The benefit of clean water on child health: An empirical analysis with specific reference to *Escherichia Coli* water contamination

Microorganism-mediated degradation of water quality is a major public health concern in developing countries. Previous literature have shown an association between household water pollution and childhood diarrhoea; however, its effects on child growth and respiratory health have not been widely investigated. This study assessed the effects of household drinking water contaminated with *Escherichia coli (E.coli)* on child's weight-for-height and weight-for-age z-scores, acute respiratory infections (ARI), and diarrhoea incidence among five years children in Pakistan. We used district-level spatial information and the latest waves of unique Multiple Indicator Cluster Survey (MICS) data containing information on 'point-of-service delivery' (POS) and 'point-of-consumption' (POC) water quality, collected for the first time on a large scale in five regions of Pakistan. We employed an instrumental variable approach to address potential endogeneity issues in household drinking water quality, finding that POC drinking water contamination significantly affected children's weight-for-height and weight-for-age z-scores and ARI, in addition to its effects on diarrhoea. The sub-sample analyses indicated that the effects of contaminated water were particularly significant in children aged 6 months and older and in children who did not receive vitamin A supplements. To protect the children from growth failure and contracting ARI and diarrhoea, household water quality should be improved.

Keywords: Child Health, Undernutrition, ARI, E.coli, Water quality, Pakistan

Introduction

Ending undernutrition and reduction of infectious illness are critical prerequisites for sustainable development. Worldwide, around half of the under-five mortality (3 million) is attributable to undernutrition (Black et al., 2013), which is linked to amplified risk of morbidity and infections including respiratory illness (Rudan et al., 2013; Liu et al., 2015). Diarrhea and acute respiratory infections (ARI) remain the leading causes of mortality and morbidity, especially in developing countries (Paulson et al., 2021; Osarogiagbon & Isara, 2018). Every year, from one billion childhood diarrhoea episodes, around 5 million result in death (Flückiger & Ludwig, 2022), and ARI contribute to 15% of deaths under the age of 5 worldwide. The cumulative health burden is evident because diarrhoea can impair child growth (Khalil et al.,2018) and trigger ARI.

Recent research and international development partners have focused on environmental contamination, which is a possible structural barricade to child development. Especially water pollution is an ‘invisible threat’ to the global development agenda, and uncontaminated water can significantly reduce morbidity and improve labour productivity and well-being (Devoto et al., 2012). *E.coli* bacterial contamination[1] was found to be one of the main causes of failure to meet the global criteria for safely managing drinking water (Bain et al., 2021). Faecal exposure through poor drinking water, sanitation and hygiene is linked to approximately 62% diarrhoeal mortality, 13% ARI burden and 16% malnutrition cases (Prüss-Ustün et al., 2019).

Water pollution, nutrition emergency and infectious illness posing threat to the lives of children are no exception to Pakistan. Bacterial contamination is increasing due to rapid urbanisation, water scarcity and poor sanitation. Access to safely managed drinking water is only 35.8% in the country (WHO & UNICEF, 2020), signifying that even if the source water is safe, unhygienic storage and water handling may lead to contamination (Julian, 2016). The E. coli presence indicates water exposure to animal or human feces (Santika et al., 2020; Usman et al., 2019; Barnes et al., 2018). As access to basic sanitation is 68.4% in Pakistan, inadequate sanitation can elevate the risk of microbial contamination due to the extensive discharge of fecal sludge into water bodies (Ammazia et al., n.d.; Zhang, 2012). The situation is exacerbated due to recent massive floods in the country which largely affected the water

[1] *Escherichia coli (E. coli)* - an indicator of fecal contamination is a species of fecal coliform group, easily cultured microorganisms and used to measure the water quality level.

and sanitation systems and enhanced the risk of diarrhoea, ARI and malnutrition in almost 10 million children (UNICEF, 2022)[2].

A growing body of literature on economics has investigated environmental effects on health, particularly diarrhoea (Flückiger & Ludwig, 2022; Rahman et al., 2021; Usman et al., 2019). Epidemiological studies have documented the impact of water quality (Khan et al., 2022; Hubbard et al., 2020; Goddard et al., 2020; Ercumen et al., 2017; Fagerli et al., 2017; Luby et al., 2015; Gruber et al., 2014; Brown et al., 2008) on diarrhoea and self-reported maternal health (Kile et al., 2014) and child mortality (He & Perloff,2016; Gamper-Rabindran et al., 2010) and found mixed results. However, empirical evidence of the impact of water quality on child growth and respiratory infections is lacking.

Other studies have investigated the effectiveness of water, sanitation and hygiene (WASH) interventions for undernutrition and ARI (Fathmawati et al., 2021; Shrestha et al., 2020; Ashraf et al., 2020; Swarthout et al., 2020; Null et al., 2018; Luby et al., 2018; Huda et al., 2012). However, only few studies have examined the impact of point-of-consumption (POC) water quality on child growth. Johri et al. (2019), who used propensity score matching (PSM) and showed that safe drinking water can reduce underweight but has no effect on wasting and stunting among children in a rural district of India and Joseph et al. (2019) using probit regression showed that highly contaminated household drinking water was associated with stunting. One limitation of these studies is that they have largely ignored the endogeneity of household drinking water quality. A few exceptions include Rahman et al. (2021), who estimated the impact of household water quality on the incidence of diarrhoea and self-reported health by treating endogeneity using a control-function approach. The

[2] Inadequate WASH, mainly attributed to intestinal issues, typhoid, hepatitis and respiratory illness, contribute to about 0.6–1.44% of the burden on the country’s GDP (Bashir et al., 2021).

study found a significant effect of E.coli presence in household's drinking water on individual's self-reported health and diarrhoea incidence between children and adults. Usman et al. (2019) examined the impact of water quality on child diarrhoea using the quality of drinking water at the sources and the existence of village water user associations (WUA) as instruments for household drinking water. They found that contaminated stored drinking water was associated with decreased childhood diarrhoea incidence of 18 percentage points.Given that the previous literature on this topic is scant and the existing studies show mixed results, it is important accumulate the evidence on the impact of water quality on child growth.

This study investigated the impact of E. coli contamination on weight-for-height and weight-for-age z-scores, ARI, and diarrhoea incidence in children under the age of 5 using Multiple Indicator Cluster Survey (MICS) data (2017–2021). The unique feature of the MICS datasets (2017–2021) is that they contain information on 'point of service delivery' (POS) and 'point-of-consumption' (POC) water quality, which was collected for the first time in a wide geographic area in Pakistan. This allowed us to directly examine the impact of POC water quality on child health, unlike previous studies that mainly focused on the effectiveness of WASH interventions. We applied instrumental variable (IV) methods to account for the possible endogeneity of POC drinking water quality using community-level source water contamination as an instrument.

Our results document that a household using contaminated drinking water has a higher probability of diarrhoeal episodes by 7.5 percentage points and raises the ARI risk among children by 6.0 percentage points. Furthermore, our findings suggest that contaminated water is correlated with a decrease in children's weight-for-height by 0.33 and weight-for-age by 0.28 standard deviations. Based on these results, we infer that E. coli-induced episodes of diarrhoea could be a risk factor for undernutrition and ARI. Clean drinking water may improve respiratory health by preventing compromised immunity and micronutrient deficiencies. In addition to diarrhoea, environmental enteric dysfunction (EED), a subclinical gut disorder triggered by relentless faecal-oral contamination, is another possible route associated with that associates water contamination with child growth (Modern et al., 2022; Campbell et al., 2018).

In addition, we conducted two subsample analyses that measured the differential effects of water quality on child health, focusing on children's age and micronutrient supplementation status. Dividing the sample by age group, we found that children aged 6 months and older were susceptible to E. coli contamination, possibly due to a larger intake of water and exposure to the contaminated environment than infants up to 6 months of age, who are generally exclusively breastfed. Moreover, periodic Vitamin A supplementation appears to protect children from contaminated disease environments as we found that children who were not given vitamin A supplement doses were more likely to have incidents of diarrhoea and ARI, and their growth in terms of acute weight loss than their counterparts. These results suggest that vitamin A supplementation is an effective means of mitigating the negative effects of contaminated water on children's health and growth.

Our contribution to the previous literature is threefold. First, as discussed, this study used unique MICS datasets (2017–2021) containing information on POC and POS water quality. Worldwide, few datasets include bacteriological water quality indicators at the national scale, and a new water quality module was added to MICS in Pakistan. These unique data allowed us to directly examine the impact of POC water quality on children's growth and ARI, unlike existing studies that have mainly examined the effectiveness of WASH interventions instead of POC water quality in improving child growth and respiratory illness. Second, previous studies have largely ignored the endogeneity of household drinking water quality, which might have caused bias in their estimates. We addressed these concerns by employing the two-stage least squares method and found that poor drinking water quality significantly and negatively affected child growth, ARI and diarrhoea. Third, we conducted subsample analyses based on children's age and vitamin A supplementation. Our findings suggest that the negative impact of contaminated water is more serious for children older than 6 months than for younger children. We also found that vitamin A supplements could mitigate the negative effects of contaminated water on children's health and growth. These subsample analyses add substantial value to our study because such analyses are lacking in the previous literature, and the results provide strong policy implications.

The remainder of this paper is organised as follows. In Section 2, we explain the datasets. Section 3 outlines the empirical strategy. Section 4 documents the regression results of the analyses across several specifications, and Section 5 discusses the results. Finally, Section 6 concludes the paper.

Data

Sampling

This study utilised data from the latest round of the Multiple Indicator Cluster Surveys (MICS) in Pakistan; a provincially representative cross-sectional survey followed a two-stage stratified random sampling technique. We used the MICS survey waves from five regions in the country from 2017 to 2021[3]. During the survey, the first primary enumeration areas were selected from rural and urban areas within each district. Subsequently, a systematic sample of 20 households was randomly selected from each enumeration area (hereafter termed 'cluster'). A unique feature of MICS is the addition of a new water quality

[3] Five survey waves include provinces MICS Punjab 2017–18, MICS Sindh 2018–19, MICS KPK 2019, MICS Baluchistan 2019–20 and a region MICS AJK 2020–21

module developed by MICS and the Joint Monitoring Program (JMP) (UNICEF, 2018) which was released as a part of latest round MICS6 .[4] Worldwide, few datasets include bacteriological water quality indicators at a national scale owing to collection challenges, and in most cases, only the quality of piped water is measured. In our datasets, water quality data at the POC and POS were collected separately for the first time on a large scale in Pakistan using a universally accepted method (Khan et al., 2017).

In the MICS datasets, 113,233 households were interviewed with information on child anthropometry and other health outcomes from study regions of the country. For water quality testing, 18,493 households were randomly selected. We limited our sample where households gave consent for the water test; enumerators visited the source for E. coli test, and information for both the source and household water test was available. For the analyses 12,547 observations remained for children aged 0–60 months after cleaning the data.

Outcome variables

This study used four outcome variables. First, we used diarrhoea prevalence, which took the value of 1 if the child's mother/caregiver reported the child had had diarrhoea 2 weeks before the survey. Second, acute respiratory infection (ARI) symptoms were used, which took the value of 1 if the child had experienced rapid or difficult breathing along with a persistent cough and the symptoms were associated with chest problems and a blocked nose 2 weeks before the survey5. The third and fourth outcomes were child growth: weight-for-height and

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[4] Methods were developed for direct water testing in MICS. Generally, laboratories conduct water tests, which often suffer from logistic challenges in term of transportation and time frame.

[5]Respiratory rate is a valuable clinical sign for diagnosing acute lower respiratory infections (e.g. pneumonia and bronchiolitis) in children coughing and breathing rapidly.

weight-for-age z-scores, which are the standard deviations of the anthropometry of the child based on the growth standards of the WHO. Weight-for-age of less than -2 represents underweight, while a child's weight-for-height of less than -2 signifies wasting – a short-term undernutrition indicator owing to acute weight loss.

Main explanatory variables

The key explanatory variable of POC-contaminated drinking water was a dummy variable, which took 1 if E. coli was found in a household's POC water[6]. The WHO drinking water quality guidelines recommend that E. coli must not be detectable in 100-ml water samples (WHO, 2017). A water test was performed on the samples provided by the households within 30 minutes of collection followed by 24–48 hours of incubation. E. coli colonies were counted as colony-forming units (CFU) per 100 ml of water sample. The E. coli contamination at the source level was calculated using a source water sample test, which was performed conducting similar method used for household water test[7].

Figure 1 shows the specific E. coli count (CFU/100 ml, ranging from 0 to 100 and above) at the POC in the left panel and at the source level in the right panel. In our sample, drinking water of around 79% was found contaminated with E. coli, and the percentage of households having contaminated water at the source level was around 61%. The variation in E. coli concentration at the POC and source levels showed that a higher E. coli risk (100 or

[6] The following precise question was asked: 'Could you please provide me with a glass of water that members of your households usually drink?'

[7] The following precise questions were asked: 'What source was this water collected from?' and 'Can you please show me the source of glass of drinking water so that I can take a sample from there as well?'

above CFU) was prevalent at POC than at POS, suggesting that contamination occurs during the process of fetching drinking water.

[Fig. 1]

In the regression analysis, we controlled for other children, mothers and household characteristics. Child-level variables included gender, age and prenatal check-ups. The mother and household characteristics comprise the age and education of the mother and household head, the household head's gender, maternal smoking, household size, number of children up to 5 years of age, cooking place, number of household members, household assets, access to flush toilets as indicator of improved sanitation[8], livestock ownership and survey year dummy. The community-level variables included rural and urban dummies. Appendix Table 1 presents the summary statistics for the variables used in the analyses.

District characteristics

We supplemented the information from the MICS with additional geospatial datasets to account for district-level characteristics that may affect health and water quality. Using raster datasets from QGIS, we constructed district-level data on rainfall, population density, slope and temperature. Based on the district's geocoded position, we link the MICS data to information on district-level characteristics. For rainfall data, we used the Climate Hazards Group InfraRed Precipitation with Station data 2.0 (CHIRPS) (Funk et al., 2015). For population density, we used WorldPop data (WorldPop; Bondarenko & Maksym, 2020). The district slope was calculated using ALOS DSM: Global 30m v3.2 data provided by the JAXA Earth Observation Research Centre (EORC). For temperature, we used the dataset provided

[8] Flush toilets reduced child weight loss, offer non-health welfare (e.g. time saving) and augments satisfaction (Wang & Shen, 2022; Rahman et al., 2021).

by the NASA LP DAAC at the USGS EROS Centre (Wan et al., 2021). To control for the economic status in each district, we used 3-arc-second (approximately 100 m at the equator) night-time light data constructed by NOAA's National Centres for Environmental Information as a proxy.

In Figure 2, using district-level spatial information, we mapped child health data from the sample and plotted the district-level risk prevalence of E. coli at POS and POC level and health-related outcomes. The figure shows that diarrhoea and ARI prevalence were higher in areas with a high possibility of E. coli concentrations in POC water. A similar tendency was observed for child growth indicators.

[Fig 2]

Empirical strategy

This section describes the empirical strategy employed to estimate the impact of household POC water quality on children's health. A linear probability model (LPM) and two-stage least squares (2SLS) were used. Following Rahman et al. (2021), we use Grossman's (1972) health production function approach as the motivation for our empirical estimation. Following the conceptual framework of this approach, we estimate the model below, where the health of child *i* is a function of the POC drinking water quality level and other demographic and socioeconomic factors:

$$\mathrm{Y}_{ijkd} = \beta_0 + \beta_1 \mathrm{WQ}_{jkd} + \beta_2 \mathrm{H}_{ijkd} + \delta_d + \theta_{dr} + \theta_t + e_{ijkd} \quad [1]$$

where Y_{ijkd} refers to the health of child *i* of household *j* in cluster *k* of district *d*. Diarrhoea prevalence, weight-for-height, weight-for-age z-score and ARI are the indicators of child health and the outcome variables of interest. WQ_{jkd} is a dichotomous variable that denotes POC water quality (presence of E. coli) in household *j* in cluster *k*. H_{ijkd} is a vector for control variables at the household and individual levels. δ_d controls district-level characteristics including population density, average rainfall and temperature during the survey year, average night-time light and slope of each district. θ_{dr} controls for district-times-rural fixed effects. Because rural and urban areas have different characteristics within each district in terms of socioeconomic and health status, we include district-times-rural fixed effects to account for any region-specific variability. θ_t is the time-fixed effect, while e_{ijkd} is the error term that elucidates the variation of Y_{ijkd}. We clustered standard errors at the MICS cluster level.

Since each household can decide whether to take any means to improve water quality, our model may suffer from a possible endogeneity problem. For instance, some households may have unobserved perceptions, preferences, behaviours and awareness that allow them to improve water quality and children's health. If households are keen on health, for example, they could invest not only in improving water quality but also in other measures to benefit their children's health. To circumvent such issues, we use 2SLS estimation and estimate the following regression equation as the first-stage equation of the 2SLS estimation of equation 1:

$$\mathrm{WQ}_{jkd} = \gamma_0 + \gamma_1 \mathrm{SWQ}_{kd} + \gamma_4 \mathrm{H}_{ijkd} + \delta_d + \theta_{dr} + \theta_t + v_{jkd} \qquad [2]$$

where the excluded instrumental variable is community-level POS water contamination, indicated as SWQ_{kd}. In the MICS, the POS water quality data were measured at the household level because each household used water from different sources. As each household cannot change the quality of the water at the source, the POS water quality should be largely exogenous for each household. There is, however, some possibility of endogeneity because each household may be able to choose sources to take their water. To circumvent this problem, we calculated community-level POS water contamination by measuring the leave-out means (except self) of the POS water quality of households within a cluster. If the community-level source contamination increases, it would positively affect household water contamination. In addition, because the average POS water contamination most likely affects children's health through drinking water quality, the variable can satisfy the exclusion restriction, although there is no direct way to test it. Therefore, we considered community-level POS water contamination as a plausible instrument for our study.

Results

Descriptive statistics

In Table 1, we compare child health and growth outcomes among households with POC drinking water with and without E. coli contamination. Table 1 shows that diarrhoea prevalence is higher by 4.6% among children from households with contaminated drinking water than households with E. coli-free water. The average weight-for-height and weight-for-age z-scores were lower among children from households exposed to E. coli contamination than among those using uncontaminated water. On average, the weight-for-height is -0.42 for children exposed to contaminated water and -0.31 for those who drink water free of E. coli. We can observe a similar tendency for weight-for-age. The weight-for-age of children with contaminated water was -1.32, while that of children with uncontaminated water was -1.1, and the difference was statistically significant. Further, the ARI prevalence is also higher by 1.2% among children exposed to contaminated water than among households using uncontaminated water, although the difference is not statistically significant.

[Table 1]

Main results

Estimates of the impact of POC E. coli in water on child diarrhoea, weight-for-height, weight-for-age and ARI prevalence are presented in Table 2. The estimated coefficients of contaminated water on weight-for-height and weight-for-age were negative and statistically significant. The results show that the having E. coli in POC water decreases the child's weight-for-height and weight-for-age by 0.08 and 0.07, respectively. In contrast, the estimated coefficients from OLS were insignificant for diarrhoea and ARI prevalence when we included district-times-rural fixed effects and time-fixed effects in the model. Conversely, the estimated coefficients of contaminated water for weight-for-height and weight-for-age were negative and statistically significant. Due to the possible correlation between e_{ijkd} and WQ_{jkd}, however, OLS estimate of β1 may suffer from endogeneity bias.

[Table 2]

To circumvent this problem, we estimated the same model using community-level POS water quality as IV for household-level POC water quality. The reduced-form estimates in Appendix Table 2 suggest that households in a cluster with contaminated water have a higher probability of diarrhoea incidence by 1.8 percentage points and of ARI by 1.5 percentage points than those having an uncontaminated water source. The estimated coefficients of the weight-for-height and weight-for-age z-scores are 0.079 and 0.067, respectively, and are thus statistically significant.

Panel A of Table 3 shows the first-stage estimation results. The dependent variable is POC water quality, while IV is community-level POS water contamination. The results show a strong positive correlation between POC water quality and IV, and diagnostic tests provide evidence of the validity of IV. For all outcomes, the null hypothesis for under-identification is rejected based on the LM version of the Kleibergen-Paap rk statistic. The null hypothesis of weak IV is rejected for all regressions using the Kleibergen-Paap rank

Wald statistic, indicating that our instrument is not weakened by the inclusion of various covariates.

In Panel B of Table 3, we estimate β_1 by applying 2SLS that captures the impact of POC water quality on child health outcomes. Column 1 shows that the probability of diarrhoea in children increases by 7.3 percentage points in households with contaminated drinking water compared to those using uncontaminated water; estimated at the 17.7% sample mean, this translates to 42 % increase in diarrhoea risk. The results for weight-for-height and weight-for-age as alternative outcomes are also shown in columns 2 and 3. Consistent with childhood diarrhoea triggering weight loss, particularly in the short run, we found that POC-contaminated drinking water was associated with a decrease in children's weight-for-height by 0.33 standard deviations and their weight-for-age by 0.28 standard deviations. Column 4 shows that the probability of ARI risk among children increased by 6.0 percentage points in households with microbial-contaminated water. The IV estimates of the effect of water contamination on child health are larger than those from OLS regressions and are all statistically significant. Although some coefficients of the OLS estimates are insignificant, the direction of the impact is the same as that of the IV estimates, suggesting the robustness of our results.

[Table 3]

Differential effects of E. coli contamination

We also assessed whether the effects of POC water quality varied across the different age groups as E. coli contamination may not similarly affect all children. The results presented in Table 4 show stark differences in the impact of contaminated water on child health among different age groups. The IV results in columns 1–4 show the impact of water quality on the health of children aged 0–5 months, while columns 5–8 show such impacts on children 6–

60 months of age. The estimated coefficients in columns 5-8 indicate that the link between E. coli-contaminated water and the risk of diarrhoea and ARI incidence was statistically significant among children older than 6 months, with an average effect of 8.6 and 7.0 percentage points respectively. Moreover, contaminated water was significantly associated with a 0.38 and 0.33 standard deviation decrease in weight-for-height and weight-for-age z-scores in children older than 6 months. In contrast, the results in columns 1–4 show that water pollution does not affect children of less than 6 months of age. This is plausible because the introduction of complementary feeding and partial weaning from the age of 6 months increases a child's exposure to a contaminated environment[9]. Children exclusively breastfed during the initial 6 months may be protected naturally from pathogen exposure through contaminated food and water, having less ARI, diarrhoeal morbidity and mortality (Mulatu et al., 2021; Arifeen et al., 2001; VanDerslice et al., 1994;) and growth failure (Dharel et al., 2020). Although the results are not shown, we found that exclusively breastfed children (aged 0–5 months) were not significantly affected by water contamination.

[Table 4]

In addition, we analysed whether the intake of vitamin A supplements mitigated the negative effects of E. coli-induced risk of diarrhoea and ARI. Vitamin A deficiency (VAD) remains a public health concern across the globe including in Pakistan, where its frequency is more than 51%. According to previous studies, vitamin A (anti-infectious) is significant for gastrointestinal and respiratory epithelial regeneration and reduces immune disorders, mortality, and morbidity among children aged 6–59 months (Kanakala et al., 2019; Imdad et al., 2011; Barreto et al., 1994; WHO, 2013). Periodic vitamin A supplementation could

[9] In terms of food intake for the previous day, the information was only solicited for children of up to 2 years at the time of the survey.

have the capacity to protect children by boosting their immune systems from contaminated disease environments and related health risks (*Action - Nutrition International - Pakistan - Vitamin A Supplementation*, n.d.).

To examine these hypotheses, we conducted subsample analyses of the impact of contaminated water on child health and growth for those who were supplemented with vitamin A and those who were not. In our analyses, the vitamin A variable took the value of 1 if the child aged 6–60 months had been provided with vitamin A supplementation in the previous 6 months. Table 5 shows the differential effects of contaminated water on the health and growth of children with and without vitamin A supplementation. Columns 1–4 show the effects of E. coli on the outcome variables for the vitamin A-supplemented group, while columns 5–8 show the effects on the non-supplemented group. The results in columns 5 and 8 show that contaminated water was statistically significantly associated with the risk of diarrhoea and ARI incidence, with an effect of 20 and 14 percentage points respectively, in the non-vitamin A-supplemented group. Likewise, as shown in column 6, contaminated water was significantly associated with a 0.55 standard deviation decrease in children's weight-for-height in the non-vitamin A-supplemented group. In contrast, we did not observe any significant effects of E. coli contamination on health among children supplemented with vitamin A, except for a negative coefficient for weight-for-age, for which we do not have a clear explanation. These results provide suggestive evidence to support our hypothesis that micronutrient supplementation can mitigate E. coli-induced health risks.

[Table 5]

Robustness checks

We conducted an array of robustness checks to document the validity and stability of our results. First, in Appendix Table 3, we examined whether the estimated 2SLS coefficients remained robust after excluding extensive covariates. In the main models, we controlled for variables related to the child, the mother, the household head, the household, district-level characteristics, district-times-rural fixed effects and time-fixed effects. We gradually excluded district and household controls in columns 1, 2, 4, 5, 7, 8, 10 and 11, while we included all these variables in columns 3, 6, 9 and 12 (the same as the main results shown in Table 2). The results show that the coefficient of water quality remained largely steady despite the inclusion or exclusion of various covariates.

Second, we added several variables which could affect water quality in the first- and second-stage regressions of our IV estimation. We included the means to extract water (motor and hand pump dummy), piped water dummy, water treatment status dummy, handwashing dummy, flush toilet dummy and animal ownership. As these can potentially determine water quality, excluding them may cause an omitted variable bias, especially in the first-stage estimation. At the same time, however, these variables are endogenous, and thus, we excluded them from our main analyses. Appendix Table 4 shows the first-stage and IV estimates with and without these variables. Column 1in Panel A show first-stage results of Table 2 and column 2 controls for the effect of potential water quality determinants. Columns 1, 3, 5 and 7 in Panel B show the 2SLS results of Table 2, without including variables that can determine water quality. In columns 2, 4, 6, and 8 of Panel B, we include potential water quality determinants. The results show that the coefficients are almost the same for the estimation results with and without these covariates, suggesting the robustness of the results.

Lastly, in Appendix Table 5, as a sensitivity analysis, we estimated our models by measuring the E. coli coliform as a continuous variable. Columns 1 and 4 show that a 1% increase in E. coli (CFU/100 ml) in water increased the probability of diarrhoea by 0.013

percentage points and ARI by 0.011 percentage points. Such an increase in E. coli was associated with a decrease in children's weight-for-height by 0.062 standard deviations and in their weight-for-age by 0.052 standard deviations; these effects were statistically significant. Overall, the robustness tests suggested that the estimated findings are robust and consistent.

Discussion

This study investigated the impact of household water quality on childhood diarrhoea, weight-for-height, weight-for-age and ARI. For this purpose, we used a unique dataset collected in Pakistan which included physically measured POC and POS water quality. Using 2SLS, we attempted to control for the endogeneity of household POC water quality. Our findings suggest that POC water contamination elevates the risk of malnutrition, diarrhoea and ARI. Generally, our findings are consistent with those of previous studies that found that household water quality affects the prevalence of diarrhoea in developing countries (e.g. Khan et al., 2022; Rehman et al., 2021; Usman et al., 2019; Luby et al., 2015). We also estimated the effect of E. coli on weight-for-height, weight-for-age and ARI and found a negative impact of water contamination on these outcomes. Our results add to the literature, which shows mixed results regarding the impact of water quality and WASH interventions on child growth and ARI.

Age-based sub-sample analyses revealed that contaminated water significantly affects child health indicators, particularly when a child turns 6 months or more. One of the reasons for this could be that after 6 months, children consume large quantities of water and are at a higher risk of being infected through contact with contaminated water. It is possible that infants (0–5 months) are naturally protected by breastfeeding; thus, we did not observe a significant negative impact of contaminated water on their health status. We also examined the differential impact of water quality on the provision of micronutrient supplements to children aged 6–60 months. Our results suggest that bacterial contamination has significant effects on diarrhoea and ARI in children who were not given vitamin A supplementation in the previous 6 months, while their counterparts were not significantly affected. These results imply the effectiveness of vitamin A supplementation in mitigating the negative impacts of contaminated water on children's health.

Despite our contributions, this study has some limitations. First, water quality was measured at a single point in time; therefore, we could only rely on cross-sectional variations to estimate the health impact of water quality. Undernutrition reflects the accumulated effects of nutritional deficiency; therefore, a longitudinal study on the effects of water quality on chronic undernutrition in children should be conducted in the future. Second, we did not have information on the seasonal variability of water quality and E. coli levels; thus, we could not examine whether rainy or dry seasons affect water contamination and child health differently. Such studies could be a challenge for the future.

Conclusion

Pakistan is among those regions most susceptible to respiratory infections and diarrhoea-related mortality, and malnutrition is among the most prevalent conditions in South Asia.This study examined the impact of microbial water contamination on childhood diarrhoea, weight-for-height, weight-for-age and ARI prevalence using data from the latest waves of MICS in five regions of Pakistan during 2017–2021. A distinctive feature of the MICS was the collection of E. coli contamination data on POC and POS for the first time on a large scale in Pakistan.

Using two-stage least squares, our key findings indicate that the presence of E. coli in POC water, which is generally used for drinking, significantly decreases a child's weight-for-height and weight-for-age and increases the risk of ARI and diarrhoea. Differential effects based on children's age show that children aged 6 months and older seem to be more vulnerable to water contamination than infants younger than 6 months, plausibly because they consume larger amounts of water than infants and are exposed to contaminated water. We further found that the effect of polluted water was greater for those who were not provided with preventive micronutrient supplements than for those who were given such a treatment, which suggests that vitamin A supplementation is effective in mitigating the negative effects of polluted water on children's health.

From the overall findings, we can extrapolate that the effects of contaminated water on child growth, diarrhoea and ARI prevalence are not trivial and highlight certain policy recommendations. First, considering the government's resource constraints, funds should be allocated towards the public health sector for the provision of safely managed drinking water to improve children's health. The establishment of waste-management treatment plants and sewerage schemes may contribute to improving children's health by reducing water contamination.

Second, we showed that children who did not take vitamin A supplements and children older than 6 months were affected more by polluted water than their counterparts; this implies that families with children should realise the importance of a clean environment for their growing children and that micronutrient supplementation and exclusive breastfeeding should be promoted. In fact, in Pakistan, only approximately 37.7% of women exercise exclusive breastfeeding, and more than 50% of children suffer from vitamin A deficiency (National Nutrition Survey, 2018). The promotion of breastfeeding and supplementation with vitamin A would not only have a direct impact on child health but also indirect effects by mitigating the negative impact of drinking water contamination.

Third, the government should promote healthy behaviours regarding sanitation, handwashing and water handling practices to improve drinking water quality. For example, in Panel A Appendix Table 4, although the detailed results are not shown, we found that treating water primarily by chlorination, boiling or using a water filter significantly reduces the probability of drinking water contamination. Therefore, policies, such as information provision on household adoption behaviour concerning proper sanitation and hygiene, can be an effective means to improve household water quality and change the general perception of seemingly clean water. Another policy measure could be to subsidise the cost of acquiring WASH infrastructure and disinfection technologies such as water filters and chlorination materials to protect individuals from health hazards. Since it is beyond our scope to discuss how to improve drinking water quality, however, further investigation is needed on this point.

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Table 1. Mean comparison tests for child health outcomes with and without E. coli in household drinking water

	Household POC water quality (E. coli)			
Variables	contaminated	uncontaminated	Total	t-test
Diarrhoea	0.187	0.141	0.177	-0.046***
Weight-for-height	-0.424	-0.316	-0.402	0.108***
Weight-for-age	-1.321	-1.107	-1.276	0.213***
ARI	0.099	0.087	0.096	-0.012
Observations	9,931	2,616	12,547	

Notes: Authors' calculations. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Test for the mean comparison between households consuming water uncontaminated and contaminated with E. coli.

Table 2. OLS estimates of the effects of drinking water quality on child health

Dependent variables	Diarrhoea	Weight-for-height	Weight-for-age	ARI
	(1)	(2)	(3)	(4)
Water quality (1=E.coli present)	0.008	-0.080**	-0.077**	0.003
	(0.010)	(0.039)	(0.035)	(0.007)
Log of population	Yes	Yes	Yes	Yes
Nighttime light	Yes	Yes	Yes	Yes
Rainfall	Yes	Yes	Yes	Yes
Temperature	Yes	Yes	Yes	Yes
Slope	Yes	Yes	Yes	Yes
Child, mother, HH head, and HH controls	Yes	Yes	Yes	Yes
District x rural FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes

Clustered standard errors (robust) at the MICS cluster level are in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. N = 12,547

Table 3. The IV estimates the effects of drinking water quality on child health

	Water quality (1=E.coli present)			
Regression stage	(1)	(2)	(3)	(4)
Panel A. First-stage regression				
Community-level source water contamination (except self)	0.250***	0.247***	0.245***	0.243***
	(0.0166)	(0.0166)	(0.0166)	(0.0166)
Control variables				
Child, mother characteristics	Yes	Yes	Yes	Yes
Household Characteristics		Yes	Yes	Yes
District Characteristics			Yes	Yes
District x rural FE				Yes
Year FE				Yes
Underidentification test				
Kleibergen-Paap rk LM statistic	182.784			
Chi-sq p-value	0.0000			
Weak identification test				
Kleibergen-Paap rk Wald *F*-statistics	214.7			
Dependent variables	Diarrhoea	Weight-for-height	Weight-for-age	ARI
	(1)	(2)	(3)	(4)
Panel B. Second-stage regression				
Water quality (1=E. coli present)	0.073*	-0.333**	-0.283*	0.060*
	(0.044)	(0.170)	(0.149)	(0.035)
Control variables				
Child, mother characteristics	Yes	Yes	Yes	Yes
Household Characteristics	Yes	Yes	Yes	Yes
District Characteristics	Yes	Yes	Yes	Yes
District x rural FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes

Clustered standard errors (robust) at MICS cluster level are in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. The endogenous variable household POC water quality is instrumented by community-level source water contamination. N = 12,547

Table 4. Differential effects of drinking water quality on child health by age group

Variables	Younger than 6 months of age (2SLS)				Aged 6 months and older (2SLS)			
	Diarrhoea	Weight-for-Height	Weight-for-Age	ARI	Diarrhoea	Weight-for-Height	Weight-for-Age	ARI
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Water quality (1= E. coli present)	-0.026	-0.231	0.145	-0.013	0.086*	-0.388**	-0.331**	0.070*
	(0.124)	(0.492)	(0.435)	(0.089)	(0.046)	(0.177)	(0.156)	(0.036)
Observations	1,254	1,254	1,254	1,254	11,293	11,293	11,293	11,293
Districts controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Child, mother, HH head, and HH controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
District x rural FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
F-Statistics		46.3				211		

Clustered standard errors at MICS cluster level are in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 5. Differential effects of drinking water quality on child health depending on Vitamin A supplementation

Variables	Vitamin A-Supplemented group (2SLS)				Vitamin A Non- Supplemented group (2SLS)			
	Diarrhoea	Weight-for-Height	Weight-for-Age	ARI	Diarrhoea	Weight-for-Height	Weight-for-Age	ARI
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Water quality (1= E. coli present)	-0.012	-0.255	-0.459*	0.021	0.207***	-0.553**	-0.269	0.143***
	(0.060)	(0.215)	(0.215)	(0.049)	(0.071)	(0.265)	(0.230)	(0.052)
Observations	5,827	5,827	5,827	5,827	5,466	5,466	5,466	5,466
Districts controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Child, mother, HH head, and HH controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
District x rural FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
F-Statistics		128.2				101.3		

Clustered standard errors at MICS cluster level are in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Appendix Table 1. Summary Statistics

Variables	Mean	Std. Dev.	Min	Max
HH water quality (1= E. coli present)	0.791	0.406	0	1
Diarrhoea	0.177	0.382	0	1
Weight-for-height z-score	-0.402	1.352	-5	5
Weight-for-age z-score	-1.276	1.299	-5.99	4.94
ARI	0.096	0.295	0	1
HH Demographic and Socioeconomic				
Child gender (1 = male)	0.514	0.499	0	1
Child age (month)	30.05	17.06	0	60
Child prenatal checks (4 or more)	0.609	0.487	0	1
Children under 5 years	2.392	1.329	1	10
HH head gender (1 = male)	0.924	0.264	0	1
HH head education	0.505	0.499	0	1
Maternal education	0.4	0.49	0	1
Maternal age (1 = < 20,…,4 = > 35)	2.557	0.844	1	4
Maternal smoking status	0.02	0.14	0	1
Wealth index quantile (1 = poorest,..., 5 = richest)	2.666	1.367	1	5
Number of HH members	9.364	4.907	2	42
Cooking place (1 = outdoor)	0.286	0.452	0	1
Flush toilet	0.473	0.499	0	1
Animal ownership	0.538	0.498	0	1
Residential area (1 = rural)	0.78	0.414	0	1
Year	2018	0.777	2017	2021
District level controls				
Log of population	5.799	1.468	1.107	10.847
Night-time light (average)	1.244	5.424	0.072	48.73
Rainfall (mm)	509.04	375.27	44.24	1535
Temperature (Celsius)	31.1	6.185	8.902	41.979
Slope (degree)	6.9	8.693	0.281	34.355

Note: Sample size = 12,547

Appendix Table 2. Results of reduced-form regression for IV estimation

	Dependent Variable			
	Diarrhoea	Weight-for-height	Weight-for-age	ARI
Variables	(1)	(2)	(3)	(4)
Community source water quality (except self)	0.0183*	-0.0792*	-0.0670*	0.0151*
	(0.010)	(0.0418)	(0.0365)	(0.00857)
Log of population	Yes	Yes	Yes	Yes
Night-time light	Yes	Yes	Yes	Yes
Rainfall	Yes	Yes	Yes	Yes
Temperature	Yes	Yes	Yes	Yes
Slope	Yes	Yes	Yes	Yes
Child, mother, HH head, and HH controls	Yes	Yes	Yes	Yes
District x rural FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes

Clustered standard errors (robust) at the MICS cluster level are in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. N = 12,547.

Appendix Table 3. Sensitivity analysis excluding covariates from the 2SLS estimation model for the impact of drinking water quality on child health

Variables	Diarrhoea			Weight-for-height		
	(1)	(2)	(3)	(4)	(5)	(6)
Water quality (1 = E. coli present)	0.073*	0.079*	0.073*	-0.332**	-0.330**	0.333**
	(0.043)	(0.043)	(0.044)	(0.167)	(0.169)	(0.170)
	Weight-for-age			ARI		
	(7)	(8)	(9)	(10)	(11)	(12)
	-0.250*	-0.247*	-0.283*	0.055	0.056	0.060*
	(0.150)	(0.149)	(0.149)	(0.035)	(0.035)	(0.035)
District characteristics			Yes			Yes
Household controls		Yes	Yes		Yes	Yes
Child,mother, HH head controls	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
District x rural FE						
F-Statistics	221	217.5	214.7	221	217.5	214.7

Notes: Clustered standard errors (robust) at the MICS cluster level are in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. N = 12,547.

Appendix Table 4. Sensitivity analysis with and without WASH infrastructure and hygiene behaviour-related variables for 2SLS estimates of the impact of drinking water quality on child health

	Without water quality determinant variables		With water quality determinant variables	
	Water quality (1 = E. coli present)			
Panel A. First-stage regression	(1)		(2)	
Community-level source water contamination	0.243*** (0.0166)		0.240*** (0.0165)	
Panel B. Second-stage regression	Diarrhoea		Weight-for-height	
	(1)	(2)	(3)	(4)
Water quality (1 = E. coli present)	0.073* (0.044)	0.070 (0.044)	-0.333** (0.170)	-0.338* (0.171)
	Weight-for-age		ARI	
	(5)	(6)	(5)	(8)
	-0.283* (0.149)	-0.274* (0.151)	0.060* (0.035)	0.060* (0.035)
Piped water		Yes		Yes
Motorized pump/borehole		Yes		Yes
Water treatment		Yes		Yes
Handwashing		Yes		Yes
Flush toilet	Yes	Yes	Yes	Yes
Animal ownership	Yes	Yes	Yes	Yes
Other controls (all)	Yes	Yes	Yes	Yes

Clustered standard errors (robust) at the MICS cluster level are in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Access to flush toilets and animal ownership are included as control variables.

Appendix Table 5: Impact of drinking water quality (measured as log of E. coli [CFU/100 ml]) on child health

Variables	Diarrhoea	Weight-for-height	Weight-for-age	ARI
	(1)	(2)	(3)	(4)
Water quality				
(log [E.coli measured in CFU/100ml])	0.013*	-0.062**	-0.052*	0.011*
	(0.008)	(0.031)	(0.027)	(0.006)
F-Statistics		353.8		
Controls (all)	Yes	Yes	Yes	Yes

Clustered standard errors (robust) at the MICS cluster level are in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. N = 12,547.

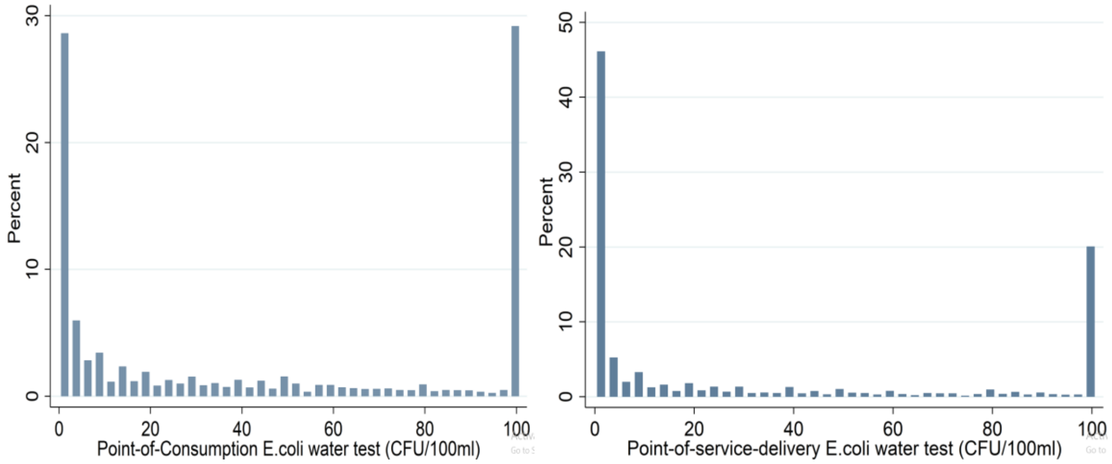

Figure 1. Point of consumption and source water quality status (E.coli [CFU/100 ml])

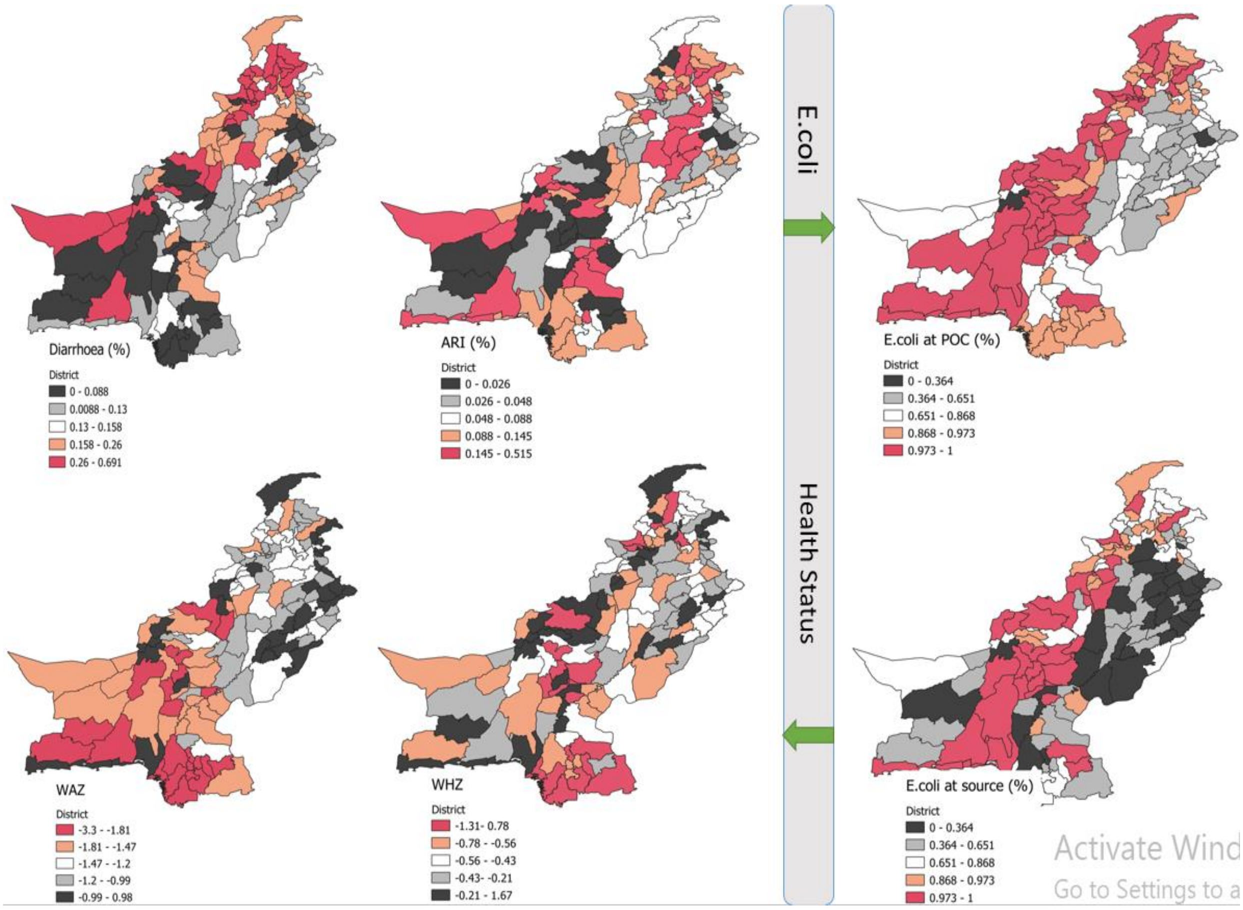

Figure 2. Microbial contamination and child health status at the district level