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Exposure to Sewage from On-site Sanitation and Child Health: A Spatial Analysis of Linkages and Externalities in Peri-Urban Bolivia

Antonella Bancalari and Sebastian Martinez*

Abstract

Exposure to fecal contamination is a leading cause of childhood infectious diseases in low- and middle-income countries. Low-quality sanitation infrastructure and inadequate maintenance can make on-site solutions such as latrines connected to septic tanks and cesspools prone to spillage, exposing children to sewage. This paper uses a unique dataset with independent verification of sewage in and around the land parcels of more than 20,000 households with access to on-site sanitation in peri-urban Bolivia. The aim is to analyze the relationship between exposure to sewage from overflowed sanitation infrastructure and the incidence of diarrhea in children under age five. The presence of sewage is associated with a 4 percentage point increase in the probability of diarrhea incidence—a relative increase of 22 percent. That statistical relationship is driven by sewage within the boundaries of the property where the child resides, which is associated with a relative increase of 30 percent in the probability of the incidence of diarrhea. Our spatial analysis of sewage density shows that the probability of the incidence of diarrhea increases with the concentration of sewage in the immediate vicinity of the child's residence, suggesting negative spillovers from neighbors with overflowed on-site sanitation facilities. The negative health externalities associated with faulty on-site sanitation infrastructure provide a persuasive argument in favor of government interventions that adequately remove and treat fecal sludge.

Key words: diarrhea, externalities, on-site sanitation, peri-urban, sewage.

JEL: I15, Q53

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INTRODUCTION

Lack of access to hygienic sanitation facilities has been associated with increased prevalence of diarrhea, which is the second leading cause of death in children under the age of five worldwide, killing around 760,000 children per year (WHO, 2013). Policy solutions to low sanitation coverage have stressed the construction of on-site facilities (i.e. to deal with excreta where it is deposited), with the aim of reducing exposure to fecal pathogens from open defecation. However, while epidemiological studies have identified a clear link between sanitation and the prevalence of diarrhea (Esrey and Habicht, 1986; Fewtrell et al., 2005; Kremer, 2007; White et al., 1972), recent studies of the impact of expanding on-site sanitation coverage in rural (e.g. Clasen et al., 2014; Patil et al., 2014) as well as urban settings (Freeman et al., 2017) have found modest or no effects on child diarrhea

A possible explanation for the lack of a health impact from increased sanitation coverage may be related to poorly constructed and maintained on-site facilities and inadequate fecal sludge management that result in sewage runoff (referred to as "blackwater"). For example, Berendes et al. (2017a) found no effect on diarrhea prevalence from the adoption of poorly constructed toilets that discharge to open drains. Besides appropriate construction for the effective underground drainage of effluent, on-site sanitation systems require routine removal of sludge to avoid spillage (Carter, 2013; Peal et al., 2014). Therefore, even if on-site sanitation coverage is high, construction is appropriate, and sanitation facilities are used consistently, septic tanks and cesspools overflow and release sewage if households fail to properly maintain their systems (Holden, 2008; Peal et al., 2014; Reed, 1994). In fact, a recent systematic review found little to no effect from on-site sanitation coverage on the presence of feces and flies and on pathogenic transmission pathways such as food and soil (Sclar et al., 2016).

Poor maintenance of sanitation facilities may occur for a host of reasons, including constraints to fix or clean the system, inadequate information regarding the importance of hygiene and sanitation, and an insufficient supply of sludge removal services. Particularly in densely populated peri-urban neighborhoods, sewage runoff from one household can produce negative externalities by contaminating public spaces such as roads and sidewalks and contributing to the spread of infectious diseases in neighboring children. Therefore, households do not assume the full costs and benefits of maintaining their sanitation systems, further reducing the incentives for proper sanitation maintenance.

The aim of this study is to estimate the association between sewage from overflowed on-site sanitation systems and the occurrence of diarrhea among children under five, and to document potential negative health externalities. To address this question, we analyze data from over 20,000 households in a low-income, peri-urban area of Santa Cruz de la Sierra, Bolivia. As with many such areas throughout the country, households in the study area have no access to piped sewerage, but near universal access to piped water and on-site sanitation. As such, the primary source of sewage contamination above ground is from septic tanks and cesspools that, when not properly maintained, leak runoff in the form of “blackwater” onto properties, streets, and sidewalks.

METHODS

Data

This study uses the Baseline Survey of Sanitation Systems in Peri-Urban Areas conducted by the Ministry of Water and Environment in the “Plan 3000” area of Santa Cruz de la Sierra, Bolivia from October to December 2013. Information was collected from all households (census) in 26 neighborhoods, covering a total of 20,637 households, out of which 7,158 had children under five years of age. As a result, health outcome information on diarrhea incidence was collected for 9,008 children. A unique feature of the survey was an independent visual inspection by the interviewer of the presence of sewage runoff inside the dwelling and in the immediate surrounding area. The survey also recorded geographic coordinates for each dwelling, household socio-demographic characteristics, the education and labor status of household members, and dwelling characteristics. The target respondent was the female head of household.

The health outcome of interest is diarrhea incidence, measured as a binary variable equal to 1 if the caretaker reported that a child in the household had diarrhea during the two weeks preceding the interview. The diarrhea prevalence of the study population is 0.18 (standard deviation of 0.38, as shown in Table 1). The explanatory variable of interest is exposure to sewage, which is obtained from the interviewer’s independent visual inspection of the presence of blackwater in and around the property. Reporting of the visual inspection was standardized across interviewers as part of a module completed by the interviewer immediately following the survey based on observations conducted in and around the property. Observation of the presence of sewage indoors was conducted as the interviewer walked through to inspect the toilet facilities, which were typically located at the back of property. Any runoff or pooling of blackwater observed on the property or within the dwelling was recorded accordingly. Observation to determine if there was sewage outdoors was done after completing the survey in each household. The presence of sewage outdoors was recorded if runoff or pooling of blackwater was observed on the sidewalk or half of the street closest to the property's front entry, anywhere between the start and endpoints of the parcel limits.

While outdoor inspection was conducted in a public space and as such is reported for the full sample, the indoor visual inspection was conditional on the household's willingness to let the interviewer onto the property and/or in the house, raising the potential for nonrandom item nonresponse. The nonresponse rate for indoor sewage for the subsample of households with children below five years of age was 9 percent. However, observed characteristics including outdoor sewage and household demographic characteristics are balanced across respondents and nonrespondents (see Appendix A), alleviating concerns of nonresponse bias. Our final sample includes 6,387 households where indoor and outdoor sewage was reported, corresponding to 8,171 children.

Table 1 presents descriptive statistics of the sanitation infrastructure: 99 percent of households have piped water and on-site sanitation facilities, and 16 percent of those facilities are inside the dwelling and 84 percent outside but within the property. Sewage is discharged primarily to septic tanks (37 percent) and cesspools (58 percent), but 58 percent of these households reported never cleaning their septic tanks or cesspools. Only 1 percent of households have no facility and 3 percent of households discharge effluent into an open ditch. As such, the observed sewage inside and/or outside half of all households is not mainly a result of open discharge, but rather of overflowed on-site facilities that leak blackwater. Variation in the presence of indoor and outdoor sewage results in four binary variables that indicate: (1) indoor and outdoor sewage (13 percent); (2) indoor sewage only (5 percent); (3) outdoor sewage only (32 percent); and (4) no indoor or outdoor sewage (50 percent). (See Appendix B for a cross-tabulation of sewage exposure and types of sanitation discharge.) The correlation between indoor and outdoor sewage is just 15 percent, suggesting a fairly high level of independence between these two variables.

Table 1. Descriptive Statistics

Variable	Mean	Standard Deviation	Minimum	Maximum	Observations
All households					
Access to piped water	0.998	0.040	0	1	20,447
Access to sanitation facility	0.992	0.088	0	1	20,509
Toilet location					
Inside dwelling	0.161	0.368	0	1	20,350
Outside dwelling, but within the property	0.839	0.368	0	1	20,350
Discharge:					
Sewerage	0.005	0.074	0	1	20,350
Septic tank	0.369	0.482	0	1	20,350
Pit latrine to cesspools	0.584	0.493	0	1	20,350
Open ditch	0.032	0.177	0	1	20,350
Other	0.009	0.095	0	1	20,350
Cleaning frequency of septic tank/cesspool					
Never	0.583	0.493	0	1	18,642
Once per year	0.209	0.407	0	1	18,642
Every 2 years	0.081	0.273	0	1	18,642
Every 3 years	0.108	0.310	0	1	18,642
More than every 3 years	0.019	0.136	0	1	18,642
Households with children under 5 years old and reported indoor and/or outdoor sewage					
Sewage exposure					
Indoor and outdoor sewage	0.134	0.340	0	1	6,387
Indoor sewage	0.049	0.216	0	1	6,387
Outdoor sewage	0.319	0.466	0	1	6,387
Children					
Prevalence of diarrhea	0.181	0.385	0	1	8,171
Age in months	29.11	16.913	0	60	8,171
Female	0.482	0.500	0	1	8,171

Source: Authors' calculations based on Plan 3000 baseline survey.

Analysis

We use multivariable logit regression models (Stock and Watson, 2007) with spatial fixed effects (at the neighborhood level) to estimate the association between the incidence of child diarrhea and exposure to sewage from overflowed on-site sanitation facilities:

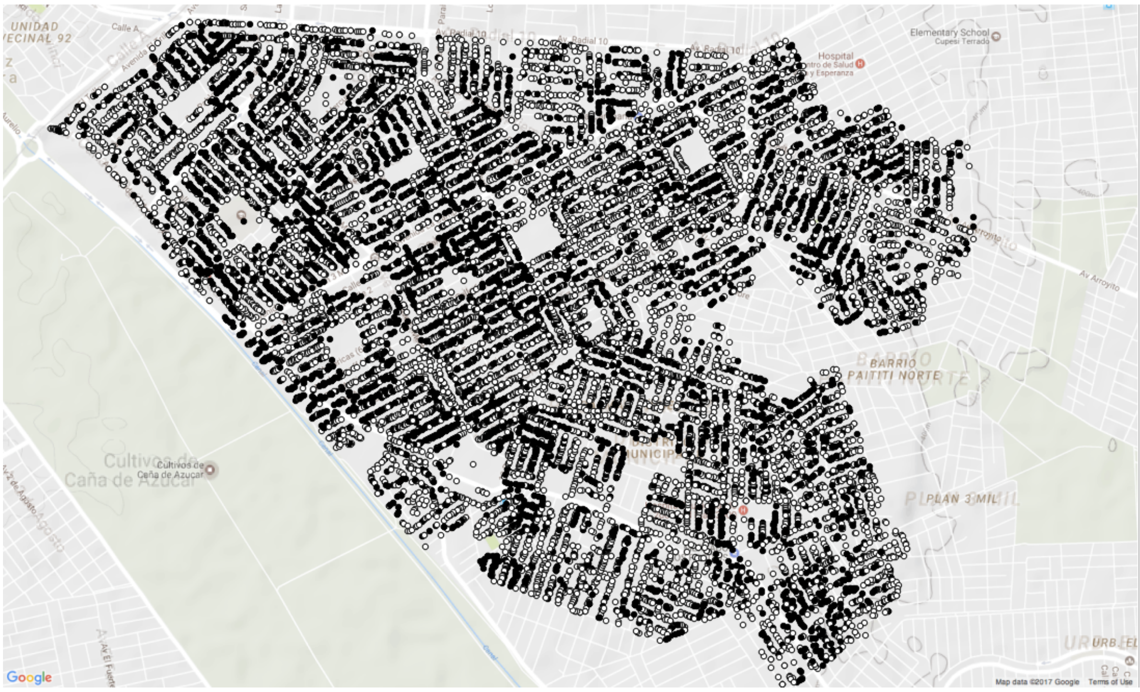
$$\Pr(y_{ihn} = 1 \,|S_{hn} \dots \alpha_n) = \text{F}(\beta_1 S_{hn} + \beta_2\, IS_{hn} + \beta_3 OS_{hn} + \gamma X_{ihm} + \theta H_{hm} + \alpha_n), \qquad (1)$$

where $\Pr(y_{ihn} = 1 \,|S_{hn} \dots \alpha_n)$ is the probability of the incidence of diarrhea for child i in household h and neighborhood n conditional on observed covariates. S_{hn}, IS_{hn}, and OS_{hn} denote binary variables for the set of households with indoor and outdoor sewage, indoor sewage only, and outdoor sewage only, respectively. The logit coefficients that appear inside the cumulative standard logistic distribution function F are estimated by maximum likelihood. β_1, β_2, and β_3 are the estimated association between the probability of the incidence of diarrhea and each type of sewage versus no exposure to sewage. The observed covariates at the child level (age and sex) are denoted by vector X_{ihm}, and at the household level (demographic composition, household head's gender, age, educational level, and occupation, asset ownership, dwelling ownership and features, social insertion, access to piped water, and presence of animals as a proxy for hygiene) are denoted by vector H_{hm} (see Appendix C for descriptive statistics). The variable α_n denotes neighborhood fixed effects. Standard errors are clustered at the household level to correct for correlation across children within the same household.

Even if a household has strong preferences for maintaining a sanitary environment, exposure to fecal matter in public spaces such as streets and sidewalks depends on the behavior of neighbors with regard to the upkeep of their own on-site sanitation systems. We exploit the rich spatial variation in the concentration of outdoor sewage to estimate the association between density of neighboring houses with outdoor sewage (henceforth, sewage density) and the incidence of diarrhea in children under five. Figure 1 shows a map of the 26 neighborhoods where the survey was conducted. Each point on the map represents a dwelling's geographic coordinate. Shaded areas represent households where outdoor sewage from overflowed on-site sanitation facilities was identified, while lightly shaded areas represent households without outdoor sewage.

We measure sewage density as the number of neighboring houses with outdoor sewage within buffer circular arcs with a radius of 100 meters around each household (constructed with ArcGIS™ software). We then estimate model (1) with sewage density as the explanatory variable of interest, instead of the binary variables of sewage exposure. We additionally control for population density, which is constructed in the same way as sewage density.

Figure 1. Plan 3000 Map of the Location of Houses with Outdoor Sewage



Source: Author's calculations using ArcGIS ™ software with data from the Plan 3000 baseline survey.
Notes: The map covers the 14 square kilometers where the 26 neighborhoods included in the survey are located. Houses with outdoor sewage are denoted with a black circle and those without outdoor sewage with a white circle.

RESULTS AND DISCUSSION

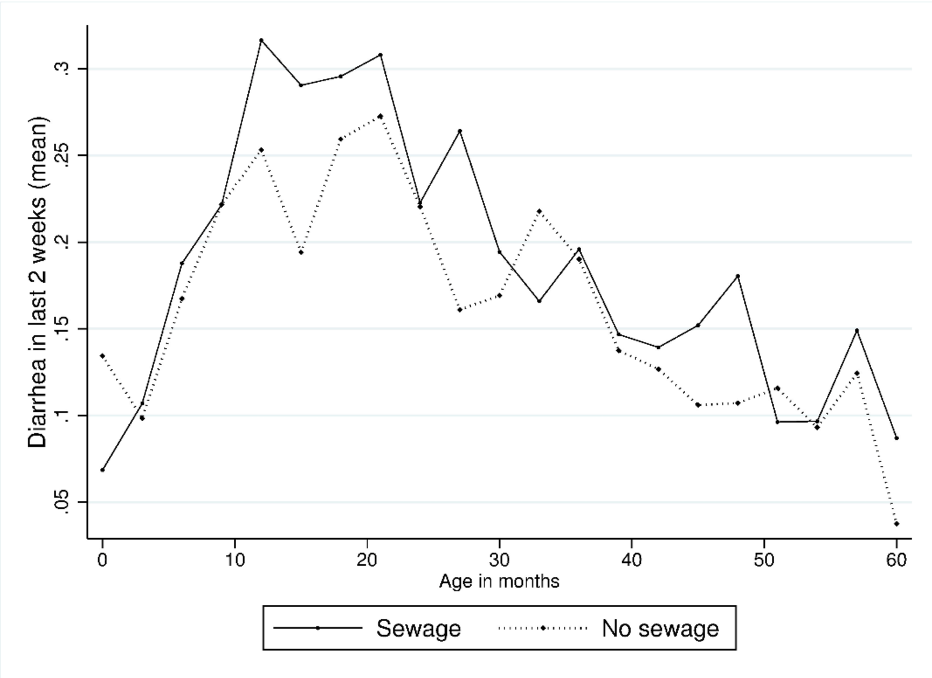
Household Sewage Exposure and Child Diarrhea

Child exposure to contaminated environments is likely to vary with age, as children change their behavioral patterns (i.e. crawl, walk with assistance, walk alone, play in the ground, etc.), increase their awareness of risks (i.e. putting dirty fingers inside the mouth), and are more able to make choices to protect their health as their immune system strengthens (WHO, 2016). Child diarrheal incidence is expected to follow a similar pattern (Kattula et al., 2015).

Figure 2 depicts the evolution of the prevalence of diarrhea by age in months for children exposed to sewage (indoor and/or outdoor) and not exposed to sewage. For both groups we observe that the prevalence of diarrhea increases with age during the first 12 months, remains more or less stable through 24 months, and then declines steadily through 60 months. Furthermore, children exposed to sewage have a systematically higher diarrhea prevalence than children of the same age not exposed to sewage over much of the age distribution, particularly in the 10-60 month range.

This observation is consistent with child development patterns that can lead to increased contact with contaminated environments, for example as children become more mobile, typically crawling around 13 months and walking without assistance by 17 months (WHO, 2006).

Figure 2. Sewage Exposure and Prevalence of Diarrhea, by Age in Months



Source: Authors' calculations based on Plan 3000 baseline survey.
Notes: The x axis measures children's age in months and the y axis measures the mean of diarrhea incidence for all children within each age. "Sewage" indicates households with any sewage exposure (indoors and/or outdoors) and "No sewage" the opposite. The dark line represents children from households exposed to sewage and the dotted line represents children not exposed to sewage.

We estimate the association between exposure to sewage and the incidence of child diarrhea using model (1) and maximum-likelihood estimation. Table 2 shows the marginal effect at the mean of the observable covariates included in model (1). Table 2 column 1 shows that, for the whole sample of children, indoor and outdoor sewage exposure is significantly associated with an increased probability of diarrhea incidence in children under five. On average, any exposure to sewage is associated with a 4 percentage point increase in the probability of diarrhea incidence, a 22 percent increase relative to children not exposed to sewage. The presence of only indoor sewage is significantly associated with a 5.4 percentage point increase in the probability of diarrhea incidence, a relative increase of 30 percent compared to children in households with no sewage exposure. Although the coefficient on indoor sewage is larger than indoor and outdoor sewage, the difference is not statistically significant. For exposure to outdoor sewage, the estimate is small and insignificant. These results suggest that sewage from improperly maintained on-site sanitation facilities is a likely contributor to the prevalence of diarrhea, and that the primary vector is from exposure to sources inside the dwelling.

Table 2. Association between Child Diarrhea Incidence among Children under Five and Exposure to Sewage

	(1) Full sample	(2) 0-12	(3) 12-23	(4) 24-36	(5) 37-48	(6) 49-60
Indoor and outdoor sewage exposure	0.040***	0.019	0.043	0.008	0.084***	0.017
	(0.014)	(0.025)	(0.033)	(0.030)	(0.022)	(0.000)
Indoor sewage exposure	0.054***	0.046	0.136***	-0.001	0.061*	0.012
	(0.020)	(0.036)	(0.050)	(0.046)	(0.035)	(0.000)
Outdoor sewage exposure	0.010	-0.012	0.020	0.022	0.010	0.002
	(0.011)	(0.021)	(0.026)	(0.022)	(0.020)	(0.000)
Age in months	-0.002***	0.019***	-0.001	-0.002	-0.001	-0.000
	(0.000)	(0.002)	(0.003)	(0.003)	(0.002)	(0.000)
Female	-0.006	-0.009	-0.009	0.032	-0.030	-0.015
	(0.012)	(0.027)	(0.035)	(0.030)	(0.025)	(0.000)
Access to piped water	-0.070*	-0.028	-0.149	-0.061	-0.084	-0.049
	(0.042)	(0.071)	(0.101)	(0.082)	(0.058)	(0.000)
Domestic animals (observation)	0.003	0.015	-0.016	0.010	0.009	-0.011
	(0.010)	(0.019)	(0.024)	(0.021)	(0.017)	(0.000)
Household covariates	Yes	Yes	Yes	Yes	Yes	Yes
p value b1 = b2	0.515	0.511	0.088	0.855	0.535	0.873
p value b1 = b3	0.042	0.258	0.526	0.660	0.002	0.512
Prevalence of diarrhea when not exposed to sewage	0.181	0.195	0.259	0.195	0.137	0.107
Observations	8,148	1,779	1,636	1,690	1,674	1,334
Households	6,387	1,760	1,617	1,660	1,653	1,333

Source: Authors' calculations based on Plan 3000 baseline survey restricted to households with children under five years old and with verification of indoor sewage.

Note: The outcome variable is diarrhea, measured as a binary variable that indicates whether a child had diarrhea during the two weeks preceding the interview. The three explanatory variables of interest are measured as binary variables that indicate whether a household has each type of sewage exposure. All models include neighborhood fixed effects and control for the following household covariates: number of males and females by age group, household head's gender, age, marital status, educational attainment, and employment status, dwelling type and ownership, asset ownership, and an indicator of whether the household can rely on somebody for emergencies and on somebody to lend money to improve the dwelling.

Clustered standard errors at the household level are reported in parentheses. Sample size varies from the original sample size due to missing values in household covariates. *Statistically different from 0 at the 10 percent level; **Statistically different from 0 at the 5 percent level; ***Statistically different from 0 at the 1 percent level.

Next, we disaggregate estimates by age, following the hypothesis that children will interact with sewage differently depending on their stage of development. Children younger than 12 months old who have more limited ability to move independently are expected to be less prone to direct contact with sewage, but more susceptible to environmental conditions given their developing immune systems. Children aged 12-23 months have increasing capacity for independent mobility around the home and land parcel, but are less prone to follow instructions or understand the risk of interacting with and ingesting soil or objects contaminated with fecal matter. Finally, children older than 48 months represent the age group with the most developed cognitive abilities, and that is better able to self-regulate their interaction with sewage.

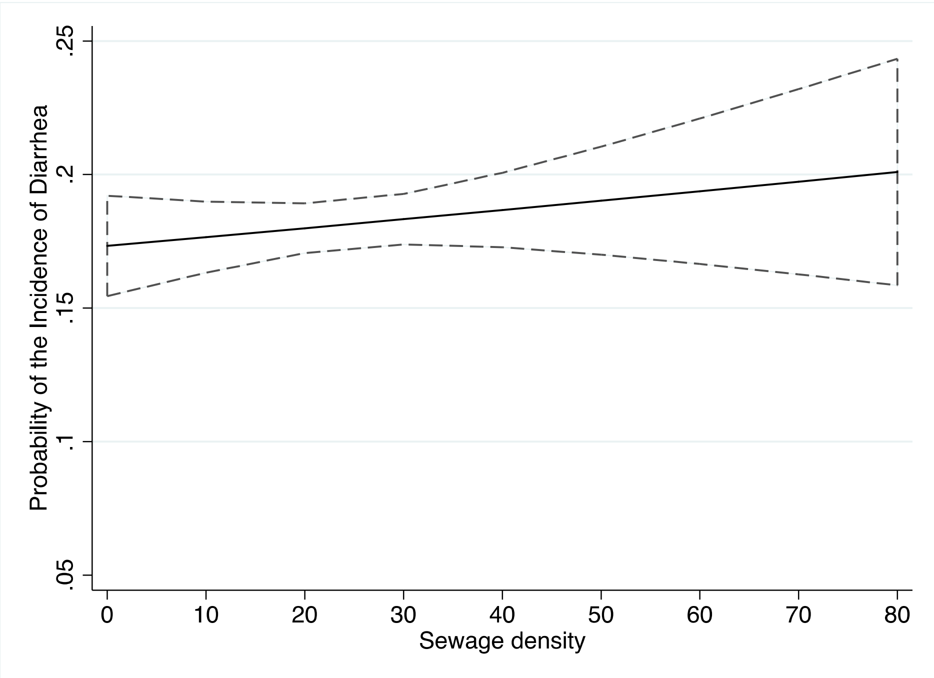
Results in Table 2 (columns 2-6) indicate that exposure to indoor and outdoor sewage is most strongly associated with increased probability of diarrhea incidence in the 37-48 month-old group. In this group, exposure to sewage increases the probability of diarrhea incidence by 8.4 percentage points, an increase of 61 percent relative to children of the same age group who are not exposed to sewage. Similarly, we find that indoor sewage is significantly associated with increased probability of diarrhea incidence in the 12-23 month-old group. Among this group, exposure only to indoor sewage is associated with a 13.6 percentage point increase in the probability of diarrhea incidence, an increase of 52 percent relative to children of the same age group who are not exposed to sewage. No significant effects of sewage are found in the 24-36 or 49-60 month-old groups. We speculate that the latter result may be attributed to children’s improved ability for self-regulation as they grow older, though the absence of a significant relationship in the 24-36 month-old range remains a puzzle.

As robustness checks to our main specification in model (1) we estimate the relationship between sewage and diarrhea using a linear probability model (LPM), a mixed model, and matching methods. We also test sensitivity to alternative sets of covariates in model (1). Results discussed in Appendix D confirm that the estimates of Table 2 are robust to these alternative specifications. Furthermore, although the presence of sewage may be seasonal and linked to the incidence of flooding, we found no association between the amount of precipitation and the extent of sewage observed on a given date during the span of the survey (see Appendix E).

Externalities

We next turn to the analysis of externalities using sewage density as the explanatory variable of interest. Figure 3 plots the marginal association of child diarrhea with sewage density conditional on observed covariates included in regression model (1) and neighborhood fixed effects. The plot provides the estimated association for each additional neighboring house with outdoor sewage. The results are consistent with the presence of negative health externalities from outdoor sewage, as the likelihood of the occurrence of diarrhea in children under five increases with the number of neighbors with outdoor sewage.

Figure 3. Marginal Association between Child Diarrhea and Sewage Density



Source: Authors' calculations based on Plan 3000 baseline survey restricted to households with children under five years old. The full sample of the Plan 3000 baseline survey is used for computing sewage density.
Notes: This figure shows the marginal association between each level of sewage density and the probability of diarrhea incidence. Standard errors are clustered at the household level and confidence intervals are shown by the dotted line. The prevalence of diarrhea in children under five years old increases with the number of neighbors with outdoor sewage.

An increase of 20 neighboring houses with outdoor sewage is associated with an increase in the probability of diarrhea incidence of about 3.8 percent. Compared to houses in areas with a low density of sewage (10 or less neighboring houses with outdoor sewage), living in a high-sewage-concentration area (70 or more neighboring houses with outdoor sewage) is associated with an approximate 14 percent increase in the probability of the incidence of diarrhea.

CONCLUSIONS

Although epidemiological studies have identified a clear link between exposure to fecal pathogens and the incidence of diarrhea, existing studies on the impact of on-site sanitation construction have found at best modest effects on the prevalence of diarrhea in children under age five. Less attention has been given to the role of sewage released into the environment from poorly constructed and maintained on-site sanitation facilities and improper fecal sludge management, which could attenuate the potential health gains from investments in on-site sanitation infrastructure.

The aim of this observational study has been to explore the association between sewage from overflowed on-site sanitation systems and the prevalence of diarrhea among children under five and to document the potential negative health externalities. Based on the independently verified presence of sewage within and just outside the properties of more than 6,000 households with children in a low-income peri-urban area of Santa Cruz de la Sierra, Bolivia, this study has found significant increases in the likelihood of the prevalence of diarrhea in children under five associated with the presence of sewage from on-site sanitation facilities. The study has also found evidence of negative externalities emerging from neighboring households with outdoor sewage. The estimates are within the range of other studies of the association of the presence of fecal contamination and diarrhea incidence, such as Bartlett et al. (1992) (2.28, 95 percent confidence interval 1.19-4.39) and Traore et al. (1994) (1.38, 95 percent confidence interval 0.98-1.95), and enteric infections, such as Berendes et al. (2017b) (3.78, no confidence interval reported).

This study contributes to further understanding the absence of detectable health effects of on-site sanitation construction (e.g. Clasen et al., 2014; Patil et al., 2014) and the importance of externalities from sanitation behavior (Geruso and Spears, 2015; Hathi et al., 2017). While much of the literature focuses on the adverse health effects of open defecation and the absence of sanitation facilities, our results highlight a potentially important but largely overlooked source of fecal contamination, that is, sewage overflow into the environment from inadequate construction, sanitation maintenance and fecal sludge management. Furthermore, while much of the epidemiological literature includes more precisely measured indicators from stool, water, and soil samples tested for microbial presence (Berendes et al., 2017a, 2017b; Pickering et al., 2012; Yajima and Koottatep, 2010), an important contribution of our study is the use of a large, high-powered sample and direct observations of sewage contamination to analyze self-reported diarrhea outcomes.

This study has notable strengths and limitations in measurement and analysis. We use a rich dataset on a sample of more than 20,000 households. Independently verifying sewage within and just outside the parcel corresponding to a household provides a unique assessment of the relationship between sewage exposure and diarrhea incidence. Rather than capturing sewage resulting from improper construction or open defecation (99 percent of households have a sanitation facility, and only 3 percent of households release fecal sludge into open ditches), most of the sewage observed in this context is the result of overflowed on-site sanitation facilities. We can thus attribute our results to sewage leakage resulting from poor maintenance and inadequate fecal sludge management. Furthermore, rich spatial variation in the geographic concentration of outdoor sewage provided an ideal dataset to test for the presence of negative health externalities from sewage exposure in neighboring properties.

Measurement of diarrhea incidence relies on the response from the household caretaker, which is prone to misreporting, and the use of a two-week recall period may underestimate diarrhea incidence (Arnold et al., 2013; Zafar et al., 2010). This misreporting, however, is unlikely to be correlated with our independently observed measure of sewage. Another potential concern is seasonal bias in diarrhea incidence (Luby et al., 2011). The survey used for this analysis was conducted over a period of less than three months, canvassing entire neighborhoods within a few days. As such, the neighborhood fixed effects should account for any differences in the timing of the interviews across neighborhoods. Lastly, because self-reported diarrhea reflects mixed etiologic agents that include viruses, intestinal parasites, and bacteria linked to enteric infections (Berendes et al., 2017a), more research is needed to better characterize the association with different groups of pathogens and further understand the implications for malnutrition, growth, and cognitive development (Humphrey, 2009; Ngure et al., 2014).

Our estimates of the association between diarrhea incidence and exposure to sewage are robust to alternative specifications, including linear probability models, mixed models, matching methods, and alternative sets of covariates, lending additional credibility to our results. The primary risk to a causal interpretation of this relationship is the presence of unobserved confounders across households within a given neighborhood, including household-level preferences and health-related behaviors. Nevertheless, even when controlling for proxies of sanitary preferences (the presence of animals, water treatment, and trash in the yard), the results are qualitatively similar. An additional risk is linked to our externality analysis, since sewage density is likely not random, but rather affected by residential choices that also affect diarrhea prevalence. Yet, we argue that identifying the association between different levels of exposure to sewage and child diarrhea is a first important step to document the health effects and potential externalities from overflowed on-site sanitation facilities.

The evidence suggesting that sewage exposure is negatively associated with child health and the documentation of potential negative externalities across neighboring houses provides a strong argument in favor of public expenditure to maintain sanitation facilities and improve fecal sludge management. Because on-site sanitation facilities may be prone to spillage, our findings highlight the need for policy alternatives that ensure that children are fully protected. Solutions such as sewer lines connected to treatment plants that incorporate proper technologies for removing and treating sludge and do not rely on routine maintenance by households may be an effective alternative (Norman et al., 2010), particularly in more densely populated urban areas where the marginal benefits may well outweigh the costs of large infrastructure investments. However, our analysis suggests that to reap the full benefits of such investments, sewage connectivity must be close to universal. Thus, sanitation policy should focus not only on the installation of sewage lines and treatment plants, but also on accelerating the connection of households to the public sewer system and properly maintaining the systems to mitigate exposure to pathogens.

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APPENDIX

Appendix A: Respondent vs. Non-respondents of Indoor Sewage

Table A1: Balance Test for Respondent and Non-Respondent Households (Sewage Indoors)

	Respondent (Mean)	Non-Respondent (Mean)	Difference (p-value)
Outdoor sewage	0.453	0.438	0.465
Household composition			
Number of men			
Aged 0-5	0.724	0.752	0.306
Aged 6-18	0.546	0.558	0.695
Aged 19-49	0.972	0.989	0.437
Aged 49+	0.113	0.142	0.040
Number of women			
Aged 0-5	0.673	0.616	0.028
Aged 6-18	0.571	0.534	0.262
Aged 19-49	1.110	1.138	0.212
Aged 49+	0.111	0.142	0.032
Household's head characteristics			
Man	0.842	0.833	0.530
Age	35.565	36.950	0.004
Married	0.864	0.868	0.766
Education attainment			
Incomplete primary	0.253	0.258	0.786
Complete primary	0.056	0.054	0.903
Incomplete secondary educated	0.231	0.228	0.888
Complete secondary or superior educated	0.460	0.459	0.949
Observations (households)	6395	661	

Source: authors' own calculations based on Plan 3000 baseline survey.
Notes: All covariates are binary except those indicated as being a count.

Appendix B: Is sewage a result of open discharge?

While 34 per cent and 57 per cent of households exposed to indoor and outdoor sewage have septic tanks and cesspool as sewage effluent methods, respectively, only 5.4 per cent discharge into open ditches. Similarly, only 8 per cent of households exposed to indoor sewage and 3.5 per cent of households expose to outdoor sewage discharge into open ditches. This evidence suggests that sewage exposure is a result of collapsed on-site sanitation facilities, rather than open discharge.

Table B1: Sewage vs. Sanitation Discharge

			Sanitation facility discharges to:					
	Children observations	Household observations	Sewerage	Septic tank	Cesspool	Open ditch	Other	Missing
Indoor and outdoor sewage	1,119	854	0.5	34.1	57.3	5.4	1.3	1.5
Indoor sewage only	417	313	0.6	28.4	61.3	8.0	1.3	0.3
Outdoor sewage only	2,565	2,037	0.4	36.2	59.2	3.5	0.5	0.2
No sewage	4,070	3,183	0.3	37.2	57.0	3.4	1.3	0.9
Total	8,171	6,387	0.4	36.0	57.9	3.9	1.0	0.7

Source: authors' own calculations based on Plan 3000 baseline survey.

Appendix C: Descriptive Statistics of Household-level Covariates

Table C1: Descriptive Statistics – Household-level Covariates

Variable	Mean	Standard Deviation	Min	Max	Number of Observations
Household composition					
Number of men aged 0-5	0.723	0.676	0	4	6387
Number of men aged 6-18	0.545	0.808	0	6	6387
Number of men aged 19-49	0.972	0.539	0	4	6387
Number of men aged more than 50	0.113	0.321	0	2	6387
Number of women aged 0-5	0.673	0.660	0	4	6387
Number of women aged 6-18	0.571	0.818	0	6	6387
Number of women aged 19-49	1.111	0.515	0	6	6387
Number of women aged more than 50	0.111	0.324	0	3	6387
Household's head characteristics					
Man	0.842	0.365	0	1	6387
Age	35.561	11.440	16	85	6387
Married	0.864	0.343	0	1	6387
Incomplete primary educated	0.253	0.435	0	1	6377
Complete primary educated	0.056	0.229	0	1	6377
Incomplete secondary or superior educated	0.231	0.421	0	1	6377
Complete secondary or superior educated	0.461	0.498	0	1	6377
Households' head occupation					
Employed	0.506	0.500	0	1	6387
Self-employed	0.319	0.466	0	1	6387
Other employment	0.106	0.307	0	1	6387
Does not work	0.065	0.247	0	1	6387
Dwelling type					
House	0.459	0.498	0	1	6385
Apartment	0.010	0.100	0	1	6385
Single room	0.528	0.499	0	1	6385
Improvised or mobile	0.002	0.045	0	1	6385
Others	0.001	0.031	0	1	6385
Dwelling ownership					
Own	0.400	0.490	0	1	6385
Rented	0.304	0.460	0	1	6385
Donated by relatives	0.237	0.425	0	1	6385
Leasing	0.045	0.208	0	1	6385
Others	0.013	0.115	0	1	6385
Dwelling and assets					
House had durable ceiling	0.913	0.282	0	1	6385
House has durable floor	0.957	0.203	0	1	6380

Variable	Mean	Standard Deviation	Min	Max	Number of Observations
House has durable walls	0.962	0.190	0	1	6385
Number of rooms	2.130	1.355	0	15	6385
House has phone	0.112	0.315	0	1	6385
House has mobile	0.876	0.329	0	1	6385
House has kitchen	0.983	0.130	0	1	6385
House has radio	0.771	0.421	0	1	6385
House has TV	0.966	0.182	0	1	6385
House has refrigerator	0.753	0.431	0	1	6385
House has vehicle	0.221	0.415	0	1	6385
House has computer	0.171	0.377	0	1	6385
Social insertion					
Has somebody to lean on in case of emergency	0.420	0.494	0	1	6385
Has somebody to lend money in case the need to improve the house	0.297	0.457	0	1	6385
Water and hygiene					
Access to piped water	0.989	0.106	0	1	6387
Domestic Animals (observation)	0.658	0.475	0	1	6387

Source: authors' own calculations based on Plan 3000 baseline survey.

Note: All covariates are binary except those indicated as being a count. Categorical variables are presented as different binary variables with the reference variable indicated in parenthesis. Robust standard errors are reported in parentheses. The number of observations varies slightly from the original sample because of missing values.

*Statistically different from 0 at the 10 percent level; **Statistically different from 0 at the 5 percent level; ***Statistically different from 0 at the 1 percent level.

Appendix D: Robustness checks

As robustness checks to our main specification in model (1) we use a linear probability model (LPM), a mixed model and matching methods. Results confirm that the estimates of Table 2 are generally robust to these alternative specifications, where the magnitudes of our estimates are generally larger and remain statistically significant. We also test the inclusion in model (1) of additional covariates measuring household hygiene, namely the observation of trash in the yard and household reports of treating water. The former addition slightly reduces the magnitude of the estimates, but indoor sewage remains highly statistically significant. It is important to highlight, however, that due to item non-response, the inclusion of "trash in the yard" reduces substantially the sample of analysis.

Table D1: Association between Child Diarrhea Incidence among Children under Five and Exposure to Sewage - Robustness Check

	(1) Logit Model	(2) Logit Model	(3) Logit Model	(4) Logit Model	(5) Linear Probability Model	(6) Mixed Model
Indoors and outdoors sewage exposure	0.044***	0.040***	0.023	0.040***	0.044***	0.046***
	(0.014)	(0.014)	(0.015)	(0.014)	(0.016)	(0.013)
Indoors sewage exposure	0.062***	0.054***	0.043**	0.054***	0.063***	0.053***
	(0.020)	(0.020)	(0.020)	(0.020)	(0.024)	(0.019)
Outdoors sewage exposure	0.009	0.010	0.004	0.010	0.010	0.007
	(0.011)	(0.011)	(0.011)	(0.011)	(0.011)	(0.010)
Age in months		-0.002***	-0.002***	-0.002***	-0.002***	-0.002***
		(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Female		-0.006	-0.000	-0.005	-0.003	0.001
		(0.012)	(0.012)	(0.012)	(0.012)	(0.010)
Domestic animals			0.001	0.003	0.003	-0.002
			(0.011)	(0.010)	(0.010)	(0.009)
Trash in the yard			0.041***			
			(0.010)			
Water treatment				0.012		
				(0.016)		
Household covariates	No	Yes	Yes	Yes	Yes	Yes
Observations	8,171	8,148	7,629	8,148	8,148	8,148
Households	6,387	6,387	6,387	6,387	6,388	6,389

Notes: Column (1) shows the estimates of model (1) without covariates; column (2) shows the estimates of model (1) with child- and household-level covariates, but excluding any hygienic variable; column (3) shows the estimates of model (1) including the following hygienic covariates: "observed domestic animals" and "observed trash in the yard"; column (4) shows the estimates of model (1) including the following hygienic covariates: "observed domestic animals" and "water is treated"; column (5) shows the estimates of an alternative estimation of model (1) using LPM and column (6) an alternative estimation of model (1) using mixed models with household random effects. Clustered standard errors at the household level are included in parenthesis. * Statistically different from 0 at the 10% level; ** Statistically different from 0 at the 5% level; *** Statistically different from 0 at the 1% level.

Matching methods

We rely on matching methods which, conditional on observables, provide efficient and consistent estimates of the association of sewage exposure and the prevalence of diarrhoea (Nichols, 2007; Rosenbaum and Rubin, 1983). We present the results of a *propensity-score matching* estimator. We estimate a logit model of the probability of exposure to sewage $(S_j = 1)$ conditional on observed characteristics (x_j) where:

$$\mathrm{P}(x_j) = \mathrm{Prob}\,(S_j = 1\,|x_j)$$

The validity of these estimations relies on two critical assumptions. The conditional independence assumption, which states that potential outcomes are independent from the presence of sewage given observable covariates, and the common support assumption, which states that there must be a set of propensity score values where the propensity score of exposed households and that of non-exposed households overlap. We employ *propensity-score nearest neighbour matching (PSM-N) and propensity-score caliper matching (PSM-C)* to match exposed and non-exposed households based on proximity of their propensity scores (Morgan and Harding, 2006; Nichols, 2007).

We also employ a more flexible approach, namely nearest neighbour matching (NNM), which pairs observations using the average of the outcomes of the nearest individuals to impute the missing potential outcome for each individual non-parametrically.

In this section, we construct three explanatory variables of interest: indoor and/or outdoor sewage, indoor sewage, and outdoor sewage. The following table provides a description of how the variables are constructed and descriptive statistics.

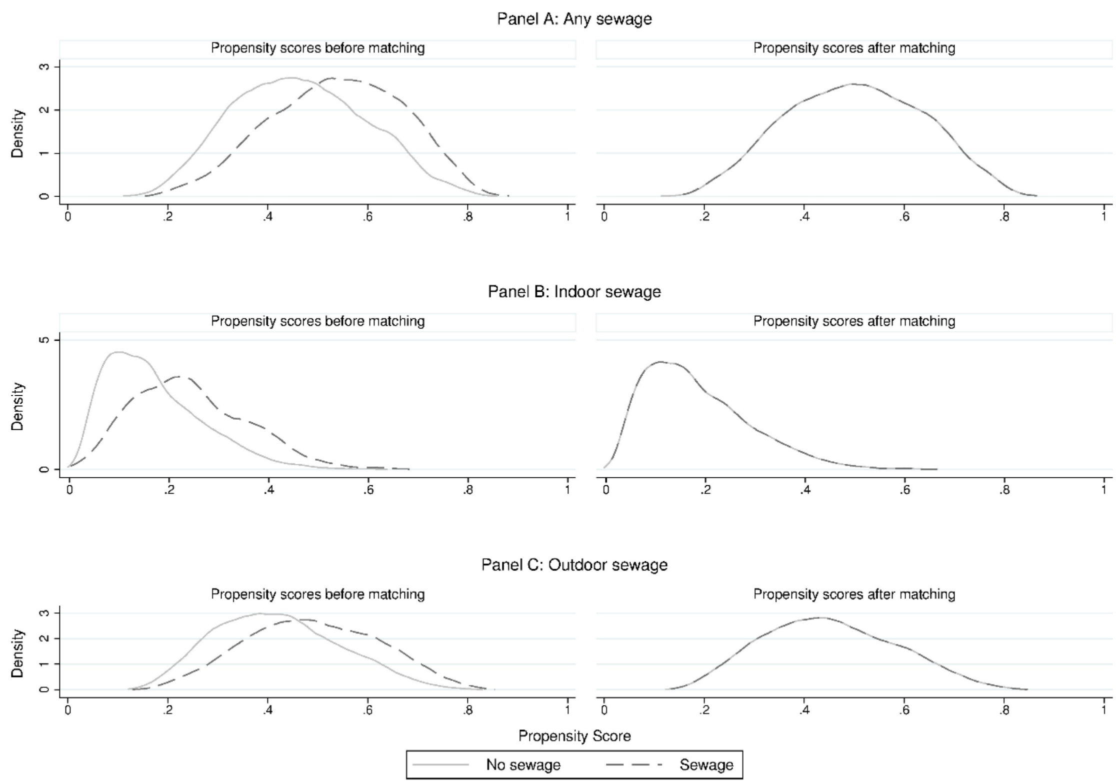
Table D2: Alternative construction of sewage indicators

(1) Name	(2) Definition	(3) Mean (SD)
Indoor and/or outdoor sewage	=1 if indoor and/or outdoor sewage =0 if no sewage exposure	0.6448 (0.4786)
Indoor sewage	=1 if indoor sewage =0 if no indoor sewage	0.4514 (0.4977)
Outdoor sewage	=1 if outdoor sewage =0 if no outdoor sewage	0.4870 (0.4999)

Source: authors' own calculations based on Plan 3000 baseline survey.

We find evidence in support of the common support assumption as show in the following figure.

Figure D3: Density of Propensity Scores for Households with and without Sewage Exposure



Source: authors' own calculations based on Plan 3000 baseline survey.
Notes: The solid line depicts the density function for households without sewage exposure and the dotted line for those with sewage exposure. This figure depicts the propensity score distributions for the two groups

and compares propensity scores before and after (caliper) matching. For the three types of sewage exposure the distributions do not perfectly overlap before matching, but they do after matching. Panel A, Panel B and Panel C show that there is a broad region of common support when estimating exposure to any sewage, indoor sewage and outdoor sewage, respectively.

Table D4: Association of Sewage and the Prevalence of Diarrhoea Using Different Matching Techniques

Diarrhoea prevalence	(1) Observations	(2) Mean for those without sewage	(3) NNM	(4) PSM-N	(5) PSM-C
<u>Panel A</u>					
Any sewage	8,512	0.1683	0.0259***	0.0213**	0.0238**
			(0.00920)	(0.00874)	(0.0101)
<u>Panel B</u>					
Indoor sewage	8,148	0.1699	0.0537***	0.0448***	0.0317**
			(0.0155)	(0.0124)	(0.0152)
<u>Panel C</u>					
Outdoor sewage	8,966	0.1763	0.0105	0.00820	0.00619
			(0.00895)	(0.00861)	(0.00961)

Source: authors' own calculations based on Plan 3000 baseline survey.

Notes: Columns (3) to (5) report the coefficients from a nearest-neighbour matching estimator (NNM); propensity-score nearest neighbour matching estimator (PSM-N); and propensity-score caliper (PSM-C), respectively. All models include the same covariates as in Table 1. Robust standard errors are reported in parentheses. * Statistically different from 0 at the 10% level; ** Statistically different from 0 at the 5% level; *** Statistically different from 0 at the 1% level.

Table D5: Robustness Check of the Association of Sewage and the Prevalence of Diarrhoea Using Different Matching Techniques, by age in months

	(1)	(2)	(3)
Diarrhoea prevalence	Observations	Mean for those without sewage	PSM - C
Panel A Indoor and outdoor sewage			
0-12	1,859	0.185	-0.00861 (0.0202)
12 -24	1,687	0.237	0.0510** (0.0249)
24 - 36	1,769	0.186	0.0334 (0.0235)
36 - 48	1,765	0.119	0.0224 (0.0164)
48-60	1,417	0.102	0.00353 (0.0182)
Panel B Indoor sewage			
0-12	1,779	0.181	0.0514* (0.0279)
12 -24	1,636	0.243	0.0813** (0.0390)
24 - 36	1,690	0.193	-0.0237 (0.0286)
36 - 48	1,694	0.120	0.0826*** (0.0194)
48-60	1,349	0.100	0.0152 (0.0240)
Panel C Outdoor sewage			
0-12	1,963	0.198	-0.0265 (0.0194)
12 -24	1,781	0.260	0.000561 (0.0242)
24 - 36	1,864	0.188	0.0156 (0.0231)
36 - 48	1,868	0.121	0.0244 (0.0191)
48-60	1,490	0.103	0.0181 (0.0192)

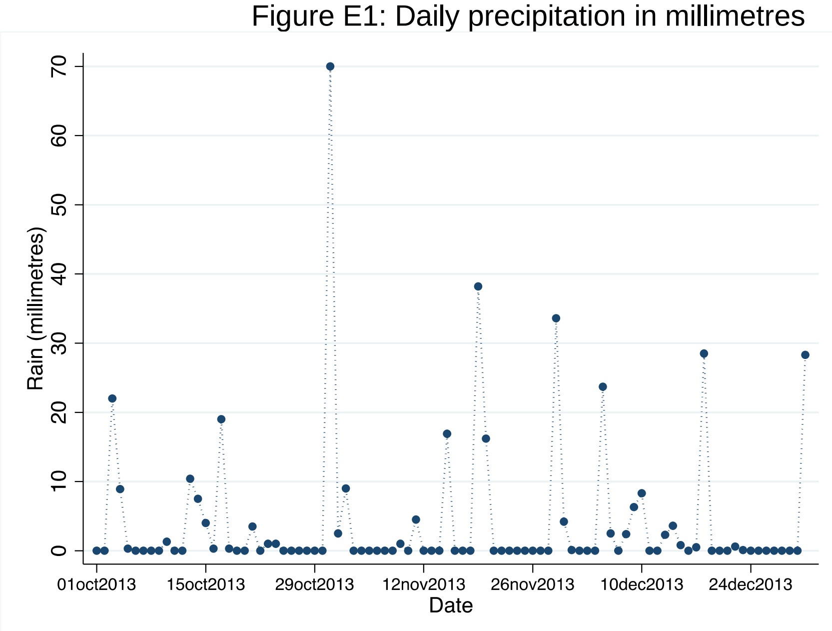
Source: authors' own calculations based on Plan 3000 baseline survey.

Notes: Column (3) reports the coefficients of the propensity-score caliper estimation (PSM-C). All models include the same covariates as Model 1. Robust standard errors are reported in parentheses. * Statistically different from 0 at the 10% level; ** Statistically different from 0 at the 5% level; *** Statistically different from 0 at the 1% level.

Appendix E: Discussion of sewage seasonality

In order to understand the extent to which sewage exposure is seasonal as it is likely to be affected by flooding, we use the rainfall dataset from the Office of Environment of Bolivia, which contains daily precipitation information in millimetres for the province of study "Santa Cruz de la Sierra". We use information during the dates when the census was undertaken during October to December 2013 and match this to each child using the date of the interview to the household. The following graph shows the variation in daily precipitation, where we can see that in general there is no flooding in this province. There are only three days in which daily precipitation was around 20mm, five days in which it was between 20 and 30mm, and one day in which it was more than 60mm. This graph forecasts that daily precipitation may be a weak predictor for sewage, as only heavy rain would be able to collapse latrines and expose children to sewage.

Figure E1: Daily precipitation in millimetres



Source: authors' own calculations based on Plan 3000 baseline survey and precipitation data from the Office of Environment of Bolivia.

Using this data on rain precipitation, we matched each household's date of interview with the corresponding precipitation level during that day. We then test for the relevance of the amount of precipitation as an instrument for sewage exposure by estimating the correlation between our three variables of exposure and precipitation amount. The amount of precipitation is a weak predictor of sewage exposure, as the correlation between precipitation amount and indoors and outdoors sewage is only 0.0008, indoors sewage only is -0.0218 and outdoors sewage only is -0.0178.