Urban Water Disinfection and Mortality Decline in Developing Countries

Sonia R. Bhalotra, Alberto Diaz-Cayeros, Grant Miller, Alfonso Miranda, and Atheendar S. Venkataramani

Abstract

Historically, improvements in the quality of municipal drinking water made important contributions to mortality decline in wealthy countries. However, water disinfection has not produced equivalent benefits in developing countries today. We investigate this puzzle by analyzing a large-scale municipal water disinfection program in Mexico in 1991 that rapidly increased access to chlorinated water. On average, the program led to a 37–48 percent decline in child diarrheal disease mortality and was highly cost-effective. However, age (degradation) of water pipes and lack of complementary sanitation infrastructure attenuate these benefits. Our results suggest that childhood diarrheal disease mortality in Mexico would have declined by 86 percent if all municipalities had good quality infrastructure—a decline consistent with historical experience.

Keywords: clean water, chlorination, child mortality, infectious disease, diarrhea, Mexico, cost-effectiveness, sanitation, behavioral responses

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1. Introduction

Historically, improvements in the quality of municipal drinking water made important contributions to population health in today's wealthy countries. Late nineteenth and early twentieth century investments in water purification led to substantial reductions in urban mortality in a number of countries, including Japan, France, Sweden, the United States, and the United Kingdom—in some cases, virtually eliminating waterborne disease (Preston and van de Walle 1978; Cain and Rotella 2001; Cutler and Miller 2005; Ferrie and Troesken 2008; Koppaka 2011; Ketzenbaum and Rosenthal 2014; Ogasawara and Inoue 2015; Knutsson 2016). These disinfection technologies were often introduced into relatively new municipal water systems with good quality pipes and sufficient supply to deliver water at full pressure without interruption (Melosi 2000).

Despite century-old knowledge about the benefits of water disinfection (Turneaure and Russell 1901), diarrheal diseases due to poor water quality remain prevalent in many low- and middle-income countries today. Worldwide, diarrhea is the second leading cause of child mortality (Liu et al. 2012; Vos et al. 2015) as well as a leading cause of morbidity (roughly 1.7 billion episodes per year) (Fischer Walker et al. 2013b). This disease burden persists despite the fact that *cities in developing countries are using many of the same disinfection technologies that were historically successful* (Gadgil 1998; Bain et al. 2014; Ercumen et al. 2015).

This study seeks to assess the effectiveness of water disinfection in developing countries, focusing on the case of Mexico—and importantly, to identify factors that limit the realization of their full potential. Recent literature on improving water quality in low- and middle-income countries has generally focused on interventions that are either small in scale or target rural populations with limited water system infrastructure (Arnold and Colford 2007; Zwane and Kremer 2007; Clasen and Haller 2008; Kremer et al. 2011; Arnold et al. 2013; Gruber et al. 2013; Duflo et al. 2015). However, the urban population is projected to reach nearly 2.5 billion worldwide by 2050 (United Nations Population Division 2014), and the rapid growth of cities will require larger-scale interventions focused on municipal water supply (United Nations Development Programme (UNDP) 2006; Fotso et al. 2007; Brown, Keath and Wong 2009; McDonald et al. 2014). The two studies (of which we are aware) examining interventions to improve urban water quality on a large scale are Galiani, Gertler, and Schargrodsky (2005), who show that privatization of municipal water companies in Argentina led to significant reductions in child mortality from water-borne diseases, and Greenstone and Hanna (2014), who find null effects of environmental regulation on water pollution in Indian cities. Rather than focus on ownership or regulation, we focus specifically on disinfection technology that is a cornerstone of urban water provision.

Improving urban water quality in developing countries on a large scale with proven disinfection technologies is difficult for many interrelated reasons. First, municipal water systems in many low- and middle-income countries are older, and thus subject to degradation. Pipe breaks and breaches allow even clean water to become contaminated (or re-contaminated) by bacterial pathogens in the surrounding soil (Lee and Schwab 2005; Shaheed et al. 2014). Low or intermittent water pressure in pipe networks can further reduce the efficacy of chlorination by increasing the degree of re-contamination (Tokajian and

Hashwa 2003; Bhutta et al. 2013; Kumpel and Nelson 2013; Ercumen et al. 2015; Jeandron et al. 2015).[1] Both problems are compounded by the fact that repairing degraded infrastructure (or building new distribution networks) may be prohibitively expensive, and financing mechanisms (either through domestic capital markets or partnerships with multinational organizations) may be unavailable (Gadgil 1998; Crocker and Masten 2002; Cutler and Miller 2006; United Nations Development Programme (UNDP) 2006; Masten 2011). Second, improvements in water quality may not be effective without complementary investments in sanitation (Alsan and Goldin 2015; Duflo et al. 2015). Third, the provision of improved water may weaken private incentives for protective health behaviors. Such compensatory behavior holds the potential to crowd-out the health benefits of water disinfection (Bennett 2012; Keskin, Shastry and Willis 2015).

A central contribution of our paper is that we study a massive nation-wide program to chlorinate municipal water systems across the entire country of Mexico within a single year. Moreover, because conditions across Mexico's municipalities varied widely at the time of implementation, we are able to isolate key factors governing program success (and failure) in improving health. Named *Programa Agua Limpia* (henceforth, PAL), this program was launched in 1991 in response to a cholera epidemic that swept rapidly through Central and South America (Gutierrez et al. 1996; Sepulveda, Valdespino and Garcia-Garcia 2006; Sepulveda et al. 2007).[2] Within eighteen months, the number of localities disinfecting their water increased dramatically, from 250 to 15,000, and the share of Mexico's population receiving disinfected water rose from 55 percent to 90 percent (CONAGUA 1994). Importantly, this coverage was achieved without expanding existing piped water infrastructure or sewage networks.

To estimate the impact of PAL on child mortality across Mexico, we use detailed mortality statistics by age and cause at both the municipality and state level. While there was little variation in the timing of PAL implementation across regions, we are able to distinguish trend breaks in waterborne disease from potentially correlated omitted trends by using event study and difference-in-differences approaches in which the "control diseases" are those not directly influenced by water quality. To strengthen the identification of PAL program effects, we also estimate triple difference specifications, comparing changes in waterborne relative to control diseases across small-/middle-sized towns versus large cities (population>500,000). This specification exploits the fact that PAL targeted small- and medium-sized towns given that water in larger cities was already chlorinated. Importantly, in doing so, it accounts for other minor cholera prevention and treatment activities that were common across smaller

[1] Unlike other disinfection technologies (like filtration, for example), residual chlorine remains in water from point of treatment to point of consumption. However, low or intermittent water pressure (on which data are not systematically available) increases the risk of recontamination as stagnant organic matter in the water supply effectively absorbs and reduces circulating chlorine levels. We thank Steve Luby for alerting us to this point.

[2] Notably, the baseline burden of diarrheal disease in Mexico around this time rivaled that of modern low-income countries. For example, data from the Global Burden of Disease project demonstrate that there were 900 deaths per 100,000 post-neonates (1-12 month olds) in Mexico in 1990. In low-income countries the corresponding rate in 1990 was 1,300 per 100,000 and 500 per 100,000 in 2015. See http://ghdx.healthdata.org/gbd-results-tool.

towns and large cities—including legal restrictions on wastewater irrigation, hygiene campaigns, provision of Oral Rehydration Therapy (ORT), and general disease surveillance (CONAGUA 1994; Sepulveda et al. 2006).[3]

These different approaches yield similar results. We find that PAL was associated with a 36-48 percent reduction in diarrheal disease mortality rates among children under age 5, amounting to nearly 6,000 averted deaths per year. These reductions were entirely concentrated in the targeted small- and medium-sized cities. We estimate a cost per life year saved by PAL of about $1,310 (2015 USD). This suggests that the program was highly cost-effective by any standard.[4] Our substantive results are robust to the use of different transformations of mortality rates, mortality counts rather than rates, different event study windows, the inclusion of state-year fixed effects, and state- rather than municipal-level data.

Motivated by the contrasting experience of wealthy countries in history and developing countries today, we then study municipal-level variation in program effects (across more than 2,000 municipalities) to investigate the circumstances under which large-scale municipal water disinfection in developing countries can be successful. First, we find that reductions in diarrheal disease mortality rates were not larger in municipalities with greater baseline piped water coverage rates. Because more extensive systems in Mexico are generally older, this result is consistent with engineering concerns about recontamination through degraded, aged infrastructure (Tulchinsky et al. 2000; Lee and Schwab 2005; Mazari-Hiriart et al. 2005) and reduced chlorine efficiency due to irregular water pressure and outages (Kumpel and Nelson 2013; Kumpel and Nelson 2014; Ercumen et al. 2015; Ashraf et al. 2017)—and we provide suggestive direct evidence in support of this hypothesis. Second, we find that the health benefits of clean piped water were greater in municipalities with more extensive sewage infrastructure. This finding is consistent with emerging evidence of complementarities between water disinfection and sanitation in the economics literature (Alsan and Goldin 2015; Duflo et al. 2015), although it stands in contrast with null results found in the epidemiology literature (Fewtrell et al. 2005). Simulations using our estimates suggest that childhood diarrheal disease mortality would have declined by 86 percent nationwide if all municipalities had equivalent levels of sewage coverage and similarly new piped water infrastructure as those in the top decile of our sample—at the cost of $868 per life year saved. This degree of mortality decline is consistent with the historical health benefits of municipal water disinfection in developed countries.

Finally, we also use detailed household survey data to study behavioral responses to water system disinfection, revealing evidence of compensatory private behavioral responses among households. In particular, households in states that benefitted more from PAL reduced their

[3] In practice water system chlorination was the overwhelming focus of the program (CONAGUA 1994).

[4] These estimates likely underestimate the true cost-effectiveness of PAL for two reasons. First, due to limitations in available cost data, we are only able to consider the period 1991-1995, but the health benefits of PALpresumably accrued far beyond this period. Second, recent studies show that clean water may have important effects on time allocation, financial transactions, and long-run human capital accumulation (Bhalotra and Venkataramani 2015a; Ashraf et al. 2017), but our calculation focuses entirely on survival benefits.

spending on bottled water, soaps, and detergents—private health investments that may substitute for clean piped water (Bennett 2012; Keskin et al. 2015). Notably, these reductions in household spending occurred only among households in small and medium-sized cities—precisely the areas targeted by PAL. Although we are unable to separately identify the direct health benefits of clean water from the indirect health decrements due to these behavioral responses, the degree of behavioral crowd-out is far from complete.

Overall, our results have two broad policy implications. First, the average effects that we estimate for childhood waterborne deaths are large, suggesting that despite misaligned incentives and political manipulation that plague many state programs (Galiani, Gertler and Schargrodsky 2005; Greenstone and Hanna 2014), there is at least the potential for state-led initiatives to be impactful.[5] Better understanding the political and organizational circumstances under which this is possible is a critical area for future research. Second, our finding that the effectiveness of urban water disinfection depends heavily on infrastructure quality—which is generally poor in developing countries—suggests a potential role for improvements in financing and access to capital—through private-public partnerships or innovations in local public finance, for example (Crocker and Masten 2002; Cutler and Miller 2006).

The rest of this paper is organized as follows. Section 2 provides background on Mexico's clean water reform, *Programa Agua Limpia,* and Section 3 describes our data. Section 4 presents changes in waterborne disease death rates associated with PAL, Section 5 examines the circumstances under which public water quality investments are most effective, and Section 6 examines behavioral responses to program impacts. Section 7 presents estimates of the cost-effectiveness of PAL, and Section 8 then concludes.

2. The History of *Programa Agua Limpia* in Mexico

As in many developing countries, infectious diseases have historically been responsible for most of Mexico's burden of disease among children. During the 1980s, diarrheal diseases and acute respiratory infections were the two leading causes of child death, and diarrhea alone was responsible for nearly a quarter of deaths under age 5 (Gutierrez et al. 1996). Diarrheal mortality was concentrated in the poorer southern region of Mexico (*Figure 1*), with rates in small and medium sized towns nearly twice as high as those in cities.[6]

In 1991, a cholera pandemic emerged in Chile and Peru and quickly spread through South and Central America (Medina 1991; Ries et al. 1992; Sepulveda et al. 2006). In an effort to limit its spread across Mexico, the Mexican Ministry of Health and the newly created

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[5] In fact, the average treatment effects we estimate are larger than found in Galiani, Gertler, and Schargrodsky (2005), who find that privatization led to an 8 percent decrease in child diarrheal disease mortality on average (26 percent in the poorest areas).

[6] Averaging over 1985-1990, the child diarrheal mortality rate in municipalities predominantly containing small towns and medium-sized cities was 7.76 deaths per 1,000 live births. In large cities (>1 million population), the corresponding mortality rate was 4.48 per 1,000 live births.

National Water Commission (*Comision Nacional del Agua*, CONAGUA) launched *Programa Agua Limpia* (PAL, or the National Clean Water Program) in April 1991 (Sepulveda et al. 2006; Sepulveda et al. 2007). PAL was in principle a multi-faceted campaign that included: (1) chlorination of previously untreated water sources; (2) restrictions on the use of wastewater for irrigation (an important component of Chile's efforts against cholera (Medina 1991)); (3) health education campaigns targeting both the general population and health care providers; and (4) expansion of the availability of Oral Rehydration Therapy (ORT).[7]

Despite these multiple components, in practice, chlorination of municipal drinking water was the centerpiece of the program (CONAGUA 1994; World Bank 1994). Because larger cities (those with more than 500,000 inhabitants) already had established chlorination and filtration systems, PAL chlorination efforts targeted small and medium sized towns (the term "localities" in the Mexican census comprises all settlements regardless of size). In contrast, other (minor) program components were not specifically targeted to these areas and implemented more broadly (Sepulveda et al. 2006). Within 6 months of PAL's launch, the fraction of Mexico's population with chlorinated piped drinking water rose from 55 percent (almost exactly the percentage of the population living in large metropolitan areas) to 85 percent. By 1994, this figure exceeded 90 percent (*Figure 2*).[8]

Achieving these gains required a vast expansion of municipal water disinfection through existing water pipe infrastructure. Nationwide, the number of water treatment plants grew from 250 to nearly 15,000, the number of residual chlorine monitoring stations expanded from 200 to over 100,000 sites, and treatment capacity (the volume of chlorinated water per unit time) doubled. In addition, to improve water quality in areas without piped water coverage, chloride tablets were disseminated to households (Sepulveda et al. 2006) and quality monitoring for commercial bottled water and ice was expanded (CONAGUA 1994), although these efforts were secondary relative to disinfection of water at the source.[9]

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[7] Prior to the cholera pandemic, Mexico's primary approach to controlling diarrheal diseases emphasized treatment with ORT, which we discuss below, and clinical case management (Frenk et al. 2003)

[8] Because implementation began in medium-size cities and then expanded to smaller towns, the increase in population coverage between 1991 and 1992 was much steeper than the corresponding increase in number of localities treated. Beginning in 1993, population coverage rose more slowly, but the number of localities treated continued to rise at the previous rate.

[9] Similarly, other components of PAL received substantially less emphasis and are also less likely to have had a meaningful impact on diarrheal disease mortality. For example, legal restrictions reduced the amount of farmland irrigated with wastewater (World Bank 1994). However, only a very small fraction of farmland was irrigated with wastewater prior to PAL (~0.1 percent) (CONAGUA 1994). Even if these crops were widely distributed, they are likely to have been in large cities as well as in small and medium-sized towns. Thus, we are able to account for this component of the policy in our triple difference models—see Section 4.1. Similarly, efforts to modify hygienic behavior included use of radio and television to disseminate messages about hand-washing and other sanitary practices (Sepulveda et al. 2006). However, experiences from other low- and middle-income settings suggest

Prior work on PAL hints at large program effects. Gutierrez et al. (1996), Velazquez et al. (2004), and Sepulveda et al. (2006) show sharp declines in childhood diarrheal disease mortality rates beginning in 1991. Focusing on morbidity, Gutierrez et al. (1996) analyze changes in aggregate morbidity rates, showing that the average number of annual episodes of diarrheal disease morbidity among children decreased from 4.6 to 2.2 between 1990 and 1993. Similarly, Velazquez et al. (2004) show that morbidity declined by over 63 percent during the period 1990-1995. However, these studies essentially only describe national trends over time.

3. Data

3.1 Data

Our core analyses use data from three sources: the Mexican Vital Statistics, the 10 percent sample of the 1990 Mexican Population Census, and the *Encuesta Nacional de Ingresos y Gastos de los Hogares* (National Survey of Income and Expenditure, ENIGH).

Mexican Vital Statistics. We obtained mortality data for neonates (age 0-1 months), postneonates (1-12 months), and children (ages 1-4) from the Mexican Ministry of Health. The vital statistics contain individual-level records of every certified death in the country.[10] Each death record contains information about the cause of death (coded using the International Classification of Diseases, 9th Edition, or ICD-9), age at death, and municipality of death. Municipalities are the next administrative division below the state (analogous to U.S. counties).

We aggregate individual-level deaths for children under the age of 5 into municipality-cause-year cells for all municipalities and years between 1985 and 1995. Given our focus on PAL, we create a category for infectious diarrheal diseases using three-digit codes from the International Classification of Diseases, Ninth Revision (ICD-9).[11] To convert diarrheal death counts into child (under-5), post-neonatal (1-12 months), and neonatal (0-1 month) mortality rates, we used data on the number of live births in each municipality and year.[12]

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that their impact on diarrheal disease mortality is likely to be small, particularly in comparison with water system disinfection (Ahuja, Kremer and Zwane 2010; Dupas 2011).

[10] Certified deaths are all deaths that are brought to the attention of the National Statistics Office, Health Ministry, Judiciary, Military, and funeral directors. Certification, which includes coding of cause of death, is provided by an individual with a license to do so (typically a physician, nurse, or Health Ministry representative).

[11] We used ICD-9 codes 001-009 to identify deaths from infectious diarrhea. These codes cover intestinal infectious diseases and include cholera (001), typhoid and paratyphoid (002), salmonella infections (003), shigellosis (004), food poisoning (005), amoebiasis (006), protozoan causes (such as giardia and cryptosporidiosis, 007), infections due to other organisms (such as rotavirus and other viruses, 008), and presumed intestinal infection due to an ill-defined cause.

[12] We obtained municipality-year data on live births from the *Instituto Nacional de Estadistica y Geographia* (INEGI, http://www3.inegi.org.mx/sistemas/microdatos/encuestas.aspx?c=33388&s=est). To compute mortality rates, we used a direct method (UNICEF et al. 2007) and divided the number of child deaths for a given cause-

We also repeat our estimation using death counts instead of death rates, finding similar results (see Section 4.1 below).

To reduce the influence of extreme values (some municipalities are very small and have no recorded infant deaths and/or births in some years, for example), we trim municipalities in the top and bottom 5 percent of the average pre-intervention (1985-1990) diarrheal disease mortality rate distribution. This yields a sample of 2,223 of 2,438 municipalities, accounting for over 94 percent of Mexico's total under-5 population. We confirm that these sample restrictions do not alter our main findings.

A note about the quality of Mexico's vital statistics is also warranted. As in many developing countries, there are important concerns about under-reporting of deaths, particularly in poorer regions and among young children (Tome et al. 1997; Lozano-Ascencio 2008; Hernandez et al. 2012).[13] Corrections for under-reporting and misclassification of deaths were made by the Ministry of Health from 1980 onwards, and these data have been used in other prominent studies, albeit at levels of aggregation above the municipality level (Cutler et al. 2002; Foster, Gutierrez and Kumar 2009; Barham 2011; Gonzalez and Quast 2011). In part because of these efforts, Mexico's Vital Registration system is now considered one of the best in the developing world in terms of completeness and quality (Mathers et al. 2005). We cannot rule out the possibility that some degree of underreporting remains, but for this to bias our results, underreporting and/or misclassification must have changed sharply in 1991, and differentially for diarrheal diseases relative to control diseases.[14]

1990 Mexican Population Census. To analyze heterogeneous effects of PAL across municipalities, we use data on pre-program municipality characteristics from a 10 percent sample of Mexico's 1990 population census (Minnesota Population Center 2015). Specifically, using appropriate sample weights, we aggregate household-level measures to create municipal-level data on the fraction of households with piped water and the fraction of households with septic system connections in their dwelling (a measure of sanitation coverage). We also create measures of average earned income among adults; the fraction of adults completing secondary schooling; and the fraction of the population speaking an

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municipality-year by the number of live births in the same municipality-year (scaled to reflect the number of deaths per 1,000 live births).

[13] Hernandez et al. (2012) show that infant and child deaths may be underreported by as much as 20 percent in a sample of low human development index municipalities in 2008. However, it is important to note that in many instances birth certification might also underreport those children. In this case, the counts in the numerator and the denominator of reported mortality rates are under-counts and, in general, it is difficult to sign any resulting bias in the rates.

[14] The direction of any bias in the estimated treatment effect is *a priori* unclear. If improvements in measurement occurred across the board, then our use of differences with respect to control diseases will help account for bias from measurement error. However, it may be that recording of diarrheal disease mortality in particular improved with the introduction of PAL (via investments in diarrheal disease recognition and surveillance). This would bias downward our estimates of mortality rate changes associated with PAL.

indigenous language. We use the 1960 and 1990 census microdata to compute measures of piped water system age.

Encuestas Nacional de Ingresos y Gastos de los Hogares (National Survey of Income and Expenditure, ENIGH). To study behavioral responses to PAL, we use the ENIGH, a nationally representative income and expenditure survey. These data include detailed information about expenditures on bottled water, soaps, and detergents, which we combine into a single category. We use the 1989, 1992, and 1994 waves, which are the only waves falling within our study period.

Table 1 shows descriptive statistics for all variables used in our analyses.

3.2. Graphical Evidence

Figure 3 shows trends in child (under age 5) mortality rates from diarrheal diseases and "control" diseases between 1985 and 1995 using unadjusted data. We use two sets of control diseases to assess the sensitivity of our results to the choice of control illnesses. These are infectious respiratory diseases and non-respiratory childhood diseases other than diarrhea, respectively. The controls satisfy the condition that they are quantitatively important infectious causes of child mortality and are not *directly* influenced by water quality. We discuss the control diseases in more detail in Section 4.1.

There is a downward trend in diarrheal disease mortality rates among children under-5 prior to 1991, which is widely attributed to Mexico's Oral Rehydration Therapy (ORT) program that began in November 1984 (Mota-Hernandez and Velasquez-Jones 1985; Gutierrez et al. 1996; Sepulveda et al. 2006). However, coincident with the implementation of PAL, in 1991, the decline becomes distinctly more rapid and pronounced. In contrast, there is no such trend break in mortality rates from the control diseases.[15,16] Importantly, trends in diarrheal and respiratory disease mortality rates prior to PAL were quite similar. *Appendix Figure 1*

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[15] We formally test for a structural break between 1985-1995 in a longer series of data (1979-1997, *Appendix Figure 1*) using the Quandt Likelihood Ratio test (Quandt 1960). This test treats as agnostic the exact break point in a time series and calculates the *F*-statistic on different user specific break points window. The test requires the data series be non-stationary, so we compute differences in mortality rates between the year in question and the prior year for each sample year. The largest *F*-statistic across tests of different time points is used to identify the break point. For diarrheal diseases, examining each year between 1987-1994 as potential break points, the test identifies a break in 1991, coincident with the start of PAL ($F = 11.16$, $p = 0.004$). We do not find evidence of a statistically significant break over the same period for both sets of control diseases (the identified break year is 1987, but this is not statistically significant - $F = 0.58$, $p = 0.46$ for non-respiratory controls; $F = 2.02$, $p = 0.17$ for respiratory controls).

[16] Notably, in the years just prior to PAL, the narrowing gap between diarrheal and non-diarrheal disease deaths appears to be driven by a slight *rise* in control disease death rates. We speculate that this slight increase may be related to Mexico's 1989-1990 measles epidemic. Mexico experienced a significant rise in measles attack rates as part of a broader regional pandemic in 1989-1990 (Katz et al. 2004). While we do not include measles mortality in either of our control disease sets, it is still possible that measles may account for the 1989-1990 uptick in these diseases given its association with respiratory diseases, congenital conditions, and skin infections (Orenstein, Perry and Halsey 2004).

shows trends over a longer period of time (1979-1997), and again the trend break in diarrhea-related mortality rates relative to control disease mortality rates remains clear.

4. Water Disinfection and Diarrheal Disease Mortality Rates

4.1. Empirical Strategy

To formally estimate the relationship between PAL and mortality rates among children under-5 (altogether, as well as separately for neonates (0-1 month), post-neonates (1-12 months), and children ages 1-4), we test for differential trend breaks in diarrheal disease mortality rates in 1991 (when PAL was implemented) relative to two sets of control diseases which should not be directly affected by PAL.[17] One includes acute upper and lower respiratory infections, including viral bronchitis and pneumonia. We choose these diseases because they were the second-leading cause of child mortality in Mexico prior to PAL[18] and because they share several common risk factors with diarrheal diseases (respiratory infections are spread through oral droplets and diarrheal diseases are spread by fecal-oral contamination). Particularly helpful for identification is the fact that respiratory diseases are sensitive to *water quantity* (which affords opportunities for preventive handwashing and thus breaking the droplet contamination cycle), while diarrheal diseases are sensitive to *water quality*, which is the focus of PAL (Ahuja et al. 2010)—poor drinking water quality is not a direct risk factor for respiratory infections (Fischer Walker et al. 2013b).

Nonetheless, if diarrheal diseases weaken immune systems, raising the likelihood of contracting respiratory infections (Sedgwick and MacNutt 1910; Ashraf et al. 2013; Fischer Walker et al. 2013a; Ashraf et al. 2017), then using respiratory diseases as control diseases will lead us to underestimate changes in mortality rates associated with PAL. For this reason, we also present results using an alternate set of control diseases that are less likely to co-vary with diarrhea (i.e., are bio-medically more 'distant').[19] These are perinatal causes (low birth weight, birth trauma, congenital infections), congenital anomalies, and a range of bacterial and viral illness (whooping cough, strep throat, scarlet fever, erysipelas, meningitis, tetanus,

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[17] A similar strategy was employed by Jayachandran, Lleras-Muney and Smith (2010) in their work on antibiotic therapy in the United States. Closer to our study, Galiani et al. (2005) use non-diarrheal causes of mortality as a falsification test in their study of water service privatization in Argentina.

[18] ICD-9 codes 460-466 and 480-487, respectively.

[19] Co-dependence between diarrheal diseases and these more bio-medically distant controls is also possible if, for example, falling diarrheal disease mortality raises the returns to health behaviors and investments more generally, which would potentially reduce the risk of all of the control diseases (Dow, Philipson and Sala-i-Martin 1999). However, again, this would imply that our estimates are conservative.

and septicemia) for which poor water quality is not a risk factor (Embrey et al. 2004; Pruss-Ustun et al. 2008).[20]

We focus our analysis on municipality-year diarrheal mortality rates in a window around program implementation, 1985-1995 (*Appendix Table 2* shows that our substantive results are robust to expanding our study period). We begin by estimating event study specifications of the general form:

$$(1)\quad M_{djt} = \alpha_d + \sum_{t=1985}^{1995} \alpha_t\, (\mathbf{1}(Diarrhea_d) \times \mathbf{1}(Year = t)) + \sum_{t=1985}^{1995} \mu_t\, (\mathbf{1}(Year = t)) + \lambda_j + e_{djt}$$

Here, M_{djt} represents the inverse hyperbolic sine transformation of the mortality rate for disease class d in municipality (or state) j and year t.[21] $\mathbf{1}(Diarrhea)$ is a dummy variable denoting whether or not the cause of death is diarrheal disease (sensitive to water quality, and hence the program intervention) versus a control disease group (not sensitive to water quality); *Year* is a dummy variable denoting observations in year t; and λ_j represent municipality fixed effects. Estimates of α_t yield the average differential percentage change in the diarrheal disease mortality rate vs. the control disease mortality rate in year t relative to the baseline year (in this specification, 1985). We estimate this equation for overall under-5 mortality rates as well as for disaggregated age intervals (neonates 0-1 months, infants 1-12 months, and children 1-4 years old).[22]

To relax the assumption that the error terms are independent and identically distributed (i.i.d.) within municipalities over time, we consistently cluster the standard-errors at the municipality level (Bertrand, Duflo and Mullainathan 2004). We also use municipality weights based on the average number of annual pre-intervention live births in all regressions.

Then, to estimate average program effects of PAL during the study period (accounting for any disease-specific pre-trends), we use parametric specifications of the following form:

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[20] ICD-9 codes are as follows: congenital anomalies (ICD9 codes 740-759), perinatal causes (low birth weight, birth trauma, congenital infections, neonatal jaundice, etc: ICD9 codes 764-779), and "other bacterial diseases" (whooping cough, strep throat/scarlet fever, erysipelas, meningitis, tetanus, and septicemia; ICD9 codes 033-038).

[21] Formally, the inverse hyperbolic sine transform of some variable, y, is $\ln(y + \sqrt{(y^2 + 1)})$. Estimates obtained using this transformation can be interpreted in the same manner as those obtained using a natural logarithm transformation of the dependent variable, with the advantage of being defined at zero (Burbridge, Magee and Robb 1988).

[22] This model effectively restricts pre-trends and breaks to be identical across each of the component control diseases which we sum together in forming our broader control disease groups. Thus, we additionally estimated versions of this model (as well as the more parametric formulations below), allowing for each of the component control diseases to have their own pre-trends, level, and trend breaks. This did not have any substantive impact on the findings.

$$(2)\ M_{djt} = \beta_0 + \beta_1\ (\mathbf{1}(Diarrhea_d) \times \mathbf{1}(Post_t) \times Year_t)) + \beta_2\ (\mathbf{1}(Diarrhea_d \times \mathbf{1}(Post_t)) + \beta_3\ (\mathbf{1}(Diarrhea_d) \times Year_t) + \beta_4\ \mathbf{1}(Diarrhea_d) + \sum_{t=1985}^{1995} \mu_t\,(\mathbf{1}(Year = t)) + \lambda_j + e_{djt}$$

Here, **1**(*Post*) is a dummy variable for post-PAL years (1991 and later), and all other variables are defined as before. Together, the parameters β_1 and β_2, measuring trend and level breaks in 1991, isolate the change in diarrheal disease mortality rates relative to the control disease mortality rates associated with PAL. β_3 captures pre-existing trends in diarrheal disease mortality relative to control diseases; the year fixed effects flexibly absorb mortality trend breaks and intercept shifts common across all diseases associated with PAL implementation, as well as common background (or pre-intervention) mortality trends; and β_4 reflects time invariant differences between diarrheal and control disease mortality rates.

Other less intensive prevention and treatment measures were also introduced around 1991. These components, which were substantially smaller in scope than chlorination, included legal restrictions on wastewater irrigation, hygiene campaigns, some provision of Oral Rehydration Therapy (ORT), and general disease surveillance (CONAGUA 1994; Sepulveda et al. 2006). We would therefore expect estimates in equations (1) and (2) to largely reflect benefits of chlorinated water. However, to isolate the role of chlorination further, we also estimate the following triple-difference specification:

$$(3)\ M_{djt} = \gamma_0 + \gamma_1\ (\mathbf{1}(Diarrhea_d) \times \mathbf{1}(Small_d) \times \mathbf{1}(Post_t)) + \gamma_2\ (\mathbf{1}(Diarrhea_d) \times \mathbf{1}(Small_d) \times \mathbf{1}(Post_t) \times Year_t) + \sum_3^4 \gamma_i\ (2\ Triple\ Interactions) + \sum_5^9 \gamma_i\,(5\ Double\ Interactions) + \sum_{10}^{11} \gamma_i\ (2\ Linear\ Terms) + \sum_{t=1985}^{1995} \mu_t\,(\mathbf{1}(Year = t)) + \lambda_j + e_{djt}$$

where **1**(*Small$_d$*) is a dummy variable denoting municipalities encompassing or contained within 'cities' with a population less than 500,000 (as enumerated in the 1990 population census),[23] and all other variables are defined as before.[24] The key parameters of interest are γ_1 and γ_2, which capture level and trend breaks in diarrheal disease mortality rates relative to

[23] An individual's town of residence in the 1990 census was divided into population sizes of 1-2,499, 2,500-14,999, 15,000-99,999, 100,000-499,999, and 500,000 and above. We calculated the fraction of individuals living in towns of 500,000 or more in each municipality. Any municipality that had a non-zero fraction living in such towns was coded as a large area, and the small area dummy is simply the inverse. Of note, 52 percent of the enumerated 1990 census population lived in larger areas, which is similar to the percentage of individuals with access to chlorinated water pre-PAL (55 percent, see *Figure 2*).

[24] The additional triple interactions terms (with subscripts omitted) are **1**(*Diarrhea*)× **1**(*Small*) × *Year* and **1**(*Small*) × **1**(*Post*) × Year. The additional double interactions are **1**(*Diarrhea*) × **1**(*Small*;, **1**(*Diarrhea*) × Year; **1**(*Diarrhea*) × **1**(*Post*); **1**(*Small*)× *Year*;, and **1**(*Small*)× **1**(*Post*). The single terms are **1**(*Diarrhea*) and **1**(*Small*). **1**(*Year*), and **1**(*Post*) × *Year* are subsumed by year fixed effects.

control disease mortality rates in small- and medium-size municipalities relative to large cities.[25] Importantly, because chlorination explicitly targeted small- and medium-sized cities, these estimates are more granular in distinguishing the effects of chlorination from any potential effects of other more minor PAL components (not differentially targeted by city size).

We also conduct several robustness tests. First, we estimate our models using the natural logarithm of mortality rates rather than the inverse hyperbolic sine transformation. Second, we introduce state-year fixed effects into our specification to flexibly control for any time-variant state-level interventions or processes that may bias our results. Third, we re-estimate our specifications using state-level (rather than municipal-level) data to assess the sensitivity of our results to accounting for *all* registered deaths and births as well as any spillovers across municipal areas.[26] Fourth, we estimate our models using death counts rather than mortality rates. Fifth, we repeat our estimation using a longer time window (1979-1997).

4.2. Results

Figure 4 plots coefficient estimates obtained by estimating Equation (1) for under-5, neonatal (0-1 months), post-neonatal (1-12 months), and child mortality rates (ages 1-4 years) by event year. Consistent with the unadjusted graphs (*Figure 3*), *Figure 4* shows a moderate decline in diarrheal disease mortality rates relative to both sets of control diseases beginning in 1985 (with the implementation of Mexico's ORT program)—and then a discrete acceleration with the implementation of PAL in 1991, continuing throughout the post-implementation years. These results highlight the importance of conditioning on disease-specific mortality rate trends and motivate the parameterization of Equation (2).

Table 2 then reports estimates from Equation (2) by age group. In each age interval, we find statistically significant level and trend breaks in diarrheal disease mortality relative to both sets of control diseases, and these breaks coincide with the introduction of PAL. Specifically, across all models, the estimate for "$\mathbf{1}(Diarrhea) \times Year$" (third row) shows that diarrhea mortality was declining before PAL, and the coefficient on "$\mathbf{1}(Diarrhea) \times \mathbf{1}(Post) \times Year$" (second row) shows a near doubling of this rate after 1991.

Overall, *Table 2* shows a sharp divergence in mortality rate trends between diarrheal diseases and control diseases that began in 1991 following the rapid implementation of PAL. For under-5 mortality rates, specifications using the non-respiratory controls (Panel A, first column) imply a 37 percent reduction in diarrheal disease mortality rates (more than 23,500

[25] Note that these models control for the full set of disease-municipality size specific pre-existing trends.

[26] As discussed in Section 3.1, we restricted our sample to 95 percent of municipalities in culling the data of implausible values. Aggregating Vital Statistics data to the state level allows us to incorporate any deaths and births that our sample selection choices left out. Because there were no zero cells at the state-year level, we employed the natural log transformation for the dependent variables. For this and all other state level models, we compute wild cluster-T bootstrap standard errors (Cameron, Gelbach and Miller 2008) to account for the relatively small number of clusters (n = 32).

deaths averted) by 1995. The corresponding reduction using respiratory diseases as controls (Panel B, first column) is 48 percent.[27] Estimates for neonatal, post-neonatal, and 1-4 mortality rates imply similar declines (columns 2-4, *Table 2*).[28]

Table 3 reports estimates from Equation (3), exploiting an additional difference between the targeted small- and medium-size municipalities relative to larger cities. The first two rows show triple-difference estimates of level and trend breaks (γ_1 and γ_2, respectively) associated with PAL. These estimates imply a 38 percent and 37 percent reduction in diarrheal mortality rates among children under age 5 in specifications using non-respiratory and respiratory controls, respectively. Notably, these estimates are nearly identical to the double-difference estimates in *Table 2*, confirming our *a priori* contention that other elements of PAL were not significant contributors to the decline in childhood diarrheal death rates.

4.3. Extensions and Robustness

Our results in *Table 2* are robust to using the natural log of mortality rates instead of the inverse hyperbolic sine (*Appendix Table 1*); the inclusion of state-year fixed effects (*Appendix Table 2*); using state-level rather than municipal-level observations (*Appendix Table 3*); using death counts instead of death rates (using both the inverse hyperbolic sine transformation in OLS regressions and raw counts in negative binomial model—see *Appendix Table 4*); a longer study window (*Appendix Table 5*).[29] Across all variants of our analyses for the time window 1985-1995, our point estimates using non-respiratory control diseases range from 35 percent to 41 percent, and our point estimates using respiratory control diseases range from 42 percent to 48 percent. Estimates using a wider event window (*Appendix Table 6*) suggest larger reductions (69 percent and 83 percent using non-respiratory and respiratory controls, respectively), although this may reflect the greater difficulty in tightly controlling for pre-trends in longer time series. Finally, we also examine if areas that experienced larger declines in diarrheal disease mortality rates also experienced larger increases (or declines) in immigration, which may bias our estimates, but we find no evidence of differential immigration (see *Appendix Table 7* and associated notes for further details).

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[27] To calculate this, we multiplied the coefficient on the trend break, $\mathbf{1}(Diarrhea)\times\mathbf{1}(Post)\times Year$, by 4 (as 1995 is four years after the start of PAL) and added this to the coefficient denoting the level break ($\mathbf{1}(Diarrhea)\times\mathbf{1}(Post)$). Estimates using state level data (*Appendix Table 2*) yield similar results for models using non-respiratory controls. For models using respiratory controls, we estimate a 40 percent decline in diarrhea attributable to PAL by 1995.

[28] Using non-respiratory controls, the estimates for imply 0-1 month olds imply 22 percent decline, a 41 percent decline for 1-12 month olds, and a 25 percent decline for 1-4 year olds (Panel A, second-fourth columns, respectively). Using respiratory disease controls, the respective declines for these ages groups was 41 percent, 31 percent, and 17 percent (Panel B, second-fourth columns). We note that it is not surprising that we find large declines for neonates (0-1 month olds), for whom infectious diarrheal diseases are in fact a major cause of death (Liu et al. 2012).

[29] Models using the longer-time series employ death counts, given restrictions on data availability on live births in prior years.

5. Under What Circumstances Is Municipal Water Disinfection Effective?

The previous section demonstrates large average treatment effects of PAL. Given mixed experiences with water system chlorination/disinfection in many developing countries, which contrasts with the more systematically positive historical experience of wealthy countries, we next investigate the circumstances under which chlorination can be most effective. We first assess heterogeneity by coverage of municipal water pipe infrastructure, which delivers drinking water to households (and, importantly, *chlorinated* drinking water under PAL). In general, we would expect to find a positive relationship between pipe network coverage and PAL program effects. We then considered the role of water system age, positing that older water systems may have been more degraded (and hence less effective in providing clean water), attenuating program effects. We also study potential complementarities between PAL chlorination efforts and sanitation infrastructure coverage.

5.1. Empirical Strategy

To examine heterogeneous program effects, we first estimate municipality-specific program effects (DID_j). To do so, we subtract the difference in diarrheal diseases mortality rates before and after PAL from the same difference in control disease mortality rates, accounting for the pre-PAL trend in both disease groups.[30]

We then relate these to municipality-level piped water coverage, piped water system age, and sewage infrastructure coverage using data from the 1990 population census. Specifically, we estimate regressions of the form:

$$(4) \quad DID_j = \delta_0 + \delta_1(Piped\ Water_j) + \delta_2(Sewage_j) + \delta_3(System\ Age_j) + \boldsymbol{\delta}(\boldsymbol{X}_j) + \pi + e_j$$

where *DID* is the municipality specific program effect; *Piped Water Coverage* and *Sewage Coverage* represents the fraction of households in the 1990 census reporting having a piped water and sewage connection, respectively; and *System age* is a proxy for the age of the water pipe infrastructure. $\boldsymbol{X}_j$ denotes a vector of municipality specific characteristics (percentage of adults completing secondary schooling, percent indigenous population, and the natural logarithms of average household earnings and population), and π denotes state fixed effects. We control for these variables to account for possible unmeasured confounders that may

[30] Specifically, we first compute the inverse hyperbolic sine transform of mortality rates and then compute the pre-trend between 1985 and 1991. We then subtract the predicted values from the post-intervention (transformed) mortality rates for each municipality-disease group. We then subtract the pre-intervention means from the de-trended post-intervention mean. Note that this is similar to estimating Equation 2 for each municipality *j* and then subtracting and using estimates of β_{1j} and β_{2j} to compute the percent change in diarrheal mortality rates in the pre- and post-PAL periods (after removing changes in control disease mortality and disease-specific pre-trends). Our results are similar in magnitude (and statistically indistinguishable) even when we account for differences in municipality-disease pre-PAL trends.

jointly influence municipality-specific treatment effects and water and sanitation infrastructure variables.[31] We estimate specifications using both the full sample and a restricted sample of small- and medium-sized cities (to focus more precisely on areas in which chlorination was introduced).

Equation (4) models the differential effect of chlorination under PAL according to pre-intervention measures of infrastructure. The coefficient estimates can be interpreted as interactions between PAL and each pre-intervention attribute. This advantage of this approach is that it allows us to examine several interactions simultaneously without loss of power.

5.2. Results

Piped Water Coverage. Figure 5 presents the bivariate non-parametric relationship between municipality-specific effects of PAL and piped water coverage; *Table 4* reports corresponding parametric estimates, both for the full sample and a restricted sample of municipalities with fewer than 500,000 people (which were targeted by PAL). Overall, we find no meaningful relationship between piped water coverage and mortality decline under PAL. While the estimates in *Table 4* show the expected sign, they are small and not statistically different from zero. Moreover, the estimated magnitudes actually *decline* when restricting the sample to those municipalities targeted by PAL. These results may help to explain the discordance between the historical experiences of wealthy countries and those of contemporary developing countries. We investigate this next.

Water System Age and Degradation. One possible explanation for the insignificant relationship between piped water coverage and PAL program effect size is that more extensive municipal water systems are older (Office of Economic Cooperation and Development (OECD) 2006; Vasquez et al. 2009; Oswald Spring 2011). Water system age is correlated with the degree of infrastructure degradation in many countries (Lee and Schwab 2005; Moe and Rheingans 2006; Larsen et al. 2016). Consequently, age-related pipe breaks, intermittent water pressure, and resulting recontamination from the surrounding soil may have undermined the full potential health benefits of the PAL (Mazari-Hiriart et al. 2005; Kumpel and Nelson 2013; Ercumen, Gruber and Colford 2014). A substantial literature on Mexico suggests that older municipal water systems are more prone to infrastructure failure and fecal contamination (World Bank 1994; Lee and Schwab 2005; Mazari-Hiriart et al. 2005; Adler 2015).[32]

[31] One such confounder could be political targeting and capacity. For example, the relationship between municipality governance and national policymakers could influence the allocation of transfers and infrastructure development, a phenomenon that has been well-studied in Mexico (Diaz-Cayeros, Estevez and Magaloni 2016). However, Fried and Venkataramani (2016) find no relationship between PAL treatment effects and the pre-PAL municipality governor's political party.

[32] For example, a recent government report estimates that 30-50 percent of drinking water nationwide may be lost due to pipe age, poor pressure control, and degraded materials (Secretaria de Medio Ambiente y Recursos

Because systematic data on water system age, direct measures of degradation, and water pressure (including pressure fluctuations) are not generally available for any country in the world,[33] including Mexico, this hypothesis is difficult to test directly. To do so, we construct a proxy measure for water system age by calculating the ratio of piped water coverage in the 1960 census to coverage in the 1990 census. Assuming that pre-existing piped water systems were not updated—which is reasonable in the Mexican context (Secretaria de Medio Ambiente y Recursos Naturales 2013)—higher ratios imply older water systems. *Figure 6* shows that this measure of pre-existing piped water coverage was positively associated with pipe breaks per kilometer in 2005 for a sample of 18 municipal systems.[34]

We then assess the relationship between our measure of water system age and piped water coverage in 1990—and ultimately, municipal-level PAL program effects. *Figure 7* shows that areas with older water systems did in fact have greater piped water coverage in 1990. *Figure 8* then plots the non-parametric relationship between our measure of water system age and municipality-specific PAL program effects. In general, municipalities with older water systems experience smaller declines in mortality under PAL, suggesting a potentially important role for water system age (and degradation) in limiting the benefits of water system chlorination. Columns 3 and 4 of *Table 4* show that this relationship persists in multivariate parametric regression models.[35] The estimates from column 4 imply that municipalities with the oldest water infrastructure experienced a 45 percentage point decrease in PAL impacts, accounting for all of the mean treatment effect (*Table 2*). Thus, the role of system age and subsequent degradation may be substantial, to the point of blunting the positive impacts of chlorination altogether.

Complementarity with Sanitation Infrastructure. *Table 4* shows a positive relationship between sanitation coverage at the municipal level and mortality decline under PAL. This suggests complementarity between water disinfection and sanitation efforts, a pattern consistent with recent work on Massachusetts during the nineteenth century (Alsan and Goldin 2015) and quasi-experimental findings from contemporary India (Duflo et al. 2015). Using the estimates in the second column of *Table 4*, an interquartile increase in municipality sewage

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Naturales 2013). This illustrates how infrastructure-driven deficits in the completeness of disinfection and increases in recontamination risk are widespread.

[33] The best available database for worldwide municipal water system characteristics is maintained by the International Benchmarking Network for Water and Sanitation Utilities (IB-NET, http://www.ib-net.org/). This database includes information on total water system output and usage, infrastructure quality (including pipe breaks), and tariffs for a number of local water systems. We searched this database for information on Mexican utilities. However, data were only available for a small number of utilities (18) and only for 2005 and onwards. Moreover, these utilities were predominantly in major cities, where PAL was less active. We use these data in some suggestive analyses (see below), but their incompleteness precludes more definitive investigation.

[34] *Appendix Table 8* presents estimates from a regression of the logged pipe break measure on the access ratio measure. We find that a 1 s.d. increase in the access measure is associated with a 97 percent increase in pipe breaks.

[35] The sample sizes for these regressions are smaller due to the small sampling frame (1.5 percent) in the 1960 IPUMS census micro data.

coverage (from 9 percent to 49 percent of the population) was associated with a 31 percentage point greater decline in diarrheal disease mortality rates under of PAL. These results suggest that inadequate sanitation could also substantially limit the benefits water system disinfection in developing countries.

Heterogeneity and Comparisons with Historical Experience: Finally, we use estimates from *Table 4* to predict treatment effects for counterfactual scenarios with varying levels of infrastructure. Specifically, we predict post-intervention declines in diarrheal disease mortality using a range of feasible values for piped water system age and sewage coverage. *Figure 9* shows these results across the distribution of our proxy for water pipe age. The blue point estimates and shaded regions depict predictions for water systems in the bottom decile of observed sewage coverage, while water systems at the top decile are shown in red.

Importantly, our estimates suggest that Mexican municipalities in the highest decile of both water pipe age and sewage coverage would have experienced an 86 percent decline in diarrheal mortality, averting 35,000 child deaths between 1991-1995. This large decline is comparable to historical experience of developed countries—suggesting that infrastructure quality plays a central role in explaining why modern disinfection efforts in many developing countries are less successful. (And by contrast, our results suggest that mortality would not have declined at all municipalities in the lowest decile of both water pipe age and sewage coverage).

6. Behavioral Responses

In this section, we estimate behavioral responses of households to public investments in municipal water quality—another potentially important determinant of ultimate program impact (Dow et al. 1999; Bennett 2012; Keskin et al. 2015).

6.1. Empirical Strategy

Because the ENIGH surveys are nationally representative repeated cross-sections that do not sample the same municipalities over time, we study behavioral responses to PAL at the state-level using the following approach:

$$(5)\quad Y_{ijt} = \alpha_0 + \alpha_1\,(\mathbf{1}(Post_t) \times Base\_Diarrhea_j) + \alpha_2\,(\mathbf{1}(Post_t) \times Base\_Control_j)$$

$$+ \boldsymbol{\alpha}\,\boldsymbol{X}_{ijt} + \lambda_i + \theta_t + u_{ijt},$$

where Y_{ijt} is the inverse hyperbolic sine transform of total spending on mineral/purified water and soaps/detergents in household *i*, state *j*, and time *t*; $Base\_Diarrhea_d$ is the average under-5 diarrheal disease mortality rate during the four years prior to PAL; $\mathbf{1}(Post_t)$ is a binary indicator = 1 if the survey year was after PAL was initiated (1991 or thereafter); $\boldsymbol{X}_{ijt}$ is a vector of individual and household characteristics (age of household head and the natural logarithm of household income); and λ_j and θ_t represent state and year fixed effects (respectively).[36] Negative estimates of α_1, the key parameter of interest, would reflect compensatory behavioral responses under PAL. Although we do not have direct measures of hygienic behaviors, our assumption, which is supported by the epidemiology literature (Pickering et al. 2010; Kamm et al. 2014), is that household spending on disinfectants and clean water from alternative sources is a reasonable marker for sanitary behaviors that reduce diarrheal disease risk.

6.2. Results

Table 5 reports estimates from Equation (4). In our full sample, we find small, negative, and imprecise estimates of compensatory behavioral responses (estimates of α_1 shown in column 1). However, among households living in small and medium cities, the areas targeted by PAL, we find a statistically significant negative relationship with household spending on soap, disinfectants, and bottled water (column 2). Specifically, moving from the worst performing quartile of states in the pre-program distribution of diarrhea mortality rates to the top quartile is associated with a 6.7 percent decrease in spending on these goods.[37] We find no statistically significant behavioral responses among households in large cities which had disinfected water prior to PAL (column 3).[38]

These results provide evidence of significant compensatory behavioral responses to PAL (or "crowd-out"). However, although we are unable to distinguish the independent health decrement associated with them from the direct health benefits of PAL, the fact that we

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[36] This strategy was introduced by Card (1992) and has recently been used in a number of health-related studies (Bleakley 2007, 2010; Cutler et al. 2010; Bhalotra and Venkataramani 2015b). Identification in this "continuous differences-in-differences" model comes from exploiting the sudden introduction of PAL (captured by *Post*) combined with variation across states in potential benefits from the program. The premise is that program impacts are larger in regions in which the disease burden is larger prior to introduction of the program, or that the program generates convergence in disease rates. We formally test for cross-state convergence in diarrheal mortality graphically and by estimating the following:

$$M_{ijt} = \alpha_0 + \alpha_1\,(\mathbf{1}(Post_t) \times Base\_Diarrhea_j + \lambda_j + \theta_t + u_{ijt},$$

where M_{ijt} = the state specific diarrhea mortality rate and the other variables are as defined for Model 5 in the main text. An estimate of $a_1 > 0$ is consistent with convergence. This model assesses absolute convergence. Estimating the same model using the logarithm of the mortality rate provides evidence of *relative* convergence. We find evidence of absolute convergence in child diarrhea mortality across states (*Appendix Figure 2* and *Appendix Table 6,* columns 2 and 4), but not of relative convergence (*Appendix Table* 6, columns 1 and 3).

[37] This effect appears to be driven primarily by soap and detergent purchases, with null findings for mineral and purified water purchases.

[38] Further, we find that impacts within these small and medium sized towns and cities were only seen for households with *both* sanitation and piped water access and not for households with only piped access or neither amenity (few households have sanitation access without piped water access). While these estimates (available upon request) are imprecisely estimated, the pattern of coefficients is consistent with the complementarity between disinfection and sanitation noted in Section 5.

nonetheless find large reductions in diarrhea mortality rates under PAL implies that the degree of crowd-out is far from complete.

7. Cost Effectiveness

We have shown that PAL was associated with large reductions in diarrheal disease mortality, but a natural question is whether this was worth the expense relative to alternative uses of these public funds. To calculate the cost per child death averted and the cost per life year saved, we use the estimates from *Table 2* for total under-5 mortality rates (using non-respiratory controls). We focus on the period 1991-1995 given that we know the total cost of the program over this time frame: PAL cost approximately U.S. $1 billion over this period (or $1.86 billion in 2015 dollars).[39] Of course, the health benefits of PAL presumably continued accruing after 1995. Depending on the costs of ongoing maintenance and operation of chlorination facilities, our results may understate the cost-effectiveness of the program.[40]

For each year between 1991 and 1995, we calculate the differential reduction in diarrheal disease mortality rates using the estimates for the level shift (*Diarrhea*×*Post)* and trend break (*Diarrhea*×*Post*×*Year)*. We multiply these estimated rate changes by the number of live births in each year to recover the implied number of averted deaths. We then sum the implied number of averted deaths across years 1991-1995. Overall, the implied cost per death averted under PAL was $78,600 (*Table 6*).

Assuming that individuals surviving childhood would have lived to the age of 60 (conservative given that the average life expectancy at the time of the policy was 71 years), the cost per life year saved was $1,310. Estimates using the upper 95 percent CI of our estimates imply a cost per life year saved of $1,792 (or $1,050 using the lower 95 percent CI).

We also use the estimates from *Table 4* to assess cost-effectiveness in settings for the counterfactual scenario in which all municipalities have good quality infrastructure (i.e, equivalent to the top decile of the pipe age proxy and sewage coverage observed in our sample). The 86 percent decline in diarrheal disease mortality predicted for this scenario, implying 35,000 averted child deaths between 1991-1995, would cost $868 per life year saved.

8. Discussion and Conclusion

Despite the widespread adoption of effective water disinfection technology worldwide over the last century, poor water quality remains a key challenge in low- and middle-income

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[39] Personal communication with Dr. Jaime Sepulveda, Mexico's Vice-Minister of Health from 1991 to 1994.

[40] Another reason our estimates may be conservative is that we do not account for additional program benefits beyond life years saved. For example, other work demonstrates robust short run benefits of water infrastructure on short-run financial transactions (Ashraf et al, 2017) and time allocations and long-run benefits of infant exposure to PAL on cognitive outcomes and schooling for girls (Bhalotra and Venkataramani 2015a).

countries. The sources of this problem likely extend beyond weak governance and regulation. In particular, existing urban water and sanitation infrastructure in developing countries are old and degraded—a challenge that is now being exacerbated by rapid urbanization (United Nations Development Programme (UNDP) 2006). Identifying underlying technological factors that alter the returns to disinfection is thus critical to maximize the potential of large-scale water quality initiatives in the future.

Mexico's *Programa Agua Limpia* provides an unusual contemporary opportunity to study the potential of state-funded municipal water disinfection on a national scale. On average, we find that the program successfully reduced childhood diarrheal disease mortality rates by over 30 percent. Moreover, we find that PAL was highly cost-effective, with a cost per life year saved of $1,300. However, while some areas experienced large reductions, others enjoyed little health benefit. We also find evidence of compensatory reductions in household hygiene investments, but the degree of crowd-out is far from complete.

To identify additional investments that may be necessary for municipal water disinfection to realize its full potential, we also examine the conditions under which PAL was effective. Studying municipal-level variation across the entire country, we find evidence suggesting that water system age, and associated degradation, may play an important role (because recontamination is more likely in degraded systems with intermittent water pressure, for example). We also find evidence of meaningful complementarities between water disinfection and pre-existing sewage infrastructure. Maximizing the returns to large-scale water quality interventions may require concurrent investments in repairing degraded water pipes and in sewage infrastructure. Overall, we emphasize the complexity of contemporary urban water and sanitation challenges in developing countries—and the need for more research on how to improve the safety of municipal drinking water.

References

Adler, D. 2015. "The war for Mexico's water." in *Foreign Policy*.

Ahuja, A., M. Kremer, and A.P. Zwane. 2010. "Providing safe water: Evidence from randomized evaluations." *Annual Review of Resource Economics* 2:237-256.

Alsan, M.and C. Goldin. 2015. "Watersheds in infant mortality: The role of effective water and sewerage infrastructure, 1880 to 1915." *NBER Working Paper No. 21263*.

Arnold, B., C. Null, S.P. Luby, L. Unicomb, C. Stewart, K.G. Dewey, T. Ahmed, S. Ashraf, G. Christensen, T. Clasen, H.N. Dentz, L.C.H. Fernald, R. Haque, A.E. Hubbard, P. Kariger, E. Leontsini, A. Lin, S.M. Njenga, P.A. J, P.K. Ram, F. Tofail, P.K. Winch, and J.M. Colford. 2013. "Cluster-randomised controlled trials of individual and combined water, sanitation, hygiene and nutritional interventions in rural Bangladesh and Kenya: the WASH Benefits study design and rationale." *BMJ Open* 3:e003476 doi:003410.001136/bmjopen-002013-003476.

Arnold, B.F.and J.M. Colford. 2007. "Treating water with chlorine at point-of-use to improve water quality and reduce child diarrhea in developing countries: A systematic review and meta-analysis." *American Journal of Tropical Medicine and Hygiene* 76(2):354-364.

Ashraf, N., E. Glaeser, A. Holland, and B. Millet Steinberg. 2017. "Water, health and wealth." *NBER working Paper No. 23807*.

Ashraf, S., M.H. Huque, M. Agboatwalla, and S.P. Luby. 2013. "Effect of recent diarrheal episodes on risk of pneumonia in children under the age of 5 years in Karachi, Pakistan." *International Journal of Epidemiology* 42(1):194-200.

Bain, R., R. Cronk, J. Wright, H. Yang, T. Slaymaker, and J. Bartram. 2014. "Fecal contamination of drinking-water in low- and middle-income countries: A systematic review and meta-analysis." *PLoS Medicine* 11(5):e1001644. doi:1001610.1001371/journal.pmed.1001644.

Barham, T. 2011. "A healthier start: the effect of conditional cash transfers on neonatal and infant mortality in rural Mexico." *Journal of Development Economics* 94:74-85.

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

Bertrand, M., E. Duflo, and S. Mullainathan. 2004. "How much should we trust differences-in-differences estimates?" *Quarterly Journal of Economics* 119(1):249-275.

Bhalotra, S.and A.S. Venkataramani. 2015a. "Human capital and infectious disease: Gender differences in investments and outcomes." *Mimeo, University of Essex*.

—. 2015b. "Shadows of the Captain of the Men of Death: Early life health interventions, human capital, and institutions." *Mimeo, University of Essex*.

Bhutta, Z.A., J.K. Das, N. Walker, A. Rizvi, H. Campbell, I. Rudan, and R.E. Black. 2013. "Interventions to address deaths from childhood pneumonia and diarrhoea equitably: what works and at what cost?" *Lancet* 381(9875):1417-1429.

Bleakley, H. 2007. "Disease and Development: Evidence from Hookworm Eradication in the American South." *The Quarterly Journal of Economics* 122(1):73-117.

—. 2010. "Malaria Eradication in the Americas: A Retrospective Analysis of Childhood Exposure." *American Economic Journal: Applied Economics* 2:1-45.

Brown, R.R., N. Keath, and T.H. Wong. 2009. "Urban water management in cities: Historical, current, and future regimes." *Water Science and Technology* 59(5):847-855.

Burbridge, J.B., L. Magee, and A.L. Robb. 1988. "Alternative transformations to handle extreme values of the dependent variable." *Journal of the American Statistical Association* 83(401):123-127.

Cain, L.P.and E.J. Rotella. 2001. "Death and spending: Urban mortality and municipal expenditure on sanitation." *Annales de Demographie Historique* 1(101):139-154.

Cameron, A.C., J.B. Gelbach, and D. Miller. 2008. "Boostrap-based improvements for inference with clustered errors." *Review of Economics and Statistics* 90(3):414-427.

Card, D. 1992. "Using regional variation in wages to measure the effects of the federal minimum wage." *Industrial and Labor Relations Review* 46(1):22-37.

Clasen, T.and L. Haller. 2008. "Water quality interventions to prevent diarrhoea: Cost and cost-effectiveness."

CONAGUA. 1994. "Informe, 1989-1994." Mexico City, Mexico: Comision Nacional Del Agua.

Crocker, K.and S. Masten. 2002. "Prospects for private water provision in developing countries: Lessons from 19th century America." in *Thirsting for Efficiency: The Economics and Politics of Urban Water Reform*, edited by M. Shirley. London: Elsevier.

Cutler, D., W. Fung, M. Kremer, M. Singhal, and T. Vogl. 2010. "Early-Life Malaria Exposure and Adult Outcomes: Evidence from Malaria Eradication in India." *American Economic Journal: Applied Economics* 2:72-94.

Cutler, D., F. Knaul, R. Lozano, O. Mendez, and B. Zurita. 2002. "Financial crisis, health outcomes and ageing: Mexico in the 1980s and 1990s." *Journal of Public Economics* 84(2):279-303.

Cutler, D.M.and G. Miller. 2005. "The role of public health improvements in health advances: The twentieth-century United States." *Demography* 42(1):1-22.

—. 2006. "Water, water everywhere: Municipal finance and water supply in American cities." Pp. 153-184 in *Corruption and Reform: Lessons from America's Economic History*, edited by E. Glaeser and C. Goldin. Chicago: University of Chicago Press.

Diaz-Cayeros, A., F. Estevez, and B. Magaloni. 2016. *The Political Logic of Poverty Relief: Electoral Strategies and Social Policy in Mexico*. New York: Cambridge University Press.

Dow, W.H., T.J. Philipson, and X. Sala-i-Martin. 1999. "Longevity complementarities under competing risks." *American Economic Review* 89(5):1358-1371.

Duflo, E., M. Greenstone, R. Guiteras, and T. Clasen. 2015. "Toilets can work: Short and medium run health impacts of addressing complementarities and externalities in water and sanitation." *NBER Working Paper No. 21521*.

Dupas, P. 2011. "Health behavior in developing countries." *Annual Review of Economics* 3:425-449.

Embrey, M., P. Hunter, J. Sellwood, P. Wyn-Jones, S.L. Percival, and R. Chalmers. 2004. *Microbiology of Waterborne Diseases*. San Diego and London: Elseview.

Ercumen, A., B. Arnold, E. Kumpel, Z. Burt, I. Ray, K. Nelson, and J.M. Colford. 2015. "Upgrading a piped water supply from intermittent to continuous delivery and association with waterborne illness: A matched cohort study in urban India." *PLoS Medicine* 12(10):e1001892. doi: 1001810.1001371/journal.pmed.1001892.

Ercumen, A., J.S. Gruber, and J.M. Colford. 2014. "Water distribution system deficiencies and gastrointestinal illness: A systematic review and meta-analysis." *Environmental Health Perspectives* 122(7):651-660.

Ferrie, J.P.and W. Troesken. 2008. "Water and Chicago's mortality transition, 1850-1925." *Explorations in Economic History* 45:1-16.

Fewtrell, L., R.B. Kaufmann, D. Kay, W. Enanoria, L. Haller, and J.M. Colford. 2005. "Water, sanitation, and hygiene interventions to reduce diarrhoea in less developed countries: a systematic review and meta-analysis." *Lancet Infectious Diseases* 5(1):42-52.

Fischer Walker, C., J. Perin, J. Katz, J.M. Tielsch, and R.E. Black. 2013a. "Diarrhea as a risk factor for acute lower respiratory tract infections among children in low income settings." *Journal of Global Health* 3(1):doi: 10.7189/jogh.7103.010402.

Fischer Walker, C., I. Rudan, H. Nair, E. Theodoratou, Z.A. Bhutta, K.L. O'Brien, H. Campbell, and R.E. Black. 2013b. "Global burden of childhood pneumonia and diarrhoea." *Lancet* 381(9875):1405-1416.

Foster, A., E. Gutierrez, and N. Kumar. 2009. "Voluntary compliance, pollution levels, and infant mortality in Mexico." *American Economic Review* 99(2):191-197.

Fotso, J.-C., A.C. Ezeh, N.J. Madise, and J. Ciera. 2007. "Progress towards the child mortality millenium development goal in urban sub-Saharan Africa: The dynamics of population growth, immunization, and access to clean water." *BMC Public Health* 7(218):doi:10.1186/1471-2458-1187-1218.

Frenk, J., J. Sepulveda, O. Gomez-Dantes, and F. Knaul. 2003. "Evidence-based health policy: Three generations of reform in Mexico." *The Lancet* 362(9396):1667-1671.

Fried, B.J.and A. Venkataramani. 2016. "Does saving lives win votes? Evaluating the electoral consequences of a water disinfection program in Mexico." *Mimeo, Brandeis University*.

Gadgil, A. 1998. "Drinking water in developing countries." *Annual Review of Energy and Environment* 23:253-286.

Galiani, S., P. Gertler, and E. Schargrodsky. 2005. "Water for life: The impact of the privatization of water services on child mortality." *Journal of Political Economy* 113(1):83-120.

Gonzalez, F.and T. Quast. 2011. "Macroeconomic changes and mortality in Mexico." *Empirical Economics* 40(2):305-319.

Greenstone, M.and R. Hanna. 2014. "Enviromental regulations, air and water pollution, and infant mortality in India." *American Economic Review* 104(10):3038-3072.

Gruber, J.S., F. Reygadas, B. Arnold, I. Ray, K. Nelson, and J.M. Colford. 2013. "A stepped wedge, cluster-randomized trial of a household UV-disinfection and safe storage drinking water intervention in rural Baja California Sur, Mexico." *American Journal of Tropical Medicine and Hygiene* 89(2):238-245.

Gutierrez, R., R. Tapia-Conyer, H. Guiscafre, H. Reyes, H. Martinez, and J. Kumate. 1996. "Impact of oral rehydration and selected public health interventions on reduction of mortality from childhood diarrhoeal diseases in Mexico." *Bulletin of the World Health Organization* 74(2):189-197.

Hernandez, B., D. Ramirez-Villalobos, M.B. Duarte, A. Corcho, G. Villareal, A. Jimenez, and L.M. Torres. 2012. "Subregistro de defunciones de menores y certificación de nacimiento en una muestra representativa de los 101 municipios con más bajo índice de desarrollo humano en México." *Salud Publica de Mexico* 54(4):393-400.

Jayachandran, S., A. Lleras-Muney, and K.V. Smith. 2010. "Modern medicine and the twentieth century decline in mortality: Evidence on the impact of sulfa drugs." *American Economic Journal: Applied Economics* 2(2):118-146.

Jeandron, A., J.M. Saidi, A. Kapama, M. Burhole, F. Birembano, T. Vandevelde, A. Gasparrini, B. Armstrong, S. Cairncross, and J.H.J. Ensink. 2015. "Water supply interruptions and suspected cholera incidence: A time-series regression in the Democratic Republic of the Congo." *PLoS Medicine* 12(10):e1001893. doi:1001810.1001371/journal.pmed.1001893.

Kamm, K., D. Feikin, G. Bigogo, G. Aol, A. Audi, A. Cohen, M. Shah, J. Yu, R. Breiman, and P.K. Ram. 2014. "Tropical Associations between presence of handwashing stations and soap in the home and diarrhea and respiratory illness in children less than five years old in rural western Kenya and International Health." *Tropical Medicine and International Health* 19(4):398-406.

Katz, S.L., J.I. Santos, M.A. Nakamura, M.V. Godoy, P. Kuri, C.A. Lucas, and R.T. Conyer. 2004. "Measles in Mexico, 1941-2001: interruption of endemic transmission and lessons learned." *Journal of Infectious Diseases* 189(Suppl 1):S243-S250.

Keskin, P., G.K. Shastry, and H. Willis. 2015. "Water quality awareness and breastfeeding: evidence of health behavior change in bangladesh." *Review of Economics and Statistics* Forthcoming.

Ketzenbaum, L.and J.-L. Rosenthal. 2014. "Income versus sanitation: Mortality decline in Paris, 1880-1914." *PSE Working Paper*.

Knutsson, D. 2016. "The effect of introducing clean piped water on mortality in Stockholm: 1850-1872." *Mimeo, Stockholm University*.

Koppaka, R. 2011. "Ten great public health achievements: Worldwide, 2001-2010." *Morbidity and Mortality Weekly Report* 60(24):814-818.

Kremer, M., J. Leino, E. Miguel, and A.P. Zwane. 2011. "Spring cleaning: Rural water impacts, valuation, and property rights institutions." *Quarterly Journal of Economics* 126(1):145-205.

Kumpel, E.and K. Nelson. 2013. "Comparing microbial water quality in an intermittent and continuous piped water supply." *Water Research* 47(14):5176-5188.

Kumpel, E.and K.L. Nelson. 2014. "Mechanisms affecting water quality in an intermittent piped water supply." *Environmental Science and Technology* 48:2766-2775.

Larsen, T.A., S. Hoffman, C. Luthi, B. Truffer, and M. Maurer. 2016. "Emerging solutions to the water challenges of an urbanizing world." *Science* 352(6288):928-933.

Lee, E.J.and K.J. Schwab. 2005. "Deficiencies in drinking water distribution systems in developing countries." *Journal of Water and Health* 3:109-127.

Liu, L., H.L. Johnson, S. Cousens, J. Perin, S. Scott, J.E. Lawn, I. Rudan, H. Campbell, R. Cibulskis, M. Li, C. Mathers, and R.E. Black. 2012. "Global, regional, and national causes of child mortality: An updated systematic analysis for 2010 with time trends since 2000." *The Lancet* 389(9832):9-15.

Lozano-Ascencio, R. 2008. "Is it possible to improve the death registries in Mexico?" *Gaceta Medica de Mexico* 144(6):525-533.

Masten, S. 2011. "Public utility ownership in 19th-century America: the "aberrant" case of water." *Journal of Law, Economics, and Organization* 27(3):604-654.

Mathers, C.D., D. Fat, M. Inoue, C. Rao, and A. Lopez. 2005. "Counting the dead and what they died from: an assessment of global status of cause of death data." *Bulletin of the World Health Organization* 83:171-177.

Mazari-Hiriart, M., Y. Lopez-Vidal, S. Ponce-de-Leon, J.J. Calva, F. Rojo-Callejas, and G. Castillo-Rojas. 2005. "Longitudinal study of microbial diversity and seasonality in the Mexico City metropolitan area water supply system." *Applied and Environmental Microbiology* 71(9):5129-5137.

McDonald, R.I., K. Weber, J. Padowski, M. Florke, C. Schneider, P.A. Green, T. Gleeson, S. Eckman, B. Lehner, D. Balk, T. Boucher, G. Grill, and M. Montgomery. 2014. "Water on an urban planet: Urbanization and the reach of urban water infrastructure." *Global Environmental Change* 27:96-105.

Medina, E. 1991. "Epidemia de cólera en Chile; 1991." *Revista medica de Chile* 119(8):943-956.

Melosi, M. 2000. *The Sanitary City: Urban Infrastructure in America from Colonial Times to the Present*. Baltimore: Johns Hopkins Press.

Minnesota Population Center. 2015. *Integrated Public Use Microdata Series, International: Version 6.4*. Minneapolis: University of Minnesota.

Moe, C.L.and R.D. Rheingans. 2006. "Global challenges in water, sanitation and health." *Journal of Water and Health* 4(S1):41-57.

Mota-Hernandez, F.and L. Velasquez-Jones. 1985. "Aspectos estrategicos para la implementacion de un Programa Nacional para la rehidratacion oral en la diarrea." *Boletin Medico del Hospital Infantil de Mexico* 42(8):463-465.

Office of Economic Cooperation and Development (OECD). 2006. "Water management policy brief for the Mexican Project." Mexico: Office of Economic Cooperation and Development, Enviromental Directorate,.

Ogasawara, K.and T. Inoue. 2015. "Public health improvements and mortality in early twentieth-century Japan." *Mimeo, Tokyo Institute of Technology*.

Orenstein, W.A., R.T. Perry, and N.A. Halsey. 2004. "The clinical significance of measles: a review." *Journal of Infectious Diseases* 189(Suppl 1):S4-S16.

Oswald Spring, U. 2011. "Water resources in Mexico: scarcity, degradation, stress, conflicts, management, and policy." edited by H.G. Brauch. Heidelberg: Springer.

Pickering, A.J., A.B. Boehm, M. Mwanjali, and J. Davis. 2010. "Efficacy of waterless hand hygiene compared with handwashing with soap: a field study in Dar es Salaam, Tanzania." *American Journal of Tropical Medicine and Hygiene* 82(2):270-278.

Preston, S.H.and E. van de Walle. 1978. "Urban French mortality in the Nineteenth Century." *Population Studies* 32:275-297.

Pruss-Ustun, A., R. Bos, F. Gore, and J. Bartram. 2008. *Safer water, better health: cost, benefits, and sustainability of interventions to protect and promote health*. Geneva: World Health Organization.

Quandt, R.E. 1960. "Test of the hypothesis that a linear regression system obeys two separate regimes." *Journal of the American Statistical Association* 55(290):324-330.

Ries, A.A., D.J. Vugia, L. Beingolea, A.M. Palacios, E. Vasquez, J.G. Wells, N. Garcia Baca, D.L. Swerdlow, M. Pollack, N.H. Bean, L. Seminario, and R.V. Tauxe. 1992. "Cholera in Piura, Peru: A modern urban epidemic." *Journal of Infectious Diseases* 166(6):1429-1433.

Secretaria de Medio Ambiente y Recursos Naturales. 2013. "Programa Nacional Hidrico, 2014-2018." Tlalpan, Mexico: Secretaria de Medio Ambiente y Recursos Naturales,.

Sedgwick, W.T.and J.S. MacNutt. 1910. "On the Mills-Reincke phenomenon and Hazen's theorem concerning the decrease in mortality from disease other than typhoid fever following the purification of public water-supplies." *Journal of Infectious Diseases* 7(4):489-564.

Sepulveda, J., F. Bustreo, R. Tapia, J. Rivera, R. Lozano, G. Olaiz, V. Partida, M.D. Garcia, and J.L. Voldespino. 2007. "Improvement of child survival in Mexico: The diagonal approach." *Salud Publica de Mexico* 49:S110-S125.

Sepulveda, J., J. Valdespino, and L. Garcia-Garcia. 2006. "Cholera in Mexico: The paradoxical benefits of the last pandemic." *International Journal of Infectious Diseases* 10(1):4-13.

Shaheed, A., J. Orgill, M.A. Montomgery, M.A. Jeuland, and J. Brown. 2014. "Why "improved" water sources are not always safe." *Bulletin of the World Health Organization* 92:283-289.

Tokajian, S.and F. Hashwa. 2003. "Water quality problems associated with intermitted water supply." *Water Science and Technology* 47(3):229-234.

Tome, P., H. Reyes, C. Pina, L. Rodriguez, and G. Gutierrez. 1997. "Characteristics associated with the under-registration of deaths in the state of Guerreo, Mexico." *Salud Publica de Mexico* 39(6):523-529.

Tulchinsky, T.H., E. Burla, M. Clayman, C. Sadik, A. Brown, and S. Goldberger. 2000. "Safety of community drinking-water and outbreaks of waterborne enteric disease: Israel, 1976-97." *Bulletin of the World Health Organization* 78(12):1466-1473.

Turneaure, F.E.and H.L. Russell. 1901. *Public Water-Supplies: Requirements, Resources, and the Construction of Works*. New York: John Wiley & Sons.

UNICEF, WHO, The World Bank, and UN Population Division. 2007. "Levels and Trends of Child Mortality in 2006: Estimates Developed by the Inter-Agency Group for Chold Mortality Estimation." New York.

United Nations Development Programme (UNDP). 2006. "Beyond Scarcity: Power, Poverty, and the Global Water Crisis, Human Development Report 2006." New York.

United Nations Population Division. 2014. "World urbanization prospects: the 2014 revision, highlights (ST/ESA/SER.A/352)." United Nations.

Vasquez, W.F., P. Mozumder, J. Hernandez-Arce, and R.P. Berrens. 2009. "Willingness to pay for safe drinking water: Evidence from Parral, Mexico." *Journal of Environmental Management* 90(11):3391-3400.

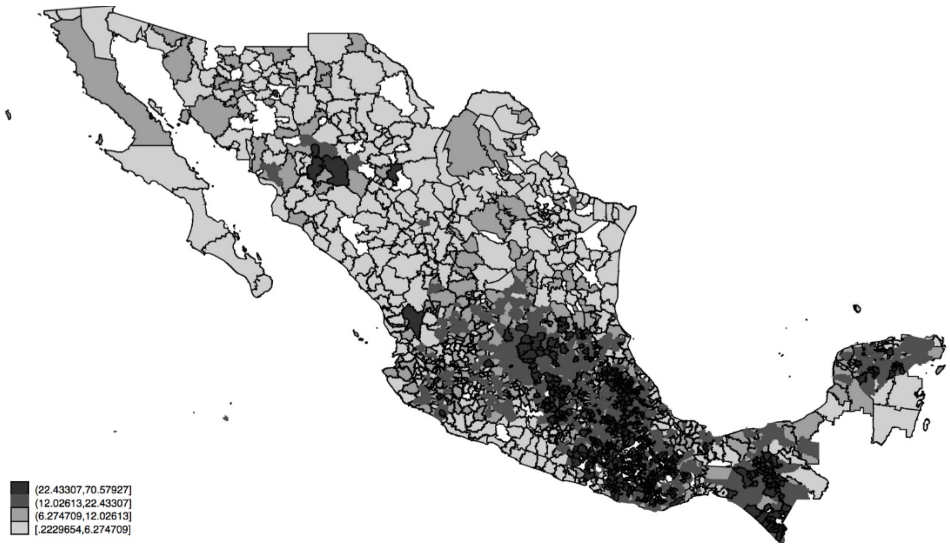
Velazquez, F.R., H. Garcia-Lozano, E. Rodriguez, Y. Cervantes, A. Gomez, M. Melo, L. Anaya, J.C. Ovalle, J. Torres, B.D. De Jesus, C. Alvarez-Lucas, T. Breuer, O. Munoz, and P. Kuri. 2004. "Diarrhea morbidity and mortality in Mexican children: Impact of rotavirus disease." *Pediatric Infectious Disease Journal* 23(10):S149-S155.

Vos, T., R.M. Barber, B. Bell, A. Bertozzi-Villa, S. Biryukov, I. Bollinger, and et al. 2015. "Global, regional, and national incidence, prevalence, and years lived with disability for 301 acute and chronic diseases and injuries in 188 countries, 1990-2013: A systematic analysis for the Global Burden of Disease Study 2013." *The Lancet* 386:743-800.

World Bank. 1994. "Staff Appraisal Report, Mexico, Second Water Supply and Sanitation Sector Project." World Bank.

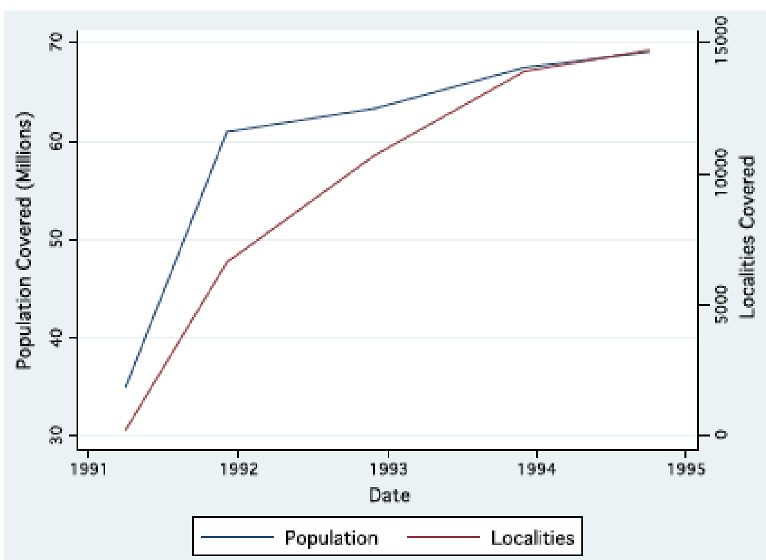
Zwane, A.P.and M. Kremer. 2007. "What works in fighting diarrheal diseases in developing countries? A critical review." *World Bank Research Observer* 22(1):1-24.

Figure 1: Pre-Intervention Under-5 Diarrheal Mortality Rates Across Mexican Municipalities (1985-1990 average)



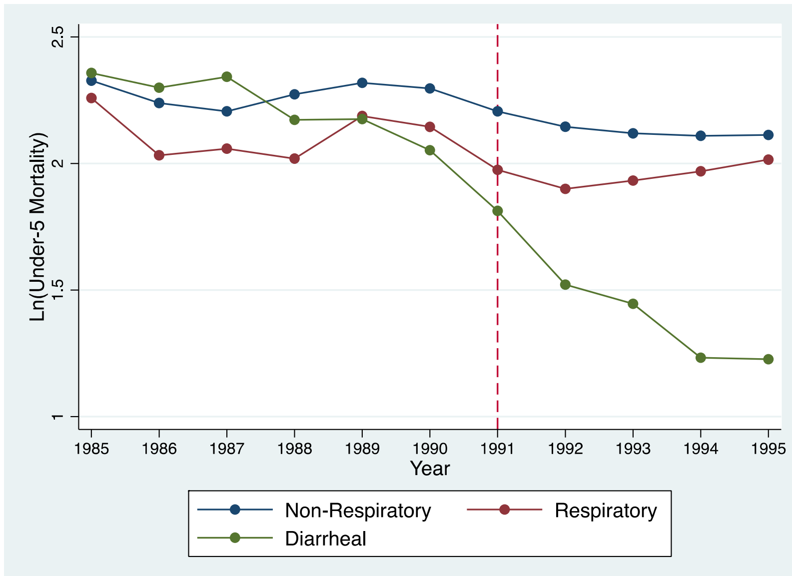
Notes: Map plots average diarrheal mortality rates per 1,000 live births over the period 1985-1990 for children under the age of 5 by municipality. Darker colors reflect higher average pre-intervention diarrheal mortality rates. Data to construct map were obtained from the Mexico Ministry of Health, Vital Statistics.

Figure 2: Chlorination Coverage under Programa Agua Limpia



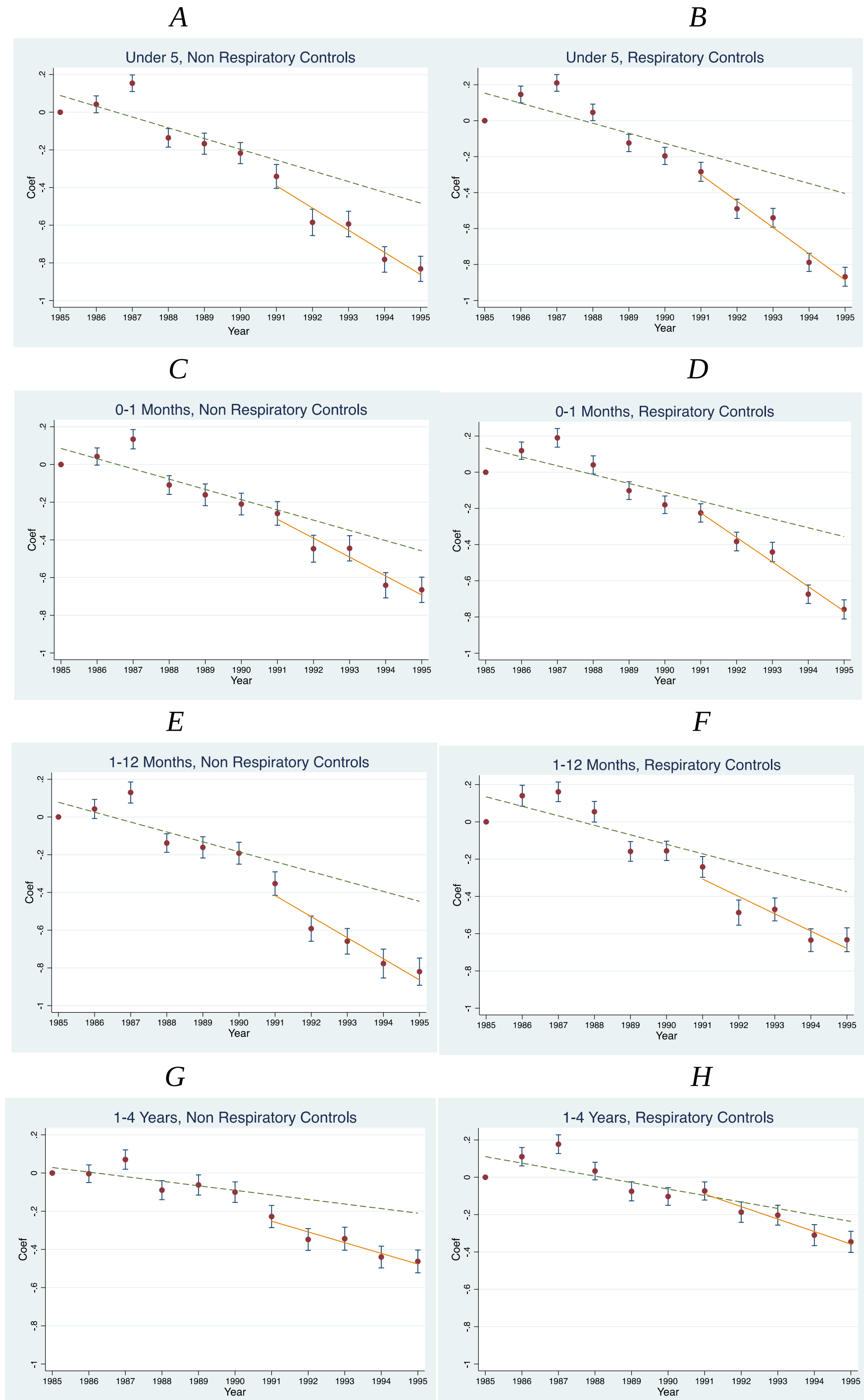
Notes: Figure plots the share of the population (blue) and number of localities (red) covered by chlorinated water between April 1991 and December 1995. The sharp uptick in the population share covered between April 1991 and December 1991 was coincident with the introduction of Programa Agua Limpia (PAL). Data were obtained from CONAGUA (1994).

Figure 3: National Trends in Log Under-5 Mortality Rates by Cause



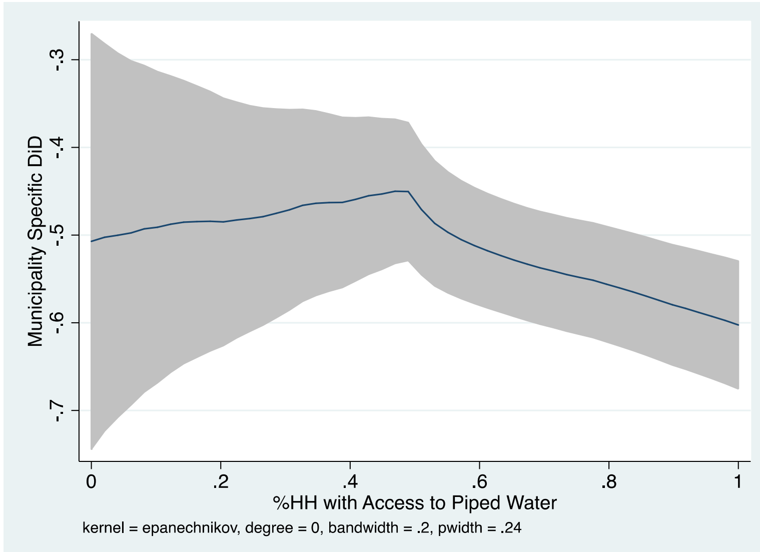
Notes: Figure plots the trends in mortality rates for diarrheal disease and the two sets of control diseases at the national level during the study period 1985-1995. Visually, we note a trend break in the diarrheal mortality series in 1991, coincident with the start of PAL. This break was confirmed econometrically using the Quandt Likelihood Ratio test (F = 11.16, p = 0.004) applied to a longer time series (1979-1997, see *Appendix Figure 1*; specifically, we assessed for the presence of breaks between 1985-1995). No statistically significant break was found for the control diseases. Data source: Ministry of Health, Vital Statistics.

Figure 4: Event Study Coefficient Plots



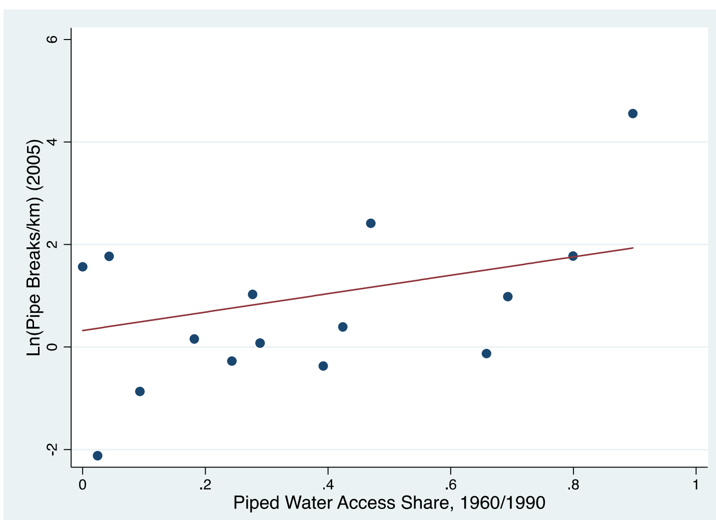
Notes: Panels A-H plot estimates of the Diarrhea × Year coefficients (αt) from Equation 1 using either non-respiratory (left panel) or respiratory (right panel) control diseases. Panels A and B plot estimates for all children under age 5 and the remaining panels examine specific age subgroups (neonatal and post-neonatal refer to 0-1 month olds and 1-12 month olds, respectively). Coefficients are denoted by the dots and the vertical line and whiskers denote the 95 percent confidence interval of the estimates. The dashed green line is a predicted trend line calculated using pre-1991 coefficients, which we extend across the time series. The solid orange line is the trend line for the 1991-1995 coefficients. The gap between the two can be interpreted as the PAL treatment effect.

Figure 5: PAL Program Effects and Piped Water Coverage



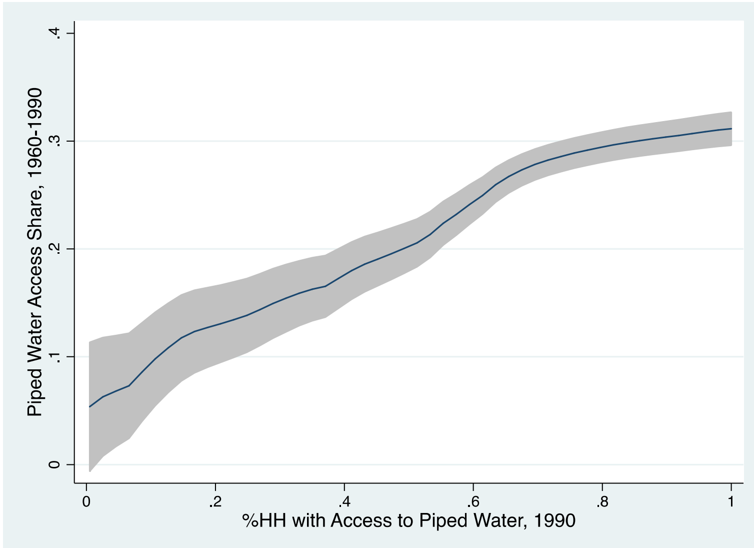
Notes: LOWESS smoothed plots (with 95 percent CI) of municipality specific differences-in-differences estimates (using respiratory disease controls) against the 1990 share of the population covered by piped water (see *Table 1* for details). More negative values on the Y-axis reflect larger program effects. The relationship plotted here is effectively flat.

Figure 6: Relationship Between Water System Age and Pipe Breaks



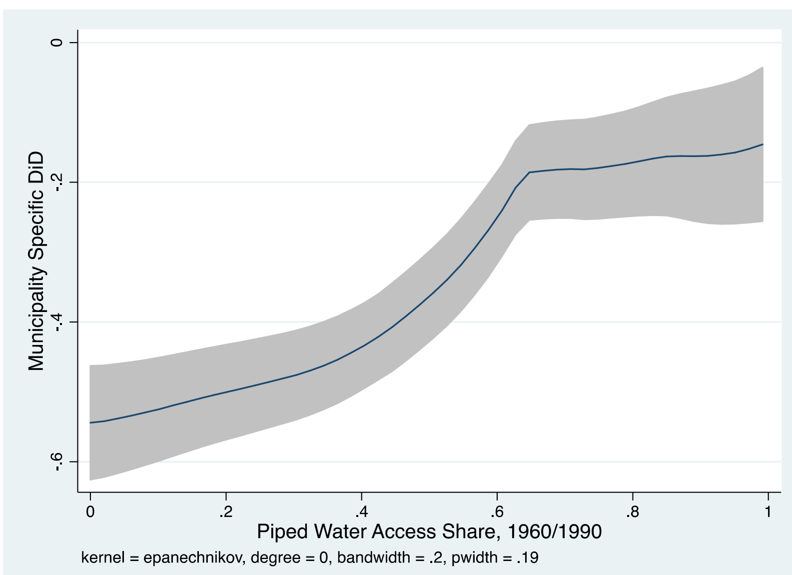
Notes: Scatter plot of logged pipe breaks per kilometer in 18 municipal water systems in 2005 against the ratio of households with access to piped water in (1960/1990), which we use as a proxy for system age. Data on pipe breaks were obtained from the International Benchmarking Network for Water and Sanitation Utilities (IB-NET, http://www.ib-net.org/). The regression line reveals a positive relationship between these variables. As seen in *Appendix Table 7*, a 1 s.d. increase in the piped water access ratio (0.21) is associated with a 97 percent increase in the number of pipe breaks per kilometer.

Figure 7: Water System Age and 1990 Population Coverage



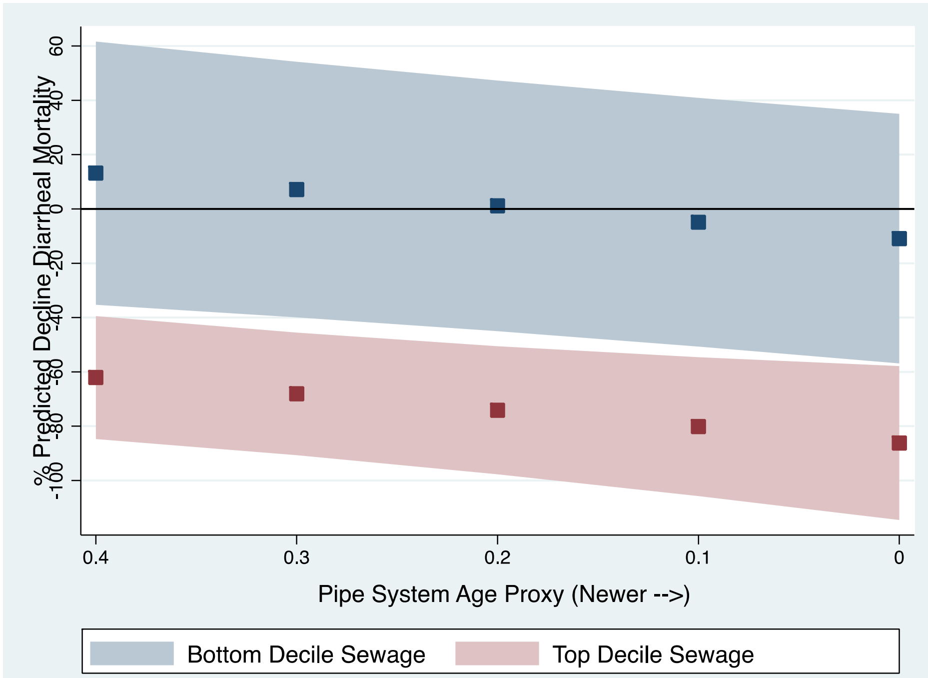
Notes: LOWESS smoothed plots (with 95 percent CI) of municipality specific ratios of household piped water coverage between 1960 and 1990 (our proxy for water system age) against coverage in 1990. The positive slope of the plot suggests that systems with higher population coverage pre-PAL may also have been older and, therefore, dilapidated. *Figure 6* directly makes the case for the latter point, linking the 1960/1990 access ratio to pipe breaks in 2005.

Figure 8: PAL Program Effects and Water System Age



Notes: LOWESS smoothed plots (with 95 percent CI) of municipality specific differences-in-differences estimates and the ratio of piped water coverage between 1960 and 1990 (our proxy for water system age).

Figure 9: Infrastructure Quality and Heterogeneous Effects of PAL



Notes: Predicted PAL treatment effects and confidence intervals for different infrastructure regimes based on regressions in column (4) of Table 4. Predictions calculated over the 90th-10th percentile interval of pipe water system age (based on the piped water share proxy variable, X-axis) for both the bottom (blue) and top (red) deciles of sewage coverage (0.2 percent and 65 percent, respectively) in the sample. The bottom right of the graph reflects predicted estimates for municipalities in the highest decile of both sewage coverage and water system age.

Table 1: Descriptive Statistics

	Pre-PAL			Post-PAL			Full Sample		
	Mean	S.D.	N	Mean	S.D.	N	Mean	S.D.	N
Vital Statistics Data (1985-1995, Municipality Level)									
Under-5 Diarrheal Mortality Rate	11.85	12.04	13,310	5.92	7.42	11,115	9.12	10.59	24,425
Control Diseases									
Under-5 Non-Respiratory Mortality Rate	10.5	10.49	13,310	9.22	7.96	11,115	9.90	9.33	24,425
Under-5 Respiratory Mortality Rate	11.01	10.19	13,310	9.24	7.41	11,115	10.19	9.60	24,425
Municipality Characteristics, 1990 Census									
% HH with Access to Piped Water	0.79	0.21	2,331						
% HH with Access to Sewage	0.60	0.29	2,331						
% Adults Completing Secondary Schooling	5.35	1.57	2,331						
Average Per Capita Earnings (Pesos, 1000)	42529.42	17434.71	2,331						
% Indigenous Population									
Population	348,272.9	1,627,442	2,331						
ENIGH Data (1989, 1992, 1994 waves; Individual Level)									
Total Expenditure on Sanitation Goods (Peso)	1428	1113.15	11,176	810.11	1360.57	22,558	1015.022	1316.469	33,734
Household Head Age	45.05	15.43	11,176	44.58	15.39	22,558	44.74	15.41	33,734
Household Head Gender (=1 if Male)	0.86	0.35	11,176	0.86	0.34	22,558	0.86	0.34	33,734
Household Head Less then Primary (=1)	0.49	0.50	11,176	0.51	0.50	22,558	0.50	0.50	33,734
Primary Complete (=1)	0.25	0.43	11,176	0.24	0.43	22,558	0.24	0.43	33,734
Secondary Complete	0.12	0.33	11,176	0.13	0.34	22,558	0.13	0.33	33,734
Diploma or Above	0.15	0.35	11,176	0.13	0.34	22,558	0.13	0.34	33,734
Household with Piped Water (=1)	0.60	0.50	11,176	0.53	0.50	22,558	0.55	0.50	33,734

Notes: Descriptive statistics divided by pre-PAL (data from prior to 1991) and post-PAL (data from 1991 or thereafter). Vital Statistics data reflect weighted under-5 deaths per 1000 live births, with the sample size denoting municipality-year observations. Diarrheal diseases denote infectious diarrhea (ICD9 codes 001-009). Non-respiratory diseases comprises of the sum of death rates from congenital anomalies (ICD9 codes 740-759), perinatal causes (low birth weight, birth trauma, congenital infections, neonatal jaundice, etc: ICD9 codes 764-779), and other bacterial diseases (whooping cough, strep throat/scarlet fever, erysipelas, meningitis, tetanus, and septicemia; ICD9 codes 033-038). Respiratory diseases consist of the sum of death rates from acute upper and lower respiratory infections (ICD9 codes 60-466, 480-487 respectively). Municipality characteristics from 1990 (taken as a pre-PAL baseline) were computed using the IPUMS 1990 Census 10 percent micro data (Minnesota Population Center, 2015), aggregated (using appropriate weights) to the municipality level. The piped water variable reflects the percentage of households in a municipality with access to piped water either at their home or via a public tap. The sewage variable reflects the percentage of households with on premises access to a sewage system. The earnings variable is the mean total annual household earned income in 1990 pesos (the large numbers reflect significant currency devaluation over the 1980s-early 1990s). Finally, the ENIGH data are taken from the 1989, 1992, and 1994 waves of the *Encuestas Nacional de Ingresos y Gastos de los Hogares*, a national household income and consumption survey. The sanitation goods variable reflects the total amount spent in the prior month on soaps, detergents, and bottled or purified water. We combine these into a single class to reduce the number of zeros, since we used logged expenditures in our empirical models.

Table 2: Differences-in-Differences Models: Diarrheal Relative to Control Disease Trend Breaks Pre-Post PAL

	Panel A - Non Respiratory Controls				**Panel B - Respiratory Controls**			
	Under-5 Years	*0-1 Months*	*1-12 Months*	*1-4 Years*	*Under-5 Years*	*0-1 Months*	*1-12 Months*	*1-4 Years*
1(Diarrhea)*1(Post)	**-0.138*** **	**-0.0480** **	**-0.181*** **	**-0.136*** **	**-0.119*** **	**-0.0651*** **	**-0.136*** **	**0.00773**
	(0.0210)	**(0.0208)**	**(0.0232)**	**(0.0199)**	**(0.0204)**	**(0.0201)**	**(0.0208)**	**(0.0199)**
1(Diarrhea)*1(Post)*Year	**-0.0572*** **	**-0.0419*** **	**-0.0582*** **	**-0.0297*** **	**-0.0909*** **	**-0.0868*** **	**-0.0422*** **	**-0.0321*** **
	(0.00867)	**(0.00919)**	**(0.00906)**	**(0.00732)**	**(0.00824)**	**(0.00819)**	**(0.00832)**	**(0.00756)**
1(Diarrhea)*Year	-0.0591***	-0.0561***	-0.0543***	-0.0259***	-0.0558***	-0.0489***	-0.0509***	-0.0347***
	(0.00543)	(0.00558)	(0.00561)	(0.00512)	(0.00467)	(0.00474)	(0.00488)	(0.00429)
1(Diarrhea)	-0.0860*	-0.643***	1.057***	0.601***	-0.133***	-0.361***	0.147***	0.144***
	(0.0485)	(0.0523)	(0.0328)	(0.0294)	(0.0387)	(0.0401)	(0.0313)	(0.0246)
N	48,906	48,906	48,906	48,906	48,906	48,906	48,906	48,906
R-squared	0.52	0.62	0.51	0.52	0.53	0.50	0.50	0.48
% Decline by 1995 Due to PAL	36.7	21.6	41.3	25.4	48.2	41.2	30.5	17.1

Notes: Estimates of Equation 2 in the main text. *** - p<0.01, ** - p<0.05, * - p<0.1. Robust standard errors, correcting for clustering at the municipality level, are provided in parenthesis. All models include municipality and year fixed effects and are weighted by municipality baseline live births (i.e., the average for 1988-1990). Each column represents a separate regression, with the panel header denoting the control diseases used and the column header the specific age group over which the inverse hyperbolic sine transformation of mortality was calculated for the dependent variable. **1**(*Diarrhea*) =1 denotes diarrheal mortality rates, while **1**(*Diarrhea*) = 0 denotes the control disease (see Table 1 notes for details). *Post* = 1 if the year of observation is 1991 or thereafter. The level (**1**(*Diarrhea*)× **1**(*Post*)) and trend (**1**(*Diarrhea*)×**1**(*Post*)×*Year*) break estimates are in bold. The coefficients on **1**(*Diarrhea*)×*Year* pick up pre-existing trends in the diarrheal disease series relative to the control diseases. Pre-trends and level and trend breaks for the control diseases are picked up the year fixed effects. The sample size reflects the number of municipality-years. The final row, *% Decline by 1995 Due to PAL* is calculated by adding the coefficient on the level break to four times that on the trend break (since 1995 is 4 years after PAL). The year variable is rescaled such that 1991 = 0 and increments above and below are denoted by positive and negative integers.

Table 3: Triple Difference Models: Diarrheal Disease Mortality × Post-intervention × Small (Targeted) vs Large Municipality

	Non-Respiratory	Respiratory
1(Diarrhea)*1(Post)*1(Small)	0.0332	0.0693
	(0.0459)	(0.0460)
1(Diarrhea)*1(Post)*1(Small)*Year	-0.104***	-0.109***
	(0.0181)	(0.0194)
N	48,906	48,906
R-squared	0.553	0.566
% Decline by 1995 Due to PAL	38.3	36.8

Notes: Estimates of Equation 3 from the main text. *** - p<0.01, ** - p<0.05, * - p<0.1. Robust standard errors, correcting for clustering at the municipality level, are in parenthesis. All models include municipality and year fixed effects and are weighted by municipality baseline live births (i.e., the average of 1988-1990). Each column is a separate regression, and reflects estimates of Equation 3 in the main text. Specifically, we include a third difference—municipality size—in these models. Size is captured by a binary indicator denoting municipalities with populations < 500,000 = 1. Those larger already generally chlorinated water systems in place. While only 5 percent of municipalities in the sample are contained in large urban areas > 1,000,000 people (Small = 0), they accounted for 52 percent of the population in 1990.

The final row, % Decline by 1995 Due to PAL is calculated by adding the coefficient on the level break to four times that on the trend break (since 1995 is 4 years after PAL). The year variable is rescaled such that 1991 = 0 and increments above and below are denoted by positive and negative integers.

Table 4: Determinants of Municipality-Specific Program Effects

	Full Sample	Municipalities in Small-Medium Sized Cities	Full Sample	Municipalities in Small-Medium Sized Cities
% HH with Access to Piped Water	-0.374	-0.307	-0.232	-0.232
	(0.311)	(0.330)	(0.358)	(0.391)
% HH with Access to Sewage System	-0.785**	-0.840*	-1.01**	-1.21**
	(0.398)	(0.450)	(0.438)	(0.509)
Piped Water Coverage Ratio (1960/1990)			0.284*	0.603**
			(0.162)	(0.258)
N	1.921	1,837	1,408	1,334
R-squared	0.16	0.16	0.18	0.19

Notes: Estimates of Equation 4 in the main text. *** - p<0.01, ** - p<0.05, * - p<0.10. All models are at the municipality level and are weighted by municipality population. The dependent variable is the municipality specific PAL treatment effect. We restrict the sample to the 5th-95th percentile of this variable in order to reduce the influence of outliers. The first and third columns include all observations meeting the stated criteria. In the second and fourth columns, we remove all municipalities within, or that contain, cities with >500,000 (see main text), as these areas already had high penetrance of chlorinated water prior to PAL. All models include municipality level controls from the 1990 census, including the % of population completing secondary education, average logged household income, % indigenous population, logged total municipality population, and state fixed effects. Robust standard errors are in parenthesis.

Table 5: Behavioral Responses: Expenditures on Soaps, Detergents, Bottled Water

	Full Sample	Small/Medium Sized Cities	Large Cities
1(Post)*Base Diarrhea	-0.00847	-0.0167**	-0.00253
	(0.0130)	(0.00739)	(0.0210)
	[0.60]	[0.13]	[0.85]
N	34,801	21,385	13,416
R-squared	0.874	0.887	0.839

Notes: Estimates of Equation 4 from the main text. *** - p<0.01, ** - p<0.05, * - p<0.1. Robust standard errors, correcting for clustering at the state level, are in parenthesis. Each column represents a separate regression, with the column header denoting the specific sub-sample of interest. Because there are only 32 states, we additionally compute cluster wild bootstrap-t corrected p-values for the coefficient of interest (Cameron et al., 2008), which are provided in the square brackets. The dependent variable is the inverse hyperbolic sine transformation of expenditures on soaps, detergents, and bottled/mineral water. All models include controls Post×Baseline Respiratory Disease, age, sex, and education of the household head, household size, and logged household total income, as well as state and survey rear FE. The main coefficient of interest is on **1**(Post)×Base Diarrhea, where Baseline Diarrhea is the average under-5 diarrheal mortality rate over 1988-1990. To interpret the results, focusing on the second column an interquartile decrease in diarrheal mortality (about 4 deaths per 1,000 live births) was associated with a 6.7 percent decrease in soap, detergent, and bottled water expenditures.

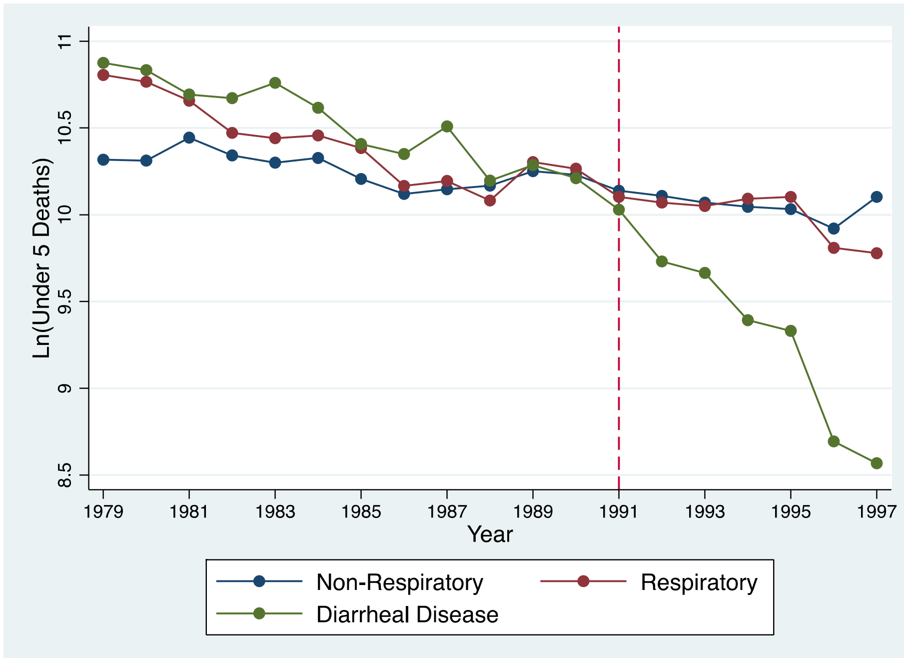
Table 6: Cost Effectiveness

Estimate	Under-5 Deaths Averted	Program Cost (2015 USD)	Cost/Death Averted (2015 USD)	Cost/Life Year Saved (2015 USD)
Point	23664	1.86 billion	78600	1310
Lower 95% CI	17298	1.86 billion	107527	1792
Upper 95% CI	29535	1.86 billion	62976	1050

Notes: Assuming 2.5 million live births each year (the average nationwide between 1985-1990), we use estimates from Col 2 of Table 2 to calculate the number of under-5 deaths averted each year between 1991-1995. We do this using both the point estimates from the model, as well as the lower and upper 95 percent CI. The column "Under-5 Deaths Averted" displays these estimates. The total program cost over 1991-1994 comes from administrative sources. The cost per death averted is simply the total cost/# of deaths averted. To calculate Cost/Life Year Saved, we assume each under-5 child whose death was averted would (conservatively) live to the age of 60 (and so we multiply the numbers in the penultimate column by 60 to get the numbers in the last column). All costs are expressed in 2015 USD.

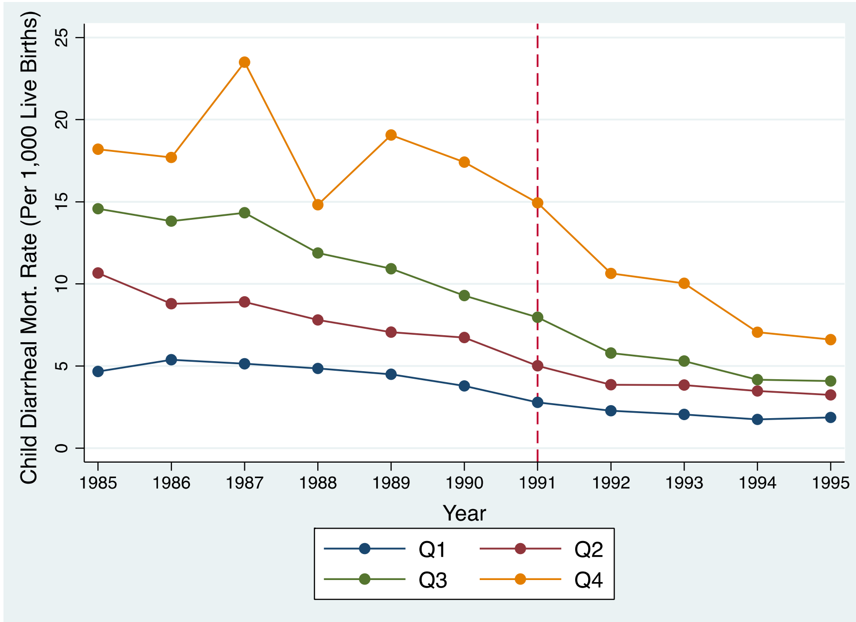
Appendix

Appendix Figure 1: National Trends in Under-5 Deaths By Cause, 1979-1997



Source: Mexican Vital Statistics. Unlike *Figure 3*, we plot deaths instead of deaths rate here because municipality specific live births were not available for the entire period.

Appendix Figure 2: Convergence in Diarrheal Mortality Rates



Source: Mexican Vital Statistics. Figure plots trends in under-5 diarrheal mortality rates by quintile of (state) pre-intervention diarrheal mortality (calculated as the average over 1988-1990). The figure demonstrates gradual convergence prior to 1991, with more rapid convergence thereafter.

Appendix Table 1: DID Trend Break Models: Logged Mortality Rates

	Non-Resp	***Respiratory***
1(Diarrhea)*1(Post)	-0.135***	-0.108***
	(0.024)	(0.023)
1(Diarrhea)*1(Post)*Year	-0.055***	-0.078***
	(0.009)	(0.010)
N	35,203	36,234
R-squared	0.59	0.64
% Decline by 1995 Due to PAL	35.7	42.3

Notes: Estimates of Equation 2 from the main text. Models are identical to those presented in *Table 2* except here we use natural logs of the mortality rates instead of the inverse hyperbolic sine transform. This accounts for the smaller sample sizes in these models. The final row, % Decline by 1995 Due to PAL is calculated by adding the coefficient on the level break to four times that on the trend break (since 1995 is 4 years after PAL). The year variable is rescaled such that 1991 = 0 and increments above and below are denoted by positive and negative integers. See *Table 2* notes for further details.

Appendix Table 2: DID Trend Break Models: Inclusion of State-Year FE

	Non-Resp	*Respiratory*
1(Diarrhea)*1(Post)	-0.138***	-0.119***
	(0.0206)	(0.0200)
1(Diarrhea)*1(Post)*Year	-0.0572***	-0.0909***
	(0.00850)	(0.00808)
N	48,906	48,906
R-squared	0.594	0.563
% Decline by 1995 Due to PAL	36.7	48.3

Notes: Estimates of Equation 2 from the main text. Models are identical to those presented in *Table 2* except here we include state-year level fixed effects. The final row, % Decline by 1995 Due to PAL is calculated by adding the coefficient on the level break to four times that on the trend break (since 1995 is 4 years after PAL). The year variable is rescaled such that 1991 = 0 and increments above and below are denoted by positive and negative integers. See *Table 2* notes for further details.

Appendix Table 3: DID Trend Break Models: State-Level Data

	Non-Resp	*Respiratory*
1(Diarrhea)***1**(Post)	-0.151***	-0.112***
	(0.038)	(0.0366)
	[p= 0.000]	[p=0.02]
1(Diarrhea)***1**(Post)*Year	-0.065**	-0.0774***
	(0.026)	(0.020)
	[p = 0.02]	[p=0.004]
N	698	698
R-squared	0.75	0.77
% Decline by 1995 Due to PAL	41	42

Notes: This table is identical to Table 2 in the main text except here we use state-level data. All models include state and year fixed effects. The dependent variable is logged under-5 mortality. *** - p<0.01, ** - p<0.05, * - p<0.1. Robust standard errors, correcting for clustering at the state level, are in parenthesis. Because there are only 32 states, we additionally compute cluster wild bootstrap-t corrected p-values for the coefficient of interest (Cameron et al., 2008), which are provided in the square brackets.

Appendix Table 4: DID Trend Break Models: Monthly Death Counts

	OLS		*Negative Binomial*	
	Non-Resp	**Respiratory**	**Non-Resp**	**Respiratory**
1(Diarrhea)***1**(Post)	-0.085**	0.032	-0.065*	0.038
	(0.032)	(0.033)	(0.034)	(0.036)
	[p=0.001]	[p=0.33]		
1(Diarrhea)***1**(Post)*Year	-0.066***	-0.119***	-0.058***	-0.116***
	(0.020)	(0.018)	(0.021)	(0.021)
	[p =0.004]	[p = 0.002]		
N	8,335	8,335	8,376	8.376
R-squared	0.86	0.85		
% Decline by 1995 Due to PAL	34.9	44.4	31.2	40.3

Notes: This table is identical to Table 2 in the main text except here we use monthly data for all states between 1985-1995 (i.e, observations are aggregated to the state-month level). We additionally include month fixed effects in these models. Observations are aggregated to the state-month level. The dependent variable in the OLS models is the logged number of deaths in each state-month. The dependent variables in the Negative Binomial models is the number of deaths. For the negative binomial models, we use the incidence rate ratios (IRR) to calculate the percent relative decline in diarrheal deaths. *** - p<0.01, ** - p<0.05, * - p<0.1. Robust standard errors, correcting for clustering at the municipality level, in parenthesis. Cluster wild bootstrap-t corrected p-values (Cameron et al., 2008), are provided in the square brackets.

Appendix Table 5: DID Trend Break Models: Municipalities, 1979-1997

	Non-Resp	*Respiratory*
1(Diarrhea)***1**(Post)	-0.0872***	-0.243***
	(0.0227)	(0.0218)
1(Diarrhea)***1**(Post)*Year	-0.151***	-0.148***
	(0.00568)	(0.00535)
N	80,766	80,766
R-squared	0.87	0.87
% Decline by 1995 Due to PAL	69.1	83.5

Notes: Estimates of Equation 2 from the main text. This table is identical to *Table 2* in the main text except here we use data from 1979-1997, instead of restricting the sample to 1985-1995. The dependent variable is the inverse hyperbolic sine transform of the number of deaths under age 5 (we do not examine mortality rates since municipality specific births data was not available during the early part of the time period). *** - p<0.01, ** - p<0.05, * - p<0.1. Robust standard errors, correcting for clustering at the municipality level, are in parenthesis.

Appendix Table 6: Cross-State Convergence

	(1)	(2)	(3)	(4)
	Log	**Level**	**Log**	**Level**
1(Post)*Base Diarrhea	**0.00758**	**-0.328*** **	**0.0312** **	**-0.0480**
	(0.0135)	**(0.116)**	**(0.0123)**	**(0.0302)**
Base Diarrhea*Year			0.00461**	0.0115
			(0.00193)	(0.0172)
1(Post)*Base Diarrhea*Year			**-0.0137*** **	**-0.0409** **
			(0.00258)	**(0.0165)**
1(Post)			-0.507***	-0.270**
			(0.0839)	(0.111)
Year			-0.0924***	-0.184***
			(0.0123)	(0.0506)
1(Post)*Year			-0.0202	0.142***
			(0.0173)	(0.0469)
N	349	352	349	352
R-squared	0.96	0.777	0.941	0.830

Notes: Estimates provided are versions of the model:

$$M_{ijt} = a_0 + a_1 \ (Post_t \times Base\_Diarrhea_j) + \lambda_j + \theta_t + u_{ijt}$$

where M_{ijt} = the state specific mortality rate, *Base_diarrhea* refers to the baseline under-5 diarrheal mortality rate (average for each state over 1988-1990), *Post = 1* for years 1991 and thereafter, and the remainder of the variables reflect state and year fixed effects. Estimating using logged mortality rates as the dependent variable evidence of *relative* convergence, where as estimates using levels recover *absolute* convergence. A negative coefficient on post*base would implies convergence. The 1985-1995 state-level sample is used for all regressions (N reflects the number of state-years).

In Cols 1 and 2, we find a precisely estimated 0 for logged mortality and a negative and significant estimate for the level, implying that there was absolute, not relative, convergence. Columns 3 and 4 decompose this convergence into a level and trend break. Again, we find strong evidence of absolute (level) convergence. While we obtain statistically significant estimates on the level and trend break for logged mortality in col 3, these effects are offsetting such that by 3 years after program initiation, the net effect on mortality rates is zero.

*** - p<0.01, ** - p<0.05, * - p<0.1. Robust standard errors, correcting for clustering at the state level, in parenthesis. Statistical significance is unchanged when we compute cluster wild bootstrap-t corrected p-values for the coefficient of interest (which we suppress here for purposes of clarity).

Appendix Table 7: Diarrheal Mortality Decline and In-Migration

	(1)	(2)	(3)
ΔDiarrhea	0.13*	0.055	0.082
	(0.07)	(0.057)	(0.065)
N	627	627	627
R-squared	0.018	0.14	0.23
BaseDiar	-0.10**	-0.033	-0.042
	(0.047)	(0.043)	(0.042)
N	627	627	627
R-squared	0.02	0.14	0.23
Controls			
Municipality SES (Education)	No	Yes	No
State FE	No	No	Yes

Notes: To assess potential non-random migration as a function of exposure to PAL, we use data from the public use 1995 Mexican Population Census Microdata, a representative 1.5 percent sample which allows us to identify individuals who lived in a different municipality 5 years prior to survey (i.e., pre-PAL, which was in 1991). In prior censuses, only interstate migration is identifiable. The identity of the municipality the individual moved from is not known, though the current municipality of residence is recorded. Focus on reproductive age adults (i.e., men and women ages 18-40), we can construct the in-migration rate for each municipality (in our data we can identify nearly 700 municipalities). On average, the share of individuals living in a given municipality who migrated from elsewhere over the preceding 5 year period was 11.1 percent. To assess whether in-migration responded to changes in diarrheal disease environment, we estimated models of the following form:

$$Migration_{ij} = a_0 + a_1 \, (\Delta Diarrhea_j) + \boldsymbol{X}_{(i)(j)} + u_{ijt}$$

And:

$$Migration_{ij} = a_0 + a_1 \, (BaseDiar_j) + \boldsymbol{X}_{(i)(j)} + u_{ijt}$$

Here, i represents the municipality and j the state. $Migration_{ij}$ is the proportion of individuals in a given county in 1995 who lived in another county 5 years prior; $\Delta Diarrhea_j$ is the change in under-5 diarrheal disease mortality in the post versus pre-periods; $BaseDiar_j$ is pre-intervention baseline diarrheal mortality rate change; and $\boldsymbol{X}_{(i)(j)}$ represent municipality specific, pre-intervention controls and/or state-fixed effects. The first regression assesses whether in-migration changed as a function of the degree of decline in diarrheal mortality. The second regression leverages the insight that areas with higher pre-intervention diarrheal mortality rates stood to gain more from PAL (see Section 6). In models without municipality controls and state fixed effects (col 1), we find that areas with larger declines in diarrheal mortality, or stood to gain more from PAL, actually had *lower* proportions of in-migrants. The estimates suggest that the average drop in diarrheal mortality pre-post PAL was associated with a 1.3 percent pt decrease in the proportion of in-migrants. However, once we control for municipality education or state fixed effects (col 2 and 3, respectively), these associations disappear entirely. We conclude that non-random migration is unlikely to be driving our findings.

Appendix Table 8: Water System Age and Pipe Breaks

	ln(Pipe Breaks/Km)
Piped Water Access Ratio, 1960/1990	4.64***
	(0.99)
% change from 1 s.d. increase in access ratio	*97%*
N	**18**
R-squared	**0.69**

Notes: Estimates from model regressing logged pipe breaks per kilometer in 2005 on the ratio of households with access to piped water in 1960/1990 (weighting by 1990 population). Data on pipe breaks were obtained from the International Benchmarking Network for Water and Sanitation Utilities (IB-NET, http://www.ib-net.org/). Percent change estimates reflects the percent increase in pipe breaks owing to a 1 s.d. change in the piped water access ratio (0.21). *** - p<0.01.