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Monitoring Drinking Water Quality in Nationally Representative Household Surveys in Low- and Middle-Income Countries: Cross-Sectional Analysis of 27 Multiple Indicator Cluster Surveys 2014–2020

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Background: The 2030 Sustainable Development Goals (SDGs) set an ambitious new benchmark for safely managed drinking water services (SMDWs), but many countries lack national data on the availability and quality of drinking water.

Objectives: We quantified the availability and microbiological quality of drinking water, monitored SMDWs, and examined risk factors for *Escherichia coli* (*E. coli*) contamination in 27 low-and middle-income countries (LMICs).

Methods: A new water quality module for household surveys was implemented in 27 Multiple Indicator Cluster Surveys. Teams used portable equipment to measure *E. coli* at the point of collection (PoC, $n = 61{,}170$) and at the point of use (PoU, $n = 64{,}900$) and asked respondents about the availability and accessibility of drinking water. Households were classified as having SMDW services if they used an improved water source that was free of *E. coli* contamination at PoC, accessible on premises, and available when needed. Compliance with individual SMDW criteria was also assessed. Modified Poisson regression was used to explore household and community risk factors for *E. coli* contamination.

Results: *E. coli* was commonly detected at the PoC (range 16–90%) and was more likely at the PoU (range 19–99%). On average, 84% of households used an improved drinking water source, and 31% met all of the SMDW criteria. *E. coli* contamination was the primary reason SMDW criteria were not met (15 of 27 countries). The prevalence of *E. coli* in PoC samples was lower among households using improved water sources [risk ratio (RR) = 0.74; 95% confidence interval (CI): 0.64, 0.85] but not for households with water accessible on premises (RR = 0.99; 95% CI: 0.94, 1.05) or available when needed (RR = 0.95; 95% CI: 0.88, 1.02). *E. coli* contamination of PoU samples was less common for households in the richest vs. poorest wealth quintile (RR = 0.70; 95% CI: 0.55, 0.88) and in communities with high (>75%) improved sanitation coverage (RR = 0.94; 95% CI: 0.90, 0.97). Livestock ownership (RR = 1.08; 95% CI: 1.04, 1.13), rural vs. urban residence (RR = 1.10; 95% CI: 1.04, 1.16), and wet vs. dry season sampling (RR = 1.07; 95% CI: 1.01, 1.15) were positively associated with contamination at the PoU.

Discussion: Cross-sectional water quality data can be collected in household surveys and can be used to assess inequalities in service levels, to track the SDG indicator of SMDWs, and to examine risk factors for contamination. There is an urgent need for better risk management to reduce widespread exposure to fecal contamination through drinking water services in LMICs. https://doi.org/10.1289/EHP8459

Introduction

The Sustainable Development Goals (SDGs) set ambitious targets for universal access to safe drinking water, sanitation, and hygiene (WASH) by 2030. Expert consultations and negotiations between United Nations Member States led to the adoption of a new global indicator 6.1.1, the "use of safely managed drinking water services." Safely managed drinking water services (SMDWs) are defined as improved sources of drinking water (piped water, boreholes/tube wells, protected dug wells and springs, rainwater collection, packaged or delivered water), that are accessible on premises and provide water that is available when needed and free from fecal and priority chemical contamination (WHO/UNICEF 2017a).

The World Health Organization (WHO) and United Nations Children's Fund (UNICEF), through the Joint Monitoring Program (JMP) for Water Supply, Sanitation and Hygiene, are mandated to monitor the SDG global indicators for WASH and released baseline estimates in July 2017 (WHO/UNICEF 2017a) and updated estimates in 2019 (WHO/UNICEF 2019) and 2021 (WHO/UNICEF 2021). The JMP reports confirm earlier studies suggesting widespread exposure to contamination through drinking water in low- and middle-income countries (LMICs) (Bain et al. 2014) and estimating that ~2 billion people drink water from sources that contain fecal indicator bacteria (Onda et al. 2012). Although the importance of water quality is increasingly recognized by policymakers, the 2019 JMP report found that only 98 of the 193 UN Member States had sufficient data at the national level to report on water quality for Target 6.1 (WHO/UNICEF 2019). There is an urgent need to expand the monitoring of drinking water quality to inform national efforts to achieve SMDW services by 2030.

WHO guidelines recommend that drinking water should be free from pathogens and elevated levels of harmful substances at all times (WHO 2017). Globally, the highest priority parameters for health are fecal contamination, arsenic, and fluoride. The presence of *E. coli* is considered a reliable indicator of fecal contamination, but brief events may escape detection even with regular testing, so its absence indicates low risk but does not guarantee safety (Charles et al. 2020). For the purposes of SDG monitoring, "free from contamination" implies that drinking water does not contain *E. coli* or thermotolerant coliforms (in a 100-mL sample) or elevated levels of arsenic (>10-μg/L), or fluoride (>1.5-mg/L).

Data on drinking water quality primarily come from administrative sources, including regulators that collect information from utilities. Regulatory coverage varies but is generally better for urban than for rural populations and for those who do not use piped water (Kumpel et al. 2016). As a result, data on water quality are often lacking for the majority of the population in many LMICs. To address this data gap, the JMP has supported the

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piloting and scale-up of water quality testing in nationally representative multitopic household surveys (WHO/UNICEF 2020). This approach enables the collection of data at comparatively low cost that can be linked with information on household characteristics (e.g., health, nutrition, education, wealth, ethnicity). Data from household surveys were critical to MDG WASH monitoring and are expected to continue to be a major data source for SDG monitoring alongside administrative sources and regulators (Bartram et al. 2014; WHO/UNICEF 2017b).

In collaboration with the UNICEF-supported Multiple Indicator Cluster Surveys (MICS), a new water quality module was developed during the fifth round of surveys (MICS5 2013–2017) and offered as a standard module in the sixth round of surveys (MICS6 2017–present) (WHO/UNICEF 2020). To date, 27 countries have published nationally representative data collected through the MICS, providing an unprecedented opportunity to examine risk factors for fecal contamination of drinking water in LMICs. The MICS used a standardized approach to achieve robust random selection of households and collect quantitative information on *E. coli* levels and samples at both the point of collection (PoC) and point of use (PoU). As such, these data address several key limitations identified by systematic reviews of water quality in LMICs (Bain et al. 2014; Shields et al. 2015; Wright et al. 2004) and enable a multicountry assessment informed by prior research on household- and community-level risk factors for *E. coli* contamination (Cronin et al. 2017; Harris et al. 2017; Kandel et al. 2017; Kirby et al. 2016; Kumpel et al. 2016; Pickering et al. 2010; Wang et al. 2017b; Wardrop et al. 2018; Yang et al. 2013).

The objectives of this study were to describe the main features of the new water quality module; to explore patterns in water quality by country, type of water source, and wealth; and to compare coverage of the MDG "improved" and SDG "safely managed" indicators for drinking water. Multivariable regression was used to examine household- and community-level risk factors for fecal contamination, including accessibility and availability of drinking water.

Methods

MICS Surveys

The MICS is a survey program supported by UNICEF and is one of the largest sources of data on populations, having covered over 120 countries with over 300 surveys in the past 25 y (Khan and Hancioglu 2019). The surveys are implemented by national governments with technical assistance from UNICEF for all stages of implementation. Surveys are cross sectional and use a multistage stratified sampling approach where enumeration areas (often between 100 and 250 households) in the national census are selected randomly, and then clusters of households (usually 20–25) are randomly selected within these enumeration areas. Each household has a known probability of selection, enabling national estimates to be generated. To ensure an adequate sample size for subnational regions, the sample is usually stratified (e.g., urban/rural and geographic regions). The MICS cover a range of topics, including household assets, water and sanitation, child labor and protection issues, health of children, women and men, and nutrition. Interview teams are composed of female and male interviewers to perform same-sex interviewers, a van driver, a supervisor, and a measurer who is tasked with taking the height and weight of children for the anthropometry module. The MICS is conducted in rounds, and countries that have implemented surveys in each round typically conduct a survey once every 3–5 y.

The water quality module was developed as a collaboration between the JMP and the global MICS program. It was first piloted in Bogra and Sirajgani districts, Bangladesh, in April/May 2012 prior to being adopted in the national MICS Bangladesh survey in 2012–2013. The procedures have evolved since the pilot study and further details are provided in the respective survey final reports (https://mics.unicef.org/surveys).

In this study, we used the most recent MICS survey in each country that integrated water quality testing in MICS between 2014 and 2020 and for which data are publicly available (Table 1; Figure 1). In total 27 surveys were included.

Water Quality Module

The procedures for the standardized module are described in the "MICS Manual for Water Quality" and "MICS Water Quality Testing Questionnaire," both available on the MICS website (https://mics.unicef.org/tools). The standardized module is available in Arabic, English, French, Russian and Spanish.

The module was conducted in a subsample of households (between 3 and 5) within each cluster. Not every household was selected in order to minimize the cost and workload and because it was anticipated that the marginal gains of increasing the sample size would be small owing to intra-cluster correlation (households in the same cluster having similar water quality).

In households selected for water quality testing, the interviewer requested permission to collect samples of drinking water, asking the respondent for a "glass of drinking water" (i.e., the PoU) and to be shown the location of the source of the drinking water (i.e., the PoC) to take a sample from that location. The two samples were analyzed to examine differences in quality between the PoC and the PoU (Shields et al. 2015; Wright et al. 2004). The water quality testing questionnaire included sections for the interviewer to record test results. It also included specific questions on the source of the glass of drinking water and an observation of water storage practices.

The field team member responsible for water quality testing differed between surveys depending on the distribution of other tasks. The measurer who was responsible for anthropometry usually conducted the water quality test. In some countries, either the male interviewer or the supervisor was selected to distribute workload more evenly across the field team.

An international water quality trainer working alongside national experts led the training of the field teams. A standard training program was used and adapted depending on the size of the survey and number of field teams. For example, in Nigeria a centralized training of trainers was followed by zonal trainings by microbiologists selected by the Federal Ministry of Water Resources. A hands-on training course lasting between 2 and 6 d usually included field practice, a strong focus on aseptic procedure, and understanding the different scenarios that testers might face through role-play. National experts from regulatory agencies, research laboratories, or ministries of health provided technical input to the training and oversight during the fieldwork through a small number of field visits to allow for observation of the testing procedure.

Water Quality Assessment

Water samples were analyzed for *E. coli* using a portable membrane filtration apparatus (Figure S1). *E. coli* was measured by field teams, who filtered 100 mL of sample through a 0.45-μm filter (Millipore Microfil), which was then placed onto CompactDry EC growth media plates (Nissui) that had been rehydrated with 1 mL of sample water. In MICS5 surveys, an additional 1-mL sample was also tested directly on a second media plate. Water samples were either collected directly into the preassembled membrane filtration apparatus or using sterile Whirl-Pak sample collection bags (Enasco). Samples were analyzed on-site within 30 min and incubated overnight (24–48 h) in either an electric incubator (Lynd) or

Table 1. Nationally representative Multiple Indicator Cluster Surveys (MICS) that had integrated water testing, 2014–2020.

Country (MICS round)	Fieldwork	Households interviewed $\{n/N$ [response rate (%)]$\}^a$	Samples at PoC $\{n/N$ [response rate (%)]$\}^b$	Samples at PoU $\{n/N$ [response rate (%)]$\}^c$	Clusters	Teams	Implementing agencies	Technical assistance for water quality testing	Training duration (d)
Algeria (MICS6)	December 2018–April 2019	29,919/30,930 (96.7)	3,137/4,097 (76.6)	4,076/4,097 (99.5)	1,253	45	Ministère de la Santé, de la Population et de la Réforme Hospitalière	Laboratory staff from Ministère de la Santé, de la Population et de la Réforme Hospitalière	5
Bangladesh (MICS6)	January–June 2019	61,242/61,602 (99.4)	6,069/6,150 (98.7)	6,140/6,150 (99.8)	3,220	34	Bangladesh Bureau of Statistics	International Center for Diarrhoeal Disease Research, Bangladesh	5
Central African Republic (MICS6)	December 2018–June 2019	8,133/8,302 (98.7)	1,048/1,228 (85.3)	1,212/1,228 (98.7)	451	20	Institut Centrafricain des Statistiques et des Etudes Economiques et Sociales	Direction Générale de l'Hydraulique	6
Chad (MICS6)	May–December 2019	18,967/19,034 (99.6)	2,166/2,284 (94.8)	2,274/2,284 (99.6)	769	25	Institut National de la Statistique, des Etudes Economiques et Démographiques	Ministère des Ressources en Eau	4
Congo (MICS5)	November 2014–February 2015	12,811/12,868 (99.6)	1,277/1,573 (81.2)	1,507/1,573 (95.8)	531	19	Institut National de la Statistique	Société nationale de distribution d'eau	5
Côte d'Ivoire (MICS5)	April–July 2016	11,879/12,303 (96.6)	1,782/1,926 (92.5)	1,908/1,926 (99.1)	511	21	Institut National de la Statistique	Institut National d'Hygiène Publique and Laboratoire National de Santé Publique	5
Gambia (MICS6)	January–April 2018	7,405/7,517 (98.5)	1,764/1,879 (93.9)	1,865/1,879 (99.3)	390	8	Gambia Bureau of Statistics	Ministry of Water Resources	5
Georgia (MICS6)	September–December 2018	12,270/13,030 (94.2)	2,429/3,059 (79.4)	2,699/3,059 (88.2)	706	13	National Statistics Office of Georgia	National Center for Disease Control and Public Health	3
Ghana (MICS6)	October 2017–January 2018	12,886/12,960 (99.4)	3,161/3,222 (98.1)	3,219/3,222 (99.9)	660	25	Ghana Statistical Service	Water Research Institute and Ghana Water Company	4
Guinea-Bissau (MICS6)	November 2018–March 2019	7,379/7,394 (99.8)	1,784/1,829 (97.5)	1,828/1,829 (99.9)	375	8	Instituto Nacional de Estatística	—	6
Iraq (MICS6)	March–May 2018	20,214/20,318 (99.5)	6,687/6,733 (99.3)	6,724/6,733 (99.9)	1,710	39	Central Statistical Organization and Kurdistan Region Statistical Office	Central Public Health Laboratory	2
Kiribati (MICS6)	November 2018–January 2019	3,071/3,113 (98.7)	589/626 (94.1)	622/626 (99.4)	164	9	Kiribati National Statistics Office	Ministry of Health and Ministry of Infrastructure and Sustainable Energy	4
Lao People's Democratic Republic (MICS6)	July–November 2017	22,287/22,443 (99.3)	3,292/3,360 (98.0)	3,346/3,360 (99.6)	1,165	25	Lao Statistics Bureau	Center for Environmental Health and Water Supply (Nam Saat)	4
Lesotho (MICS6)	April–September 2018	8,847/9,227 (95.9)	1,339/1,376 (97.3)	1,373/1,376 (99.8)	400	15	Bureau of Statistics	Ministry of Health and Ministry of Water Affairs	3
Madagascar (MICS6)	August–November 2018	17,870/18,291 (97.7)	3,265/3,439 (94.9)	3,433/3,439 (99.8)	774	30	L'Institut National de la Statistique de Madagascar	Ministre de Santé and the Ministre de l'Eau	3
Mongolia (MICS6)	September–December 2018	13,798/14,041 (98.3)	2,598/2,764 (94.0)	2,736/2,764 (99.0)	580	19	National Statistical Office	UNICEF Mongolia	3

Table 1. (*Continued.*)

Country (MICS round)	Fieldwork	Households interviewed {n/N [response rate (%)]}[a]	Samples at PoC {n/N [response rate (%)]}[b]	Samples at PoU {n/N [response rate (%)]}[c]	Clusters	Teams	Implementing agencies	Technical assistance for water quality testing	Training duration (d)
Nepal (MICS6)	May–November 2019	12,655/12,687 (99.5)	2,445/2,547 (96.0)	2,536/2,547 (99.6)	512	16	Central Bureau of Statistics	Environment and Public Health Organization	5
Nigeria (MICS5)	September 2016–January 2017	33,901/34,289 (98.9)	2,722/3,058 (89.0)	3,053/3,058 (99.8)	2,239	78	National Bureau of Statistics	Federal Ministry of Water Resources	5
Palestine (MICS6)	December 2019–January 2020	9,326/9,751 (95.6)	1,819/1,909 (95.3)	1,848/1,909 (96.8)	420	36	Palestinian Central Bureau of Statistics	Palestinian Water Authority	5
Paraguay (MICS5)	June–September 2016	7,313/7,594 (96.3)	1,750/1,814 (96.5)	1,790/1,814 (98.7)	499	15	Dirección General de Estadística, Encuestas y Censos	Ente Regulador de Servicios Sanitarios	2
Sao Tome and Principe (MICS6)	August–October 2019	3,426/3,469 (98.8)	342/572 (59.8)	571/572 (99.8)	127	8	Instituto Nacional de Estatística	—	6
Sierra Leone (MICS6)	May–August 2017	15,309/15,364 (99.6)	1,748/1,784 (98.0)	1,780/1,784 (99.8)	600	24	Statistics Sierra Leone	Ministry of Water Resources	5
Suriname (MICS6)	March–August 2018	7,915/8,771 (90.2)	1,619/1,982 (81.7)	1,701/1,982 (85.8)	470	10	General Bureau of Statistics	Suriname Water Supply Company and the Bureau of Public Health	4
Togo (MICS6)	July–October 2017	7,916/8,065 (98.2)	1,088/1,157 (94.0)	1,153/1,157 (99.7)	420	16	Institut National de la Statistique et des Etudes Economiques et Démographiques	Institut National d'Hygiène	5
Tonga (MICS6)	October–December 2019	2,498/2,543 (98.2)	543/628 (86.5)	613/628 (97.6)	139	8	Tonga Statistics Department	Ministry of Health	4
Tunisia (MICS6)	March–May 2018	11,225/11,473 (97.8)	2,664/2,805 (95.0)	2,769/2,805 (98.7)	600	32	Institut National de la Statistique	Ministry of Health, Department of Environmental Hygiene and Environmental Protection	3
Zimbabwe (MICS6)	January–April 2019	11,091/11,313 (98)	2,043/2,138 (95.6)	2,124/2,138 (99.3)	462	17	Zimbabwe National Statistics Agency	Ministry of Health and Child Care	4
Total	—	391,553/398,692 (98.2)	61,170/65,939 (92.8)	64,900/65,939 (98.4)	20,147	615	—	—	—

Note: —, not applicable; MICS5, fifth round of Multiple Indicator Cluster Surveys; MICS6, sixth round of Multiple Indicator Cluster Surveys; PoC, point of collection; PoU, point of use; UNICEF, United Nations Children's Fund.
[a]Household response rate: proportion of completed household interviews of all occupied households.
[b]PoC response rate: Proportion of households with water quality samples at PoC of occupied households selected for water quality testing. Number of samples does not exclude invalid test results. See Figure 1 for the number of samples excluded from analysis.
[c]PoU response rate: proportion of households with water quality samples at PoU of occupied households selected for water quality testing. Number of samples does not exclude invalid test results. See Figure 1 for the number of samples excluded from analysis.

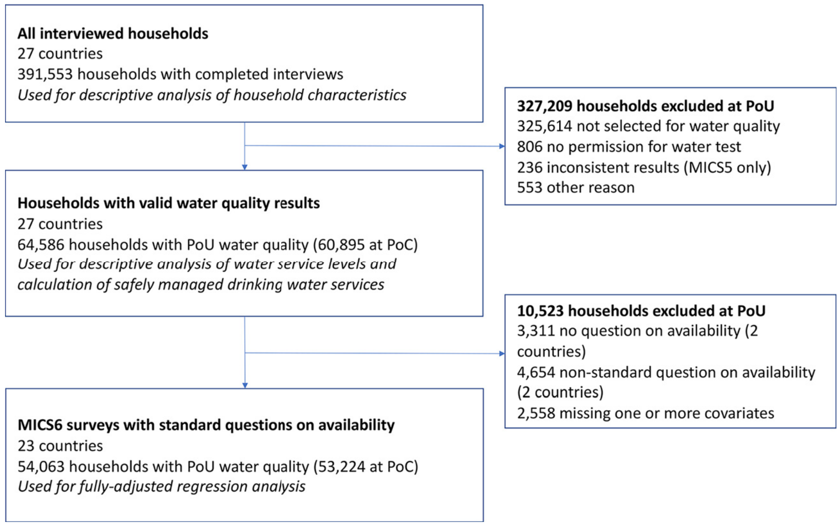

Figure 1. Study flow diagram. Note: MICS5, fifth round of the Multiple Indicator Cluster Surveys; MICS6, sixth round of the Multiple Indicator Cluster Surveys; PoC, point of collection; PoU, point of use.

incubation belt/pouch specifically designed to keep samples at close to body temperature. The number of *E. coli* (blue) and total coliform (red/purple) colonies were enumerated by eye the following day and recorded in the water quality testing questionnaire. Survey teams recorded cases where there were >100 colonies on a given plate and in cases where the plate turned red/purple or blue as "too numerous to count." For more recent surveys (i.e., MICS6), "*E. coli* only" CompactDry plates were used, with the advantage that the second media plate was not needed to count up to 100 *E. coli*. The levels of *E. coli* were classified according to the number of colony forming units (CFUs) per 100 mL as follows: <1, low risk; 1–10, moderate risk; 11–100, high risk; and >100, very high risk (WHO/UNICEF 2012; WHO 2017).

The use of 100- and 1-mL samples in MICS5 allowed for inconsistency checks to examine whether the combination of results was improbable and suspected to be the result of errors in the test procedure or data recording. Results were excluded from analysis if the 100-mL test was <10 *E. coli* CFUs and 1-mL test had at least one CFU (Flag I) or the 1-mL sample count was greater than the 100-mL sample count, provided both were nonzero and countable (Flag II). The proportion of samples recorded as potentially inconsistent and excluded from analysis was found to range from 1.6% in Côte d'Ivoire to 4.9% in Nigeria (Table S1). Inconsistency checks were not required for MICS6 surveys owing to the use of "*E. coli* only" CompactDry plates, which meant only a 100-mL sample was assessed.

A key measure of quality control used in water quality analysis is a blank test, a sample used to ensure that the analyst has not inadvertently contaminated the sample and is able to consistently produce the expected negative results. In each survey, blank tests (usually one per cluster) were conducted by the field teams to provide confidence in the results. Water for the blank test was obtained from a reliable brand of mineral water or distilled/deionized water. The proportion of positive blanks was ≤2.5% in 24 of 27 countries, indicating high levels of compliance with testing procedures, but there were elevated proportions in Côte d'Ivoire (8.2%), Gambia (6.2%), and Chad (3.6%) (Table S2).

Accessibility and Availability of Drinking Water Services

The WASH module in the MICS started with a question enquiring what type of drinking water source is usually used by household members. Households were then asked where the water source is located (inside dwelling, in yard/plot, elsewhere) and, for water not located on premises, how long it takes to collect drinking water from the main source. Drinking water "accessible on premises" refers to water sources that were located on premises by definition (piped to dwelling, plot, or yard) or reported as being located within the dwelling or in the yard/plot. Households reporting using a source located elsewhere but where members did not collect water themselves were considered to have water accessible on premises.

The MICS6 household questionnaire (https://mics.unicef.org/tools) was adapted to include a new question on the availability of drinking water aligned with the JMP core questions (WHO/UNICEF 2018a): "In the last month, has there been any time when your household did not have sufficient quantities of drinking water?" In MICS5, different availability questions were asked in Nigeria ("Was the water from this source not available for at least one full day?") and Paraguay ("In the last 15 days has there been any time you have not been able to access water in sufficient quantities?"). Households without sufficient water in the preceding month were then asked to identify the main reason (water not available from source, water too expensive, source not accessible or other reason).

SMDW services were calculated based on the household's main source of drinking water. Households were asked whether the glass of drinking water provided by the respondent was from their main source ("Is this water from the main source of drinking water used by members of your household?"). In all countries, the main source of drinking water and the source of the water quality sample (where this differed) were recorded. Overall, 93% of samples were from the same category of water source, but concordance was lower for Kiribati (73%) and Chad (79%) (Table S3). Multiple source use has previously been documented (Daly et al. 2021), including in the Pacific (Elliott et al. 2017), and may be the reason for these differences.

Calculation of SMDW Services

SDMW services are defined as improved sources of drinking water, accessible on premises, available when needed, and free from fecal and priority chemical contamination (United Nations 2017). For the countries with information on accessibility, availability, and quality ($n = 25$) we estimated the proportion of the national population using improved drinking water sources

(MDG indicator) and SMDW services (SDG indicator) taking into consideration all three criteria. For the remaining countries ($n = 2$, Congo and Côte d'Ivoire) all improved water sources meeting the quality and accessibility criteria were assumed to be available when needed.

We calculated estimates for SMDW services based on information from individual households (household-level) and also using the approach taken by the JMP whereby a minimum of the three criteria for whether drinking water services are safely managed is used at the domain-level. For global monitoring the JMP uses the domain-level approach to accommodate estimates drawn from different data sources because relatively few countries have all of the information required to calculate the new SMDW indicator from a single data source (WHO/UNICEF 2018b). The JMP calculates SMDW as the minimum of improved and accessible, improved and available, and improved and free from *E. coli* contamination. When information on all of the criteria for SMDW are available from a single data source, as is the case in the MICS, they can be combined at the household level, which produces substantially lower estimates.

Data Analysis

Descriptive Analysis

Data were downloaded from the MICS website (https://mics.unicef.org/surveys). Data analysis was conducted using Stata (release 16; StataCorp). For each survey, descriptive statistics and 95% CIs were calculated using appropriate sample weights and taking into account the stratification and clustering using the *svy* command. Separate sample weights were calculated for the source and household water quality samples because of the different subsamples used and the response rates. Normalized sample weights for each country and indicator were used to calculate pooled mean estimates. Information on drinking water quality was combined with data from the household questionnaire (type of water source, household assets) to examine patterns in water quality for different population subgroups and to calculate the proportion of the population using SMDW services. To examine differences in water quality between the PoC and the PoU, we calculated the difference in *E. coli* risk level for households with samples at both locations to determine whether the risk level was lower, higher, or the same between the PoC and the PoU. This analysis was repeated for the subset of households with *E. coli* detected at the PoC and self-reporting appropriate household water treatment practices (i.e., boiling, filtration, adding chlorine, and solar disinfection). As a measure of absolute inequalities, we calculated risk differences (RDs) in *E. coli* contamination between the richest and poorest quintiles at the PoC and the PoU.

Risk Factors for Contamination

To explore risk factors for fecal contamination of drinking water at the PoC and the PoU, we used bivariate and multivariable modified Poisson regression models, with the results reported as risk ratios (RRs) (Zou 2004). Modified Poisson regression is particularly suited to indicators with a high prevalence and has been used in recent studies of handwashing and the association between water and sanitation and trachoma (Garn et al. 2018; Wolf et al. 2019). The binary dependent variables in these models were the detection of any *E. coli* contamination (≥ 1 CFU/100 mL) or very high *E. coli* contamination (>100 CFU/100 mL) at the PoC or the PoU. Pooled estimates were generated using a multilevel model with random intercepts for each country (Gelman and Hill 2007). Random intercepts for clusters were not included in order to improve convergence, and we used equiprobability weights for the regression analysis. Separate country-level models with cluster random intercepts were fit to examine their contributions to the pooled estimates and to calculate unadjusted and adjusted RRs for each country. Covariates were excluded from country-level models where there were <25 households in a response category (e.g., for open defecation in Georgia).

To examine the relationships between the criteria for SMDW services and water quality, we modeled the presence of *E. coli* (any and very high) in PoC or PoU samples in relation to improved water source (yes/no), drinking water source accessible on premises (yes/no), and available when needed (yes/no; based on the standardized questions in MICS6 surveys). These models were adjusted for household-level covariates: rural or urban residence, wealth index quintiles (poorest 20% through richest 20%, as defined in MICS), improved sanitation (yes/no), shared sanitation (yes/no), education (head of household; none/primary vs. secondary or higher), female head of household (yes/no), livestock ownership (yes/no), and wet season (yes/no). In addition, we adjusted for cluster-level indicators of improved sanitation ($>75\%$ of households vs. $\leq 75\%$), and open defecation (≥ 1 household in cluster or none). Models of contamination at the PoU were also adjusted for household-level natural flooring (earth, sand, or dung; yes/no), handwashing (observed facilities with soap and water; yes/no), water storage (storage in covered or uncovered containers vs. direct from source; yes/no), and appropriate water treatment practices (self-reported boiling, filtration, addition of chlorine/bleach, or solar disinfection; yes/no.). Wet seasons were defined based on a simplified version of the accumulation method (Wright et al. 2012). For each country, mean monthly precipitation data 2000–2020 were obtained from the Climatic Research Unit (Harris et al. 2020). We defined the wet season as consecutive months with the highest cumulative precipitation above the yearly average (Table S4). For Congo and Sao Tome and Principe, we identified two distinct wet seasons.

In a second set of models, we modeled fecal contamination in association with specific improved water sources (piped, packaged, boreholes/tube wells, rainwater collection, delivered water, protected wells and springs), using unimproved sources as a common reference group instead of modeling a dichotomous indicator for water from any improved source (yes/no). These models also included indicators for water accessibility (yes/no) and availability (yes/no), as well as the covariates listed above.

Sensitivity Analysis

We conducted sensitivity analyses to assess the robustness of the pooled regression models to alternative specifications. First, we examined the impact of excluding MICS6 surveys with the highest proportion of positive blank tests (Chad, Gambia) and excluding clusters with positive blank test results from the regression models. Second, we constructed custom wealth index quintiles, excluding WASH variables from the principal component analysis to account for potential tautology between the definition of wealth and other predictors of water quality (Martel 2017). The custom wealth quintiles were prepared in SPSS by removing all WASH assets from existing MICS wealth quintile scripts. It was hypothesized that inclusion of WASH variables in the definition of wealth might influence the association between contamination and wealth. Third, we restricted the analysis at the PoU to samples that were contaminated at the PoC in order to assess whether self-reported household water treatment was associated with reduced risk of contamination at the PoU for the subset of households where drinking water was contaminated at the PoC. Last, we reran the pooled regression models with weights based on the inverse of the sample size for each country to assess whether giving equal weight to each country would impact the pooled estimates.

Results

Survey Characteristics

The total number of households interviewed ranged from 2,498 (Tonga) to 61,242 (Bangladesh), with a total sample size of >390,000 households (Table 1). Most households selected for the water quality module provided a sample of drinking water at the PoU (mean = 98%; range: 86–100%) and at the PoC (mean = 93%; range: 60–100%). The main reasons 5% of households did not show the interviewer their source of drinking water were that the source was too far (37%), not functional (22%), and not accessible (20%) (Table S5). The number of water quality samples collected per country ranged from 571 to 6,724 at the PoU ($n = 64{,}900$ in total) and 342 to 6,687 at PoC ($n = 61{,}170$ in total) (Table 1).

The proportion of the population using improved drinking water sources (the MDG indicator for drinking water) ranged from 43% in Madagascar to >95% in 10 countries (Excel Table S1). Drinking water was accessible on premises for <50% of the population in 12 countries and for >95% in Paraguay, Suriname, and Tonga. Availability of drinking water when needed ranged from 61% in Central African Republic (CAR) and 68% in Kiribati to >95% in Bangladesh and Lao People's Democratic Republic (Lao PDR). The main reasons given for water being unavailable in the past month (18%) were that the water was not available from the source (75%) and that the source was not accessible (10%) (Table S6). In 16 countries, <10% of the population self-reported appropriate treatment practices, but self-reported treatment practices were common in Kiribati (88%) and Mongolia (83%) (Excel Table S1). Where respondents were observed filling a glass of drinking water, this was often from a storage container (>50% in 17 of 24 countries), but in 5 countries (Georgia, Iraq, Palestine, Tunisia, and Suriname) >75% obtained water directly from the source.

Use of improved sanitation facilities ranged from 16% in Chad and 22% in CAR to >95% of the population in Algeria, Palestine, Tonga, and Tunisia (Excel Table S1). The proportion of the population with handwashing facilities with soap and water ranged from 12% in Nigeria to 97% in Iraq and was <50% in 12 countries. The proportion of household heads having a secondary education or higher ranged from 13% in CAR to 90% in Georgia. Livestock ownership ranged from 10% in Algeria to 89% in Kiribati. Natural flooring ranged from <1% in 6 countries to 61% in Bangladesh. Surveys were conducted primarily or exclusively in the dry season (overall, 8.1% of samples were conducted in the wet season).

Water Quality Results at the National Level

The proportion of the population using a drinking water source (either improved or unimproved) with detectable *E. coli* (≥1 *E. coli* CFUs/100 mL) ranged from to 16% (95% CI: 13, 18) in Mongolia and 16% (95% CI: 14, 19) in Algeria to 86% (95% CI: 84, 88) in Chad and 90% (95% CI: 87, 92) in Sierra Leone (Figure 2). More than one-third of the population used very high risk (>100 *E. coli* CFUs/100 mL) drinking water sources (>100 *E. coli* CFUs/100 mL) in CAR, Chad, Côte d'Ivoire, Kiribati, Lao PDR, Madagascar, Nigeria, Sierra Leone, and Togo.

The proportion of the population consuming drinking water with detectable *E. coli* at the PoU ranged from 19% (95% CI: 17, 22) in Mongolia to 99% (95% CI: 99, 100) in Chad. Over half the population were exposed to very high risk drinking water at the PoU in Chad, Madagascar, Nigeria, Sierra Leone, and Togo (Figure 3).

Differences in Water Quality between the PoC and the PoU

For the households with paired samples at the PoC and the PoU, it was possible to assess differences in risk level between the two sampling locations. A similar pattern was seen across the countries: The risk level was more often higher (10–66% of households) than lower (3–20% households) at the PoU; however, for most households, there was no difference in the risk level between the paired PoC and PoU samples (Figure S2).

For the majority of households with paired samples that used a contaminated drinking water source and self-reported appropriate water treatment practices, the risk level was the same or higher at the PoU than the PoC, except in Mongolia, where 72% of samples had a lower risk level at the PoU (Figure S3). For these households, *E. coli* was often detected at the PoU (>90% in 14 of 25 countries) and often very high risk (>25% in 15 of 25 countries) (Figure S4).

Water Quality by Water Source Type

E. coli contamination of PoC samples varied between water source types and between countries, but contamination in all source types ranged from low (<1 *E. coli* CFU/100 mL) to very high (>100 *E. coli* CFU/100 mL) (Figure 4; Excel Table S2). The general pattern suggests that piped water was often the most likely be free from *E. coli* contamination, followed by water from boreholes/tube wells then by packaged and delivered water. The quality of piped water varied considerably between countries, with >20% of the population using piped water that exceeded 100 *E. coli* CFUs/100 mL in Chad, Lao PDR, Nepal, Nigeria, and Sierra Leone. In Bangladesh, boreholes provided considerably higher quality water than piped water supplies (63% vs. 44% free from *E. coli*). Rainwater and protected wells and springs consistently had significant levels of contamination but appeared to be less frequently contaminated than unimproved sources. In countries with >25 samples for delivered water, it was usually free from *E. coli* in Algeria, Mongolia, Palestine, and Tunisia, but this was not the case in Iraq and Nigeria. Patterns at the PoU were similar, but risk levels were often higher (Excel Table S2).

Inequalities in Water Quality by Wealth Quintile

In all countries except Bangladesh, Kiribati, and Palestine, households in the poorest quintile were significantly more likely to use sources with *E. coli* at the PoC than households in the richest quintile (Figure 5; Excel Table S3). In Bangladesh, households in the poorest quintile were less likely than those in the richest quintile to use a contaminated drinking water source (RD = −8.5%; 95% CI: −13.5, −3.6) but more likely at the PoU (RD = 9.6%; 95% CI: 5.9, 13.4). Differences in proportion of the population with *E. coli* at the PoC between the richest and poorest quintiles exceeded 25% points in 17 countries (16 at the PoU) and 50% points in 7 countries (3 at the PoU). For example, in Georgia, 0.5% (95% CI: 1.7, 7.2) of PoC samples were contaminated among households in the richest quintile compared with 55.8% (95% CI: 58.0, 69.5) of samples among those in the poorest quintile.

Across all wealth quintiles, the proportion of samples with very high *E. coli* contamination was lower in PoC than PoU samples (Figure 5; Excel Table S3). In countries with lower national contamination levels (e.g., Palestine), absolute inequalities were generally larger for any contamination than for very high risk drinking water. In countries with higher national contamination levels (e.g., Chad), absolute inequalities were generally larger for very high risk drinking water than for any contamination.

Safely Managed Drinking Water Services

In 15 of 27 countries, the quality criterion for SMDW services was the least likely to be met, and in most other countries, accessibility on premises was the limiting factor (Table 2). The adjustment for accessibility, availability, and quality resulted in a

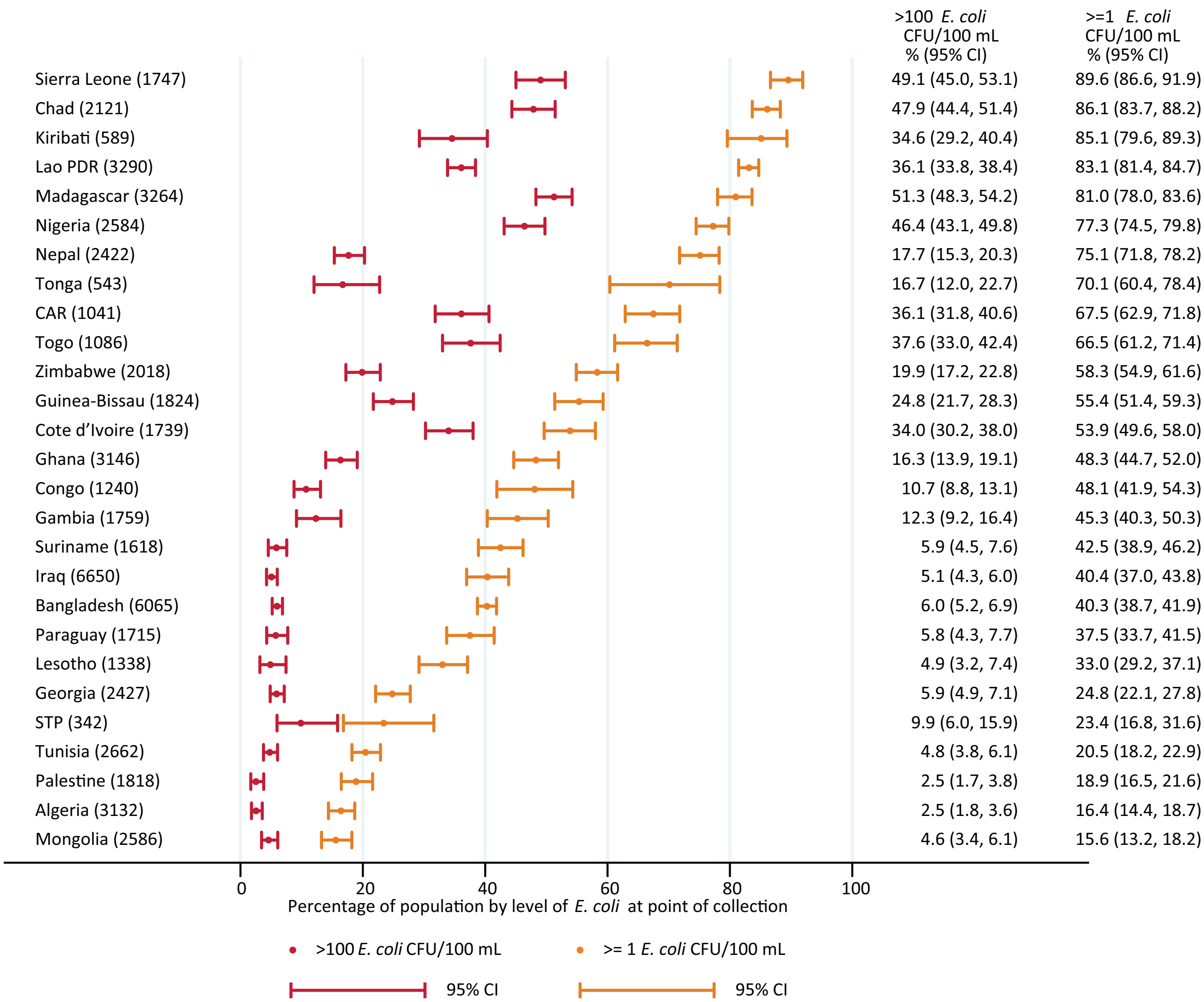

Figure 2. Proportion of population by level of *E. coli* in drinking water at point of collection in 27 low- and middle-income countries, 2014–2020. Corresponding numeric data are provided in Excel Table S2. Note: CAR, Central African Republic; CFU, colony forming unit; *E. coli*, *Escherichia coli*; Lao PDR, Lao People's Democratic Republic; STP, Sao Tome and Principe.

substantial reduction in all countries, including countries with a higher coverage of improved drinking water sources.

On average, 84.3% (95% CI: 83.8, 84.8) of households used an improved drinking water source, and 30.5% (95% CI: 29.3, 31.6) met all of the SMDW criteria (household-level SMDW). SMDW calculated at the domain level was higher than calculated at the household level.

Risk Factors for E. coli Contamination

Regression analyses were restricted to MICS6 surveys with standardized questions on availability of drinking water. Unadjusted (bivariate) regression analyses of *E. coli* contamination (any or very high, in PoC and PoU samples) showed that the three other SMDW criteria (improved, accessible, and available drinking water) and every covariate included in the fully adjusted multivariable models was a significant predictor of contamination in at least one country (Excel Table S4). In the pooled unadjusted estimates, *E. coli* at the PoC was strongly associated with improved water (RR = 0.63; 95% CI: 0.53, 0.74), and accessibility (RR = 0.80; 95% CI: 0.72, 0.90) but not availability (RR = 0.95; 95% CI: 0.87, 1.04).

Fully adjusted pooled estimates of associations between the individual SMDW criteria and fecal contamination indicated that the prevalence of any *E. coli* contamination in PoC samples was significantly lower in association with improved water sources (RR = 0.74; 95% CI: 0.64, 0.85), whereas the associations with accessibility (RR = 0.99; 95% CI: 0.94, 1.05) and availability (RR = 0.95; 95% CI: 0.88, 1.02) were close to the null and not significant (Table 3). Results for any contamination in PoU samples indicated an association with accessibility (RR = 0.94; 95% CI: 0.90, 0.99), but associations with improved water (RR = 0.96; 95% CI: 0.92, 1.01) and availability (RR = 0.96; 95% CI: 0.91, 1.01) were close to null and not significant. Corresponding associations with the prevalence of very high contamination (>100 *E. coli* CFU/100 mL) in PoC and PoU samples were stronger for improved water sources [RR = 0.43 (95% CI: 0.33, 0.56) and RR = 0.74 (95% CI: 0.66, 0.83) for the PoC and the PoU, respectively], but similar to associations with any contamination for accessibility and availability. All country-specific RRs for any contamination of PoC and PoU samples were ≤1 for improved water (except for PoC samples in Nepal and PoU samples in Mongolia and Nepal, all of which were nonsignificant) (Excel Tables S5 and S6). Country-specific estimates for accessibility

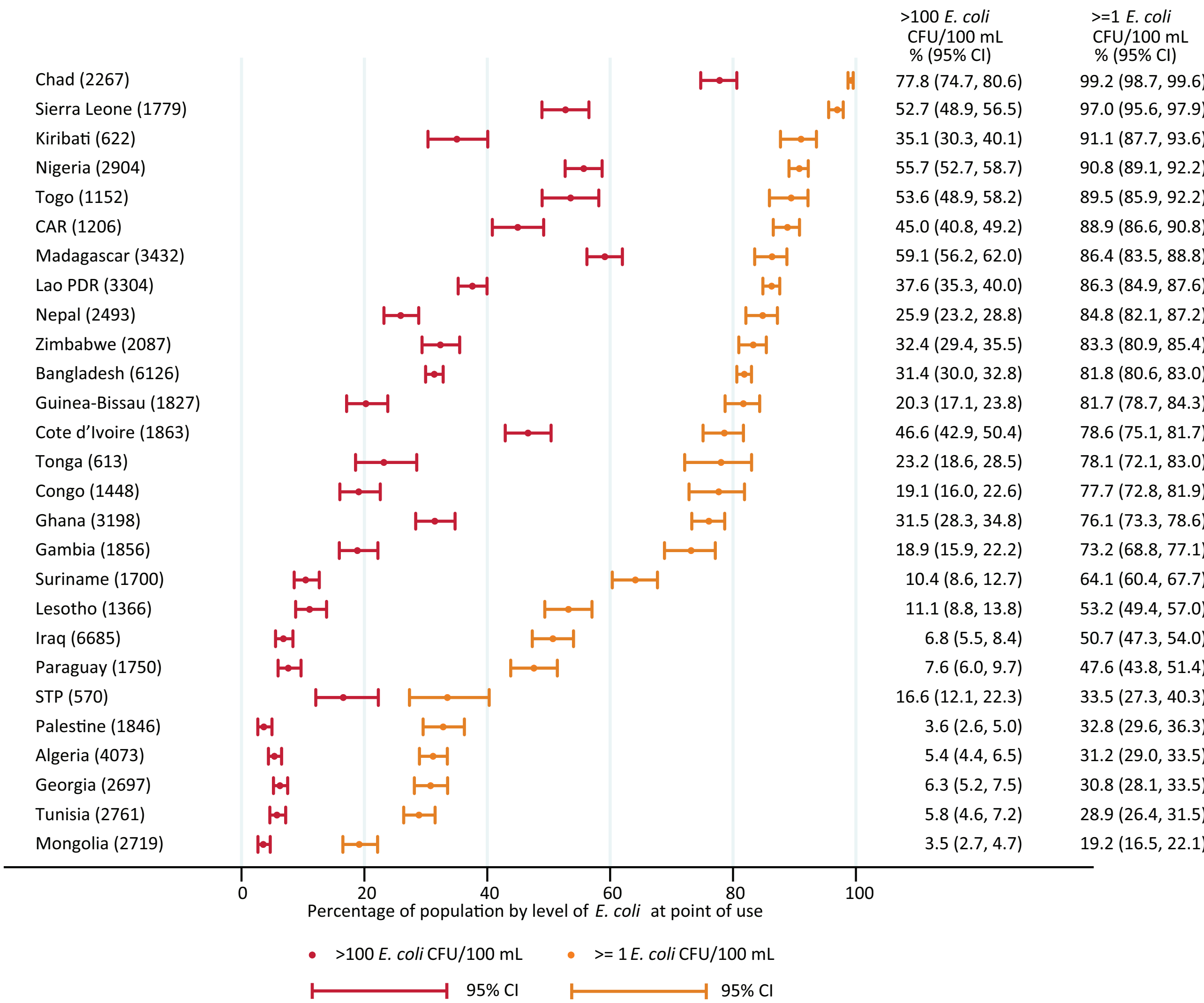

Figure 3. Proportion of population by level of *E. coli* in drinking water at point of use in 27 low- and middle-income countries, 2014–2020. Corresponding numeric data are provided in Excel Table S2. Note: CAR, Central African Republic; CFU, colony forming unit; *E. coli*, *Escherichia coli*; Lao PDR, Lao People's Democratic Republic; STP, Sao Tome and Principe.

and availability were heterogeneous, ranging from RR = 0.65 (95% CI: 0.42, 1.01) for Lesotho to RR = 1.31 (95% CI: 0.82, 2.10) for Tonga and RR = 0.61 (95% CI: 0.50, 0.74) for Algeria to RR = 1.35 (95% CI: 0.96, 1.90) for Sao Tome and Principe, at PoC. Country-specific estimates for very high contamination generally had lower RRs for improved water but were similar for accessibility and availability (Excel Tables S7 and S8).

Compared with unimproved water sources, pooled estimates suggest that for PoC samples, piped water (RR = 0.65; 95% CI: 0.55, 0.76) and boreholes/tube wells (RR = 0.59; 95% CI: 0.48, 0.72) were associated with a significantly lower prevalence of any *E. coli* contamination (Table 4). There was no clear difference in any contamination at the PoC for rainwater, delivered water, and protected wells and springs compared with unimproved sources (Table 4). In PoU samples, only piped water was associated with a significantly lower prevalence of *E. coli* contamination compared with unimproved sources (RR = 0.87; 95% CI: 0.82, 0.93). Compared with unimproved sources, packaged water, piped water, and boreholes were also associated with a significantly lower prevalence of very high risk drinking water (>100 *E. coli* CFUs/mL) for both PoC and PoU samples (Table 4).

Several covariates were also associated with the prevalence of *E. coli* contamination in PoC or PoU samples based on pooled estimates (Table 4). The prevalence of any contamination decreased as the wealth index increased, with RR = 0.70 (95% CI: 0.55, 0.88) for PoU contamination in the wealthiest quintile. Of the sanitation and hygiene indicators, only the cluster-level indicator for >75% improved sanitation was a significant predictor (PoU RR = 0.94; 95% CI: 0.90, 0.97). Having water storage onsite and self-reported use of appropriate water treatment were also associated with a lower prevalence of contamination, although associations were not significant [PoU RR = 0.91 (95% CI: 0.80, 1.04) and RR = 0.92 (95% CI: 0.83, 1.02), respectively]. Rural vs. urban residence and livestock ownership were positively associated with contamination [PoU RR = 1.10 (95% CI: 1.04, 1.16) and RR = 1.08 (95% CI: 1.04, 1.13), respectively]. Samples collected in the wet season were also positively associated with contamination at the PoU (RR = 1.07; 95% CI: 1.01, 1.15) but this was not significant at the PoC (RR = 1.05; 95% CI: 0.96, 1.16). Associations between covariates and any contamination of PoC samples, and very high contamination of PoC and PoU samples, were generally consistent with patterns for any contamination of PoU samples. Country-specific models showed

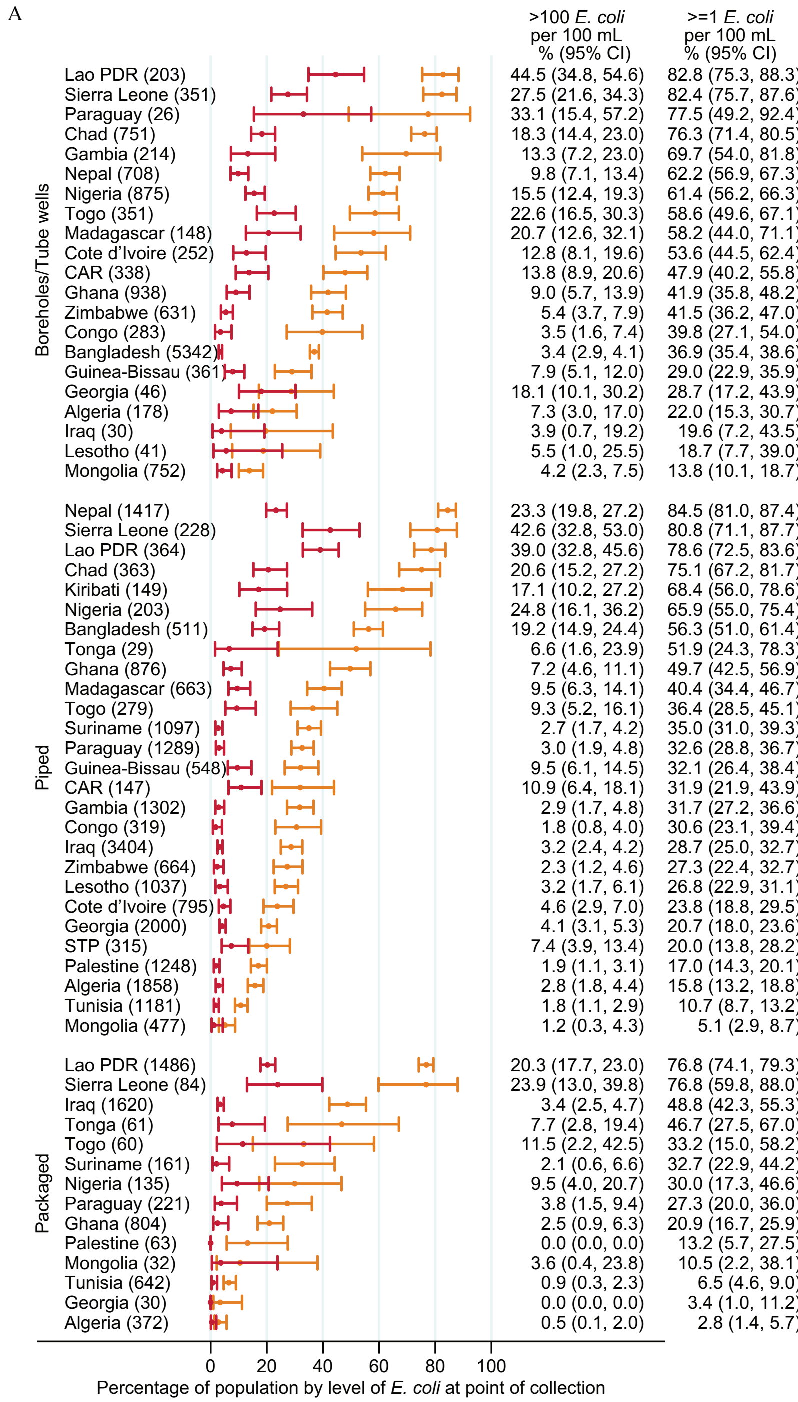

Figure 4. *E. coli* contamination of drinking water at point of use, by type of water source in 27 low- and middle-income countries, 2014–2020 for source types with at least 25 samples: (A) packaged, piped, and boreholes/tube wells; and (B) rainwater, delivered water, protected wells and springs, and unimproved water sources. Numbers in parentheses are the unweighted number of water sources tested for *E. coli* at point of collection. Corresponding numeric data are provided in Excel Table S2. Note: CAR, Central African Republic; CFU, colony forming unit; *E. coli*, *Escherichia coli*; Lao PDR, Lao People's Democratic Republic; STP, Sao Tome and Principe.

that all selected covariates were significantly associated with contamination at the PoC and the PoU in the fully adjusted models in at least one country (Excel Tables S9–S12). Self-reported household water treatment was significantly associated with a lower prevalence of any *E. coli* at the PoU in Lao PDR, Mongolia, Nepal, and Suriname, and Zimbabwe (Excel Table S11) and a lower prevalence of very high risk water in Lao PDR, Mongolia, and Sierra Leone (Excel Table S12).

Sensitivity Analysis

Excluding countries with the worst blank test results (Gambia, Chad) or clusters where blank tests were positive had a negligible impact on the RRs (Excel Table S13). Use of a custom wealth index excluding WASH variables marginally decreased the RRs for water supply types [e.g., RR = 0.65 (95% CI: 0.55, 0.76) to RR = 0.64 (95% CI: 0.54, 0.75) for piped water] and decreased the strength of the association with wealth [e.g., RR = 0.73 (95%

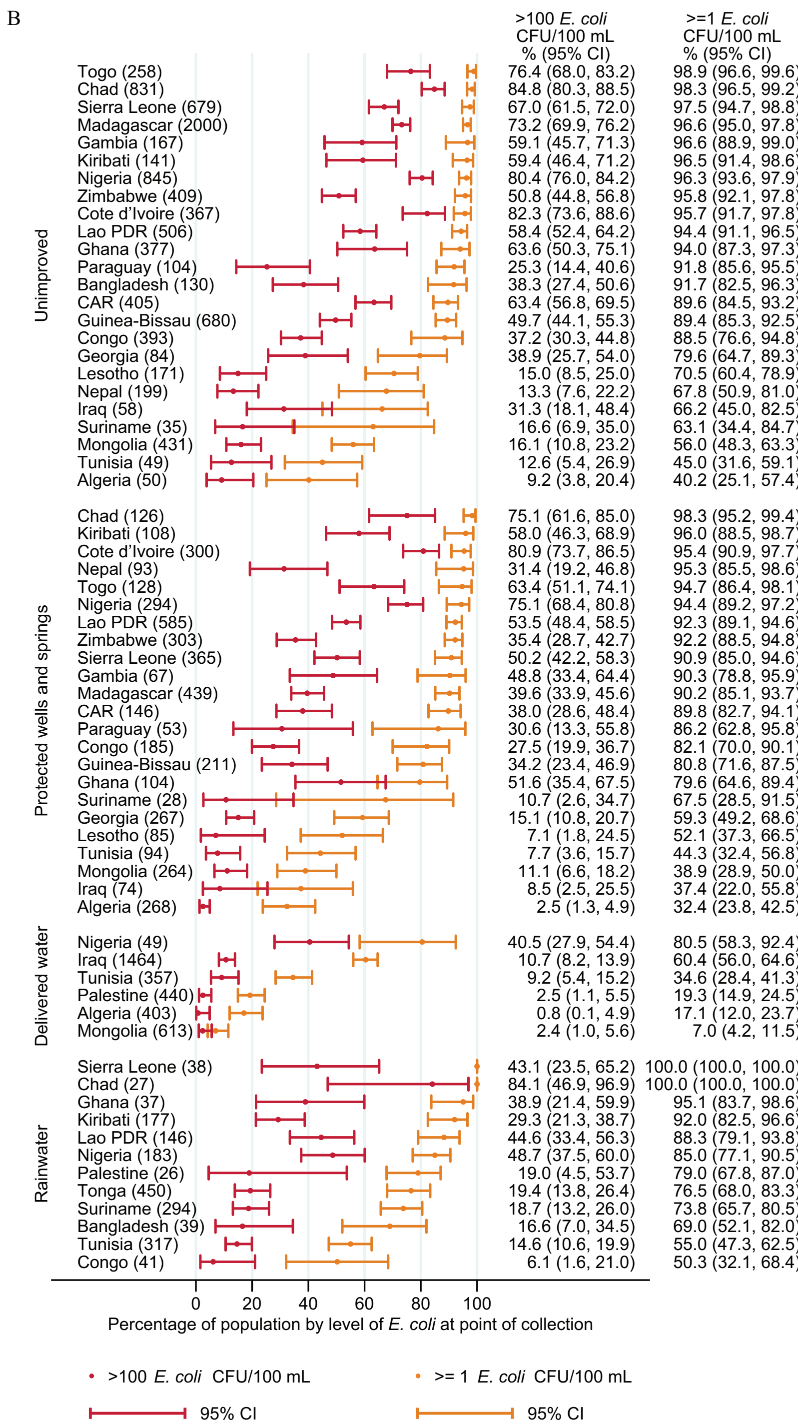

Figure 4. (*Continued.*)

CI: 0.56, 0.95) to RR = 0.77 (95% CI: 0.61, 0.96) for the richest quintile] for any *E. coli* at the PoC (Excel Table S14). Restricting the PoU model to samples contaminated at the PoC narrowed the CIs for the RR for self-reported water treatment, which was significant for this subset of households [from RR = 0.92 (95% CI: 0.83, 1.02) to RR = 0.92 (95% CI: 0.87, 0.97)] (Excel Table S15). Equal weighting for countries had a marginal impact on RRs; for example, decreasing the strength of the association with wealth [from RR = 0.73 (95% CI: 0.56, 0.95) to RR = 0.81 (95% CI: 0.70, 0.92) for the richest quintile] for any *E. coli* at the PoC (Excel Table S16).

Discussion

The new SDG indicator for drinking water "safely managed services" reflects consensus on the need to go beyond monitoring the types of water sources used by households and to monitor the level of service received. Integration of water testing in multi-topic household surveys has demonstrated the feasibility of this approach for collecting national data on drinking water service levels and the ability to link them with information on the socioeconomic characteristics of the population. Integrating water testing into existing surveys provides a cost-effective approach compared with running a dedicated water quality survey.

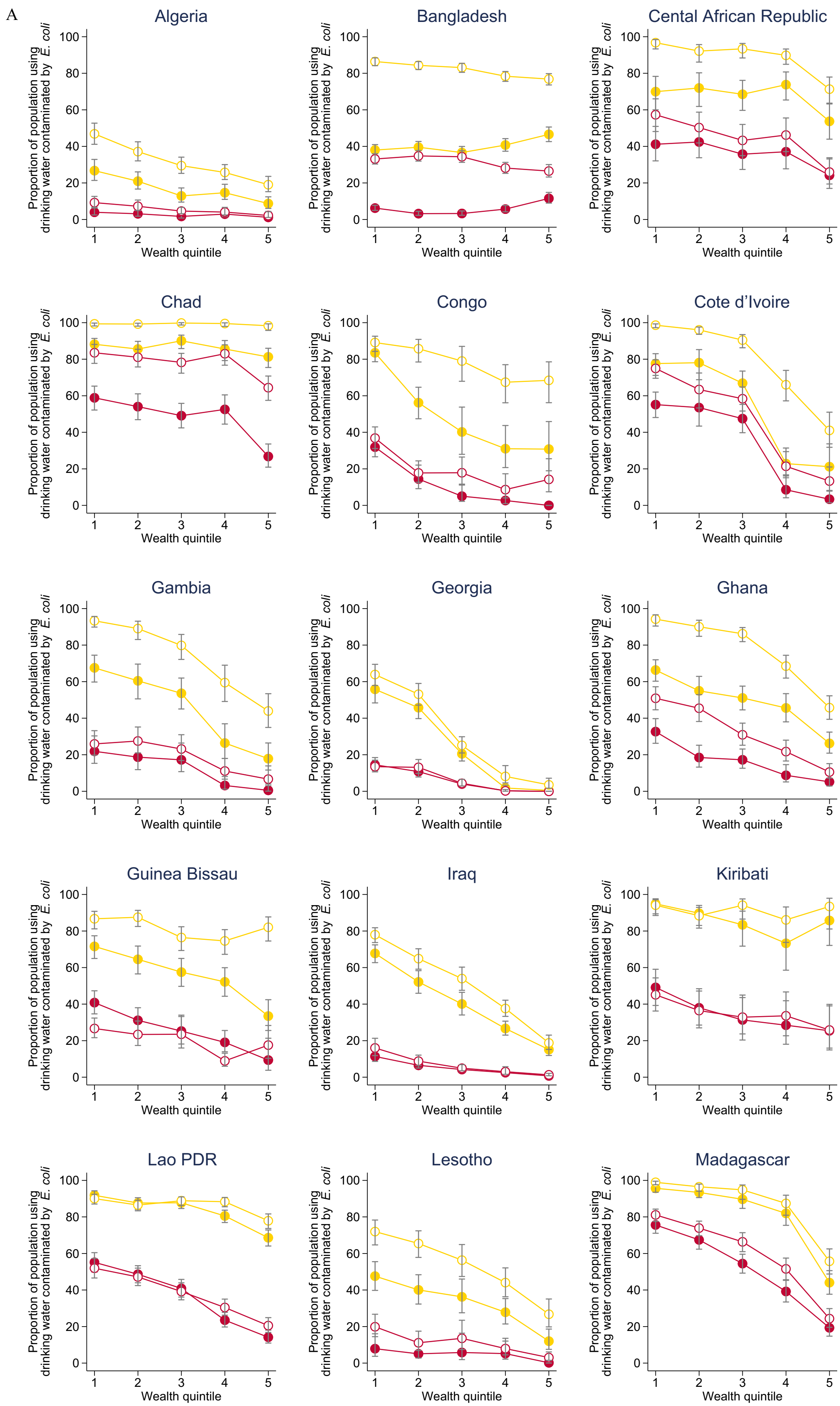

Figure 5. *E. coli* contamination of drinking water at point of collection and point of use by wealth quintile in 27 low- and middle-income countries, 2014–2020: (A) Algeria to Madagascar, and (B) Mongolia to Zimbabwe. Wealth quintiles from 1 (poorest) through 5 (richest). Wealth quintiles reflect a relative measure of inequality within each country based on asset ownership. Corresponding numeric data are provided in Excel Table S3. Note: CFU, colony forming unit; *E. coli*, *Escherichia coli*; Lao PDR, Lao People's Democratic Republic.

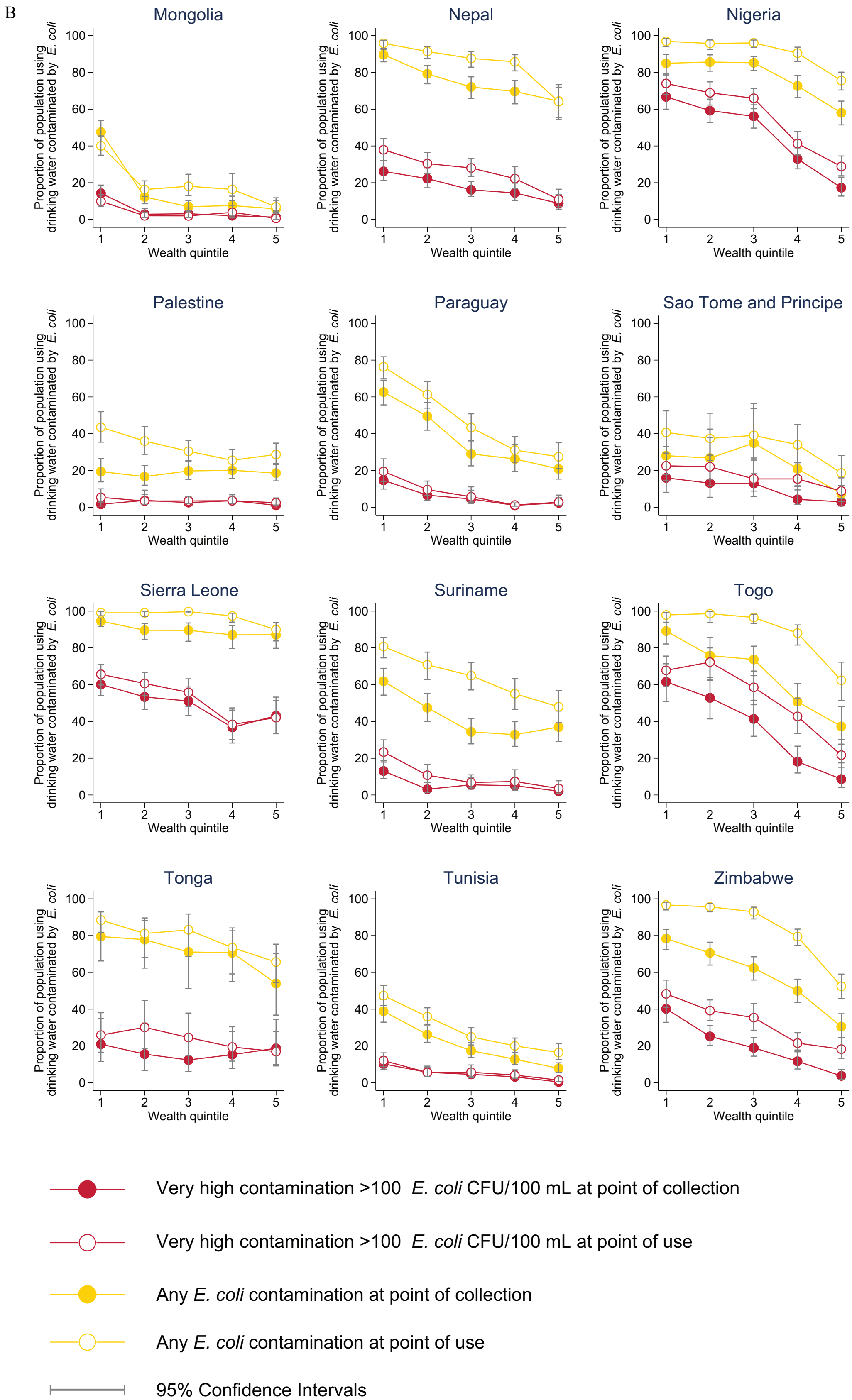

Figure 5. (*Continued.*)

Table 2. Proportion of population using improved and safely managed drinking water services in 27 Multiple Indicator Cluster Surveys (MICS) in low- and middle-income countries.

Country	Improved		Improved and accessible on premises		Improved and available when needed		Improved and free from *E. coli* contamination		Safely managed calculated at domain level[a]		Safely managed calculated at household level[b]	
	Percentage (95% CI)	*N*	Percentage (95% CI)	*N*	Percentage (95% CI)	*N*	Percentage (95% CI)	*N*	Percentage (95% CI)	*N*	Percentage (95% CI)	*N*
Algeria	99.1 (98.9, 99.3)	29,919	75.3 (73.3, 77.3)	29,893	72.5 (70.8, 74.1)	29,882	82.7 (80.5, 85)	3,132	72.5 (70.8, 74.1)	3,132	53.8 (50.8, 56.7)	3,129
Bangladesh	98.5 (98.2, 98.8)	61,242	82.5 (81.8, 83.1)	61,241	95.6 (95.2, 95.9)	61,230	59.6 (58.0, 61.1)	6,065	59.6 (58.0, 61.1)	6,065	49.1 (47.5, 50.6)	6,065
Central African Republic	58.7 (55.3, 62.1)	8,133	6.9 (5.8, 8.0)	8,132	35.7 (33.2, 38.3)	8,131	28.2 (23.9, 32.5)	1,041	6.9 (5.8, 8.0)	1,041	1.8 (1.0, 2.6)	1,040
Chad	61.8 (58.7, 64.9)	18,967	9.6 (8.2, 11.0)	18,949	49.2 (46.5, 52.0)	18,964	13.2 (10.9, 15.5)	2,121	9.6 (8.2, 11.0)	2,121	1.6 (0.8, 2.3)	2,116
Congo	84.6 (82.3, 86.9)	12,811	55.9 (51.2, 60.5)	12,804	NA	0	50.3 (43.7, 56.9)	1,240	50.3 (43.7, 56.9)	1,240	32.4 (26.1, 38.6)	1,240
Côte d'Ivoire	80.9 (78.3, 83.6)	11,879	53.1 (49.6, 56.6)	11,877	NA	0	45.3 (40.8, 49.9)	1,739	45.3 (40.8, 49.9)	1,739	34.2 (29.7, 38.8)	1,739
Gambia	90.4 (88.0, 92.9)	7,405	45.2 (40.8, 49.6)	7,404	78.7 (76.1, 81.3)	7,402	54.1 (48.8, 59.4)	1,759	45.2 (40.8, 49.6)	1,759	27.7 (23.4, 32.0)	1,759
Georgia	97.5 (97.0, 98.0)	12,270	91.6 (90.4, 92.8)	12,265	75.6 (73.5, 77.7)	12,240	74.6 (71.5, 77.7)	2,427	74.6 (71.5, 77.7)	2,427	56.0 (52.1, 59.9)	2,426
Ghana	86.0 (83.0, 88.9)	12,886	24.5 (22.4, 26.7)	12,884	75.8 (73.0, 78.6)	12,885	50.9 (47.0, 54.7)	3,146	24.5 (22.4, 26.7)	3,146	15.7 (13.4, 18.0)	3,146
Guinea-Bissau	66.8 (63.4, 70.2)	7,379	26.8 (22.9, 30.8)	7,379	54.7 (51.7, 57.7)	7,379	41.1 (36.9, 45.3)	1,824	26.8 (22.9, 30.8)	1,824	11.3 (8.3, 14.3)	1,824
Iraq	86.4 (83.5, 89.4)	20,214	65.7 (62.5, 68.9)	20,210	65.9 (63.0, 68.7)	20,190	54.7 (51.0, 58.3)	6,650	54.7 (51, 58.3)	6,650	35.5 (31.9, 39.1)	6,634
Kiribati	82.1 (78.8, 85.4)	3,071	59.9 (55.8, 64.0)	3,071	51.6 (48.7, 54.6)	3,070	14.3 (9.4, 19.1)	589	14.3 (9.4, 19.1)	589	4.0 (1.9, 6.1)	589
Lao People's Democratic Republic	83.9 (82.1, 85.7)	22,287	77.5 (75.5, 79.4)	22,287	80.9 (79.1, 82.7)	22,282	16.0 (14.3, 17.7)	3,290	16.0 (14.3, 17.7)	3,290	15.1 (13.5, 16.7)	3,290
Lesotho	88.9 (86.6, 91.1)	8,847	34.0 (30.5, 37.5)	8,846	74.3 (71.8, 76.8)	8,844	63.6 (59.3, 67.9)	1,338	34.0 (30.5, 37.5)	1,338	24.5 (20.7, 28.2)	1,338
Madagascar	43.0 (40.1, 45.9)	17,870	15.4 (13.7, 17.1)	17,869	35.8 (33.3, 38.3)	17,866	17.1 (14.3, 20.0)	3,264	15.4 (13.7, 17.1)	3,264	5.7 (4.4, 7.0)	3,264
Mongolia	88.2 (86.0, 90.4)	13,798	33.8 (28.5, 39.1)	13,787	74.5 (71.9, 77.2)	13,793	79.4 (76.0, 82.7)	2,586	33.8 (28.5, 39.1)	2,586	22.7 (18.7, 26.7)	2,581
Nepal	90.8 (89.1, 92.6)	12,655	72.9 (70.3, 75.4)	12,654	74.6 (72.1, 77.1)	12,654	21.6 (18.8, 24.3)	2,422	21.6 (18.8, 24.3)	2,422	17.5 (14.9, 20.1)	2,422
Nigeria	69.0 (67.0, 71.0)	33,901	23.1 (21.8, 24.4)	33,886	56.8 (54.9, 58.7)	32,135	21.5 (18.8, 24.2)	2,584	21.5 (18.8, 24.2)	2,584	3.8 (2.8, 4.9)	2,482
Palestine	99.1 (98.8, 99.3)	9,326	92.5 (91, 93.9)	9,322	88.4 (87.1, 89.6)	9,319	80.1 (77.3, 82.9)	1,818	80.1 (77.3, 82.9)	1,818	66.8 (63.5, 70.2)	1,813
Paraguay	95.4 (94.2, 96.5)	7,313	94.1 (92.8, 95.4)	7,312	78.9 (76.7, 81.2)	7,313	62.1 (58.1, 66.2)	1,715	62.1 (58.1, 66.2)	1,715	53.0 (49.1, 57)	1,715
Sao Tome and Principe	97.5 (96.4, 98.6)	3,426	57.5 (52.9, 62.0)	3,426	68.3 (64.9, 71.6)	3,426	76.3 (68.2, 84.5)	342	57.5 (52.9, 62.0)	342	37.5 (28.5, 46.5)	342
Sierra Leone	67.8 (65.3, 70.2)	15,309	14.5 (13.2, 15.8)	15,306	47.4 (45.2, 49.6)	15,306	9.6 (7.2, 12.0)	1,747	9.6 (7.2, 12.0)	1,747	1.4 (0.7, 2.1)	1,747
Suriname	98.2 (97.6, 98.7)	7,915	96.7 (95.8, 97.6)	7,909	82.1 (80.3, 83.9)	7,904	57 (53.3, 60.7)	1,618	57 (53.3, 60.7)	1,618	48.3 (44.6, 52.0)	1,617
Togo	74.6 (70.9, 78.3)	7,916	17.3 (15.2, 19.4)	7,916	62.4 (59.1, 65.8)	7,916	33.2 (28.0, 38.5)	1,086	17.3 (15.2, 19.4)	1,086	6.2 (4.0, 8.5)	1,086
Tonga	99.2 (98.7, 99.8)	2,498	98.6 (97.9, 99.3)	2,497	90.5 (88.8, 92.2)	2,498	29.8 (20.7, 38.9)	543	29.8 (20.7, 38.9)	543	26.0 (17.6, 34.5)	543
Tunisia	98.0 (97.4, 98.6)	11,225	89.8 (88.4, 91.2)	11,223	79.6 (77.8, 81.3)	11,223	78.5 (76.2, 80.9)	2,662	78.5 (76.2, 80.9)	2,662	58.8 (56, 61.6)	2,662
Zimbabwe	77.1 (74.3, 79.9)	11,091	29.3 (26.4, 32.2)	11,091	61.5 (58.9, 64.1)	11,091	40.1 (36.5, 43.7)	2,018	29.3 (26.4, 32.2)	2,018	10.1 (7.8, 12.5)	2,018
Mean[c]	84.3 (83.8, 84.8)	391,553	51.1 (50.3, 51.8)	391,440	68.7 (68.2, 69.3)	364,943	46.7 (45.8, 47.7)	60,766	46.7 (45.8, 47.7)	60,766	30.5 (29.3, 31.6)	60,627

Note: CI, confidence interval; *E. coli*, *Escherichia coli*; JMP, Joint Monitoring Program; NA: availability questions not included in Congo and Côte d'Ivoire; UNICEF, United Nations Children's Fund; SMDWs, safely managed drinking water services; WHO, World Health Organization.

[a]Domain-level calculation of SMDWs based on the minimum of the safely managed criteria (improved and accessible, improved and available, and improved and free from *E. coli* contamination) assessed at the national level. The domain-level assessment is used by the WHO/UNICEF JMP when data must be combined from different sources to estimate SMDWs either at the national level or separately for urban and rural areas.

[b]Household-level calculation of SMDWs is based on the individual household responses. Only households that meet all criteria are considered to use SMDWs. The household-level calculation is possible in MICS because the surveys collect information on the accessibility, availability, and quality of drinking water for the same households.

[c]Mean values based on equality weighting for each country.

Table 3. Adjusted RRs for *E. coli* contamination at the PoC and the PoU in 23 MICS6 in low- and middle-income countries (improved water sources only).

Variable	PoC ≥1 *E. coli* CFUs/100 mL	PoC >100 *E. coli* CFUs/100 mL	PoU ≥1 *E. coli* CFUs/100 mL	PoU >100 *E. coli* CFUs/100 mL
Improved	0.74 (0.64, 0.85)	0.43 (0.33, 0.56)	0.96 (0.92, 1.01)	0.74 (0.66, 0.83)
Accessible	0.99 (0.94, 1.05)	1.08 (0.96, 1.21)	0.94 (0.90, 0.99)	0.96 (0.88, 1.06)
Available	0.95 (0.88, 1.02)	0.95 (0.88, 1.02)	0.96 (0.91, 1.01)	0.94 (0.89, 0.99)
Observations	53,224	53,224	54,063	54,063

Note: Data are shown as exponentiated coefficients from modified Poisson regression with random intercepts for each country and 95% confidence intervals. Regression models were based on MICS6 and are unweighted. Adjusted for PoC and PoU wealth quintile, education of household head, sex of household head, rural residence, improved sanitation, cluster improved sanitation >75%, open defecation in cluster, livestock ownership, and season (PoU only) handwashing, water storage, household water treatment, natural flooring. Covariates and country-specific models are included in Excel Tables S5 and S7. CFU, colony forming unit; *E. coli*, *Escherichia coli*; MICS6, sixth round of Multiple Indicator Cluster Surveys; PoC, point of collection; PoU, point of use; RR, risk ratio.

Water Quality and Risk Factors for Contamination

The findings in the countries included in the analysis show that large proportions of the population are exposed to fecal contamination through their drinking water. This includes many people who are exposed to very high levels of contamination.

In line with a systematic review of the quality of water from different sources (Bain et al. 2014) and large-scale assessments of regulatory water quality data from sub-Saharan Africa (Kumpel et al. 2016), we find that piped water, packaged water, and boreholes are generally providing higher quality water than unimproved sources and that they offer substantial protection against very high risk drinking water. Rainwater harvesting, delivered water, and protected wells and springs often do not provide drinking water that is less likely to be contaminated than unimproved sources. Piped water was the only source type significantly associated with water free from *E. coli* contamination at the PoU in the adjusted models as found in a systematic review of PoC to PoU contamination (Shields et al. 2015). Unlike previous research on accessibility (Brown et al. 2013; Swerdlow et al. 1992) and availability (Jeandron et al. 2015; Kumpel and Nelson 2013), we did not find significant associations between *E. coli* and availability (at the PoC and the PoU) and accessibility (at the PoC) in the pooled fully adjusted models.

By combining data on water quality with information on the socioeconomic status of households, it was possible to explore patterns by wealth quintile. We find pronounced differences between rich and poor in almost all countries, as documented elsewhere (Graham et al. 2018; Yang et al. 2013). Differences were smaller in Bangladesh, where the richest were found to be more likely to use water from a contaminated source. This reflects the high degree of contamination of piped water supplies in Bangladesh disproportionately used by the wealthy, compared with the less contaminated boreholes used by most of the population.

Table 4. Adjusted RRs for *E. coli* contamination at the PoC and PoU in 23 MICS6 in low- and middle-income countries (full model including water supply types).

Variable	PoC ≥1 *E. coli* CFUs/100 mL	PoC >100 *E. coli* CFUs/100 mL	PoU ≥1 *E. coli* CFUs/100 mL	PoU >100 *E. coli* CFUs/100 mL
Main source of drinking water (Ref: unimproved)				
Packaged water	0.74 (0.52, 1.04)	0.34 (0.20, 0.58)	0.89 (0.66, 1.21)	0.55 (0.32, 0.93)
Piped water	0.65 (0.55, 0.76)	0.34 (0.23, 0.51)	0.87 (0.82, 0.93)	0.63 (0.53, 0.75)
Boreholes/tube wells	0.59 (0.48, 0.72)	0.24 (0.16, 0.34)	0.95 (0.89, 1.01)	0.69 (0.61, 0.79)
Rainwater	1.13 (0.90, 1.42)	0.77 (0.59, 1.01)	1.14 (0.93, 1.39)	0.97 (0.77, 1.21)
Delivered water	0.87 (0.66, 1.16)	0.46 (0.31, 0.69)	1.16 (0.96, 1.40)	0.91 (0.70, 1.18)
Protected wells and springs	1.02 (0.95, 1.09)	0.82 (0.75, 0.91)	1.05 (1.00, 1.11)	0.92 (0.84, 1.00)
Accessibility and availability				
Accessible	0.98 (0.92, 1.04)	1.02 (0.92, 1.13)	0.95 (0.91, 1.00)	0.96 (0.88, 1.04)
Available	0.94 (0.86, 1.02)	0.96 (0.89, 1.03)	0.95 (0.89, 1.01)	0.93 (0.88, 0.98)
Wealth quintile (Ref: poorest)				
Second	0.94 (0.90, 0.99)	0.91 (0.88, 0.95)	0.93 (0.90, 0.97)	0.91 (0.84, 0.97)
Middle	0.89 (0.81, 0.99)	0.87 (0.81, 0.95)	0.89 (0.81, 0.97)	0.86 (0.77, 0.97)
Fourth	0.84 (0.73, 0.98)	0.76 (0.68, 0.86)	0.81 (0.71, 0.94)	0.77 (0.66, 0.88)
Richest	0.73 (0.56, 0.95)	0.68 (0.52, 0.89)	0.70 (0.55, 0.88)	0.66 (0.53, 0.84)
Other household and cluster-level characteristics				
Education of household head	0.97 (0.93, 1.01)	0.94 (0.87, 1.01)	0.98 (0.96, 1.00)	0.93 (0.87, 0.99)
Sex of household head	0.98 (0.95, 1.01)	0.99 (0.93, 1.05)	1.00 (0.99, 1.02)	0.97 (0.93, 1.02)
Rural	1.17 (1.09, 1.26)	1.24 (1.07, 1.42)	1.10 (1.04, 1.16)	1.21 (1.10, 1.32)
Improved sanitation	1.03 (0.97, 1.09)	0.99 (0.93, 1.06)	1.04 (1.00, 1.07)	0.97 (0.93, 1.03)
Shared sanitation	1.00 (0.97, 1.03)	0.96 (0.91, 1.02)	1.02 (0.99, 1.05)	1.01 (0.97, 1.05)
>75% cluster improved sanitation	0.91 (0.85, 0.97)	0.82 (0.73, 0.92)	0.94 (0.90, 0.97)	0.90 (0.83, 0.97)
Any open defecation in cluster	0.95 (0.88, 1.03)	1.04 (0.94, 1.15)	0.98 (0.95, 1.02)	1.01 (0.89, 1.14)
Livestock ownership	1.10 (1.03, 1.18)	1.15 (1.03, 1.28)	1.08 (1.04, 1.13)	1.15 (1.07, 1.24)
Wet season	1.05 (0.96, 1.16)	1.13 (1.01, 1.25)	1.07 (1.01, 1.15)	1.24 (1.01, 1.51)
Handwashing	—	—	1.00 (0.97, 1.03)	1.00 (0.96, 1.04)
Water storage	—	—	0.91 (0.80, 1.04)	0.89 (0.77, 1.03)
Household water treatment	—	—	0.92 (0.83, 1.02)	0.91 (0.81, 1.03)
Natural floor	—	—	0.93 (0.87, 0.99)	0.97 (0.91, 1.05)
Observations	53,224	53,224	54,063	54,063

Note: Data are shown as exponentiated coefficients from modified Poisson regression with random intercepts for each country and 95% confidence intervals. Regression models were based on MICS6 and are unweighted. Country-specific models are included in Excel Tables S6 and S8. —, Not applicable; CFU, colony forming unit; *E. coli*, *Escherichia coli*; MICS6, sixth round of Multiple Indicator Cluster Surveys; PoC, point of collection; PoU, point of use; Ref, reference; RR, risk ratio.

The surveys also find substantial differences in quality between the PoC and the PoU (Shields et al. 2015; Wright et al. 2004). In many countries, households stored water in containers prior to consumption, but self-reported appropriate household water treatment practices were relatively uncommon except in Kiribati and Mongolia. Our analysis suggests that self-reported household water treatment may provide limited protection (Table 4; Excel Table S15), and that many households reporting these practices are still exposed to *E. coli* contamination at the PoU (Figure S4). These findings may be attributable to a lack of correct and consistent water treatment practices, ineffective treatment technologies, or self-reporting bias (which has been documented in other countries) (Pickering et al. 2010; Rosa et al. 2016; Rosa and Clasen 2017). We find that livestock ownership (Wardrop et al. 2018), rural residence (Kirby et al. 2016), and high community sanitation coverage (Harris et al. 2017) are significantly associated with contamination at the PoC and the PoU in the adjusted regression models.

We attempted to control for seasonality using a simplified definition of wet and dry seasons (Wright et al. 2012). Our finding that the wet season was associated with any *E. coli* contamination at the PoU in the fully adjusted models supports the findings of a systematic review (Kostyla et al. 2015) and more recent studies examining seasonality (Kumpel et al. 2017; Nguyen et al. 2021) or the impact of rainfall on water quality (Kirby et al. 2016). Integration of water quality testing in large-scale longitudinal surveys may offer insights into the dynamics of water quality at a national scale. The cross-sectional nature of the MICS water quality data, and the predominance of samples from the dry season may understate the importance of some risk factors. Geolocation of household survey clusters would also enable a wider range of environmental risk factors to be considered (Poulin et al. 2020).

The risk factors for contamination vary considerably between countries, and this heterogeneity is reflected in the range of effect sizes in the individual country models. Further work is required to understand the relationship between household- and community-level risk factors and the extent to which these can be mitigated through interventions to improve infrastructure and change behaviors. Future studies could examine changes in risk levels between the PoC and the PoU and examine alternative modeling approaches (Harris et al. 2019). Many potential risk factors for water quality were not considered in the regression analysis either because they are not collected in or could not be combined with MICS (e.g., high-resolution meteorological data, sanitary risk assessments) or because the number of missing values was large (e.g., child feces disposal practices). We chose not to include variables that might plausibly be considered outcomes of poor water quality (e.g., child anthropometry or diarrhea) and did not include country-level covariates (e.g., income classification). Our main regression results were not weighted to reflect population sizes, and the contribution of each survey to the pooled estimates reflects the varying number of samples taken in each country. The sample size, especially in Kiribati, Sao Tome and Principe, and Tonga, limits the precision of estimates for subpopulations and inference from country-specific regression models.

Monitoring SMDW Services

In addition to integrating the water quality module, questions that address the availability and accessibility of drinking water are required to monitor SMDW services. Questions on the location and time to collect drinking water have been included since the second round of MICS in 1999–2003 and form part of the JMP's updated guidance on monitoring WASH in household surveys (WHO/UNICEF 2018a). New questions to assess the availability of drinking water services were asked in 25 of 27 countries to establish whether the population was lacking sufficient drinking water when needed. In MICS6 surveys with standardized questions on availability, the proportion of the population drinking water that was not accessible on premises or which was contaminated with *E. coli* was generally much higher than the proportion reporting lacking sufficient water in the past month. A notable exception was Algeria, where availability was the limiting factor for SMDW.

Our study documents substantial differences between the MDG and SDG indicators, underscoring the importance of accounting for accessibility, availability, and quality of drinking water. We also find considerable differences between SMDW calculated at the domain and household levels (Table 2). The domain-level approach is used by the JMP for SDG monitoring at the global level to accommodate information from multiple data sources (e.g., combining household surveys and administrative data). A key advantage of integrating water quality testing and new questions on availability of drinking water in household surveys is that all criteria for SMDW are available from the same data source. The overestimate of SMDW coverage using the domain-level approach will depend on the extent to which individual SMDW criteria are met for the same populations. The multivariable regression analysis suggests that sources meeting the criteria for accessibility and availability are not necessarily more likely to be free from *E. coli* contamination in LMICs.

We focused on fecal contamination as indicated by *E. coli* and did not consider contamination from priority chemical contaminants, including arsenic and fluoride, which are widespread in many LMICs (Amini et al. 2008; Podgorski and Berg 2020). In Bangladesh and Nepal, arsenic contamination was also measured in the MICS using field test kits. *E. coli* remained the limiting factor for SMDW in both countries, with arsenic exceeding the WHO guideline value of 10 ppb at the PoC for 18.6% and 2.8% of the population (vs. 40.3% and 75.3% with *E. coli*) in Bangladesh and Nepal, respectively.

Water quality testing in household surveys should complement, not compete with, ongoing efforts to strengthen surveillance of water quality by regulatory authorities. A single measurement of water quality, often during a season when weather is favorable for fieldwork, is not a substitute for routine monitoring by the responsible authorities in each country. Data collected through household surveys are more likely to be representative of the full range of water sources used by different population groups, but as a snapshot of quality, they will likely underestimate exposure to fecal indicator bacteria at all times. Furthermore, *E. coli* as an indicator of fecal contamination has known limitations (Charles et al. 2020; Gleeson and Grey 1996), including greater sensitivity to chlorine compared with pathogens such as *Cryptosporidium* (WHO 2017). In many LMICs, water quality data from regulatory authorities are limited, especially for rural areas and nonpiped supplies (Kumpel et al. 2016). Nationally representative data from household surveys can provide a cost-effective means of filling these data gaps in the short term and draw attention to inequalities in service levels in the absence of regulation. Furthermore, the responsibility of the service provider usually ends at the household connection or public tap; as a result, regulators rarely collect samples from within the home (Kumpel et al. 2016).

Recommendations for Water Testing in Future Household Surveys

The water quality module has been integrated into an increasing number of MICS and other national and subnational surveys with support from the JMP team, including national household surveys in Ghana, Democratic People's Republic of Korea, Ethiopia, Ecuador, Lebanon, and the Philippines (WHO/UNICEF 2020). There have also been subnational pilots in the Demographic and Health Survey in Peru (Wang et al. 2017a), the National Socioeconomic Survey in Indonesia (Cronin et al. 2017), and the Afghanistan Living Conditions Survey (Saboor et al. 2021). This illustrates the growing demand for understanding the quality of services and the willingness of national authorities to shine a light on this important but politically sensitive issue.

Several key lessons from these experiences of taking water testing to scale could inform the design and implementation of future surveys. Testing drinking water in a subsample of households for a limited number of priority parameters is critical to the cost effectiveness and practicability of this approach. Further work is required to support the JMP recommendation for selecting 3–5 households per cluster (WHO/UNICEF 2020). Involvement of regulatory authorities is strongly recommended given their mandate for oversight of water service provision. Quality control measures are important during fieldwork and to build confidence in the results, and blank tests are especially valuable to confirm that detection of *E. coli* is not the result of poor hygiene by field teams. Further work could examine the associations between positive blank tests and risk factors for contamination. Field duplicate tests were conducted in Bangladesh MICS 2012–2013, with the same risk level recorded for 71% of duplicate samples ($n = 55$) conducted by the MICS teams and the International Centre for Diarrhoeal Disease Research, Bangladesh laboratory staff and 85% of samples within one risk level (Bangladesh Bureau of Statistics and UNICEF 2017). The interpretation of duplicates is challenging given that some inconsistency is expected purely due to inherent sampling variability (McBride 2005). Duplicates are thus less actionable during fieldwork than blank tests. Close attention is needed for the training which, depending on the number of teams and facilitators, should last 3–5 d and include sufficient practice (preferably at least 15 tests) for each step in the process. In a few countries, leaflets explaining contamination risks and methods for safe water treatment and storage were provided to households selected for the water quality module. Further work is needed to determine how best to share information on water quality with households and their communities in order to inform decisions on data sharing by implementing agencies (Khan et al. 2017).

There are several *E. coli* tests that could potentially be integrated into household surveys (Bain et al. 2012). In the MICS, an adapted membrane filtration process has been used, yielding reliable quantitative results (Brown et al. 2020). The costs are ∼$2.50 per test using the new "*E. coli* only" Compact Dry plates and $1,500 per team for hardware [mainly the filtration equipment (Figure S1)], but these costs are expected to decrease over time. For example, a low-cost kit (<$100) has successfully been piloted in the Afghanistan Living Conditions Survey (Saboor et al. 2021). In the longer term, it is hoped that novel, rapid tests will replace the culture-based approaches that dominate the water quality testing market (Rompré et al. 2002; UNICEF 2019).

Integration of water testing into the MICS has demonstrated that it is feasible to include water testing in nationally representative household surveys and that the data generated can be used to monitor the SDG SMDW services indicator. We find that water quality is often the limiting factor for SMDW services, and there was a substantial difference between the MDG and SDG indicators for all countries in the present study. The large proportions of the population exposed to very high levels of *E. coli* and the deterioration in quality between the PoC and the PoU within the home suggest that interim targets and approaches are needed to reduce risks and to strengthen water quality surveillance. Countries should be supported to localize and adapt the SDG targets to the national context and to develop plans to progressively improve drinking water quality and to identify and target populations at greatest risk.

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