Why does piped water not reduce diarrhea for children? Evidence from urban Yemen[1]

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Abstract

This paper investigates why household connections to piped water supply can increase diarrheal diseases among under-5-year-old children. Using a unique mix of household data, microbiological test results and spatial information from urban Yemen it is possible to distinguish the adverse impacts of malfunctioning water pipes from unhygienic household behavior on water pollution and health outcomes. The analysis consists of three parts: First, exogenous variations of pipe construction are used as instrumental variables to quantify the health impact of access to piped water, which is found to increase the risk of child diarrhea by 4.6 percentage points. Second, by exploiting the spatial correlation of pollution among households connected to the same water pipe, it is shown that broken pipes and interruptions of water supply are responsible for most of the water pollution. Third, unhygienic water storage and handling at household level further increase water pollution. These results show for the first time that water rationing can jeopardize the intended health benefits of providing access to clean drinking water. Importantly, these results apply to many urban areas in Africa and the Middle East where water resources are limited and piped water supply is frequently interrupted.

JEL Codes: I38, O12, O16

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1. Introduction

Clean drinking water is a key to human development and can directly affect health, educational attainments and future income (Zwane and Kremer 2007). Polluted drinking water can cause diarrheal diseases which are responsible for 20% of mortality among under-5-year-old children in developing countries (Kosek *et al.* 2003). In fact, diarrhea creates an immense health burden in developing countries and has been found to account for 8% of all total lost life years in developing countries (Smith *et al.* 1999). Since contaminated drinking water is the cause of almost 90% of all diarrheal diseases, the provision of clean drinking water enjoys high priority among developing country policy makers, development banks and many bilateral donors. The World Bank alone reports an increase in water related lending by 55% between 1997 and 2007, reaching activities worth 8 billion per year, a third of which is spent on providing access to piped drinking water and sewerage (World Bank 2010). Over the last two decades such infrastructure investments have helped in meeting the millennium development goal of halving the proportion of people without access to safe water (Gulland 2012).

Surprisingly, very little is known about the actual health impacts of piped water schemes. The empirical evidence is mixed at best, although most often no signs of improved health are found. For example, after reviewing several hundred World Bank funded water projects the Bank's IEG evaluation department concluded that "evidence of improved water quality is rare, as are indications of the improved health of project beneficiaries" (World Bank 2010, p.xiii). Indeed, most empirical studies only find limited health impacts from access to drinking water (some recent quasi-experimental examples include Gamper-Rabindran *et al.* 2010, and Devoto *et al.* 2011). Apparently, drinking water is typically polluted at point-of-use despite access to clean piped water. In their review of 57 peer-reviewed publications Wright *et al.* (2004) find that water pollution at point-of-use remains severe in more than half of the evaluated projects.

In Yemen, diarrhea is the primary cause of child mortality and currently stands at 88 per 1000 children under 5 years of age (World Bank 2009). In addition, the country suffers from severe water stress and uses more than 150% of its renewable water resources every year. In several urban areas, water use is fourfold of annual recharge (World Bank 2005). As a result, groundwater levels are falling rapidly, leading to ever deeper wells and serious operational problems for many water utilities. Given the extreme water scarcity in combination with rapid population growth of annually 2.9%, access to clean drinking water remains a major challenge in Yemen.

This article first quantifies the health impacts among under-5-year-old children by using an instrumental variable (IV) approach based on exogenous variation of pipe construction. By using the instruments *distance to city center* and *rocky ground* for endogenous project implementation, piped water is found to increase the probability of diarrhea among under-five-year old children by 4.6%.

Second, this study looks at the determinants of drinking water pollution in this recently improved scheme. It scrutinizes *why* drinking water in the treatment group is more polluted than in control groups, where households only use unimproved water sources. Building on exiting literature, several potential transmission channels are proposed that might cause pollution between clean wells and consumption at the final point-of-use. Spatial analysis of coliform pollution in water pipes shows that a large number of pipes provide polluted water to household tanks. Importantly, much of the pipe pollution is associated with lengthy interruptions of water supply. Third, substantial water pollution occurs within households. Improved water handling and storage, such as the use of closed water containers that prevent hand-to-water transmission of pathogens can help to reduce such 'intra-household pollution'.

This paper makes a number of contributions to the existing literature. First, unique water quality data from several testing points at each house makes it possible to quantify the degree of water pollution before and after piped water reaches the household. Second, using spatial information of pipes, streets and neighborhoods this paper is able to test alternative causes of water pollution while controlling for heterogeneity of urban neighborhoods

The remainder of this paper is structured as follows. Section 2 briefly reviews the existing empirical evidence on piped water supply and diarrheal diseases and extracts potential causes of water pollution and child diarrhea. Section 3 presents the project design and introduces the data. Section 4 introduces the identification strategy used to detect the determinants of water pollution and child diarrhea. Section 5 presents the empirical results for child health, and for water pollution as caused by pipes vs. behavior. Section 6 concludes and offers some policy recommendations.

2. Drinking Water and Diarrhea

The earliest contribution on piped water and diarrheal diseases comes from the epidemiologist John Snow who in 1855 used differences in disease prevalence during a cholera epidemic in the city of London to show that cholera was being spread through the drinking water pipes (Snow, 1855). At the time, London had several water companies providing water from the Thames River through a piped scheme to public wells. Some companies were taking water from the river upstream, while others took their water downstream after the river had passed through the city and had been polluted with sewage. Using an early form of spatial analysis Snow was able to show that cholera related mortality was much higher in parts of the city that were supplied by the downstream water companies. In addition, mortality counts helped him to identify a particular public well as the original source of the cholera epidemic. Once the city had removed the pump handle from the affected public well the epidemic was contained (Cameron and Jones 1983). Snow's analysis reveals several things. First, his contribution makes it clear that knowledge about water borne diseases is relatively young. Most advances on the transmission of such pathogens and effective measures against them have only been identified in the past 100 years. This might help explain why knowledge on hygienic behavior and water handling is not yet as universal as many practitioners would hope. Second, Snow's study shows that piped water schemes can pose a serious threat to human health when poorly maintained or operated.

The empirical evidence on causal health impacts of access to piped drinking water is largely ambiguous and very often causal links are missing. For example, in their influential evaluation of a water-pipe scheme in rural India, Jalan and Ravallion (2003) find that any reduction of diarrhea incidence among under-5-year-old children crucially depends on hygienic water handling at household level, which is proxied by education. Using propensity score matching techniques the authors do not find any health benefits among children from poor families with little educated mothers. While this finding underscores the importance of water handling at household level, the authors do not have any information on behavior or water quality. They are thus unable to attribute the health impact to water quality and water handling. A similar problem affects a recent study on in-yard water supply in rural China (Mangyo 2008). Although the paper finds that health outcomes are conditional on maternal education, no data is available to show how maternal education translates into actual water handling, and how that affects water quality and subsequently child health.

In contrast, Semenza *et al.* (1998) measure chlorine residues at point-of-use to quantify the effect of water handling at household level.[2] The piped water system in urban Uzbekistan appeared to be ill maintained and piped water to be severely polluted, causing a lack of chlorine residues in a third of all connected households. The authors randomized water purification at home by providing half of the sample with free chlorine tablets. The results clearly show the effectiveness of water pollution purification near the point-of-use (at least in the short run). The authors conclude pipe pollution is a serious problem and that irregular water pressure and water rationing can sever the situation further, as rationing allows pollutants to spread in all directions of the piped network. The external validity of this paper is somewhat limited because of the fairly small sample of connected households (N=120). In addition, no information is available on the health burden.

The study by Zhang (2012) is the first to distinguish between access to chlorinated and non-chlorinated drinking water. Using longitudinal data from 1989 to 2006 which cover some 150 Chinese villages he presents evidence that the quality of water supply is of immense importance to health. In the long run, anthropometrics outcomes substantially improve among children, as does the incidence of diarrheal diseases among adults. Unfortunately, there is a lack of water quality data that could further support the claim that these health improvements are solely due to water chlorination at purification plants.

Overall, causal evidence on the health impact of piped water and sanitation is very limited. Water contamination may be a result of broken pipes, changing water pressure and interruptions of piped water supply (i.e. rationing) before even reaching the households. In addition, unhygienic water storage and handling may cause additional pollution at household level. Irregular hand washing opens up additional routes of pathogen transmission. Although previous studies have found much piece-wise evidence that pollution from pipes, rationing, and household behavior can jeopardize the potential health effects of clean water, none of these existing studies has been able to simultaneously quantify the various sources of water pollution between source and point-of-use.

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[2] Chlorine is typically added to piped water at the main pump station of the water company. It is highly reactive and eradicates pathogens which make it useful for water purification. In the process, chlorine changes its structure. Thus, a lack of chlorine residues at the point-of-use implies that the water system contained more pathogens than the chlorine could eliminate, since all chlorine has been used up. Consequently, drinking water is most likely polluted if no chlorine residues can be found. This is a very useful testing method, which is easy to implement, highly cost effective and could become a standard in testing for water pollution in piped schemes in developing countries.

3. Project and Data

3.1 Project Background

Until the late 1960s, electricity, telephone, cars and other technological inventions of the previous century were banned by the caliphate ruling Northern Yemen. Limited funds and difficult topographical conditions meant that provision of public services only expanded slowly afterwards. As a result, many towns continue to lack improved water and sanitation systems until today.[3] As a response, the Provincial Towns Project (PTP) was initiated in the early 1990s covering eight towns with populations between 30,000 and 60,000. Given the largely rural character of Yemen these are major urban centers. Three of the towns are located in the central highlands and the remaining five on the coastal plains on Yemen's western and southern coast. The project included installation of treatment plants for water and sewage and pipes connecting households to piped water and sewerage. For a more detailed project description, please see Klasen *et al.* (2011).

Intervention History

Construction first began in the city of Zabid on the Red Sea coast. The water scheme was completed by 1998 and connects to all buildings in the city. Background interviews indicate that water pressure is good with very few interruptions in recent years. This is confirmed by the household survey, which did not detect a single household without connection to piped water in Zabid. The city's sewerage system was only completed in 2005. Until today, only about 85% of households are connected to sewerage pipes. The city of Amran is located in the central highlands, some 70km north of the capital Sana'a. Construction of the water and sewerage grids was completed in 2004. Construction started in the old city center and expanded from there in all directions. Access to piped water is only about 56%, and only 32% for piped sewerage (KfW 2008).

Selection Effects

The selection of towns for the project followed clearly defined criteria based on population size and water availability (KfW 2004, KfW 2006). To evaluate the impact of the interventions in water and sanitation two of the eight project towns were purposefully selected (cf. Klasen *et al.* 2012). The selection for the evaluation survey was rule-based to ensure that (a) towns were from the mountainous highlands and the coastal plains to represent the urban population in Yemen. (b) Towns which received

[3] For a more detailed introduction to the modern institutional history of Yemen see e.g. Phillips (2008).

additional interventions in the water and sanitation sector after the project were excluded to guarantee a clear assignment of impacts to treatment. (c) In the remaining towns the urban structure was analyzed and preference was given to towns showing a connected urban structure that can be exploited for spatial analysis (rather than dispersed semi-urban conglomerations). (d) In addition, towns with existing baseline data were preferred for the impact analysis.

Note that households had no choice regarding project participation. Water engineers planned the grid network according to topographic conditions, since both water and sanitation pipes work best when they follow the natural slope of the cities.[4] Planning always started in the city center and moved outwards from there. During construction, some non-essential pipe segments were skipped when hard rock was encountered. This needed to be done, because nearly all trenches were hand dug with simple tools as part of a public works program.

3.2 Technical Design

Piped Water

To identify possible sources of drinking water pollution it is straightforward to follow the water flow. Water utilities in Yemen rely on ground water, pumped up from many hundred meters below the ground. Chlorine is added before pumping water into the main feed pipes into the city. The feed pipes branch off into medium sized water pipes that run below the larger roads. From there, smaller pipes connect small side streets and all nearby buildings.

Water grids are built in a way that water companies can cut off parts of the grid along the main feed pipes. Cut-off points are useful during repairs of the pipes. In practice however, cut-off points are used for water rationing. When the wells are running low and water pressure cannot be maintained for the entire city, the water company shuts off some neighborhoods from the piped water supply. Such scheduled rationing is common in towns with scare ground water sources throughout North Africa and the Middle East. The situation in the mountain town of Amran is particularly precarious. Three out of five source wells are depleted, which leads to excessive water rationing that can last up to several weeks.

[4] Otherwise additional pumping stations are needed, which can be costly to operate and maintain.

Truck Water

As in most cities around the world, urban households without access to piped water purchase water from vendors with trucks. Water trucks use ground water from special wells in the countryside and deliver water within a few hours. Because trucks rely on a network of such truck wells, their services are not affected by low water pressure or pump failure at a particular well. Water trucks are unregulated and interviews with water vendors and pump operators revealed that no chlorine is added to the trucks. Clearly, truck water can pose health risks. Note that households affected by extended periods of water rationing also rely on water trucks, which might confound the treatment effects (see discussion below).

Water Storage Tanks

Because of low water pressure and frequent water rationing, nearly all urban households in Yemen install additional water storage tanks on the roof of their building.[5] These tanks are made from steel and typically hold 2-3 cubic meters of water. Using gravity, roof tanks provide sufficient water pressure to operate showers, faucets and flush toilets.

Water pipes are directly connected to storage tanks and will automatically fill the tanks when water is available.[6] A simple mechanism closes the water pipe by itself once the tank is full. While this is very practical, there is a risk that any pollution built up during periods of water rationing is flushed into the storage tanks once water pressure resumes. Because pipes are physically connected to the tanks, there is no obvious solution to this. In principle, chlorination of tank water might be a good method to clean the water in the tank. However, only few households reported doing so.

Truck water is also pumped to storage tanks using a pipe that extends to the ground outside the house. It is possible that some pollution occurs during refilling. Otherwise tanks are completely closed and inaccessible to birds and other animals. Beyond the storage tank, there is no further difference between households with and without access to piped water.

Water Handling

Since water in the storage tanks heats up during the day, families fill small kitchen containers with 10-20 liters of cold water every morning. These containers are traditionally made out of clay and without cover, which might cause additional water

[5] Occasionally, households need to install the storage tanks on the ground. Ground tanks are only used the roof is not strong enough to carry (additional) tanks.
[6] By design, no backward water flow into the pipes is possible.

pollution. Increasingly, covered plastic containers with taps are used instead. Their insulation keeps the water cold for longer, and, which is relevant here, might be less prone to pollutants. Very few households in the survey report boiling their water before drinking or the use of water filters on their kitchen faucet (although filters are available on local markets). Overall, less than 10% of the sample purifies drinking water in any way. In addition, most families share a single drinking cup that stands next to the kitchen container, which further facilitates pathogen transmission at the point-of-use. In fact, subjective data on the cleanliness of the drinking cup correlates with micro-biological pollution in the cup (result not shown).

3.3 Data

Household Sample

The data used here comes from a post-intervention survey covering 2500 households in two treatment and two control towns. The control towns are located within a 20 km radius of each treatment town. Importantly, they are located on top of the same ground water aquifer as the respective treatment town. Since water pollution among the counterfactual population is essential to identification, this research design ensures that treatment and control groups are using the same ground water. Please refer to Table A.1 (in the appendix) for a full overview of covariates by treatment group and town.

The research design comes with two distinct control groups, the *control towns* and the unconnected *control areas* in the *project towns*. There are also two intersecting treatment groups in the project towns, one containing all the households connected to *piped water*, and a second, sub-group of households that is additionally connected to *piped sanitation*. Given the heterogeneous composition of most towns, sampling made sure that no urban areas were excluded. This was achieved by employing geographic stratification using square grids which provide a representative coverage of all neighborhoods in the survey towns.[7] The sampling frame was constructed using high-resolution remote satellite images, which are better suited for densely populated urban areas than typical census enumeration maps. The interviews were conducted in the summer of 2010 with female respondents in each household. Pilots showed that female respondents are best informed about illnesses among children and water handling at household level. To avoid any confounding health effects, re-call periods were designed to avoid any overlap with the holy month Ramadan, when fasting is required during the day and large celebrations mark the nights.

[7] For a detailed description of the sampling frame and survey instruments see Klasen *et al.* (2011).

Micro-Biological Water Tests

After the household survey was completed, a team of micro-biologists visited a random subsample of 500 households and tested water samples from storage tanks and drinking cups for coliform pollution. They also tested the source wells of the water companies and the main feed pipes. In the control towns they tested the wells used by water vendors. The test results show that piped water is without any pollution when it leaves the treatment plant. By the time it enters the roof tanks, over two thirds of project households receive polluted water (see Table A.2 in the appendix).[8]

Because of security problems and logistical difficulties, water tests were not conducted at the time of the household survey. This may be problematic if conditions affecting water quality or child health changed in between survey and test. Fortunately, monthly rainfall was less than 10mm in the study areas during the household survey, the microbiological tests, and in between. In addition, the micro-biological survey came with a short 2-page questionnaire to verify water conditions. The results showed that water supply, rationing and truck use were virtually unchanged (Klasen *et al.* 2011). It is therefore little surprising that the coliform pollution can be directly linked to child diarrhea, as is shown below.

Coliform Pollution

Total coliforms are the standard for measuring microbiological water contamination and are directly associated with human faeces. Coliforms are typically among the first bacteria present in contaminated water. They can be found in much larger quantities and are easier to detect than other pathogenic microbes that may be present. Therefore, coliforms act as indicators of possible contamination. Coliforms can enter water supplies from a contaminated source, cracks in the water pipes or backflow of piped water. Especially during water rationing, reversing water flow allows dirt and dead organisms to enter the pipe system (Gascón *et al.* 2000). Project engineers in Yemen have been suspecting old underground cesspits in project towns as a possible source of pollution. Coliforms are not a single type of bacteria. They include various strains, such as E. coli, which causes poisoning and typically leads to a particular form of diarrhea (dysentery). When found, dysentery clearly suggests fecal pollution of drinking water. Table 1 shows the relationship between total coliform pollution at point-of-use (drinking cup) and dysentery for children and adults. Note that the effect becomes stronger when household characteristics and hand washing are controlled for.

[8] For a comprehensive presentation of descriptive results please refer to Klasen *et al.* (2011).

Table 1: Coliform Pollution at Point-of-use and Diarrhea

Dysentery	(1)	(2)	(3)	(4)	(5)	(6)
	Illness		Severity		Duration	
Total Coliform	0.0020**	0.0029**	0.0014*	0.0020*	0.0070**	0.0098**
at Drinking Cup	(0.001)	(0.001)	(0.001)	(0.001)	(0.003)	(0.004)
Observations	3,703	3,703	3,703	3,703	3,703	3,703
Controls	NO	YES	NO	YES	NO	YES

Robust standard errors in parentheses; Significance levels *** p<0.01, ** p<0.05, * p<0.1

Controls include age, gender, education, hygiene behavior, improved water and sanitation, location fixed effects

Coliform pollution is measured using the standard membrane method with mobile field laboratories which ensures that the incubation process is immediately started after taking the water sample. To address measurement error, micro-biological test protocols require repeating water tests at least three times. Here, samples were tested five times for additional certainty. Coliform pollution is a binary variable of value 1 when a water sample is polluted and zero otherwise. Two types of coding are used. The high threshold indicates pollution when all five samples test positive for coliform. While this reduces type 1 error (i.e. falsely classifying clean water samples as polluted), it comes with a higher type 2 error (i.e. falsely classifying polluted water as clean). Therefore in practice, a lower threshold is used that requires four out of five positive test results.

Water Pipes and Neighborhoods

Lastly, some geographical information is used for analysis. Besides the location of each household within the city this includes the location of water pipes and the location of urban neighborhoods. Using original planning documents and satellite images it is fairly straightforward to identify the location of the underground water pipes. By construction, water pipes are located below the main streets and alleys and can be mapped accordingly. Urban neighborhoods are equally easily to define. Using anthropological methods, one can follow the historic expansion of these ancient cities starting from the traditional city center, the *Medina Kadima* (Arabic: Old City). Over the centuries, new neighborhoods have grown around the Old City, each following waves of prominence and decay. As in ancient cities around the world, this process has shaped the distinct character of each neighborhood and cohesive construction patterns of alleys and houses that can be detected on the detailed maps and satellite images. In case of doubt, the demarcation of neighborhoods was guided by locally used maps of neighborhood names.

To allow for smooth changes of (unobserved) characteristics between neighborhoods, robustness analysis includes an indicator of distance to the nearest adjacent neighborhood.[9]

4. Empirical Strategy

This paper aims to identify the causes of drinking water pollution in a process evaluation that follows the water from the source towards the point-of-use in four steps. To motivate the analysis, it is first shown that access to piped drinking water is causal to *increased* diarrhea incidence among under-five-year old children.[10] This finding begs the question: Why are there any unintended negative health impacts?

The second part uses variation of water pollution inside water storage tanks to quantify to which degree water pipes are causal to micro-biological water contamination. Since all wells supplying water to the pipe system were tested as clean, tank pollution can be interpreted as a direct measure of pollution from the piped system. The aim of the third part is to understand how water handling and hygiene behavior by household members affects intra-household water pollution. It looks at intra-household water pollution, i.e. changes of water contamination between the storage tank and the point-of-use (drinking cup) which is affected by behavior.

Lastly, a note on the unit of analysis. Analysis takes place on child level (N=2330) for the health impact, since illness is idiosyncratic and affects individual household members differently. Individual characteristics such as age and gender are related to health outcomes, which is reflected by the within-household-variance of water related diseases. The causes of water pollution are analyzed on household level (N=498), since each household only has one piped connection.

4.1 Methods

The impact of access to piped water on health outcomes is analyzed using a two-stage instrumental variables approach similar to Klasen *et al.* (2011). For the first stage, consider the following linear probability model:

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[9] Note however, that neighborhoods are rather small with as little as 10 survey observations and do not yield much statistical power. Small neighborhoods are essential for identification to distinguish between neighborhood effects and pipe effects.

[10] In principle adult health might also be affected by water pollution. Adults are exposed to numerous unobserved possible channels of infection during the day, including food, water and Qat consumed outside the home, which prevents a clear causal assignment of diarrhea to piped water. In contrast, children below school age are largely fed at home and only have limited exposure to water and food outside their home and are too young to chew Qat leaves.

$$D_{ij} = X_{ij}\beta_1 + Z_{ij}\eta_1 + N_j\mu_1 + \upsilon_{ij} \quad (1)$$

where treatment D_{ij} of each household i is predicted using a vector of household characteristics X_{ij}, the two instrumental variables Z_{ij} (i.e. distance to center and rocky ground), a vector of socio-demographic characteristics N_j that is constant within each neighborhood j and a nonsystematic error υ_{ij} that varies over households such that $E[\upsilon_{ij} \,|X_{ij}, Z_{ij}, N_{ij}] = 0$. The first stage coefficients are β_1, η_1 and μ_1. The second stage employs the predicted treatment status $\widehat{D}_{ij}$ from equation 1 to estimate the treatment effect on outcome Y_{ij}, such that

$$Y_{ij} = X_{ij}\beta_2 + \widehat{D}_{ij}\theta + N_j\mu_2 + \varepsilon_{ij} \quad (2)$$

where X_{ij} and N_j are the same covariates as used in stage 1. Simultaneous estimation methods are used which allows the estimation of both stages in a single procedure using the more efficient maximum likelihood. Note that the standard linear IV estimator is not identified when both treatment and outcome are binary indicators. In fact, even when the error distribution is known, the nonlinearity arising from the error distribution is insufficient to identify the impact of piped water on child diarrhea. Nevertheless, Imbens and Angrist (1994) show that the identification of Local Average Treatment Effects (LATE) is possible with linear IV methods. LATE results can be interpreted as the causal effect for the subpopulation of treatment and control households that complies with the instrument.

Instrumental Variable Probit Estimators

Alternatively to standard linear IV methods, Greene (2000) and Wilde (2000) show that ATE effects can be obtained by a bivariate probit model (BP). Developed for binary outcome variables, BP is a simultaneous equation probit model of the first and second stage, and uses maximum likelihood estimation. Error terms of the first and second stage are assumed to be jointly distributed as standard bivariate normal and to be independent of the instrument. BP models have been widely employed to estimate treatment effects in a variety of applications, ranging from health and labor economics to medicine and political science.[11] Nevertheless, until recently BP models have been seen with some skepticism because of the central role played by the functional form when it

[11] For example, Do and Wong (2012) use an instrumental variables BP model to estimate the impact of health awareness on vaccine demand. Christin and Hug (2012) examine how the geographic distribution of ethnic groups determines outbreaks of civil conflict. Afxentiou and Hawley (1997) estimate the impact of early sexual behavior on teenage pregnancies. Wissoker and Kenney (1994) analyze discrimination of Hispanic job-seekers. Connelly (1992) estimates the effect of child care costs on the labor force participation of married women. Montmarquette, Mahseredjian and Houle (2001) study the determinants of university dropouts.

comes to identification. Addressing these concerns, Chiburis, Das and Lokshin (2011) use Monte Carlo simulations to test the asymptotic and finite sample properties of the instrumental variables BP model. The authors show that the BP estimator outperforms linear IV analysis for binary outcomes and small sample sizes (as is the case here). Most importantly, the simulations show that in practice moderate deviations from the assumed error term structure do not affect the precision of the estimated treatment effects.

Halfway between the IV and BP methods is the combination of a binary probit model for the first stage and a linear model for the second stage, henceforth BL for 'binary linear model'.[12] Angrist and Pischke (2009) show that a linear IV model with a binary first stage does not yield different results from the standard fully linear IV model, despite the somewhat more appealing first stage for binary treatment. However, improved result can be expected when additional control variables are used as included instruments, as long as the probit model of the first stage is correctly specified and the functional form assumptions of the Probit hold. Both the BP and BL models come with a convenient test for the endogeneity of treatment. When the correlation between the error terms of the first and second stage equations ρ is positive (negative), the estimated treatment effect from the single-equation model with a binary treatment indicator will be biased away from zero (towards zero). If $\rho = 0$ and the functional form is valid, there is no selection bias and the single-equation estimates are consistent, i.e. the Probit model can be used instead of BP and the OLS model can be used instead of BL.

5. Results

5.1 Impact of Piped Water on Child Health

Identification: Treatment, Assignment and Instruments

The classic evaluation problem with observational data relates to unobserved self-selection decisions of individuals entering and leaving the treatment group. This is different here. As in most infrastructure projects, households do not have a choice about participation. Nevertheless, connection rates in the project towns are not universal (with the exception of a 100% connection rate of piped water in the coastal town of Zabid). Project engineers made a choice about which streets to connect based on topographic conditions and population density. Using project planning documents it is possible to

[12] See Brown and Mergoupis (2010) for a thorough discussion on assumptions and interpretations of the binary-linear instrumental variable estimator.

construct exogenous instruments that determine project participation. As part of preparing the research design, I identified several instruments which I also included in the questionnaire and which are discussed in more detail in Klasen *et al.* (2011).

The first instrument is *distance from city center*. Engineering work always started in the historic city center and expanded from there. The distance of a house to the city center could thus be a relevant and exogenous instrument, given that families did not move into the treatment area because of the access to piped water and sanitation (which would be equivalent to self-selecting into the treatment group). Descriptive statistics show that only a handful of families have moved into the connected areas of the project towns since construction begun.[13] We can also exclude the possibility that particularly poor or uneducated families live in the center, which could directly predict health outcomes and would prohibit the use of the instrument (Klasen *et al.* 2011).

The second instrument is *rocky ground*. Since the project came with a labor component, much of the digging of trenches for the pipes was done by local manpower with little help of heavy machinery. Buildings at non-vital parts of the network that were built on hard rock were therefore not connected, since project managers decided that it would be too costly and take up too much time. Rocky ground can be considered exogenous, since it does not affect health outcomes.[14]

Results: Impact of Piped Water on Child Health

The impact of access to piped water on diarrhea in under-five-year old children is presented in Table 2. As in all subsequent result tables, columns 1 and 2 report the single stage endogenous treatment effects with selection bias for the linear probability model (OLS) and the binary probability model (Probit). Columns 3-5 show the results of the instrumental variable approach for the standard linear IV model (IV), the binary-linear IV model (BL), and the bivariate probit model (BP). Note that in all five specifications, access to pied water is causing a significant increase of diarrhea among young children. In the preferred BP framework, the impact of access to piped water on child diarrhea is large and statistically significant at the 1% level, with a marginal effect of 0.0349; that is, the probability of child diarrhea is 3.49 percentage points higher in households with piped water (regression 5 of table 2). Using sample predictions it is

[13] This is little surprising given the lack of space in the (mostly ancient) city centers for building new houses and a virtual absence of rental markets for apartments in these provincial towns. Families moving into town rather settled in the city outskirts, i.e. control areas, where land is available for constructing a new building. Removing the very few recently moved households from the sample does not change the results.

[14] The third available instrument *age of house* (see Klasen *et al.* 2011) which proxies the Old City which was always connected, is not used here because it did not turn out to be a significant predictor of treatment at child level, when distance to city center is already controlled for.

possible to derive the Average Treatment Effect, which suggests that piped water causes an increase of the risk of diarrhea in under five-year old children by 4.6%. The Local Average Treatment Effect (LATE) is even higher at 12.4% (regression 3 of table 2, reported as ATE of the IV estimates). These results cast serious doubt on the assumed health impact of piped water supply.

Regarding the control variables, mothers of ill children tend to be younger, although there is no association in the preferred BP model. Surprisingly, reported hand washing with soap by the mother has no impact on child diarrhea. Child age is significant and negative, implying a reduction of diarrhea incidence as newborns grow older.[15] Concerning gender, girls and boys are equally affected by diarrhea. The household dependency ratio does not correlate with child diarrhea in this model, although it would seem plausible that children in larger families are exposed to increased health risks from the larger number of hand-to-water pathways of pathogen transmissions. Per capita income (in logs) is negatively associated with child diarrhea.[16] The negative income effect is in line with the existing literature which shows that wealthier households are typically less affected by water pollution (see e.g. Jalan and Ravallion, 1993).[17] Children growing up in rented apartments seem to suffer more from diarrhea.[18] This relates to a common problem in developing countries where landlords under-invest in the maintenance of water and electricity installations. In addition, the neighborhood effects are jointly significant, as is the indicator for the mountain region.[19]

[15] Nonlinearities were considered by taking the square and splitting the sample. Child age square has no significant effect. Reducing the sample to under-two-year old children affects statistical power and nearly all significant effects disappear.

[16] Income is negative and significant for regressions 1, 3 and 4 at 10% level of statistical significance, regression 2 at 10% level; in the preferred BP model the coefficient is significant at 10% level, however the reported average marginal effect is only weakly significant with p=0.151.

[17] The negative income coefficient also implies that over-reporting of illness by the rich is not (overly) present in the data, because it would imply a positive income coefficient.

[18] The negative effect of rented housing is significant at 10% level in regressions 1-4. In the BP model shown in regression 5, the estimated coefficient is also significant at 10% level, yet the reported average marginal effect is only weakly significant p=0.152.

[19] Relevant variables include the neighborhood means of household size, the housing quality (a PCA index from the quality of the floor, walls, and ceiling of the apartment or house) and the education of mothers (reading and writing skills).

Table 2. Health effect of piped water: diarrhea in under five-year-old children

Watery Diarrhea Children <5yrs	(1) OLS	(2) Probit	(3) IV	(4) BL	(5) BP	(6) BP	(7) BP
Piped Water	0.0390**	0.0366**	0.1236***	0.0815***	0.0349***	0.0318**	0.0291
	(0.019)	(0.017)	(0.037)	(0.028)	(0.012)	(0.013)	(0.030)
Health Knowledge						0.0013	
						(0.009)	
Water Rationing							0.0960***
							(0.023)
Mother Age	-0.0020*	-0.0020*	-0.0023**	-0.0021**	-0.0005	-0.0006	-0.0015
	(0.001)	(0.001)	(0.001)	(0.001)	(0.000)	(0.000)	(0.002)
Mother Soap Use	0.0031	0.0023	-0.0034	-0.0002	0.0060	0.0053	-0.0023
	(0.017)	(0.016)	(0.016)	(0.017)	(0.007)	(0.007)	(0.019)
Child Age	-0.0189***	-0.0194***	-0.0180***	-0.0185***	-0.0087***	-0.0083***	-0.0066
	(0.005)	(0.006)	(0.006)	(0.005)	(0.002)	(0.002)	(0.006)
Child Female	0.0069	0.0056	0.0056	0.0063	0.0040	0.0018	-0.0156
	(0.016)	(0.016)	(0.016)	(0.016)	(0.006)	(0.006)	(0.018)
Dependency Ratio	-0.0390	-0.0388	-0.0217	-0.0303	-0.0286	-0.0211	-0.0139
	(0.053)	(0.053)	(0.053)	(0.053)	(0.022)	(0.022)	(0.054)
Income per capita	-0.0094**	-0.0099*	-0.0099**	-0.0096**	-0.0032	-0.0034	-0.0024
	(0.005)	(0.005)	(0.005)	(0.005)	(0.002)	(0.002)	(0.007)
House rented	0.0407*	0.0372*	0.0418*	0.0413*	0.0116	0.0108	0.0124
	(0.023)	(0.020)	(0.024)	(0.024)	(0.008)	(0.008)	(0.021)
Household Size	-0.0088	-0.0100	-0.0048	-0.0068	-0.0117***	-0.0123***	-0.0183*
(Neighborhood mean)	(0.009)	(0.009)	(0.009)	(0.009)	(0.004)	(0.004)	(0.010)
Housing Index	0.0732	0.0780	0.1081	0.0908	-0.0225	-0.0082	0.0331
(Neighborhood Mean)	(0.129)	(0.130)	(0.129)	(0.128)	(0.053)	(0.052)	(0.150)
Mother Education	-0.0101	-0.0046	-0.1391*	-0.0750	0.0878***	0.0876***	0.0036
(Neighborhood Mean)	(0.054)	(0.053)	(0.072)	(0.065)	(0.023)	(0.024)	(0.061)
Mountain Region	0.0343	0.0343	0.0167	0.0254	0.0621***	0.0614***	0.0296
	(0.022)	(0.024)	(0.024)	(0.023)	(0.010)	(0.010)	(0.027)
Observations	2,276	2,276	2,276	2,276	2,276	2,254	459
Model F-Test	3.274		3.865				
Model Chi2		39.032		44.163	1997.597	1510.817	8373.678
Model p-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Probit rho chi2				4.244	3.796	1.902	0.785
Probit rho p-value				0.120	0.051	0.168	0.375
ATE water	0.039	0.037	0.124	0.029	0.046	0.042	0.039
ATT water	0.039	0.017	0.124	0.014	0.033	0.033	0.037

Robust standard errors in parentheses; Significance *** p<0.01, ** p<0.05, * p<0.1
Probit, BL and BP in average marginal effects

The negative impact of piped water on child health is worrying. Hygiene training might help to reduce water related diseases. Unfortunately, health knowledge on water related diseases has no significant effect on child diarrhea and even has the wrong sign (regression 6 in table 2). Clearly, health knowledge does not automatically translate into improved child health. A reason for that could be that water pollution is not primarily caused by poor hygiene behavior, but rather by broken water pipes in combination with frequent water rationing. In fact, water rationing during the four weeks before the water test is highly significant and associated with an increased risk of child diarrhea by 9.6 percentage points (regression 7 in table 2). While this marginal effect should be taken cautiously, it does suggest that the problem with piped water may be found in the pipes.[20]

Similar to the linear IV model, the identification of the BL and BP two-stage models requires a strong treatment prediction in the first stage. The first stage regressions for the least squares and probit models show a sizable and statistically significant relationship between the instruments and the treatment variable with (Table A.3 in the appendix). The first stage is robust with and without second stage controls. For the BP model, the test of endogeneity is significant at 10% and almost at 5% (p=0.051). For the IV model with two instruments, the over-identification restriction is not violated (Hansen J test is not rejected).

Robustness

The adverse health impact associated with piped water is robust to model specification and age. Even without controls, the positive impact of piped water on child diarrhea is significant at 1% level (results not shown). Importantly, the effect also holds for household members of all ages, albeit with lower magnitude (Table A.4 in the appendix). Other potential determinants of child diarrhea have also been tested but do not appear to affect child health.[21] In addition, the results are also robust to different error structures, including clustering at household and neighborhood level, and also remain significant with and without sampling weights. The preferred specification (i.e. regression 5 in table 2) uses member level weights and heteroskedasticity consistent error terms, which provides conservative confidence intervals and corresponds best to the sampling frame. The results are also robust when restricting the sample to treatment households without access of piped sewerage (results not shown). With regard to existing studies, the unexpected harmful health impact of piped water confirms previous analysis by Klasen *et al.* (2011) who use propensity score matching techniques and linear instrumental variable regressions on household means of child illness, and similarly report an increase of water-related illnesses among children and adults.

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[20] Note that the analysis is only possible for a random subsample of the second interview. However, the results are not driven by the reduced sample size, since the positive effect of piped water on child health remains significant when the specification of table 2 are implemented with the reduced sample. Also note that there is a possible dislink between the regressor and the outcome variable, since diarrhea incidence was elicited during the first interview, while rationing was recorded in the second interview.

[21] Additionally tested covariates include water boiling before drinking, save water storage in the kitchen, and father's age and education. In addition, endogenous access to piped sewerage (i.e. project treatment) did not turn out significant.

5.2 Impact of Water Pipes on Tank Pollution

Empirical Model

The starting point is the instrumental variable approach laid out in the previous section, where access to piped water is the endogenous treatment and the binary outcome variable indicates contamination of the water storage tank.[22] The project was implemented on the premises that truck water is polluted while pipe water is clean. If so, a negative coefficient of the impact of piped water on tank pollution can be expected. Recall that the concern here lies with the possibility of broken pipes and the adverse effects of water rationing. Therefore, an additional approach is needed to explicitly model pipes.

Causal analysis of water pipes on tank pollution is straightforward. Pollution in the tanks is assumed to only enter through the pipes, when tank characteristics such as location and size are controlled for. Since all source wells of the pipe system were tested as clean, any pollution found in the water tanks can be attributed to problems in the pipes.[23] Using city maps, pipe grids and the geographical coordinates of each building, it is possible to link each household to a particular pipe. To illustrate identification of water pipe pollution, consider a city with only two water pipes. The first pipe ($p = 1$) provides perfectly clean drinking water, while the second pipe ($p = 2$) is polluted. Water tanks connected to pipe 1 will have an expected pollution of zero after controlling for tank characteristics. In contrast, pollution in tanks connected to pipe 2 can be expected to have a non-zero mean and will be highly correlated. The model of tank pollution Y_{ijp} for household i connected to piped water can be written as

$$Y_{ijp} = P_p\gamma + T_{ijp}\varphi + N_j\mu + \varepsilon_{ijp} \qquad \text{(3a)}$$

where P_p is a vector of binary pipe indicators for each pipe p, the household specific vector T_{ijp} measures tank characteristics, N_j is a vector of neighborhood characteristics, and ε_{ijp} is the stochastic error term. The model is estimated for the treatment group sample and a Wald test of joint significance of the γ coefficients can be used to test for pipe pollution, with the null hypothesis that none of the pipe coefficients is significantly different from zero.

[22] Note, however, that from an engineering perspective it is not obvious why treatment selection would affect storage tank pollution.
[23] In fact, tests in the coastal town found that one of the two main pies leading into town showed signs of coliform pollution.

Mixing of Piped Water with Truck Water

Most storage tanks are large enough to provide drinking water for one to two weeks without being refilled. However, once the tank is empty (as can happen during extended periods of water rationing), truck water is purchased and pumped into the tank.[24] Such mixing of water sources may be to blame for (some of) the pollution inside the storage tanks. Pollution from truck water can be directly shown by including a covariate for truck water use in the estimation of equation 3a. Additionally, the full sample (including treatment and control groups) can also be used, which also increases efficiency. To econometrically illustrate the effect of water source mixing, consider a town with one clean water pipe ($p = 1$) that connects half of the town. Dependent on tank characteristics, pollution in water tanks connected to the clean pipe will be zero, $E[Y_{ijp} \mid T_{ijp}] = 0$. The remaining part of the town relies on a water truck. Assume for now that truck water is polluted. During water rationing, households connected to pipe 1 start using truck water. Tank pollution along pipe 1 begins to increase. What is important here is that even when all households in the treatment area switch to tank water, tank pollution in the treatment area will still *not exceed* tank pollution in control area, since all households would be using truck water. Empirically, this can be tested by expanding the sample of model 3a to include control households C_i without piped water,

$$Y_{ijp} = C_i\alpha + P_p\gamma + T_{ijp}\varphi + N_j\mu + \varepsilon_{ijp} \qquad (3b)$$

where α captures pollution from truck water.[25] When mixing of water sources drives tank pollution in the treatment group, conditional tank pollution in the treatment area does not exceed conditional tank pollution in the control area. The null hypothesis, $E[\gamma_p \leq 0]$, can be rejected when additional pollution from the water pipes γ_p is positive and jointly significant,

Results: Impact of Water Pipes on Tank Pollution

To better understand what causes contamination of piped water, the focus is now shifted to coliform pollution in the water storage tanks which are the end point of the water pipes. Any pollution found in water storage tanks can be directly attributed to the pipe system for those with piped water access. Recall that water storage tanks were not part of the intervention and are used by treatment and control groups alike.

[24] Water is pumped into the tanks through a valve on the ingoing pipe. Tanks are not opened.

[25] Note that truck water might be considered clean if the alpha coefficient is insignificant. The model is estimated without constant since the reference pollution (and thus the intercept) is zero per definition.

Descriptive analysis shows that tank pollution in the treatment area is alarmingly high. In the mountains 68.2% of all storage tanks connected to the water pipe system show signs of contamination with total coliform. In the coastal area, 88.2% of the tanks are affected (see Table A.5 in the appendix).[26] Such widespread pollution is surprising, especially since piped water is treated with chlorine by the water utility. The amount of added chlorine is calibrated to eliminate any water pollution detected shortly after the well. Tank contamination is therefore a clear sign of broken pipes, which allow the intrusion of waste water and pollutants. Periods of water rationing can have similar effects.

To rule out that tank pollution is merely the result of endogenous project treatment, the instrumental variable analysis is implemented for tank pollution. Table 3 shows the impact of access to piped water on total coliform levels inside the storage tanks. The first stage is equivalent to that reported in the previous section. Overall, there is no significant impact of piped water on tank pollution. This is surprising, because one would expect that piped water is cleaner than traditional truck water, i.e. the coefficient should be negative and significant. Here, however, positive coefficients are found in all specifications. Since both the endogenous treatment and the outcome variable are binary indicators, the preferred estimates are from the bivariate IV regressions with the full set of controls (regression 8 of table 3). The main controls are introduced in regressions 5, 6 and 7. The table also includes the least squares and probit model with endogenous treatment (regressions 1 and 2) and the instrumental variable results for the linear IV model and the bivariate linear BL model (regressions 3 and 4). Importantly, none of the specifications show any indication of water quality improvement from being connected to piped water.

The preferred marginal effects reported in column 8 show that households with roof tanks are about 15.4% less likely to suffer from polluted drinking water at tank level. Apparently, ground tanks are prone to pollution, which might suggest that they are not always properly closed. Tank size does not seem to affect water quality. Recent water rationing seems to deteriorate water quality in the storage tanks. Rationing during the 4 weeks prior to the water quality test is associated with an increase in the average probability of having polluted tank water by 88.8% (at covariate means). While the average marginal effect appears large in magnitude, it confirms the result from the

[26] These shares are calculated using the more cautionary lower pollution threshold. When using the higher threshold approximately 47.1% (mountains) and 70.1% (coastal region) of all storage tanks are polluted (see table D.6 in the appendix).

previous section where it was shown that children living in households affected by water rationing are more prone to suffer from diarrhea.

Table 3. Water pipe pollution: Total Coliform, low threshold

Total Coliform Low Pollution Threshold	(1) OLS	(2) Probit	(3) IV	(4) BL	(5) BP	(6) BP	(7) BP	(8) BP
Piped Water	0.0228	0.0202	0.2009	0.0586	0.0111	0.0118	0.0198	0.0328
	(0.050)	(0.046)	(0.131)	(0.137)	(0.030)	(0.030)	(0.041)	(0.052)
Roof Tank	-0.0948	-0.0953	-0.0760	-0.0910		-0.1910***	-0.1947***	-0.1544***
	(0.064)	(0.064)	(0.069)	(0.066)		(0.066)	(0.064)	(0.058)
Tank Size (100L)	0.0009	0.0007	0.0011	0.0009		0.0002	-0.0007	-0.0003
	(0.001)	(0.001)	(0.001)	(0.001)		(0.001)	(0.001)	(0.001)
Water Rationing	-0.0505	-0.0336	-0.1427	-0.0690			1.4169***	0.8881***
	(0.075)	(0.053)	(0.100)	(0.102)			(0.108)	(0.079)
Household Size	0.0327*	0.0360*	0.0417**	0.0345*				-0.0154
(Neighborhood mean)	(0.019)	(0.022)	(0.020)	(0.020)				(0.024)
Housing Index	0.3903	0.4585	0.4750	0.4073				-0.3143
(Neighborhood Mean)	(0.308)	(0.335)	(0.313)	(0.314)				(0.316)
Mother Education	-0.1756	-0.2342*	-0.3889**	-0.2185				0.4547***
(Neighborhood Mean)	(0.128)	(0.126)	(0.190)	(0.205)				(0.142)
Income per capita	-0.0662	-0.0736	-0.1032*	-0.0736				0.0955**
(Neighborhood Mean)	(0.050)	(0.052)	(0.055)	(0.053)				(0.044)
Mountain Region	-0.2561***	-0.2597***	-0.3134***	-0.2676***	0.2654***	0.4058***	0.3609***	0.2818***
	(0.074)	(0.073)	(0.086)	(0.084)	(0.036)	(0.067)	(0.071)	(0.069)
Observations	446	446	446	446	481	464	446	446
Model F-Test	5.680		6.376					
Model Chi2		39.38		53.23	4158.8	1297.4	2393.0	5288.3
Model p-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Probit rho chi2				0.098	2.546	2.715	2.201	0.283
Probit rho p-value				0.952	0.111	0.099	0.138	0.595
ATE water	0.023	0.020	0.201	0.040	0.020	0.022	0.036	0.061
ATT water	0.023	0.024	0.201	0.033	0.021	0.025	0.041	0.070

Robust standard errors in parentheses; Significance *** p<0.01, ** p<0.05, * p<0.1
Probit, BL and BP in average marginal effects

The same results are found when using the less cautionary higher threshold of total coliform pollution, albeit with slightly reduced coefficients (see Table A.7 in the appendix). Similar results are also obtained when splitting the sample by region, although the effects of water rationing only hold in the mountains, since rationing was only very rarely reported in the coastal town.

Although water rationing is able to explain an important part of overall tank pollution in the treatment group, broken pipes may be an additional cause. As sketched out in the previous section, pipe pollution can be shown by using a model of water tank pollution with pipe fixed effects. Tank pollution will be more frequent among households connected to a broken pipe. Table A.8 (in the appendix) shows the effect of water pipes while controlling for water rationing and tank and neighborhood characteristics. Water pipes are jointly significant determinants of tank pollution in all specifications. As a starting point, regression 1 does not include pipe fixed effects but only tank characteristics. Roof tanks appear less polluted than ground tanks. However, once pipe fixed effects are introduced (regressions 2-6) the effect vanishes. The model is consecutively expanded by introducing neighborhood characteristics (regression 3-6), a binary indicator for water rationing (regression 4), a binary indicator of truck water purchase (regression 5), and the full model which also includes the interaction effect of water rationing and truck water use (regression 6). Aside from some neighborhood characteristics, none of these covariates is statistically significant. The absent effect of water rationing is in line with econometric theory, since water rationing affects entire pipes. Any pollution from rationing is captured by the pipe fixed effects. The insignificant result of truck water use suggests that truck water is not significantly more polluted than piped water (but also not less). In other words, piped water does not improve water quality at the point-of- entrance at household level.[27]

Table A.8 (in the appendix) also includes specifications to explicitly test for the role of truck water that compares treatment and control areas. In regressions 7-9 the sample is expanded and included control towns. The pipe fixed effects only cover the treatment areas (where pipes exist). Hence, the in the expanded sample, the constant measures the average tank pollution in the control group, i.e. truck water. The pipe fixed effects are jointly significant and all are positive, suggesting that conditional pollution of piped water is larger than could be explained through polluted truck water alone. This finding confirms the hypothesis that broken pipes and water rationing are to blame for (some of) the tank pollution among connected households.

Robustness

The analysis is repeated for the higher pollution threshold (Table A.9 in the appendix). The results for regressions 1-9 are virtually identical. Most importantly, in models 7-9 all pipe fixed effects have positive coefficients and are jointly significant, which suggests that tank pollution in the treatment group is not the result of water mixing but rather related to a combination water rationing and broken pipes.

[27] In principle, this could capture neighborhood effects. Therefore a number of neighborhood characteristics was tested (including average education, income, wealth, household size, tank size and location in the neighborhood) which did not yield any significant results and should address such concerns.

5.3 Impact of Household Behavior on Water Pollution

Empirical Model

This section looks at intra-household water pollution. The starting point is the water in the storage tanks, which by construction is unaffected by household behavior. Before reaching the point-of-use (drinking cup), water is exposed to possible contamination from unhygienic water handling. Intra-household water pollution ΔY_{ij} for treatment and control groups can be written as

$$\Delta Y_{ij} = \alpha + B_i\pi + X_{ij}\beta + N_j\mu + \varepsilon_{ij} \qquad (4)$$

where B_i is a binary measure of coliform pollution inside the water tank of household i, X_{ij} is a vector of household behavior that increases the risk of spreading of pathogens, N_j is a vector of neighborhood characteristics, and ε_{ij} is a random household specific error term.[28] When tank pollution B_i is not random and project treatment includes hygiene training, results may suffer from another bias. Consider the case when tank pollution is dependent on access to piped water, $E[B_i|D_i]$, and tank pollution is higher in the treatment group. Further assume that household behavior X_{ij} is dependent on access to piped water, $E\left[X_{ij}|D_i\right]$, for instance because of hygiene training for hand washing during the intervention. Under such conditions the coefficient of hand washing β would be biased because households with polluted water wash their hands more often. In fact, results of a naïve linear estimation might even absurdly suggest that behavior such as hand washing *increases* intra-household water pollution. Instrumenting hand washing with an exogenous variable that is independent of treatment could solve this problem, which is discussed below. Ideally for the estimation, however, household behavior should be independent from project participation.[29]

Results

Any pollution between the storage tank and the point-of-use (drinking cup) can be assigned to behavioral aspects, which is shown in table 5.[30] Of principal focus are kitchen water storage containers, because they provide the most obvious source of intra-household water pollution. Recall that kitchen water storage containers are manually refilled every morning to keep drinking water cold throughout the day. All household

[28] Note that in this model we are not interested in treatment effects of piped water. Hence, the model does not include an indicator for piped water and pipe related pollution is captured by π.
[29] Although project reports contains some descriptions of hygiene training, less than 1% of the interviewed households reported ever participating in a training. The influence of project participation on hygiene behavior X_{ij} can be modeled $X_{ij} = D_{ij}\theta + N_j\mu + \varepsilon_{ij}$, with the Null asserting that $\theta = 0$.
[30] Note that pro-hygienic behavior such as water boiling can also lead to an improvement of water quality.

members take water from these containers. In fact, improved kitchen water storage containers can significantly reduce the risk of intra-household water pollution by about 6% (regression 1 of table 5).[31]

Table 5: Intra-household water pollution: changes in total coliform, low threshold

Total Coliform Low Pollution Threshold	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS	(6) OLS	(7) OLS
Improved water storage	-0.0610**				-0.0583*	-0.0582*	-0.0683**
	(0.031)				(0.031)	(0.031)	(0.031)
Water boiling		-0.1156			-0.1050	-0.1049	-0.1261
		(0.112)			(0.109)	(0.109)	(0.117)
Soap use			0.0084			0.0069	0.0091
			(0.042)			(0.041)	(0.045)
Health Knowledge				0.0114			-0.0010
				(0.038)			(0.041)
Dependency Ratio	0.0292	0.0265	0.0260	0.0212	0.0304	0.0313	0.0286
	(0.062)	(0.062)	(0.062)	(0.063)	(0.062)	(0.062)	(0.063)
Income per capita	0.0023	0.0031	0.0022	0.0014	0.0031	0.0031	0.0025
	(0.011)	(0.011)	(0.011)	(0.011)	(0.011)	(0.011)	(0.011)
House rented	-0.0099	-0.0151	-0.0141	0.0066	-0.0109	-0.0108	0.0113
	(0.044)	(0.044)	(0.044)	(0.043)	(0.044)	(0.044)	(0.042)
Household Size	0.0041	0.0050	0.0055	0.0015	0.0038	0.0039	-0.0006
(Neighborhood mean)	(0.013)	(0.013)	(0.013)	(0.013)	(0.013)	(0.013)	(0.013)
Housing Index	-0.0249	-0.0498	-0.0358	-0.0526	-0.0364	-0.0349	-0.0468
(Neighborhood Mean)	(0.236)	(0.235)	(0.238)	(0.235)	(0.236)	(0.240)	(0.240)
Mother Education	0.1977**	0.2259**	0.2147**	0.1905**	0.2082**	0.2077**	0.1840*
(Neighborhood Mean)	(0.096)	(0.095)	(0.097)	(0.097)	(0.095)	(0.096)	(0.096)
Mountain Region	-0.0674	-0.0379	-0.0442	-0.0356	-0.0610	-0.0613	-0.0552
	(0.058)	(0.055)	(0.056)	(0.057)	(0.057)	(0.057)	(0.058)
Control town mountains	0.1335***	0.1247***	0.1302***	0.1160***	0.1294***	0.1303***	0.1185***
	(0.042)	(0.042)	(0.043)	(0.042)	(0.042)	(0.044)	(0.044)
Control town coast	0.0441	0.0522	0.0513	0.0465	0.0456	0.0458	0.0418
	(0.043)	(0.043)	(0.042)	(0.043)	(0.043)	(0.043)	(0.043)
Tank Pollution	-0.866***	-0.868***	-0.868***	-0.880***	-0.865***	-0.864***	-0.875***
	(0.046)	(0.046)	(0.046)	(0.047)	(0.046)	(0.046)	(0.047)
Constant	0.708***	0.641***	0.634***	0.692***	0.704***	0.696***	0.760***
	(0.140)	(0.137)	(0.137)	(0.138)	(0.140)	(0.140)	(0.141)
Observations	480	480	480	472	480	480	472
adj R2	0.550	0.549	0.547	0.556	0.550	0.550	0.560
Model F-Test	40.883	41.336	40.762	44.086	37.872	34.857	35.208
Model p-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Robust standard errors in parentheses
Significance *** p<0.01, ** p<0.05, * p<0.1

[31] Improved containers are covered with a lid and provide water through a tap. This modern design decreases the direct exposure of drinking water to hands. In comparison, traditional clay containers are open and household members typically need to dive the drinking cup into the water to fill the cup, allowing a direct transmission from hands to water. Qualitative interviews revealed that households prefer the improved containers because they are additionally insulated and keep the water cold longer, which might be a useful argument for future interventions.

When testing the role of actual hygiene behavior on water quality in linear single stage regression framework, no other effects become visible. Water boiling does not seem to improve water quality (regression 2 in table 5).[32] Also, hand washing with soap does not have the expected effect (regression 3 in table 5). Nevertheless, the importance of hand washing can be indirectly shown using qualitative measurement of observable cleanliness of the drinking cup used by the family. Without hand washing, drinking cups will be dirty. Dirty drinking cups are associated with increased intra-household water pollution by approximately 10% (Table A.10 in the appendix). More generally, health knowledge, which is a commonly used as proxy for water related behavior, has no significant effect on intra-household coliform pollution.[33] This confirms the earlier results but stands in contrast to previous studies from piped water in rural areas (Jalan and Ravallion 2003).[34] Most of these results are also confirmed for the high pollution threshold (Table A.11 in the appendix). Overall, the results suggest that intra-household water pollution can be significantly reduced when direct contact between hands and water is interrupted. Since defecation can be a major source of hand contamination, the following sub-section looks at the role of sewage and sanitation.

6. Conclusion

Despite millions spent on piped water supply in developing countries, water at point-of-use is often polluted and causes increased levels of diarrhea and child mortality. Surprisingly little research has so far been devoted to identifying the causes of pollution in these improved piped schemes. This paper uses unique data from a large household survey and from micro-biological water quality tests and applies these to causal quasi-experimental methods to establish the sources of water pollution along the water flow. Situated in urban Yemen, the intervention consists of a treatment group for piped water, and a subgroup that was also connected to piped sewerage. In addition, the research design includes control groups in the project towns as well as nearby control towns without any treatment. This setup allows the use of instrumental variables which reflect the decision making of the engineering firm during project construction. By doing so, the paper is able to contribute to the existing water and sanitation literature in four important ways.

[32] Controlling for the use of water filters does not change the results. Both absent effects could be related to statistical power because boiling and filter use is limited.
[33] Binary variable, takes the value 1 if at least 4 out of 5 health knowledge questions are correctly answered. The test asks about symptoms of 5 water borne diseases. Measurement error is expected to be random.
[34] The results don’t change when the formal education level, years of schooling or reading and writing abilities are used instead of knowledge.

First, using instrumental variable analysis it is shown that piped water has detrimental effects on child health by increasing diarrhea among under-five-year old children. Illness is more common in families that experience water rationing. Second, the central role of water rationing and broken pipes is shown by analyzing water tank pollution. Tank pollution is a proxy for the water quality inside the main city pipes. Modern piped water is found to be no improvement over truck water. In addition, tank characteristics such as location or size are not related to pollution levels in the storage tanks. Differencing between treatment and control groups also allows the rejection of alternative hypotheses of tank pollution (such as mixing with truck water). Overall, water in many pipes is found to be of poor quality.

Third, the analysis then shifts to behavior related pollution that occurs within households. Intra-household water pollution can be attributed to household behavior by exploiting variation in the differences of water pollution that occurs between the storage tanks and the point-of-use (drinking cup). Water pollution within households is only partly driven by observable household behavior such as hand washing or, more broadly, parental education, a common proxy for behavior. Quality improving behavior such as water boiling or filtering does not have any effect, possibly due to low statistical power arising from too few households actively attempt to purify drinking water before consumption.

In the econometric domain, the paper uses a combination of different instrumental variable approaches to better correspond to the scale of treatment and outcome variables. Robustness analysis shows that correct model specification is important to remove any bias obtained from standard linear IV methods when applied to bivariate data. Future research should test the external validity of these findings. Especially the role of conditional impact of piped sewerage in situations with frequent water rationing remains unclear.

Several policy recommendations can be derived follow from this study. First, the widely assumed health effects of piped water need to be reconsidered, especially in countries with severe water stress that often inhibits a reliable operation of piped systems. Second, water engineers and project designers should consider and test alternative solutions in providing drinking water to communities with limited ground water. For example, one could engage with vendors of truck water, which are common in most urban centers throughout the developing world. Third, it needs to be recognized that water purification at household level is a possible solution to clean drinking water at the point-of-consumption. In fact, more studies are needed to finally show how household-level water purification activities can be made sustainable.

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Appendix

Table A.1: Covariate means for under-5-year old Children, by Access to Piped Water

Water	Treatment	Control	Difference
Diarrhea (low threshold)	0.127	0.082	0.045***
			(0.013)
Mother Age	28.023	28.126	-0.103
			(0.285)
Mother Soap Use	0.679	0.518	0.160***
			(0.020)
Child Age	2.081	2.185	-0.104*
			(0.058)
Child Female	0.493	0.489	0.004
			(0.021)
Dependency Ratio	0.521	0.553	-0.033***
			(0.007)
Income per capita	2.086	1.768	0.318***
			(0.063)
House rented	0.173	0.208	-0.035**
			(0.016)
Household Size	7.445	8.122	-0.677***
(Neighborhood mean)			(0.046)
Housing Index	0.297	0.324	-0.027***
(Neighborhood Mean)			(0.004)
Mother Education	0.515	0.322	0.193***
(Neighborhood Mean)			(0.006)
Mountain Region	0.469	0.667	-0.198***
			(0.020)
Observations	1,080	1,250	2,330

Table A.2: Tank Pollution, Total Coliform

Water	Treatment	Control	Difference
Low Threshold			
Mountains	0.682	0.722	-0.039
			(0.059)
Coast	0.882	0.932	-0.050
			(0.038)
High Threshold			
Mountains	0.471	0.525	-0.053
			(0.065)
Coast	0.701	0.852	-0.151**
			(0.054)
Observations	282	204	486

Robust standard errors in parentheses

Significance *** p<0.01, ** p<0.05, * p<0.1

Table A.3: Access to Piped Water, First Stage

Piped Water	(1)	(2)	(3)	(4)
	Least Squares		Probit	
Distance to Center (100m)	-0.0360***	-0.0242***	-0.0279***	-0.0142***
	(0.001)	(0.002)	(0.001)	(0.002)
House built on rocky ground	-0.1245***	-0.0839***	-0.1211***	-0.0566**
	(0.033)	(0.028)	(0.037)	(0.027)
Controltown Mountains	-0.8077***	-0.6443***		
	(0.020)	(0.026)		
Observations	2,281	2,276	2,281	2,276
Stage 2 controls	NO	YES	NO	YES
Model F-Test	442.020	226.261		
Model Chi2			317.813	574.739
Model p-value	0.000	0.000	0.000	0.000
Instruments jointly p-value	0.000	0.000	0.000	0.000
IV Hansen overident. p-value	0.769	0.531		

Robust standard errors in parentheses; Sign: *** p<0.01, ** p<0.05, * p<0.1;
Probit in average marginal effects

Table A.4: Impact of Piped Water on Diarrhea in children and adults (all ages)

Watery Diarrhea	(1)	(2)	(3)	(4)	(5)
	OLS	Probit	IV	BL	BP
Piped Water	0.0083*	0.0081*	0.0267***	0.0140**	0.0064*
	(0.005)	(0.005)	(0.009)	(0.007)	(0.003)
Age	-0.0007***	-0.0008***	-0.0007***	-0.0007***	-0.0004***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Female	0.0086**	0.0086**	0.0085**	0.0086**	0.0039**
	(0.004)	(0.004)	(0.004)	(0.004)	(0.002)
Dependency Ratio	0.0198*	0.0202*	0.0222**	0.0205*	0.0068
	(0.011)	(0.012)	(0.011)	(0.011)	(0.006)
Income per capita	0.0017	0.0019	0.0016	0.0017	0.0010
	(0.002)	(0.002)	(0.002)	(0.002)	(0.001)
House rented	0.0145**	0.0116**	0.0146**	0.0145**	0.0038*
	(0.006)	(0.005)	(0.006)	(0.006)	(0.002)
Household Size	-0.0083***	-0.0097***	-0.0076***	-0.0081***	-0.0069***
(Neighborhood mean)	(0.002)	(0.002)	(0.002)	(0.002)	(0.001)
Housing Index	0.0865***	0.0830***	0.0962***	0.0895***	0.0154
(Neighborhood Mean)	(0.030)	(0.029)	(0.031)	(0.030)	(0.013)
Mother Education	0.0030	0.0039	-0.0245	-0.0055	0.0332***
(Neighborhood Mean)	(0.014)	(0.014)	(0.019)	(0.016)	(0.007)
Mountain Region	0.0056	0.0085	0.0019	0.0045	0.0212***
	(0.005)	(0.005)	(0.006)	(0.005)	(0.003)
Observations	17,961	17,961	17,961	17,961	17,961
Model F-Test	10.509		10.937		
Model Chi2		87.282		103.979	36735.087
Model p-value	0.000	0.000	0.000	0.000	0.000
Probit rho chi2				1.541	1.144
Probit rho p-value				0.463	0.285
ATE water	0.008	0.008	0.027	0.001	0.014
ATT water	0.008	0.008	0.027	0.004	0.013

Robust standard errors in parentheses; Sign. *** p<0.01, ** p<0.05, * p<0.1
Probit, BL and BP in average marginal effects

Table A.5: Water Pollution in Storage Tanks: Total Coliform, low threshold

Water	Treatment	Control	Difference
Mountains	0.682	0.722	-0.039
			(0.059)
Coast	0.882	0.932	-0.050
			(0.038)
Observations	282	204	486

*** p<0.01, ** p<0.05, * p<0.1

Standard errors in parentheses

Table A.6: Water Pollution in Storage Tanks: Total Coliform, high threshold

Water	Treatment	Control	Difference
Mountains	0.471	0.525	-0.053
			(0.065)
Coast	0.701	0.852	-0.151**
			(0.054)
Observations	282	204	486

*** p<0.01, ** p<0.05, * p<0.1

Standard errors in parentheses

Table A.7: Water Tank Pollution: Total Coliform, high threshold

Total Coliform High Pollution Threshold	(1) OLS	(2) Probit	(3) IV	(4) BL	(5) BP	(6) BP	(7) BP	(8) BP
Piped Water	-0.0829	-0.0824	0.2291	0.0487	0.0116	0.0124	0.0205	0.0233
	(0.061)	(0.057)	(0.147)	(0.120)	(0.036)	(0.036)	(0.045)	(0.059)
Roof Tank	-0.0810	-0.0759	-0.0482	-0.0672		-0.1445**	-0.1495***	-0.1158**
	(0.076)	(0.077)	(0.083)	(0.078)		(0.058)	(0.057)	(0.053)
Tank Size (100L)	0.0015	0.0012	0.0017	0.0016		0.0006	-0.0001	0.0001
	(0.001)	(0.001)	(0.001)	(0.001)		(0.001)	(0.001)	(0.001)
Water Rationing	-0.0252	-0.0143	-0.1867*	-0.0933			1.0663***	0.6936***
	(0.084)	(0.072)	(0.112)	(0.097)			(0.079)	(0.067)
Household Size	-0.0604	-0.0653	-0.1252*	-0.0877				0.0651*
(Neighborhood mean)	(0.061)	(0.061)	(0.069)	(0.064)				(0.039)
Housing Index	-0.0024	-0.0026	0.0133	0.0042				-0.0267
(Neighborhood Mean)	(0.030)	(0.030)	(0.031)	(0.031)				(0.023)
Mother Education	0.4704	0.5188	0.6188	0.5330				-0.1639
(Neighborhood Mean)	(0.377)	(0.397)	(0.402)	(0.381)				(0.279)
Income per capita	-0.0392	-0.0578	-0.4129*	-0.1968				0.3936***
(Neighborhood Mean)	(0.162)	(0.167)	(0.222)	(0.204)				(0.136)
Mountain Region	-0.3198***	-0.3024***	-0.4203***	-0.3622***	0.1668***	0.2549***	0.2236***	0.1751**
	(0.091)	(0.089)	(0.101)	(0.100)	(0.031)	(0.059)	(0.063)	(0.070)
Observations	446	446	446	446	481	464	446	446
Model FTest	6.347		6.524					
Model chi2		46.172		57.234	4166.570	1853.053	3578.627	6277.813
Model pval	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Probit rho chi2				1.842	5.331	5.216	4.283	1.916
Probit rho pval				0.398	0.021	0.022	0.038	0.166
ATE water	-0.083	-0.082	0.229	0.330	0.022	0.024	0.038	0.044
ATT water	-0.083	-0.087	0.229	0.313	0.024	0.026	0.042	0.048

Robust standard errors in parentheses
Significance *** p<0.01, ** p<0.05, * p<0.1
Probit, BL and BP in average marginal effects

Table A.8 Pollution from broken Water Pipes and Water Rationing: Total Coliform, low threshold

Total Coliform	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Low Pollution Threshold	OLS	OLS	OLS	OLS	OLS	OLS	OLS	OLS	OLS
Roof Tank	-0.2091***	-0.1001	-0.0994	-0.1064	-0.0981	-0.1048	-0.1497**	-0.1431**	-0.1498**
	(0.067)	(0.128)	(0.127)	(0.127)	(0.128)	(0.128)	(0.061)	(0.059)	(0.061)
Tank Size (100L)	0.0009	0.0001	0.0004	0.0005	0.0003	0.0004	-0.0004	-0.0007	-0.0005
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Water Rationing				-0.0609		-0.0568	-0.0762		-0.1147
				(0.091)		(0.124)	(0.090)		(0.108)
Truck Water					0.0541	0.0520		0.0139	0.0049
					(0.070)	(0.090)		(0.040)	(0.043)
Truck Water * Water Rationing						0.0095			0.0974
						(0.165)			(0.138)
Household Size (Neighborhood mean)			0.0771*	0.0754*	0.0735*	0.0719*	0.0184	0.0197	0.0172
			(0.040)	(0.040)	(0.041)	(0.042)	(0.020)	(0.020)	(0.020)
Housing Index (Neighborhood Mean)			-0.3078	-0.2291	-0.2901	-0.2076	0.0795	0.0451	0.0877
			(0.603)	(0.597)	(0.602)	(0.599)	(0.325)	(0.326)	(0.329)
Mother Education (Neighborhood Mean)			0.1272	0.0670	0.1171	0.0537	-0.2622*	-0.2407	-0.2692*
			(0.215)	(0.224)	(0.214)	(0.227)	(0.152)	(0.148)	(0.152)
Income per capita (Neighborhood Mean)			0.0099	0.0226	0.0121	0.0252	-0.0094	-0.0126	-0.0082
			(0.087)	(0.089)	(0.087)	(0.088)	(0.051)	(0.051)	(0.052)
Constant	YES	NO	NO	NO	NO	NO	YES	YES	YES
Regional Effects	NO	NO	NO	NO	NO	NO	NO	NO	NO
Pipe FE	NO	YES	YES	YES	YES	YES	YES	YES	YES
Pipe FE p-value		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
adj R2	0.042	0.805	0.803	0.803	0.803	0.802	0.067	0.060	0.064
Observations	269	269	269	263	269	263	446	464	446

Robust standard errors in parentheses
Significance *** p<0.01, ** p<0.05, * p<0.1

Table A.9: Pollution from broken Water Pipes and Water Rationing: Total Coliform, high threshold

Total Coliform High Pollution Threshold	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS	(6) OLS	(7) OLS	(8) OLS	(9) OLS
Roof Tank	-0.2790***	-0.1776	-0.1776	-0.1917	-0.1755	-0.1912	-0.1929***	-0.1777**	-0.1928***
	(0.079)	(0.128)	(0.129)	(0.127)	(0.130)	(0.128)	(0.072)	(0.071)	(0.072)
Tank Size (100L)	0.0016	0.0005	0.0007	0.0006	0.0005	0.0005	-0.0003	-0.0006	-0.0003
	(0.001)	(0.001)	(0.002)	(0.002)	(0.002)	(0.002)	(0.001)	(0.001)	(0.001)
Water Rationing				-0.1526		-0.1625	-0.1569		-0.1997*
				(0.102)		(0.131)	(0.099)		(0.117)
Truck Water					0.0895	0.0469		0.0324	0.0047
					(0.080)	(0.105)		(0.052)	(0.057)
Truck Water * Water Rationing						0.0414			0.1080
						(0.169)			(0.140)
Household Size (Neighborhood mean)			0.0063	-0.0074	0.0005	-0.0128	-0.0372	-0.0421	-0.0385
			(0.056)	(0.058)	(0.056)	(0.059)	(0.030)	(0.030)	(0.030)
Housing Index (Neighborhood Mean)			-0.1188	-0.0810	-0.0895	-0.0514	0.2829	0.2322	0.2927
			(0.707)	(0.717)	(0.701)	(0.714)	(0.418)	(0.414)	(0.421)
Mother Education (Neighborhood Mean)			0.1150	0.0558	0.0984	0.0358	-0.0886	-0.0959	-0.0963
			(0.285)	(0.298)	(0.282)	(0.301)	(0.191)	(0.185)	(0.192)
Income per capita (Neighborhood Mean)			-0.0685	-0.0683	-0.0650	-0.0658	-0.0457	-0.0360	-0.0444
			(0.106)	(0.107)	(0.106)	(0.107)	(0.065)	(0.065)	(0.065)
Constant	YES	NO	NO	NO	NO	NO	YES	YES	YES
Regional Effects	NO	NO	NO	NO	NO	NO	NO	NO	NO
Pipe FE	NO	YES	YES	YES	YES	YES	YES	YES	YES
Pipe FE p-value		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
adj R2	0.048	0.634	0.629	0.629	0.630	0.627	0.102	0.095	0.099
Observations	269	269	269	263	269	263	446	464	446

Robust standard errors in parentheses
Significance *** p<0.01, ** p<0.05, * p<0.1

Table A.10: Dirty drinking cups and intra-household water pollution: changes in total coliform

Total Coliform	(1)	(2)	(3)	(4)
	Low Pollution Threshold		High Pollution Threshold	
	OLS	OLS	OLS	OLS
Drinking cup dirty	0.0985*	0.1013*	0.1087*	0.1106*
	(0.056)	(0.057)	(0.062)	(0.062)
Improved water storage		-0.0628**		-0.0238
		(0.030)		(0.050)
Water boiling		-0.1335		0.0129
		(0.119)		(0.126)
Soap use		0.0027		0.0117
		(0.046)		(0.065)
Health Knowledge		0.0020		0.0763
		(0.041)		(0.054)
Dependency Ratio	0.0367	0.0395	-0.0505	-0.0480
	(0.062)	(0.062)	(0.088)	(0.087)
Income per capita	0.0021	0.0025	0.0072	0.0080
	(0.011)	(0.011)	(0.013)	(0.014)
House rented	-0.0209	0.0041	0.0164	0.0285
	(0.045)	(0.043)	(0.057)	(0.058)
Household Size	0.0010	-0.0050	0.0176	0.0217
(Neighborhood mean)	(0.013)	(0.014)	(0.025)	(0.024)
Housing Index	0.0285	0.0155	-0.5175	-0.5735*
(Neighborhood Mean)	(0.234)	(0.238)	(0.318)	(0.322)
Mother Education	0.2202**	0.1910*	0.3196**	0.2671**
(Neighborhood Mean)	(0.098)	(0.098)	(0.134)	(0.135)
Mountain Region	-0.0449	-0.0537	-0.0893	-0.1067
	(0.055)	(0.058)	(0.072)	(0.076)
Control town	0.1338***	0.1212***	0.1554**	0.1570**
mountains	(0.042)	(0.044)	(0.066)	(0.069)
Control town coast	0.0453	0.0361	-0.0099	-0.0263
	(0.042)	(0.043)	(0.062)	(0.062)
Tank Pollution	-0.861***	-0.869***	-0.737***	-0.756***
	(0.045)	(0.046)	(0.047)	(0.048)
Constant	0.5595***	0.6754***	0.3807*	0.3767*
	(0.150)	(0.152)	(0.210)	(0.217)
Observations	476	468	476	468
adj R2	0.548	0.560	0.413	0.421
Model F-Test	46.157	38.907	25.094	19.029
Model p-value	0.000	0.000	0.000	0.000

Robust standard errors in parentheses
Significance *** p<0.01, ** p<0.05, * p<0.1

Table A.11: Intra-household water pollution: changes in total coliform, high threshold

Total Coliform High Pollution Threshold	(1) OLS	(2) OLS	(3) OLS	(4) OLS	(5) OLS	(6) OLS	(7) OLS
Improved water storage	-0.0440				-0.0453	-0.0449	-0.0290
	(0.049)				(0.049)	(0.049)	(0.049)
Water boiling		0.0384			0.0470	0.0476	0.0192
		(0.118)			(0.115)	(0.115)	(0.124)
Soap use			0.0285			0.0279	0.0119
			(0.063)			(0.063)	(0.065)
Health Knowledge				0.0920*			0.0849
				(0.052)			(0.055)
Dependency Ratio	-0.0723	-0.0757	-0.0714	-0.0735	-0.0729	-0.0692	-0.0710
	(0.088)	(0.088)	(0.087)	(0.087)	(0.088)	(0.087)	(0.087)
Income per capita	0.0065	0.0062	0.0064	0.0074	0.0062	0.0061	0.0072
	(0.013)	(0.013)	(0.013)	(0.014)	(0.014)	(0.013)	(0.014)
House rented	0.0299	0.0269	0.0269	0.0365	0.0304	0.0307	0.0391
	(0.057)	(0.057)	(0.057)	(0.059)	(0.057)	(0.056)	(0.058)
Household Size	0.0274	0.0283	0.0285	0.0324	0.0275	0.0278	0.0319
(Neighborhood mean)	(0.025)	(0.025)	(0.025)	(0.024)	(0.025)	(0.025)	(0.024)
Housing Index	-0.5750*	-0.5814*	-0.5790*	-0.6517**	-0.5697*	-0.5635*	-0.6393**
(Neighborhood Mean)	(0.320)	(0.320)	(0.320)	(0.321)	(0.321)	(0.322)	(0.324)
Mother Education	0.3328**	0.3426**	0.3441**	0.2957**	0.3282**	0.3263**	0.2867**
(Neighborhood Mean)	(0.133)	(0.134)	(0.134)	(0.133)	(0.133)	(0.134)	(0.133)
Mountain Region	-0.1080	-0.0915	-0.0909	-0.0985	-0.1109	-0.1120	-0.1108
	(0.075)	(0.073)	(0.073)	(0.073)	(0.076)	(0.076)	(0.076)
Control town	0.1516**	0.1496**	0.1521**	0.1454**	0.1535**	0.1573**	0.1502**
mountains	(0.067)	(0.067)	(0.068)	(0.067)	(0.068)	(0.069)	(0.069)
Control town coast	-0.0093	-0.0049	-0.0037	-0.0204	-0.0098	-0.0090	-0.0224
	(0.061)	(0.062)	(0.062)	(0.063)	(0.062)	(0.061)	(0.062)
Tank Pollution	-0.751***	-0.749***	-0.747***	-0.768***	-0.751***	-0.750***	-0.769***
	(0.048)	(0.048)	(0.048)	(0.048)	(0.048)	(0.048)	(0.048)
Constant	0.4710**	0.4213**	0.3908*	0.4007**	0.4731**	0.4432**	0.4242**
	(0.207)	(0.202)	(0.206)	(0.200)	(0.207)	(0.211)	(0.210)
Observations	480	480	480	472	480	480	472
adj R2	0.417	0.416	0.416	0.429	0.416	0.415	0.426
Model F-Test	25.557	25.568	25.484	26.428	23.485	21.634	20.754
Model p-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Robust standard errors in parentheses
Significance *** p<0.01, ** p<0.05, * p<0.1

Table A.12: Impact of Hand Washing, First Stage

Piped Water	(1)	(2)	(3)	(4)
	Least Squares		Probit	
Mother Madrasa Schooling	0.1027**	0.0800**	0.1062**	0.0806*
	(0.041)	(0.038)	(0.045)	(0.043)
Mountain Region	-0.0997***	-0.2012***	-0.0988***	-0.1997***
	(0.024)	(0.031)	(0.023)	(0.031)
Observations	2,277	2,272	2,277	2,272
Stage 2 controls	NO	YES	NO	YES
Model F-Test	11.310	13.226		
Model Chi2			21.145	100.011
Model p-value	0.000	0.000	0.000	0.000
Instrument p-value	0.013	0.038	0.019	0.064

Robust standard errors in parentheses
Significance *** p<0.01, ** p<0.05, * p<0.1

Table A.13. Impact of Hand Washing on Diarrhea among under-5-year old children, no controls

Watery Diarrhea Children <5yrs	(1) OLS	(2) Probit	(3) IV	(4) BL	(5) BP
Mother Soap Use	0.0047	0.0047	-0.3275	-0.4453***	-0.2032**
	(0.016)	(0.016)	(0.320)	(0.020)	(0.101)
Mountain Region	0.0411***	0.0406***	0.0089	-0.0027	0.0068
	(0.016)	(0.016)	(0.034)	(0.020)	(0.019)
Observations	2,281	2,281	2,277	2,277	2,277
Model F-Test	3.358		2.985		
Model Chi2		6.387		530.015	56.850
Model p-value	0.035	0.041	0.051	0.000	0.000
Probit rho chi2				217.285	3.488
Probit rho p-value				0.000	0.062
ATE water	0.005	0.005	-0.328	0.015	-0.283
ATT water	0.005	0.005	-0.328	0.016	-0.403

Robust standard errors in parentheses
Significance *** p<0.01, ** p<0.05, * p<0.1
Probit, BL and BP in average marginal effects