + \nu_{i,t} \tag{2}$$

where $Y_{i,d,t}$ is a water quality indicator, represented by the logarithm of fecal coliform, at monitoring station i inside district d in year t. $Latrine_{d,t}$ is the number of latrines per square kilometer at district d of monitoring station i in year t. $Precip_{d,t}$ is precipitation at district d in year t, which is added to control for the rainfall and associated floods that may affect both water quality and latrine construction. A time-variant instrument for the panel data analysis is constructed by interacting time-invariant AWC at district d with a post-SBM indicator that takes the value one after 2014 when SBM started. δ_i is monitoring station fixed effects, and θ_t is year fixed effects. Standard errors are clustered at the district level because the variation in the number of latrines is observed at the district level. The coefficient of interest is β_{IV}, and I expect it to be positive.

The IV design builds on a key assumption of exclusion restriction. In this analysis, the instrument, $AWC_d \cdot Post_t$, must affect outcomes only through the channel of latrine construction after controlling for precipitation, monitoring station fixed effects, and year fixed effects.

In the water quality analysis, I choose fecal coliform as a water quality indicator to address the concern of the exclusion restriction. One potential concern is that AWC, which measures soil quality, affects the agricultural yield of crops. This, in turn, could affect the volume of agricultural runoff, leading to changes in water quality. Therefore, I use fecal coliform as a water quality outcome, because it is primarily affected by fecal sludge from latrines and is unrelated to crop production.

For the analysis of the health effect, there are also legitimate concerns regarding the exclusion restriction, leading to the adoption of the upstream-downstream specification in Section 4.2. For instance, AWC might affect the agricultural yield of crops, which in turn could determine a household's income. This change in income could then affect the level of health investments, leading to changes in health conditions.[25] To address this concern, I adopt the upstream-downstream specification, where I use upstream AWC as an instrument for upstream latrine construction and examine its effect on downstream outcomes, as described in the following section.

[25] Although district fixed effects control for time-invariant agricultural productivity across districts, differential growth in agricultural yield caused by different levels of AWC might be present. This could lead to potential differential increases in income and health investment.

4.2 Upstream-Downstream Specification

The negative externalities on water and health may spill over to downstream districts because dumped fecal sludge can flow downstream along rivers. Thus, I adopt additional upstream-downstream specification to examine the effects of upstream latrine construction on downstream water quality and health.

The upstream-downstream specification addresses the concern of exclusion restriction in the baseline IV specification. The baseline specification is modified by using upstream AWC as an instrument for upstream latrine construction to examine its effects on downstream outcomes, while controlling for downstream AWC. Upstream AWC might affect upstream agricultural output and income, which in turn affects health outcomes in the same area However, it is not expected that upstream AWC would affect downstream health outcomes through changes in downstream agricultural income, as the upstream AWC is unlikely to be associated with the downstream agricultural output. Therefore, by adopting upstream AWC, which is unrelated to downstream agricultural output and income, as an instrument, and focusing on downstream health as an outcome, this specification addresses the concern of the exclusion restriction. This concern pertains to the possibility that AWC might affect health outcomes through changes in agricultural income, representing a causal path other than that of latrine construction. In other words, the upstream-downstream specification, which relys on the instrument and outcome being in different locations along rivers, enhances the validity of the exclusion restriction.[26]

I identify upstream-downstream relationships among monitoring stations and districts using the elevation data along 43 major rivers.[27] Thus, this specification focuses on a subset of districts (stations) located along major rivers that have further upstream districts.[28] As shown in Appendix Figure 4, the upstream districts of a given district (station) are selected as the districts that intersect with river segments whose elevations are higher than the elevation of the given district (station).

The definition of upstream districts, i.e., how far upstream I should search for districts, matters because the pollution decays as it flows downstream. Because the decay rates depend

[26] This approach to using upstream-downstream relationship in the IV design aligns with the methodology adopted in Dias et al. (2023).

[27] I focus on major rivers included in the Version 4.1.0 GIS polygons of rivers provided by the Natural Earth. Upstream-downstream relationships along major rivers are less susceptible to measurement errors because the river systems are simpler than those that include hundreds of rivers. I use 90-meter raster digital elevation data, called the Shuttle Radar Topography Mission (SRTM) data Version 4.1 (Reuter et al., 2007).

[28] The focus on major rivers results in a sample of 365 stations in 154 districts in the water quality analysis. In the district-level health analysis, I further drop districts where more than one major rivers flow due to the complexity of determining the upstream-downstream relationships, resulting in a sample of 103 districts.

on the temperature and other environmental factors of rivers, I adopt a variety of distances from a given district (station) for identifying upstream districts. Specifically, for a given district (station), the upstream districts are selected from districts that fall within a range of $[X, Y]$ kilometers from the given district (station), where $X \in \{0, 50, 100\}$, $Y \in \{100, 150\}$, and $X < Y$. I use a range of $[0, 150]$ kilometers as the baseline specification, but the results remain robust when using alternative buffer sizes or considering all upstream districts without buffers, as shown in Appendix Table D2.[29]

In this upstream-downstream analysis, I use the following regressions 3 and 4 modified from the baseline specification. The independent variable is changed to the upstream number of latrines per square kilometer, and the instrument is changed to the upstream AWC.[30] I also control for AWC in the reference district because the instrument (upstream AWC) can be spatially correlated with AWC in the reference district, which can also affect outcomes.

$$Y_{i,d,t} = \alpha + \beta_{IV}^{U} Upstream\_Latrine_{d,t} + \gamma_1 Precip_{d,t} + \gamma_2 AWC_d \cdot Post_t + \delta_i + \theta_t + \varepsilon_{i,t} \quad (3)$$

$$\begin{aligned} Upstream\_Latrine_{d,t} = \pi_1 + \pi_2 Upstream\_AWC_d \cdot Post_t + \pi_3 Precip_{d,t} \\ + \pi_4 AWC_d \cdot Post_t + \delta_i + \theta_t + \nu_{i,t} \end{aligned} \quad (4)$$

For the health analysis, the outcome variable, $Y_{d,t}$, is redifined as the district-level diarrheal mortality rate. I specifically focus on post-neonatal mortality because it is the closest available measure to infant mortality, which is frequently used as an outcome in studies of sanitation and water pollution (Do et al., 2018; Geruso and Spears, 2018).[31] As the health analysis uses district-level panel data, I use district fixed effects in place of monitoring station fixed effects. Standard errors are similarly clustered at the district level.

The coefficient of interest, β_{IV}^{U}, captures the effect of upstream latrine construction, which comprises two underlying channels: (i) the direct effect of upstream latrine construction on outcomes and (ii) the indirect effect of upstream latrine construction on outcomes via correlated latrine construction in the reference district, as illustrated in Appendix Figure C3.[32] In the first channel, I expect that upstream latrine construction leads to water pollution

[29] The same procedure is repeated to identify downstream districts for a placebo test. These are selected as the districts that intersect with river segments whose elevations are lower than the elevation of the given district (station).

[30] If there are multiple upstream districts, I compute the independent variable by dividing the total number of latrines by the total area of these districts. Additionally, I calculate the instrument by taking the average of the AWC values from these districts.

[31] Post-neonatal mortality and infant mortality refer to the probabilities of a child dying between 28 days after birth and the age of one year and dying between the birth and the age of one year, respectively.

[32] The correlation between latrine construction in upstream districts and the reference district exists because I do not explicitly control for latrine construction in the reference district. Another approach would be to control for latrine construction in the reference district by using AWC in that district as an additional instrument. However, this approach is not adopted due to the weak instrument issue when dealing with two

that flows downstream, subsequently causing a negative externality on health in the reference district. In the second channel, I expect that latrine construction in the reference district, which is positively correlated with upstream latrine construction, contributes to increased water pollution in that district.[33] The sign of the health effect depends on the relative magnitude of direct positive health effects and water pollution externalities resulting from latrine construction in the reference district. Therefore, the β^U_{IV} is expected to be positive for the water quality outcome, as an increase in water pollution is expected in both channels. However, the sign of the overall health effect is ambiguous because it depends on the sign and relative magnitude of the health effect in each channel.

4.3 Validity of Exclusion Restriction

I conduct two tests to check the validity of the exclusion restriction.

As a first test, I run reduced-form regressions of water quality and health outcomes on the interaction of AWC with year dummies. The exclusion restriction implies that AWC should not affect these outcomes prior to the implementation of the SBM policy. During the pre-SBM period, AWC is unlikely to affect latrine construction because the official technical guideline, which requires consideration of soil infiltration rate, had not been published until 2013, just before the start of the SBM.[34] Thus, the association of AWC and outcomes during the pre-SBM period captures the causal pathways other than through latrines. Conversely, after the SBM started to incentivize latrine construction in 2014, AWC is expected to have a strong relationship with outcomes. By extending to the upstream-downstream specification, I also test whether upstream AWC have differential effects on outcomes in the reference district in both the pre-SBM and post-SBM periods.

The reduced-form event study results show that upstream AWC does not have a differential effect on either water quality or health prior to the SBM policy (up to 2013), supporting the validity of the exclusion restriction (Panels B and C in Figure 5). Furthermore, I find that AWC does not have a differential effect on water quality prior to the SBM policy in the baseline specification (Panel A).[35] In contrast, starting from 2014, larger AWC values lead to an increase in fecal coliform and a decrease in diarrheal post-neonatal mortality rate in

endogenous variables and two instruments.

[33] The positive correlation of latrine construction is expected because upstream and reference districts are usually influenced by same sanitation policies of the same state. This is further explained in Section 5.2.

[34] The non-differential effect of AWC on latrine construction during the pre-SBM period is illustrated in the first-stage event study plots presented in Appendix Figure C2. The differential effect of AWC starts to be statistically significant from the year 2014 onwards.

[35] Conversely, a differential effect of AWC on health prior to the SBM policy is observed in the baseline specification in Appendix Figure C4, suggesting a violation of the exclusion restriction. Therefore, I present only the upstream-downstream results for the health outcome in subsequent sections.

both the baseline and upstream-downstream specifications.[36]

As a second test of the validity of the exclusion restriction, I conduct falsification tests that examine the effects on other water quality and health indicators unrelated to fecal contamination. Specifically, I examine the effects of latrine construction on water temperature, pH, and the prevalence of overweight in children aged 0-5.[37] The exclusion restriction suggests that latrine construction should not affect these irrelevant outcomes. Reassuringly, I find no effects on water temperature, pH, and overweight prevalence (Columns 1-2 and 6 of Appendix Table D5).[38]

5 Results

5.1 Effects on Water Quality

I find that latrine construction under the SBM degrades river water quality and this water pollution externality spills over to downstream areas.

As for results in the baseline specification, Panel A of Table 2 shows that one additional latrine per square kilometer increases fecal coliform by 3% on average (Column 3). This estimate of the effect on water quality in the IV design is substantially larger than in the OLS regression, which is about 0.6% (Column 1). This difference comes from the downward bias from the endogeneity in the OLS regression, possibly due to measurement errors in the number of latrines and omitted variables, including persistent belief in open defecation that increases water pollution but slows down latrine construction. Moreover, the standard errors remain stable even when adjusted for spatial dependence with a cutoff of 150 kilometers, following the Conley (1999) approach.

The result of the first stage shows the positive association between AWC and the number of latrines as expected (Column 2 of Panel A). Although the F-statistics of the first stage are not low (29.954), I also compute the 95% confidence interval of the Anderson and Rubin (1949) test that is robust to the weak instrument. Reassuringly, the positive left and right

[36] The lagged effect on water quality, becoming statistically significant starting from 2017, can be explained by the fact that it typically takes between 1.5 to 3 years for latrines to fill up with fecal sludge and subsequently be emptied, as per the requirement stated in the technical guideline (CPHEEO, 2013).

[37] This test uses water quality data of the NWMP and overweight prevalence estimates from IHME (2020b).

[38] In further analysis, I examine the effects on BOD and DO, which measure water contamination from various pollution sources including industrial and agricultural wastewater. I find no significant effects on these variables (see Columns 3-4 of Appendix Table D5). Additionally, I find no effect on Nitrate-Nitrite, which primarily captures contamination from agricultural wastewater (Columns 5). These results suggest that there are no significant sources of water contamination resulting from other programs implemented concurrently with the SBM, apart from fecal contamination.

ends of the 95% confidence interval ([0.15, 0.49]) show that the result is robust to this Anderson and Rubin (1949) specification.[39]

A total effect of the SBM (hereinafter called "average policy effect") is a 72% increase in fecal coliform, which shows a substantial negative externality on the water quality (Column 3 of Panel A). The average policy effect is calculated by multiplying the estimated coefficient by the difference between the mean number of latrines per square kilometer during the pre-SBM (2012-2013) period and during the post-SBM period (2014-2019).[40]

This 72% increase in fecal coliform due to latrine construction surpasses the estimates of most previous studies conducted in different settings. This significant rise can be attributed to the more than doubling of latrine coverage during the SBM period. It is considerably larger than the effect of each additional border crossing induced by a border change on water pollution levels (3% increase) in Brazil (Lipscomb and Mobarak, 2016) and the effect of each additional Clean Water Act grant to municipal wastewater treatment plants on fecal coliform (3.6 % decrease) in the United States (Keiser and Shapiro, 2019).

In the upstream-down specification, I also find that the water pollution externality of latrine construction spills over to downstream districts. Panel B of Table 2 shows that one additional upstream latrine construction per square kilometer increases fecal coliform by 1.5% on average (Column 3). While this effect is found to be imprecise, the reduced-form event study results indicate statistically significant effects around the years 2017-2019 (Panel B of Figure 5). On the other hand, in a placebo test, I find no effect of downstream latrine construction on water quality in the reference district (Column 1 of Appendix Table D3). This result aligns with expectations because water pollution should not spill over from downstream to upstream areas.

5.2 Effects on Health

I find that latrine construction under the SBM improves health overall, which suggests that the direct positive health effect outweighs the negative externality on health due to increased water pollution.

In the upstream-downstream specification, I find that upstream latrine construction reduced diarrheal mortality in the reference district overall (Column 3 of Panel A of Table 3). Although upstream latrine construction can negatively affect health by causing water pollution spillovers to the reference district (direct effect discussed in Section 4.2), it can also improve the health outcome in the reference district via correlated latrine construction

[39] The Anderson and Rubin (1949) confidence intervals are also shown for other results in subsequent sections.

[40] When I calculate average policy effects for other results, I use the difference in the mean number of latrines per square kilometer in each sample.

in that district (indirect effect discussed in Section 4.2). The overall positive health effect indicates that the net positive health effect from increased latrine construction in the reference district outweighs the water pollution externalities from upstream districts. This overall positive health effect result remains robust when using diarrheal mortality rate for other age groups as outcomes (Appendix Table D4). Additionally, in a placebo test, I reassuringly find no effect of downstream latrine construction on health in the reference district (Column 2 of Appendix Table D3).

As supporting evidence of the indirect effect, I find a positive correlation between latrine construction in upstream and reference districts (Column 3 of Panel B of Table 3). This positive correlation can be attributed to the fact that these districts are usually located within the same state, given that the buffer sizes for identifying upstream districts are less than or equal to 150 kilometers. Since states play a central role in implementing sanitation policies in India, districts within the same state are likely to undertake similar levels of latrine construction.[41]

As for the magnitude of the health effect, one additional upstream latrine construction per square kilometer reduces the diarrheal post-neonatal mortality rate per 1,000 live births by 0.011, which is a 0.4% decrease from the pre-SBM period (Column 3 of Panel A of Table 3).[42] The average policy effect of the SBM is calculated to be a 0.269 reduction in diarrheal post-neonatal mortality rate per 1,000 live births, which amounts to a 10% reduction from the pre-SBM period. This total 10% reduction in diarrheal mortality under the SBM policy is smaller compared to the effects noted in past studies, such as the one by Geruso and Spears (2018), which reported a 48% decrease in the infant mortality rate associated with a 60 percentage point reduction in the fraction of neighbors defecating in the open, a change similar in magnitude to the SBM policy. This discrepancy may arise from the inclusion of water pollution externalities in the district-level analysis of this paper.

5.3 Robustness Checks

The results are robust to an alternative difference-in-differences (DID) design, the consideration of spillovers from neighboring districts, influence from urban areas, and a balanced

[41] To directly test this claim, I estimate the intra-cluster correlation coefficient, which measures the proportion of the overall variance that is explained by the within-state variance in the change in the number of latrines per square kilometer from 2013 to 2019. The coefficient is estimated to be 0.704, indicating that districts within the same state behave similarly in terms of latrine construction.

[42] The magnitude of the effect on health in the IV design (Column 3) is larger than that in the OLS regression (Column 1). This difference comes from the endogeneity in the OLS regression, possibly due to measurement errors in the number of latrines and reverse causality when an increase in diarrheal mortality encourages the latrine construction to address this health issue.

panel, and an alternative mortality dataset.[43]

Alternative Difference-in-Differences Design.—I adopt a DID design that exploits a differential increase in latrine coverage across districts with different levels of baseline coverage. According to the SBM database, all districts had achieved almost universal latrine coverage by the target date of 2019, regardless of their baseline latrine coverage. Therefore, districts with lower baseline latrine coverage have experienced a larger increase in latrine coverage, which may lead to a larger increase in water pollution. The DID design uses the baseline latrine non-coverage in 2013, interacted with a post indicator that takes the value one after 2014, when SBM started, as a treatment (More details in Appendix B).

As shown in Appendix Table B1, I find results that are similar to those of the IV design. I find a negative effect on water quality, although the overall effect becomes imprecise (Column 1). Regarding the heterogeneous effects by treatment capacity of fecal sludge, as examined in Section 6, I find that the negative externality on water quality is concentrated in areas with lower treatment capacities (Columns 2-5), consistent with the IV results. The event study results show that the parallel pre-trends hold, and the water pollution effect becomes more pronounced over time in states with lower treatment capacities (Panel B of Appendix Figure B3).

Spillovers from Neighboring Districts.—My baseline analysis assumes that water quality in a given monitoring station is affected only by the latrine construction in the district where that monitoring station is located. However, monitoring stations can be situated on rivers that flow along the border of several districts. In this case, water quality in those stations is likely to be affected by several neighboring districts. Therefore, I conduct an additional analysis that incorporates spillover effects from neighboring districts. For the monitoring stations that are located within 2 kilometers of more than one district, I compute the weighted average of variables of neighboring districts by using district areas as weights. The data of other monitoring stations remain unchanged. Then, I run the regressions of the baseline IV specification for the water quality outcome.

As shown in Column 1 of Appendix Table D6, I find results that are similar to the baseline results. I find a negative effect on water quality, and the effect is driven by areas with lower treatment capacities.

Influence from Urban Areas.—While my focus is on the effects of latrine construction in rural India, it is possible that the my baseline results are partly driven by latrine construction

[43] While I mainly test the robustness of the baseline results that serves as the basis for the heterogeneity analysis in Section 6, I also include results of heterogeneous effects in this section.

in urban areas. Therefore, I conduct a robustness check that estimates the effects after excluding monitoring stations and districts that are close to urban areas from the sample. Specifically, I drop monitoring stations and districts that are within 50/100/150 kilometers of cities with a population of 1 million and above, according to the 2011 Census.

As shown in Appendix Table D7, the results are robust to excluding urban areas regardless of distance. As in the baseline results, I find a negative effect on water quality and an overall positive health effect, although the health effect becomes imprecise possibly due to smaller sample sizes.

Balanced Panel.—The baseline analysis uses unbalanced panel data on water quality, so I conduct a robustness check using a balanced panel. Using the balanced panel mitigates the concern that monitoring stations may have been endogenously installed in less polluted locations over the sample periods. As shown in Column 1 of Appendix Table D8, I similarly find a negative effect on water quality, especially in areas with lower treatment capacities.

Alternative Mortality Dataset.—The baseline analysis uses diarrheal mortality rate estimates from IHME (2020a) as health outcomes, but these are predicted estimates based on several household surveys. For a robustness check, I conduct the same analysis using original household survey data. Specifically, I use the infant mortality data frin the National Family Health Survey 5 (NFHS-5), conducted in 2019-2021. The NFHS-5 interviews all women aged 15-49 within the sample households and records detailed information about their birth histories. In their birth histories, I use the data concerning the year of birth and whether the child died within 12 months of birth, i.e., an infant mortality indicator.[44] Then, I conduct the same upstream-downstream analysis on this new outcome by focusing on children living close to rivers (within 5 or 10 kilometers). This focus stems from the fact that children in proximity to rivers are more likely to be affected by the water pollution externalities of latrine construction, making them more suitable for an upstream-downstream analysis.

As shown in Column 1 of Appendix Table D9, I similarly find an overall positive health effect. Regarding the heterogeneous effects by treatment capacity of fecal sludge, examined in Section 6, I find that the positive health effects are smaller when upstream areas have lower capacities for the treatment of fecal sludge (Columns 2-5), as demonstrated in the baseline analysis.

[44] This mortality indicator encompasses all types of mortality, not solely those driven by water pollution, which is a limitation of this dataset. To match this NFHS-5 dataset with other datasets, I use the year of birth of the child and the geocoordinates of NFHS clusters (villages).

6 Heterogenous Effects by Treatment Capacity of Fecal Sludge

To identify the mechanism behind the negative externalities on water quality and health, I examine wether the effects of latrine construction on water quality and health vary by the level of complementary treatment of fecal sludge. The negative externalities are found to be more pronounced in areas with lower treatment capacities, where dumping of fecal sludge is more likely to happen. This result suggests that poor treatment (or dumping) of fecal sludge is the primary mechanism driving these negative externalities.

In this analysis, I use geographical variation in the treatment capacities of sewage treatment plants (STPs). Based on the inventory of STPs compiled by the CPCB (CPCB, 2015), I calculate the STP capacities at both state and district levels in 2013, one year before the SBM started.[45] In the baseline specification, I compare effects in states/districts that have higher treatment capacities than the median in the sample with those in states/districts with lower treatment capacities.[46] In the upstream-downstream specification, I similarly examine the heterogeneous effects by the different levels of treatment capacities in upstream states/districts. This heterogeneity analysis uses the baseline level of STP capacities to address the concern of endogenous construction of STPs in response to water pollution caused by latrine construction under the SBM.[47]

6.1 Effects on Water Quality

I find that the negative externality on water quality is more pronounced in areas with lower treatment capacities. As shown in Panel A of Table 4, one additional latrine per square kilometer leads to a 3.7% increase in fecal coliform in states with lower treatment capacities (Column 3). Conversely, I find no effect in states with higher treatment capacities (Column 2). Similarly, one additional latrine per square kilometer results in a 5.1% increase in fecal coliform in districts with lower treatment capacities (Column 5), although the effect is not significant in districts with higher treatment capacities (Column 4). In the upstream-downstream specification, I find a similar negative externality from upstream

[45] The district-level STP capacities are highly susceptible to measurement errors due to missing observations of STPs in the CPCB inventory. Some districts may be flagged as districts with zero treatment capacity due to missing observations, even though they may actually have STPs. Therefore, I also use state-level STP capacities, which are less susceptible to measurement errors due to broader aggregation.

[46] The median value is calculated after assigning zero capacity to the states/districts without any STP.

[47] Consistent with the fact that planning and constructing STPs can take 5-10 years, there was not a substantial increase in STP capacity during the SBM period. The total STP capacity increased by 52% from 2013 to 2021, even though latrine coverage more than doubled in the same timeframe. Moreover, areas with lower baseline STP capacities did not experience a more substantial increase in STP construction, as indicated by the positive correlation between the baseline level of STP capacity in 2013 and the change in STP capacity from 2013 to 2021 at the state level (CPCB, 2015, 2021).

latrine construction on downstream water quality only when upstream states/districts have lower treatment capacities (Columns 3 and 5 of Panel B of Table 4).

These differential effects of the SBM by the treatment capacity of fecal sludge suggest that the dumping of fecal sludge emptied from latrines is the primary mechanism contributing to increased river pollution. In contrast, the lack of effect on water quality in areas with higher treatment capacities suggests other channels (e.g., the seepage of fecal matter from latrines to rivers) are unlikely to be the cause.

6.2 Effects on Health

The analysis of heterogeneous effects allows me to explicitly investigate the negative externality on health. The negative externality can be captured as the difference between the health effects in areas with lower treatment capacities (where significant river pollution is observed) and those in areas with higher treatment capacities (where river pollution is insignificant).

Panel A of Table 5 shows the results of heterogeneous effects on diarrheal post-neonatal mortality at different levels of treatment capacities at both state and district levels. I find that the average policy effect of the SBM is a 15% (42%) decrease in diarrheal mortality when upstream districts (states) have higher treatment capacities (Columns 2 and 4). This corresponds to cases where water pollution externalities are found to be insignificant in the water quality analysis. However, the positive health effect is eliminated when upstream districts (states) have lower treatment capacities and water pollution externalities are significant.

These findings, together with the results on water quality effects, suggest that the increased water pollution due to the SBM, which is pronounced in areas with lower treatment capacities, offsets the direct positive health effects. Although the overall health effect is positive, the water pollution externalities diminish the overall effectiveness of latrine construction in improving human health.

7 Conclusion

My analysis documents an unintended negative consequence of latrine construction when it is scaled up as a nationwide policy. Although open defecation has been commonly blamed for causing negative externalities, I show that latrine construction has larger water pollution externalities than open defecation due to poor treatment of fecal sludge. I then show that investments in latrines are less effective at improving child health in areas where the water pollution effects are larger.

Specifically, I examine the consequences of the world's largest sanitation policy, the SBM in India. I exploit a requirement on latrine construction under the SBM to identify its causal effects on water quality and health. Soil infiltration rate determines the cost and difficulty of latrine construction after the SBM started according to the official technical guidelines. So, I use soil infiltration rate interacted with a post-SBM indicator as an instrument for latrine construction.

I find that the SBM increases river pollution by 72%, which is a substantial effect. The negative externality on water quality exists only in areas with lower treatment capacities for treatment of fecal sludge, where the dumping of fecal sludge is more likely to happen. Moreover, I show that the SBM reduces diarrheal mortality by 10% overall. However, this positive health effect is eliminated when upstream areas have lower treatment capacities, which suggests that water pollution externalities offset direct positive health effects.

The back-of-the-envelope calculations show that the mortality benefit alone is not worth the cost of the SBM policy under insufficient treatment of fecal sludge.[48] The mortality benefit, i.e., reduction in diarrheal post-neonatal mortality, is calculated to be 5.6 million USD, which is about one-third of the subsidy cost for latrine construction (16.9 million USD) at the district level.[49] However, sufficient treatment of fecal sludge would increase the mortality benefit significantly with a lower additional cost. The additional mortality benefit of higher treatment capacity are similarly calculated to be 7.4 million USD, which is larger than the additional cost of constructing and operating more sewage treatment plants (4.5 million USD).[50] These results suggest that complementing latrine construction with sufficient treatment infrastructure is crucial in improving the cost-effectiveness of the sanitation policy.

My results present several policy implications for developing countries promoting sanitation and other similar policies. The first clear implication is that policymakers should

[48] The total benefits would be larger than the estimated mortality benefit in this calculation if I took into account the health effects for other age groups and other benefits such as improved educational outcomes.

[49] The mortality benefit is estimated by multiplying the total number of reduced mortalities under the SBM (10.4) by the estimate of the value of a statistical life in India (0.54 million USD according to Majumder and Madheswaran (2018)). The total number of reduced mortalities is calculated based on the estimated average policy effect (0.269 per 1,000 live births) and the estimate of the district-level mean population of age 0-1 (0.039 million people). This population estimate is calculated from the district-level mean population (1.66 million people) and the percentage of the population of age 0-4 (9.32%) in the 2011 Census. The population of age 0-1 is assumed to be one-fourth of the population of age 0-4. The subsidy cost is calculated by multiplying the amount of the SBM subsidy (144.1 USD) by the mean change in the number of latrines (0.12 million).

[50] The additional benefit are calculated based on the difference in the estimated average policy effects between districts with higher and lower treatment capacities at the district level (0.364-0.009=0.355 per 1,000 live births). The additional cost consists of the capital cost (0.03 million USD/million liters per day) and the O&M cost over a period of 5 years (0.07 million USD/million liters per day) for the most commonly used technology, the Upflow Anaerobic Sludge Blanket (estimated based on CPCB (2013)). These 5 years correspond to the duration of the post-SBM period in my analysis. Assuming the lifetime of STPs to be 15 years, the capital cost for this calculation is set at one-third of the total capital cost. The total additional cost is calculated by multiplying the unit cost with the district-level difference in STP capacity between districts with higher and lower treatment capacities, which amounts to 45.0 million liters per day.

consider the possibility of negative externalities of sanitation investment on water quality and health. An enabling environment that includes effective treatment of fecal sludge can make sanitation policies more effective, which should be strengthened in the second phase of the SBM that started in 2020. The need for better fecal sludge management is also a common issue in other South Asian countries, including Bangladesh, Nepal, and Pakistan, where sewage and fecal sludge have been inadequately treated regardless of making good progress in improving access to toilets (WaterAid, 2019). Future studies may investigate the causal effects of the treatment of fecal sludge on water quality and health because my approach herein is to examine heterogeneous effects by the baseline variation in the treatment capacity of fecal sludge.

Second, my findings on the negative externalities have implications for other policies, such as waste management. Waste management policy similarly requires consideration of the various stages involved, ranging from the collection of waste to safe recycling and disposal of waste. Focusing only on the collection of waste may cause negative externalities on the environment due to untreated waste. Investigating the existence of negative externalities associated with other similar policies may be a fruitful area for future research.

References

Adukia, Anjali. 2017. "Sanitation and education." *American Economic Journal: Applied Economics*, 9(2): 23–59.

Adukia, Anjali, Marcella Alsan, Kim Babiarz, Jeremy D Goldhaber-Fiebert, and Lea Prince. 2021. "Religion and Sanitation Practices." *The World Bank Economic Review*, 35(2): 287–302.

Allen, George H, and Tamlin M Pavelsky. 2018. "Global extent of rivers and streams." *Science*, 361(6402): 585–588.

Alsan, Marcella, and Claudia Goldin. 2019. "Watersheds in child mortality: The role of effective water and sewerage infrastructure, 1880–1920." *Journal of Political Economy*, 127(2): 586–638.

Anderson, Theodore W, and Herman Rubin. 1949. "Estimation of the parameters of a single equation in a complete system of stochastic equations." *The Annals of Mathematical Statistics*, 20(1): 46–63.

Bancalari, Antonella. 2020. "Can White Elephants Kill? Unintended Consequences of Infrastructure Development in Peru." IFS Working Paper W20/32.

Bennett, Daniel. 2012. "Does clean water make you dirty? Water supply and sanitation in the Philippines." *Journal of Human Resources*, 47(1): 146–173.

Bleakley, Hoyt. 2007. "Disease and development: evidence from hookworm eradication in the American South." *The Quarterly Journal of Economics*, 122(1): 73–117.

Brainerd, Elizabeth, and Nidhiya Menon. 2014. "Seasonal effects of water quality: The hidden costs of the Green Revolution to infant and child health in India." *Journal of Development Economics*, 107 49–64.

Buchmann, Nina, Erica M Field, Rachel Glennerster, and Reshmaan N Hussam. 2019. "Throwing the baby out with the drinking water: Unintended consequences of arsenic mitigation efforts in Bangladesh." National Bureau of Economic Research (NBER) Working Paper 25729.

Cameron, Lisa, Paul Gertler, Manisha Shah, Maria Laura Alzua, Sebastian Martinez, and Sumeet Patil. 2022. "The dirty business of eliminating open defecation: The effect of village sanitation on child height from field experiments in four countries." *Journal of Development Economics*, p. 102990.

Cameron, Lisa, Susan Olivia, and Manisha Shah. 2019. "Scaling up sanitation: evidence from an RCT in Indonesia." *Journal of Development Economics*, 138 1–16.

Cameron, Lisa, Paulo Santos, Milan Thomas, and Jeff Albert. 2021. "Sanitation, financial incentives and health spillovers: a cluster randomised trial." *Journal of Health*

Economics, 77, p. 102456.

Conley, Timothy G. 1999. "GMM estimation with cross sectional dependence." *Journal of econometrics*, 92(1): 1–45.

CPCB. 2013. "Performance Evaluation of Sewage Treatment Plants under NRCD." Central Pollution Control Board (CPCB), Ministry of Environment and Forests, Government of India.

CPCB. 2015. "Inventorization of Sewage Treatment Plants." Central Pollution Control Board (CPCB), Ministry of Environment and Forests, Government of India.

CPCB. 2021. "National Inventory of Sewage Treatment Plants." Central Pollution Control Board (CPCB), Ministry of Environment, Forest, and Climate Change, Government of India.

CPHEEO. 2013. "Manual on sewerage and sewage treatment systems - Part A Engineering." Central Public Health & Environmental Engineering Organisation (CPHEEO), Ministry of Housing and Urban Affairs, Government of India.

DDWS. 2020. "National Annual Rural Sanitation Survey (NARSS) Round-3 (2019-20) National Report." Department of Drinking Water and Sanitation (DDWS), Ministry of Jal Shakti, Government of India.

Dias, Mateus, Rudi Rocha, and Rodrigo R Soares. 2023. "Down the River: Glyphosate Use in Agriculture and Birth Outcomes of Surrounding Populations." *Review of Economic Studies*, p. rdad011.

Do, Quy-Toan, Shareen Joshi, and Samuel Stolper. 2018. "Can environmental policy reduce infant mortality? Evidence from the Ganga Pollution Cases." *Journal of Development Economics*, 133 306–325.

Duflo, Esther. 2001. "Schooling and labor market consequences of school construction in Indonesia: Evidence from an unusual policy experiment." *American Economic Review*, 91(4): 795–813.

Duflo, Esther, Michael Greenstone, Raymond Guiteras, and Thomas Clasen. 2015. "Toilets can work: Short and medium run health impacts of addressing complementarities and externalities in water and sanitation." National Bureau of Economic Research (NBER) Working Paper 21521.

Ebenstein, Avraham. 2012. "The consequences of industrialization: evidence from water pollution and digestive cancers in China." *Review of Economics and Statistics*, 94(1): 186–201.

Elvidge, Christopher D, Mikhail Zhizhin, Tilottama Ghosh, Feng-Chi Hsu, and Jay Taneja. 2021. "Annual time series of global VIIRS nighttime lights derived from monthly averages: 2012 to 2019." *Remote Sensing*, 13(5): , p. 922.

Flynn, Patrick, and Michelle M Marcus. 2021. "A watershed moment: The Clean Water Act and infant health." National Bureau of Economic Research (NBER) Working Paper 29152.

Geruso, Michael, and Dean Spears. 2018. "Neighborhood sanitation and infant mortality." *American Economic Journal: Applied Economics*, 10(2): 125–62.

Graham, Jay P, and Matthew L Polizzotto. 2013. "Pit latrines and their impacts on groundwater quality: a systematic review." *Environmental Health Perspectives*, 121(5): 521–530.

Greenstone, Michael, and Rema Hanna. 2014. "Environmental regulations, air and water pollution, and infant mortality in India." *American Economic Review*, 104(10): 3038–72.

Guiteras, Raymond, James Levinsohn, and Ahmed Mushfiq Mobarak. 2015. "Encouraging sanitation investment in the developing world: A cluster-randomized trial." *Science*, 348(6237): 903–906.

Gupta, Sanjay, Shubhra Jain, and Shikha Shukla Chhabra. 2018. "Draft Guidance Note on Co-Treatment of Septage at Sewage Treatment Plants in India."

Hammer, Jeffrey, and Dean Spears. 2016. "Village sanitation and child health: effects and external validity in a randomized field experiment in rural India." *Journal of Health Economics*, 48 135–148.

Hossain, Md Amzad, Kanika Mahajan, and Sheetal Sekhri. 2022. "Access to toilets and violence against women." *Journal of Environmental Economics and Management*, 114, p. 102695.

IHME. 2020a. "Global Under-5 Diarrhea Incidence, Prevalence, and Mortality Geospatial Estimates 2000-2019." Institute for Health Metrics and Evaluation (IHME).

IHME. 2020b. "Global Under-5 Overweight Prevalence Geospatial Estimates 2000-2019." Institute for Health Metrics and Evaluation (IHME).

Jeuland, Marc, Marcella McClatchey, Sumeet R Patil, Subhrendu K Pattanayak, Christine M Poulos, and Jui-Chen Yang. 2021. "Do Decentralized Community Treatment Plants Provide Clean Water? Evidence from Rural Andhra Pradesh, India." *Land Economics*, 97(2): 345–371.

Kahn, Matthew E, Pei Li, and Daxuan Zhao. 2015. "Water pollution progress at borders: the role of changes in China's political promotion incentives." *American Economic Journal: Economic Policy*, 7(4): 223–42.

Keiser, David A, and Joseph S Shapiro. 2019. "Consequences of the Clean Water Act and the demand for water quality." *The Quarterly Journal of Economics*, 134(1): 349–396.

Kleibergen, Frank, and Richard Paap. 2006. "Generalized reduced rank tests using the singular value decomposition." *Journal of Econometrics*, 133(1): 97–126.

Lipscomb, M, and L Schechter. 2018. "Subsidies versus mental accounting nudges: Harnessing mobile payment systems to improve sanitation." *Journal of Development Economics*, 135 235–254.

Lipscomb, Molly, and Ahmed Mushfiq Mobarak. 2016. "Decentralization and pollution spillovers: evidence from the re-drawing of county borders in Brazil." *The Review of Economic Studies*, 84(1): 464–502.

Majumder, Agamoni, and S Madheswaran. 2018. "Value of statistical life in India: A hedonic wage approach." Institute for Social and Economic Change (ISEC) Working Paper 407.

MDWS. 2018. "Guidelines for Swachh Bharat Mission (Gramin)." Ministry of Drinking Water and Sanitation (MDWS), Government of India.

Moe, CL, MD Sobsey, GP Samsa, and Virginia Mesolo. 1991. "Bacterial indicators of risk of diarrhoeal disease from drinking-water in the Philippines.." *Bulletin of the World Health Organization*, 69(3): 305–317.

Motohashi, Kazuki, and Michiyoshi Toya. 2022. "Impacts of municipal mergers on pollution control: Evidence of river pollution in Japan." Mimeo.

Orgill-Meyer, Jennifer, and Subhrendu K Pattanayak. 2020. "Improved sanitation increases long-term cognitive test scores." *World Development*, 132, p. 104975.

Orner, KD, C Naughton, and TA Stenstrom. 2018. "Pit toilets (latrines)." *Water and Sanitation for the 21st Century: Health and Microbiological Aspects of Excreta and Wastewater Management (Global Water Pathogen Project).*

Pai, DS, M Rajeevan, OP Sreejith, B Mukhopadhyay, and NS Satbha. 2014. "Development of a new high spatial resolution (0.25× 0.25) long period (1901-2010) daily gridded rainfall data set over India and its comparison with existing data sets over the region." *Mausam*, 65(1): 1–18.

Pattanayak, Subhrendu K, Jui-Chen Yang, Katherine L Dickinson, Christine Poulos, Sumeet R Patil, Ranjan K Mallick, Jonathan L Blitstein, and Purujit Praharaj. 2009. "Shame or subsidy revisited: social mobilization for sanitation in Orissa, India." *Bulletin of the World Health Organization*, 87 580–587.

Prasad, CS, and Isha Ray. 2019. "When the pits fill up:(in) visible flows of waste in urban India." *Journal of Water, Sanitation and Hygiene for Development*, 9(2): 338–347.

Prüss-Ustün, Annette, Jennyfer Wolf, Jamie Bartram, Thomas Clasen, Oliver Cumming, Matthew C Freeman, Bruce Gordon, Paul R Hunter, Kate Medlicott, and Richard Johnston. 2019. "Burden of disease from inadequate water, sanitation and hygiene for selected adverse health outcomes: an updated analysis with a focus on low-and middle-income countries." *International Journal of Hygiene and Environmental Health*, 222(5): 765–777.

Rao, Krishna C, Sasanka Velidandla, Cecilia L Scott, and Pay Drechsel. 2020. "Business models for fecal sludge management in India." *International Water Management Institute (IWMI): Resource Recovery & Reuse Series*, 18: Special Issue, p. 199.

Reuter, Hannes Isaak, Andy Nelson, and Andrew Jarvis. 2007. "An evaluation of void-filling interpolation methods for SRTM data." *International Journal of Geographical Information Science*, 21(9): 983–1008.

Spears, Dean. 2018. "Exposure to open defecation can account for the Indian enigma of child height." *Journal of Development Economics*, p. 102277.

Spears, Dean, and Sneha Lamba. 2016. "Effects of Early-Life Exposure to Sanitation on Childhood Cognitive Skills: Evidence from India's Total Sanitation Campaign." *Journal of Human Resources*, 51(2): 298–327.

Spears, Dean, and Amit Thorat. 2019. "The puzzle of open defecation in rural India: evidence from a novel measure of caste attitudes in a nationally representative survey." *Economic Development and Cultural Change*, 67(4): 725–755.

Wang, Dongqin, and Yanni Shen. 2022. "Sanitation and work time: Evidence from the toilet revolution in rural China." *World Development*, 158, p. 105992.

WaterAid. 2019. "Faecal sludge management landscape in South Asia." Urban Sanitation Working Group, South Asia Region, WaterAid.

Yishay, Ariel Ben, Andrew Fraker, Raymond Guiteras, Giordano Palloni, Neil Buddy Shah, Stuart Shirrell, and Paul Wang. 2017. "Microcredit and willingness to pay for environmental quality: Evidence from a randomized-controlled trial of finance for sanitation in rural Cambodia." *Journal of Environmental Economics and Management*, 86 121–140.

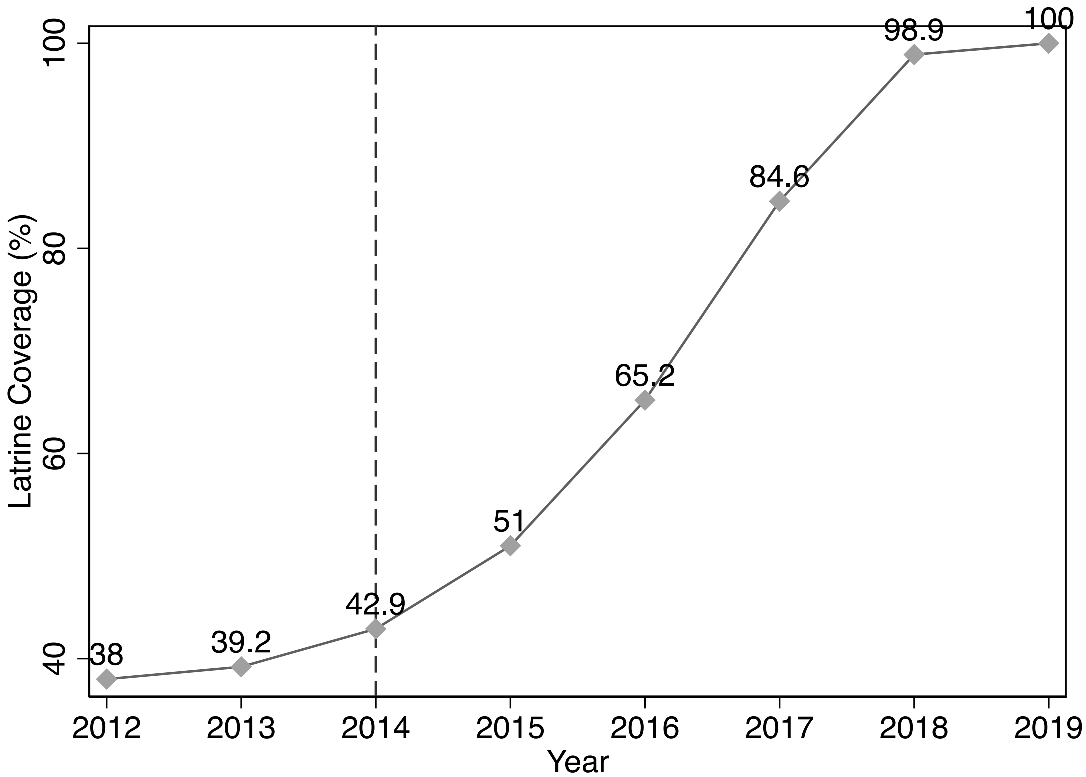


Figure 1: Latrine Coverage in Rural India

Notes: This figure documents the proportion of households that have latrines in rural India between 2012 and 2019. A vertical dashed line shows the starting year of the Swachh Bharat Mission.

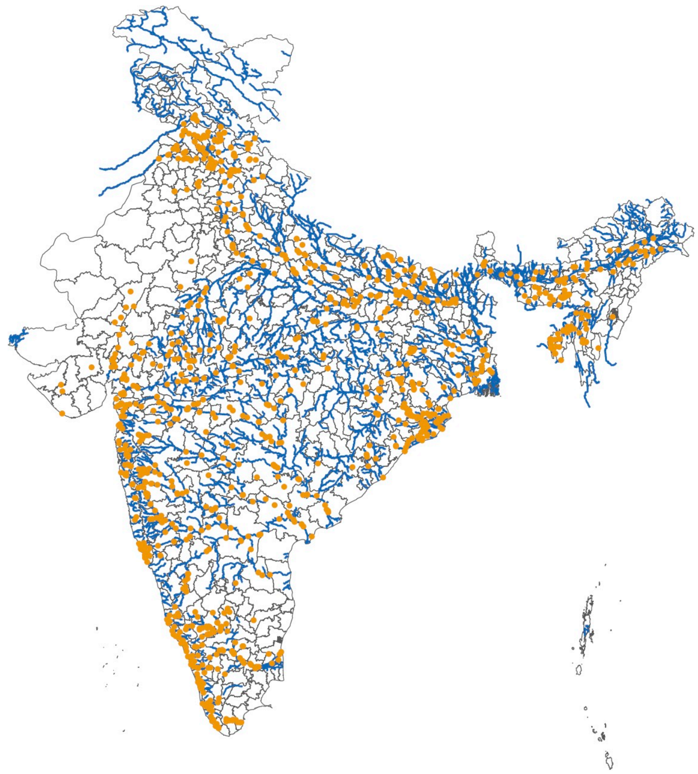


Figure 2: Distribution of Water Quality Monitoring Stations in India

Notes: This figure shows water quality monitoring stations in orange dots, district boundaries in black lines, and rivers in blue lines. The data source of river lines is Allen and Pavelsky (2018).

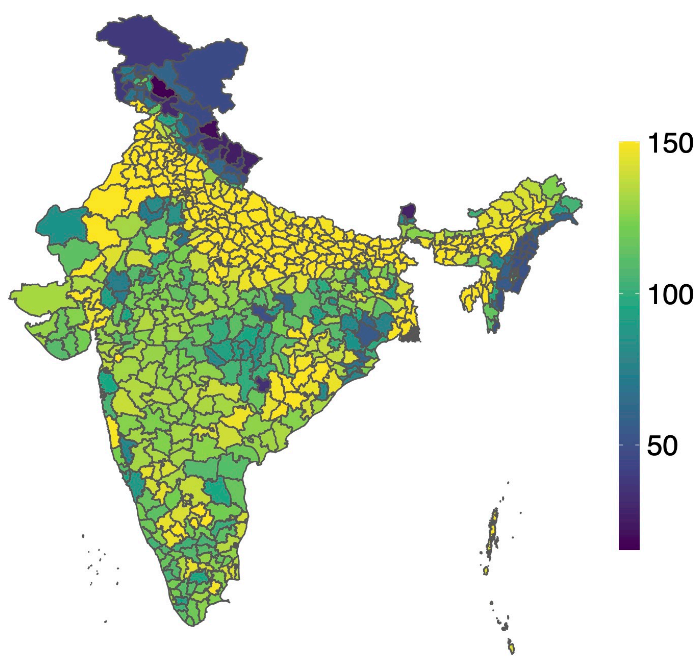


Figure 3: Available Water Capacity (mm/m) across Districts

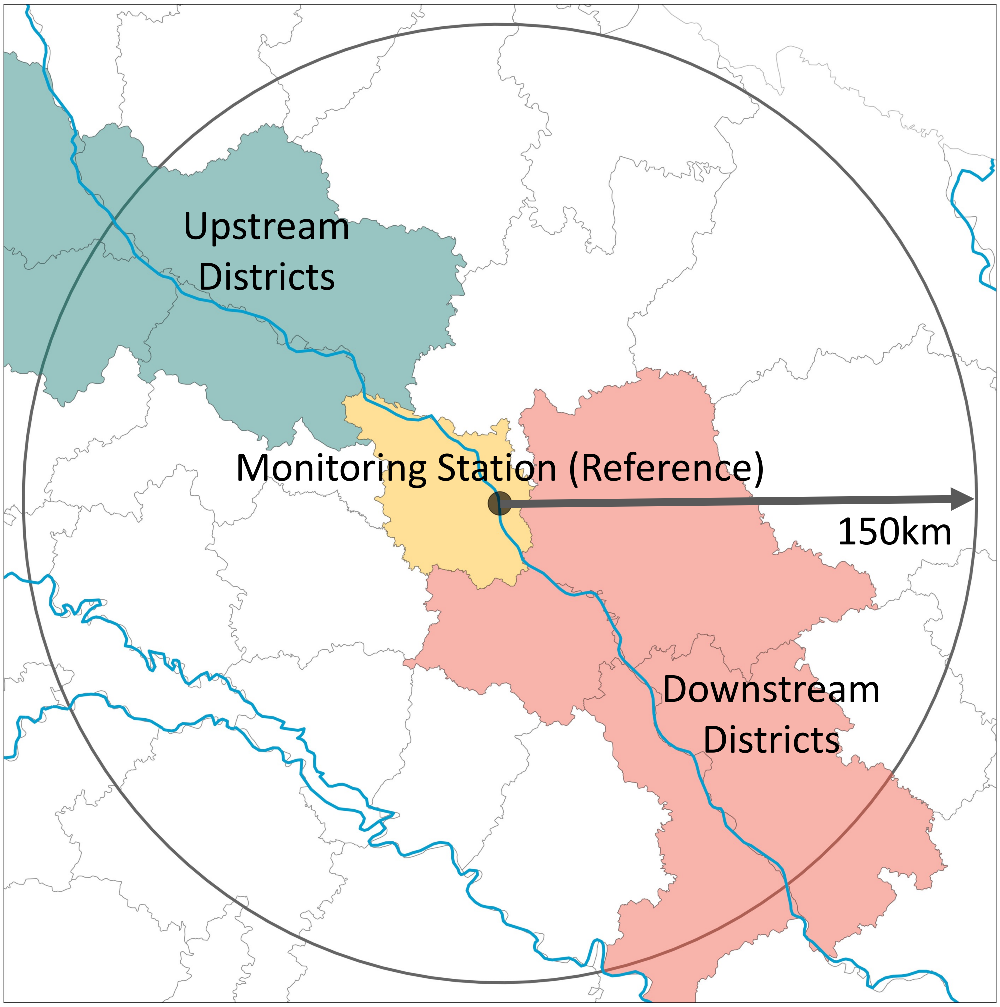


Figure 4: Illustration of Upstream-Downstream Analysis

Notes: This figure illustrates the upstream-downstream analysis, which analyzes the effect of upstream latrine construction on water quality in a reference monitoring station (or health in a reference district). Upstream districts are selected as districts that (i) intersect with river segments whose elevations are higher than the elevation of the reference station (district) and (ii) fall within a range of [0, 150] kilometers from the reference station (district) in the baseline specification. This figure shows district boundaries in grey lines and rivers in blue lines. It highlights the upstream districts in green, the reference district in yellow, and the downstream districts in red.

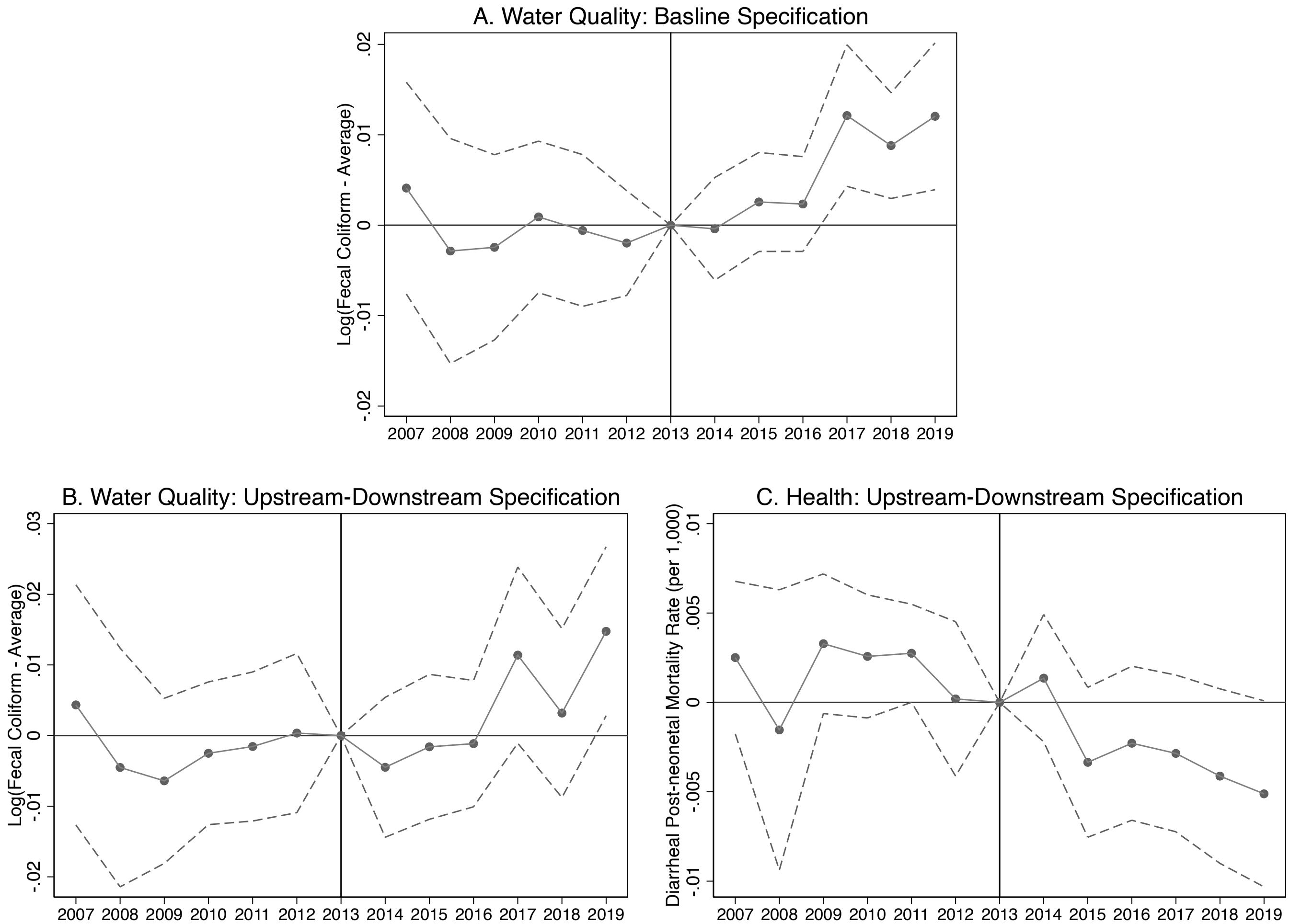


Figure 5: Event Study Plots of Reduced-Form Regressions of Available Water Capacity

Notes: This figure shows the regression coefficients of the logarithm of fecal coliform (Panels A and B) and diarrheal post-neonatal mortality rate per 1,000 live births (Panel C) on the interaction terms between Available Water Capacity in Panel A (upstream Available Water Capacity in Panels B and C) and year dummies. The 95% confidence intervals are shown with dashed lines. Standard errors are clustered at the district level. Panel A includes monitoring station fixed effects, year fixed effects, and precipitation as a control. Panel B includes monitoring station fixed effects, year fixed effects, and the following controls: precipitation and the interaction of Available Water Capacity and the post-SBM indicator of a reference district, while Panel C includes district fixed effects, year fixed effects, and the same controls.

Table 1: Summary Statistics

	Mean	SD	Min	Max	Obs.
Panel A. Time-varying variables: pre-SBM (2007-2013)					
Fecal coliform - average (million MPN/100ml)	2.61	143.77	0	10000.04	4939
Diarrheal post-neonatal mortality rate (per 1,000)	2.69	1.8	0.07	9.48	2359
Number of latrines (ten thousand)	12.93	13.39	0.01	89.7	586
Number of latrines per sq. km	35.55	41.92	0.03	283.01	586
Precipitation (thousand mm)	1.34	0.78	0.21	5.59	1946
Panel B. Time-varying variables: post-SBM (2014-2019)					
Fecal coliform - average (million MPN/100ml)	0.72	30.39	0	1750.01	5553
Diarrheal post-neonatal mortality rate (per 1,000)	1.46	1.07	0.05	5.21	2022
Number of latrines (ten thousand)	22.52	18.96	0.01	146.87	1814
Number of latrines per sq. km	59.06	57.05	1.12	430.09	1814
Precipitation (thousand mm)	1.31	0.88	0.2	10.06	1814
Panel C. Variables not varying over time					
Available water storage capacity (mm/m)	128.03	25.91	19.79	150	337
2013 district-level sewage treatment plant capacity (MLD)	28.17	105.03	0	947.5	337
2013 state-level sewage treatment plant capacity (MLD)	709.5	782.06	0	2307.75	337

Notes: This table shows summary statistics of time-varying variables for pre-SBM periods (2007-2013) in Panel A and post-SBM periods (2014-2019) in Panel B, and summary statistics of time-invariant variables in Panel C. The latrine data are available only from 2012-2019, while data of other time-varying variables are available from 2007-2019. MPN and MLD denote "most probable number" and "million liters per day," respectively.

Table 2: The Effect on Water Quality (Log of Fecal Coliform)

	OLS	IV - First Stage	IV - Second Stage
	(1)	(2)	(3)
	Log(Fecal Coliform)	# of Latrines per sq. km	Log(Fecal Coliform)
Panel A. Baseline Specification			
Number of latrines	0.006***		0.030***
per sq. km	(0.002)		(0.008)
AWC * Post (=1)		0.283***	
		(0.052)	
Observations	7,201	7,201	7,201
R^2	0.020	0.091	-
Number of Stations	1,189	1,189	1,189
Number of Districts	337	337	337
KP F-Stat	-	29.954	-
AR 95% CI	-	-	[.015, .049]
Conley SE	(0.003)	-	(0.010)
Average Policy Effect	0.142	-	0.719
Panel B. Upstream-Downstream Specification			
Upstream number of	0.009***		0.015
latrines per sq. km	(0.003)		(0.011)
Upstream AWC		0.322***	
* Post (=1)		(0.045)	
Observations	2,228	2,228	2,228
R^2	0.057	0.301	-
Number of Stations	365	365	365
Number of Districts	154	154	154
KP F-Stat	-	50.475	-
AR 95% CI	-	-	[-.008, .039]
Conley SE	(0.003)	-	(0.012)
Average Policy Effect	0.250	-	0.431

Notes: The coefficients are reported. Standard errors, clustered at the district level, are in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. Regressions in Panel A include monitoring station fixed effects, year fixed effects, and precipitation as a control. Regressions in Panel B include monitoring station fixed effects, year fixed effects, and the following controls: precipitation and the interaction of Available Water Capacity and the post-SBM indicator of a reference district. In Panel B, the sample is limited to monitoring stations located along major rivers in India, and upstream districts are defined as those within the range of $[0, 150]$ kilometers from a reference station. The KP F-Stat refers to the Wald version of the Kleibergen and Paap (2006) rk-statistic on the excluded instrumental variables for non-i.i.d. errors. The AR 95% CI reports the 95% confidence interval, which is robust to the weak instrument based on the Anderson and Rubin (1949) test. The Conley SE refers to the standard errors that are spatially clustered with a cutoff of 150 kilometers following the Conley (1999) approach. Average policy effects are calculated by multiplying the estimated coefficients by the change in the number of latrines per square kilometer after the SBM started in 2014.

Table 3: The Effect on Health (Diarrheal Post-neonatal Mortality Rate)

	OLS	IV - First Stage	IV - Second Stage
	(1)	(2)	(3)
	Mortality/Latrine	# of Latrines per sq. km	Mortality/Latrine
Panel A. Dependent Variable: Diarrheal Post-neonatal Mortality Rate (per 1,000 live births)			
Upstream number of latrines per sq. km	-0.005**		-0.011*
	(0.002)		(0.006)
Upstream AWC * Post (=1)		0.301***	
		(0.034)	
Observations	824	824	824
R^2	0.664	0.342	-
Number of Districts	103	103	103
KP F-Stat	-	78.696	-
AR 95% CI	-	-	[-.023, .001]
Mean of Dep. Variable	2.576	23.684	2.576
Average Policy Effect	-0.111	-	-0.269
Panel B. Dependent Variable: Number of Latrines per sq. km in a Reference District			
Upstream number of latrines per sq. km	0.894***		0.726***
	(0.109)		(0.154)
Upstream AWC * Post (=1)		0.301***	
		(0.034)	
Observations	824	824	824
R^2	0.796	0.342	-
Number of Districts	103	103	103
KP F-Stat	-	78.696	-
AR 95% CI	-	-	[.404, 1.05]
Mean of Dep. Variable	33.054	23.684	33.054

Notes: The coefficients are reported. Standard errors, clustered at the district level, are in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. All regressions include district fixed effects, year fixed effects, and the following controls: precipitation and the interaction of Available Water Capacity and the post-SBM indicator of a reference district. The sample is limited to districts that have monitoring stations used in the water quality regression along major rivers in India. Upstream districts are defined as those within the range of $[0, 150]$ kilometers from a reference district. The KP F-Stat refers to the Wald version of the Kleibergen and Paap (2006) rk-statistic on the excluded instrumental variables for non-i.i.d. errors. The AR 95% CI reports the 95% confidence interval, which is robust to the weak instrument based on the Anderson and Rubin (1949) test. Means of dependent variables are calculated for the pre-SBM period. Average policy effects are calculated by multiplying the estimated coefficients by the change in the number of latrines per square kilometer after the SBM started in 2014.

Table 4: The Heterogenous Effects on Water Quality by Treatment Capacity of Fecal Sludge

	All	State-level Capacity		District-level Capacity	
	(1)	(2)	(3)	(4)	(5)
	All	High	Low	High	Low
Panel A. Dependent Variable: Log(Fecal Coliform) - Baseline Specification					
Number of latrines per sq. km	0.030***	-0.031	0.037***	0.014	0.051***
	(0.008)	(0.025)	(0.007)	(0.009)	(0.017)
Observations	7,201	3,453	3,748	2,902	4,299
Number of Stations	1,189	579	610	466	723
Number of Districts	337	182	155	96	241
KP F-Stat	29.954	7.576	39.516	13.648	11.931
AR 95% CI	[.015, .049]	[-.123, .018]	[.025, .054]	[-.012, .034]	[.023, .105]
Average Policy Effect	0.719	-0.666	0.976	0.286	1.342
Panel B. Dependent Variable: Log(Fecal Coliform) - Upstream-Downstream Specification					
Upstream number of latrines per sq. km	0.015	-0.046	0.031***	-0.004	0.037*
	(0.011)	(0.032)	(0.011)	(0.011)	(0.023)
Observations	2,228	1,107	1,119	1,097	1,131
Number of Stations	365	171	194	180	185
Number of Districts	154	73	84	75	93
KP F-Stat	50.475	19.767	41.298	53.262	15.137
AR 95% CI	[-.008, .039]	[-.112, .040]	[.010, .063]	[-.033, .018]	[-.013, .121]
Average Policy Effect	0.431	-1.367	0.820	-0.092	1.139

Notes: The coefficients are reported. Standard errors, clustered at the district level, are in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. Regressions in Panel A include monitoring station fixed effects, year fixed effects, and precipitation as a control. Regressions in Panel B include monitoring station fixed effects, year fixed effects, and the following controls: precipitation and the interaction of Available Water Capacity and the post-SBM indicator of a reference district. In Panel B, upstream districts are defined as those within the range of $[0, 150]$ kilometers from a reference station. In Panel A, Column 2 reports a result in states where treatment capacities of sewage treatment plants are higher than the median, while Column 3 reports a result in states with lower treatment capacities. Panel B instead uses variation in treatment capacities of upstream states in Columns 2 and 3. Columns 4 and 5 compare results based on the different levels of treatment capacities at the district level. The KP F-Stat refers to the Wald version of the Kleibergen and Paap (2006) rk-statistic on the excluded instrumental variables for non-i.i.d. errors. The AR 95% CI reports the 95% confidence interval, which is robust to the weak instrument based on the Anderson and Rubin (1949) test. Average policy effects are calculated by multiplying the estimated coefficients by the change in the number of latrines per square kilometer after the SBM started in 2014.

Table 5: The Heterogenous Effects on Health by Treatment Capacity of Fecal Sludge

	All	State-level Capacity		District-level Capacity	
	(1)	(2)	(3)	(4)	(5)
	All	High	Low	High	Low
Panel A. Dependent Variable: Diarrheal Post-neonatal Mortality Rate (per 1,000 live births)					
Upstream number of latrines per sq. km	-0.011*	-0.041***	-0.010	-0.014**	-0.000
	(0.006)	(0.010)	(0.006)	(0.007)	(0.010)
Observations	824	432	392	456	368
Number of Districts	103	54	49	57	46
KP F-Stat	78.696	33.304	33.484	59.873	18.756
AR 95% CI	[-.023, .001]	[-.073, -.024]	[-.026, .002]	[-.030,-.000]	[-.029, .026]
Mean of Dep. Variable	2.576	2.534	2.623	2.428	2.759
Average Policy Effect	-0.269	-1.058	-0.230	-0.364	-0.009
Panel B. Dependent Variable: Number of Latrines per sq. km in a Reference District					
Upstream number of latrines per sq. km	0.726***	1.327***	0.684***	0.649***	0.907**
	(0.154)	(0.214)	(0.160)	(0.170)	(0.358)

Notes: The coefficients are reported. Standard errors, clustered at the district level, are in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. All regressions include district fixed effects, year fixed effects, and the following controls: precipitation and the interaction of Available Water Capacity and the post-SBM indicator of a reference district. The sample is limited to districts that have monitoring stations used in the water quality regression along major rivers in India. Upstream districts are defined as those within the range of $[0, 150]$ kilometers from a reference district. Column 2 reports results when upstream states have higher treatment capacities of sewage treatment plants than the median, while Column 3 reports results in the case of upstream states with lower treatment capacities. Columns 4 and 5 compare results based on the different levels of upstream treatment capacities at the district level. The KP F-Stat refers to the Wald version of the Kleibergen and Paap (2006) rk-statistic on the excluded instrumental variables for non-i.i.d. errors. The AR 95% CI reports the 95% confidence interval, which is robust to the weak instrument based on the Anderson and Rubin (1949) test. Means of dependent variables are calculated for the pre-SBM period. Average policy effects are calculated by multiplying the estimated coefficients by the change in the number of latrines per square kilometer after the SBM started in 2014.

Online Appendix

Unintended Consequences of Sanitation Investment: Negative Externalities on Water Quality and Health in India

Kazuki Motohashi

Contents

List of Figures

List of Tables

A Conceptual Framework on Negative Externalities of Latrine Construction

I present a simple conceptual framework to show how latrine construction under the SBM causes negative externalities that offset direct health benefits. A decrease in a latrine price under the subsidy increases the number of constructed latrines, which increases the marginal damage (negative externalities), which offsets the marginal benefit (health benefits). The magnitude of these negative externalities depends on the treatment capacity of fecal sludge.

I consider a district that has N households which can decide whether or not to construct latrines. I suppose that a given household can build a latrine by paying a fixed price (p_{pre}).[51] I denote the maximum number of latrines that can be built in this district as $Q^{max} = N$.

The fecal sludge emptied from latrines in this district is treated by sewage treatment plants (STPs). I give the treatment capacity of fecal sludge as $Q^{stp} \in [0, Q^{max}]$ where Q^{stp} can be interpreted as the number of latrines whose fecal sludge can be treated by STPs. Thus, when the number of latrines (Q) exceeds Q^{stp}, $Q - Q^{stp}$ amount of fecal sludge is dumped into rivers, which causes negative externalities on water quality and health. In this conceptual framework, I analyze two cases: (i) low treatment capacity ($Q^{stp} \leq \frac{Q^{max}}{2}$) and (ii) high treatment capacity ($Q^{stp} > \frac{Q^{max}}{2}$).

Appendix Figure A1 shows the marginal benefit (MB), marginal cost (MC), marginal damage (MD), and social marginal cost (SMC) of latrine construction for low treatment capacity case (Panel A) and high treatment capacity case (Panel B).

Both panels show the same MB and MC curves. The MB curve represents direct health benefits that come from reduced open defecation and exposure to fecal matter near human habitation.[52] This curve is downward-sloping because some households benefit more than other households — for instance, if they have more infants who are vulnerable to diarrhea. As for MC, the pre-SBM curves are constant at the constant price of latrines ($MC_{pre} = p_{pre}$). The MC curves are shifted down by subsidy under the SBM. Households receive a subsidy of about 145 USD for latrine construction, so the post-SBM effective price of latrines ($MC_{post} = p_{post}$) becomes significantly lower than p_{pre}.

The main difference between Panels A and B is SMC. If the treatment capacity (Q^{stp}) is low (Panel A), the MD, i.e., the negative externality on health due to river pollution, becomes non-zero, starting from the lower number of latrines. On the other hand, if the

[51] The latrine price can include both the initial construction cost of a latrine and the present value of marginal costs for emptying fecal sludge periodically.

[52] In this conceptual framework, MB is assumed to only represent direct health benefits, i.e., reduction in the risks of diarrhea and diarrheal mortality, although there could be other benefits, including an improvement in educational outcomes and reduction in violence against women.

treatment capacity (Q^{stp}) is high (Panel B), the MD occurs only at a larger number of latrines. Here I assume the non-linear dose-response relationship: the larger the volume of dumped fecal sludge ($Q - Q^{stp}$), the larger the marginal negative externality on health (MD).[53] The SMC curves reflect the differences in MD curves because $SMC = MC + MD$.

Based on this conceptual framework, I examine the welfare effects of latrine construction under the SBM in Appendix Figure A1. If the treatment capacity is low (Panel A), pre-SBM market equilibrium quantity is Q^e_{pre} at the intersection of MB and MC_{pre}, and pre-SBM optimal quantity is Q^*_{pre} at the intersection of MB and SMC_{pre}. The wedge between Q^e_{pre} and Q^*_{pre}, caused by MD (negative externality), generates deadweight loss (DWL_{pre}). Then, the effect of the SBM is to decrease the marginal cost from MC_{pre} to MC_{post} through subsidy. Thus, the number of latrines increases significantly from Q^e_{pre} to Q^e_{post}. This increase in latrines causes a large increase in negative externality due to low treatment capacity. Deadweight loss significantly increases from DWL_{pre} to DWL_{post}. On the other hand, if the treatment capacity is high (Panel B), the increase in deadweight loss due to latrine construction is limited because the negative externality only occurs at a large number of latrines. The comparison of Panels A and B suggests that subsidies under the SBM adversely impact welfare more significantly in the case of low treatment capacity.

Moreover, I examine the effects of latrine construction under the SBM on water quality and health in Appendix Figure A2, which is based on the welfare analysis in Appendix Figure A1. In Appendix Figure A2, the total benefit represents the total direct health effects, while the total damage represents the total negative externality on health due to water pollution.[54] The difference in the total benefit and total damage (net benefit) is examined as a health outcome in the empirical analysis.[55] The total damage can be interpreted as a degree of water pollution, which corresponds to the water quality outcome in the empirical analysis.

This paper estimates the effects of the increase in the number of latrines at market equilibrium from Q^e_{pre} to Q^e_{post} on water quality and health under the SBM. According to Appendix Figure A2, there are three testable hypotheses in the empirical analysis. The first hypothesis is tested in the baseline analysis (Section 5), and the second and third hypotheses are tested in the heterogeneity analysis (Section 6).

1. The SBM improves health overall (increase in net benefit) if the total benefit increases

[53] The non-linear relationship is suggested by a classic epidemiological study (Moe et al., 1991), which shows the evidence of threshold effects where significantly higher rates of diarrheal disease are observed once the fecal contamination level in drinking water reaches a certain threshold.

[54] The total benefit in Appendix Figure A2 is the area under the MB curves of Appendix Figure A1. The total damage in Appendix Figure A2 is the area bounded by the SMC and MC curves of Appendix Figure A1.

[55] I assume that the total benefit is larger than the total damage. In this case, the net benefit is positive, which means that latrines are health-improving. This is consistent with the empirical results of this paper.

more substantially than the total damage and increases water pollution (increase in total damage) regardless of treatment capacity.[56]

2. The magnitude of positive health effects is smaller in the case of low treatment capacity.
3. The magnitude of negative effects on water quality (increased water pollution) is larger in the case of low treatment capacity.

[56] While theoretically, net benefit may decrease, Appendix Figure A2 demonstrates a case where the total benefit increases more substantially than the total damage (increase in net benefit), which is consistent with the empirical results of this paper.

Panel A. Treatment Capacity Low

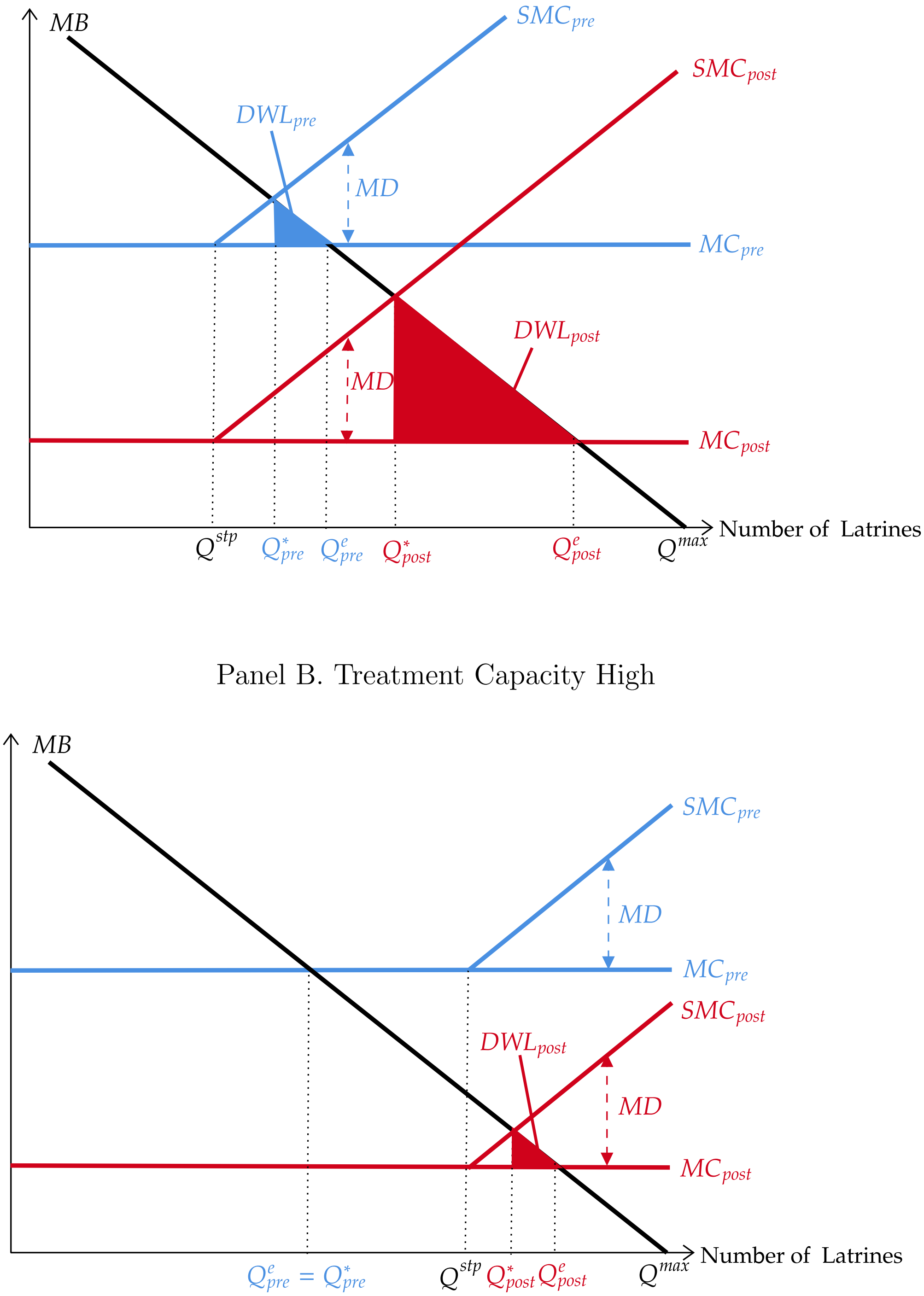
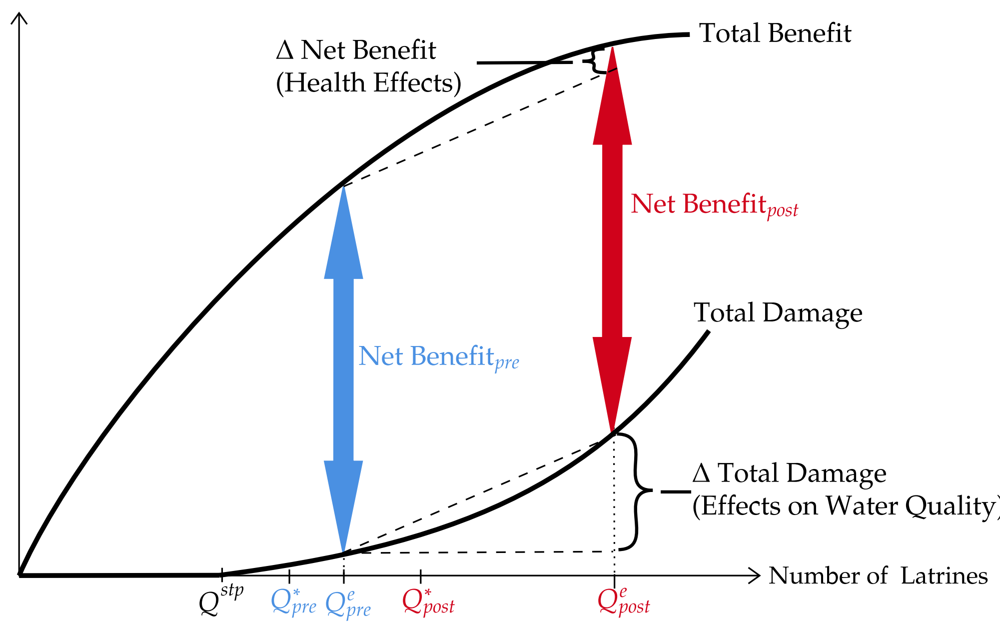


Figure A1: Welfare Effects of the Swachh Bharat Mission

Notes: This figure examines how the subsidy under the SBM changes the deadweight loss (DWL) in two cases: (A) low treatment capacity (low Q^{stp}) and (B) high treatment capacity (high Q^{stp}). The subsidy shifts down the marginal cost (MC) from MC^{pre} to MC^{post}. Marginal damage (MD) represents the negative externality on health, which occurs when the number of latrines is larger than the treatment capacity level (Q^{stp}). Marginal benefit (MB) represents direct health benefits because of reduced open defecation. This figure shows that DWL increases more significantly in the case of low treatment capacity in Panel A.

Panel A. Treatment Capacity Low



Panel B. Treatment Capacity High

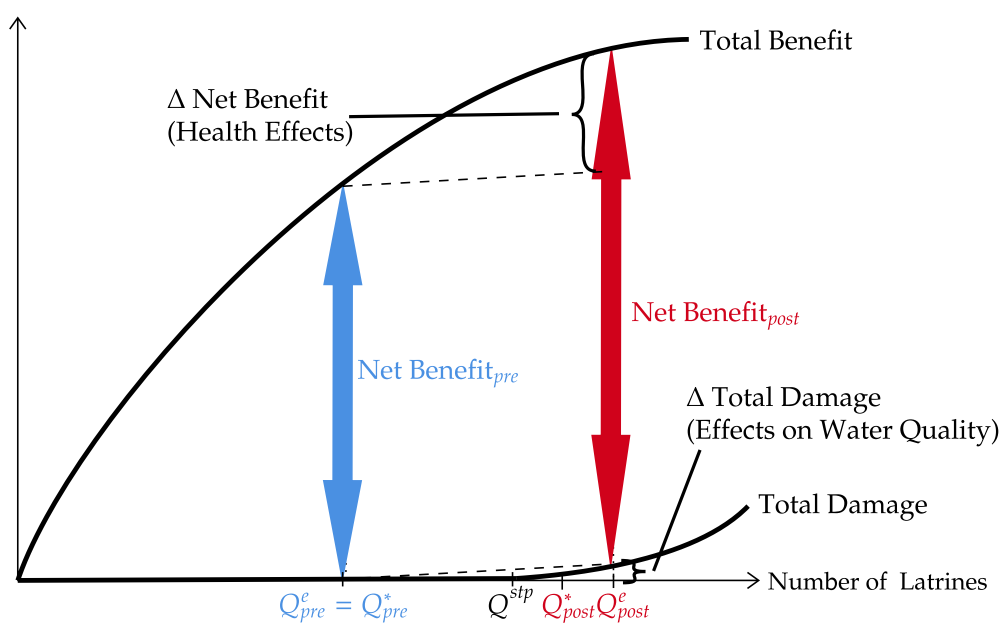


Figure A2: Effects of the Swachh Bharat Mission on Water Quality and Health

Notes: This figure examines how the SBM affects water quality and health in two cases: (A) low treatment capacity (low Q^{stp}) and (B) high treatment capacity (high Q^{stp}). Total benefit and total damage in this figure are based on the marginal benefit and marginal damage plotted in Appendix Figure A1. Effects on health and water quality are represented by the changes in net benefit and total damage, respectively. This figure shows that SBM improves health overall and increases water pollution. In the case of low treatment capacity in Panel A, the magnitude of health effects is smaller, and the magnitude of effects on water quality is larger.

B Robustness Check: Difference-in-Differences Design

As a robustness check, I adopt an alternative difference-in-differences (DID) design that exploits a differential increase in latrine coverage across districts with different levels of baseline coverage.

B.1 Empirical Strategy

An alternative DID design uses district-level baseline latrine coverage as a continuous treatment, which affects how many latrines are constructed under the SBM.[57] This design exploits the fact that all districts had achieved almost universal latrine coverage by the target date of 2019, regardless of their baseline latrine coverage. Thus, districts with lower baseline latrine coverage have experienced a larger increase in latrine coverage. As shown in Appendix Figure B1, there are substantial differences in the baseline latrine coverage across districts in 2013, which suggests a differential increase in the number of latrines by 2019. As expected, I find that lower baseline coverage and the number of latrines constructed under the SBM are positively correlated in Appendix Figure B2. Then, I expect that districts with higher latrine non-coverage (lower latrine coverage) in 2013 experienced a higher increase in water pollution due to a larger increase in latrine coverage.

In this DID design, I adopt the following baseline regression.

$$Y_{i,d,t} = \alpha + \beta_{DID}(1 - Latrine_d^{pre}) \cdot Post_t + \gamma \mathbf{X_{d,t}} + \delta_i + \theta_{b,t} + \varepsilon_{i,t} \tag{5}$$

where $Y_{i,d,t}$ is a water quality indicator, represented by the logarithm of fecal coliform, at monitoring station i inside district d in year t. $Latrine_d^{pre}$ is a latrine coverage in district d in 2013, which was one year before the SBM started. $Post_t$ is an indicator that takes the value one after 2014 when SBM started. $\mathbf{X_{d,t}}$ are a set of control variables, which are time-varying precipitation and time-invariant district characteristics, including VIIRS nighttime luminosity in 2013, population, the proportions of Scheduled Caste and Scheduled Tribe members, and literacy rates in 2011. Time-invariant variables are added as control variables after being interacted with year dummies. Monitoring station fixed effects, δ_i, and basin-year fixed effects, $\theta_{b,t}$, are included. Standard errors are clustered at the district level since the baseline latrine coverage varies across districts. The coefficient of interest is β_{DID}, and I expect it to be positive, i.e., a higher increase in water pollution.

To examine pre-trends and the dynamic evolution of the treatment effects, I also adopt

[57] This DID design that uses variation in baseline degree of policy implementation is in the same vein as Duflo (2001) and Bleakley (2007).

the following event-study specification.

$$Y_{i,d,t} = \alpha + \sum_{l=2007}^{2019} \beta_l (1 - Latrine_d^{pre}) \cdot T_l + \gamma \mathbf{X_{i,t}} + \delta_i + \theta_{b,t} + \varepsilon_{i,t} \tag{6}$$

where the baseline year is 2013, and T_l is a year dummy variable. Standard errors are similarly clustered at the district level. The coefficients of interest are the β_l's, which measure the treatment effects on water quality in each year relative to 2013. The β_l's of 2007-2012 are examined to test the assumption of parallel pre-trends, while the β_l's of 2014-2019 capture the dynamic evolution of the treatment effects. Based on this test of parallel pre-trends, I use this DID design only for the water quality outcome.

B.2 Data

This DID design uses the same datasets on water quality and latrines introduced in Section 3. This design uses longer panel data of water quality data from 2007 to 2019 as an outcome. It also uses latrine coverage in 2013 as a treatment, which is computed by dividing the number of household latrines in 2013 by the total number of recorded households in each district.

This design uses two additional datasets to account for other district characteristics that affect latrine construction and water quality and then achieve a better balance between treatment and control groups.

First, I use 15 arc second (<500m at the Equator) raster data of nighttime light to account for the size of the economy at the district level. Specifically, I use the V.2 annual composites of Visible and Infrared Imaging Suite (VIIRS) Day Night Band (Elvidge et al., 2021).[58] I compute the district-level mean of nighttime luminosity in the pre-SBM period based on the annual composite of 2013.

Second, I use data on district-level socio-demographic characteristics, including population, the proportions of Scheduled Caste and Scheduled Tribe members, and literacy rates in rural India, in the 2011 Census of India.

B.3 Results

As in the IV design, I find that latrine construction under the SBM increases river pollution, especially in areas with lower treatment capacities. The positive coefficient in Column 1 of Appendix Table B1 suggests that latrine construction increases water pollution overall, although the effect becomes imprecise in the DID design. Heterogeneity analysis by

[58] I use the values of masked average radiance that represents stable lights from which background noises, biomass burning, and aurora are removed.

treatment capacity of fecal sludge shows that the negative externality on water quality is substantial in areas with lower treatment capacities in Columns 2-5 of Appendix Table B1. The coefficients of $(1 - Latrine_d^{pre}) \cdot Post_t$ show that a district with baseline latrine coverage of 50% would experience an increase in fecal coliform of about 75-90%, relative to a district with 100% baseline latrine coverage, in areas with lower treatment capacities (Columns 3 and 5). Considering the fact that the baseline latrine coverage was 39.2% in 2013, the average effects of the SBM in states with lower treatment capacities can be calculated as $(1 - 0.392) \times 1.790 = 1.088$, which is relatively close to the average policy effect (0.976) in Panel A of Table 4 in the IV design. On the other hand, consistent with the results of the IV design, I do not find negative externality in areas with higher treatment capacities (Columns 2 and 4).

As for the dynamic evolution of the treatment effects, the event study design shows the negative externality on water quality in areas with lower treatment capacities has become substantial two years after the start of SBM, and this effect has become larger over time. The estimated coefficients from the event-study specification in regression 6 are reported in Appendix Figure B3. First, Appendix Figure B3 reassuringly shows no differential pre-trends for almost all panels (except Panel D), which enhances the validity of the parallel pre-trends assumption. Second, Appendix Figure B3 highlights that the negative externality in states with lower treatment capacities has become substantial since 2016, two years after the start of the SBM, and this effect becomes larger over time from 2016 to 2019 (Panel B).[59] The lagged effect is consistent with the fact that a differential increase in the number of latrines among districts with different levels of baseline coverage starts around 2016, as shown in Appendix Figure B2.

[59] Appendix Figure B3 also shows event study plots that compare districts with higher and lower treatment capacities. Because I find differential pre-trends in the case of districts with lower treatment capacities (Panel B), I focus on the results based on state-level variation in treatment capacities.

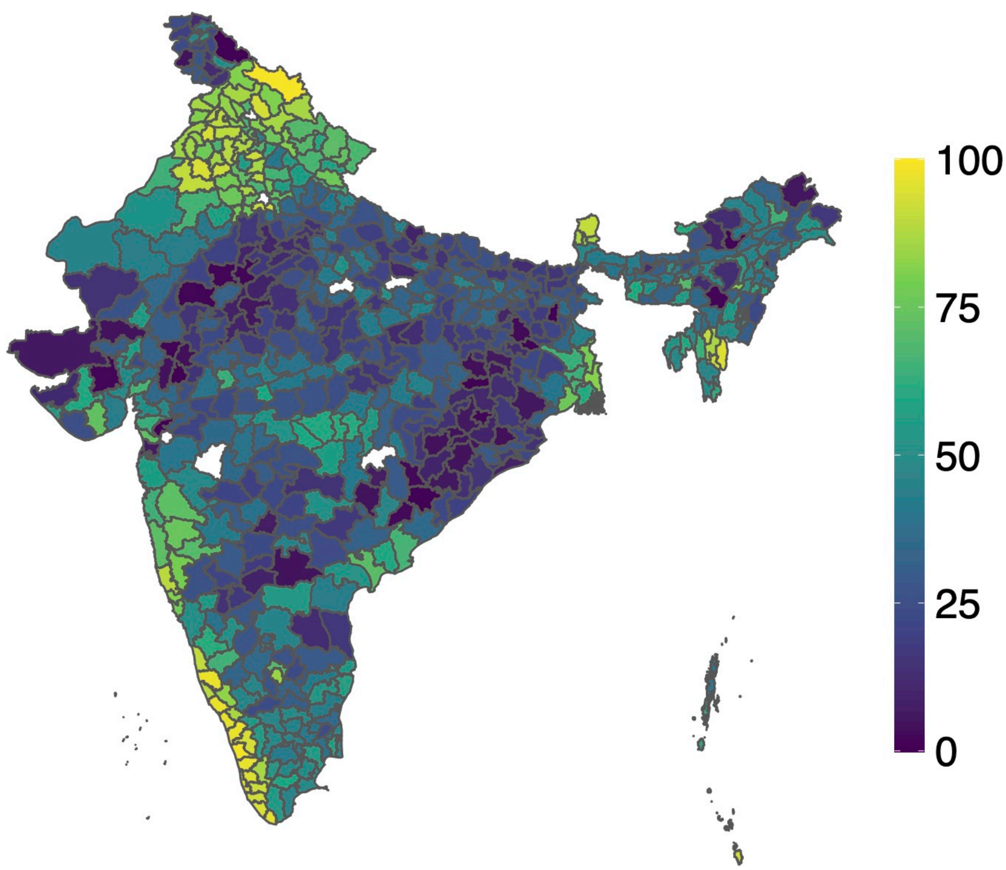


Figure B1: Latrine Coverage (%) in 2013 across Districts

Notes: Districts with no data on latrine coverage are displayed to be blank. These districts correspond to urban areas where latrine data are not recorded under the SBM.

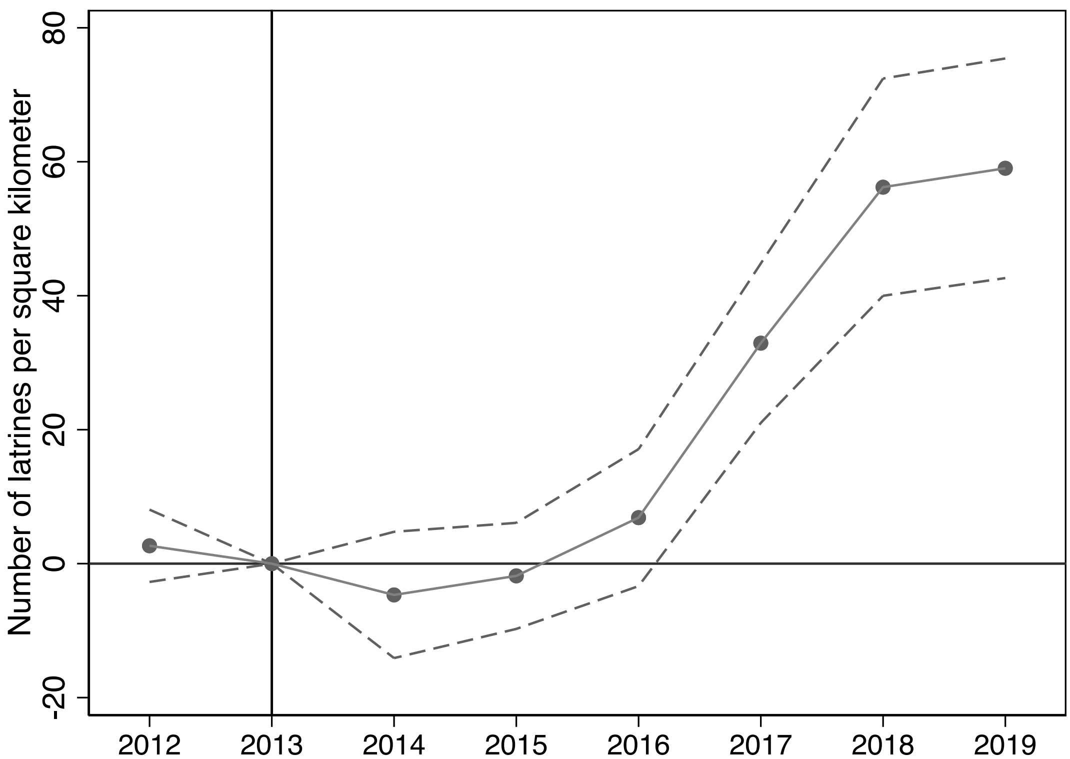


Figure B2: Differential Change in the Number of Latrines between Districts with Lower Baseline Coverage and Districts with Higher Baseline Coverage

Notes: This figure shows the regression coefficients of the number of latrines per square kilometer on the interaction terms between (1- baseline latrine coverage in 2013) and year dummies at the district level. The regression includes district fixed effects, year fixed effects, and the following controls: precipitation, VIIRS nighttime luminosity, population, the proportions of Scheduled Caste and Scheduled Tribe members, and literacy rates. The 95% confidence intervals are shown with dashed lines. Standard errors are clustered at the district level.

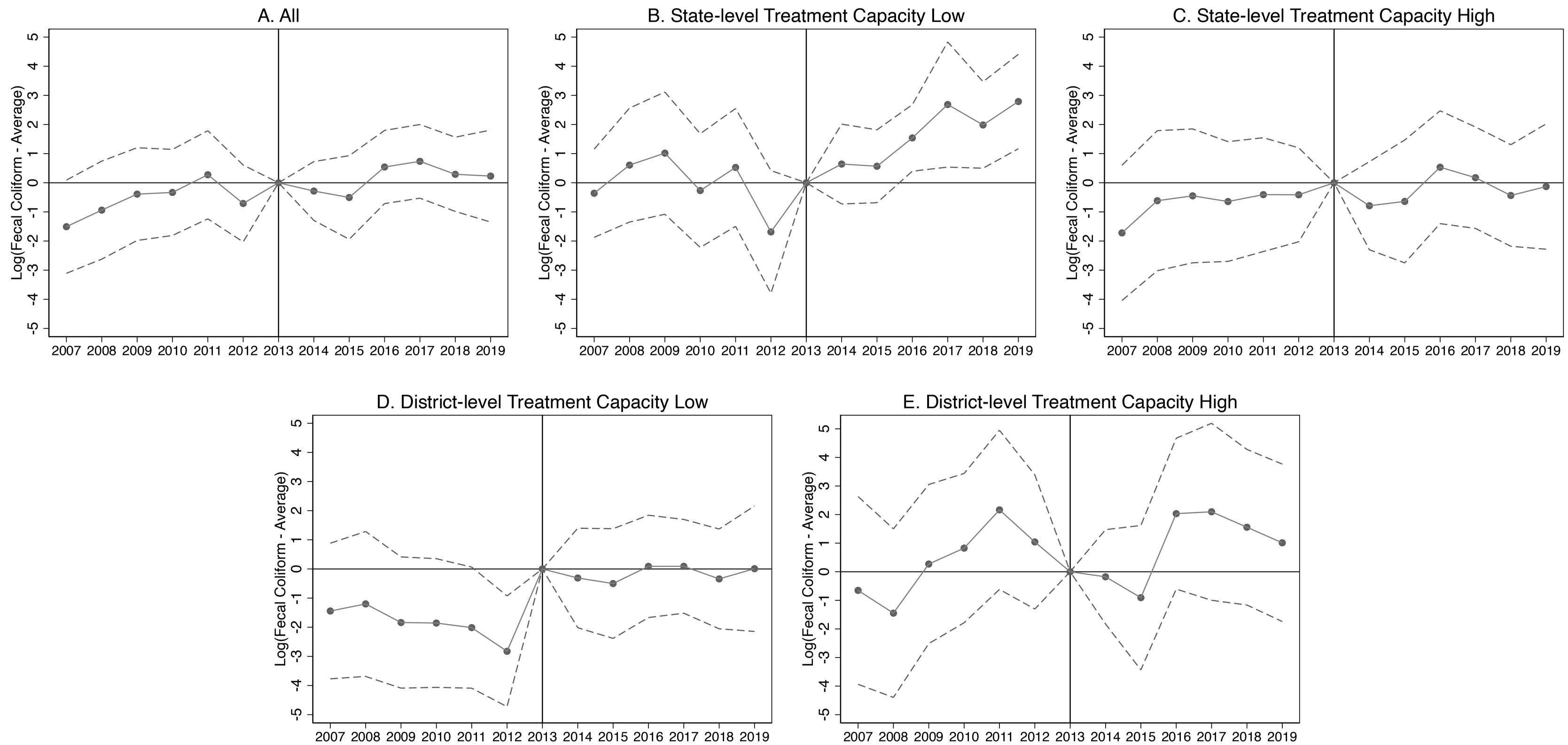


Figure B3: The Dynamic Effects on Water Pollution (Log of Fecal Coliform)

Notes: This figure shows the regression coefficients of the logarithm of fecal coliform in regression 6. The 95% confidence intervals are shown with dashed lines. Standard errors are clustered at the district level. All regressions include monitoring station fixed effects, basin-year fixed effects, and the following controls: precipitation, VIIRS nighttime luminosity, population, the proportions of Scheduled Caste and Scheduled Tribe members, and literacy rates. Panel B shows a result in states where treatment capacities of sewage treatment plants are lower than the median, while Panel C shows a result in states with higher treatment capacities. Panel D shows a result in districts where treatment capacities of sewage treatment plants are lower than the median, while Panel E shows a result in districts with higher treatment capacities.

Table B1: DID Results: The Effect on Water Quality (Log of Fecal Coliform)

	All	State-level Capacity		District-level Capacity	
	(1)	(2)	(3)	(4)	(5)
	All	High	Low	High	Low
(1 - 2013 Latrine Coverage) * Post (= 1)	0.647	0.372	1.790***	0.496	1.496**
	(0.527)	(0.775)	(0.660)	(0.911)	(0.654)
Observations	10,385	5,075	5,281	4,240	6,110
R^2	0.860	0.869	0.883	0.881	0.879
Number of Stations	1,187	577	606	465	719
Number of Districts	335	182	151	95	238

Notes: This table reports the regression coefficients of the logarithm of fecal coliform in regression 5. Standard errors, clustered at the district level, are in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. All regressions include monitoring station fixed effects, basin-year fixed effects, and the following controls: precipitation, VIIRS nighttime luminosity, population, the proportions of Scheduled Caste and Scheduled Tribe members, and literacy rates. Column 2 reports a result in states where treatment capacities of sewage treatment plants are higher than the median, while Column 3 reports a result in states with lower treatment capacities. Columns 4 and 5 compare results based on the different levels of treatment capacities at the district level.

C Additional Figures

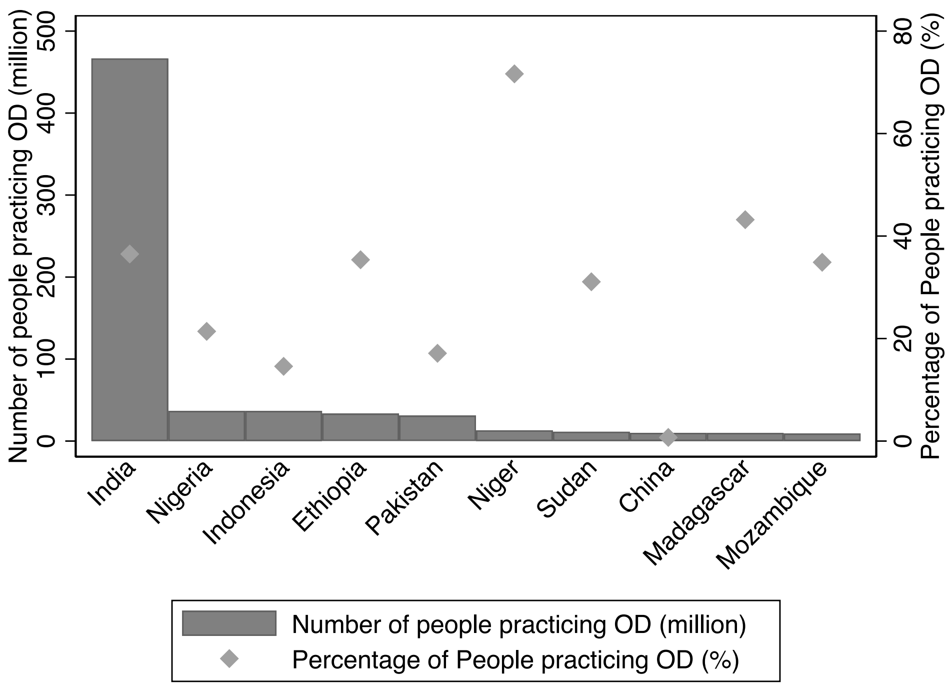


Figure C1: Top 10 Countries by the Number of People Practicing Open Defecation in 2013

Notes: This figure documents the top 10 countries by the number of people practicing open defecation. It plots both the number of people practicing open defecation and the percentage of people practicing open defecation for these 10 countries. The data source is the database of the WHO/UNICEF Joint Monitoring Programme for Water Supply, Sanitation, and Hygiene.

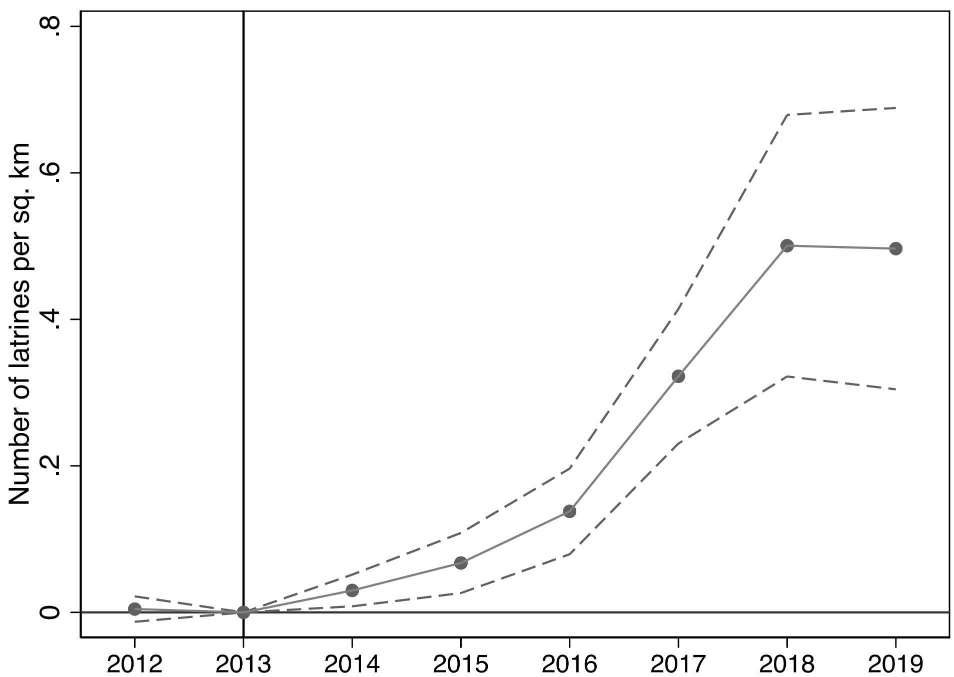


Figure C2: Event Study Plots of First-Stage Regressions of Available Water Capacity on Number of Latrines

Notes: This figure shows the regression coefficients of the number of latrines per square kilometer on the interaction terms between Available Water Capacity and year dummies in the water quality regression. The 95% confidence intervals are shown with dashed lines. Standard errors are clustered at the district level. The regression includes monitoring station fixed effects, year fixed effects, and precipitation as a control.

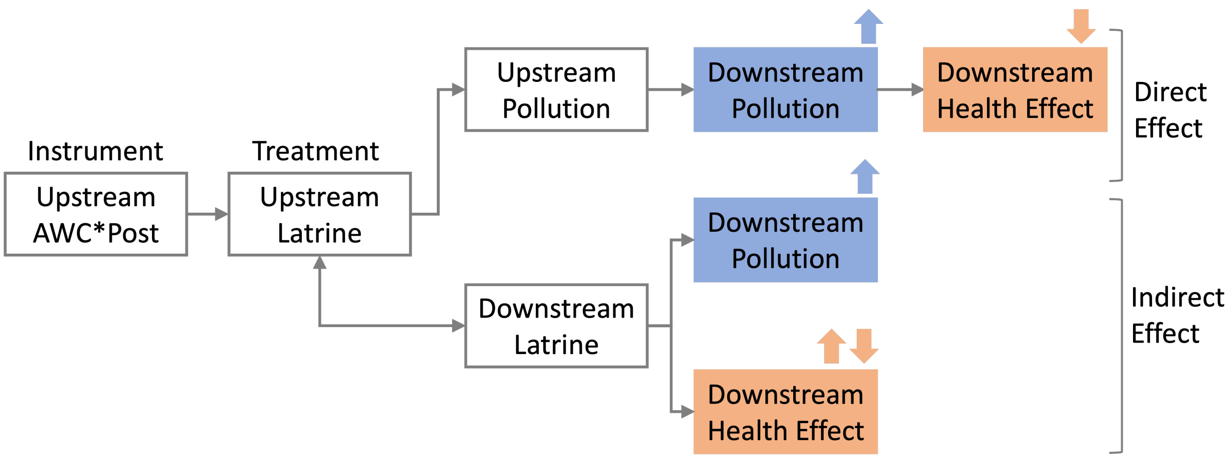


Figure C3: Two Underlying Channels in Upstream-Downstream Analysis

Notes: This figure illustrates two underlying channels in the upstream-downstream analysis. The β_{IV}^{U} in regression 3 represents the composite of these two underlying effects. In this figure, a reference district is referred to as a downstream area. The first underlying channel is a direct effect where upstream latrine construction leads to water pollution that flows downstream, subsequently causing a negative externality on health in downstream areas. The second underlying channel is an indirect effect where downstream latrine construction, which is correlated with upstream latrine construction, contributes to increased water pollution in downstream areas. In the second channel, the sign of the health effect depends on the relative magnitude of direct positive health effects and water pollution externalities resulting from latrine construction in downstream areas.

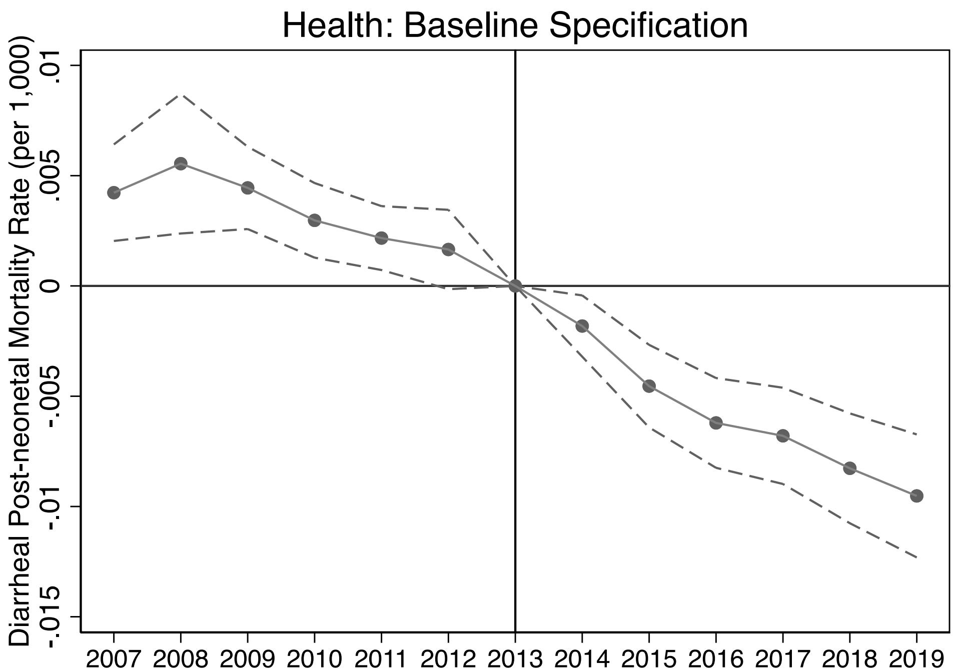


Figure C4: Event Study Plots of Reduced-Form Regressions of Available Water Capacity on Diarrheal Mortality Rate in Baseline Specification

Notes: This figure shows the regression coefficients of the logarithm of diarrheal post-neonatal mortality rate per 1,000 live births on the interaction terms between Available Water Capacity and year dummies. The 95% confidence intervals are shown with dashed lines. Standard errors are clustered at the district level. The regression includes district fixed effects, year fixed effects, and precipitation as a control.

D Additional Tables

Table D1: Summary Statistics of Variables for Robustness Checks

	Mean	SD	Min	Max	Obs.
Panel A. Time-varying variables: pre-SBM (2007-2013)					
Temperature - average (°C)	24.82	5.07	2.9	143	5207
pH - average	7.62	0.54	2.55	9.6	5244
Biochemical Oxygen Demand - average (mg/L)	5.4	17.17	0	534.5	5219
Dissolved Oxygen - average (mg/L)	6.77	1.75	0	38.85	5204
Nitrate/Nitrite - average (mg/L)	1.8	2.77	0	24.5	2436
Diarrheal early-neonatal mortality rate (per 1,000)	20.2	13.65	0.5	71.86	2359
Diarrheal late-neonatal mortality rate (per 1,000)	9.22	6.19	0.23	32.41	2359
Diarrheal age 1-4 mortality rate (per 1,000)	0.48	0.34	0.01	1.83	2359
Diarrheal under 5 mortality rate (per 1,000)	1.07	0.72	0.03	3.87	2359
Overweight prevalence age 0-5 (%)	6.77	2.33	0.77	17.57	2359
Infant mortality rate (per 1,000) $<$ 5 km from rivers	36.44	187.37	0	1000	63125
Infant mortality rate (per 1,000) $<$ 10 km from rivers	36.9	188.53	0	1000	101045
Latrine coverage (%)	43	25.48	0.08	100	586
Panel B. Time-varying variables: post-SBM (2014-2019)					
Temperature - average (°C)	24.85	4.36	0	35	5765
pH - average	7.72	5.49	2.6	409.45	5843
Biochemical Oxygen Demand - average (mg/L)	5.5	18.52	0	719.5	5739
Dissolved Oxygen - average (mg/L)	6.61	1.81	0	51.1	5766
Nitrate/Nitrite - average (mg/L)	2.19	19.84	0	1150.02	5521
Diarrheal early-neonatal mortality rate (per 1,000)	9.79	7.28	0.29	35.57	2022
Diarrheal late-neonatal mortality rate (per 1,000)	4.64	3.44	0.14	16.76	2022
Diarrheal age 1-4 mortality rate (per 1,000)	0.2	0.15	0.01	0.73	2022
Diarrheal under 5 mortality rate (per 1,000)	0.51	0.38	0.02	1.86	2022
Overweight prevalence age 0-5 (%)	7.35	2.73	0.57	25.49	2022
Infant mortality rate (per 1,000) $<$ 5 km from rivers	34.45	182.38	0	1000	41946
Infant mortality rate (per 1,000) $<$ 10 km from rivers	35.31	184.56	0	1000	67633
Latrine coverage (%)	76.78	27.43	3.58	100	1814
Panel C. Variables not varying over time					
Population (thousand) - 2011	1572.08	1077	28.99	6074.19	337
% Scheduled caste population - 2011	16.75	9.69	0	53.39	337
% Scheduled tribe population - 2011	16.98	25.24	0	98.10	337
% Literate population - 2011	61.16	10.44	28.66	88.7	337
VIIRS nighttime luminosity (nW/cm2/sr) - 2013	0.71	1.57	0.01	17.98	337

Notes: This table shows summary statistics of time-varying variables for pre-SBM periods (2007-2013) in Panel A and post-SBM periods (2014-2019) in Panel B, and summary statistics of time-invariant variables in Panel C. The latrine data are available only from 2012-2019, while data of other time-varying variables are available from 2007-2019.

Table D2: Upstream-Downstream Analysis: Alternative Buffer Sizes

	Buffer Distances from Reference Stations/Districts					
	(1) 0-50km	(2) 0-100km	(3) 0-150km	(4) 50-150km	(5) 100-150km	(6) Full
Panel A. Dependent Variable: Log(Fecal Coliform)						
Upstream number of latrines per sq. km	0.014 (0.012)	0.017 (0.013)	0.015 (0.011)	0.003 (0.009)	0.001 (0.007)	0.037** (0.016)
Observations	1,758	2,152	2,228	2,008	1,488	2,235
Number of Stations	287	352	365	325	238	367
Number of Districts	133	151	154	140	112	155
KP F-Stat	23.148	36.766	50.475	38.427	49.767	73.913
AR 95% CI	[-.011, .049]	[-.010, .048]	[-.008, .039]	[-.018, .021]	[-.019, .014]	[.005, .074]
Average Policy Effect	0.427	0.481	0.431	0.098	0.021	0.754
Panel B. Dependent Variable: Diarrheal Post-neonatal Mortality Rate (per 1,000 live births)						
Upstream number of latrines per sq. km	-0.011* (0.006)	-0.012* (0.006)	-0.011* (0.006)	-0.012* (0.006)	-0.017*** (0.006)	0.003 (0.010)
Observations	688	808	824	704	488	840
Number of Districts	86	101	103	88	61	105
KP F-Stat	58.692	61.264	78.696	78.481	77.325	83.728
AR 95% CI	[-.026, .002]	[-.025, .001]	[-.023, .001]	[-.026, .001]	[-.030, -.004]	[-.014, .027]
Mean of Dep. Variable	2.695	2.571	2.576	2.763	3.078	2.570
Average Policy Effect	-0.309	-0.294	-0.269	-0.303	-0.458	0.049

Notes: The coefficients are reported. Standard errors, clustered at the district level, are in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. The sample is limited to monitoring stations (Panel A) and districts (Panel B) located along major rivers in India. In Columns 1-5, I change buffer sizes for identifying upstream districts. In Column 6, I include all upstream districts without the restriction on a buffer size. Regressions in Panel A includes monitoring station fixed effects, year fixed effects, and the following controls: precipitation and the interaction of Available Water Capacity and the post-SBM indicator of a reference district. Regressions in Panel B includes district fixed effects, year fixed effects, and the same controls as Panel A. The KP F-Stat refers to the Wald version of the Kleibergen and Paap (2006) rk-statistic on the excluded instrumental variables for non-i.i.d. errors. The AR 95% CI reports the 95% confidence interval, which is robust to the weak instrument based on the Anderson and Rubin (1949) test. Means of dependent variables are calculated for the pre-SBM period. Average policy effects are calculated by multiplying the estimated coefficients by the change in the number of latrines per square kilometer after the SBM started in 2014.

Table D3: Upstream-Downstream Analysis: Placebo Test

	Log(Fecal Coliform)	Dirrheal Post-neonetal Mortality Rate
	(1)	(2)
Downstream number of latrines per sq. km	0.050	-0.025
	(0.042)	(0.016)
Observations	2,215	760
Number of Stations	365	-
Number of Districts	147	95
KP F-Stat	2.391	2.375

Notes: The coefficients are reported. Standard errors, clustered at the district level, are in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. The sample is limited to monitoring stations (Column 1) and districts (Column 2) located along major rivers in India. Downstream districts are defined as those within the range of $[0, 150]$ kilometers from a reference station (district). A regression in Column 1 includes monitoring station fixed effects, year fixed effects, and the following controls: precipitation and the interaction of Available Water Capacity and the post-SBM indicator of a reference district. A regression in Column 2 includes district fixed effects, year fixed effects, and the same controls as Panel A. The KP F-Stat refers to the Wald version of the Kleibergen and Paap (2006) rk-statistic on the excluded instrumental variables for non-i.i.d. errors.

Table D4: The Effects on Multiple Types of Diarrheal Mortality Rate (per 1,000 live births)

	(1) Early-neonatal	(2) Late-neonatal	(3) Post-neonatal	(4) Age 1-4	(5) Under 5
Upstream number of latrines per sq. km	-0.092**	-0.042*	-0.011*	-0.002**	-0.005**
	(0.046)	(0.021)	(0.006)	(0.001)	(0.002)
Observations	824	824	824	824	824
Number of Districts	103	103	103	103	103
KP F-Stat	78.696	78.696	78.696	78.696	78.696
AR 95% CI	[-.190, .005]	[-.086, .003]	[-.023, .001]	[-.005, .000]	[-.010, .000]
Mean of Dep. Variable	18.562	8.656	2.576	0.411	0.969
Average Policy Effect	-2.221	-1.004	-0.269	-0.057	-0.116

Notes: The coefficients are reported. Standard errors, clustered at the district level, are in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. All regressions include district fixed effects, year fixed effects, and the following controls: precipitation and the interaction of Available Water Capacity and the post-SBM indicator of a reference district. The sample is limited to districts that have monitoring stations used in the water quality regression along major rivers in India. Upstream districts are defined as those within the range of $[0, 150]$ kilometers from a reference district. The KP F-Stat refers to the Wald version of the Kleibergen and Paap (2006) rk-statistic on the excluded instrumental variables for non-i.i.d. errors. The AR 95% CI reports the 95% confidence interval, which is robust to the weak instrument based on the Anderson and Rubin (1949) test. Means of dependent variables are calculated for the pre-SBM period. Average policy effects are calculated by multiplying the estimated coefficients by the change in the number of latrines per square kilometer after the SBM started in 2014.

Table D5: Falsification Tests

	Log(Temperature)	Log(pH)	Log(BOD)	Log(DO)	Log(Nitrate/Nitrite)	Overweight Prevalence
	(1)	(2)	(3)	(4)	(5)	(6)
Number of latrines per sq. km	-0.0023	0.0001	-0.0034	-0.0008	0.0003	
	(0.0015)	(0.0005)	(0.0037)	(0.0010)	(0.0162)	
Upstream number of latrines per sq. km						-0.0131
						(0.0184)
Observations	7,103	7,176	7,084	7,094	6,379	824
Number of Stations	1,179	1,189	1,184	1,181	1,142	-
Number of Districts	334	337	336	336	319	103
KP F-Stat	28.358	29.240	28.067	29.955	7.991	78.696
AR 95% CI	[-.005, .001]	[-.001, .001]	[-.011, .005]	[-.003, .001]	[..., .033]	[-.050, .027]
Mean of Dep. Variable	24.847	7.638	5.157	6.653	2.110	6.781

Notes: The coefficients are reported. Standard errors, clustered at the district level, are in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. Regressions in Columns 1-5 includes monitoring station fixed effects, year fixed effects, and precipitation as a control. A regression in Column 6 includes district fixed effects, year fixed effects, and the following controls: precipitation and the interaction of Available Water Capacity and the post-SBM indicator of a reference district, and upstream districts are defined as those within the range of $[0, 150]$ kilometers from a reference district. Column 6 uses overweight prevalence (%) for ages 0-5 as an outcome. The KP F-Stat refers to the Wald version of the Kleibergen and Paap (2006) rk-statistic on the excluded instrumental variables for non-i.i.d. errors. The AR 95% CI reports the 95% confidence interval, which is robust to the weak instrument based on the Anderson and Rubin (1949) test. The open-ended confidence interval shows that the searched grids do not extend far enough to capture the point where the rejection probability crosses above the 95%. Means of dependent variables are calculated for the pre-SBM period.

Table D6: Robustness Check - Spillovers from Neighboring Districts: The Effect on Water Quality (Log of Fecal Coliform)

	All	State-level Capacity		District-level Capacity	
	(1) All	(2) High	(3) Low	(4) High	(5) Low
Number of latrines per sq. km	0.027*** (0.007)	-0.027 (0.019)	0.037*** (0.006)	0.017* (0.009)	0.043*** (0.013)
Observations	7,253	3,605	3,648	3,300	3,953
Number of Stations	1,197	603	594	529	668
Number of Districts	489	260	229	185	304
KP F-Stat	44.626	14.440	54.539	26.013	15.433
AR 95% CI	[.013, .042]	[-.076, .010]	[.027, .050]	[-.003, .036]	[.021, .081]
Average Policy Effect	0.655	-0.599	0.952	0.362	1.140

Notes: The coefficients are reported. Standard errors, clustered at the district level, are in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. All regressions include monitoring station fixed effects, year fixed effects, and precipitation as a control. Column 2 reports a result in states where treatment capacities of sewage treatment plants are higher than the median, while Column 3 reports a result in states with lower treatment capacities. Columns 4 and 5 compare results based on the different levels of treatment capacities at the district level. The KP F-Stat refers to the Wald version of the Kleibergen and Paap (2006) rk-statistic on the excluded instrumental variables for non-i.i.d. errors. The AR 95% CI reports the 95% confidence interval, which is robust to the weak instrument based on the Anderson and Rubin (1949) test. Average policy effects are calculated by multiplying the estimated coefficients by the change in the number of latrines per square kilometer after the SBM started in 2014.

Table D7: Robustness Check - Influence from Urban Areas

	No Exclusion	50km Exclusion	100km Exclusion	150km Exclusion
	(1)	(2)	(3)	(4)
Panel A. Dependent Variable: Log(Fecal Coliform)				
Number of latrines per sq. km	0.030***	0.039***	0.050***	0.072**
	(0.008)	(0.010)	(0.015)	(0.035)
Observations	7,201	5,295	3,716	2,492
Number of Stations	1,189	890	623	421
Number of Districts	337	284	196	125
KP F-Stat	29.954	25.785	17.574	5.693
AR 95% CI	[.015, .049]	[.021, .067]	[.026, .099]	[.026, ...]
Average Policy Effect	0.719	1.035	1.369	1.902
Panel B. Dependent Variable: Diarrheal Post-neonatal Mortality Rate (per 1,000 live births)				
Upstream number of latrines per sq. km	-0.011*	-0.010	-0.007	-0.009
	(0.006)	(0.008)	(0.011)	(0.015)
Observations	824	480	288	152
Number of Districts	103	60	36	19
KP F-Stat	78.696	49.232	22.506	29.583
AR 95% CI	[-.023, .001]	[-.026, .008]	[-.031, .025]	[-.045, .042]
Mean of Dep. Variable	2.576	2.577	2.561	2.670
Average Policy Effect	-0.269	-0.208	-0.150	-0.137

Notes: The coefficients are reported. Standard errors, clustered at the district level, are in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. In Columns 2-4, I exclude monitoring stations (Panel A) and districts (Panel B) that are within a specified distance from cities that have a population of 1 million and above. Panel A includes monitoring station fixed effects, year fixed effects, and precipitation as a control. Panel B includes district fixed effects, year fixed effects, and the following controls: precipitation and the interaction of Available Water Capacity and the post-SBM indicator of a reference district, and upstream districts are defined as those within the range of $[0, 150]$ kilometers from a reference district. The KP F-Stat refers to the Wald version of the Kleibergen and Paap (2006) rk-statistic on the excluded instrumental variables for non-i.i.d. errors. The AR 95% CI reports the 95% confidence interval, which is robust to the weak instrument based on the Anderson and Rubin (1949) test. The open-ended confidence interval shows that the searched grids do not extend far enough to capture the point where the rejection probability crosses above the 95%. Means of dependent variables are calculated for the pre-SBM period. Average policy effects are calculated by multiplying the estimated coefficients by the change in the number of latrines per square kilometer after the SBM started in 2014.

Table D8: Robustness Check - Balanced Panel: The Effect on Water Quality (Log of Fecal Coliform)

	All	State-level Capacity		District-level Capacity	
	(1)	(2)	(3)	(4)	(5)
	All	High	Low	High	Low
Number of latrines	0.024***	-0.010	0.031***	0.009	0.039***
per sq. km	(0.009)	(0.022)	(0.008)	(0.012)	(0.014)
Observations	3,776	1,552	2,224	1,600	2,176
Number of Stations	472	194	278	200	272
Number of Districts	158	75	83	53	105
KP F-Stat	12.357	12.512	13.449	4.018	7.917
AR 95% CI	[.009, .048]	[-.072, .032]	[.018, .053]	[..., .048]	[.018, .086]
Average Policy Effect	0.644	-0.209	0.926	0.210	1.137

Notes: The coefficients are reported. Standard errors, clustered at the district level, are in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. The sample is limited to monitoring stations that have observations every year from 2012 to 2019, which yields a balanced panel. All regressions include monitoring station fixed effects, year fixed effects, and precipitation as a control. Column 2 reports a result in states where treatment capacities of sewage treatment plants are higher than the median, while Column 3 reports a result in states with lower treatment capacities. Similarly, Columns 4 and 5 compare results based on the different levels of treatment capacities at the district level. The KP F-Stat refers to the Wald version of the Kleibergen and Paap (2006) rk-statistic on the excluded instrumental variables for non-i.i.d. errors. The AR 95% CI reports the 95% confidence interval, which is robust to the weak instrument based on the Anderson and Rubin (1949) test. The open-ended confidence interval shows that the searched grids do not extend far enough to capture the point where the rejection probability crosses above the 95%. Average policy effects are calculated by multiplying the estimated coefficients by the change in the number of latrines per square kilometer after the SBM started in 2014.

Table D9: The Effects on Health on Individuals Living Close to Rivers (Infant Mortality Rate (per 1,000 live births))

	All	State-level Capacity		District-level Capacity	
	(1)	(2)	(3)	(4)	(5)
	All	High	Low	High	Low
Panel A. Living within 5 kilometers from rivers					
Upstream number of latrines per sq. km	-1.414***	-4.030**	-1.000**	-2.138***	-0.953*
	(0.419)	(1.931)	(0.377)	(0.763)	(0.487)
Observations	13,204	5,894	7,310	5,641	7,563
Number of Districts	69	38	31	36	33
KP F-Stat	47.077	7.240	41.982	30.768	18.766
Mean of Dep. Variable	34.233	41.327	7.796	39.296	30.700
Average Policy Effect	-31.693	-78.053	-24.836	-48.668	-20.763
Panel B. Living within 10 kilometers from rivers					
Upstream number of latrines per sq. km	-1.149***	-3.115*	-0.807***	-1.589**	-0.843*
	(0.354)	(1.783)	(0.289)	(0.606)	(0.454)
Observations	21,064	9,822	11,242	9,340	11,724
Number of Districts	70	38	32	36	34
KP F-Stat	47.196	8.152	36.305	34.194	15.730
Mean of Dep. Variable	34.907	37.488	9.019	39.615	31.423
Average Policy Effect	-25.300	-61.879	-19.297	-34.974	-18.209

Notes: The coefficients are reported. Standard errors, clustered at the district level, are in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. All regressions include district fixed effects, year fixed effects, and the following controls: precipitation and the interaction of Available Water Capacity and the post-SBM indicator of a reference district. Upstream districts are defined as those within the range of $[0, 150]$ kilometers from a reference district. Column 2 reports a result when upstream states have higher treatment capacities of sewage treatment plants than the median, while Column 3 reports a result in the case of upstream states with lower treatment capacities. Columns 4 and 5 compare results based on the different levels of upstream treatment capacities at the district level. The KP F-Stat refers to the Wald version of the Kleibergen and Paap (2006) rk-statistic on the excluded instrumental variables for non-i.i.d. errors. Means of dependent variables are calculated for the pre-SBM period. Average policy effects are calculated by multiplying the estimated coefficients by the change in the number of latrines per square kilometer after the SBM started in 2014.