UNIVERSIDADE FEDERAL DE PELOTAS
FACULDADE DE MEDICINA
PROGRAMA DE PÓS-GRADUAÇÃO
EM EPIDEMIOLOGIA

PhD Thesis

Water, sanitation, and hygiene services in low- and middle-income countries: the urban-rural divide and other inequalities

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Doctoral advisors: Professor Aluísio J. D. Barros
Associate Professor Meghan A. Bohren

Pelotas, RS

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Thiago Melo Santos

Water, sanitation, and hygiene services in low- and middle-income countries: the urban-rural divide and other inequalities

Thesis presented to the Postgraduate Program in Epidemiology at the Federal University of Pelotas, as a partial requirement for obtaining the title of Doctor in Epidemiology.

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To the women who collect water for their families

Acknowledgment of Country

I would like to acknowledge the Aboriginal and Torres Strait Islander peoples, who are the original custodians of the unceded lands and waterways across the Australian continent. I would like to pay respect to the Elders, past and present, and acknowledge the importance of Indigenous knowledge and ways of doing in the Academy.

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I would like to thank Meghan for opening a new world to me. Your kindness and knowledge have a been a haven for learning and exploration. There are many fights to fight in the future, and I could not be more excited to have you guiding me along the way. I would also like to thank Josh and Kelly, for receiving me in their home and making me feel welcome beyond measure.

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Resumo

Santos, Thiago M. **Água, saneamento e higiene em países de baixa e média renda: a divisão urbano-rural e outras desigualdades.** Tese de doutorado. Programa de Pós-Graduação em Epidemiologia. Universidade Federal de Pelotas; 2024.

A Agenda 2030 para o Desenvolvimento Sustentável das Nações Unidas estabeleceu metas ambiciosas para alcançar o acesso universal e equitativo a água, saneamento e higiene (em inglês, WASH) como parte do Objetivo de Desenvolvimento Sustentável (ODS) 6. O mundo não está a caminho de alcançar essas metas e a falta de WASH tem um efeito desproporcional sobre mulheres e meninas. Nossos objetivos foram: 1) investigar a contaminação por *Escherichia coli* em fontes de água potável; 2) criar um índice de empoderamento econômico das mulheres e investigar sua associação com serviços básicos de WASH; e 3) determinar a cobertura combinada de serviços de WASH (chamado WASH completo) de acordo com a área de residência, riqueza e regiões subnacionais em países de baixa e média renda. Utilizamos dados de 38, 31 e 32 pesquisas domiciliares nacionalmente representativas, respectivamente, para calcular prevalências nacionais e estratificadas. Contaminação fecal foi encontrada em 70,8% dos domicílios investigados. A contaminação foi generalizada e alarmante em quase todos os países e fontes de água, incluindo algumas fontes consideradas melhoradas. Também mostramos que mulheres mais empoderadas tinham maior probabilidade de viver em domicílios com serviços básicos de WASH, com uma amplitude média de cerca de 20 pontos percentuais na prevalência de WASH entre os diferentes níveis de empoderamento. Finalmente, apenas 16,7% dos domicílios tinham acesso ao WASH completo. Os países se dividiram em dois cenários: ou tinham poucos domicílios com acesso ao WASH completo (<10%) ou tinham distribuição altamente desigual de acordo com a área de residência, riqueza ou regiões subnacionais. Em conjunto, nossos resultados mostram uma cobertura dramaticamente baixa e desigual dos serviços de WASH, com a contaminação da água representando um desafio crucial. Eles também sugerem uma oportunidade de esforços combinados para alcançar a igualdade de gênero, garantindo que mulheres tenham acesso igual a recursos econômicos e poder de tomar decisões, ao mesmo tempo em que alcançam acesso universal a WASH seguro.

Palavras-chave: Água Potável; Saneamento; Higiene; Inequidades em Saúde; Saúde Global.

Abstract

Santos, Thiago M. **Water, sanitation, and hygiene services in low- and middle-income countries: the urban-rural divide and other inequalities.** PhD Thesis. Postgraduate Program in Epidemiology. Universidade Federal de Pelotas; 2024.

The United Nations' 2030 Agenda for Sustainable Development set ambitious targets for achieving universal and equitable access to water, sanitation, and hygiene (WASH) as part of the Sustainable Development Goal (SDG) 6. The world is not on track to achieve these targets and the lack of WASH has a disproportionate effect on women and girls. Our goals were: 1) to investigate *Escherichia coli* contamination in drinking water sources; 2) to create a women's economic empowerment score and investigate its association with WASH services; and 3) to determine the combined coverage of WASH services (full WASH) according to area of residence, wealth, and subnational regions in low- and middle-income countries. We used data from 38, 31, and 32 nationally representative household surveys, respectively, to calculate national and stratified prevalences. Fecal contamination was found in a glass of drinking water of 70.8% of the households investigated. Contamination was widespread and alarmingly high in almost all countries and water sources, including some sources which are considered improved. We have also shown that more empowered women were more likely to live in households with basic WASH, with a median amplitude of approximately 20 percentage points in WASH prevalence across the different levels of empowerment. Finally, only 16.7% of households had access to full WASH. Countries fell into one of two scenarios: they either had very few households with access to full WASH (<10%) or had highly unequal distribution according to area of residence, wealth, or subnational regions. Combined, our results show a dramatically low and unequal coverage of WASH services, with water contamination representing a pivotal challenge. They also suggest an opportunity for combined efforts to achieve gender equality, ensuring that women have equal access to economic resources and power to make decisions, at the same time as achieving universal access to safe WASH.

Keywords: Drinking Water; Sanitation; Hygiene; Health Inequities; Global Health.

Table of Contents

Presentation

This PhD thesis was created under the supervision of Professor Aluísio J. D. Barros from the Universidade Federal de Pelotas, Brazil, and Associate Professor Meghan A. Bohren, from the University of Melbourne, Australia. It is composed of the Research Project – defended and approved in August of 2022 – a project adjustments section, three original research articles, and a press release describing the main findings of the thesis. The thesis is also accompanied by an Excel file with the articles' supplementary tables.

The first article is titled "*E. coli* contamination of drinking water sources in rural and urban settings: an analysis of 38 nationally representative household surveys (2014–2021)" and was published in the Journal of Water and Health. The second article is titled "What is the relationship between women's economic empowerment and basic water, sanitation, and hygiene in the home? An equity analysis of 31 low- and middle-income countries" and will be submitted to the Journal of Global Health. The third article is titled "Combined coverage of water, sanitation, and hygiene services: an equity analysis of 32 nationally representative household surveys (2017–2021)" and will also be submitted to the Journal of Global Health. All articles have been formatted accordingly.

1. PhD Research Project

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Basic and safely managed water, sanitation, and hygiene services in low- and middle-income countries: the urban-rural divide and other inequalities

Research project

PhD Candidate: Thiago Melo Santos
Doctoral advisors: Professor Aluísio J. D. Barros
Associate Professor Meghan A. Bohren

Pelotas, RS
August 2022

List of figures

Abbreviations

CHE: Centre for Health Equity at the University of Melbourne
CFU: colony forming unit
DeCS: Descritores em Ciências da Saúde
DHS: Demographic and Health Surveys
EWI: Empowerment in Water, Sanitation and Hygiene Index
FIB: faecal indicator bacteria
HIC: high-income country
ICEH: International Center for Equity in Health at the Universidade Federal de Pelotas
JMP: Joint Monitoring Programme for Water Supply, Sanitation and Hygiene
LMIC: low- and middle-income country
MeSH: Medical Subject Headings
MICS: Multiple Indicator Cluster Surveys
OR: odds ratio
PCA: principal component analysis
PoC: point of collection (water source)
PoU: point of use (glass of drinking water offered by the survey respondent)
RR: risk ratio
RSM: Reproductive, Sanitation and Malaria Group from the ICEH
SDG: Sustainable Developmental Goal
SWPER: survey-based women's empowerment index
TTC: thermotolerant coliform
UFPel: Universidade Federal de Pelotas
WASH: water, sanitation, and hygiene

1.1. Introduction

The United Nations' 2030 Agenda for Sustainable Development has established a goal of "ensuring availability and sustainable management of water and sanitation" under the Sustainable Developmental Goal (SDG) 6[1]. More specifically, targets 6.1 and 6.2 state[2]:

- Target 6.1: "By 2030, achieve universal and equitable access to safe and affordable drinking water for all".
- Target 6.2: "By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations".

Five years after the beginning of the SDG era, the world is not on track to reach targets 6.1 and 6.2. In order to achieve universal access to safely managed water, sanitation, and hygiene (WASH) by 2030, the world would have to quadruple its current rate of progress[1]. In 2020, one in four people in the world lacked safely managed drinking water, nearly half lacked safely managed sanitation and three out of ten lacked basic hygiene services[1].

Although universal access is an ambitious goal that might not be feasible in reality, Europe and Northern America have achieved widespread access to safely managed drinking water (96% of population) and basic hygiene (91%) in 2020[1]. Nevertheless, only 78% of their population had access to safely managed sanitation, showing that even in the wealthiest regions of the world there is need for improvement[1]. In comparison, only 30% of the population of Sub-Saharan Africa had access to safely managed drinking water, 21% to safely managed sanitation and 26% to basic hygiene[1]. This indicates the necessity of monitoring not only the achievement of universal access, but also how far many regions are to achieve those targets and how unequal is the access both between and within those regions.

Many countries and subnational regions lack the necessary systems to monitor targets 6.1 and 6.2, especially in terms of water contamination and safe disposal and treatment of human waste[1]. For such countries, household surveys are an important data source as they allow for data disaggregation and equity analyses, especially the comparison between urban and rural settings and wealth-related inequalities. In particular, the

UNICEF-supported Multiple Indicator Cluster Surveys (MICS) have implemented a new water quality module in their sixth round of surveys (2017-present) that allows for the collection of quantitative information on *E. coli* contamination in drinking water in low- and middle-income countries (LMICs) [3]. Currently, 36 countries have available surveys.

For monitoring drinking water, two main indicators have been used in survey and monitoring agencies' reports [1,4]: basic water services and safely managed water services. The first considers the water source and water collection time and is more easily calculated. The second adds faecal contamination, which requires biological testing, making it harder to evaluate. While coverage estimates of basic water services are available for 99% of the world's population, only 45% have data for safely managed water services [1]. The region with the worst data coverage is Oceania (Melanesia, Micronesia, and Polynesia excluding Australia and New Zealand), with coverage estimates available for only 11% of the population [1].

For both indicators, some water sources are considered improved (such as piped water and protected dug wells) while others are considered unimproved (such as surface water and unprotected dug wells) [1]. An improved water source is defined by the Joint Monitoring Programme for Water Supply, Sanitation and Hygiene (JMP) of WHO/UNICEF as a source that "by nature of its construction or through active intervention, is protected from outside contamination, in particular from contamination with faecal matter" [5]. The water quality module implemented by MICS provides a unique opportunity to calculate not only national estimates for both indicators, but also to evaluate how contaminated the sources classified as improved are in the context of LMICs. A more detailed investigation of the level of contamination by water source is necessary – especially with disaggregation by urban and rural areas – given the current evidence of contamination in some improved sources [3], in order to help preventing global investments in water sources that fail to provide clean water.

Another important aspect of target 6.2 is the disproportionate effect that the lack of access to WASH can have on women and girls. This is due to their increased vulnerability to infection during menstruation and childbirth, their marked role in water collection and unpaid domestic labour, and their exposure to violence and sexual assault while using services that lack privacy and security[6,7]. These activities can have a further impact on women's health due to spinal injury and neck pain, and also reduce the time available for education and income-generating activities[6]. There is evidence from LMICs that women perceive water insecurity as being more severe or frequent than men[8]. This is not surprising, considering that women and girls are responsible for water collection in 8 out of 10 households with water off premises[9], and also for housework and food preparation, which require a consistent and adequate supply of water[8].

Women's participation in water, sanitation and hygiene decision-making and governance has been called a priority area of research based on expert input and literature review[6]. It has been argued that improvement in WASH access may be achieved through women's empowerment, via ownership and control of assets and resources, including income, land and credit[10,11]; decision-making in household purchases and construction, including WASH infrastructure[12,13]; group membership that allow women to discuss issues in their communities[10,11]; intrinsic attitudes about WASH roles and responsibilities[14]; personal agency and supportive environments[15]; access and sharing of WASH information and other learning opportunities[14,15]; available time[10]; and leadership and participation in local WASH institutions and authorities[14]. It should be noted that evidence is still scarce, often anecdotal, and based on local studies. More robust studies that systematically compare the relationship between WASH indicators and women's empowerment in different countries are still necessary.

Demographic and Health Surveys (DHS) are household surveys that are highly comparable to MICS. They collect both information related to women's economic autonomy and decision making and allow estimating access to basic WASH services, providing an opportunity to evaluate the association of women's empowerment and those services. In fact, a 2021 report by the JMP states that "DHS does have several questions related to general household-decision making, which could be leveraged. [...] Exploratory analyses could investigate if there is any association with women's household decision making power and household access to sanitation or water facilities"[16].

Finally, even though water and sanitation/hygiene are in separate targets, they do not operate separately in the household. Poor community sanitation coverage and lack of proper handwashing infrastructure can lead to faecal contamination of drinking water and are important risk factors to diarrhoea and infant mortality[3,17–19]. There is also evidence that water interventions combined with either hygiene education or improved sanitation can lead to an additional effect of reducing diarrhoeal disease in LMICs[20]. In 2012, an analysis of 59 countries showed that only half of their population had access to both improved water source and sanitation, while 75% had access to improved water and 59% to sanitation[21]. In a 2017 study from Sub-Saharan Africa, only 4% of the population had access to combined basic WASH services, leaving almost a billion people lacking basic coverage[22]. With the new MICS' water quality module and the extended version of the sanitation questionnaire applied in 34 countries, there is an opportunity to investigate the combined coverage of not only basic WASH, but also safely managed water and sanitation services.

1.2. Justification

The world is not on track the achieve universal access to WASH services and there are major regional inequalities. The Least Developed Countries [23] still have a long way ahead, especially those in fragile contexts. Many more countries are facing challenges to promote WASH services in rural, impoverished, and fragile communities within their borders [1]. There are large inequalities in access to WASH services between urban and rural communities[1] and marked differences in infrastructure, agricultural activities, socioeconomic development, and social structure that create distinct urban and rural environments [15]. Girls and women have a double burden as the ones more vulnerable to the absence of WASH services and as those with a larger role in WASH activities [6]. On the other hand, data coverage is increasing. MICS and DHS surveys – including extended WASH and women's empowerment questionnaires, and water quality testing – provide an opportunity to increase our understanding of who is being left behind, where are they located, in which step are we failing and what mechanisms can we use to change the situation.

In this project, we want to expand our knowledge in three topics:

1) what water sources are more likely to be contaminated and in which context (urban/rural) is this more likely to happen;

2) what is the relationship between women's empowerment – in particular their economic autonomy and decision-making – and basic WASH services in the household; and

3) what is the simultaneous coverage of safely managed water and sanitation services and basic hygiene in LMICs and how unequal is that coverage between different levels of wealth, rural and urban communities, and subnational regions.

The literature reviews presented in Section 1.4 show that there are gaps in knowledge that our work will help to fill. In doing so, we will expand our knowledge on the state of global inequality in WASH services and contribute to accomplish the goals of SDG 5 – "Achieve gender equality and empower all women and girls"; SDG 6 – "Ensure availability and sustainable management of water and sanitation for all”; and SDG 10 – “Reduce inequality within and among countries” [24].

1.3. Proposed articles

The following are the provisional titles of the proposed research for the thesis:

- **Original research article 1:** "Drinking water sources *E. coli* contamination in rural and urban settings of nationally representative household surveys from 36 low- and middle-income countries"
- **Original research article 2:** "What is the relationship between married/in union women's empowerment and basic water, sanitation, and hygiene in the home? An equity analysis of 24 low- and middle-income countries"
- **Original research article 3:** "Complete coverage of safely managed water and sanitation, and basic hygiene services: an equity analysis of 34 low- and middle-income countries"

1.4. Literature review

Three separate structured literature reviews were performed, one for each research article. All reviews were executed using Mendeley (www.mendeley.com) as a reference manager and Rayyan (rayyan.ai) for the selection process. Since the reviews are not going to be published and are exclusive to the project, they were performed by only one reviewer (the author). Keywords and search strategies were selected based on relevant research articles and literature reviews. There were no restrictions in terms of language of the articles or publication type, unless specified in the exclusion criteria of each review. We also reviewed the "Reports" section of the JMP website (https://washdata.org/reports) for reports that could be relevant for any of the three research articles. We complemented the information in the reviews with the most recent and globally representative reports where applicable.

1.4.1. Water quality in national surveys

Objective

To identify published research articles that include national estimates of contamination in drinking water. Ideally, they would also include results stratified by water source, but we did not consider this as a criterion in order to avoid being too restrictive.

Inclusion and exclusion criteria

- Inclusion criteria:
  - Measurement of contamination in drinking water
  - Nationally representative sample of urban or rural areas or both areas combined
- Exclusion criteria:
  - Without water quality testing
  - Methodological (e.g., biochemical and engineering studies), experimental, or simulation studies
  - Restricted to one water source
  - Focus on wastewater

Search query

We searched the PubMed (pubmed.ncbi.nlm.nih.gov) and Web of Science (www.webofknowledge.com) databases on the 6th of May 2022 using the terms presented in Figure 1. All terms were included between quotation marks, and we searched all fields. The terms were selected based on the Medical Subject Headings (MeSH) database (www.ncbi.nlm.nih.gov/mesh), the Descritores em Ciências da Saúde (DeCS) database (decs.bvsalud.org) and the keywords from several research articles that had been previously selected.

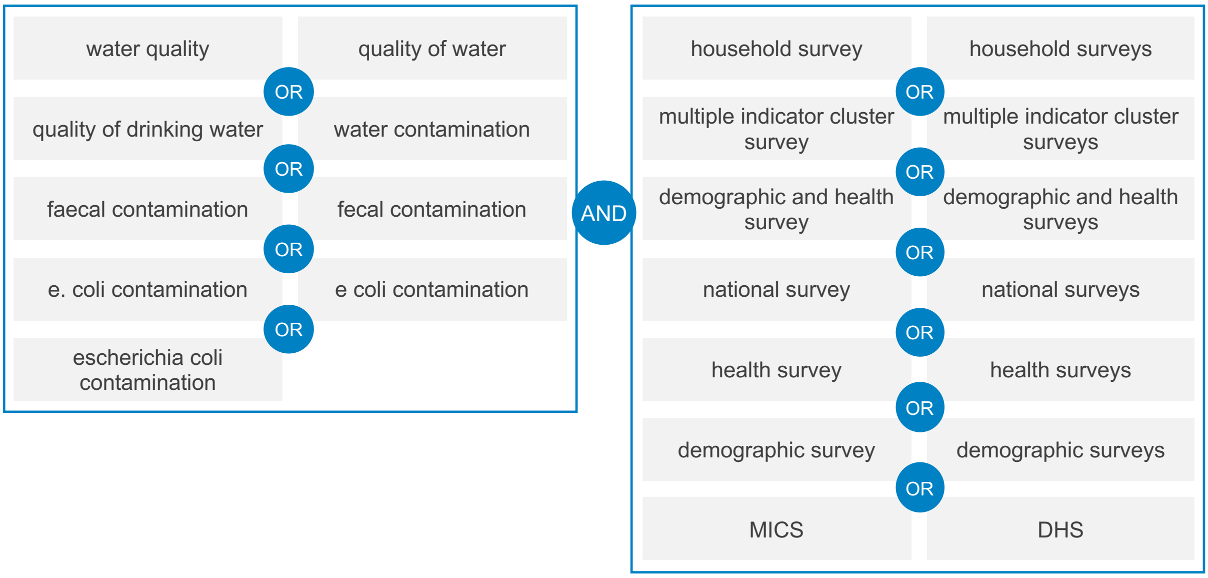


Figure 1 – Diagram of the search query used for the "Water quality in national surveys" literature review

Results

Figure 2 is the flow diagram representing the article selection process and Table 2 summarizes the articles included in the review. From 396 unique articles, 15 were included after the selection process. 11 articles presented results for a single country, 1 article for 3 countries, 1 for 27 countries, and 2 had global estimates. 11 articles focused on LMICs, 2 on high-income countries (HICs) and 2 included both LMICs and HICs, considering the World Bank's 2021 income classification [25].

MICS surveys were the most common data source, being used in 8 articles. All articles were published in the last 10 years, with the earliest one in 2012. Nine articles presented some form of association between water contamination and source type and 10 articles between water contamination and urban/rural settings.

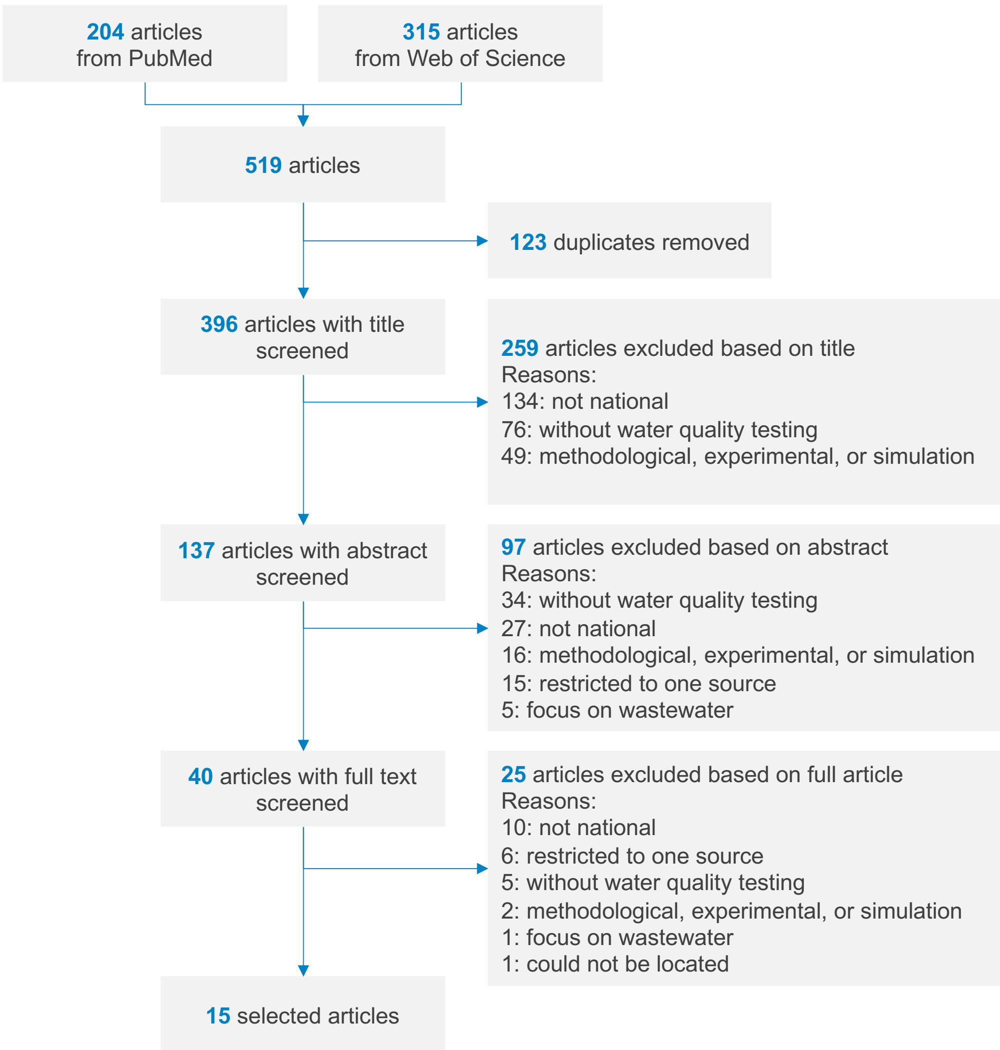


Figure 2 – Flow diagram of the “Water quality in national surveys” literature review

We will focus our discussion on two main topics:

- Safely managed drinking water services: this section discusses global estimates of the safely managed water services indicator based on a 2018 article [26] and an update from a 2021 report [1]
- Contamination according to water source: this section discusses the articles that investigated water quality according to the water source type in multiple countries [3,27,28], published between 2014 and 2021

Safely managed drinking water services

An article by Bain *et al.* published in 2018 described the methods used to generate national, regional, and global estimates for the new household WASH indicators included in the SDGs [26]. Monitoring those estimates is the responsibility of the WHO and UNICEF through the JMP [26]. This includes the SDG 6.1.1 indicator: the proportion of the population using safely managed drinking water services (improved water source located on premises, available when needed and free from contamination) [26].

The article presents the results for the JMP's 2017 update. It projected that 29% of the global population had no access to a safely managed drinking water service, based on 3000 national data sources, including primarily household surveys, censuses, and administrative data [26]. 26% had no service available on premises, 21% had no service available when needed and 27% lived in households with contaminated water [26]. Rural areas had worse results in all indicators in comparison to urban areas [26]. 45% of the rural population lived in households with contaminated water, compared to 11% of the urban population [26]. Sub-Saharan Africa had the highest proportion of contamination (58%) and Europe and Northern America the lowest (3%) [26].

Those projections were updated in the 2021 report entitled "Progress on Household Drinking Water, Sanitation and Hygiene 2000-2020 – Five Years into the SDGs" available in the JMP website [1]. In 2020, 26% of the global population had no access to a safely managed drinking water service [1]. 23% had no service available on premises, 22% had no service available when needed and 25% lived in households with contaminated water [1]. 40% of the rural population lived in households with contaminated water, compared to 14% of the urban population [1]. Sub-Saharan Africa continued with the highest proportion of contamination (64%) and Europe and Northern America the lowest (2%). Northern Africa and Western Asia gained estimates (21%) [1].

For the JMP's 2017 update, 228 countries (99.6% of the global population) had data for the basic drinking water service indicator [26]. Only 96 countries (34% of the global population) had data for the safely managed indicator [26]. In the 2021 report, the latter increased to 138 countries, covering 45% of the global population [1]. Of all the components of the safely managed indicator, water quality was the one with the least countries with available data, making it the bottleneck for the indicator's estimation [1].

There are significant inequalities in data coverage among the SDGs regions, resulting in many of those regions with no estimates due to insufficient data [1,26]. In the 2017's update, the western Pacific region had the worst data coverage [26]: 3 countries (6% of the population) of the Oceania region, 7 countries (11%) of the Eastern and South-eastern Asia region, and only New Zealand (16%) from the Australia and New Zealand region had data for the safely managed indicator [26]. In the 2021 report, they were 11 countries (11%) for Oceania, 12 countries (19%) for Eastern and South-eastern Asia, and only New Zealand (16%) for Australia and New Zealand [1]. Only Europe and Northern America achieved 100% coverage in the 2021 report, followed by Latin America and the Caribbean (18 countries, 77% of the population) and Sub-Saharan Africa (21 countries, 57% of the population) [1]. Special attention in necessary for the Small Island Developing States, with only 16 out of 53 countries with data available (19% of the population) [1].

Contamination according to water source

There were two selected articles that investigated water quality according to the water source type in multiple countries [3,27]. Table 1 presents their findings. The ranges found by Wardrop *et al.* were narrower with higher levels of contamination, as expected, given that it was restricted to three LMICs [27]. Results will be discussed based on the findings of Bain *et al.* that includes a more comprehensive list of 27 LMICs [3].

The percentage of households with faecal contamination covers almost the full spectrum (0 to 100%) for many source types, indicating that contamination is highly country specific [3]. For all source types, including improved sources, a high contamination percentage can be found in many countries [3]. The source type with the lowest upper limit was packaged water (sachet and bottled water): 77% in Laos [3]. Even piped water, considered the most desirable water source [5], had contamination prevalence as high as 85% in Nepal [3]. Rainwater, considered an improved source, has a contamination prevalence range that is even worse than the category that includes all unimproved sources combined [3].

One other article had similar estimates, but they were based on a systematic review of the literature not restricted to nationally representative samples, followed by statistical modelling[5,28]. They estimated that rural piped water supplies were frequently contaminated (as high as 58% of samples in Africa), except in high income Americas (1%), Europe (1%), and Western Pacific (1%)[28]. Urban piped supplies were frequently contaminated in Africa (27%), LMICs in the Eastern Mediterranean region (20%), and South-East Asia (11%)[28]. Only piped water was stratified by urban/rural settings. Between 10 and 41% of borehole samples and 78 to 97% of unprotected groundwater were contaminated[28]. Protected groundwater and tanker trucks had only pooled estimates: 56% and 33% of contaminated samples, respectively[28].

Table 1 – Water contamination according to water source

Water source classification	Type of water source	Range of the % of households with faecal contamination in drinking water (≥1 CFU/100 ml)	
		Wardrop *et al.,* 2017 (point of use)[1]	Bain *et al.,* 2021 (point of collection)[2]
Improved	Piped on premises	65.5–77.2	–
	Piped	–	5.1–84.5
	Standpipe, tanker, or neighbours tap	55.5–88.6	–
	Tubewell or borehole	60.8–89.5	13.8–82.8
	Protected well or spring	88.2–90.4	32.4–98.3
	Sachet or bottled water	31.2–66.0	2.8–76.8
	Rainwater	92.9[3]	50.3–100.0
	Delivered water	–	7.0–80.5
Unimproved	Unprotected well or spring	76.3–96.2	–
	Surface water	90.9–95.4	–
	Unimproved	–	40.2–98.9

[1]Countries: Bangladesh, Ghana, and Nepal
[2]Countries: Algeria, Bangladesh, Central African Republic, Chad, Congo, Côte d'Ivoire, Gambia, Georgia, Ghana, Guinea-Bissau, Iraq, Kiribati, Lao People's Democratic Republic, Lesotho, Madagascar, Mongolia, Nepal, Nigeria, Palestine, Paraguay, São Tomé and Príncipe, Sierra Leone, Suriname, Togo, Tonga, Tunisia, and Zimbabwe
[3]Only available for one country (Ghana)

Combined, the available evidence indicates that water contamination is high in LMICs. It also varies significantly between countries and between water sources and some improved sources are as likely to be contaminated as some unimproved sources. The contamination of piped water is higher in the rural setting. Although there is evidence that the likelihood of water contamination is higher in rural households, investigation of source-specific inequalities is still necessary.

Gaps in the literature

We did not find any articles that present the prevalence of contaminated water according to water source stratified by urban/rural settings based on multiple nationally representative surveys.

The article published by Bain *et al.* in 2021 is the most comprehensive of all the selected articles [3]. It presents the contamination prevalence according source type, using the water quality module from 27 MICS surveys [3]. In fact, the preliminary results presented in Section 1.12 were calculated before the article was published in the Environmental Health Perspectives Journal in September 2021. Specifically in terms of analytical results, we can expand on the work of Bain *et al.* by:

- Including 9 new countries with recently published data.
- Including separate categories for unimproved sources (unprotected wells, unprotected springs, surface water and others) which are presented as a single category by Bain *et al.* This is important for evaluating the different likelihoods of contamination between unimproved sources. Separating the categories of unprotected wells and unprotected springs is essential for comparing them with their counterparts: protected wells and protected springs, respectively. This comparison can help to inform if protection is helping to prevent water contamination or if respondents can actually differentiate between protected and unprotected wells and springs, since the classification is based on their perception and report.
- Calculating results separately by urban and rural settings. This stratification is necessary considering the current evidence that piped water contamination varies significantly between urban and rural households [28], and the different challenges of water services/collection in urban and rural environments

(population growth, overcrowding, population sparsity, land tenure, social structures, service profitability, availability of sanitation infrastructure, etc.). [29–31]

Table 2 – Articles included in the "Water quality in national surveys" literature review

Author, year, country	Data source	Sample	Water quality indicator	Water quality result	Other relevant information
Bain, 2014, global[28]	Review of the literature followed by multilevel modelling of secondary data	345 studies of microbial contamination, resulting in 133,460 water samples	*E. coli* or thermotolerant coliform in water source	26.0% of the global population using a water source with ≥1 faecal indicator bacteria (FIB) per 100 ml	• In 2012, 55.9% of the global population use piped water on premises • 1.8 billion people with a contaminated water source (1.1 billion with at least moderate risk, i.e., >10 FIB per 100 ml). • 10% of improved sources may contain at least 100 FIB per 100 ml • Water sources in rural areas are more contaminated (41%, CI: 31%–51%) than in urban areas (12%, CI: 8–18%) • Contamination is most prevalent in Africa (53%, CI: 42%–63%) and South-East Asia (35%, CI: 24%–45%) • Rural piped supplies are frequently contaminated, except in high-income regions
Bain, 2018, global[26]	Secondary national datasets identified by the UNICEF and WHO regional and country offices and by systematic review performed by the JMP staff[32]	3000 national data sources, primarily household surveys (n = 1,443), censuses (n = 309) and administrative data (n = 1,494)	*E. coli* or thermotolerant coliform, and priority chemicals where applicable	73.2% of the global population with drinking water free from contamination	• In 2015, 2.1 billion (29%) people lacked safely managed drinking water services • In the 2017 JMP update, there were 96 countries (34.4% of the global population) for which data were available for the safely managed drinking water services indicator • 88.9% of the urban population and 54.8% of the rural population with drinking water free from contamination
Bain, 2021, 27 LMICs[3]	MICS surveys (2014-20)	27 countries, 61,170 samples at the point of	*E. coli* at point of collection and at point of use	Point of collection: range 16–90%	• 84% of households used an improved drinking water source

Author, year, country	Data source	Sample	Water quality indicator	Water quality result	Other relevant information
		collection and 64,900 at the point of use		Point of use: range 19–99% (households with ≥1 colony forming units (CFU) per 100 ml)	• 31% of households had safely managed drinking water services • *E. coli* contamination was the primary reason for failing to have safely managed services (15 of 27 countries) • Contamination less common in improved water sources at the point of collection (risk ratio (RR) = 0.74; 95%CI: 0.64, 0.85) • Contamination more common in rural residences at the point of use (RR = 1.10; 95%CI: 1.04, 1.16) • Improved water sources were highly contaminated in many countries
Brainerd, 2014, India [33]	Water quality data from the Central Pollution Control Board of India (covers all rivers and their tributaries, creeks, wells, tanks, lakes, ponds, and canals) merged with the 2005 DHS' children dataset	Water quality: information is available for each state and month. DHS: 12,201 children for the largest sample	Presence of agrichemicals and level of biochemical oxygen demand in water samples from the child's month of conception and state	Presence of agrochemicals: 45.2% Level of biochemical oxygen demand: 0.004 mg/l	• The article does not focus on measurement of water quality, but rather its influence on child's health • There is very little information available on how water quality in measured • They use contamination levels of the whole state and conception month of the child for the analyses • The results seem to indicate that the presence of fertilizer chemicals in water in the month of conception significantly increases the likelihood of infant mortality, particularly neo-natal mortality
Dahl, 2013, Norway [34]	Water quality data from the Norwegian Waterworks Register (covers all waterworks supplying more than 50 persons or 20	Water quality: information available for each waterwork from 1993 to 2008	Water pH	39% were consuming water with acidic pH, i.e., pH <7.0	• The article does not focus on measurement of water quality, but rather its influence on forearm fracture • The coordinates of the individual waterworks were used to link the water

Author, year, country	Data source	Sample	Water quality indicator	Water quality result	Other relevant information
	households) merged with the population-based Cohort of Norway	Cohort: 173,236 subjects			register information to each participant in the cohort • The highest risk of forearm fracture was found at a pH of around 6.75
Dorea, 2020, Democratic People's Republic of Korea [35]	MICS survey (2017)	8,500 households	*E. coli* at point of collection and at point of use	76.5% of the population used a drinking water source that was free from faecal contamination	• This result is particularly important, given the fact the North Korea's MICS datasets have restricted access • 93.7% of the population used an improved drinking water source • The main source was piped water (58.5%) followed by tubewell/borehole (15.8%) • 60.9% of the population used a safely managed drinking water service • 90.3% of the urban population and 54.8% of the rural population used a drinking water source that was free from faecal contamination • Households with tubewell/boreholes were the least likely to be free of contamination (62.3%)
Flanagan, 2012, Bangladesh [36]	MICS survey (2009)	14,442 households	Arsenic contamination in drinking water	32% of households with arsenic concentration above the WHO's guideline value of 10 μg/l	• The article does not focus on measurement of water quality, but rather its influence on adult deaths • About 45 million people were found to be exposed to concentrations above 10 μg/l • It was estimated that arsenic exposures to concentrations > 10 μg/l account for an annual 43,000 adult deaths in the country
Kandel, 2017, Nepal [18]	MICS survey (2014)	1,421 households for drinking water	*E. coli* in drinking water	82.0% (95%CI: 78.7–84.7%) of households had	• 92.6% (95%CI: 90.4–94.2%) of households had access to improved water sources

Author, year, country	Data source	Sample	Water quality indicator	Water quality result	Other relevant information
				contaminated drinking water	• 81.2% (95%CI: 77.9–84.2%) of households using improved water sources and 89.6% (95%CI: 80.4–94.7%) of households using unimproved water sources had contaminated drinking water • 71.1% (95%CI: 64.2–77.1%) of urban households and 84.6% (95%CI: 80.9–87.6%) of rural households had contaminated drinking water • In a multivariable model, the odds of fecal contamination of water from improved sources were not different to water from unimproved sources
Khan, 2019, Bangladesh [37]	MICS survey (2012-3)	2,592 households	*E. coli* in drinking water	62% of households had contaminated drinking water	• The spatial analysis indicates that water contamination in households from adjacent districts tend to be more similar • Water contamination was more likely among households with unimproved water source (OR = 1.65; 95%CI 1.06–2.60) • No significant rural-urban difference was observed
Khan, 2022, Bangladesh [38]	MICS survey (2019)	2,232 children	*E. coli* at point of collection and at point of use	40.6% of children in households with contaminated water at point of collection and 83.8% at point of use	• The article does not focus on measurement of water quality, but rather its influence on child's episodes of diarrhoea • Children from households with moderate level of contamination (1-10 CFU per 100 ml) were 1.68 more likely to have diarrhoea than those without contamination. Children from

Author, year, country	Data source	Sample	Water quality indicator	Water quality result	Other relevant information
					households with high level (> 10 CFU per 100 ml) were 2.28 more likely
Kirby, 2016, Rwanda [39]	Own national survey	870 households	Thermotolerant coliform (TTC) in drinking water	24.9% (95%CI 20.9–29.4%) of households had no detectable contamination	• 42.5% (95%CI 38.0–47.1%) of households had high risk of contamination (> 100 TCC/100 ml) • 44.1% (95%CI 29.6–59.6%) of urban households had no detectable contamination. This number was 23.7% (95%CI 14.1–37.0%) for peri-urban households and 21.9% (95%CI 17.8–26.7%) for rural ones • Households using public tap/borehole (adjusted OR = 4.11), protected spring/well (adjusted OR = 4.10) and surface water (adjusted OR = 15.91) had significantly higher odds of contamination then those using piped water into yard/plot
Moreno, 2020, Ecuador [40]	2016 and 2019 National Survey on Employment, Unemployment, and Subemployment	2016: 4,442 households 2019: 7,331 households	*E. coli* at point of collection (2016 and 2019) and at point of use (2019)	73.4% of households were free of contamination at the point of collection in 2019	• A significant decrease in water quality of −5.9% was found between 2016 and 2019. The decrease was of −9.5% for rural areas and -4.3% for urban areas • The main barrier to safely managed drinking water was water quality • 52% of households using a piped source were free of contamination. 73.1% of households using other improved sources and 43.6% for those using unimproved water sources were free of contamination

Author, year, country	Data source	Sample	Water quality indicator	Water quality result	Other relevant information
Tugulea, 2017, Canada [41]	National Survey of Disinfection By-Products and Selected Emerging Contaminants	5 samples each for 65 water treatment systems under summer and winter conditions	Six iodo-trihalomethanes (iodo-THMs)	In two water systems the total concentration of iodo-THMs exceeded the concentration of regulated THMs	• Iodo-THMs are water disinfection by-products • The water systems were representative of Canadian drinking water • Samples collected at the water source, at the exit of the treatment plant, and three samples from the distribution system at progressively distant points • One or more iodo-THMs were detected at 31 out of 64 water systems in winter and in 46 out of 64 in summer • Total iodo-THM concentrations ranged from 0.02 mg/L to 21.66 mg/L
Wardrop, 2017, Ghana, Nepal and Bangladesh [27]	Ghana Living Standards Survey (2012-3), Bangladesh (2012-3) and Nepal's (2014) MICS surveys.	Ghana: 2,972, Bangladesh: 2,592, and Nepal: 1,492 households	*E. coli* at point of use	Ghana: 28.0%, Bangladesh: 37.3%, and Nepal: 17.8% of households were free of contamination	• The article main focus was on the influence livestock ownership on water contamination • Ownership of five or more large livestock was significantly associated with water contamination in Ghana and Bangladesh • Ownership of eight or more poultry was significantly associated with water contamination in Bangladesh • Households using sachet or bottled water were the least likely to be contaminated in Ghana and Nepal and standpipe, tanker or neighbours tap in Bangladesh
Wright, 2016, Ghana [42]	Ghana Living Standards Survey	3096 households	*E. coli* at point of use	28% of households were free of contamination	• Households using surface water were the least likely to be free of contamination (5.1%) • Households using sachet or bottled water were the most likely to be free of contamination (68.8%)

Author, year, country	Data source	Sample	Water quality indicator	Water quality result	Other relevant information
					• 15.5% of urban and 38.4% of rural households were free of contamination • The number of *E. coli* colonies showed digit preference (tendency to report values ending in zero)

1.4.2. Women's empowerment and WASH services

Objective

To identify published research articles that involve the association between a water, sanitation, or hygiene (handwashing) household indicator and women's empowerment.

Inclusion and exclusion criteria

- Inclusion criteria:
  - Women's empowerment indicator
  - Water, sanitation, or hygiene (handwashing) household indicator
  - Measurement of association between the WASH and empowerment indicators
- Exclusion criteria:
  - Exclusively oral hygiene
  - Women's empowerment measurement based solely on education or wealth indicators

Search query

We searched the PubMed and Web of Science databases on the 27th of June 2022 using the terms presented in Figure 3. All terms were included between quotation marks, and we searched Titles/Abstracts in PubMed and Topics (Titles/Abstracts/Author Keywords/Keywords Plus®) in Web of Science. We have restricted the search to Titles/Abstracts in PubMed and Topics in Web of Science based on the experience of the review from Section 1.4.1 and tests performed in the beginning of this review. Those restrictions maintained similar search sensitivity, and improved search specificity. The terms were selected based on the MeSH and DeCS databases and keywords from several research articles that have been previously selected.

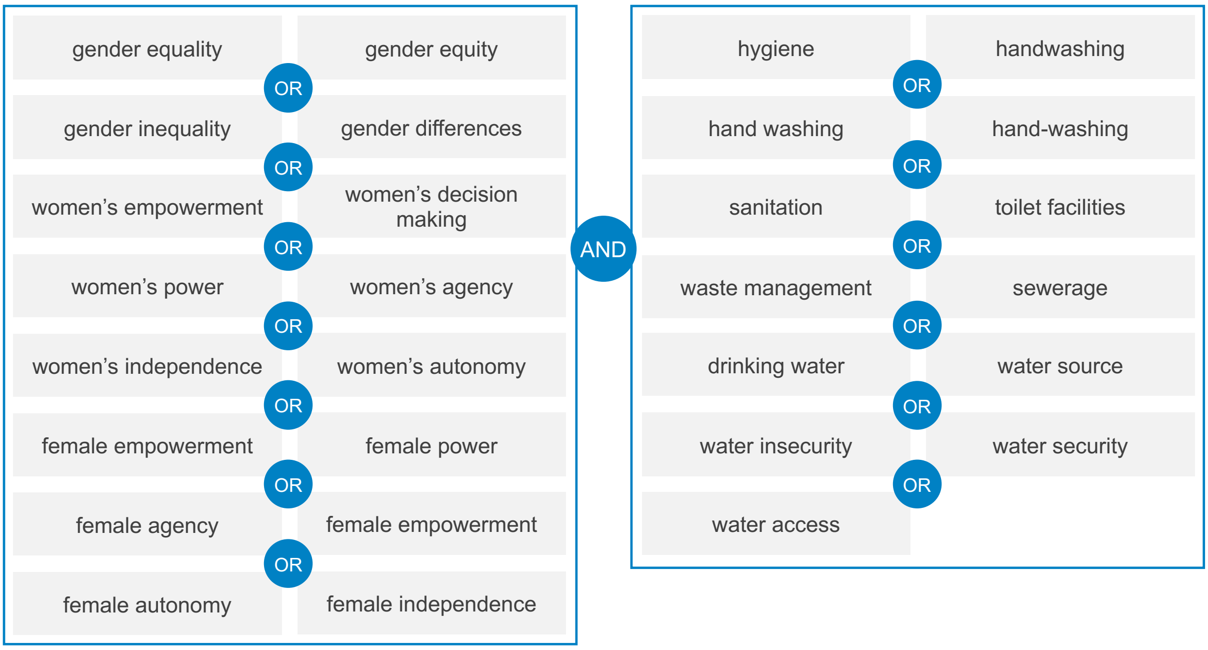


Figure 3 – Diagram of the search query used for the "Women's empowerment and WASH services" literature review

Results

Figure 4 presents the flow diagram of the article selection process and Table 3 summarizes the articles included in the review. From 535 unique articles, 9 were included after the selection process. 8 articles presented results for a single country and 1 article for 35 countries. All articles focused on LMICs, considering the World Bank's 2021 income classification[25].

There was no common data source between studies. All articles were published after 2015. Five articles included a water related indicator, 6 of sanitation and only 1 of hygiene. Empowerment indicators varied widely between studies, but the women's decision-making power was the most common dimension. Two articles had empowerment indicators specifically related to the WASH context, such as the women's involvement in decision making around stages of latrine building.

Many of the articles excluded in the full text reading were qualitative research articles that discussed but did not include a direct measurement of association between a WASH indicator and empowerment. Even though they were not included, some of their findings should be noted. These articles examined the relationship between empowerment and

WASH and the experience of women navigating WASH access and improvement, most commonly in local contexts. Definitions of empowerment varied, but many explored it in the community level, including women's participation in WASH organizations and interventions. Many of them argued that WASH improvement is a step towards women's empowerment, through reduction of WASH workloads and availability of discretionary time that can be used for employment and education [6,43]; increased school enrolment due to toilet installation [44]; direct employment in water services [45]; participation in community-led interventions that can increase social status [46]; increased sense of responsibility and capacity building in disaster-related activities [47]; access to roles and responsibilities usually reserved for men [48]; etc.

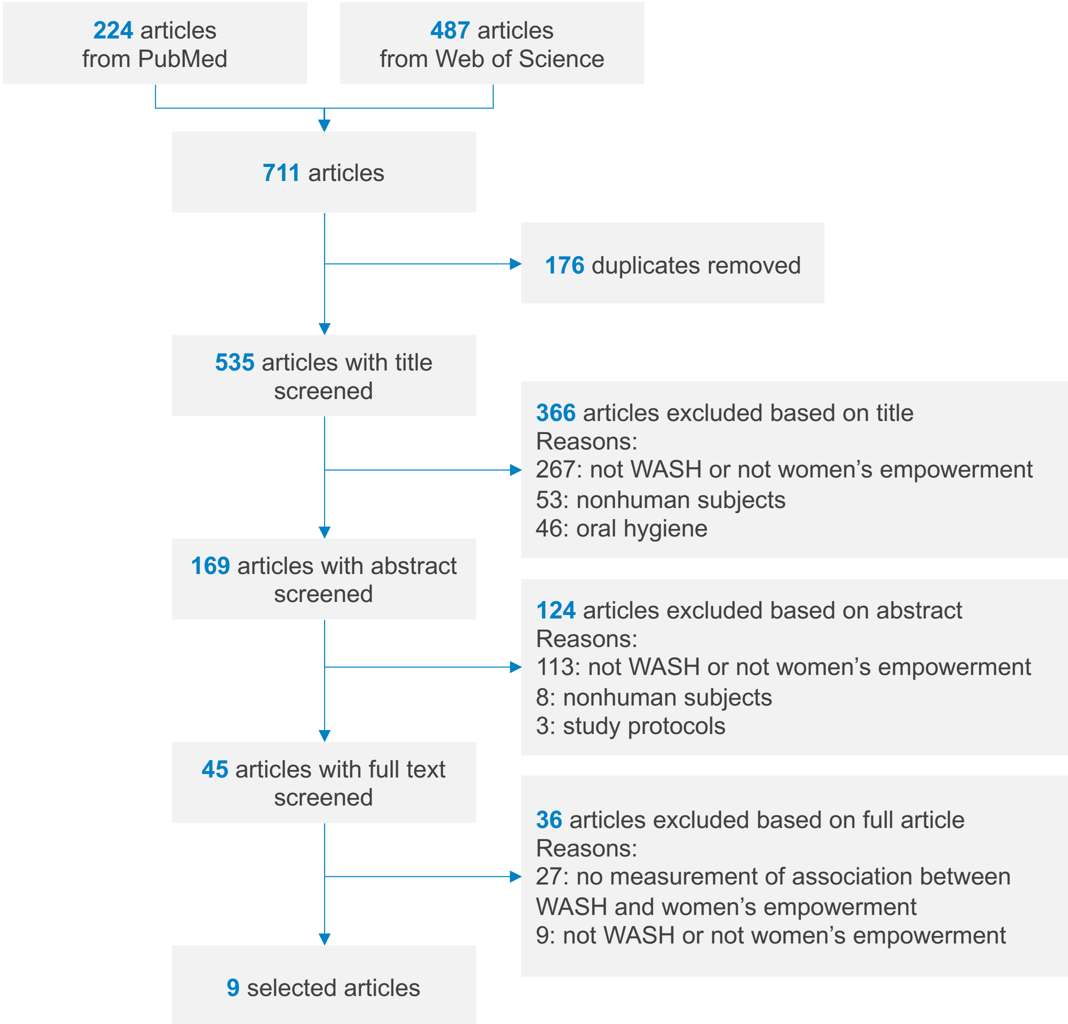


Figure 4 – Flow diagram of the "Women's empowerment and WASH services" literature review

In contrast, most of the articles included in the review discussed women's empowerment as a possible determinant of WASH (not the other way around) or did not establish a directionality for the relationship. They argued that improvement in WASH access can be achieved through women's ownership and control of assets and resources, including income, land and credit [10,11]; decision-making in household purchases and construction, including WASH infrastructure [12,13]; group membership that allow women to discuss issues in their communities [10,11]; intrinsic attitudes about WASH roles and responsibilities [14]; personal agency and supportive environments [15]; access and sharing of WASH information and other learning opportunities [14,15]; available time [10]; and leadership and participation in local WASH institutions and authorities [14].

The current state of the literature has been summarized as falling into four categories [12]:

- studies of how WASH programs differentially benefit women
- studies of programs that take a gendered approach to improve WASH indicators
- studies of how WASH programs empower women
- studies examining how women influence WASH decisions

Although no reports that included a measurement of association between WASH and women's empowerment were found in the JMP website, two 2021 reports on gender equality in WASH were available. The first one [49] presented a conceptual framework used to inform the review presented in the second one [16]. One of the aims of the review was to find opportunities to leverage existing data for monitoring dimensions of gender equality in WASH [16]. Among the listed opportunities, they indicate that "DHS items on how income is spent and who makes decisions on major household purchases may be WASH inclusive or leveraged to discover who has decision-making power for WASH purchases" [16].

Association between WASH and women's empowerment

Eight out of 9 articles found statistically significant associations between women's empowerment and at least one WASH indicator. There is evidence that more empowered women were more likely to have access to better WASH facilities and practices in general [10], to spend less time fetching water [11], to have or install improved water sources and sanitation facilities in their households [12,14,15,50,51], to report being satisfied with water quality and having enough water for growing crops and raising livestock [15], and to benefit from watershed interventions [52].

One article found no association between the women's involvement in decision making of their own personal lives and household items with latrine ownership and functionality [13]. Women's involvement was generally low, resulting in small observed counts for many categories and making the results inconclusive. There was also low women's involvement in the final decision to build a latrine (only 20% of households) and the qualitative research conducted indicated that women's non-involvement was due to low socioeconomic status and lack of land, confidence, and influence in the households' financial decisions [13].

One article created an extensive empowerment indicator specific for the WASH context that was calculated for both men and women in Burkina Faso – the Empowerment in Water, Sanitation and Hygiene Index, composed of 12 individual, household, and societal indicators [14]. A higher proportion of men (63%) were considered empowered than women (26%) [14]. For women, empowerment was significantly associated with both improved water source and sanitation facilities. For men, there was no significant association with sanitation, just water [14].

In summary, the literature suggests that women's empowerment is positively associated with WASH. Female empowerment might be even more relevant than male empowerment for sanitation services. Nevertheless, in contexts of general low empowerment, individual empowerment might not be enough to achieve access to those services. One should keep in mind that evidence is still sparse and context specific, and different measurements of empowerment and WASH indicators are used. Distinct definitions of women's empowerment are likely to have distinct relations with specific WASH services.

Gaps in the literature

We did not find any articles that present the association between women's empowerment – more specifically related to their economic autonomy and decision making – and access to basic WASH services based on multiple nationally representative surveys.

The only article that investigated multiple countries use data from the probability-based and nationally representative Gallup World Poll [15]. Their sample consists of non-institutionalized women aged 15 and older from 35 countries from Sub-Saharan Africa [15]. It uses only water indicators, including improved water source, but not access to basic water services [15]. Its empowerment score is based on three questions related to 1) freedom to choose what you do with life; 2) being treated with respect all day during the day before; and 3) learning or doing something interesting during the day before [15]. The only article using DHS surveys was from Kenya. It was restricted to improved household sanitation and women's decision making power on major household purchases and health care [50].

We can address those gaps by:

- Creating a women's empowerment indicator specifically related to economic autonomy and decision making. This component of women's empowerment represents her access and ability to control economic assets that can be used for installation, maintenance, and payment of WASH services.
- Investigating how consistent is the association of this indicator with access to basic WASH services in multiple LMICs.

Table 3 – Articles included in the "Women's empowerment and WASH services" literature review

Author, year, country	Data source and sample	WASH indicator	Empowerment indicator	Association	Other relevant information
Ahmadi, 2018, Ethiopia [11]	Growing Nutrition for Mothers and Children study in the regions of Afar, East and West Hararghe. 1,261 mothers with children younger than 5 years	Mothers' fetching water time > 30 minutes	1) Decision making (mothers vs others) 2) Gender equality attitudes (low vs high) 3) Group membership (no vs yes)	WASH was the outcome. Unadjusted odds ratio: 1) 0.97 ($p>0.05$) 2) 1.43 ($p<0.01$) 3) 2.20 ($p<0.01$)	• Mother's access to land was also included, but not coded as empowerment (odds ratio = 1.38, $p<0.01$, no vs yes) • The study also investigated the relationship time fetching water and children's anthropometric status (as an outcome)
Cunningham, 2019, Nepal [10]	Cross-sectional survey conducted in 16 districts throughout Nepal's three agro-ecological zones during the rainy season of 2012. 1,402 children aged 6 to 24 months	WASH facilities and practices (10 questions involving improved water sources, toilet ownership, hygiene habits, etc.)	Women's empowerment in agriculture construct (5 domains: production, resources, income, leadership, and time)	WASH was the outcome. Unadjusted β: 1.33 ($p<0.05$)	• Only 9% of the mothers were categorized as empowered • WASH was a mediator between empowerment and child length-for-age z-scores, with a positive association between the last two (Unadjusted β: 0.17, $p<0.001$)
Dickin, 2021, Burkina Faso [14]	Pilot study in Banfora in South-West Burkina Faso for the Empowerment in Water, Sanitation and Hygiene Index (EWI). 300 women	Type of water source used for drinking and type of sanitation facility	Empowerment in Water, Sanitation and Hygiene Index (12 individual, household, and societal indicators)	The EWI was associated with both the type of water source and sanitation facility. Empowered women lived in households with better water sources and sanitation facilities	• The EWI is an extensive indicator specific for the WASH context. It can also be calculated for men, which allows for the comparison of gaps in the same household • A higher proportion of men (63%) were considered empowered than women (26%) • For men, there was no significant association between empowerment and sanitation, just water. Empowered men lived in households with better water sources

Author, year, country	Data source and sample	WASH indicator	Empowerment indicator	Association	Other relevant information
Hirai, 2016, Kenya [50]	DHS Survey (2008-9). 4,682 married women (aged 15–49)	Using improved sanitation facilities	Women's decision-making power (health care and major purchases)	WASH was the outcome. Marginal change in probability: Health care: 0.046 ($p<0.01$) Major purchases: 0.087 ($p<0.001$)	• Women who shared or had full responsibility for health care decisions had a 0.046 higher likelihood to live in a household with an improved facility. For major household purchases, it was 0.087 higher • Women currently working had a 0.049 higher likelihood to live in a household with an improved facility
Lee, 2017, India [51]	India Human Development Survey in two rounds: 2004-5 and 2011-12. 19,124 women in rural households included in both rounds	Change in latrine ownership (1 if the household constructed a flush toilet or ventilated improved pit latrine between rounds and 0 otherwise)	Women as main decision-maker for household purchases	WASH was the outcome. The odds of change in latrine ownership were about 1.17 times higher in households where women are the main decision-makers. Results were statistically significant	• The model includes state fixed effects and adjustment for women's mass media usage, and health knowledge, as well as household literacy, wealth, latrine subsidies, handwashing practice, and caste/tribe/class • Women's regular mass media usage and accurate health knowledge were also positively associated with change in latrine ownership
Monteith, 2020, Sub-Saharan Africa [15]	Data from the Gallup World Poll 2017 of 35 countries from Sub-Saharan Africa. 17,891 women.	Water access score (perception of quality, water source, and availability) ranging from 0 to 4	Empowerment score (perception of freedom, respect, and learning or doing something interesting) ranging from 0 to 3	Women with lower water access score had significantly lower levels of empowerment in both rural and urban areas	• For rural areas, the coefficients are (water score 4 is the reference): ○ 0: -0.32 ($p<0.001$) ○ 1: -0.15 ($p<0.001$) ○ 2: -0.14 ($p<0.001$) ○ 3: -0.00 ($p=0.9$) • For urban areas: ○ 0: -0.32 ($p<0.001$) ○ 1: -0.24 ($p<0.001$) ○ 2: -0.14 ($p<0.001$) ○ 3: -0.04 ($p=0.3$)

Author, year, country	Data source and sample	WASH indicator	Empowerment indicator	Association	Other relevant information
					• Results were adjusted for household size, and income, and women's education, and employment
Padmaja, 2020, India [52]	Survey of three villages in India where watershed interventions were implemented. 222 households	Benefitting from watershed interventions (any of 9 outcomes, including availability of water and reduction in time spent fetching water)	Decision maker in household (male and female adult = 1; male adult only = 0)	WASH was the outcome. OR = 2.5 ($p<0.05$), meaning that households with shared decision making were more likely to benefit from any of the nine outcomes	• The outcome was benefitting from any of the nine outcomes studied (including water availability and other such as farm income, school enrolment and health status). Therefore, the results do not indicate necessarily that empowerment and WASH are associated • Based on performed interviews, decisions about water allocation were mostly made by men and strong patriarchal norms limited women's decision making and access to discussions about the project
Routray, 2017, India [13]	Survey in rural villages in the coastal district of Puri in 2015. 475 households for latrine ownership and 258 households for latrine functionality	1) Latrine ownership (no latrine, non-functional latrine, or functional latrine) 2) Latrine functionality (non-functional or functional latrine)	1) Women's involvement in decision making of their own personal lives and household items. 2) Women's involvement in decision making around stages of latrine building	WASH was the outcome. Women's decision making had no strong association with latrine ownership and functionality	• The selected villages were a part of a prior larger randomized control trial • Women's involvement in the decision to build sanitation facilities was low. In only 20% of households women were involved in those decisions • The qualitative research conducted indicates that women's non-involvement was due to low socioeconomic status and lack of land, confidence, and influence in the households' financial decisions
Thomas, 2021, Vietnam [12]	Survey at baseline and endline of a septic tank construction campaign	Household purchase of a septic tank	Women's leadership on home	WASH was the outcome. Households in which	• Women were 33% more likely to lead the sanitation decision if a campaign

Author, year, country	Data source and sample	WASH indicator	Empowerment indicator	Association	Other relevant information
	in 25 communes between 2017 and 2019. 1,251 households without hygienic latrines at baseline		construction decisions	women led on home construction decisions were 24% more likely to buy a septic tank ($p<0.05$)	promoter spoke to them rather than to a male householder • Campaign promoters who were older, trained, and educated were more successful in selling tanks

1.4.3. Combined WASH services

Objective

Our main interest was in articles that present a combined WASH indicator, but that criteria was too restrictive for the search. Therefore, our objective in this review was to identify published research articles that include simultaneously at least one national indicator of household's access to drinking water, one of sanitation, and one of hygiene, even if no combined indicator was presented. Given our main interest, our discussion was focused on the articles with a combined indicator.

Inclusion and exclusion criteria

- Inclusion criteria:
  - At least one indicator of drinking water, one of sanitation, and one of hygiene (handwashing). Any indicators were accepted
  - Nationally representative sample of urban or rural areas or both areas combined for any country
- Exclusion criteria: none

Search query

We searched the PubMed and Web of Science databases on the 11th of July 2022 using the terms presented in Figure 5. All terms were included between quotation marks, and we searched Titles/Abstracts in PubMed and Topics (Titles/Abstracts/Author Keywords/Keywords Plus®) in Web of Science. The terms were selected based on the MeSH and DeCS databases and keywords from several research articles that have been previously selected.

Results

Figure 6 is the flow diagram representing the article selection process and Table 4 summarizes the articles included in the review. From 224 unique articles, 13 were included after the selection process. Lack of hygiene (handwashing) indicators was the most common cause for exclusion. Ten articles presented results for a single country, 1 article for 8 countries, 1 for 25 countries, and 1 with global estimates. 11 articles focused on LMICs, 1 on a HIC and 1 included both LMICs and HICs, considering the World Bank's 2021 income classification.[25] DHS surveys were the most common data source, being used in 9 articles. All articles were published after 2017. Only 3 articles included some form of a combined WASH indicator.

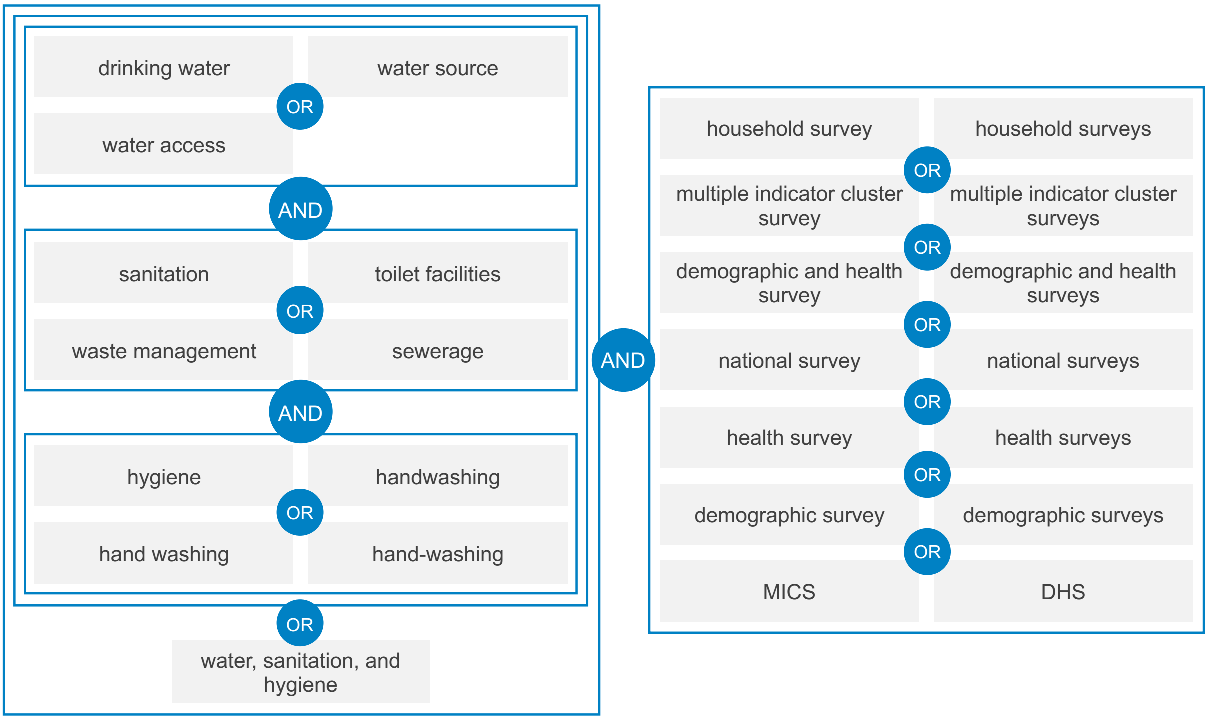


Figure 5 – Diagram of the search query used for the "Combined WASH services" literature review

Combined WASH indicators

The combined coverage of basic WASH services (simultaneous access to an improved water source and an improved sanitation facility, water collection time within 30 minutes and handwashing facility with soap and water) was presented in two articles and one report from the JMP website. The coverage was 40% of households in Bangladesh (2019)[53] and 4% of the population in 25 Sub-Saharan African countries (2010-2014)[22]. Coverage was worse for rural than urban areas in both articles: 37% for rural and 52% for urban households in Bangladesh[53]; and 1% for the rural and 9% for the urban population in Sub-Saharan Africa[22]. In the JMP's 2021 report entitled "Progress on Household Drinking Water, Sanitation and Hygiene 2000-2020 – Five Years into the SDGs", coverage was available for 41 countries stratified by wealth quintiles and sub-national regions, but no national estimates were reported[1]. Basic hygiene services tended to be the lowest in coverage and therefore the limiting factor in the combined "basic WASH services" indicator in most countries[1].

In Bangladesh, an almost linear relationship can be observed between wealth quintiles and the combined WASH coverage: as wealth increases, the coverage also increases [53]. The poorest wealth quintile had a coverage of 14% and the wealthiest of 75%, representing a gap of more than 60 percentage points [53]. On the other hand, in Sub-Saharan Africa, the top inequality pattern [54] was the most common among countries, meaning that coverage was much higher for the wealthiest quintile in comparison to the others [22]. Namibia and Eswatini had the largest gaps between the wealthiest and the poorest [22]. It was as high as 70 percentage points for their urban population and 30 percentage points for their rural population [22]. In the JMP report, wealth inequalities followed a pattern similar to the one in Sub-Saharan Africa, except in high-coverage countries where the poorest often lag behind [1].

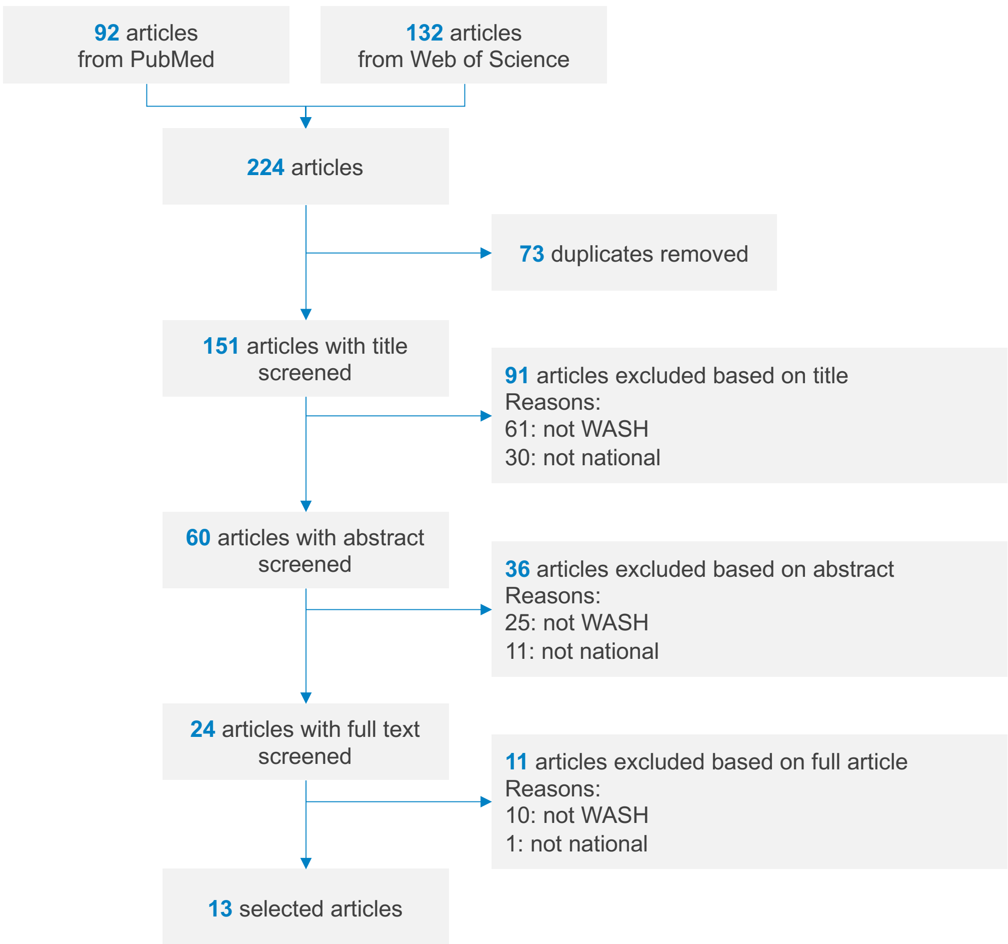


Figure 6 – Flow diagram of the “Combined WASH services” literature review

Although there were important inequalities in coverage according to the administrative divisions of Bangladesh (subnational regions), they were not as marked as wealth inequalities [53]. The Barishal division, located in the south-central region of the country, had the lowest coverage: 25% [53]. The Rangpur division, the northernmost division of Bangladesh, had the highest coverage: 48%. Most of the other regions had a coverage close to 40% [53]. In the JMP report, inequalities among sub-national regions were not as wide as for wealth quintiles, but still considerable. The Lao People's Democratic Republic (2017) had the widest gap: almost 80 percentage points [1].

There were two other combined WASH indicators in a third article [55]: the high-risk WASH practices index and the WASH Resource Index. The high-risk WASH practices index was created summing the number of the following practices present in the household: drinking unsafe water (surface water without treatment), open defecation, absence of handwashing place and water collection time ≥ 30 min [55]. The WASH Resource Index was created via principal component analysis based on the household's source of drinking water, water collection time, toilet facilities, the practice of sharing those facilities, and the presence of a place for handwashing with water and soap, detergent, or other cleansing agent [55]. Both indicators were calculated for the 2011 Uganda DHS survey clusters (e.g. a city block or a village) [55]. Results were worst (higher practices index and lower WASH Resource Index) in the region of Karamoja, in the northeast of the country [55]. Many clusters were exposed to at least two high-risk WASH practices [55]. The best results were found in the Central regions of the country (around Lake Victoria), were most clusters had an average of one or less high-risk practices [55].

The other 10 articles did not have a combined WASH indicator and presented separate results for water, sanitation, and hygiene. Only two of those articles included measurements of safely managed water and sanitation services [26,40].

There is a scarcity of studies which investigate the combined coverage of WASH services. Furthermore, we did not find any combined indicator that included safely managed water and sanitation services. From the few articles we could find, the combined coverage of basic WASH services tends to be really low in LMICs [22,53,55]. Rural households have worse coverage than urban households and there are significant inequalities in terms of subnational regions [22,53,55]. In Sub-Sharan Africa, only the wealthiest households tend to have much higher coverage, when compared to all the other wealth quintiles [22].

Gaps in the literature

We did not find any articles that presented a combined WASH indicator (including access to safely managed water and sanitation services and basic hygiene services) based on multiple nationally representative surveys.

One article with multiple countries calculated the safely managed water and sanitation services and basic hygiene services indicators but did not include a combined coverage indicator. [26] Another article with multiple countries calculated a combined indicator, but it was restricted to basic WASH services [22]. None of the combined indicators found – even if restricted to one country – included the safely managed water and sanitation services indicators.

We can address those gaps by:

- Creating a combined WASH indicator that is based on the safely managed water and sanitation services and the basic hygiene services indicator
- Determining this indicator's prevalence and assess inequalities in LMICs with available data

Table 4 – Articles included in the "Combined WASH services" literature review

Author, year, country	Data source and sample	Water indicator	Sanitation indicator	Hygiene indicator	Other relevant information
Ahamad, 2021, Bangladesh [56]	DHS survey (2017-8). 19,457 households	Location of water source: Own dwelling: 16.7% Own yard/plot: 73.9% Elsewhere: 9.4%	Toilet sharing: No: 69.6% Yes: 30.4%	Handwashing places with soap: Without soap: 61.2% With soap: 38.8%	• There was no combined WASH indicator • The study focuses on factors associated with observed handwashing places that lack soap in the richest households
Ahmed, 2021, Bangladesh [53]	MICS survey (2019). 61,209 households (weighted)	Basic water services: 99.5% (95%CI 99.4–99.6%)	Basic sanitation services: 60.7% (95%CI 60.0–61.5%)	Basic hygiene services: 56.3% (95%CI 55.6–57.0%)	• Combined coverage: 40.2% (95%CI 39.4–40.9%) • The richest households (adjusted OR = 29.6, 95%CI 26.3–33.4) and those from rural areas (adjusted OR = 1.64, 95%CI 1.50–1.79) were more likely to have basic WASH services. The odds were lower for rural households in the unadjusted model (OR = 0.54, 95%CI 0.49– 0.59) • They presented a map of subnational regions showing the South and South-East regions had lower coverages of the combined indicator
Bain, 2018, global [26]	Secondary national datasets identified by the UNICEF and WHO regional and country offices and by systematic review performed by the JMP staff [32]. 3000 national data sources,	Safely managed drinking water services: 71.2% Basic drinking water services: 88.5%	Safely managed sanitation services: 39.3% Basic sanitation services: 68.1%	Basic hygiene services: 15.4% in Sub-Saharan Africa and 76.3% in Northern Africa and Western Asia	• There was no combined WASH indicator • Estimates for the 2017 JMP update • Basic hygiene services had no global estimate. Only 29.7% of the global population lived in areas with data available for this indicator. In comparison, this number was 34.4%

Author, year, country	Data source and sample	Water indicator	Sanitation indicator	Hygiene indicator	Other relevant information
	primarily household surveys (n = 1,443), censuses (n = 309) and administrative data (n = 1,494)				for safely managed drinking water services • All indicator with available information had worst results for the rural areas • The study also presents estimations for SDG regions and the individual components of each indicator (such as "free from contamination" or "accessible on premises")
Balasubramanya, 2022, Nepal[57]	DHS survey (2016). 10,957 households	Drinking water source: Surface and/or unprotected: • rural: 3.9% • urban: 4.1% Public standpipe: • rural: 22.3% • urban: 18.3% Piped: • rural: 30.6% • urban: 35.1% (other sources not presented)	Toilet facilities: None: • rural: 20.9% • urban: 10.8% Pit/latrine: • rural: 10.9% • urban: 6.2% Flush: • rural: 66.9% • urban: 81.3%	Handwashing facilities: Water available: • rural: 69.1% • urban: 82.1% Soap and water available: • rural: 30.6% • urban: 57.2%	• There was no combined WASH indicator • Access to piped water, flushed toilets, and soap and water available for handwashing increased with wealth quintiles (+36.2, +31.5, and +62.6 percentage points for the wealthiest compared to the poorest, respectively)
Dhital, 2022, Nepal[58]	DHS survey (2016). 10,040 households	Improved water source: 95.5% Distance to water source: ≤30 min walk: 94.9%	Improved sanitation facilities: 83.8%	Fixed handwashing facility: 80.9% Soap and water available: 46.9%	• There was no combined WASH indicator • Poor households had lower odds of improved water (OR = 0.22, 95%CI 0.10–0.50), sanitation (OR = 0.17, 95%CI 0.13–0.24), soap and water (OR = 0.13, 95%CI 0.10–0.15), and

Author, year, country	Data source and sample	Water indicator	Sanitation indicator	Hygiene indicator	Other relevant information
					fixed place (OR = 0.25, 95%CI 0.20–0.31) then rich households • Urban households had higher odds of improved sanitation (OR = 2.3, 95%CI 1.5–3.5), soap and water (OR = 3.6, 95%CI 2.8–4.6), and fixed place (OR = 2.4, 95%CI 1.8–3.1) then rich households. There was no difference for improved water • There were significant differences between provinces for all indicators
Girma, 2021, Ethiopia [59]	DHS surveys (2000, 2005, 2011, and 2016). 61,715 households	Basic water service: 18% in 2000 and 50% in 2016	Basic sanitation service: <1% in 2000 and 6% in 2016	Basic hygiene service: <1% in 2000 and 8% in 2016	• There was no combined WASH indicator • Results varied markedly between subnational regions. For basic water services, all regions saw improvements between 2000 and 2016. For basic sanitation and hygiene, improvements were small or non-existent • Wealthier and urban households had higher access for the three indicators • The gap between the wealthiest and poorest households increased for all three indicators, mostly due to improvement in the wealthiest households • The gap between the urban and rural households increased for all three indicators, mostly due to improvement in the urban households

Author, year, country	Data source and sample	Water indicator	Sanitation indicator	Hygiene indicator	Other relevant information
Hirai, 2016, Uganda [55]	DHS survey (2011). 7,019 children under the age of 5	Drinking surface water without any treatment at point of use: 6.1% Water collection time ≥ 30 min: 41.3%	Open defecation: 11.1%	Absence of handwashing place: 56.9%	• The WASH Resource Index was constructed with the main source of drinking water, types of household sanitation facilities, practice of sharing sanitation facilities, handwashing materials in the household, and water collection time. Principal component analysis was used, and quintiles were created • Another indicator was created summing the four high-risk WASH practices • The WASH Resource Index and the high-risk practices indicator were higher in the northeast region of the country and lower closer to Lake Victoria (southeast) • The study investigated the association between the WASH Resource Index and child diarrhoea and only found a weak association
Lynch, 2022, Nauru [60]	Nauru's national trachoma population survey (2019). 818 children aged 1–9 years	Improved source of drinking water: 96.2% Drinking water source in the yard (no travel required): 67.5% Improved source of washing water: 95.7%	Adults in the household who usually defecate in private latrines: 96.3% Improved household latrine: 88.9%	Handwashing available with water and with soap: 87.5%	• There was no combined WASH indicator • The study focuses on factors associated with trachomatous inflammation - follicular. There was no association with any WASH indicator

Author, year, country	Data source and sample	Water indicator	Sanitation indicator	Hygiene indicator	Other relevant information
		Washing water source in the yard: 49.0%			
Moreno, 2020, Ecuador [40]	Ecuador's National Survey on Employment, Unemployment, and Subemployment (2016 and 2019). 4,442 and 7,331 households, respectively	Safely managed water services: 70.1% in 2016 and 67.8% in 2019	Safely managed sanitation services: 41.8% in 2016 and 42.2% in 2019	Basic hygiene services: 85.5% in 2016 and 89.1% in 2019	• There was no combined WASH indicator • From all the components of the safely managed water services indicator, the water contamination component had the worst result in 2019 (73.4% while all others were above 90%) • 76.9% of urban households and 48.5% of rural households had safely managed water services in 2019 • The percentage of households with water free from contamination significantly decrease between 2016 and 2019 (-5.9%). Results were worst for the rural area (-9.5%)
Patrick, 2021, Peru [61]	DHS survey (2011). 7,560 children under the age of 5	22.0% had access to an unimproved source of drinking water	43.2% had access to an unimproved sanitation facility	40.6% had access to an unimproved hygiene facility	• There was no combined WASH indicator • The main focus of the paper was the impact of scaling up WASH intervention in childhood diarrhoea
Rakotomanana, 2020, East Africa [62]	DHS surveys from Burundi, Ethiopia, Kenya, Malawi, Rwanda, Tanzania, Uganda, and Zambia (2013 to 2017). 1177 (Rwanda) to 2963	Basic water services: from 31.8% in Ethiopia to 57.1% in Kenya	Basic sanitation services: from 4.2% in Ethiopia to 52.8% in Rwanda	Basic hygiene services: from 5.5% in Burundi to 46.1% in Tanzania	• There was no combined WASH indicator • The main focus of the study was the association between WASH and child length

Author, year, country	Data source and sample	Water indicator	Sanitation indicator	Hygiene indicator	Other relevant information
	(Zambia) children aged 6 to 23 months				
Roche, 2017, Sub-Saharan Africa[22]	DHS and MICS surveys (2010 to 2014) from 25 sub-Saharan African countries	Improved water source: 64.5% (95%CI 60.8–68.0%) Basic water service: 53.6% (95%CI 50.0–57.1%)	Basic sanitation service: 25.7% (95%CI 23.1–28.6%)	Basic handwashing service: 9.3% (95%CI 7.9–10.9%)	• There were several combined WASH indicators • The results were combined to create estimates for the Sub-Saharan Africa region • Improved water and basic sanitation: 19.7% (95%CI 17.4–22.3%) • Basic sanitation and hygiene: 5.0% (95%CI 4.2–6.1%) • Basic water, sanitation, and hygiene: 4.2% (95%CI 3.3–5.5%) • Basic water, sanitation, and hygiene: 9.0% for urban and 1.0% for rural populations • Most countries showed a top wealth inequality pattern, meaning that coverage was higher in the highest wealth quintile with very low rates in the lower quintiles
Shrestha, 2020, Nepal[63]	DHS survey. 2,352 children under the age of 5	Living in a household with practice of water purification: 18.3%	Living in a household with improved sanitation: 75.7%	Living in a household with water and soap available: 37.5%	• There was no combined WASH indicator • The main focus of the study was the association between WASH and child height-for-age, weight-for-height and weight-for-age

1.5. Conceptual model for the association between women's empowerment and WASH

The proposed research articles 1 and 3 of this project will be descriptive articles that present the prevalence of their respective outcomes of interest (water contamination in research article 1 and simultaneous coverage of WASH services in research article 3) according to common inequality stratifiers. We do not intend to investigate general associated factors with the outcomes, but rather monitor specific inequalities in their prevalence. In particular, for research article 1, it is not our intention to explain why some sources are more or less likely to be contaminated, but rather to inform if contamination is present, regardless of the distal and proximal factor that led to contamination.

In contrast, for research article 2, we intend to investigate the association between women's empowerment and WASH services, based on the idea that women's empowerment might be a possible causal pathway towards better WASH services. Although we will not be able to make any causal claims in our research, it is important to establish a conceptual model to guide the analysis and interpretation of our results. Therefore, this section presents our proposed conceptual model for research article 2, describing our current understanding of how women's empowerment and WASH services are related.

1.5.1. Introduction

For the second proposed article of this project, we plan to investigate the association between a specific facet of women's empowerment – related to their economic autonomy and decision-making power – and the presence of basic WASH services in their households. We will use data from DHS surveys, which are cross-sectional by design. Both empowerment and WASH indicators are measured simultaneously, and they represent the woman and her household's current state. This can be the result of recent changes or reflect more structural conditions that persist throughout the woman's life. Therefore, temporality cannot be established.

Another challenge for causal inference is the need to eliminate biases such as confounding, which requires appropriate covariate adjustment. In the experience of the

ICEH's members, there is a still-open debate between peers, research partners, and journal reviewers about the necessity of adjusting the association between women's empowerment and health outcomes for common dimensions of inequality. Frequently, the debate centres around household's wealth, women's education, and area of residence. It is our understanding that this decision should be made based on 1) the research question at issue; 2) a conceptual model that takes into account the life-course approach (presented in section 1.5.3); and 3) the strengths and limitations of the study design in question.

Despite the current global goal of achieving clean water and sanitation for all and the research priority of understanding women's participation in WASH decision making and governance [6], the investigation of causal pathways between women's empowerment and the availability of WASH services remains a challenge. Our proposed article will not and cannot investigate causality between them. But what it can do is to explore how consistently associated women's empowerment and WASH services are in LMICs, therefore helping to establish the research background for future causal research and for interventions to improve WASH services coverage under SDG 6 and women's empowerment under SDG 5.

1.5.2. The empowerment indicator

First, we define the latent construct that our empowerment indicator will try to capture as the personal possession and control over economic assets by a married/in union woman and her relational ability to influence the decision-making process around her husband/partner's and her household's economic assets. By definition, this construct is limited to women who are married/in union, as its second component is related to her ability to influence and share the decision-making power with her husband/partner. A further discussion of this limitation is presented in section 1.8.2.

An economic asset is defined by the Organisation for Economic Co-operation and Development as:

> *"…entities functioning as stores of value and over which ownership rights are enforced by institutional units, individually or collectively, and from which economic benefits may be derived by their owners by holding them, or using them, over a period of time (the economic benefits consist of primary incomes derived from the use of the asset and the value, including possible holding gains/losses, that could be realised by disposing of the asset or terminating it)."*[64]

This definition of empowerment is based on the Oxfam's 'How to' Guide to Measuring Women's Empowerment[65]. It encompasses two of the three dimensions proposed in the Oxfam framework: empowerment at the **personal** and at the **relational** level[65]. The personal level is related to the woman's individual power to access savings, credit, and material assets and personal autonomy to acquire and control those assets. The relational level materializes in the power relations within the woman's marriage/union and her household[65]. More specifically, it is related to her control over household assets and her involvement and influence in the household decision-making process.

Our definition does not involve the **environmental** dimension of empowerment, i.e., in a broader social context, including a political and legislative framework. There are indexes that capture this dimension, such as the Empowerment in Water, Sanitation and Hygiene Index with the inclusion of indicators related to group membership and leadership in WASH implementation and accountability within WASH institutions and authorities[14]. However, data that could capture this dimension of empowerment in not available in DHS surveys for individual women.

We have chosen this definition based on three criteria: 1) data availability in nationally representative household surveys that also include WASH indicators; 2) our current expectations of what specific dimensions of women's empowerment might be more directly associated with WASH services; 3) our desire to be more specific and avoid mixing many dimensions that might make covariate adjustment even more ambiguous.

In terms of data availability, our definition focus on two dimensions identified by Caruso *et al.* as opportunities for leveraging existing data in DHS surveys to increase gender focus in current monitoring of WASH [16]. The first dimension is "Financial Resources & Physical Assets", defined as the "Individuals' control over economic resources and long-term stocks of value, such as land, for the purposes of meeting individual and household WASH needs" [16]. The second one is "Household Decision-Making", defined as the "Individuals' opportunities to influence and make decisions about water, sanitation, and hygiene within their homes" [16].

The reasons why the women's economic autonomy and decision making might be more directly associated with WASH are presented throughout section 1.5.3. But it is important to note that our definition is not the only viable one. In fact, other dimensions of women's empowerment could and should be investigated using DHS and other data sources. The report by Caruso *et al.* presents an extensive list of opportunities for leveraging existing data to investigate the role gender and women's empowerment plays in access to WASH services [16].

In particular, DHS surveys also include data that have been used to capture other dimensions of women's empowerment, such as the woman's attitude towards violence (whether she thinks that wife-beating is justified in specific situations), differences in education and age between wife and husband, age at some important life events, and decision-making power not directly related to economic assets [13,50,52,66]. Although these are important components of a more general definition of women's empowerment, we did not include them because of the aforementioned second and third criteria. For example, women's attitude towards violence might be an unlikely candidate for a consistent association with WASH services (second criteria). Women's education might be more directly related to WASH services, but, if included, would make the covariate adjustment even more ambiguous (third criteria).

We will implement our definition of empowerment via an empowerment index to be created based on a list of questions available in DHS surveys. For the possession and control over economic assets dimension, we will use the woman's current employment in a paying job and her current possession of a bank account, a mobile phone used for financial transactions, a house, and land. For the decision-making dimension, we will use her current participation on the decision-making process regarding her money, her husband/partner's money, and the household's major purchases.

We have selected these questions trying to balance availability in a larger number of surveys – in order to include as many countries as possible – with face validity, i.e., our subjective understanding of the extent to which they cover the concepts we will try to measure. Although subjective, it was based on our experience creating other empowerment indexes [66,67] and reports for the literature [10,16,65]. In a 2021 conceptual framework for gender equality in WASH by Caruso *et al.*, money, land, equipment, credit, savings, time, and labour were all assets deemed critical for accessing WASH facilities and services and for enabling individuals to participate in public and private decision-making around WASH [49]. When women lack or have limited financial resources and asset control, it can be difficult for them to access their preferred sanitation locations, water sources, and water treatment methods [49]. Lack of land and housing – or gendered barriers to their control when these assets exist – can limit women's decision-making around latrine construction. Women's exclusion from these decisions can lead to latrines that do not accommodate women's privacy needs, rendering them unusable [49].

It should be noted that by this definition and operationalization, there is an overlap between the woman's empowerment and the general household's wealth. In DHS surveys, wealth is typically measured using a wealth index, based on a series of household indicators, including its building materials, ownership of appliances, presence of electricity, water, and sanitation, etc [68]. This relation between household's wealth and women's empowerment – including its implication for the statistical analyses – will be discussed in sections 1.5.3 and 1.5.4.

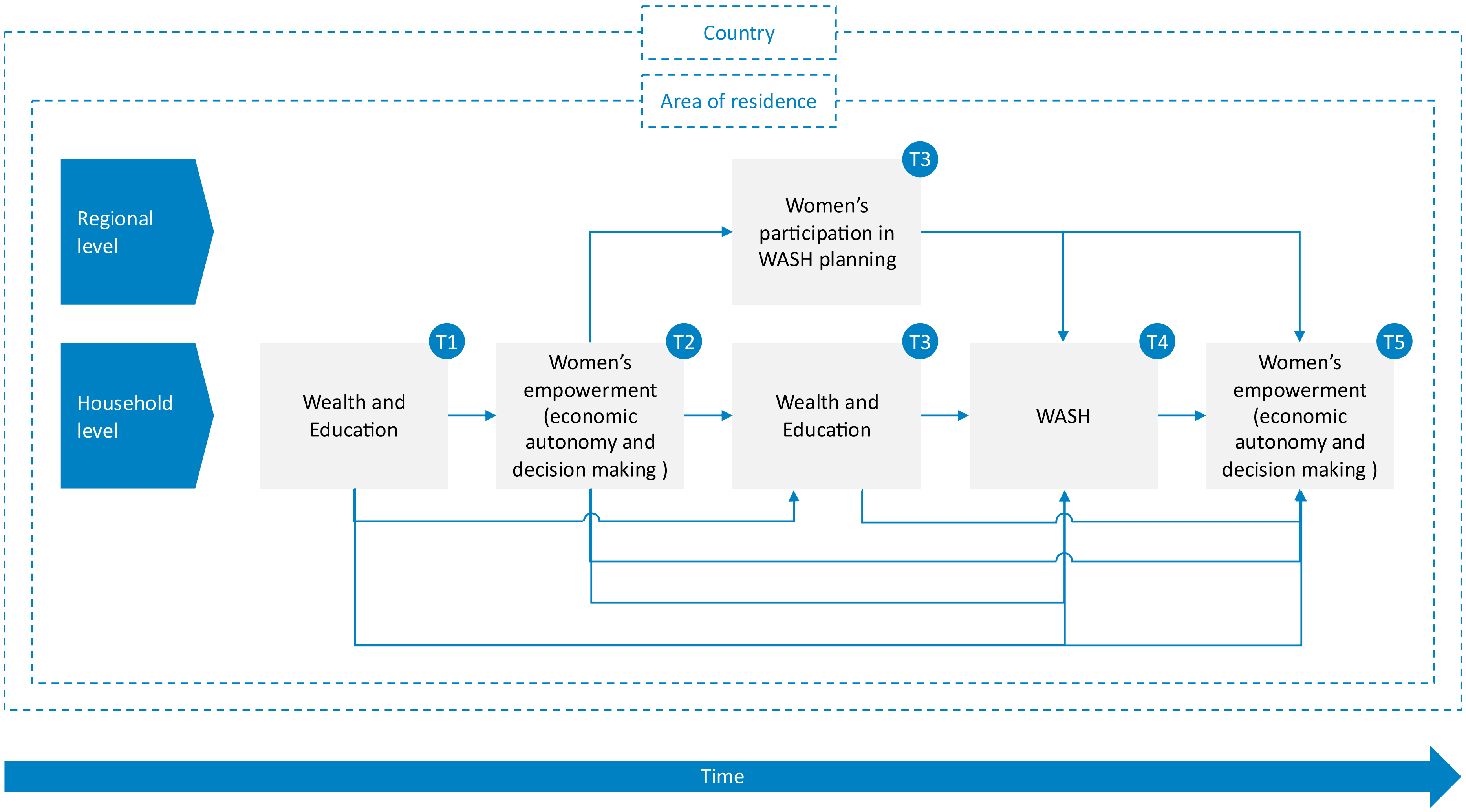


Figure 7 – Conceptual model for relationship between women's empowerment (economic autonomy and decision making) and WASH services in the household.

1.5.3. The conceptual model

In order to guide our analysis, we propose the conceptual model presented in Figure 7. The model focuses primarily on the relationship between 1) women's empowerment; 2) WASH services; and 3) three important dimensions of inequality: wealth, education, and area of residence (urban/rural). First, it should be noted that, in this theoretical model, indicators are measured at different points in time, following the direction of the woman's life cycle. These are indicated by the blue circles at the top-right corners of the rectangles. For example, wealth and education are measured at both T1 and T3. T1 indicates that they were measured before T2 – the time of the first measurement of women's empowerment – and T3 is after. This model does not reflect the data we will analyse, which is cross-sectional in nature. We chose to create a model that follows the life cycle in order to display our understanding and assumptions about the relationship between women's empowerment and WASH indicators over time. This is useful to highlight the limitations we have with cross-sectional data, guide our analytical choices, and interpret our results based on a broader conceptual model.

Wealth and education (T1) to women's empowerment (T2)

First, let's start at the household level, from left to right. Early-life education and wealth are important steps towards women's empowerment. Women's wealth, including assets received by inheritance, can affect their social mobility, occupational choice, asset accumulation, as well as their bargaining power in the household [69]. Access and control over land and credit are particular important to women's autonomy in agrarian societies where land is considered the most productive asset. Also, women's employment outside the home can increase their decision-making power and control over household's assets [70].

More educated women are expected to have higher economic autonomy and decision making via several pathways: 1) Education increases women's resources, including income. Those resources are not only a part of economic autonomy in themselves, but they can also increase a woman's bargaining power in family negotiations. 2) Education exposes women to more egalitarian gender attitudes, helping them to achieve power within themselves and exert that power in the household's decision-making process. 3)

Highly educated women tend to marry highly educated men, who are inclined to have more egalitarian gender attitudes and share power with their wives. 4) Education, including basic financial education, increases the women's ability to make more informed financial decisions, shifting the power balance in family negotiations [71–73].

Women's empowerment (T2) to wealth and education (T3)

More empowered women – more specifically with higher economic autonomy and decision making – are expected to be wealthier and more educated later in life. The women's economic autonomy includes the possession of economic assets and access to a paying job, that both contribute directly to the household's wealth accumulation. And wealth is a well establish predictor of access to higher education in LMICs, increasing the later likelihood of a person to be in the labour force, to find employment and to have higher earnings [74,75].

Women's empowerment (T2) and WASH (T4)

The impact of women's empowerment on WASH services should be both direct, mediated through wealth and education (T3) and through women's participation at the regional level.

In terms of a direct effect, there is evidence that women tend to perceive water insecurity as more severe/frequent than men [8], making them more likely to take steps to ensure water security. Although women's participation in WASH planning and decision making tend to be lower than men's [14], findings suggest that women's decision-making power in the household can lead to better WASH services [14,50]. In fact, using the same measurement of empowerment for both men and women (that includes both ownership of assets and decision-making power), a study from Burkina Faso found that both men's and women's empowerment were associated with using an improved water source, but only women's empowerment was associated with improved sanitation facilities [14].

In terms of wealth, available income is an essential condition for both installation and maintenance of sustainable WASH services. Intra-household budget allocations, the lack of credit, limited ability to save money, and the lack of an income source can all hinder the affordability of the investment costs, monthly bills and regular spending required for continuous access to WASH services [76,77]. Other components of wealth, such as land ownership, are also important. A study from rural India indicated that lack of land, as well as the women's lack of proprietary rights over land, can hinder the installation of latrines. Women from landless families who worked as labourers reported that even though they had some money available and were ready to contribute with labour, they only owned their house's land and had nowhere to build a latrine. On the other hand, many women whose family owned land reported they had to seek permission from their father-in-law or husband (the land's owner) in order to build a latrine [13].

In terms of education, it may increase the women's receptiveness to WASH information, her understanding of the benefits of basic WASH services, her awareness of WASH subsidies provided by governments and her skills to navigate bureaucracy and demand those subsidies, her ability to overcome apprehensions and misconceptions about using latrines, and her knowledge on disease causation and the role that human waste plays on transmission [7,51,78]. In fact, women's education was significantly associated with the presence of an improved sanitation facility in the household even after controlling for decision-making power in Kenya [50].

In terms of WASH planning at the regional level, it is argued that women's participation and decision making in WASH governance is essential for more sustainable and fairer systems [45] that can also address gender-related design considerations (privacy, lighting, safety, menstrual hygiene management, etc.) [44]. In general, women's participation is low compared to men. Even in contexts where formal steps are taken to include women, gendered norms, stereotypical assumptions of female leadership, skills and interests, and self-perceived barriers undermine actual participation [45,46,48]. In practice, women's participation on community interventions can increase women's status and prioritize women's needs during the planning stages of an intervention, but also reinforce gendered norms via limited decision-making and restrictions on women's presence in meetings and building activities [46,48].

WASH (T4) and women's empowerment (T5)

As discussed in Section 1.4.2, access to WASH services may lead to later women's empowerment through reduction of WASH workloads and availability of discretionary time that can be used for income-generating activities and education [6,43,79]; direct employment in water services [45] and access to roles and responsibilities usually reserved for men [48].

Despite that, it is important to acknowledge that the evidence for WASH increasing empowerment – and the other way around, for that matter – is still circumstantial and fragile. The argument is logical and anecdotal evidence is available, but there is still a critical gap for more robust studies [14]. For example, not all time saving provided by the installation of WASH service might lead to earning income and education. Women might use their free time for leisure activities, domestic work, or to relax [80].

Area of residence

In the model, the area of residence (urban/rural) is the context in which all of the aforementioned relationships take place, within the same country. This represents how these relations can interact with the different urban and rural environments, possibly expressing associations with different magnitudes.

Even though access to WASH services is usually better in urban environments, important inequality patterns are observed within urban communities. Slums, long-term camps for refugees and internally displaced people, and other informal settlements in urban areas can be located in hazardous urban land and be deprived of basic WASH services. The urban environment is associated with different WASH risks, including: rapid population growth that leads to services failing to keep up with demand; limited political capability to implement WASH policies that are inclusive to marginalized urban populations; lack of land tenure, leading to the absence of connection to public water and sanitation services; overcrowding that can overwhelm already fragile public systems; and social structures that can challenge public action and hinder the ability of service providers to implement and maintain WASH services [31].

In the rural environment, other challenges are present: the disperse nature of human settlements and small population size that can increase travelling time to a water source and result in low revenue collections by service providers, making the installation of services like piped water and sanitation less feasible; lack of political attitude and accountability; inadequate resources for installing and maintaining infrastructure; and climate seasonality coupled with the effects of climate change, including long dry seasons that can reduce available water in nearby streams and wells and heavy rainfall and flood events that can increase water contamination, especially in the absence of proper sanitation [29,30]. Farming also plays an important role: increasing demand for irrigation water and domestic water use can increase competition for resources and farming activity can lead to water contamination with fertilizer agrichemicals [33,81]. At the same time, investment in multi-purpose water systems and sanitation solutions that can make productive agricultural use of human waste represent opportunities for developing both farming and basic WASH needs [81].

Country

Above the area of residence level, we have the country level. The relation between women's empowerment and WASH is expected to be country-specific – or at least it should not be assumed to be uniform – given varied levels of empowerment, gender-differentiated roles in WASH, and cultural norms in each country. Among LMICs, countries in the regions of Europe & Central Asia and Latin America & Caribbean show the highest scores in the social independence and decision-making domains of women's empowerment as measured by the SWPER (Survey-based Women's emPowERment Index) Global index [67]. Countries in the African regions, especially West & Central Africa, and some countries from South Asia have the lowest scores [67]. And although water collection falls disproportionately on women in most LMICs, in a few countries like Mongolia men are primarily responsible for this task [9]. Cultural norms can also affect public water and sanitation participation. In a study in Northern Thailand women tended to choose men as leaders for water committees because they believed public leadership roles are more suitable for men and men tended to view domestic water as women's main responsibility [82]. On the other hand, in a study in Uganda, women were described as trustworthy members of Water User Committees by both men and women and although men tended to be less likely to trust a Committee with female members, women were more likely to do so [83].

1.5.4. Implications of the conceptual model in a cross-sectional survey

The conceptual model presented in Figure 7 describes an ideal situation where information can be collected throughout the women's lifecycle, including different measurements of the same indicator, such as wealth and empowerment, at different points in time. In this scenario, if we accept the validity of the conceptual model, we can state:

- Wealth and education measured at T1 are confounding factors in the association between women's empowerment (T2) and WASH services (T4)
- Wealth and education measured at T3 are mediators in the association between women's empowerment (T2) and WASH services (T4)
- Women's empowerment (T2) leads to WASH services (T4)
- WASH services (T4) lead to women's empowerment (T5)

This ideal scenario could be achieved in a cohort study, but this project deals with data collected in cross-sectional surveys. Wealth, education, the components of women's empowerment, and WASH services were measured simultaneously. This implies that:

- Measured wealth and education might be reflecting both their confounding and mediating effects
- There is an overlap between what the women's empowerment and household wealth indexes try to measure
- The directionally of the association between women's empowerment and WASH services cannot be determined

Therefore, we will only calculate the crude association between women's empowerment and WASH services. We will not statistically adjust for household wealth nor women's education and we will stratify all the measurements of association according to area of residence.

1.6. Objectives

Research article 1:

- To determine the prevalence of *E. coli* contamination in drinking water in low- and middle-income countries according to both water source and urban/rural setting

Research article 2:

- To create a women's empowerment indicator specifically related to economic autonomy and decision making in the context of low- and middle-income countries
- To investigate the association between this empowerment indicator and access to basic water, sanitation, and hygiene services in urban and rural settings

Research article 3:

- To create a Full WASH indicator: an indicator of household complete access to safely managed water, sanitation, and hygiene
- To investigate inequalities in the Full WASH indicator regarding wealth, area of residence (urban/rural), country and subnational regions of low- and middle-income countries
- To discuss the Full WASH indicator in one of the Pacific Islands as a sample case (see Section 1.8.3 for further details)

1.7. Hypotheses

1.7.1. Research article 1

- The prevalence of contamination varies substantially between and within countries.
    - Between countries, water contamination ranges from less than 10% to more than 90% of households. The Pacific Islands and West and Central Africa have the highest prevalence of water contamination globally
    - Within the same country, distinct types of water sources have very different prevalences of contamination
    - In the worst contexts, almost all water is contaminated independently of source
- The prevalence of contamination varies substantially between sources.
    - Households with piped water sources are the least likely to have contaminated water
    - Improved sources have lower prevalence of contamination when compared to unimproved sources
    - Protected wells and protected springs are highly contaminated despite being currently classified as improved water sources. Some improved sources have higher contamination than some unimproved sources.
- In general, water sources from rural areas have higher prevalence of contamination then those from urban areas
    - The inequality between urban and rural settings varies significantly according to water source
    - Urban wells are as likely to be contaminated as rural wells
    - Rural piped water is significantly more contaminated than urban piped water, having one of the highest gaps among all sources

1.7.2. Research article 2

- The empowerment indicator (higher economic autonomy and decision making) is lowest for women in countries from West and Central Africa

- More empowered women are more likely to live in households with basic WASH services
    - For the majority of countries (around 60%), there is a positive association between women's empowerment and WASH indicators. For some (around 30%), there is no significant association between women's empowerment and WASH indicators. For only a few countries (around 10%) this association is negative
- The strongest association is between women's empowerment and basic hygiene, followed by basic water. Basic sanitation has the weakest association with women's empowerment
- Women's empowerment is generally more strongly associated with WASH indicators in the urban environment than in the rural

1.7.3. Research article 3

- The coverage of the Full WASH indicator is generally low for most countries in the sample (below 50%), with significant inequalities between those countries
    - The Pacific Islands and West and Central Africa have the lowest coverage of the Full WASH indicator
    - Some countries, such as Chad, have a Full WASH coverage close to 0%
- The safely managed water services indicator is responsible for the low coverage of the Full WASH indicator in most countries, followed by the safely managed sanitation services indicator. The hygiene indicator is the component with highest coverage.
- There are important inequalities regarding wealth, area of residence (urban/rural), and subnational regions within most countries
    - Subnational region is the stratifier with the highest level of inequality
    - The poorest and rural populations have significantly lower coverage of the Full WASH indicator

1.8. Methods

1.8.1. Research article 1

Data source

The most recent MICS surveys that includes a water quality module will be used. Currently, this includes 36 countries, presented in Table 5.

Table 5 – MICS surveys selected for article 1

Country	Year
Algeria	2018
Bangladesh	2019
CAR	2018
Chad	2019
Congo Brazzaville	2014
Congo, Democratic Republic	2017
Côte d'Ivoire	2016
Dominican Republic	2019
Gambia	2018
Georgia	2018
Ghana	2017
Guinea Bissau	2018
Guyana	2019
Honduras	2019
Iraq	2018
Kiribati	2018
Kosovo	2019
Lao	2017
Lesotho	2018
Madagascar	2018
Malawi	2019
Mongolia	2018
Nepal	2019
Nigeria	2016
Paraguay	2016
Samoa	2019
São Tomé and Príncipe	2019
Sierra Leone	2017
State of Palestine	2019
Suriname	2018
Togo	2017
Tonga	2019
Tunisia	2018

Country	Year
Turks and Caicos	2019
Tuvalu	2019
Zimbabwe	2019

Indicators

Water contamination

Household drinking water contamination will be measured by the level of *E. coli* contamination in water samples collected in the water quality module of MICS surveys. Typically, the water quality module is designed to produce estimates that are representative at the national and first subnational level (provinces, regions, or states) and also for urban and rural areas of a country. A random subsample of all households visited during a survey is selected in order to create a reliable estimate of water quality while reducing costs and workload. A very common strategy used by MICS is to select 25 households in each survey cluster for the regular interview and 5 of these for water quality testing, taking advantage of the fact that households from the same cluster tend to have similar water sources [3,84].

In most cases, the person responsible for collecting the water samples is also responsible for anthropometric measurements of children under the age of 5. Those field testers are trained by national specialists and should have practiced the water sampling procedure at least 15 times [84]. In the field, the collector requests permission to collect water samples, asking for a “glass of drinking water” and to be shown the location of the households regular drinking water source. 100 ml samples are collected from the glass, known as “point of use” or PoU, and the source, known as “point of collection” or PoC [3].

Samples are analysed on site within 30 minutes. This consists of filtering the sample through a 0.45 µm paper membrane, which is added to growth media plates rehydrated with 1 ml of sample water. The samples are then incubated overnight (24 to 48 hours) in electrical incubators or using “incubation belts” worn around the body of interviewers during the day and underneath their pillow or under their bed covers during the night [3,84]. The enzyme substrate on the growth media plates gives the *E. coli* colonies a blue colour. The interviewer counts the number of blue colonies and registers it on the water quality questionnaire [84].

For quality control, blank testing is also performed using bottled or distilled water during training and execution of the survey. Blank testing is done at regular intervals, usually after 10 actual tests. It provides a general measurement of errors during testing procedure in the survey, but it cannot identify in which specific household cross contamination might have occurred [84]. For most surveys (24 out of 27), only a small proportion (≤2.5%) of blanks were positive. The exceptions were Côte d'Ivoire 2016 (8.2%), Gambia 2018 (6.2%), and Chad 2019 (3.6%) [3]. Bain *et al.* performed two sensitivity analyses while investigating the risk of *E. coli* contamination according to water source: 1) excluding countries with high proportion of positive blank tests and 2) excluding survey clusters with any positive blank tests. The differences were negligible [3]. Although measures of association remain the same, the prevalence of contamination in these countries is very likely overestimated. We will perform similar sensitivity analyses, and also include the prevalence of positive blank testing in each survey.

For global monitoring, water is considered "free from contamination" if no *E. coli* colonies are detected in the sample [1]. Therefore, we will classify a sample as contaminated if at least one blue colony is detected and as not contaminated otherwise.

Water sources

The household's drinking water source is determined by the respondent's self-report after a question similar to "What is the main source of drinking water used by members of your household?" [4], with the assistance of pictures of different source types [85]. Although these vary between MICS surveys, the categories in the most recent surveys tend to be fairly standardized. Some sources are classified as "improved" due to their supposed protection from outside contamination, especially from faecal matter [5]. Table 6 presents the original water source categories available in the datasets from the surveys in Table 5, Section 1.8.1. We will recategorize the original variables in the datasets of each country into water source groups and as improved or unimproved sources, considering the current classification system proposed by the JMP [1].

Table 6 – Water source categories available in MICS surveys, their grouping and improvement classification

Classification	Water source group	Water source original category in the dataset
Improved	Piped into dwelling	Piped water: piped into dwelling Robinet: dans le logement Agua canalizada: no interior da casa Tubería dentro de la vivienda
Improved	Piped to yard/plot	Piped water: piped to yard/plot Robinet dans la concession, cour ou parcelle Robinet: dans la concession/jardin/parcelle Torneira: no quintal Tubería dentro del terreno, patio o lote
Improved	Piped to neighbour	Piped water: piped to neighbour Robinet: chez le voisin Robinet du voisin Agua canalizada: na casa do vizinho
Improved	Public tap/standpipe	Piped water: public tap/standpipe Robinet: robinet public/borne fontaine Torneira: do chafariz público Agua canalizada: fontenário público/boca do incendio
Improved	Tube well/borehole	Tube well/borehole Tube well/borehole protected well Tube well/borehole unprotected well Puits à pompe/forage Poço com bomba ou furo artesiano
Improved	Protected well	Dug well: protected well Protected well Puits creuse: protege Puits protégé Poço escavado: poço protegido Pozo protegido
Unimproved	Unprotected well	Dug well: unprotected well Unprotected well Puits creusé: pas protègé Puits non protégé Poço escavado: poço não protegido
Improved	Protected spring	Spring: protected spring Protected spring Source: source protegee Source protégée Agua da nascente: nascente protegida
Unimproved	Unprotected spring	Spring: unprotected spring Unprotected spring

Classification	Water source group	Water source original category in the dataset
		Source: source non protegee Source non protégée Agua da nascente: nascente não protegido
Improved	Rainwater	Rainwater Rain, snow water Rainwater: own cement or other tank Rainwater: neigbour's cement or other tank Rainwater: community cement or other tank Eau de pluie
Improved	Tanker truck	Tanker-truck Camion-citerne
Improved	Cart with small tank/drum	Cart with small tank/drum Cart with small tank Animal drawn water cart Charrette avec petite citerne Careta com pequena cisterna
Improved	Other forms of delivered water	Packaged water: water cooler Bidon, bassin, seau livre a domicile
Improved	Water kiosk	Water kiosk Water kiosk (water selling plant) Water kiosk connected with piped water Water kiosk not connected with piped water Kiosque a eau
Unimproved	Surface water	Surface water (river, dam, lake, pond, stream, canal, irrigation channel) Eau de surface (riviere, barrage, lac, mare, courant, canal, systeme d'irrigation) Eau de surface (rivière, fleuve, barrage, lac, mare, canal, canal d'irrigation) Eau de surface (oued, lac, barrage,..) Agua de superficie (rio, barragem, lago, mar, corrente, canal, sistema de irrigação)
Improved	Bottled water	Packaged water: bottled water Bottled water Eau conditionnée: eau en bouteille Eau en bouteille (minérale) Agua embotellada/envasada Agua condicionada: agua engarrafada
Improved	Sachet water	Packaged water: sachet water Sachet (pure) water Eau conditionnee: eau en sachet Eau conditionnée: eau en sachet (pure water) Agua condicionada: Agua empacotada

Classification	Water source group	Water source original category in the dataset
Improved	Other forms of packaged water	Packaged water: jar
Unimproved	Other	Other Other (specify) Autre Autre (préciser) Packaged water: desalinized & sterilized water Disalination plant water

Analysis

The article will be divided into two sections. The first one will be a quantitative analysis of *E. coli* contamination for each group of water sources. The second one will be a narrative analysis to understand the historical context of the classification system that divides water sources as improved and unimproved.

For the quantitative analysis, we will calculate the prevalence and 95% confidence intervals of *E. coli* contamination – as defined in Section 1.8.1 – for each country and water source group, stratified by area of residence (urban/rural). All analyses will take into account the complex survey design used by MICS surveys (i.e., sample weights, clustering, and stratification) using the "survey" package from R. We will also create a pooled analysis, combining all countries together into one single dataset, to estimate a general trend of level of contamination according to water source. We will edit the strata variable provided by MICS in order to include each country as part of the sample stratification. We will recalculate the sample weights using the following equation [86]:

$$w_{ij,adj} = \left(\frac{w_{ij}}{\sum_i w_{ij}}\right)\left(\frac{pop_j}{\sum_j pop_j}\right)N$$

where:

- *i* indicates a household and *j* a country
- $w_{ij,adj}$ is the adjusted sample weight
- w_{ij} is the original sample weight

- pop_j is the total population of the country *j* in the median year of all surveys included in the analysis
- *N* is the total number of households in the sample

The new sample weights will give each country a weight proportional to its population size, making the pooled analysis a weighted average of the national results. Therefore, our results can be interpreted as estimates for the population in the 36 countries.

We will compare the calculated prevalences and their respective confidence intervals and display graphically the level of contamination between:

- Water source groups
- Water source groups in urban vs. rural settings
- Countries
- Improved vs. unimproved sources
- Point of collection vs. point of use

The narrative review will be performed evaluating the history of the current classification of improved and unimproved water sources in the SDGs. Combined with the *E. coli* contamination results, we will perform a critical assessment of the current classification system. The review will be based primarily on an article published by Bartram *et al.* in 2014[85], that investigated the history and methods used for international monitoring of access to drinking water and sanitation. We will update their historical analysis based on the most recent published literature in PubMed and Web of Science, as well as reports and articles from the Institutional Repository for Information Sharing from the WHO (https://apps.who.int/iris/) and the websites of UNICEF (https://www.unicef.org/) and the JMP (https://washdata.org/). Ideally the review will be presented as a separate panel in the final article, but its structure will depend on the chosen journal's formatting guidelines.

Strengths and limitations

The strengths of this article are: it will include a direct measurement of *E. coli* contamination in samples from the point of collection and the point of use of drinking water; it will use highly comparable nationally representative surveys of LMICs; it will include 36 different countries (or more, if new surveys are resealed in time); it will include the prevalence of contamination according to a more comprehensive list of water source types; and it will provide results stratified according to area of residence, allowing the investigation of specific patterns of contamination in the urban and rural environments.

There are two main limitations of this paper. The first one is the cross-contamination of samples during water quality testing which will overestimate the prevalence of contamination, especially in countries with high positive blank testing. The second one is the misclassification of water source types, which are based on the responds report with the help of the interviewer. This will reduce our ability to discriminate water contamination between water source types, especially in categories like “protected well” vs “unprotected well” and “protected spring” vs “unprotected spring”.

1.8.2. Research article 2

Data source

We will select DHS surveys from 2010 onwards that included both: 1) the information necessary to calculate the basic water, sanitation, and hygiene indicators and 2) questions from the women's questionnaire necessary to calculate our women's empowerment indicator. For countries with more than one survey that meet those criteria, we will select the most recent survey. We restricted our selection to surveys from 2010 onwards to avoid using surveys that no longer reflect the rapidly changing WASH scenario in many LMICs. The choice of the year 2010 is arbitrary, but it is quite common in the field of global health and at the ICEH as a round number used for selecting surveys from the last decade. Currently, this includes 24 countries, presented in Table 7.

Table 7 – DHS surveys selected for article 2

Country	Year
Armenia	2015
Benin	2017
Burundi	2016
Cameroon	2018
Ethiopia	2016
Gambia	2019
Guinea	2018
Haiti	2016
Liberia	2019
Malawi	2015
Mali	2018
Nepal	2016
Nigeria	2018
Pakistan	2017
Papua New Guinea	2016
Philippines	2017
Rwanda	2019
Senegal	2019
Sierra Leone	2019
Tanzania	2015
Timor-Leste	2016
Uganda	2016
Zambia	2018
Zimbabwe	2015

Indicators

For this article, we will use the WASH basic service indicators, not the safely managed services indicators. This is necessary because the questions used for creating a women's empowerment indicator are only available in DHS surveys and DHS surveys do not collect information on drinking water contamination and safely disposal/removal/treatment of excreta necessary to calculate the safely managed water and sanitation services indicators, respectively.

Basic water services

A household with basic water service is defined as having drinking water from an improved source, provided collection time is not more than 30 minutes for a round trip, including queuing [1]. Improved sources are defined in Table 6. The water collection time is determined by a question similar to "How long does it take for members of your household to go there, get water, and come back?" [4]

Basic sanitation services

A household with basic sanitation service is defined as having improved sanitation facilities that are not shared with other households. Improved facilities include flush/pour flush toilets connected to piped sewer systems, septic tanks or pit latrines, pit latrines with slabs (including ventilated pit latrines), and composting toilets [1]. Flush/pour flush toilets connected to "don't know where" will not be considered improved.

The household's sanitation facility is determined by the respondent's self-report after a question similar to "What kind of toilet facility do members of your household usually use?" [4], with the assistance of pictures of different facility types [85]. Facility sharing is determined by a question similar to "Do you share this facility with others who are not members of your household?" [4].

Basic hygiene services

A household with basic hygiene service is defined as having a handwashing facility with soap and water. Handwashing facility may be located within the dwelling, ward, or plot. They may be fixed or mobile. They may include a sink with tap water, buckets with taps, tippy-taps, and jugs or basins designated for handwashing. Soap includes bar soap, liquid soap, powder detergent, and soap water but does not include ash, soil, sand or other handwashing agents[1].

The handwashing facility and the presence of water and soap are observed by the interviewer after the respondent is prompted by the question "We would like to learn about where members of this household wash their hands. Can you please show me where members of your household most often wash their hands?". The interviewer observes the presence of water by checking the tap, bucket, or other water container as well as the presence of soap[4]. Some surveys also include the respondent's report on the handwashing facility/water/soap, besides the interviewer observation. For comparability, we will not include this information.

Empowerment indicator

We will create a women's empowerment indicator specifically related to economic autonomy and decision making in the context of LMICs. It will be based on questions from the women's questionnaire related to:

- having a paying job. Example: "Have you done any work in the last 12 months?" followed by "Are you paid in cash or kind for this work or are you not paid at all?"[87]
- having a bank account. Example: "Do you have an account in a bank or other financial institution that you yourself use?"[87]
- owning and using a mobile phone for financial transactions. Example: "Do you own a mobile telephone?" followed by "Do you use your mobile phone for any financial transactions?"[87]
- owning a house. Example: "Do you own this or any other house either alone or jointly with someone else?"[87]
- owning land. Example: "Do you own any agricultural or non-agricultural land either alone or jointly with someone else?"[87]
- deciding on how the woman spends her money. Example: "Who usually decides how the money you earn will be used: you, your husband, or you and your husband jointly?"[87]

- deciding on how the husband/partner spends his money. Example: “Who usually decides how your (husband's/partner's) earnings will be used: you, your (husband/partner), or you and your (husband/partner) jointly?[87]
- deciding on major household purchases. Example: “Who usually makes decisions about making major household purchases?”[87]

Some of these questions are restricted to married/in union women. Therefore, our sample will be restricted to married/in union women. As in the same household there might be more than one woman who is married/in union, and WASH information is obtained at the household level, we will include only women who are the head of the household or who are married/in union with the head of the household, as defined by each survey.

Analysis

The women’s empowerment indicator will be created via principal component analysis (PCA) of the items related to economic autonomy and decision making mentioned in the previous section. Items will be recoded so that categories that indicate higher empowerment will have higher values. We will perform the PCA in each country separately and check the results for consistency in terms of items loadings. Based on the ICEH’s experience creating the SWPER women’s empowerment index in 2017 for African countries (that was later expanded to all LMICs in 2020 and named SWPER Global), we expect fairly consistent loadings[66,67]. Items may be removed or added based on the results from this exploratory analysis. If the results are similar between countries, we will then perform the PCA in a combined dataset, creating an indicator applicable to all countries. The combined dataset will be created as described in Section 1.8.1, weighting each country according to its population size, in order to avoid overrepresenting women living in really small countries. We will check the indicator’s external validity by calculating its correlation with the Gender Development Index at the country level[66], and also compare the loadings of the combined PCA with the ones obtained for individual countries.

We will determine the percentage and 95% confidence intervals of married/in union women aged 15 to 49 years living in households with access to basic WASH services by terciles of empowerment in each country. All analyses will take into account the complex survey design used by DHS surveys (i.e., sample weights, clustering and stratification) using the “survey” package from R. We will also create a pooled analysis, combining all countries together into one single dataset, to provide a general trend of service coverage according to women’s empowerment. Based on the conceptual model described in Section 1.5, we will not perform adjustments for wealth and education in order to avoid controlling for mediators. We will stratify all the results by area of residence (urban/rural). Sample weights for pooled analysis will be recalculated as described in Section 1.8.1, except we will use the national population of women aged 15 to 49 years.

Strengths and limitations

The strengths of this article are: it will create a custom women’s empowerment indicator specifically related to the women’s economic autonomy and decision making; it will use highly comparable nationally representative surveys of LMICs; it will include 24 different countries (or more, if new surveys are resealed in time); it will compare the association of women’s empowerment with not only one, but three different basic WASH indicators using the same methodology and samples.

There are three main limitations of this article. The first one is the cross-sectional nature of study. We will not be able to establish directionality in the relation between women’s empowerment and WASH services and no covariate adjustment will be performed, as discussed in Section 1.5.4. We can only measure the association between women’s empowerment and WASH services, and we expect it will reflect the confounding and mediating effects of wealth and education.

The second limitation is the fact that there will be an overlap between what the women’s empowerment and the household wealth indexes try to measure. Nevertheless, it is important to notice that there are important practical and conceptual distinctions and that one will not encompass the other. First, our empowerment index will only use a fraction of the questions typically included while creating the wealth index in DHS. Second, many of the questions that will be included in the empowerment index are not used and do not belong conceptually in wealth index, such as those of the decision-making dimension. Third, the household's wealth index combines wealth from all household members – not only the woman's assets. In LMICs, there are substantial gender inequalities in asset ownership and wealth within the same household, overall and for specific assets [88], which makes the two index even more distinct.

The third limitation in the sample restriction to women who are married or in union. Many women in the positive and negative extremes of empowerment might be less likely to marry. Highly empowered women might marry later or never marry and also have better access to WASH services. Sex workers and disabled women are among the most marginalized and disempowered women and may be less likely to marry [66] and to have access to WASH services. Both of these scenarios would introduce bias and reduce the strength of our association. This can also impact the comparability between countries, since countries in Africa and Asia tend to have higher proportion of married adolescent girls [66,67].

1.8.3. Research article 3

Data source

We will select the most recent MICS household survey that includes the water quality module, the extended version of the sanitation questionnaire and the basic household hygiene questions. Currently, this includes 34 surveys, presented in Table 8.

Table 8 – MICS surveys selected for article 3

Country	Year
Algeria	2018
Bangladesh	2019
CAR	2018
Chad	2019
Congo, Democratic Republic	2017
Dominican Republic	2019
Gambia	2018
Georgia	2018
Ghana	2017
Guinea Bissau	2018
Guyana	2019
Honduras	2019
Iraq	2018

Country	Year
Kiribati	2018
Kosovo	2019
Lao	2017
Lesotho	2018
Madagascar	2018
Malawi	2019
Mongolia	2018
Nepal	2019
Nigeria	2016
Paraguay	2016
Samoa	2019
São Tomé and Príncipe	2019
Sierra Leone	2017
State of Palestine	2019
Suriname	2018
Togo	2017
Tonga	2019
Tunisia	2018
Turks and Caicos	2019
Tuvalu	2019
Zimbabwe	2019

Indicators

For this article, we will use the safely managed water and sanitation and the basic hygiene services indicators.

Safely managed drinking water services

A household with safely managed drinking water services is defined as having an improved source that is accessible on premises, available when needed and free from faecal and priority chemical contamination [1]. Improved sources are defined in Table 6.

Accessibility on premises is defined by the type of water source (piped to dwelling, for example) or by the answer to a question similar to "Where is that water source located?" indicating that the source is in the dwelling, yard, or plot. Households whose water source is located elsewhere but whose members do not collect water themselves are considered as having water available on premises [3,4].

Availability when needed is defined as a negative answer to a question similar to "In the last month, has there been any time when your household did not have sufficient quantities of drinking water?"[3,4].

Priority chemical contamination is defined by each country according to the national context. In order to make the national estimates comparable, we will not include measurements of chemical contamination when available. Faecal contamination will be determined as described in Section 1.8.1.

Safely managed sanitation services

A household with safely managed sanitation services is defined as having improved sanitation facilities that are not shared with other households and where excreta are safely disposed of in situ or removed and treated off-site[1]. Both improved facilities and sharing are described in Section 1.8.2.

Households with sewer connection are considered safely managed if the sewer delivers the wastewater to a treatment facility that provide secondary treatment or better. In order to calculate national estimates, the JMP multiplies the proportion of households connected to sewers systems by the proportion of wastewater that receives at least secondary treatment in the country[26]. This allows for the estimation of the proportion of households connected to the sewer systems that are safely managed. That information is not available for individual households in the MICS survey. Therefore, we will not be able to calculate the full version of the safely managed indicator, but rather a "non-shared toilet facility connected to a sewer system or safely managed sanitation service" indicator. As a sensitivity analysis, we will randomly assign households with sewer connection the status of "safely managed" or "not safely managed" according to the proportion of wastewater that receives at least secondary treatment in the country and recalculate the results. Wastewater treatment data will be sourced from the United Nations Water website (https://sdg6data.org/). This is an important limitation of our research that will be acknowledged in the final article.

Households with other improved facilities are considered safely managed if: 1) their on-site storage facilities have never been emptied, 2) if they have been emptied and treated off-site by a service provider, or 3) if they have been emptied and then buried locally by the household members[1]. That information will be obtained from questions from the extended version of the sanitation questionnaire similar to “Has your toilet facility ever been emptied?” and “The last time it was emptied, where were the contents emptied to?”[4].

Basic hygiene services

A household with basic hygiene service is defined in Section 1.8.2.

Full WASH indicator

The Full WASH indicator will be a measure of the household’s full access to WASH services. A household will be considered positive for the indicator if it has all of the following:

- Access to a safely managed water service
- Access to a non-shared toilet facility connected to a sewer system or another safely managed sanitation service
- Access to a basic hygiene service

If the household lacks any of these services, it will be considered negative for the Full WASH indicator.

Analysis

We will determine the coverage and 95% confidence intervals of the Full WASH indicator for each country. We will also investigate inequalities in the indicator regarding household wealth, area of residence (urban/rural), and subnational regions using dumbbell plots (also known as equiplots) and national maps. All analyses will take into account the complex survey design used by MICS surveys (i.e., sample weights, clustering, and stratification) using the “survey” package from R. We will also create a pooled analysis, combining all countries together into one single dataset, to provide a general trend of the inequalities in coverage of Full WASH indicator. Sample weights for pooled analysis will be recalculated as described in Section 1.8.1.

We will select one of the Pacific Islands included in the sample (as of today: Kiribati, Tonga, and Tuvalu) and create a national case report to be presented in a separate panel in the article. This choice is due to the fragility, natural vulnerability and limited resources that contribute to WASH challenges in these countries, especially in the context of climate change[89]. With the help of one native researcher from the selected country, we will discuss both the national WASH context and the public health implications of our results.

Strengths and limitations

The strengths of this article are: it will include a custom new indicator, the Full WASH, which will allow us to investigate the simultaneous coverage of safely managed and basic WASH services; it will include a direct measurement of *E. coli* contamination in samples of drinking water; it will use the extended version of the MICS sanitation questionnaire that includes information about excreta treatment/disposal; it will use highly comparable nationally representative surveys of LMICs; it will include 34 different countries (or more, if new surveys are resealed in time); and it will include a case sample from one of the Pacific Islands, allowing us to both investigate general trends in multiple countries and also discuss the specific scenario of a country with a fragile WASH context.

There are two main limitations of this paper. The first one is the cross-contamination of samples during water quality testing which will overestimate the prevalence of contamination, especially in countries with high positive blank testing. The second one is the fact that we lack information on waste treatment for households with sewer connection. Without this information, the Full WASH indicator will overestimate WASH coverage. We will try to circumvent this limitation in a sensitivity analysis by randomly assigning households with sewer connection the status of “safely managed” or “not safely managed” according to the proportion of wastewater that receives at least secondary treatment in the country. This strategy will only minimize the problem for national estimates. It will underestimate inequalities in our analyses stratified by household wealth, area of residence (urban/rural), and subnational regions, since it is very unlikely that secondary treatment is not associated with these indicators.

1.9. Ethical considerations

Our research will only use anonymized datasets that are already publicly available through MICS (https://mics.unicef.org/) and DHS (https://dhsprogram.com/). MICS surveys are conducted under technical supervision of the UNICEF, while DHS under the United States Agency for International Development (USAID) in partnership with local governmental, non-governmental, or private-sector organizations such as a National Statistical Office or a Ministry of Health[90]. Ethical clearance in each survey was the responsibility of the institutions that administered the surveys, according to the requirements of each country, in addition to criteria established by the institutions responsible for the surveys. Information is disclosed in order to maintain the confidentiality and non-traceability of respondents.

1.10. Results dissemination

The dissemination of results from this project will occur via the final thesis, letters to the media, publications in appropriate scientific journals, and online news articles in the University of Melbourne's research newsletter (https://pursuit.unimelb.edu.au/) and the ICEH's website (https://equidade.org/).

1.11. Funding

This project is funded by the Bill & Melinda Gates Foundation (grant number: OPP1148933) and the Wellcome Trust (grant number: 101815/Z/13/Z) through the ICEH. The internship at the University of Melbourne is funded by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – financing code 001.

1.12. Preliminary results

Research article 1

Figure 8 presents the percentage of households using a water source for each country and all countries combined. Tubewell/borehole is the most commonly used type of water source, with 34.4% (95%CI 33.5–35.4%) of households having it as their main source of drinking water. Only 10.2% (95%CI 9.7–10.6%) have piped water delivered directly into the dwelling.

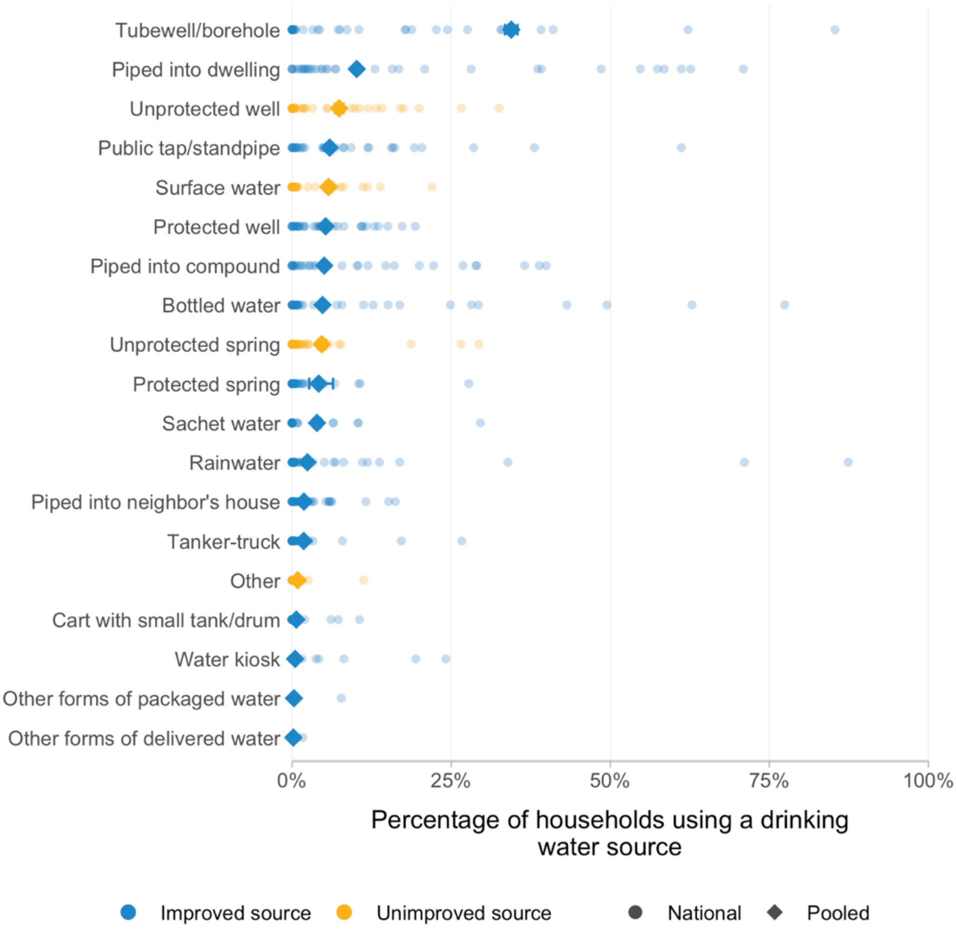


Figure 8 – Household's sources of drinking water in 36 LMICs. Sources are ordered according to the pooled percentage of households using that water source.

Figure 9 represents the pooled and national estimates of *E. coli* contamination according to water source at the point of collection and point of use. An alarming 53.5% (95%CI

52.0–54.9%) of all households have water contaminated with *E. coli* at the point of collection and 73.8% (95%CI 72.7–75.0%) at the point of use.

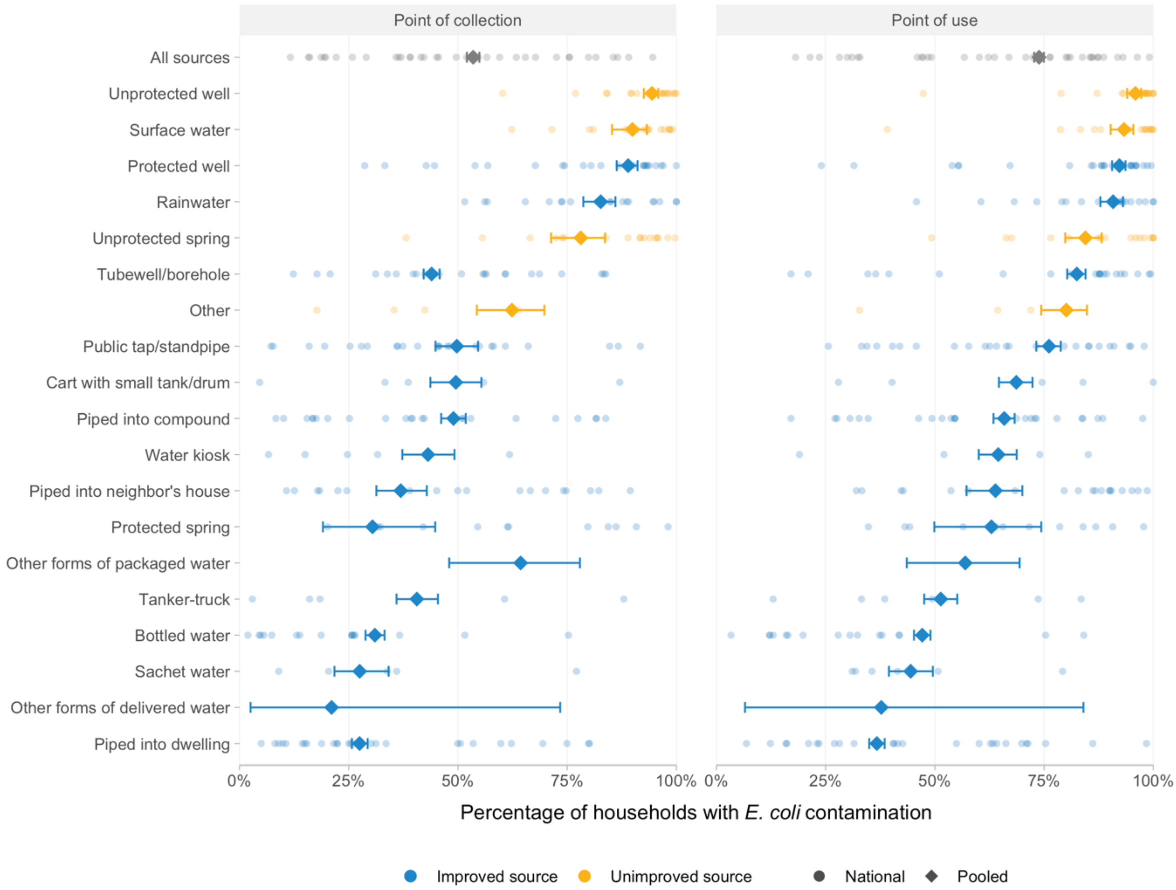


Figure 9 – *E. coli* contamination in the water samples collected from the water source (point of collection) and from a glass of drinking water (point of use) for each water source. Sources are ordered according to the pooled percentage of households with *E. coli* contamination in the point of use.

More than 75% of households using wells (protected or unprotected), surface water, rainwater or unprotected springs have water already contaminated at the point of collection. From these, both rainwater and protected wells are currently considered improved sources of water. 82.7% (CI95% 78.7–86.0%) of households using rainwater have water contaminated at the point of collection and 90.8% (CI95% 87.9–93.1%) at the point of use. For protected wells, those numbers are 89.0% (CI95% 86.3–91.1%) and 92.2% (CI95% 90.6–93.6%), respectively. There is barely any distinction in terms of contamination from protected and unprotected wells. 94.4% (CI95% 92.5–95.6%) of households using unprotected wells have water contaminated at the point of collection and 95.9% (CI95% 94.0–97.2%) at the point of use.

Water piped into dwelling was the least contaminated water source: 27.5% (CI95% 25.7–29.3%) at the point of collection and 36.7% (CI95% 35.0–38.5%) at the point of use. This is unacceptable considering the current goal of universal access to safe drinking water. Furthermore, the level of contamination varies markedly between countries. While only 4.9% (CI95% 2.9–8.4%) of households with piped water into the dwelling are contaminated at the point of collection in Mongolia, 80.1% (CI95% 57.1–92.4%) are contaminated in Chad.

The increase in the level of contamination from the point of collection to the point of use should also be noted. Tubewells/boreholes are the most common source of water in the sample and also the one with the largest gap (38.5 percentage points). While 44.0% (CI95% 42.1–45.8%) of households have water contaminated at the point of collection, 82.5% (CI95% 80.3–84.5%) are contaminated at the point of use. This represents how handling, transportation and storage can have a crucial impact in water contamination and how using water source alone as an indicator paints a very narrow view of global access to safe drinking water.

Figure 10 presents the percentage of households with contaminated water for each country according to individual sources and for all sources combined. Maps with pooled results are presented in Figure 11 (point of collection) and Figure 12 (point of use).

The three countries with the highest level of contamination at the point of collection are Tuvalu (94.6%, CI95% 89.6–97.2%), Sierra Leone (89.1%, CI95% 86.6–91.2%), and Kiribati (86.5%, CI95% 82.1–90.0%). At the point of use, they are Chad (99.1%, CI95% 98.5–99.5%), Sierra Leone (96.4%, CI95% 94.9–97.4%), and Malawi (93.1%, CI95% 91.7–94.2%). The staggering result of Chad should be acknowledged: virtually all the households in the country have drinking water contaminated with *E. coli* at the point of use, independently of water source.

The three countries with the lowest level of contamination at the point of collection are Turks and Caicos (11.6%, CI95% 4.9–25.1%), Mongolia (15.8%, CI95% 13.6–18.2%), and Algeria (16.1%, CI95% 14.1–18.2%). At the point of use, they are Mongolia (18.1%, CI95% 15.8–20.6%), Kosovo (21.4%, CI95% 18.5–24.7%), and Turks and Caicos (23.6%, CI95% 15.5–34.1%).

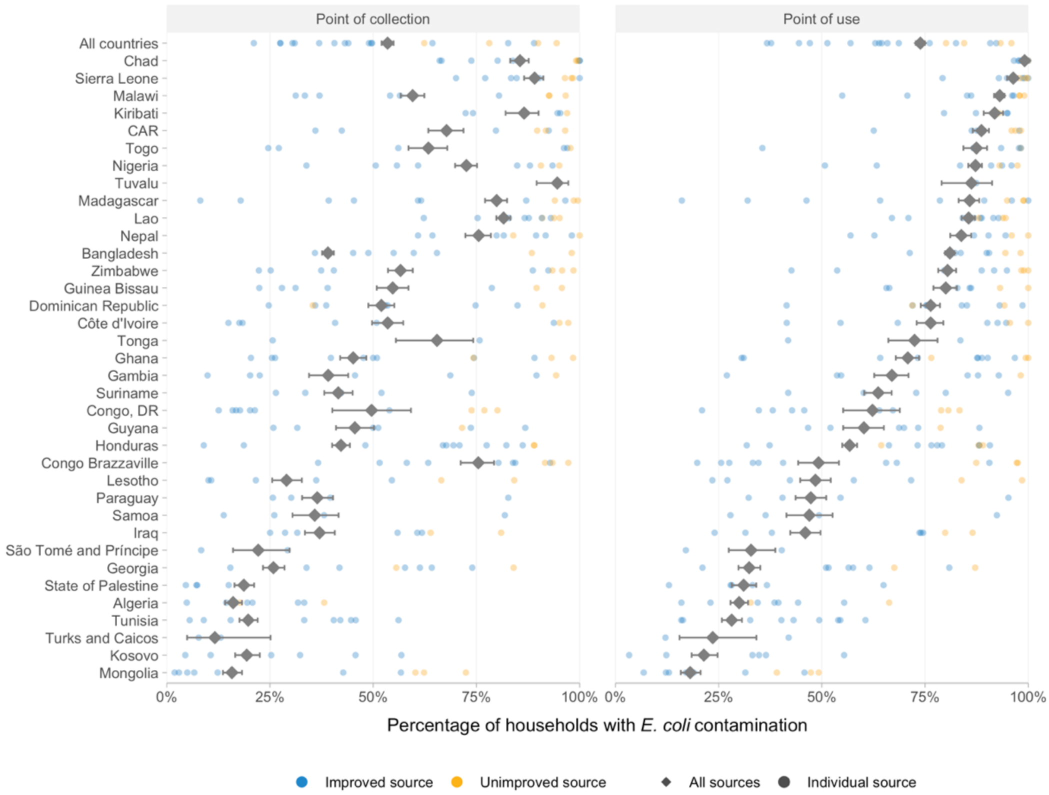


Figure 10 – *E. coli* contamination in the water samples collected from the water source (point of collection) and from a glass of drinking water (point of use) for each country. Countries are ordered according to the pooled percentage of households with *E. coli* contamination in the point of use.

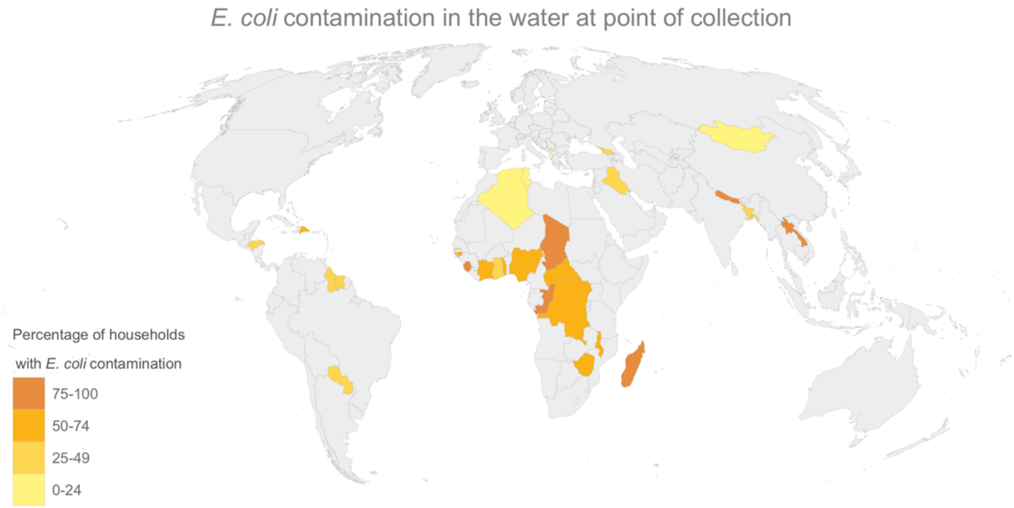


Figure 11 – Map of *E. coli* contamination in the water samples collected from the water source (point of collection).

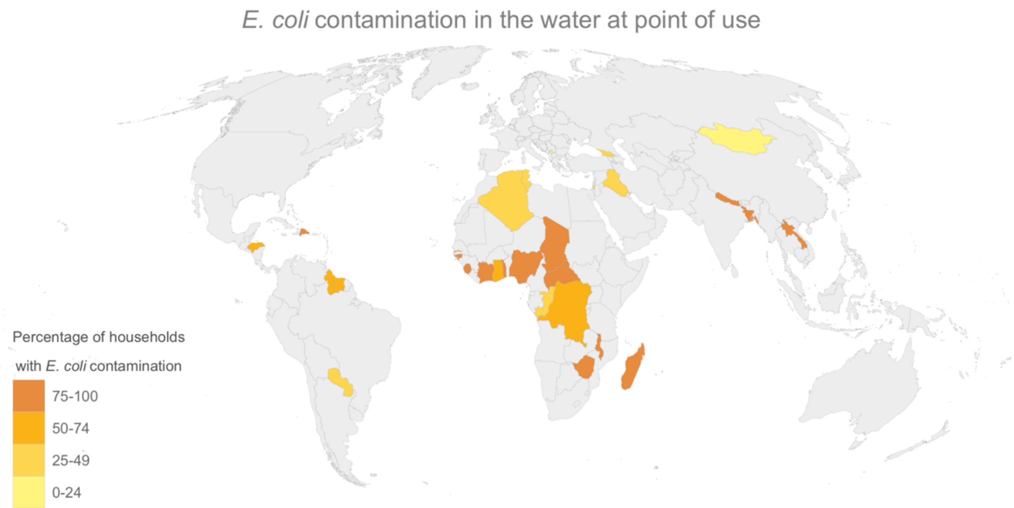
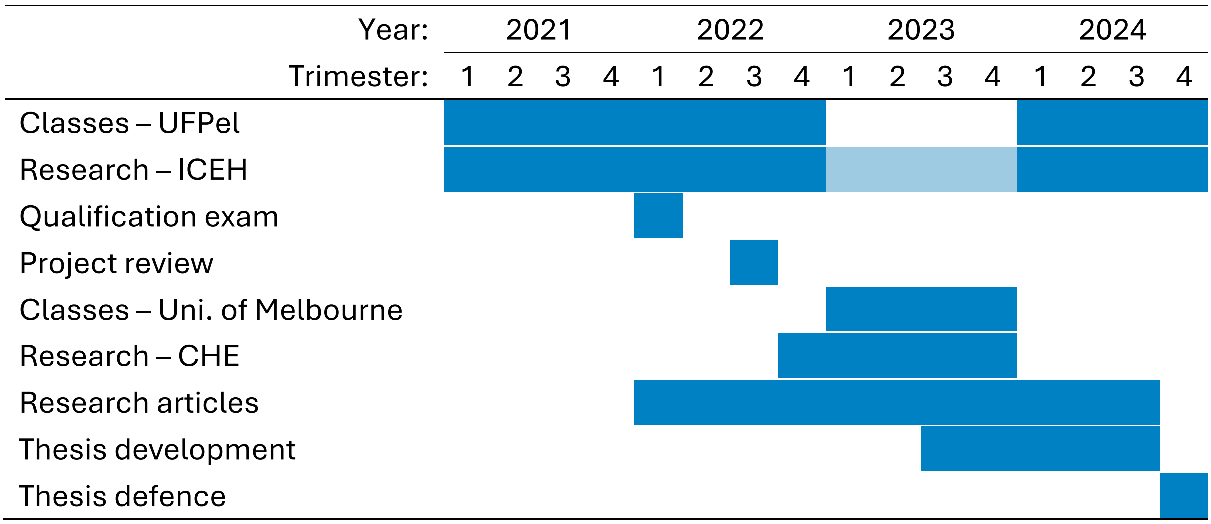


Figure 12 – Map of *E. coli* contamination in the water samples collected from a glass of drinking water (point of use).

1.13. Schedule

Table 9 provides a general description of the entire PhD timeline, divided by trimesters.

Table 9 – PhD schedule



Classes will take place at UFPel throughout the PhD program and at the University of Melbourne during 2023 as part of the CAPES/Print initiative.

Research work will take place at the International Center for Equity in Health (ICEH) at UFPel throughout the PhD program and the Centre for Health Equity (CHE) at the University of Melbourne during 2023.

The ICEH is a research centre that monitors equity in health and nutrition around the world, especially in low- and middle-income countries. It has compiled a database of over 450 national surveys – mostly MICS and DHS surveys – with information on reproductive, maternal, new-born, and child health and household characteristics, including WASH indicators (www.equidade.org). The research work at the ICEH will be comprised of the articles of thesis as well as other specific assignments, including participation in the RSM (Reproductive, Sanitation and Malaria) group, responsible for analysing WASH, lifestyle, gender, malaria, sexual, and reproductive health indicators.

The CHE at University of Melbourne is a research centre with social, behavioural, and public health expertise, using multi-disciplinary and cross-sectoral approaches and partnering with scholars and agencies in the Asia-Pacific region. Within it, there is the Gender and Women's Health Unit, a research group dedicated to gender inequity and women's health. They are an interdisciplinary team with expertise in public health, health services research, social psychology, sociology, geography, medical anthropology, epidemiology, evaluation, and applied ethics. The research activity will be allocated at the Gender and Women's Health Unit, which will provide extensive support for the second article of the thesis.

The qualification exam was already taken and the necessary grades for approval were achieve. The research articles will be produced during 2022 to 2024. The thesis will be developed during 2023 and 2024. The thesis defence will happen at the end of 2024.

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2. Project adjustments along the course of the work

According to the schedule in Section 1.13, the thesis defense would happen in the last quarter of 2024. Due to professional reasons, we have decided to bring forward the date of the defense for the second quarter of 2024, shortening the expected duration of the PhD. We have also revised the research articles compared to the proposals outlined in the Research Project. Those revisions are presented in the following sections.

2.1. Research Article 1

We made the following changes in Research Article 1, compared to Research Project presented in Section 1:

- The number of countries included in the sample increased from 36 to 38, due to the inclusion of the Fiji 2021 and Vietnam 2020 surveys.
- We included the percentage of positive blank tests in the Supplementary Materials of the article but did not perform sensitivity analyses excluding clusters and countries with high proportion of positive blanks. This was because the percentage of positive blank tests was generally low and Bain *et al.* (2021) had already performed similar analyses, showing that changes in the results were negligible.
- The narrative review was not presented in a separate panel in the article but was instead interwoven in the Discussion section.

2.2. Research Article 2

We made the following changes in Research Article 2, compared to Research Project presented in Section 1:

- The number of countries included in the sample increased from 24 to 31, due to a reduction in the number of questions necessary for creating the women's economic empowerment score (described below), allowing for more surveys to be included.
- We excluded questions related to owning a house and owning land from the women's economic empowerment score. In our early analyses, these two indicators showed very different associations with the overall score across the

countries in our sample. They were initially included with some skepticism due to the numerous challenges women face in exercising control over their properties. These challenges include possessing a title deed, having their name on the title deed, and overcoming social norms about the acceptability of women possessing and controlling property. The statistical results were in line with those challenges. Consequently, we decided to exclude these questions from the analysis.

- We combined having a paying job and the woman deciding on how she spends her money into a single indicator. This was because the decision-making question was conditional to the woman having a paying job.
- We included a question related to the husband/partner having a paying job when creating the indicator of whether the woman participates in the decision of how to spend his earnings. This was because the decision-making question was conditional to the husband/partner having a paying job.
- Instead of presenting a principal component analysis (PCA) in the final article, we decided to use a simple score that is the sum of positive answers to the score's components. We then calculated the Kaiser-Meyer-Olkin index to assess whether there was an acceptable level of common variance to compose the score. We made this choice because in the early PCA analyses the factor loadings were very consistent between countries, showing that the components were similarly related even in very different contexts. Furthermore, a simple score would make the article more understandable for a wider audience and the score more easily reproducible by other researchers.
- In the pooled analysis, we decided to give each country the same weight instead of weighting results based on the population of women aged 15 to 49 years. This is because India represented 57% of the women's population in the countries of our final sample. Therefore, pooled results would be heavily dependent on only one country. We also restricted pooled results to the descriptive analysis of the women's economic empowerment score. The main association analyses were based instead on the distribution of national results without a pooled estimate.
- We included two sensitivity analyses in the article:

- We repeated the main analyses including only one randomly selected woman in the households with multiples wives from polygynous marriages. This was necessary because all co-wives living together had the same WASH status, meaning that their observations were not independent.
- We recalculated national results controlling for wealth and education. After reading the first version of the full manuscript, we believed that this would be a common request from reviewers. Therefore, we included this analysis as well as a critical discussion of its implications, arguing that wealth and education represent both possible confounders and mediators in our analysis.

2.3. Research Article 3

We made the following changes in Research Article 3, compared to Research Project presented in Section 1:

- The number of countries included in the sample decreased from 34 to 32. New surveys were included (Fiji 2021 and Vietnam 2020) and four were excluded (Guinea Bissau 2018, Kosovo 2019, Nigeria 2016, and Paraguay 2016) because upon further investigation, their questionnaires were not comparable to the rest of the surveys. For example, Guinea Bissau 2018 included ash, mud, and sand in their question related to the presence of soap for handwashing, while the other surveys did not. The number of countries included in Research Article 3 is smaller than the number of countries in Research Article 1 because the former also includes sanitation and hygiene indicators that were not available for all countries in the latter.
- We renamed the safely managed sanitation indicator to safely disposed sanitation. We decided to change the name to avoid misunderstandings related to the fact that our indicator does not include off-site excreta treatment and therefore does not fully reproduce the JMP's safely managed sanitation indicator.
- We decided to not perform the sensitivity analysis in which we would randomly assign households with sewer connection the status of "safely managed" or "not

safely managed" according to the proportion of wastewater that receives at least secondary treatment in each country. This was because not all countries in our final sample had available data on wastewater treatment, and because it does not allow for proper stratified equity analyses. Since wastewater treatment is likely associated with area of residence, wealth quintiles, and subnational regions, assigning status randomly would lead to non-differential misclassification and an underestimation of inequalities.

- Due to time constraints, the national case report has not been included in the article at the time of thesis submission. We are currently working with Dr Litea Meo-Sewabu to create a national case study of Fiji that will be included in the final article before submission to a journal, which is expected to the end of August, 2024.

3. PhD activities

The research activities took place in two research centers:

- The International Center for Equity in Health (ICEH) at UFPel, during the first, second, and fourth years of the PhD (2021, 2022, and 2024)
- The Gender and Women's Health Unit from the Nossal Institute for Global Health at the University of Melbourne, during the third year of the PhD (2023). The Gender and Women's Health Unit was originally part of the Centre for Health Equity, as mentioned in section 1.13, but was reallocated to the Nossal Institute for Global Health by 2023.

In combination with the work that I started during my master's degree in Epidemiology at the ICEH (2019–20), my research activities so far have resulted in the publication of 24 peer-review publications (four of which as first author), with multiple others in different stages of development. My research contribution has been acknowledged in the UNICEF's flagship publication "The State of the World's Children 2023: For every child, vaccination". I have also contributed to the official translation to Portuguese of the WHO's manual "Inequality monitoring in immunization: a step-by-step manual".

During my PhD, I have won three awards for my presentations in scientific conferences. The first one was at the 11th Brazilian Congress of Epidemiology; the second at the 2023 Faculty of Medicine, Dentistry and Health Sciences (MDHS) Early Career Academic Network Symposium from the University of Melbourne; and the third at the 2023 MDHS Graduate Research Conference.

3.1. International Center for Equity in Health | UFPel

At the ICEH, my activities can be divided into three main areas:

- In the RSM (Reproductive, Sanitation and Malaria) group, monitoring inequalities in WASH, lifestyle, gender, malaria, sexual, and reproductive health indicators, using MICS and DHS surveys. This included the creation of indicators, management of datasets, and analysis of surveys, in addition to the stratification of results according to common dimensions of inequality (e.g., wealth, area of residence, and education). The results of these analyses supply data to the WHO's

Health Equity Assessment Toolkit (who.int/data/inequality-monitor/assessment_toolkit) and the Countdown to 2030 Initiative (countdown2030.org).

- In a long-standing research project in partnership with Gavi, the Vaccine Alliance. The main objective of this project is to investigate possible drivers of vaccination uptake in LMICs, including religious affiliation, ethnicity, women's empowerment, multiple deprivation, and vaccine cards. This knowledge can then be used to target unvaccinated children and tailor interventions to their characteristics and needs. So far, this project has resulted in multiple internal reports and seven scientific publications.
- In ad hoc projects with the other researchers at the ICEH and our institutional partners. This includes research related to nutrition, breastfeeding, intimate partner violence, child marriage, genital mutilation/cutting, WASH, and vaccination.

3.2. Gender and Women’s Health Unit | University of Melbourne

At the Gender and Women’s Health Unit, I have worked in five research projects:

- Evaluation of sanitation and handwashing facilities in Ethiopia, Indonesia, Nepal, Uganda, and Zambia in partnership with FH Designs, an Australian-based development consultancy.
- Process evaluation of the E-MOTIVE trial, an international cluster-randomized trial for early detection and treatment of postpartum hemorrhage, in partnership with researchers from the WHO and the University of Birmingham.
- Systematic review on community engagement in the development of health norms, standards, and guidelines, in partnership with researchers from WHO.
- Inequities in smoking prevalence and cessation rates among Australians with and without disability using longitudinal data from 20 years of the Household, Income and Labour Dynamics in Australia (HILDA) Survey, in partnership with the Melbourne Disability Institute.

- Creation of an evidence map for a scoping review about models of care in the perinatal period that are culturally responsive, trauma-aware, or related to continuity of care(r).

During my stay at the University of Melbourne, I also audited the following five subjects (visiting research students were only allowed to audit subjects):

- Gender and Health
- Women and Global Health
- Climate Change and Health
- Planetary and Global Health
- Qualitative Research in Public Health

3.3. Other research activities

In partnership with researchers from the Postgraduate Program in Epidemiology of UFPel, I also participated in two other research projects:

- We used data from the 2015 Pelotas Birth Cohort to identify predictors during pregnancy of poor child development at age 4 years. The goal was to use those predictors to screen pregnant women in primary health care settings for a large-scale child development program (Primeira Infância Melhor) in Brazil.
- We investigated the non-linear association between head circumference at birth and IQ, education attainment, and employment in young adulthood via systematic review of the literature and longitudinal analysis of the 1993 Pelotas Birth Cohort.

4. Research Article 1

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E. coli contamination of drinking water sources in rural and urban settings: an analysis of 38 nationally representative household surveys (2014–2021)

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ABSTRACT

The world is not on track to achieve universal access to safely managed water by 2030, and access is substantially lower in rural areas. This Sustainable Development Goal target and many other global indicators rely on the classification of improved water sources for monitoring access. We aimed to investigate contamination in drinking water sources, comparing improved and unimproved sources in urban and rural settings. We used data from Multiple Indicator Cluster Surveys, which tested samples from the household water source and a glass of water for *Escherichia coli* contamination across 38 countries. Contamination was widespread and alarmingly high in almost all countries, settings, and water sources, with substantial inequalities between and within countries. Water contamination was found in 51.7% of households at the source and 70.8% in the glass of water. Some improved sources (e.g., protected wells and rainwater) were as likely to be contaminated as unimproved sources. Some sources, like piped water, were considerably more likely to be contaminated in rural than urban areas, while no difference was observed for others. Monitoring water contamination along with further investigation in water collection, storage, and source classification is essential and must be expanded to achieve universal access to safely managed water.

Key words: drinking water, *Escherichia coli*, global health, health inequities, water quality

HIGHLIGHTS

- Water sources classified as improved – in particular, protected wells and rainwater – had high prevalence of *E. coli* contamination.
- Piped water sources were much more likely to be contaminated in rural areas.
- Contamination was more prevalent at the point of use than at the source, but this varied significantly according to the water source.
- We provided a list of suggestions to improve monitoring of the Sustainable Development Goal 6.

INTRODUCTION

Access to safe and clean water was recognised as a human right in 2010, and the first target of the Sustainable Development Goal (SDG) 6 is to 'achieve universal and equitable access to safe and affordable drinking water for all' by 2030 (UN General Assembly 2010; United Nations 2023a). The world is not on track to reach this target, and 2 billion people still lacked access to safely managed drinking water in 2020 (WHO, UNICEF and World Bank 2022). Even though significant progress was achieved in the last 20 years, with access increasing from 62% in 2000 to 74% in 2020 – equivalent to an additional 2 billion people – regional inequalities remain alarmingly high. While 96% of the population in Europe and North America had access to safely managed water in 2020, only 30% had access in sub-Saharan Africa (WHO, UNICEF and World Bank 2022).
A safely managed water service is an improved water source, which is located on the premises, available when needed, and free from contamination (WHO, UNICEF and World Bank 2022). Improved water sources are 'those that, by nature of their design and construction, have the potential to deliver safe water' (WHO, UNICEF and World Bank 2022). For example, piped supplies and boreholes are classified as improved sources, while surface water is not (WHO 2022). Contamination refers to

microbiological – typically *Escherichia coli* – and chemical contamination, including arsenic, fluoride, lead, and nitrate, depending on regional priorities (WHO, UNICEF and World Bank 2022). In case of water contamination data not being available, the WHO/UNICEF Joint Monitoring Programme for Water Supply, Sanitation and Hygiene (JMP) can provide estimates for other indicators, most notably the basic water service indicator, which refers to using an improved water source with water collection time equal to or lower than 30 min (WHO and UNICEF 2021). Therefore, it is heavily reliant on the definition of an improved water source.

While the JMP can provide estimates for 211 countries (representing 99% of the global population) for the basic water service indicator, only 138 countries (representing 45% of the global population) have data for the safely managed indicator (WHO and UNICEF 2021). This limitation is because many countries and regions lack the necessary capacity and infrastructure to monitor the water contamination component of the indicator (WHO and UNICEF 2021). Nationally representative household surveys represent a valuable data source that not only can include measurements of water quality but also can allow for the disaggregation of estimates according to important dimensions of inequality and household characteristics. In particular, from 2017 onwards, the UNICEF-supported Multiple Indicator Cluster Survey (MICS) have implemented a water quality module that measures *E. coli* contamination in drinking water samples, mostly in low- and middle-income countries (LMICs) (Bain *et al.* 2021). Data are available for 38 countries.

Current evidence indicates that water contamination is high in LMICs, but it markedly varied between countries, urban and rural settings, and water sources (Bain *et al.* 2021; WHO UNICEF and World Bank 2022). A recent analysis of 27 LMICs showed that the proportion of the population using a contaminated water source ranged from 16% in Mongolia and Algeria to 90% in Sierra Leone (Bain *et al.* 2021). Furthermore, living in a rural household was associated with a 10% increase in the risk of water contamination compared to an urban household, after adjusting for water source, sanitation infrastructure, wealth, and other household characteristics (Bain *et al.* 2021). Unimproved water sources – such as surface water and unprotected wells and springs – have the highest contamination levels, but the water from all sources can be contaminated depending on the country (WHO UNICEF and World Bank 2022). Evidence on whether specific source contamination varies according to urban and rural settings is scarce. In a meta-analysis of faecal contamination in drinking water, there was only weak evidence that piped water is more contaminated in rural areas, and stratified results were not available for other sources separately (Bain *et al.* 2014).

Our objective is to investigate the risk of *E. coli* contamination in drinking water according to the water source and urban/ rural setting. We aimed to examine contamination at the point of collection (directly from the source) and at the point of consumption (after storage and handling in the household). In particular, we want to compare water sources currently classified as improved or unimproved by the JMP in terms of their ability to provide water that is free from contamination in urban and rural settings.

METHODS

Data sources and study sample

We selected all MICS surveys with the water quality testing module publicly released until 8 February 2023 (UNICEF 2023). We included the most recent survey if more than one was available for the same country (Bangladesh and Nepal). Thirty-eight countries with surveys from 2014 to 2021 were included and are presented in Supplementary Table 1. MICS surveys use a multistage sample design to provide nationally representative samples for multiple indicators, including water, sanitation, and hygiene (WASH) (Khan & Hancioglu 2019). The first stage of sampling is typically based on census enumeration areas, and different allocation methods can be used. For the second stage, households in the selected enumeration areas are listed, and 20–25 households are selected using random systematic sampling (Khan & Hancioglu 2019). The sample is typically stratified by urban/rural areas and sub-national regions to provide adequate sample sizes for these areas (Bain *et al.* 2021). Our unit of analysis was the household.

E. coli as an indicator of faecal contamination

Water quality testing is performed in a subsample of the households surveyed by MICS, and the presence of *E. coli* is used as an indicator of faecal contamination, henceforth referred simply as ‘contamination’ (UNICEF and WHO 2020). Typically, 5 out of the 25 households in each survey enumeration area are selected, considering that households in the same cluster tend to have similar contamination levels since they are more likely to have similar water and sanitation infrastructure (UNICEF and WHO 2020). The field tester requests permission from a knowledgeable respondent from the household – aged 18 years older – to collect water samples: one glass of drinking water and another directly from the household's water source (UNICEF and WHO 2020). Samples of 100 ml are collected from the glass (point of use) and the source (point of collection) using a sterile Whirl-Pak collection bag or a preassembled membrane filtration apparatus (UNICEF 2016; Bain *et al.* 2021). For each sample, the field tester withdraws 1 ml of water using a disposable syringe and uses it to hydrate a CompactDry EC growth media plate (Nissui). The rest of the 100 ml sample is filtered with a 0.45-μm filter membrane (Millipore Microfil). The filtered water is discarded, and the filter is plated on the rehydrated growth media plate (UNICEF 2016; Bain *et al.* 2021). The plate is then incubated for 24–48 h in an electric incubator or in an incubator belt worn around the body of the field tester at a temperature between 25 and 40 °C (UNICEF 2016). The chromogenic enzyme (β-glucuronidase) substrate on the plate gives *E. coli* colonies a blue colour (UNICEF and WHO 2020). After incubation, the field tester counts and registers the number of blue colonies in the survey questionnaire. For quality control, blank tests are regularly performed using bottled or distilled water, usually after every 10 samples (UNICEF and WHO 2020). Water was considered free from contamination in our analyses if no *E. coli* colonies were detected and contaminated otherwise (WHO and UNICEF 2021).

Stratifiers

Water contamination was explored by the source and by the urban or rural household location. The urban/rural classification was based on each country's definition, generally dependent on the population density of the settlement, but additional criteria – such as the percentage of the population engaged in agriculture – might be used depending on regional specificities (Bartram *et al.* 2014; United Nations 2017).

The water source typically refers to where the household members collect water, not the origin of the water. If water is collected from a public tap supplied with water from a dam, the household water source would be the tap, not the dam (UNICEF and WHO 2018). In case of multiple sources, it refers to the main water source, i.e., the place from which the household members most frequently collect drinking water (UNICEF 2020). The water source is classified based on the respondent's response, whom the interviewer assists. Interviewers are trained and tested during the survey preparation and data collection phases and have access to pictorials depicting different water sources during the interview (Bartram *et al.* 2014; UNICEF 2021a).

Water source categories are fairly standardised in the most recent MICS surveys using the JMP naming convention. Improved water sources include piped to yard/plot, piped to neighbour, public tap/standpipe, tubewell/borehole, protected well, protected spring, rainwater, tanker truck, cart with small tank/drum, other forms of delivered water (such as buckets delivered at home), water kiosk, bottled water, sachet water, and other forms of packaged water (such as water coolers) (WHO and UNICEF 2021). Unimproved water sources include unprotected well, unprotected spring, and surface water (river, dam, lake, irrigation channel, etc.), and any other sources not listed (WHO and UNICEF 2021).

Protected wells are dug wells protected from runoff water and falling material, with some form of casing raised above the ground level and a top coverage structure. Protected springs are those protected by a 'spring box' around them that directs water to a pipe or cistern without contact with runoff water. Unprotected wells and springs are those that fail to meet those criteria (UNICEF and WHO 2018).

Statistical analysis

First, we calculated the percentage of households using each type of water source. We then calculated the percentage of households with contaminated water at the point of collection and the point of use according to the water source and the area of residence. Groupings with less than 25 households were dropped from this analysis due to low precision (UNICEF 2021b). All proportions were estimated with respective 95% confidence intervals (95% CIs).

We calculated the percentage of contaminated blank tests for each country as a form of quality control. Contaminated blank tests can indicate the general risk of cross-contamination in a specific survey but cannot be used to identify households where cross-contamination might have occurred.

We performed country-specific analyses and also for all countries pooled together to identify general patterns. For the pooled results, we combined all survey datasets into one and recalculated the survey weights to account for the country's population size. Thus, the pooled results are equivalent to a weighted average considering the national population as the weight. We used the 2018 population estimates (median survey year) from the World Bank website (World Bank 2022). A more comprehensive description is available in the Supplementary Material.

We used the ‘survey’ package (Lumley 2004) in R (version 4.2.2, R Foundation for Statistical Computing, Vienna, Austria) to take into account the complex survey design used by MICS (including weighting, strata, and clustering). We used the weights provided for the water quality testing subsample when available. Otherwise, we used the household sample weights.

RESULTS

Our sample consisted of 95,070 households in 38 countries. Using the SDG world regions, we had 16 countries in sub- Saharan Africa, five in Northern Africa and Western Asia, two in Central and Southern Asia, three in Eastern and South-East- ern Asia, five in Oceania, six in Latin America and the Caribbean, and one in Europe and Northern America (Supplementary Table 1) (United Nations 2023b).

Across all countries, tubewells or boreholes and piped water into the dwelling were the two most common sources of drinking water in the sample, which were used by 30.7% (95% CI: 29.8–31.5%) and 18.0% (17.3–18.6%) of households, respectively (Figure 1 and Supplementary Table 2). In urban settings, piped water into the dwelling was the most common source (30.5%; 29.1–31.9%), followed by tubewells/boreholes (17.5%; 16.3–18.8%). In rural settings, tubewells/boreholes were the most common source (40.5%; 39.5–41.5%), followed by unprotected wells (9.8%; 9.0–10.7%). The most common sources of drinking water varied considerably between countries: 87.4% (80.1–92.3%) of households in Tuvalu used rainwater; 85.3% (84.4–86.2%) in Bangladesh used tubewells/boreholes; 80.5% (77.5–83.3%) in Vietnam used piped water into dwelling; and 77.4% (75.1–79.6%) in the Dominican Republic used bottled water.

Across all countries, faecal water contamination – indicated by the presence of *E. coli* – was found in 51.7% (50.3–53.0%) of households at the point of collection and 70.8% (69.8–71.9%) at the point of use (Figures 2 and 3 and Supplementary Tables 3 and 4). Contamination was more prevalent in rural than in urban areas. The contamination prevalence at the point of collection was 59.5% (57.3–61.6%) vs. 39.8% (38.3–41.4%) in rural and urban areas, respectively. At the point of use, it was 82.1% (80.9–83.3%) vs. 55.8% (54.1–57.5%).

Contamination varied substantially between water sources. For households using unprotected wells, the contamination prevalence was 94.3% (92.4–95.7%) at the point of collection and 95.9% (94.0–97.2%) at the point of use. Meanwhile, for households with piped water into the dwelling, it was 27.9% (26.1–29.8%) and 37.3% (35.2–39.3%), respectively. There was a gradient in the prevalence between those sources with no clear cut-off point that could separate sources into low and high likelihood of contamination. For tubewells/boreholes, the most commonly used water source in the sample, the contamination prevalence was 44.1% (42.3–46.0%) at the point of collection and 82.4% (80.2–84.5%) at the point of use.

In general, households using unimproved sources were more likely to have contaminated water at the point of collection and use. Together with unprotected wells, both surface water and unprotected springs had a high likelihood of contamination. For surface water, the contamination prevalence was 90.1% (85.5–93.4%) at the point of collection and 93.4% (90.4–95.5%) at the point of use. For unprotected springs, it was 78.2% (71.4–83.7%) and 84.5% (79.9–88.2%), respectively.

Nevertheless, several improved sources were as likely to be contaminated as unimproved sources. In particular, protected wells and rainwater – both improved sources – were among the most contaminated water sources regardless of the setting (urban or rural). For households using rainwater, the contamination prevalence was 84.7% (81.1–87.7%) at the point of col- lection and 90.7% (87.9–92.9%) at the point of use. For protected wells, it was 89.0% (86.4–91.1%) and 92.1% (90.5–93.5%), respectively. This was only slightly lower than those from their counterpart, unprotected wells: 94.3% (92.4–95.7%) at the point of collection and 95.9% (94.0–97.2%) at the point of use.

Unlike wells, protection for springs was associated with strong reduction in contamination. Households using protected springs were considerably less likely to be contaminated than those using unprotected springs. At the point of collection, 31.0% (19.5–45.4%) were contaminated for protected springs and 78.2% (71.4–83.7%) for unprotected springs. At the point of use, the difference was smaller but still substantial: 63.2% (50.1–74.6%) for protected springs and 84.5% (79.9– 88.2%) for unprotected springs.

There was substantial variation in contamination between piped sources. Water piped into the dwelling had the lowest prevalence of contamination: 27.9% (26.1–29.8%) at the point of collection and 37.3% (35.2–39.3%) at the point of use. Meanwhile, water piped into the compound and public taps/standpipes had a significantly higher likelihood of contamination. For water piped into the compound, the contamination prevalence was 53.5% (50.4–56.5%) at the point of collection and 68.6% (66.0–71.0%) at the point of use. For public taps/standpipes, the contamination prevalence was

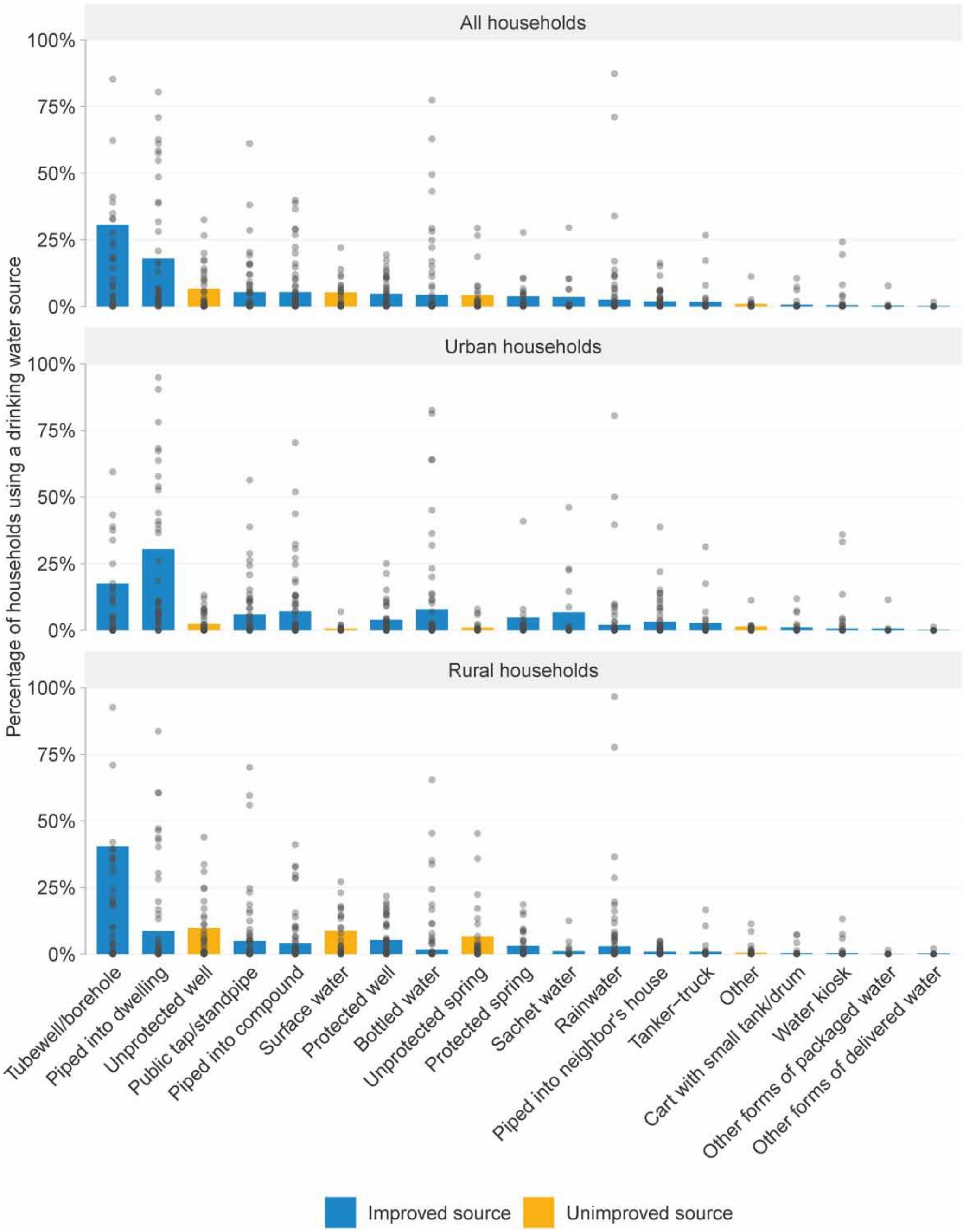

Figure 1 | Percentage of households using a specific drinking water source for all households combined (first panel) and in urban and rural settings (second and third panels, respectively). National estimates are represented by circles, while pooled estimates are represented by the bars. Water sources are ordered according to the pooled percentage of all households using those water sources.

50.1% (45.2–55.0%) and 76.3% (73.4–79.0%). Water piped into the neighbour's house had an intermediate result: 38.3% (33.0–43.9%) at the point of collection and 64.2% (57.6–70.2%) at the point of use.

The contamination prevalence of delivered water sources and water kiosks was around the 50% mark. For carts with a small tank/drum, the contamination prevalence was 49.6% (43.8–55.5%) at the point of collection and 69.0% (65.0– 72.8%) at the point of use. For tanker-trucks, it was 42.0% (37.3–46.9%) and 53.2% (49.2–57.2%), respectively. For water kiosks, it was 43.7% (37.8–49.8%) and 64.8% (60.4–69.0%).

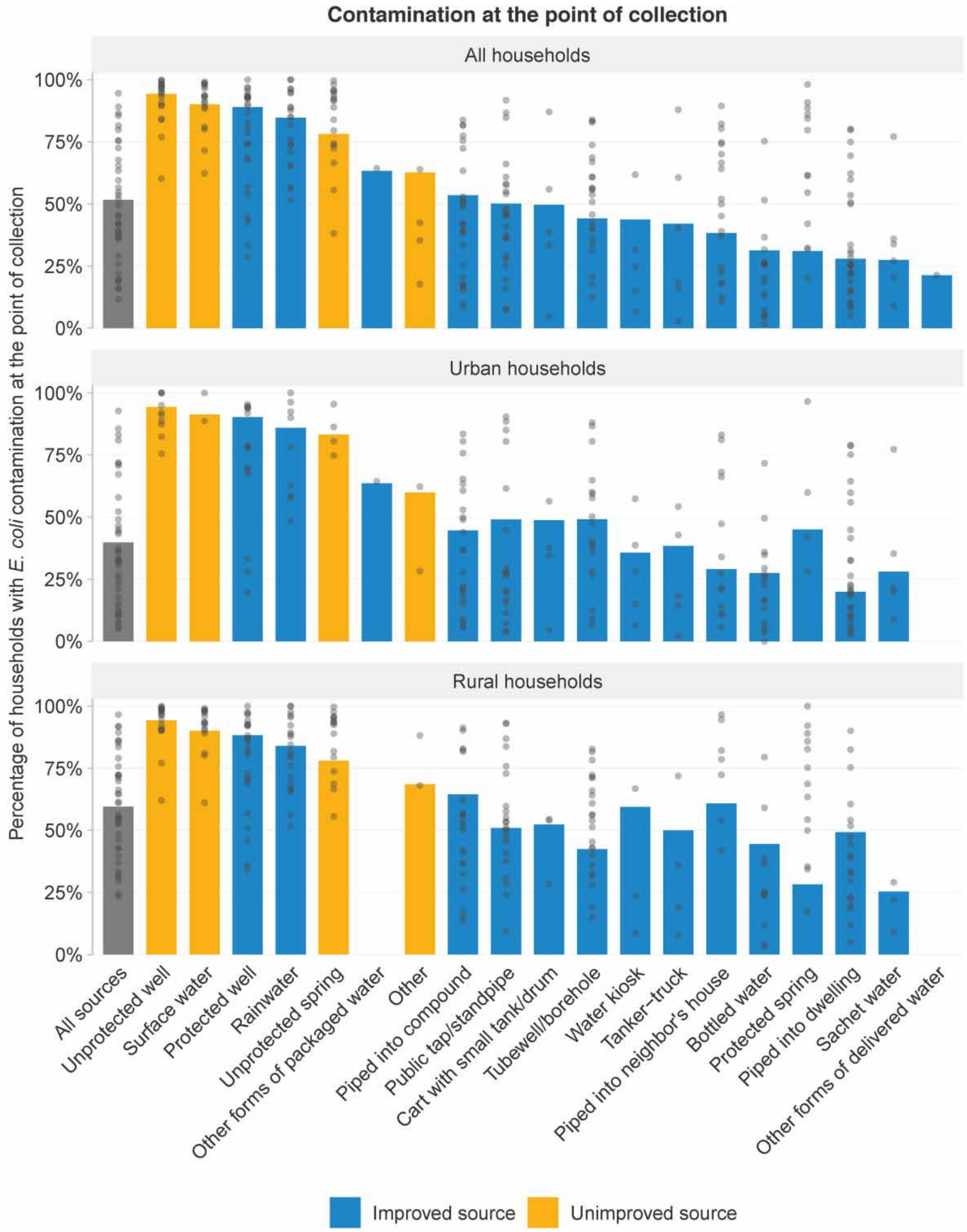

Figure 2 | Percentage of households with *E. coli* contamination at the point of collection according to the water source. Results are presented for all households combined (top panel) and in urban and rural settings (middle and bottom panels, respectively). National estimates are represented by circles, while pooled estimates are represented by bars. Water sources are ordered according to the pooled percentage of all households with *E. coli* contamination.

Packaged water sources were among the sources with the lowest prevalence of contamination. For bottled water, the contamination prevalence was 31.2% (28.9–33.6%) at the point of collection and 46.9% (45.0–48.8%) at the point of use. For sachet water, it was 27.4% (21.7–34.0%) and 44.4% (39.4–49.4%), respectively.

Other packaged and other delivered sources were only present in a few countries and had large confidence intervals, which is expected given the small sample size and the heterogeneous nature of the categories. For other packaged water sources, the contamination prevalence was 63.3% (47.3–76.8%) at the point of collection and 56.4% (43.3–68.7%) at the point of use. For

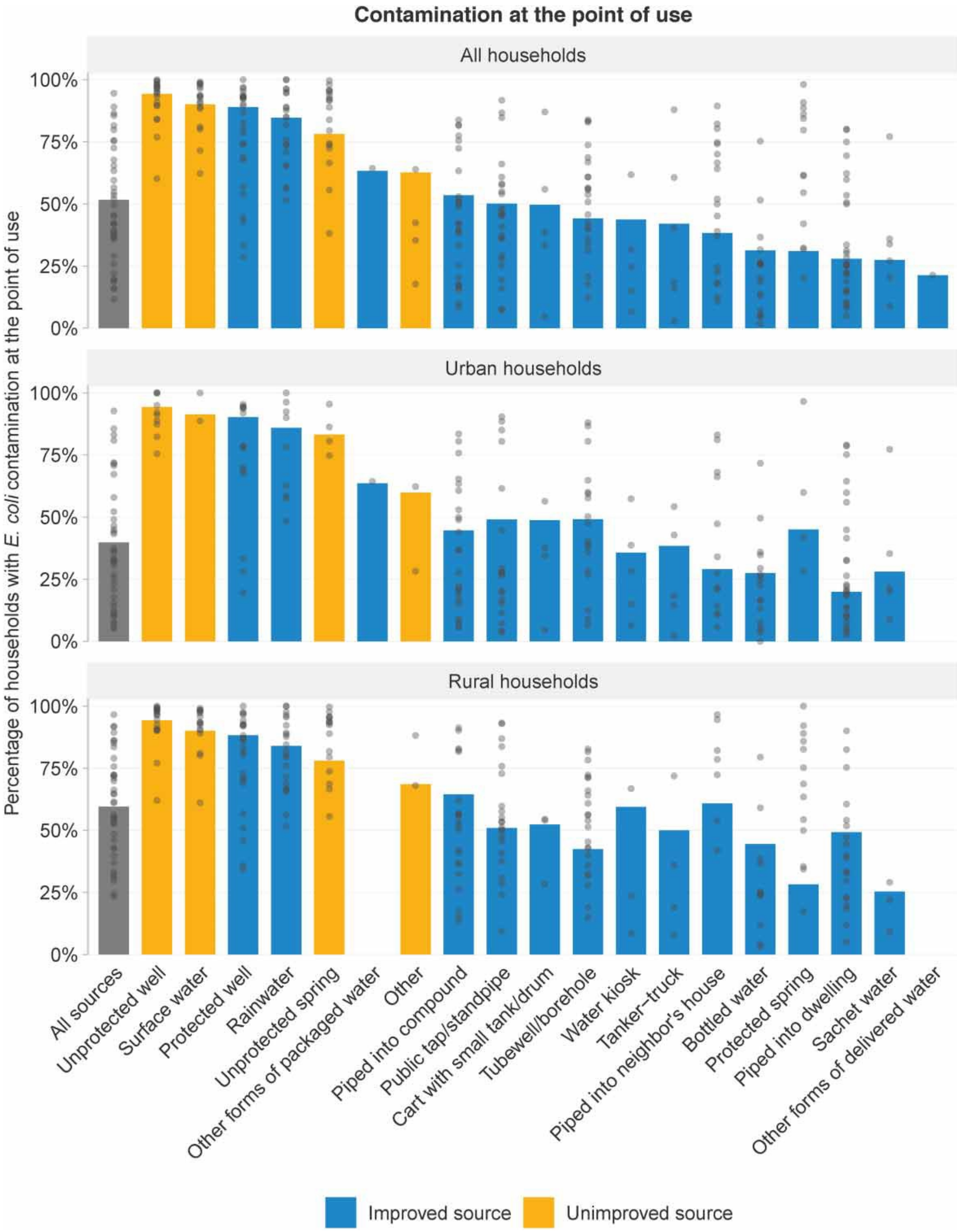

Figure 3 | Percentage of households with *E. coli* contamination at the point of use according to the water source. Results are presented for all households combined (top panel) and in urban and rural settings (middle and bottom panels, respectively). National estimates are represented by circles, while pooled estimates are represented by bars. Water sources are ordered according to the pooled percentage of all households with *E. coli* contamination.

other delivered water sources, it was 21.3% (2.2–76.6%) and 38.1% (5.7–86.3%), respectively. For the category that combined any other sources not listed, it was 62.7% (54.0–70.6%) and 80.2% (73.9–85.2%).

For all water sources, the frequency of contamination increased between the point of collection and the point of use, with the exception of other forms of package water, which had a non-significant decrease (Figure 4 and Supplementary Tables 3 and 4). Tubewells/boreholes – the most common water source in the sample – had the largest difference in the frequency of contamination: 44.1% (42.3–46.0%) at the point of collection and 82.4% (80.2–84.5%) at the point of use, or a difference of

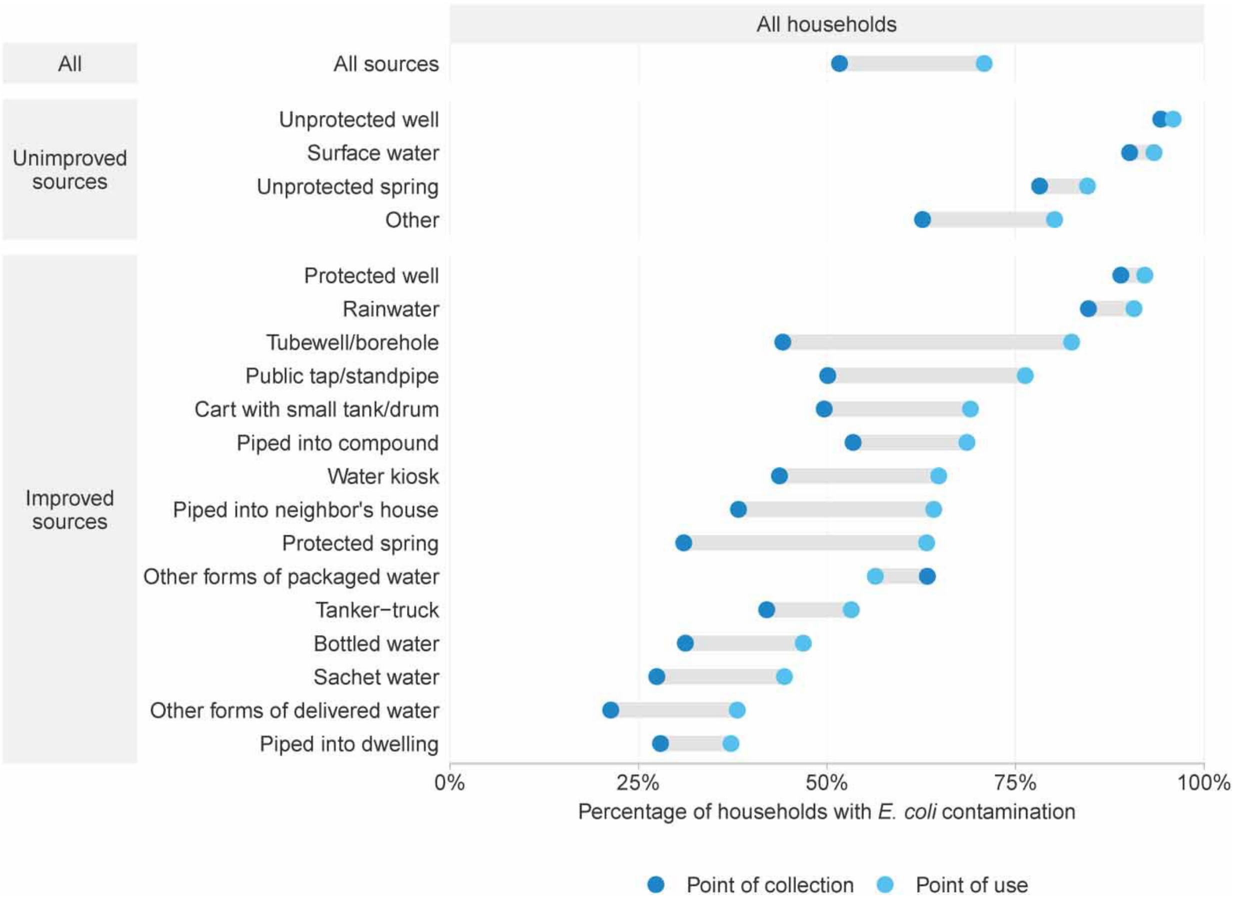

Figure 4 | Comparison in the percentage of households with *E. coli* contamination between the points of collection and use.

almost 40 percentage points. Protected springs, public taps/standpipes, piped water into the neighbour's house, and water kiosks had a difference in the frequency of contamination larger than 20 percentage points.

Differences in contamination between urban and rural households were highly dependent on water sources (Figure 5 and Supplementary Tables 3 and 4). Piped water sources (into dwelling, into the compound, and into the neighbour's house) and water kiosks had the largest absolute differences. In particular, for piped water into dwelling, at the point of collection, contamination was found in 19.9% (18.1–21.8%) of urban households and in 49.3% (44.5–54.1%) of rural households. At the point of use, contamination was found in 28.8% (26.7–31.1%) of urban households and in 59.7% (55.0–64.2%) of rural house- holds. For many other sources, whether they had a high likelihood of contamination at the source, such as wells; an intermediate likelihood, such as tubewells/boreholes; or a lower likelihood, such as sachet water, there was no statistically significant difference in contamination at the point of collection.

There was a wide variation in the prevalence of contamination at the national level (Supplementary Tables 3 and 4). At the point of collection, contamination varied from 11.6% (4.9–25.1%) in Turks and Caicos to 94.6% (89.6–97.2%) in Tuvalu. At the point of use, it varied from 18.1% (15.8–20.6%) in Mongolia to 99.1% (98.5–99.5%) in Chad. For most countries, differences in contamination between water sources were similarly variable. At the point of collection in Madagascar, contamination varied from 8.1% (3.3–18.8%) for piped water into dwelling to 99.6% (98.1–99.9%) for unprotected wells. By comparison, at the point of use in Chad, all sources had contamination higher than 95%.

The prevalence of contamination in blank testing was low in the overall sample, 1.5% (1.1–1.8%) (Supplementary Table 5). Only three countries had a prevalence of contamination in blank testing higher than 5%: Turks and Caicos with 5.4% (1.1– 23.1%), Côte d'Ivoire with 7.9% (5.4–11.4%), and Gambia with 8.8% (5.4–14.2%). There was no statistically significant difference in the prevalence of contamination in blank testing between the urban and rural settings: 1.1% (0.8–1.5%) and 1.7% (1.2–2.4%), respectively.

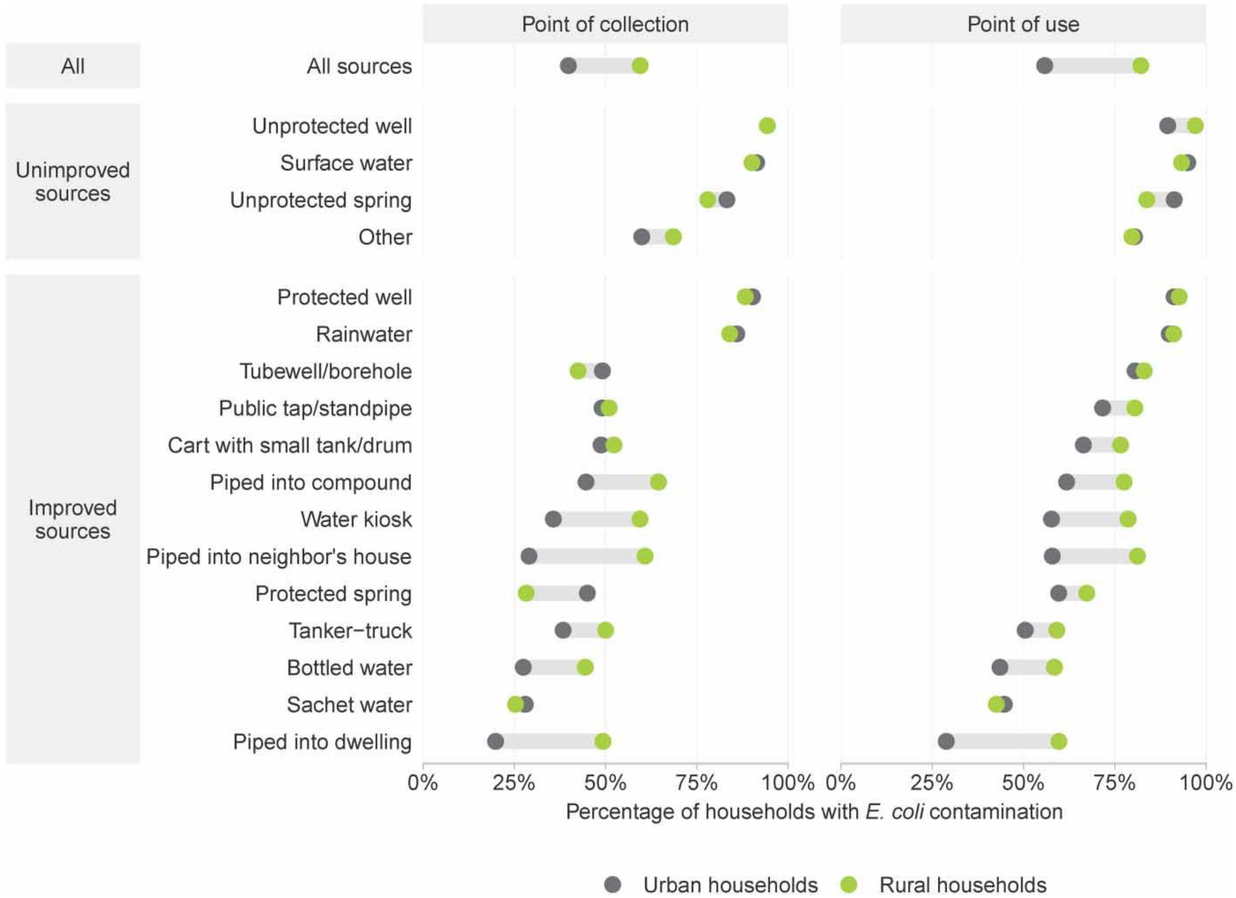

Figure 5 | Comparison in the percentage of households with *E. coli* contamination between urban and rural households. Water sources are ordered according to the pooled percentage of households with *E. coli* contamination at the point of use. In case estimates could not be calculated ($n < 25$) for either the urban or rural setting, and results were not shown for that source.

DISCUSSION

Considering the global target of universal and equitable access to safely managed water by 2030, our results show that *E. coli* contamination was widespread and unacceptably high in almost all water sources, settings, and countries in our sample (predominantly LMICs), with substantial inequalities between and within countries. Some water sources currently classified as improved were as likely to be contaminated as unimproved sources. Furthermore, the capacity of a water source to provide water that did not have *E. coli* contamination was highly context-dependent. Contamination for piped water, in particular, was markedly higher in rural than urban areas. In some countries where contamination was widespread (e.g., Chad, Sierra Leone, and Kiribati), almost all sources had high a likelihood of contamination.

Our results highlight the importance of water quality measurement and how vital it is to measure the last step in providing drinking water. Monitoring activities that use source-centred indicators are strongly reliant on the current classification of improved and unimproved water sources. They also ignore any deterioration in quality that can happen between the source and the point of use. From a public health perspective, monitoring of water quality at the point where people drink the water, instead of at the source, is a better indicator of the health risks associated with water contamination and is an indispensable step towards achieving SDG 6. For example, in Chad, 50.9% of the population had access to basic water services in 2019, but only 1.4% had access to a safely managed water service (INSEED and UNICEF 2020). This means that half of the population had access to an improved source with a collection time of 30 min or less, but almost no one had access to drinking water that was free from faecal contamination (*E. coli*), accessible on the premises and available when needed. The main driver of this difference was water contamination (INSEED and UNICEF 2020), which if not measured leads to a serious overestimation of progress. We urge other nationally representative surveys to include water quality measurement as a standard module for LMICs. This is especially important for the Demographic and Health Surveys and the Living Standards Measurement Study, given that the MICS module has already been adapted to be used for both (JMP 2023).

Classification of water sources

Even though relying on water source for monitoring has serious drawbacks, more than half of the world's population still lack water quality data and depend on the basic water service indicator (WHO and UNICEF 2021). Our findings showed that there were important differences in contamination between improved and unimproved sources. Nevertheless, they also highlight that some sources' classifications need further scrutiny, in particular protected wells and rainwater.

Protected and unprotected wells had a very similar likelihood of contamination, which suggests that protected wells (as currently defined and measured) fail to provide enough protection against *E. coli* contamination. Wells, even when protected against surface water runoff and harmful materials that can fall inside, are still susceptible to contamination via groundwater flow. This can happen when wells are located close to sanitation infrastructures such as pit latrines – where contaminants can travel through the ground – especially in areas with high population density and a large number of latrines (Kiptum & Ndambuki 2012).

The high likelihood of contamination for rainwater emphasises the challenge of properly handled rainwater harvesting systems, especially in lower income settings. In many areas of the Caribbean, southeast Asia, and the Indian and Pacific Oceans – especially in low-lying islands – many communities intensively rely on rainwater for drinking and cooking (Bailey *et al.* 2018). Although initially free from contamination, rainwater becomes progressively more contaminated as it stays in contact with the atmosphere and the structures used for water collection and storage. Faecal contamination is quite common and dependent on the design, structure, materials, maintenance, and the weather (WHO 2022). Based on our results, a single rain- water category classified as improved may not be the best approach for household surveys. It might be beneficial to use separate 'protected rainwater' and 'unprotected rainwater' categories – similar to springs – taking into account the presence of automatic diverters, detachable downpipes, wire meshes, inlet filters, appropriate roof material, and/or storage tank covers as indicators of harvesting systems that limit water contamination.

Since the Millennium Development Goals era, the JMP has updated both its definition of improvement and what sources are classified as improved (Bartram *et al.* 2014). An improved source used to be defined as a source that 'by the nature of its construction and design adequately protects the source from outside contamination, in particular by faecal matter' (WHO 2017). The current definition does not mention contamination, instead focusing on the 'potential to deliver safe water' (WHO, UNICEF and World Bank 2022). This definition is broader, but also more ambiguous, since there is no universally recognised definition of safe water (Dinka 2018). On the one hand, it is more aligned with the WHO's delineation that an adequate drinking water supply should provide not only quality but also accessibility, quantity, continuity, and affordability (WHO 2022). On the other hand, its ambiguity makes the interpretation of global indicators that rely on it less clear. It raises important questions on what specific criteria to include when defining a source as improved and how they should be weighted when they contradict each other. In order to improve public accountability, the JMP could include a clearer definition of 'safe water' and the criteria being used for source classification in their website and their technical reports. Further studies are also necessary to evaluate water sources in terms of their potential to simultaneously provide accessibility, quantity, quality, continuity, and affordability of water supply. Nevertheless, if contamination is the main criteria, there is overwhelming evidence that neither protected wells nor rainwater should remain as improved sources.

Water quality deterioration between the source and the point of use

For many water sources, the prevalence of contamination at the point of use was higher than the prevalence at the point of collection. This was expected, given that contamination can occur during the many stages of water handling and storage that happen between the point of collection and the point of use, especially in LMICs with a deficient sanitation and hygiene infrastructure (WHO and UNICEF 2021). A study conducted in Malawi in 2019 investigated *E. coli* contamination in water in four different stages of water collection: at the water source, at the collection container, at the storage container, and at the cup of drinking water. That study found that the level of contamination would increase in every stage, but the critical steps were filling the collection container and during water storage (Cassivi *et al.* 2021). Most MICS surveys with the water quality module investigate water storage via only one question that classifies households on whether water is collected directly from the source or from a covered or uncovered container. There is an opportunity for more categories and questions to be included that can better differentiate and investigate the water collection, transportation, handling, and storage stages. They also need to be investigated simultaneously with sanitation and hygiene infrastructure to provide evidence for comprehensive WASH interventions that can effectively reduce contamination and achieve major impacts in public health (Cumming *et al.* 2019).

Contamination in urban and rural areas

For many improved sources, the prevalence of contamination was higher in rural areas when compared to urban areas. That difference was particularly high for piped water sources. Therefore, indicators that rely on the classification of improved/unimproved sources or that are based on access to piped water – without measuring water contamination – tend to overestimate the quality of water infrastructure in the rural context. This needs to be taken into account in the interpretation of equity analysis of those indicators. For example, in a region where the urban and rural areas have the same prevalence of access to piped water, the situation is likely to be worst in the rural areas because faecal contamination is likely higher. This is in line with the multiple structural challenges faced by rural populations. Lower population density, larger distances between households, and the lack of political will and resources make the installation and maintenance of WASH infrastructure less feasible, resulting in higher risk of water contamination (Abrams *et al.* 2021; Bain *et al.* 2021; Apatinga *et al*. 2022). In 2020, while 64% of the global urban population had access to sewer connections, only 15% of the rural population had similar access (WHO and UNICEF 2021). Furthermore, farming and animal husbandry can create competition for water resources and result in contamination with agrichemicals and animal waste. Likewise, climate seasonality and extreme weather events exacerbated by climate change can reduce water availability and increase contamination, especially when coupled with improper sanitation (Abrams *et al.* 2021; Apatinga *et al*. 2022).

Limitations and strengths

There are important limitations to our research. First, we only investigated *E. coli* contamination and did not include other important chemical contaminants. This was due to lack of data availability and also the fact that there are region-specific contaminants that are prioritised in different surveys and their inclusion would result in the lack of comparability between national estimates. Second, we focused on the prevalence of any *E. coli* contamination but did not evaluate the level of contamination in the samples (based on the number of colonies found after incubation). This choice was made to align our investigation with SDG 6, which targets the complete absence of water contamination.

Third, the similar likelihood of contamination between protected and unprotected wells might be influenced by misclassification error, i.e., the interviewees might be misclassifying protected wells as unprotected wells and *vice versa*. In the field, there is not always a clear cut difference between these types of wells. Different materials, shapes, and structures can be used, and they offer different levels of protection and are found in different states of repair. Even though interviewees are assisted by the interviewers, errors are still possible and would introduce bias towards similar likelihoods of contamination. A 2019 study in Kenya showed strong inter-observer agreement in classifying water sources, but some sources were more likely to be misclassified, including protected and unprotected wells (Okotto-Okotto *et al.* 2020). Nevertheless, it is unlikely that misclassification alone would be responsible for this pattern, given the fact that the same was not observed for protected and unprotected springs. Protected springs were significantly less likely to be contaminated than unprotected ones. If misclassification is happening for springs, we would expect the difference to be even larger, therefore providing compelling evidence that spring protection is strongly associated with lower risk of contamination. The same cannot be said for wells. Fourth, even though cross-contamination identified by blank tests was low in most surveys, it was higher than 5% in three countries. A previous study with a similar sample found that excluding countries and clusters with high contamination in the blank tests had only a negligible impact in the final results (Bain *et al.* 2021). Fifth, although we had a large number of households and countries, our sample is not representative of the whole world or of all LMICs. As more surveys become available, these analyses need to be updated to increase the external validity of their results. Despite these limitations, our analyses provide robust evidence of water contamination according to water sources based on a highly comparable multicountry sample stratified by urban and rural settings.

CONCLUSIONS

Our results have shown the pervasiveness of *E. coli* contamination in drinking water sources. Immediate change is necessary to guarantee universal access to water that is free from contamination and from where water is first sourced to the glass where people drink it. There are many opportunities to improve global monitoring of SDG 6 and it would be beneficial (1) to increase the number of nationally representative surveys that include a water quality module, in particular, in Demographic and Health Surveys (DHS) and Living Standards Measurement Study (LSMS) surveys; (2) to present clearer definition, criteria, and evidence used for classifying water sources as improved or unimproved; (3) to further investigate water sources according to those multiple criteria and update the classification of wells and rainwater; and (4) to expand the current investigation of water collection, transportation, handling, and storage in the water quality module of MICS. Monitoring water contamination is essential if we want to achieve SDG 6, especially in rural settings where other simpler indicators might be overestimating the level of the development of water supply systems.

ETHICS STATEMENT

The organisations who administered the surveys were responsible for ethical clearance according to the norms of each country.

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DATA AVAILABILITY STATEMENT

All the analyses were carried out using publicly available datasets that can be obtained directly from the MICS website (mics.unicef.org). Datasets are continuously sourced and updated by the International Center for Equity in Health (equidade.org) as they are released. We used the last available versions on 8 February 2023.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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Supplementary Materials

Supplementary tables are available at: https://doi.org/10.2166/wh.2023.174

Survey weighting

For our pooled analyses, we combined all countries together into one single dataset. We recalculated the sample weights using Equation S.1:

$$w_{ij,adj} = \left(\frac{w_{ij}}{\sum_i w_{ij}}\right)\left(\frac{pop_j}{\sum_j pop_j}\right) N$$

where:

- *i* indicates a household and *j* a country
- $w_{ij,adj}$ is the adjusted sample weight
- w_{ij} is the original sample weight
- pop_j is the total population of the country *j* in the median year of all surveys included in the analyses (2018)
- *N* is the total number of households in the sample.

MICS provides different sample weights for the point of collection and point of use samples. We used them accordingly for the point of collection and point of use analyses. For the blank tests presented in Supplementary Table 5, we used the point of collection sample weights. Results were very similar when using the point of use sample weights (not shown).

5. Research Article 2

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What is the association between women's economic empowerment and basic water, sanitation, and hygiene in the home? An equity analysis of 31 low- and middle-income countries

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Abstract

Background

The lack of adequate water, sanitation, and hygiene (WASH) services has a disproportionate effect on women and girls. They also remain primarily responsible for water carriage and for WASH-dependent domestic chores in many low- and middle-income countries (LMICs). Women's participation in WASH decision-making and governance is a priority research area. Therefore, we aimed to investigate the relationship between women's economic empowerment and basic WASH in the household.

Methods

We analyzed a sample of 278,536 partnered women in 31 LMICs using Demographic and Health Surveys data. We created an economic empowerment score based on having a bank account and a mobile phone used for financial transactions; and deciding about household purchases and how to spend her and her partner's money. We explored the association between economic empowerment and basic WASH in the household in rural and urban settings. We did this by calculating the slope index of inequality (SII), representing the difference in basic WASH prevalence between the most and least empowered women in percentage points (pp).

Findings

More empowered women were significantly more likely to live in a household with basic WASH. For basic water, the median SII was 5.5 pp in urban areas and 15.3 pp in rural areas. For basic sanitation, the medians were 21.1 and 12.8 pp, respectively. For basic hygiene, they were 18.6 and 7.6 pp, respectively. The urban areas of Burundi had the largest SII observed for all indicators and countries. The prevalence of basic sanitation was 36.8% for the least empowered women and 81.0% for the most empowered.

Conclusions

Using a nationally representative, multicountry sample, our study adds to the growing body of evidence of women's empowerment as a possible pathway to better WASH and

vice-versa. Interventions and programs aiming to improve WASH infrastructure could invest in women's economic empowerment both as a goal and as a possible tool for greater effectiveness.

Keywords

Drinking water; Sanitation; Hygiene; Gender equity; Women's Empowerment

Introduction

Under the Sustainable Development Goal (SDG) 6, the United Nations aims to achieve access to safe drinking water and adequate sanitation and hygiene for all by 2030 [1]. At the midpoint between the SDGs adoption (2015) and their target year (2030), 700 million people still lacked basic water, 1.5 billion lacked basic sanitation, and 2 billion lacked basic hygiene [2]. To achieve universal coverage by 2030, the current rates of improvement would have to double for basic water and sanitation, and triple for basic hygiene [2]. Access to water, sanitation, and hygiene (WASH) services is highly unequal between urban and rural areas which – when combined with differences in social structure, socioeconomic development, private and public infrastructure, and land use – create distinct urban and rural environments and unique challenges for improving WASH access [2,3].

The lack of access to WASH has a disproportionate effect on women and girls [4]. Women and girls are primarily responsible for water collection and unpaid domestic roles related to WASH, reducing their time available for education and income-generating activities, and increasing the risk of spinal injury and neck pain from heavy workloads [2,4]. Women and girls also have increased vulnerability to infection during menstruation and childbirth due to inadequate WASH; and are exposed to physical, sexual and psychological violence when practicing open defecation or using shared sanitation facilities [4,5]. These gender-based WASH inequalities sit at the intersection between SDG 6 (WASH) and SDG 5 (gender equality and empowerment of women and girls) [6]. Indeed, women's participation in WASH decision-making and governance is a priority research area [4].

There is evidence that access to WASH may be increased via women's empowerment, including women's control over economic resources (such as income and credit) and their participation in decision-making about household purchases and infrastructure [7–10]. Better WASH access may also lead to women's empowerment via reduction of WASH workloads and increase of discretionary time, school enrollment, direct employment in water services, and access to roles and responsibilities typically reserved for men [4,11–14]. Nevertheless, the evidence is mostly based on local studies. Even though the focus on women's empowerment in WASH research is increasing, clearly defined and comparable measurements of empowerment in this field remain scarce [15].

Demographic and Health Surveys (DHS) are nationally representative surveys of mostly low- and middle-income countries (LMICs) that collect information on both household WASH infrastructure and some aspects of women's empowerment [16,17]. In fact, a recent review of gender indicators in WASH pointed that DHS surveys represent an opportunity to "identify associations between who has decision-making power over major purchases and likelihood of having a water or sanitation facility at the house" [18]. Our goal is to investigate the association between women's economic empowerment and their household's WASH infrastructure in urban and rural areas of LMICs.

Methods

Data sources and study sample

We identified all DHS surveys from 2010 to 05 June 2023. We then selected surveys with the questions necessary for calculating the women's empowerment score and the basic WASH indicators. If more than one survey was available for the same country, we included the most recent survey.

Our unit of analysis was women 15 to 49 years married or in union, using data from those women and their respective households. We restricted our sample to women who were married or in union because questions related to decision-making are not asked to unpartnered women. Considering that the WASH indicators are available at the household level, we selected only women who were either the head of the household or married/in union with the head of the household. In the case of polygynous marriages with multiple women living in the same household, all women were included. For simplicity, we henceforth refer to “married/in union women” as “partnered women” and “husband/partner” as “partner”.

Women’s economic empowerment score

We defined women’s economic empowerment as the personal possession and control over economic assets by a partnered woman and her relational ability to influence the decision-making process around hers, her partner’s and her household’s economic assets [19,20]. This definition is based on Oxfam’s ‘How to’ Guide to Measuring Women’s Empowerment [20] and was designed around the current evidence from the literature [7–14] and DHS data availability.

To search and select variables, we followed a similar approach used for the creation of the Survey-based Women’s Empowerment Index (SWPER Global) [16,17]. We investigated the DHS women’s questionnaire for standard questions that were available in multiple countries and that could be combined to create a women’s economic empowerment score closely related to our definition. Based on those questions, we created the following five dichotomous indicators:

1. Whether the woman has and uses an account in a bank/financial institution.
2. Whether she has a mobile phone and uses it for financial transactions.
3. Whether she does any paid work (paid totally or partly in cash) and decides, alone or with her partner, on how to spend her earnings.
4. Whether her partner has paid work, and she participates in the decision of how to spend his earnings.
5. Whether she participates in the decision about major household purchases.

All five indicators were given the same weight and the final score is the sum of positive answers. This results in an integer score varying from zero to five, in which zero represents the lowest score of economic empowerment and five the highest.

WASH indicators

We selected three standard household WASH indicators, as established by the WHO/UNICEF Joint Monitoring Programme (JMP) [2], that can be calculated using DHS data: basic water, basic sanitation, and basic hygiene services:

1. Basic water is defined as the household having drinking water from an improved source, provided that the water collection time does not exceed 30 minutes (including the round trip, queuing, and collection time) [2]. Improved sources are: piped water, boreholes, tubewells, protected dug wells and springs, rainwater, and packaged or delivered water [2].
2. Basic sanitation is defined as the household having an improved toilet facility that is not shared with other households [2]. Improved facilities are: flush/pour flush toilets connected to piped sewer systems, septic tanks or pit latrines; pit latrines with slabs, ventilated pit latrines, and composting toilets [2].
3. Basic hygiene is defined as the household having a handwashing facility with soap and water at home [2].

Stratifiers

The area of residence (urban/rural) followed each country's definition as provided in the DHS surveys. This classification is generally based on population density, but might also include other characteristics, such as percentage of the population working in agriculture [21,22]. The wealth quintiles are created by DHS using principal component analysis of household indicators, such as building materials and ownership of assets [23,24]. Separate scores are created for urban and rural areas to account for the different effects of household assets in those settings. These scores are then scaled so that a specific value on each score reflects the same level of wealth, resulting in a single score. This unified score is then used to classify household into five equally sized groups [25]. Woman's education was based on her report of the highest level of school she attended: none, primary, secondary, or higher.

Statistical analyses

We calculated the distribution of the women's economic empowerment score for each country and for the pooled sample, according to area of residence, wealth quintiles, and education level. We also calculated the percentage of women possessing each component of our score for each level of empowerment attained (e.g., the percentage of women with a score 3 that have an active bank account). To investigate the empowerment score's external validity, we calculated the Spearman correlation coefficient between the country's mean score and its Gender Development Index in 2017 (median survey year) [26]. We also calculated the Kaiser-Meyer-Olkin index for the score to assess the proportion of the variance that could be attributed to underlying factors (considered adequate if above 0.5) [27].

For the main analysis, we recoded our empowerment score into three categories: lower empowerment (0–1), intermediate (2–3), and higher empowerment (4–5) to increase sample size in each category. We then calculated in each country the percentage of women with basic WASH in their household according to their empowerment category. We stratified all analyses by area of residence because of the different challenges in WASH infrastructure faced by urban and rural populations related to differences in population size, distribution, and growth, socioeconomical structure, agricultural activities, and political influence [28,29]. We then calculated the respective slope index of inequality (SII). It represents the difference in WASH prevalence between the most and the least empowered women, considering the intermediate category in its calculation, as well as the sample size of each category [30]. Positive values indicate better WASH for more empowered women; negative values indicate the opposite; and zero indicates no absolute inequality.

We carried out our analyses in Stata (StataCorp. 2023. Stata Statistical Software: Release 18. College Station, TX: StataCorp LLC) and R (version 4.3.1, R Foundation for Statistical Computing, Vienna, Austria). All analyses considered the complex survey design used in DHS (including clustering, stratification, and survey weighting). For pooled analyses, survey weights were recalculated to give each country the same total weight. In practice, the pooled results are equivalent to the mean of the national results. This is described in more detail in the Supplementary Materials.

Sensitivity analyses

Since the WASH information was collected at the household level, all co-wives from polygynous marriages living together had the same WASH status, meaning that their observations were not independent. To investigate the effect this had on our results, we repeated the main analyses including only one randomly selected wife in the households with multiples wives.

Household wealth and the woman's education are possible confounders and mediators in the association between basic WASH and women's economic empowerment, given the cross-sectional nature of the surveys (see Supplementary Figure S1 for a conceptual model). As a sensitivity analysis, we recalculated the SIIs adjusting for: 1) wealth; 2) education; and 3) wealth and education combined.

Results

Thirty-one countries were included with surveys conducted between 2015 and 2022 (Supplementary Table 1). Nineteen were low income, nine were lower-middle income, and three were upper-middle income in 2017 [31]. Twenty countries were from Sub-Saharan Africa, five from Central and Southern Asia, and three from Eastern and South-Eastern Asia. Latin America and the Caribbean, Northern Africa and Western Asia, and Oceania had one country each [32]. Our sample consisted of 278,536 women (Table 1). 63.2% lived in rural areas, 32.2% had no education, and 88.3% lived in a male-headed household. 66.7% had access to basic water, 40.1% to basic sanitation, and 29.1% to basic hygiene.

Women's economic empowerment score

The overall Kaiser-Meyer-Olkin index was 0.58 (Supplementary Table S2), indicating that there was just an acceptable level of common variance for these items to compose a score. However, given that the items are limited by what is asked in the surveys, we believe their use in a score is justified. The resulting economic empowerment score presented a moderate positive correlation with the GDI at the country level, with a Spearman correlation coefficient of 0.58 ($p < 0.01$) (Supplementary Figure S2).

Table 1 – Descriptive characteristics of 278,536 women in 31 low- and middle-income countries in the sample

Indicator	Median % (IQR)[1]
Rural area of residence	63.2 (55.6 – 77.5)
Education	
No education	32.2 (12.7 – 54.5)
Some or completed primary	20.4 (15.9 – 44.5)
Some or completed secondary	24.8 (15.2 – 34.2)
Some or completed higher	4.9 (3.2 – 8.3)
Age	
15–19	2.9 (0.9 – 5.3)
20–24	12.3 (6.9 – 15.4)
25–29	19.3 (15.7 – 20.8)
30–34	19.3 (18.5 – 20.6)
35–39	19.2 (16.8 – 21.5)
40–44	14.2 (12.2 – 17.9)
45–49	11.6 (9.2 – 15.7)
Male headed household	88.3 (82.5 – 91.1)
The woman has an active bank account	13.6 (7.3 – 21.0)
The woman has a mobile phone used for financial transactions	14.9 (6.4 – 27.0)
The woman has a paid job and participates in the decision of how to spend her earnings	42.3 (26.1 – 53.8)
The partner has a paid job, and the woman participates in the decision of how to spend his earnings	64.0 (38.5 – 79.4)
The woman participates in decisions on major household purchases	69.3 (48.3 – 86.5)
Economic empowerment score	
0	16.3 (3.4 – 26.7)
1	16.1 (9.9 – 22.9)
2	28.4 (24.5 – 33.5)
3	20.8 (12.7 – 31.5)
4	9.5 (3.8 – 12.8)
5	1.7 (0.7 – 5.6)
Basic water in the household	66.7 (55.9 – 89.2)
Basic sanitation in the household	40.1 (20.8 – 59.7)
Basic hygiene in the household	29.1 (15.4 – 51.5)

[1]The percentages represent the median between countries. In parenthesis, we present the limits of the interquartile range.

The women's economic empowerment score had a right-skewed distribution and women with a score 2 were the most frequent: 29.2% (95% CI: 28.9 – 29.6%) (Supplementary Table S3 and Figure 1). Only 3.8% (CI: 3.6 – 3.9%) of the women presented a score 5, while 17.8% (CI: 17.5 – 18.2%) presented score 0. Niger had the lowest average empowerment score, with only 6 of 6,563 women with a score 5, and 68.1% (CI: 65.2 – 70.9%) with a score 0 (Supplementary Tables S1 and S4). South Africa had the highest average score, with 18.0% (CI: 15.4 – 20.9%) of the women in score 5 and only 2.7% (CI: 1.9 – 3.7%) in score 0.

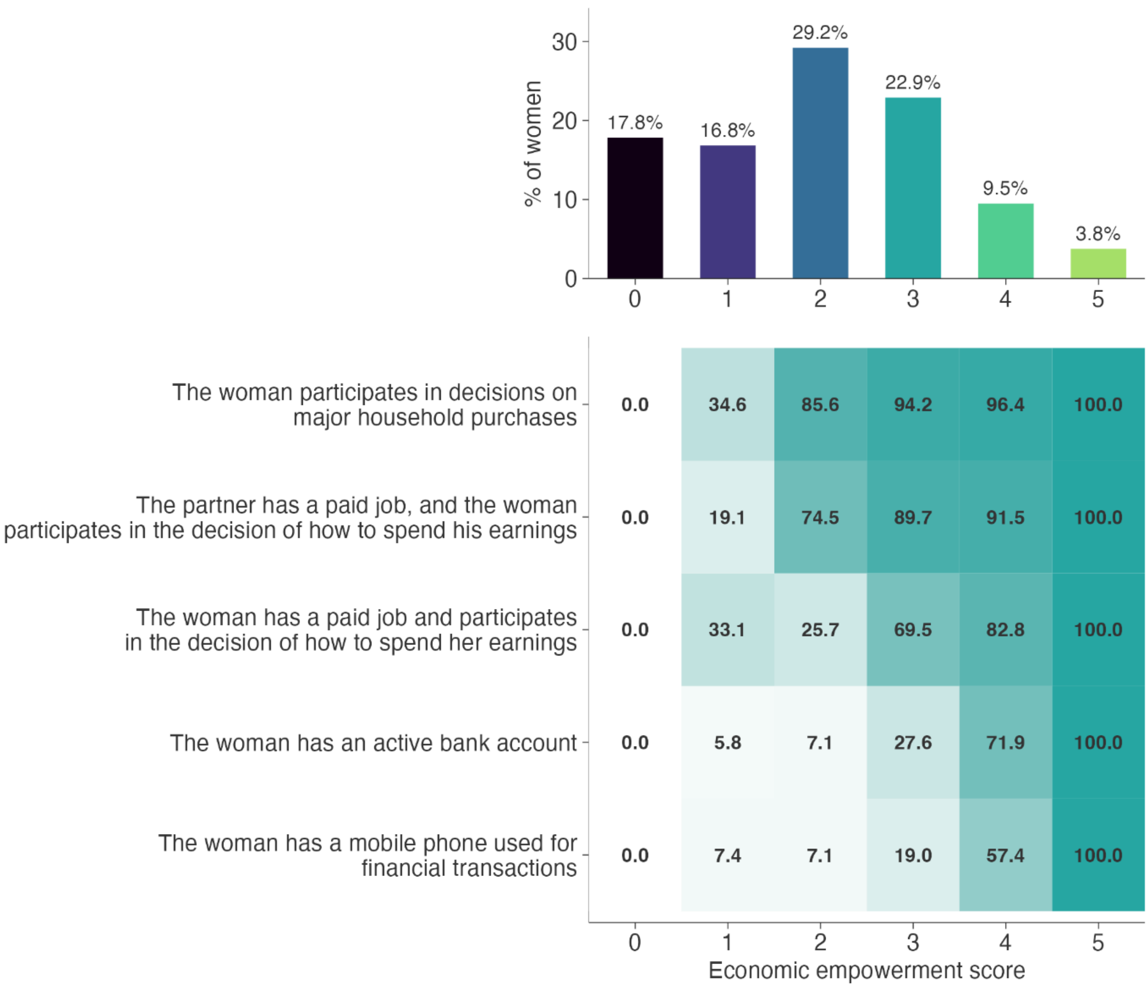

Figure 1 – Pooled distribution of the women's economic empowerment score (top bar plot) and the pooled percentage of women with each component of our score for each score of empowerment (bottom tile plot). Example: 29.2% of all women in the sample had a score of 2 and among those women, 85.6% participated in decisions about major household purchases.

Throughout the empowerment scores, women were more likely to participate in decisions about major household purchases, followed by decisions about her partner's earnings, then their own earnings; they were least likely to have a bank account and a mobile phone used for financial transactions (Figure 1 and Supplementary Table S5). As expected, the empowerment score was significantly greater for urban, wealthier, and more educated women (Supplementary Figures S3–S5 and Supplementary Table S3). Despite this association, women of all empowerment scores were present in all areas of residence, wealth quintiles, and educational levels. For example, 9.5% (CI: 9.0 – 10.1%) of the wealthier women and 2.8% (CI: 2.5 – 3.2%) of women with higher education had the lowest score of economic empowerment.

WASH and women's economic empowerment

More economically empowered women were significantly more likely to live in households with basic WASH in both urban and rural areas, with large inequalities in WASH prevalence throughout (Figures 2–4 and Table S6). In general, a "pro-empowered" pattern of inequality was observed, meaning that women in the higher economic empowerment category had a markedly greater prevalence of basic WASH, compared to women in the lower and intermediate categories.

Comparing the three WASH indicators, basic water in urban areas had the smallest absolute inequalities, with a median SII of 5.5 pp (interquartile range (IQR): 3.2 – 14.9 pp) (Figure 2 and Supplementary Tables S6–7). This is due to the high prevalence of basic water in the urban areas of many countries (15 countries above 90%). Nevertheless, 17 countries still had statistically significant positive SIIs, indicating higher prevalence of basic water among more empowered women. Meanwhile, in rural areas, the prevalence of basic water was significantly lower and absolute inequalities significantly larger. The median SII was 15.3 pp (IQR: 7.2 – 20.4 pp) and 23 countries had significant positive SIIs. Papua New Guinea had some of the largest SIIs for both the urban and rural areas. In urban areas, 67.7% (CI: 49.8 – 81.6%) of women with lower empowerment had basic water, compared to 95.0% (CI: 90.0 – 97.6%) of women with higher empowerment. In rural areas, they were 29.7% (CI: 26.2 – 33.5%) and 78.6% (CI: 69.1 – 85.8%), respectively.

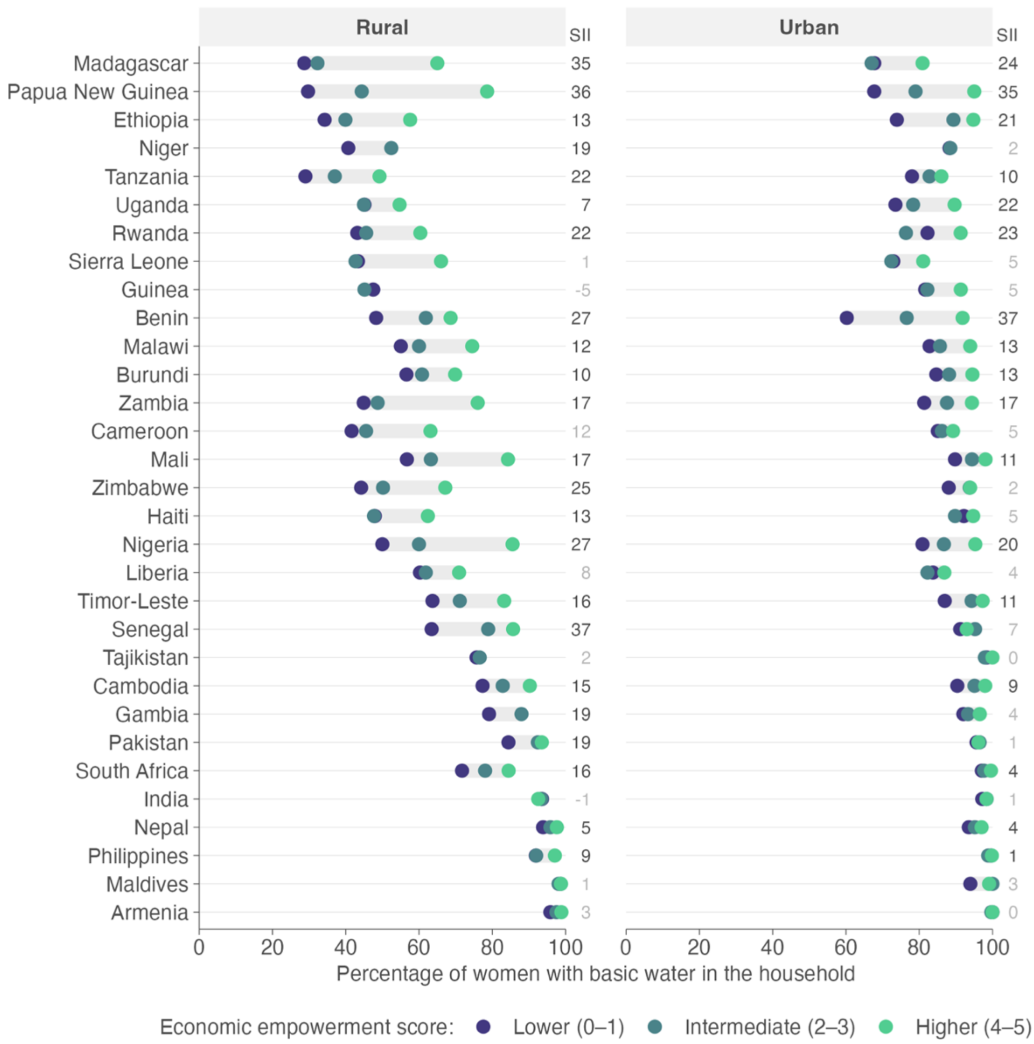

Figure 2 – Percentage of women with basic water in the household in urban and rural areas according to the women's economic empowerment score. The SII (slope index of inequality) represents the difference in basic water prevalence between the most and the least empowered women. Darker text colors indicate statistically significant SII ($p < 0.05$).

The prevalence of basic sanitation was greater in urban areas, and so were absolute inequalities (Figure 3 and Supplementary Tables S6–7). The pro-empowered pattern of inequality was particularly marked, with women in the most empowered category having better access to basic sanitation than the other categories in most countries. In urban settings, the median SII was 21.1 pp (IQR: 10.8 – 35.0 pp) and 23 countries had significant positive SIIs. In rural settings, the median SII was 12.8 pp (IQR: 3.1 – 17.5 pp) and 20 countries had significant positive SIIs. Smaller inequalities were the exception and were mostly found in settings with basic sanitation prevalence close to 0% or 100% (e.g., Tajikistan and Maldives; and the rural areas of Ethiopia and Niger, respectively). Urban areas of Burundi had the highest SII observed for all indicators and countries. The prevalence of basic sanitation was 36.8% (27.9 – 46.7%) for women with lower empowerment and 81.0% (71.6 – 87.7%) for women with higher empowerment.

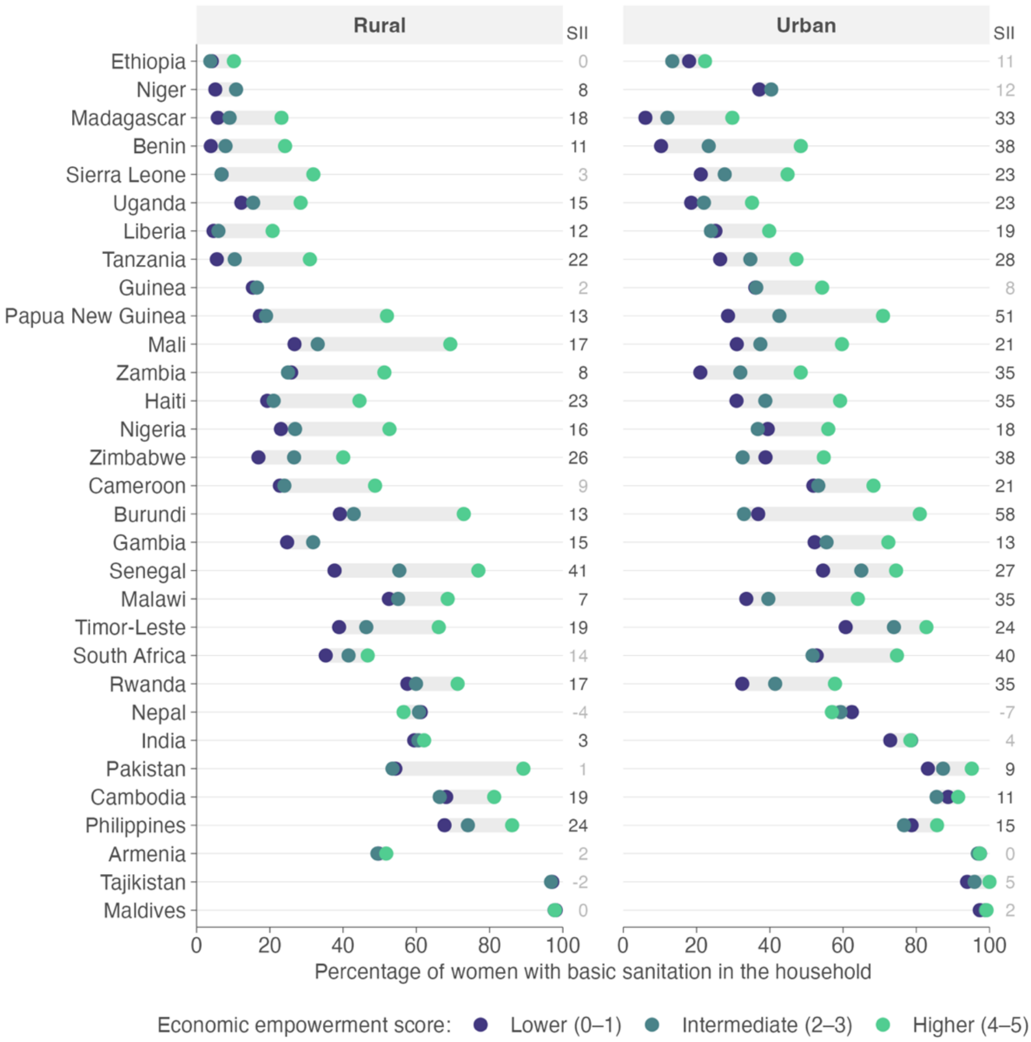

Figure 3 – Percentage of women with basic sanitation in the household in urban and rural areas according to the women's economic empowerment score. The SII (slope index of inequality) represents the difference in basic sanitation prevalence between the most and the least empowered women. Darker text colors indicate statistically significant SII ($p < 0.05$).

Similar to sanitation, the prevalence of basic hygiene was greater in urban areas, and so were inequalities (Figure 4 and Supplementary Tables S6–7). A pro-empowered pattern of inequality was observed, but it wasn't as pronounced as it was for basic sanitation. In urban settings, the median SII was 18.6 pp (IQR: 9.0 – 31.9 pp) and 23 countries had significant positive SIIs. In rural settings, the median SII was 7.6 pp (IQR: 3.0 – 18.3 pp) and 18 countries had significant positive SIIs. This smaller median SII is due to the many countries with low basic hygiene prevalence in rural areas (8 countries below 10%). Similar to water, Papua New Guinea had the largest SIIs for both the urban and rural areas. In urban areas, 49.7% (38.8 – 60.7%) of women with lower empowerment had basic hygiene, compared to 89.1% (83.1 – 93.2%) of women with higher empowerment. In rural areas, they were 19.4% (16.5 – 22.6%) and 65.1% (52.5 – 76.0%), respectively.

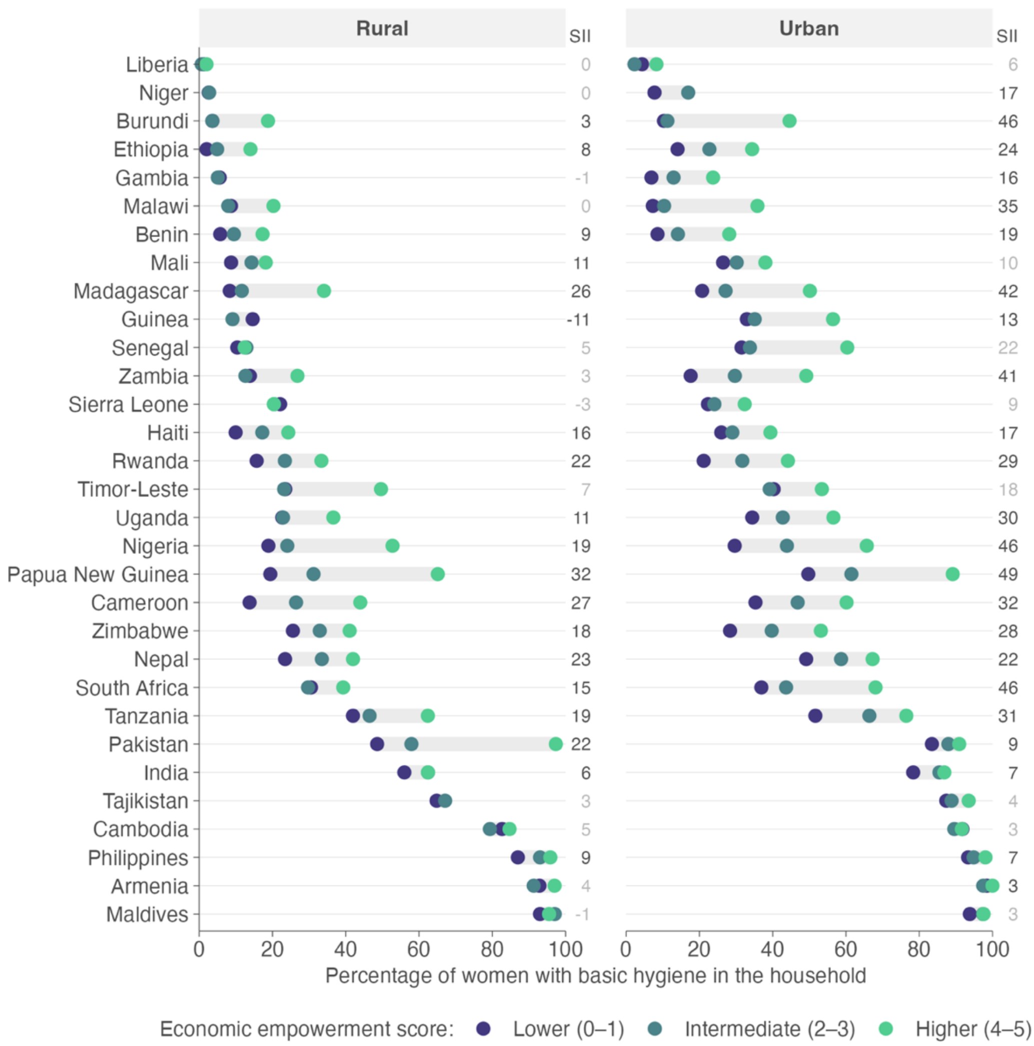

Figure 4 – Percentage of women with basic hygiene in the household in urban and rural areas according to the women's economic empowerment score. The SII (slope index of

inequality) represents the difference in basic hygiene prevalence between the most and the least empowered women. Darker text colors indicate statistically significant SII ($p < 0.05$).

Sensitivity analyses

We repeated the main analyses including only one randomly selected woman in the households with multiples wives from polygynous marriages. Only 3% of our sample was composed of women living with other co-wives and the impact on the results was negligible (Supplementary Table S8).

After statistical adjustment for household wealth and woman's education, the national SIIs were considerably reduced, but remained significant and positive in 17 countries for at least one WASH indicator/area of residence (Supplementary Figure S6). For basic water, significant positive SIIs were still found in the urban areas of only one country and in the rural areas of eight countries. For basic sanitation, it was four and seven countries, respectively. For basic hygiene, three and eight countries, respectively.

Discussion

Our results show that women with greater economic empowerment were considerably more likely to live in households with basic water, sanitation, and hygiene in both urban and rural areas. Large absolute inequalities were observed in multiple countries for all WASH indicators but were even larger for basic sanitation and hygiene. A pro-empowered pattern of inequality was observed, with the most empowered women having greater prevalence of basic WASH. Our results add to the growing body of evidence demonstrating the positive relationship between women's empowerment and household WASH infrastructure.

The women's economic empowerment score addressed both the women's ownership of economic assets and their participation in decision-making related to those assets, using standard questions applied in multiple LMICs. The pooled sample showed a distribution centered around an intermediate score of empowerment, with more than 8,000 women in each score. Women's economic empowerment had a statistically significant correlation with GDI at the country level, suggesting evidence of its validity as measure of women's empowerment. The score was also positively associated to wealth, education, and urban residence, as expected. Nevertheless, all score levels of empowerment were present across all levels of wealth, education, and area of residence. This indicates that even though there was an association with these indicators, it is unlikely that the economic empowerment score is only measuring the same social determinants. Combined, all those characteristics provide evidence of our score's usefulness for investigating inequalities in terms of women's economic empowerment.

The consistent association found in our study between women's economic empowerment and WASH highlights the importance of prioritizing gender in WASH policy, planning, and practice [33]. WASH and women's economic empowerment are desired outcomes in themselves, but both might also be leveraged to achieve each other [15]. For example, a study of a septic tank promotion program in Viet Nam found that households where women led on construction decisions were significantly more likely to later purchase a septic tank [9]. Similarly, a panel study in India found that households where women had control over large purchases were significantly more likely to later build an improved toilet [34]. In Uganda, women were also more likely than men to financially contribute to communally-owned water source maintenance [35]. Regarding WASH leading to empowerment, a study in India found that the installation of piped water coupled with micro-enterprise opportunities for women (like handicrafts, plantations, and dairying) led to the reduction in the time women spent collecting water and an increase in time invested in income-generating activities [36]. It also led to more women having their own savings and participating in water management decisions [36]. In Ghana, a water and sanitation improvement program also led to women spending less time collecting water (from 6 hours per day to 1 hour per day) and spending more time on education (almost +1 hour per day) and economic activities (almost +2 hours per day) [37]. Collectively, these initiatives indicate that WASH and women's economic empowerment act symbiotically, and may be employed to mutually enhance each other, given the right approach.

There is a substantial body of gender-sensitive evidence in WASH research, meaning that it is conducted in awareness of gender norms, roles, and relations [15]. Nevertheless, gender-transformative research – i.e., that addresses the causes of gender-based inequalities and help to transform damaging gender norms, roles, and relations – is still lacking [15,38]. More specifically, there is a gap in WASH research that directly addresses women's empowerment with a clear definition and conceptualization of the term [15]. We have tried to address this gap and also complement the evidence provided by many qualitative and local studies [14,39–41] with our multicountry quantitative study. Our results are aligned with existing literature and highlight the prevailing gender-based inequalities in WASH access. They also represent an opportunity for gender-transformative WASH interventions that can leverage women's economic empowerment to improve WASH and vice versa. That should include not only economic resources – such as those provided by cash transfer programs that target women – but also structural changes that address the power imbalance between men and women over decision making in the household [42].

There are limitations to our research. Our sample was restricted to women who were married or in union, removing a relevant number of women from our analysis and reducing its external validity. Furthermore, the association between women's economic empowerment and WASH we found does not establish a causal relationship. Due to the cross-sectional nature of the surveys, the association found could be due to: 1) women's economic empowerment leading to better WASH in the household; 2) better WASH leading to improvement in the women's economic empowerment; 3) confounding caused by wealth, education and other factors, that lead to both greater empowerment and better WASH. Under SDGs 5 and 6, situations 1 and 2 represent synergistic targets for action that could lead to both women's economic empowerment and better WASH. However, situation 3 leads to overestimation of the association between women's economic empowerment and WASH and it is likely to be present in our research. After adjusting for wealth and education, inequalities were considerably reduced, but did not disappear. It is important to note that wealth and education are also possible mediators in the association women's economic empowerment and WASH. Therefore, adjusting for these variables can also underestimate this association and adjusted inequalities should be interpreted with caution. The adjustments were applied as an exercise to examine how much the association depends on household wealth and women's education, rather than to obtain a more accurate measure of the association. It is not possible to separate those effects using only cross-sectional data. Further well-structured longitudinal studies are necessary to investigate both the directionality and confounding structure in this relationship.

Using highly comparable, nationally representative samples of 31 LMICs, we developed a women's economic empowerment score that allowed us to investigate its relationship with basic WASH in the household. We have shown that more empowered women are more likely to live in households with basic WASH in both urban and rural areas, with large inequalities throughout. Under SDG 5 and 6, this represents an opportunity for combined efforts to achieve gender equality and ensure that women have equal access to economic resources and power to make decisions; at the same time as achieving universal access to safe WASH, eliminating the disproportionate effect its inadequacy has on women and girls.

Conflict of Interest

All authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Data statement

All the analyses were carried out using publicly available datasets that can be obtained directly from the DHS website (dhsprogram.com). Datasets are continuously sourced and updated by the International Center for Equity in Health (equidade.org) as they are released.

Ethics statement

The organizations who administered the surveys were responsible for ethical clearance according to the norms of each country.

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Supplementary Materials

Supplementary tables are available at:

https://docs.google.com/spreadsheets/d/1Kbv571cQsntcFO2_xkERJ2jE4JqWIBgN

Survey weighting

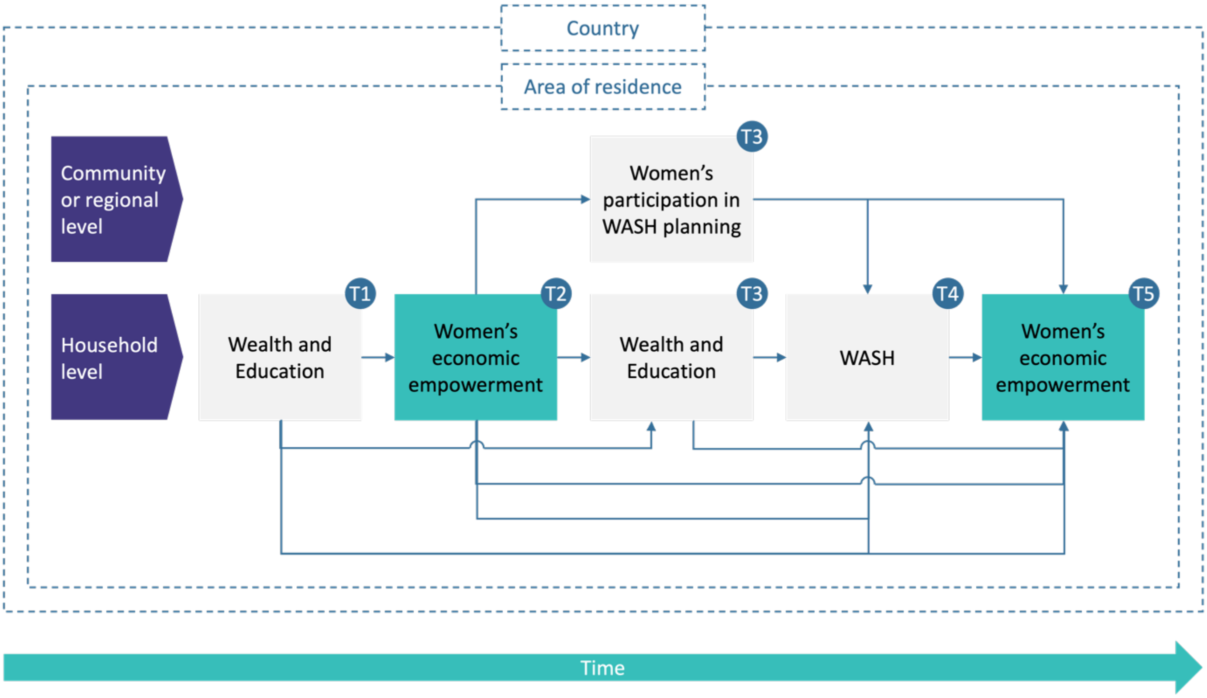
For our pooled analyses, we combined all countries together into one single dataset. We recalculated the sample weights using Equation S.1:

$$w_{ij,adj} = \left(\frac{w_{ij}}{\sum_i w_{ij}}\right)\left(\frac{N_W}{N_C}\right)$$

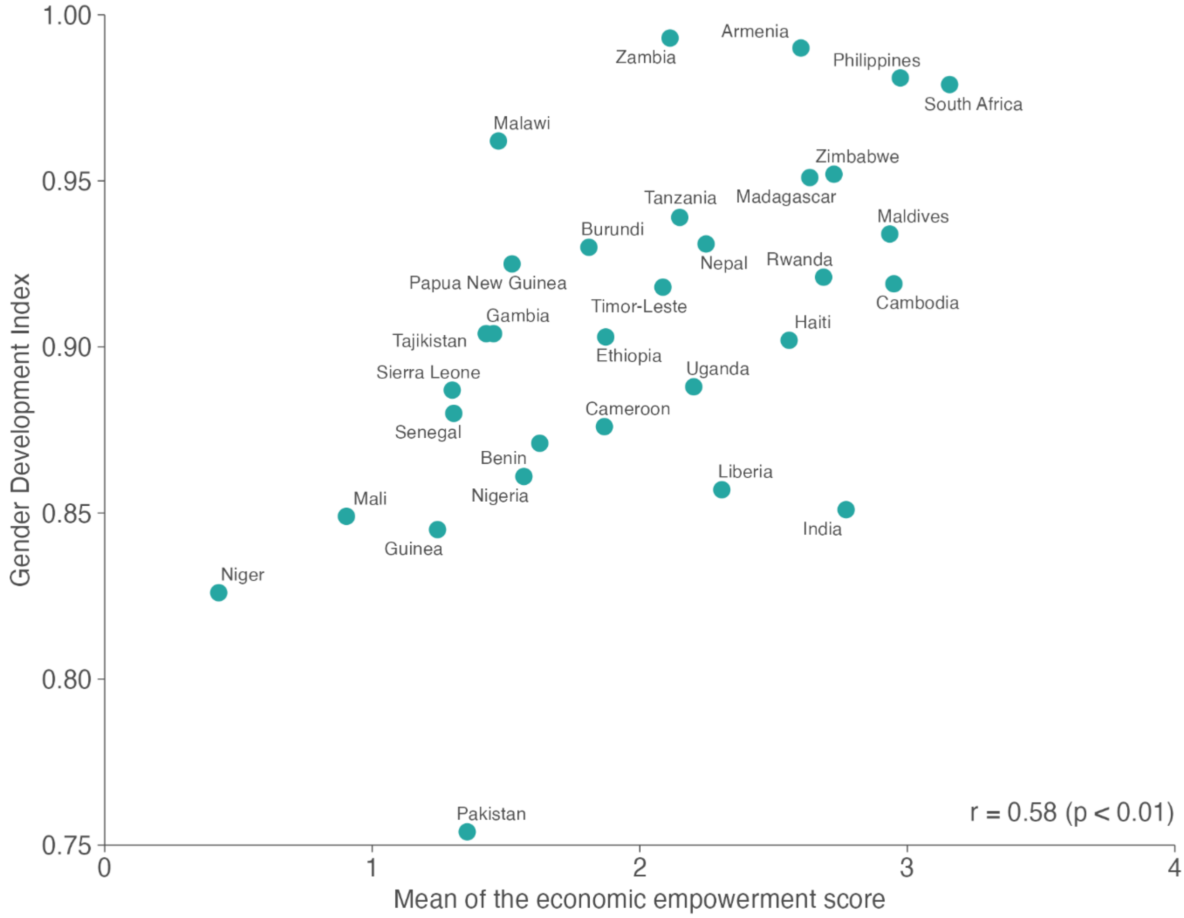
where:

- i indicates a woman and j a country
- $w_{ij,adj}$ is the adjusted sample weight
- w_{ij} is the original sample weight
- N_W is the total number of women in the sample
- N_C is the total number of countries in the sample

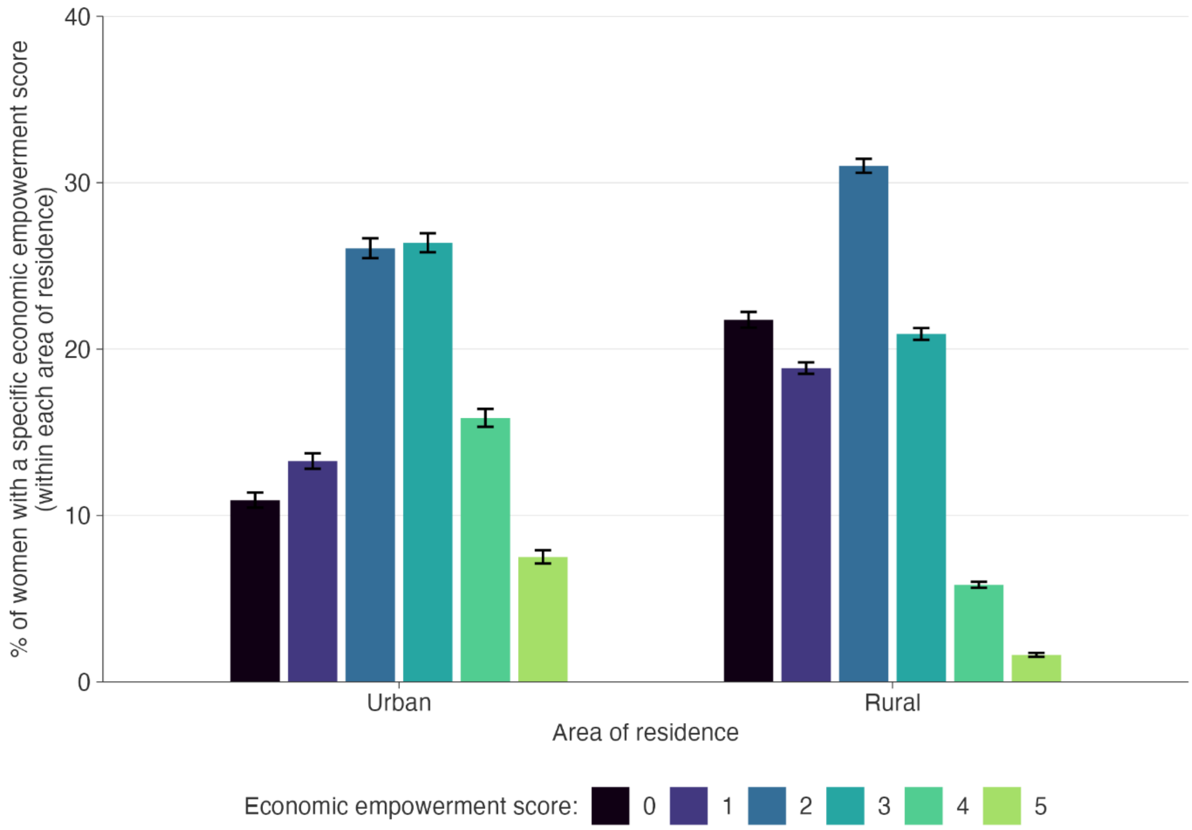
Supplementary figures



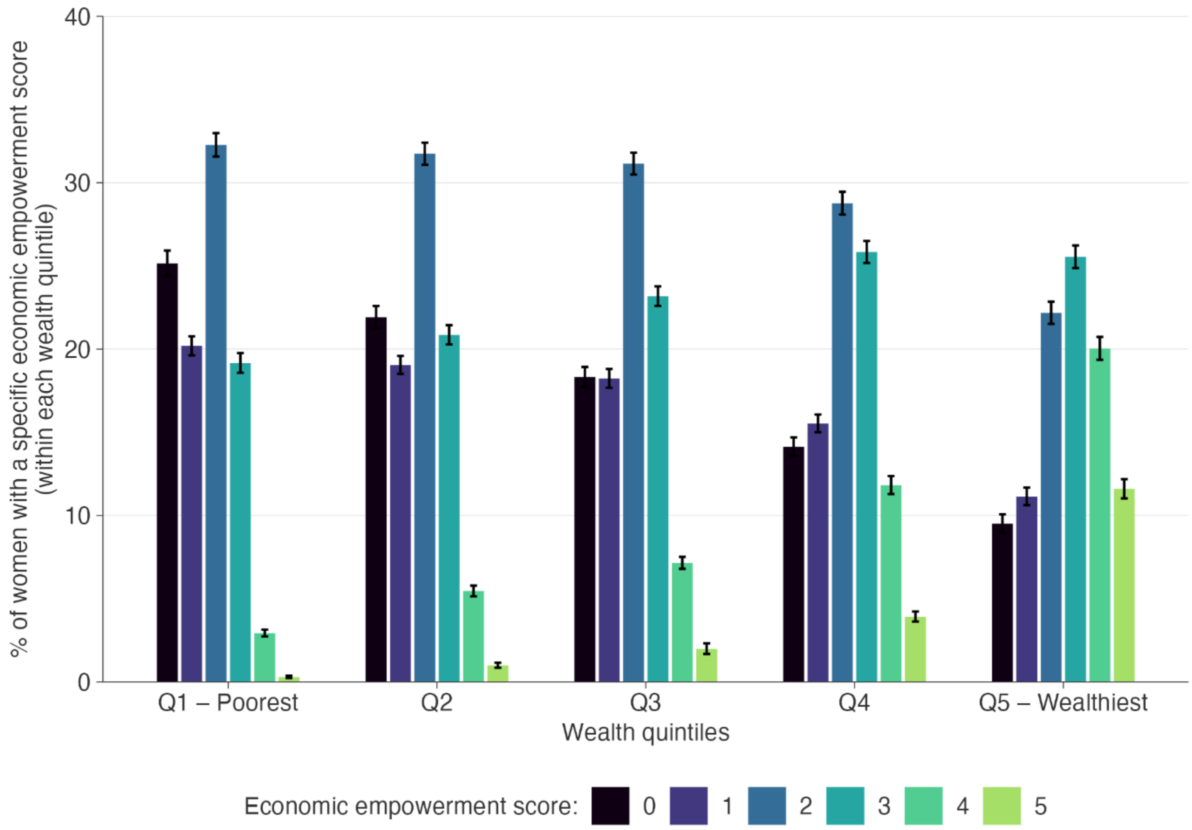
Supplementary Figure S1 – Conceptual model for relationship between women's economic empowerment and WASH in the household. Indicators are theoretically measured at different points in time, following the direction of the woman's life course (unlike in our study, where we used cross-sectional data). These are indicated by the blue circles at the top-right corners of the rectangles. Wealth and education are measured at both T1 and T3. T1 indicates that they were measured before T2 – the time of the first measurement of women's empowerment – and T3 is after.



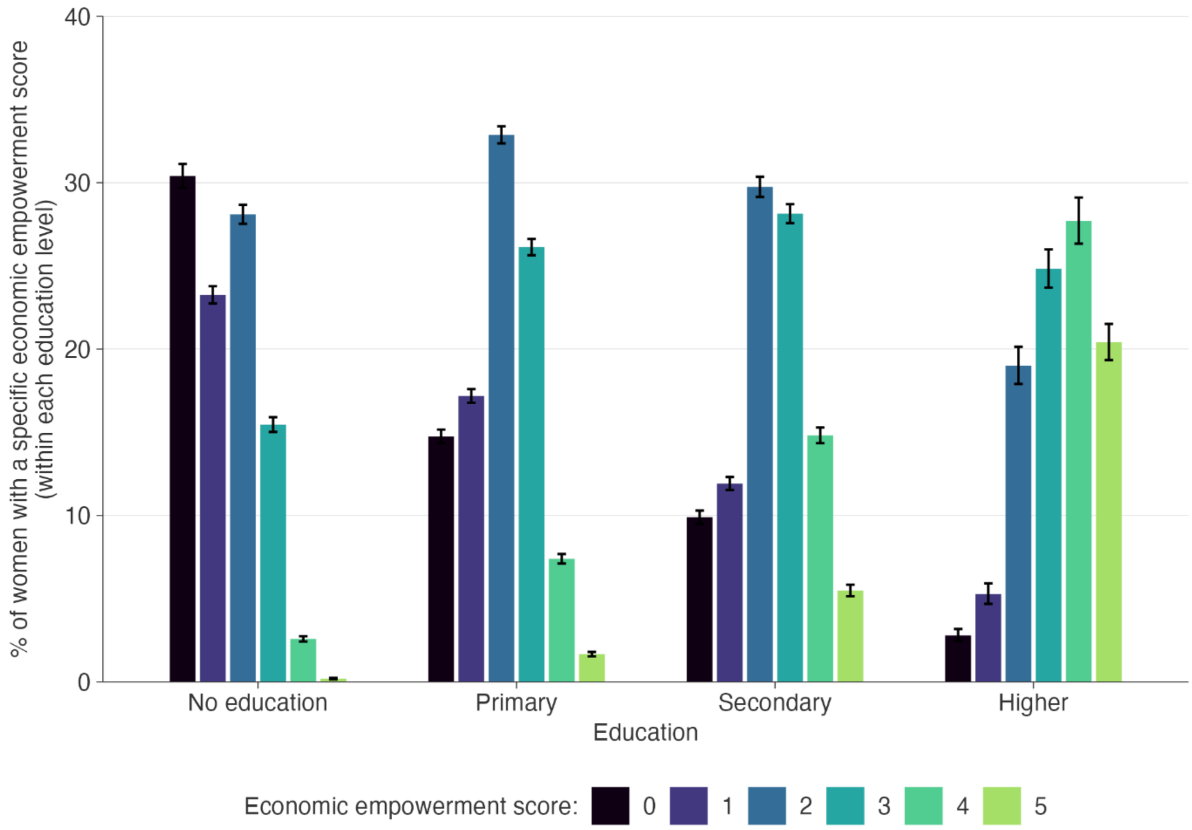
Supplementary Figure S2 – Association between the mean of the economic empowerment score and the Gender Development Index (2017). The Spearman correlation coefficient (r) is presented at the bottom right of the plot.



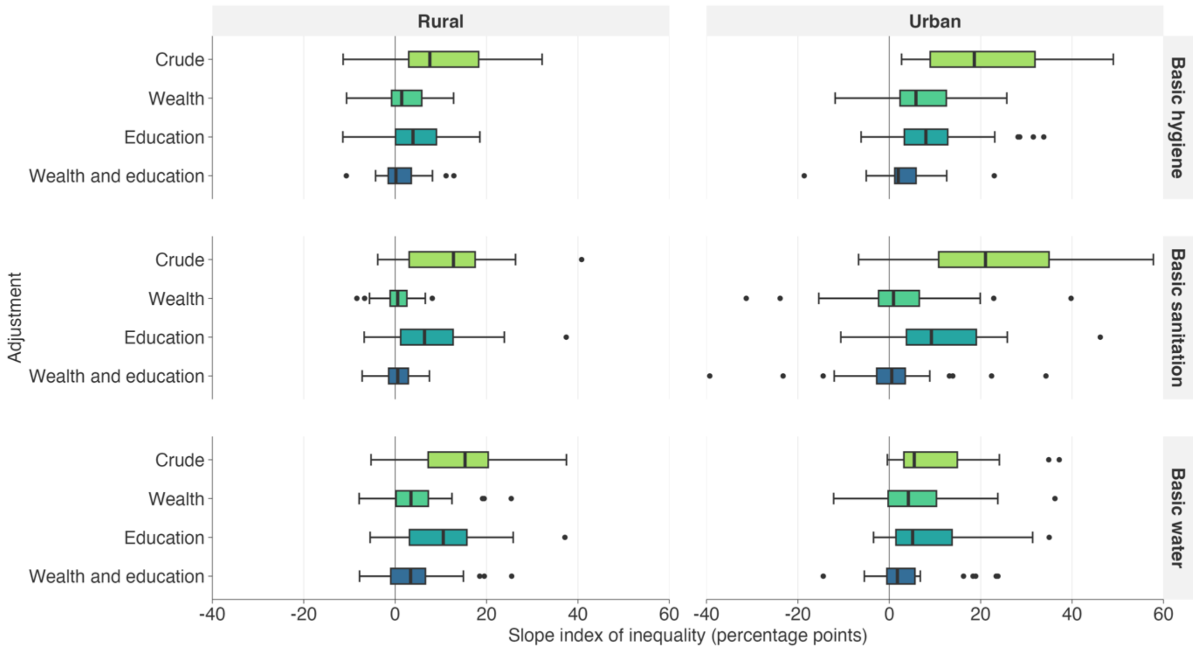
Supplementary Figure S3 – Distribution of the women's economic empowerment score according to area of residence



Supplementary Figure S4 – Distribution of the women's economic empowerment score according to wealth quintile



Supplementary Figure S5 – Distribution of the women's economic empowerment score according to education level



Supplementary Figure S6 – Distribution of the slope index of inequalities for different adjustments and areas of residence. The unit of analysis is the countries.

6. Research Article 3

To be submitted to the Journal of Global Health

Combined coverage of water, sanitation, and hygiene services: an equity analysis of 32 nationally representative household surveys (2017–2021)

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Abstract

Background

The United Nations set a global target of universal and equitable access to adequate water, sanitation, and hygiene (WASH) by 2030. It is unlikely that the world will reach that target, with rural, poor and other vulnerable populations often left behind. WASH services are routinely monitored individually, even though they are intrinsically connected, and each can impact the others. Our goal was to investigate the combined coverage of WASH services using nationally representative household surveys and to explore inequalities between and within countries.

Methods

We investigated 68,444 households in 32 countries using data from Multiple Indicator Cluster Surveys. We developed an indicator ("full WASH"), based on a household having: 1) safely managed water: drinking water from an improved source that is accessible on premises, available when needed, and free from fecal contamination; 2) safely disposed sanitation: an improved sanitation facility, that is not shared with other households and is connected to a sewer or safely disposed/removed; and 3) basic hygiene: a handwashing facility with soap and water. We calculated full WASH prevalence per country and all countries combined, stratified according to area of residence, wealth quintiles, and subnational regions.

Findings

Only 16.7% of households had access to full WASH, and safely managed water was the critical constraint. Individual countries followed one of two patterns: either very few households with access to full WASH (<10%), or a highly unequal distribution of full WASH, according to area of residence, wealth, or subnational regions. Urban areas had higher prevalence (23.0%) than rural areas (13.1%), and the wealthiest households also had higher prevalence (31.1%) than the poorest (4.9%). The prevalence of full WASH varied significantly in the subnational regions of 21 countries.

Conclusions

Improving WASH services is an essential step in reducing poverty and promoting equality and socio-economic progress. Despite this, full WASH coverage was low and markedly unequal, with the most vulnerable being left behind. Our results document the substantial challenges faced by countries and communities – especially those in low-resource settings – towards ensuring access to WASH for all (Sustainable Development Goal 6).

Keywords

Drinking Water; Sanitation; Hygiene; Health Inequities; Global Health

Introduction

The United Nations' 2030 Agenda for Sustainable Development set ambitious targets for achieving universal and equitable access to adequate water, sanitation, and hygiene (WASH) as part of the Sustainable Development Goal (SDG) 6.[1] The world is not on track to achieve those targets.[2] In 2022, 27% of the world population still lacked safely managed water, 43% lacked safely managed sanitation, and 25% lacked basic hygiene services.[2] To achieve universal access by 2030, the current rates of improvement would need to be increased by sixfold for safely managed water, by fivefold for safely managed sanitation, and by threefold for basic hygiene.[2] The regional distribution of those services is also highly unequal, with Sub-Saharan Africa and Small Island Developing States consistently lagging behind most other countries.[2]

Water, sanitation, and hygiene are often monitored individually,[1–3] and there is a scarcity of studies that investigate their combined coverage[4–6] despite the fact that WASH services are intrinsically connected. For example, from the household water source to the point of use, drinking water contamination can occur due to inadequate sanitation infrastructure in the household's vicinity or where the water source is located and due to poor water handling and hygiene practices.[7,8] Similarly, some of the more advanced sanitation facilities – like flush toilets – rely on the continuous influx of water for proper functioning. Finally, hygiene infrastructure and behaviors can also be affected by water availability and by the type of sanitation facility in use.[9–11] Therefore, the combined presence of adequate WASH services in the same household represents an optimum scenario under SDG 6.[1,5]

The World Health Organization and United Nations Children's Fund Joint Monitoring Programme for Water Supply, Sanitation and Hygiene (JMP) is responsible for reporting global WASH progress.[2] The JMP has developed WASH service ladders that provide benchmarks for different levels of service and can be used to monitor a country's progress of SDG 6.[2] At the household level, three WASH indicators are used to represent the top level of service in those ladders: safely managed water, safely managed sanitation and basic hygiene services. A household with safely managed water has drinking water from an improved source that is accessible on premises, available when needed and free from fecal contamination.[2] A household with safely managed sanitation uses improved sanitation facilities that are not shared with other households and where excreta are safely disposed of on-site or removed and treated elsewhere.[2] A household with basic hygiene has a handwashing facility with soap and water.[2]

Many countries lack the necessary systems to continuously monitor WASH indicators and often rely on household surveys for data collection. These surveys represent an important source of information for national estimates, and allow disaggregated analyses used to explore inequalities in their coverage. More specifically, safely managed water and basic hygiene can be monitored using household survey data; however, not all components of safely managed sanitation can be monitored with these surveys. Household surveys can provide information about the type of sanitation facility being used, and excreta containment, emptying and on-site disposal.[12] However, they are less reliable in terms of off-site treatment, as these processes take place away from the household and survey participants may not be able to provide reliably reports.[12]

In 2017, the Multiple Indicator Cluster Surveys (MICS) implemented a standardized water quality module in their household surveys.[7] It includes the measurement of *Escherichia coli* (*E. coli*) contamination in drinking water, as well as all the questions necessary for estimating safely managed water and basic hygiene coverage.[13] MICS also included an extended version of the sanitation questionnaire, measuring many components of the safely managed sanitation indicator, except off-site excreta treatment.[13] By collecting information on the three WASH services, it presents an opportunity for a more detailed and holistic exploration of those services within the same households.

The aims of this paper were to estimate the combined coverage of WASH services in countries with MICS surveys, and to quantify inequalities between countries, areas of residence (urban/rural), wealth quintiles, and subnational regions. The study of combined WASH coverage can aid in tracking progress toward SDG 6, as well as help policymakers and organizations to design more comprehensive public health interventions that consider the interactions between WASH infrastructures.

Methods

Data sources and study sample

We identified all MICS surveys that included the water quality module and were publicly released until 29 February 2024.[14] We then selected the surveys with all the questions necessary for calculating the full WASH indicator (definition below). If more than one survey was available for the same country, we selected the most recent survey. Our unit of analysis was the household.

WASH indicators

The full WASH indicator was defined as a household having safely managed water, safely disposed sanitation, and basic hygiene at the same time – and was based on the JMP's WASH service ladders and MICS standard indicators.[2] Safely managed water was defined as a household having all the following:

- Improved water source: if the household's drinking water source was piped water, borehole, tubewell, protected dug well, protected spring, rainwater, packaged water, or delivered water.[2]
- Water available when needed: if the household always had enough drinking water during the previous month.
- Water accessible on premises: if the household's drinking water source was 1) located in the dwelling, yard, or plot; or 2) located elsewhere, but the household members did not collect water themselves.
- Water free from fecal contamination: if a sample from the household's main drinking water source was free from *E. coli* contamination.[13] In summary, a 100 ml sample is collected at the water source. The field tester draws 1 ml from the sample and uses it to hydrate a growth media plate. The rest of the sample is filtered with a 0.45-µm filter membrane, the water is discarded, and the filter is plated on the growth media plate. The plate is then incubated for 24–48 hours at 25–40 °C. An enzyme substrate in the plate gives a blue color to *E. coli* colonies. After incubation the field tester counts the number of blue colonies and writes it down in the questionnaire.[15,16] We considered the sample free from fecal

contamination if no colonies were detected. A more detailed description of the water testing procedure is available elsewhere.[16,17]

The safely disposed sanitation indicator was created based on the JMP's safely managed sanitation indicator. The difference between the two is that the safely disposed sanitation indicator does not include information related to off-site excreta treatment, since it is not available in MICS. Safely disposed sanitation was defined as a household having all the following:

- Improved sanitation facility: if the household's sanitation facility was a flush and pour-flush toilet connected to a piped sewer system, septic tank or pit latrine; a ventilated improved pit latrine; a pit latrine with slab; a composting toilet; or container based sanitation.[2,18]
- Not shared sanitation facility: if the sanitation facility was only used by household members.
- Connected to sewer or safely disposed/removed: if the household had 1) a flush or pour flush sanitation facility connected to a piped sewer system; or 2) other improved on-site sanitation facilities whose contents were safely disposed of in situ or removed for treatment off-site.[2] A more detailed description is presented in Figure S1 of the Supplementary Materials.

Basic hygiene was defined as a household having all the following:

- Has handwashing facility: if the interviewer observed a handwashing facility in the dwelling, yard, or plot.
- Has water for handwashing: if the interviewer observed the presence of water at the handwashing facility.
- Has soap/detergent for handwashing: if the interviewer observed the presence of soap or detergent at the handwashing facility. Ash, mud, or sand were not included.

Equity stratifiers

We determined the prevalence of full WASH and its three components (safely managed water, safely disposed sanitation, and basic hygiene) according to the household's area of residence, wealth quintiles, and subnational regions. The area of residence (urban/rural) is based on each country's definition, as provided in the MICS surveys. This usually takes into account population density but can also include other indicators, such as the percentage of the population working in agriculture.[19,20] The wealth quintiles are created by MICS using principal component analysis of household characteristics (such as type of flooring) and ownership of assets (such as television).[21] Separate analyses are performed for urban and rural areas, and a composite score is created by scaling the urban and rural scores.[22] The composite score is then used to classify households into five wealth quintiles, the first containing the 20% poorest, up to the fifth with the 20% richest in the sample.

Statistical analyses

We calculated the prevalence of each indicator and its respective 95% confidence intervals (95% CI) for each country and all countries combined. We also calculated the national and pooled prevalence stratified by area of residence, wealth quintile, and subnational region. We only calculated the prevalence for groups with at least 25 households. To evaluate the statistical significance of the difference in prevalence across the levels of each stratifier, we conducted univariate logistic regressions and Wald tests.

All analyses considered the complex survey design, including sample weights, clusters, and strata. For the pooled analyses, we recalculated the survey weights to make them proportional to each country's national population in 2019 (the median year).[23] The pooled analyses are equivalent to the weighted mean of the national results, using the country's population as the weight. The weight calculation is further described in the Supplementary Materials.

We created a global map of the full WASH subnational prevalence using shapefiles provided by the geoBoundaries Global Administrative Database[24] and the Natural Earth project.[25] Survey regions were adjusted to match those provided in the shapefiles. All analyses were performed in R (version 4.3.1, R Foundation for Statistical Computing, Vienna, Austria) and in Stata (StataCorp, 2023, Stata Statistical Software: Release 18, College Station, TX: StataCorp LLC).

Results

We included 68,444 households from 32 countries with surveys conducted between 2017 and 2021 (Supplementary Table S1). Twelve countries were from Sub-Saharan Africa; five from Latin America and the Caribbean, Northern Africa and Western Asia, and Oceania each; three from Eastern and South-Eastern Asia; and two from Central and Southern Asia.[26]

In the pooled sample, only 16.7% (16.0 – 17.5%) of households had access to full WASH (Figure 1 and Supplementary Table S2). Safely managed water was the critical constraint in achieving full WASH coverage, which, in turn, was mainly constrained by having water accessible on premises and free from fecal contamination (Figure 1 and Supplementary Figure S2). Across all countries, 27.6% (26.6 – 28.7%) of households had safely managed water, 53.5% (51.8 – 55.2%) had safely disposed sanitation, and 57.7% (56.5 – 58.8%) had basic hygiene.

Results varied substantially between countries for all indicators (Figure 1 and Supplementary Table S2). The full WASH prevalence varied from 0.1% (0.0 – 0.4%) in the Democratic Republic of Congo to 45.5% (42.2 – 48.8%) in Georgia. Safely managed water varied from 1.1% (0.6 – 2.2%) in the Central African Republic to 56.2% (52.8 – 59.5%) in Georgia. Safely disposed sanitation had the largest amplitude out of all indicators: from 6.3% (5.2 – 7.7%) in Madagascar to 94.7% (92.1 – 96.5%) in Samoa. Similarly, basic hygiene coverage varied from 11.2% (8.8 – 14.1%) in Lesotho to 97.3% (96.6 – 97.9%) in Iraq.

The pooled prevalence of full WASH was significantly higher in urban areas compared to rural areas: 23.0% (21.9 – 24.1%) and 13.1% (12.2 – 14.1%), respectively (Figure 2 and Supplementary Table S2). The largest inequality was observed for Georgia, where 64.4% (59.1 – 69.4%) of urban households had full WASH compared to only 18.1% (15.1 – 21.5%) of rural households. Out of 19 countries with significant differences, 17 had higher prevalence in urban areas and only the State of Palestine and Turks and Caicos had higher prevalence in the rural areas. The pooled prevalence of safely managed water, safely disposed sanitation, and basic hygiene were also significantly higher in urban areas compared to rural areas: 32.2% (31.0 – 33.5%) vs. 25.0% (23.6 – 26.5%); 67.5% (66.2 – 68.8%) vs. 45.4 (43.2 – 47.6%); and 73.9% (72.6 – 75.1%) vs. 48.3% (46.9 – 49.7%), respectively (Supplementary Figures S3–5 and Supplementary Table 2).

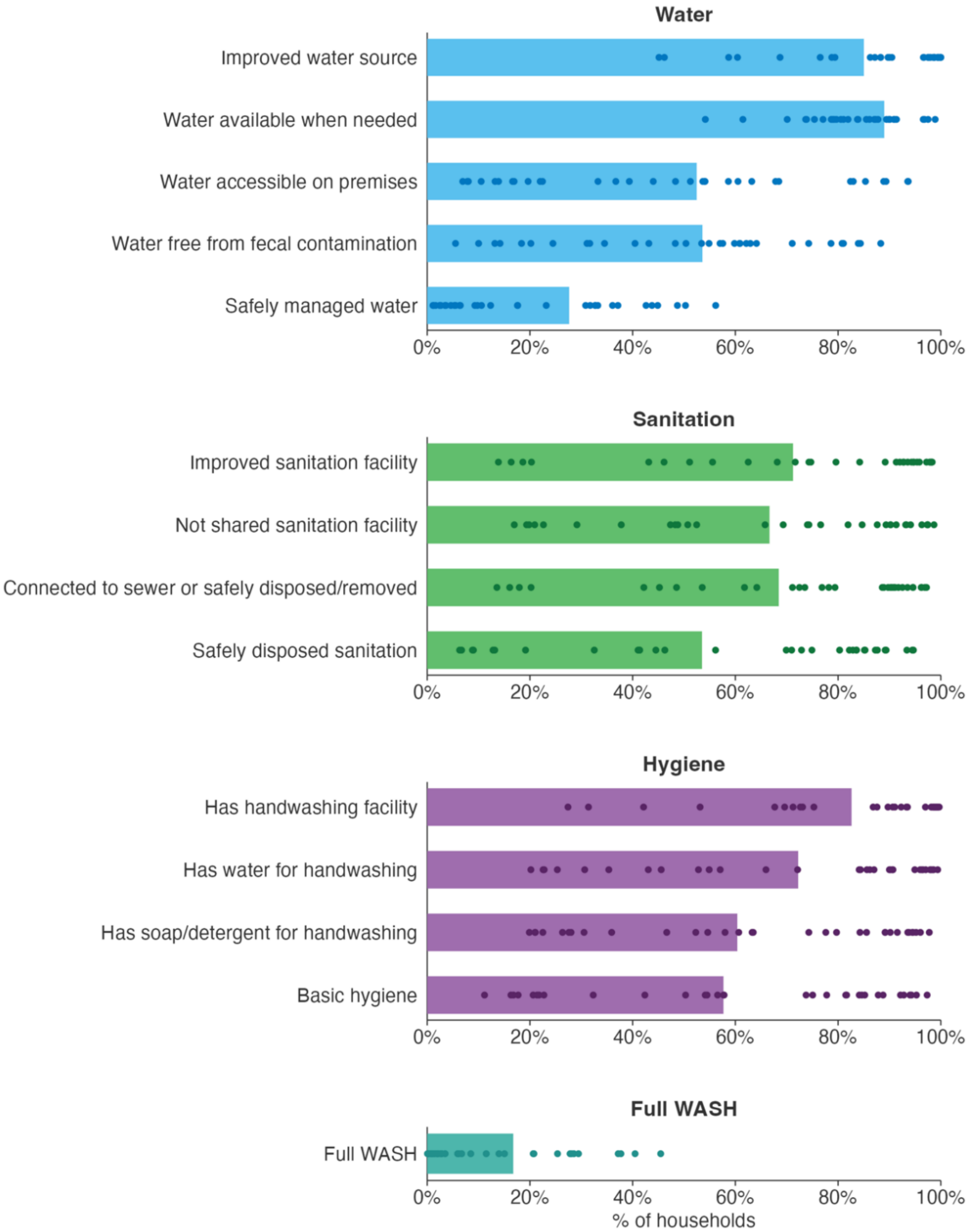

Figure 1 – Prevalence of the fourteen WASH indicators. Water contamination refers to contamination at the source where water is collected. The bars represent the pooled prevalence, and each dot represents a country.

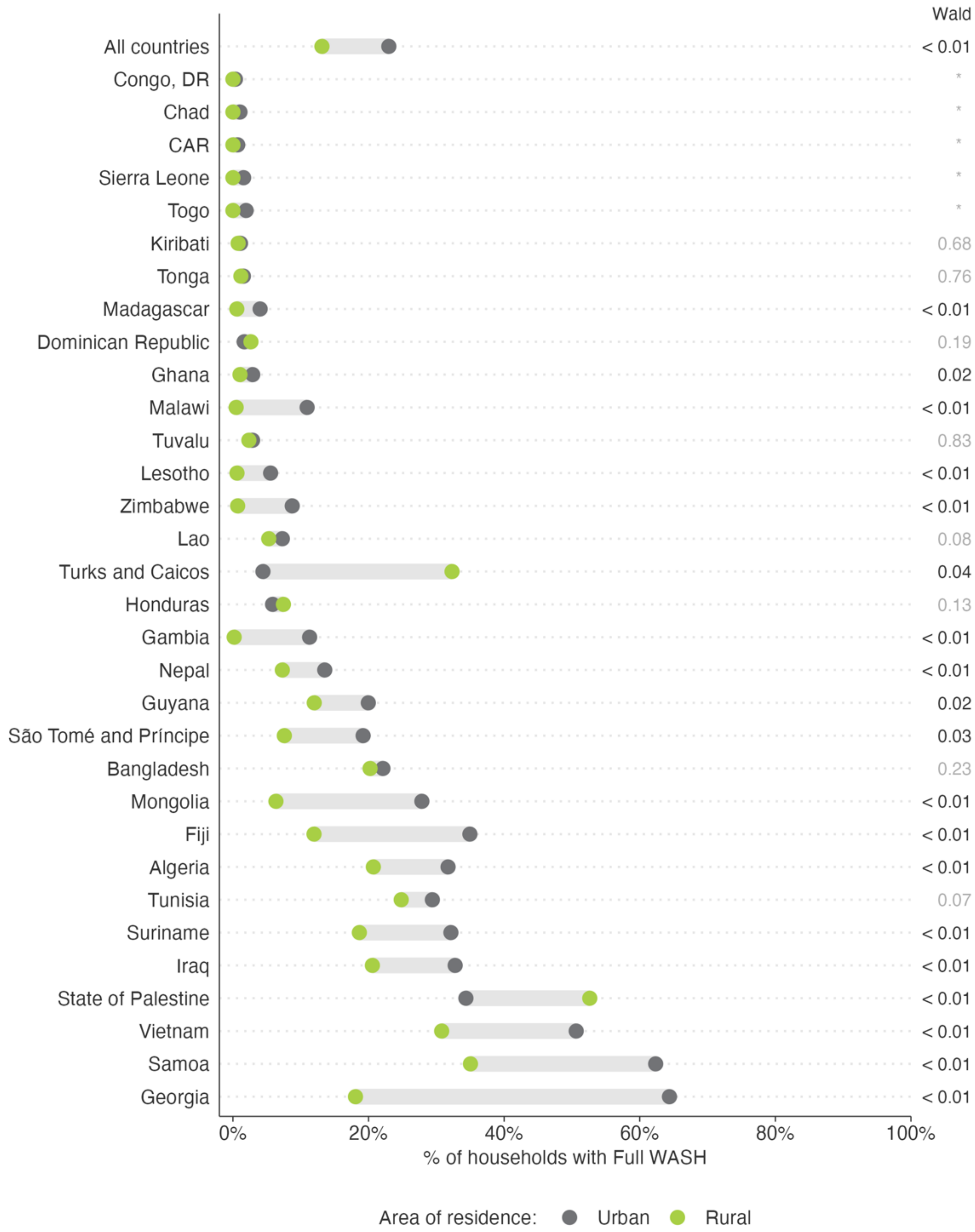

Figure 2 – Percentage of households with access to full WASH, according to area of residence (urban/rural). The p value of the Wald test of heterogeneity between areas is presented on the right. Darker text colors indicate statistically significant results ($p < 0.05$).

* p value could not be calculated because one of the areas had zero households with full WASH

The pooled prevalence of full WASH was significantly higher for wealthier households compared to poorer households: 4.9% (4.3 – 5.7%) for the poorest wealth quintile, 12.1% (10.8 – 13.4%) for the second, 17.1% (15.6 – 18.6%) for the third, 21.5% (20.1 – 22.9%) for the fourth and 31.1% (29.5 – 32.8%) for the wealthiest (Figure 3 and Supplementary Table S2). The largest absolute inequality between the wealthiest and the poorest was observed for Iraq, where 65.3% (59.4 – 70.7%) of the wealthiest households had full WASH compared to only 5.3% (3.0 – 9.2%) of the poorest households. Different patterns of inequality were observed among countries with significant inequalities. A linear pattern was present in countries like Samoa and Bangladesh, with prevalence increasing by a comparable amount for each wealth quintile. A top pattern of inequality was observed for countries like Gambia and São Tomé and Príncipe, with the wealthiest quintile having a much higher prevalence than all the other quintiles. For example, in Gambia, 34.6% (27.5 – 42.4%) of households in the wealthiest quintile had full WASH compared to only 1.9% (0.6 – 5.7%) in the fourth quintile. Finally, in Tunisia, an "inverted U-shape" pattern was present, with higher prevalence in the middle quintiles compared to the poorest and wealthiest. The pooled prevalence of safely managed water, safely disposed sanitation, and basic hygiene all followed a pattern similar to full WASH in the pooled sample, increasing monotonically with wealth (Supplementary Figures S6–8 and Supplementary Table 2).

The prevalence of full WASH varied significantly in the subnational regions of 21 countries (Figure 4, Supplementary Figure S9, and Supplementary Table S2). The eleven countries where the differences were not statistically significant were either in Sub-Saharan Africa or were island nations (Kiribati, Tuvalu, and Turks and Caicos) and had a median prevalence of only 0.9% (interquartile range: 0.5 – 2.7%). The country with the largest amplitude in prevalence was Iraq, varying from 1.7% (0.7 – 3.9%) in the Thiqar Governorate to 80.1% (71.2 – 86.8%) in the Sulaimaniya Governorate. In fact, the Sulaimaniya Governorate had the highest prevalence out of all regions in the sample. Even though Georgia had the highest national prevalence, the region of Guria in the western part of the country had a prevalence of only 12.8% (8.5 – 18.9%), compared to Tbilisi (the capital) with a prevalence of 67.1% (58.3 – 74.8%). The prevalence of safely managed water, safely disposed sanitation, and basic hygiene varied significantly in the subnational regions of 26 countries (Supplementary Figures S10–12 and Supplementary Table S2).

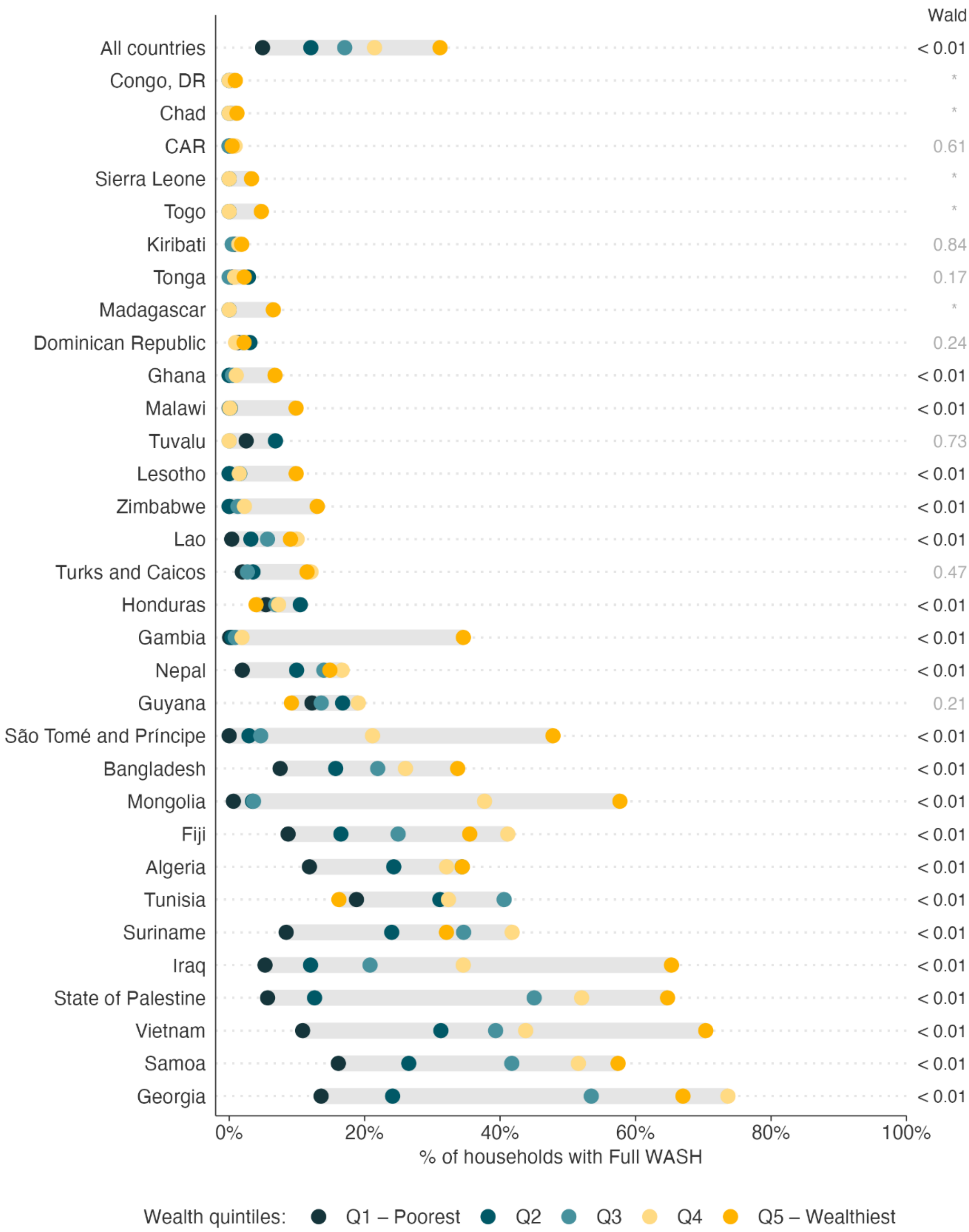

Figure 3 – Percentage of households with access to full WASH according to wealth quintiles. The p value of the Wald test of heterogeneity between quintiles is presented on the right. Darker text colors indicate statistically significant results (p < 0.05).

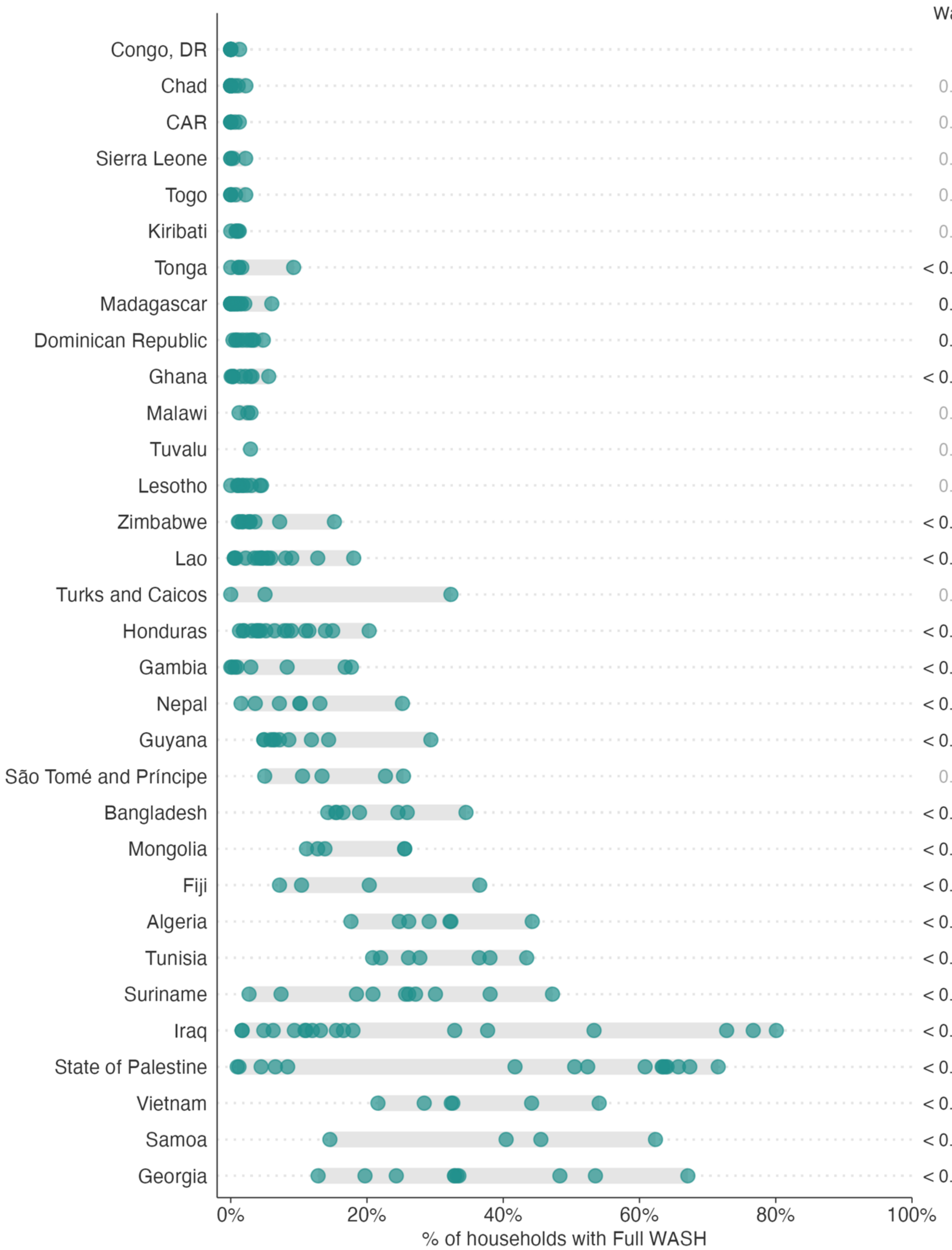

Figure 4 – Percentage of households with access to full WASH according to subnational regions. Each dot represents a region. The p value of the Wald test of heterogeneity between regions is presented on the right. Darker text colors indicate statistically significant results ($p < 0.05$).

[*] p value could not be calculated because all but one regions had zero households with full WASH

Discussion

The 32 countries in our sample are far from achieving universal access to full WASH, with two distinct patterns being observed. Approximately half of the countries had very few households with access to full WASH, concentrated in Sub-Saharan Africa or island nations. The other half had highly unequal distributions of full WASH, according to area of residence, wealth, or subnational regions. The highest coverage of full WASH among the poorest quintile was observed in Tunisia (only 18.8%). Both patterns highlight the substantial challenges faced by these countries, communities, and households towards achieving SDG 6, especially those in low-resource settings.

Improving WASH services is an essential step in reducing poverty and promoting equality and socio-economic progress. Improved WASH services can lead to better physical health, time saved that can be used for leisure, education, and income-generating activities, environmental protection, gender equality, and overall dignity in life.[27] These are especially important in poor and vulnerable populations for which inadequate WASH can exacerbate the effects of communicable diseases, child undernutrition, and poor access to health services.[27,28] Furthermore, SDG 6 explicitly calls for equitable access to WASH services.[1] Despite this, full WASH coverage was markedly unequal, with the most vulnerable being left behind. This is in line with the literature, which indicates that WASH services are often among the most unequal interventions in global public health.[28]

Our results support the inverse equity hypothesis (Supplementary Figure 13), i.e., interventions and services first become available and are adopted by those with more resources (wealthier families, urban dwellers, those living closer to capital cities and wealthier regions of their countries), resulting in low absolute inequalities at very low coverages and increasing absolute inequalities as the national coverage increases, reaching the widest gaps when the national prevalence is close to 50%.[29] Georgia provides a good example: with a national full WASH prevalence of 45.4%, Georgia had some of the largest inequalities among all countries in terms of area of residence, wealth, and subnational regions. Safely managed water, safely disposed sanitation, and basic hygiene also followed a similar pattern.

Our study further documents the importance of exploring WASH services combined, and not only individually. Bangladesh serves as a notable example: 48.7% of households had safely managed water, 56.1% had safely disposed sanitation, and 56.5% had basic hygiene, suggesting that WASH progress hovers around the 50% mark. Nevertheless, only 20.6% of households had full WASH, indicating that progress is not necessarily happening within the same households.

At the household level, safely managed water was the key limiting factor in achieving full WASH coverage. This is influenced by how the WASH indicators were created and by how rigorous the water indicator is, comparatively to sanitation and hygiene. For sanitation, off-site excreta treatment was not included in the sanitation indicator because that information is not available at the household level. Household surveys provide less reliable information about off-site treatment, and new methods for linking administrative and service provider data with household surveys are needed.[12] Sewer treatment can be considered at the country-level using national wastewater treatment data and would substantially reduce sanitation coverage,[2,30] but that does not allow for stratified equity analyses and was not available for all countries in our sample. Similarly, basic hygiene does not consider if the water used for handwashing has any form of contamination. This is line with the fact that, in low- and middle-income countries, washing hands with locally available untreated water still tends to reduce the concentration of pathogens on the hands.[31] However, safely managed water could have even more rigorous if it was based on contamination at the point where people actually drink the water, not at the water source. We used contamination at the source for consistency with the MICS standard indicator,[13] but note that this underestimates exposure to fecal contamination that can happen during water collection, transportation, handling, storage, and use in the household.[17]

A limitation of our research is missing data. 12% of all households that were selected for the water quality module did not have all the data necessary to calculate the full WASH indicator (Supplementary Table S3). Households with missing data were also significantly more urban than households with complete data (Supplementary Table S4), thus likely leading to an underestimation of the overall prevalence given the lower coverage of WASH in rural areas. There was no clear pattern of difference in missing data for wealth. As a sensitivity analysis, we recalculated pooled prevalences using all available data for each individual indicator and results remained virtually unchanged (Supplementary Figure 14). Missing data was not evenly distributed between countries, and eight (Algeria, Dominican Republic, Georgia, Guyana, Honduras, São Tomé and Príncipe, Suriname, and Togo) had more than 20% of households with missing data. Therefore, the estimates for these countries should be interpreted with caution.

Despite these limitations, we used nationally representative samples from 32 countries and a comprehensive list of standardized WASH components to explore the combined access to WASH services, showing that coverage is low and highly unequal. Even though WASH plays a crucial role in socioeconomic development, wealthier and urban households tended to further benefit from WASH progress as national coverage increased.

Our research highlights the importance of exploring combined WASH services and shows how far humanity is from achieving universal and equitable access to these services. Water and sanitation are universal and inalienable human rights and are essential for people to enjoy a full and dignified life.[32] In order to guarantee that everyone can exercise these rights, we need to expand the global capacity to monitor WASH services. We also need to invest in comprehensive packages of infrastructure interventions that can not only increase national WASH coverage, but also reduce regional and socioeconomic inequalities, ensuring that people in vulnerable settings are not left behind.

Conflict of Interest

All authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Data statement

All the analyses were carried out using publicly available datasets that can be obtained directly from the MICS website (mics.unicef.org). Datasets are continuously sourced and updated by the International Center for Equity in Health (equidade.org) as they are released.

Ethics statement

The organizations who administered the surveys were responsible for ethical clearance according to the norms of each country.

Funding

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Supplementary Materials

Supplementary tables are available at:

https://docs.google.com/spreadsheets/d/1Kbv571cQsntcFO2_xkERJ2jE4JqWIBgN

Survey weighting

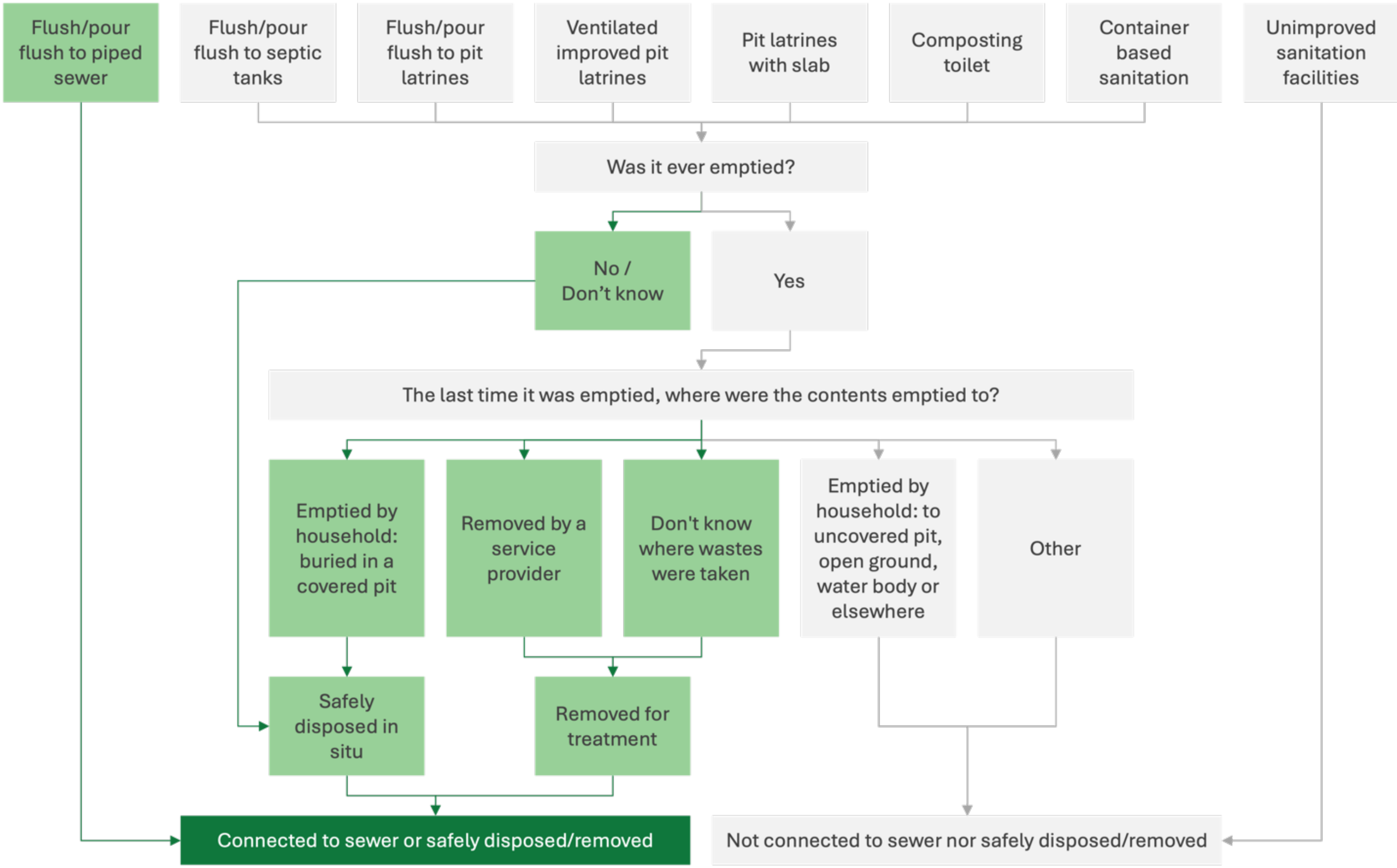
For our pooled analyses, we combined all countries together into one single dataset. We recalculated the sample weights using Equation S.1:

$$w_{ij,adj} = \left(\frac{w_{ij}}{\sum_i w_{ij}}\right)\left(\frac{pop_j}{\sum_j pop_j}\right)N$$

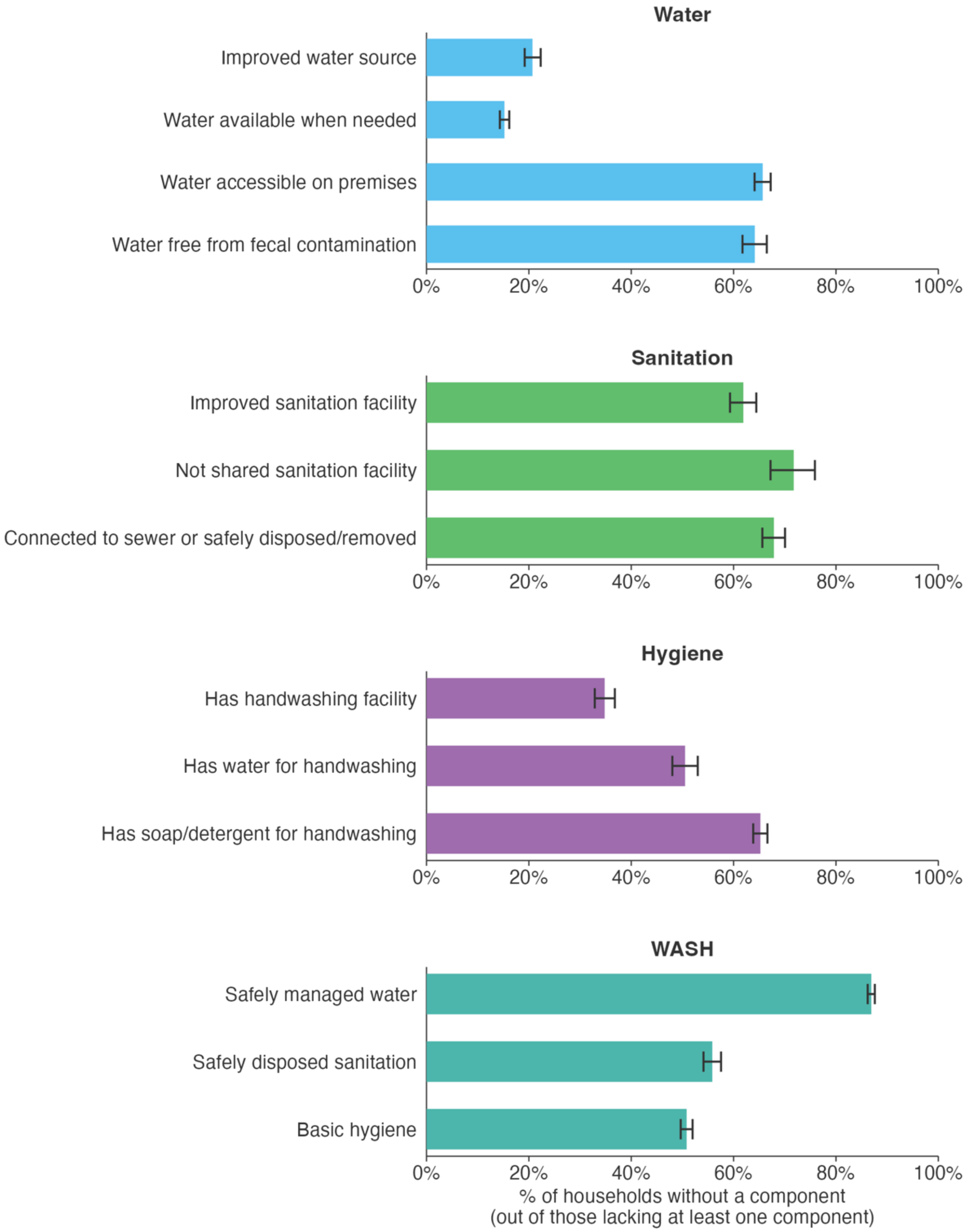
where:

- *i* indicates a household and *j* a country
- $w_{ij,adj}$ is the adjusted sample weight
- w_{ij} is the original sample weight
- pop_j is the total population of the country *j* in the median year of all surveys included in the analyses (2019)
- *N* is the total number of households in the sample

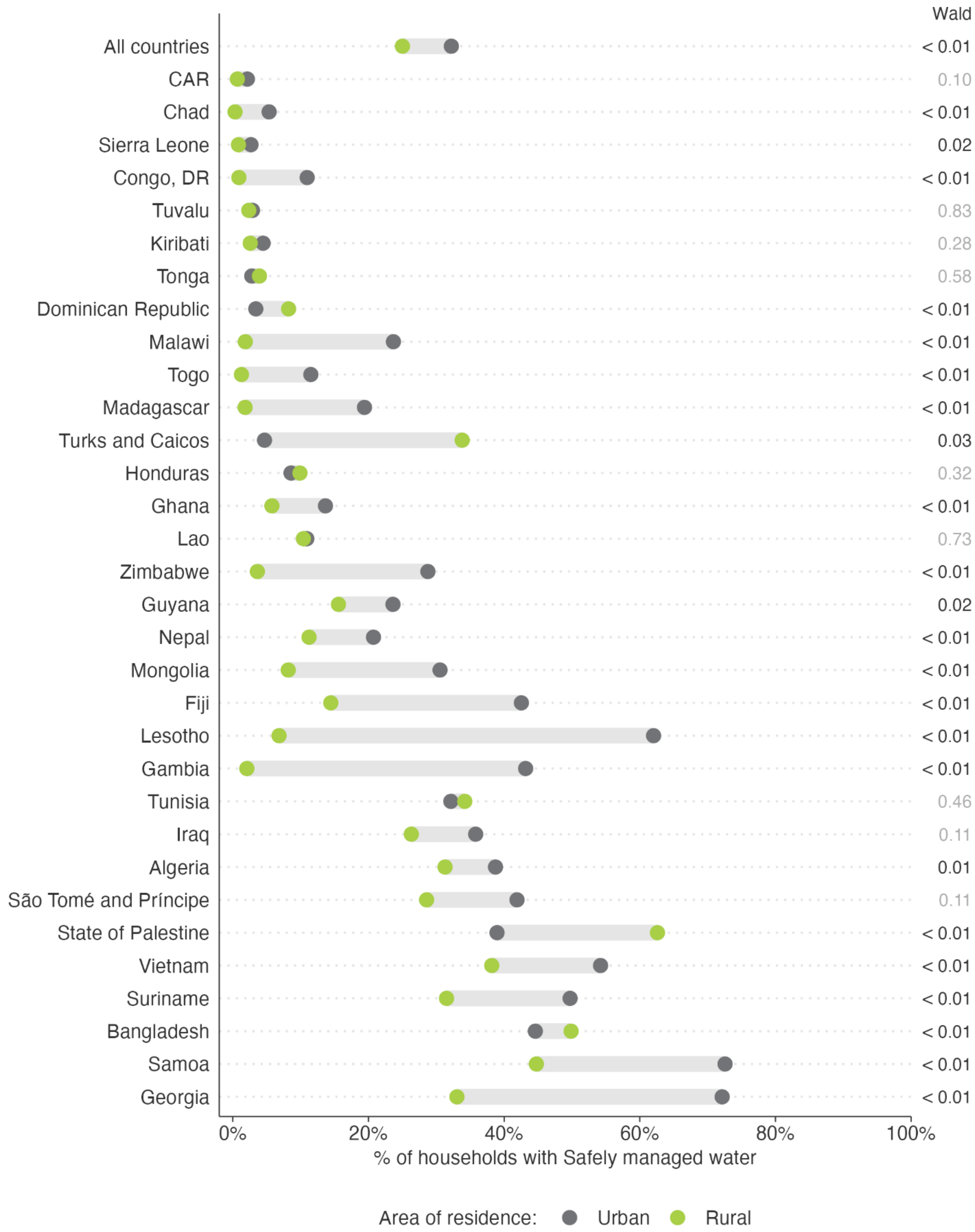
Supplementary figures



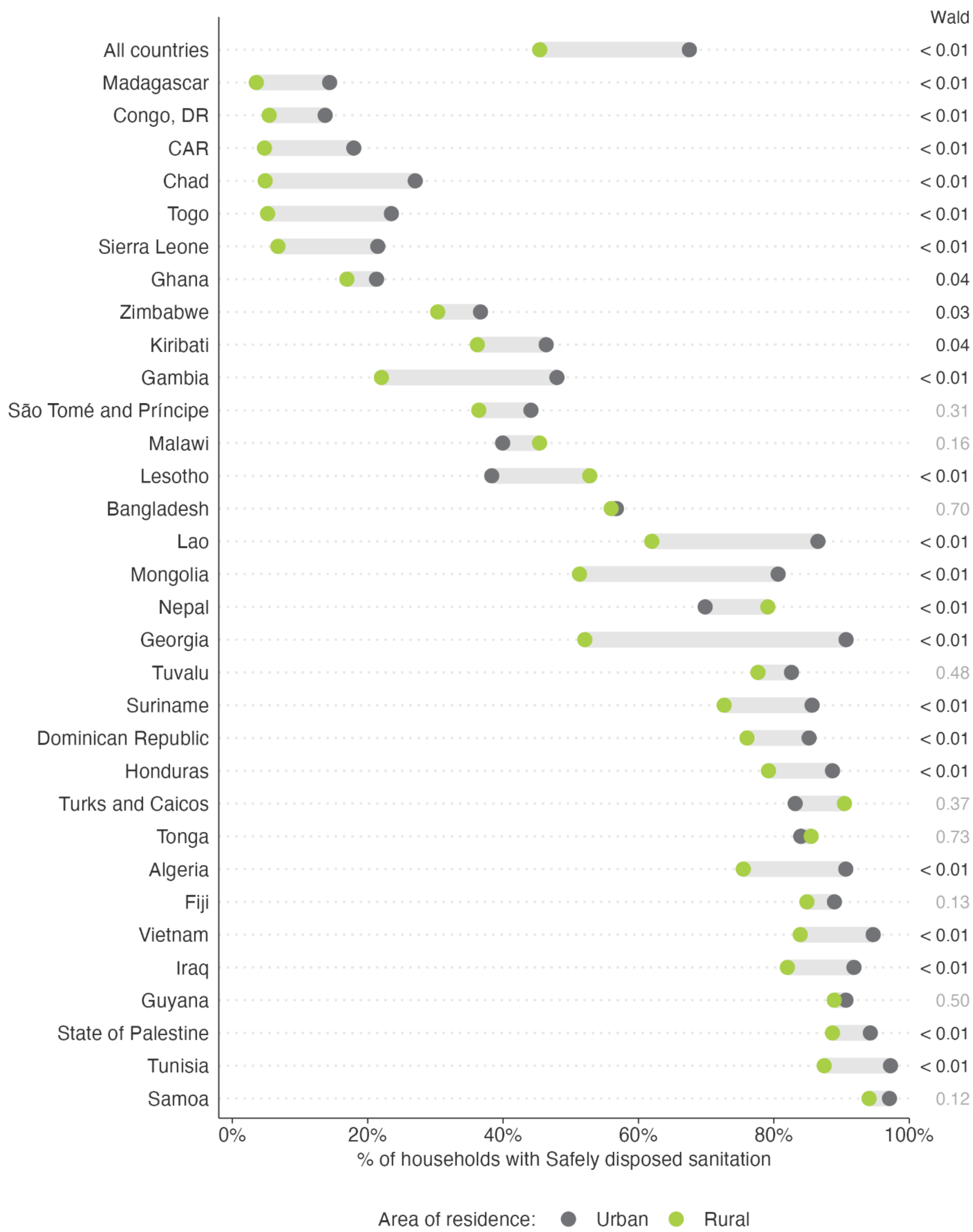
Supplementary Figure S1 – Description of how the safely disposed sanitation indicator was created. The first row represents the household's sanitation facility.



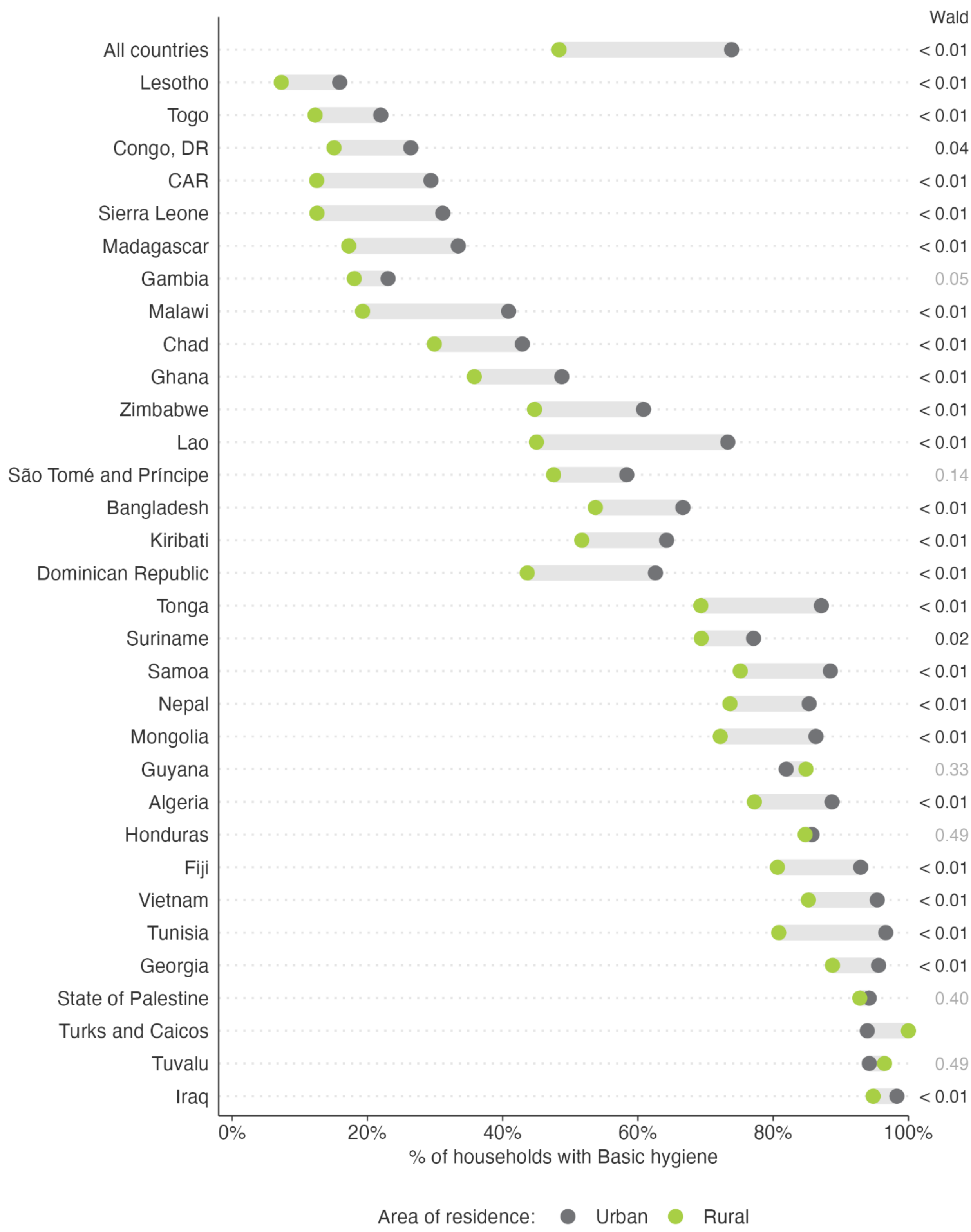
Supplementary Figure S2 – % of households without a WASH component out of those households lacking at least one component. For example: out of all households without at least one of the four water components, 20.7% lacked improved water.



Supplementary Figure S3 – Percentage of households with access to safely managed water according to area of residence. The p value of the Wald test of heterogeneity between areas is presented on the right. Darker text colors indicate statistically significant results ($p < 0.05$).

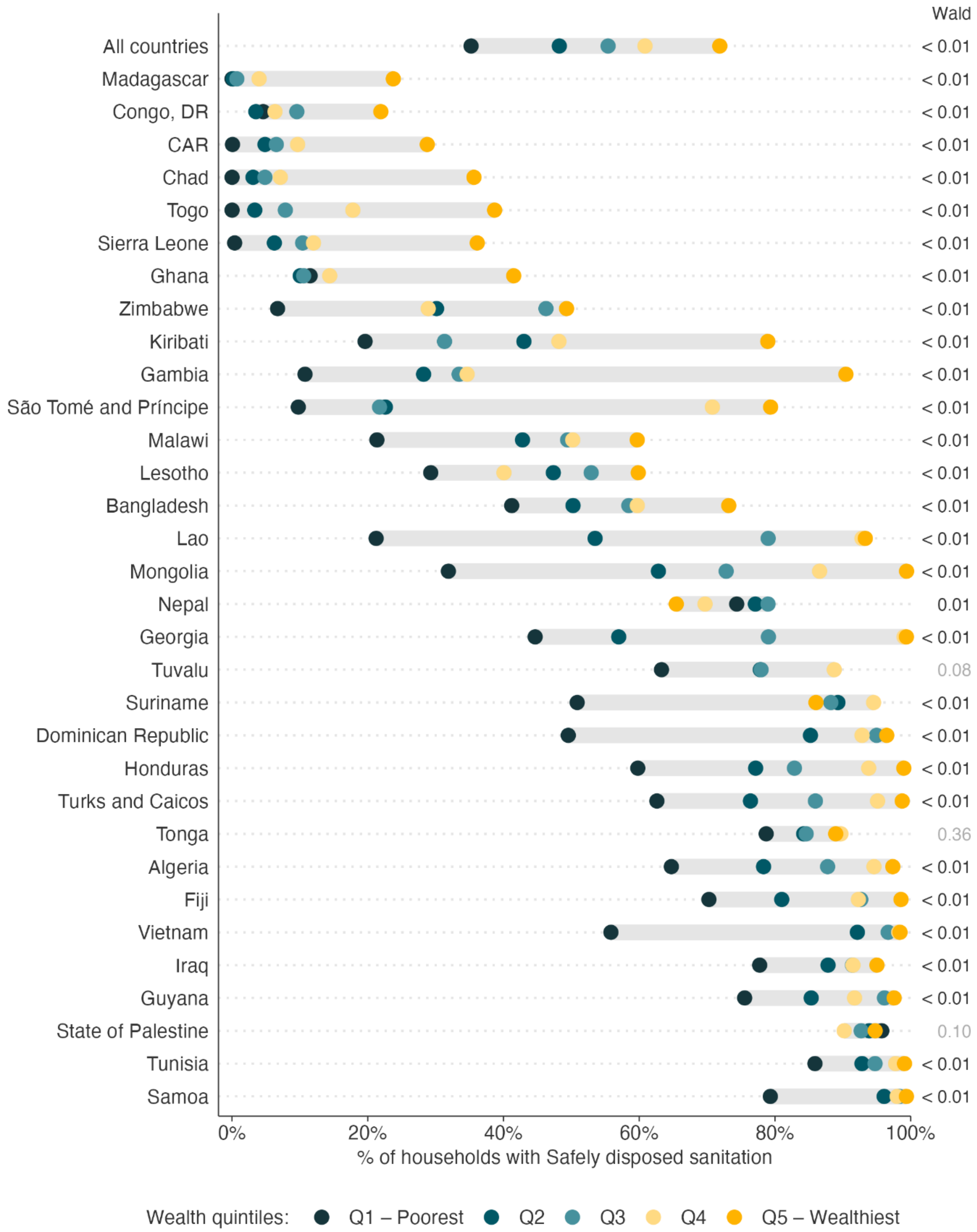


Supplementary Figure S4 – Percentage of households with access to safely disposed sanitation according to area of residence. The p value of the Wald test of heterogeneity between areas is presented on the right. Darker text colors indicate statistically significant results ($p < 0.05$).

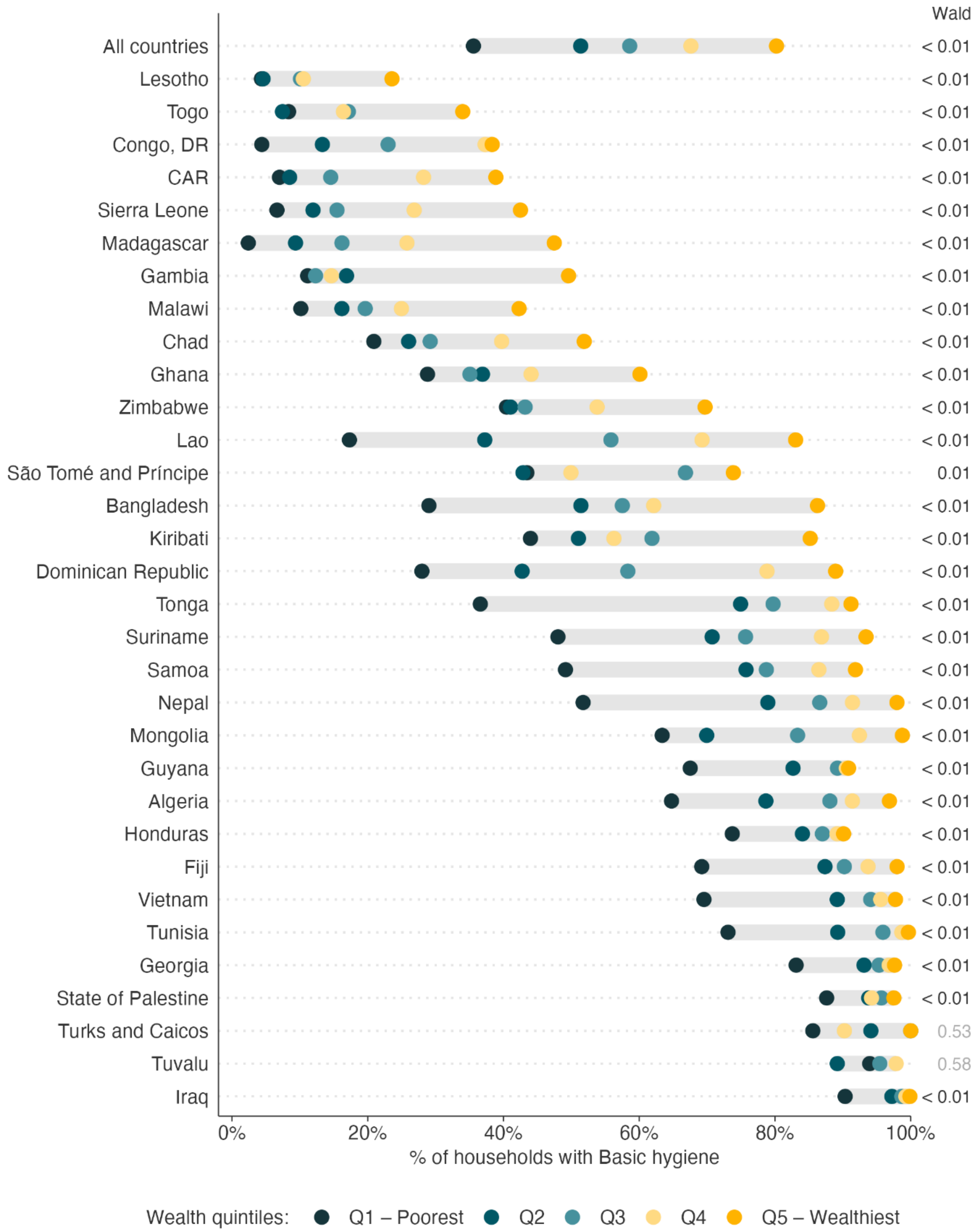


Supplementary Figure S5 – Percentage of households with access to basic hygiene according to area of residence. The p value of the Wald test of heterogeneity between areas is presented on the right. Darker text colors indicate statistically significant results ($p < 0.05$).

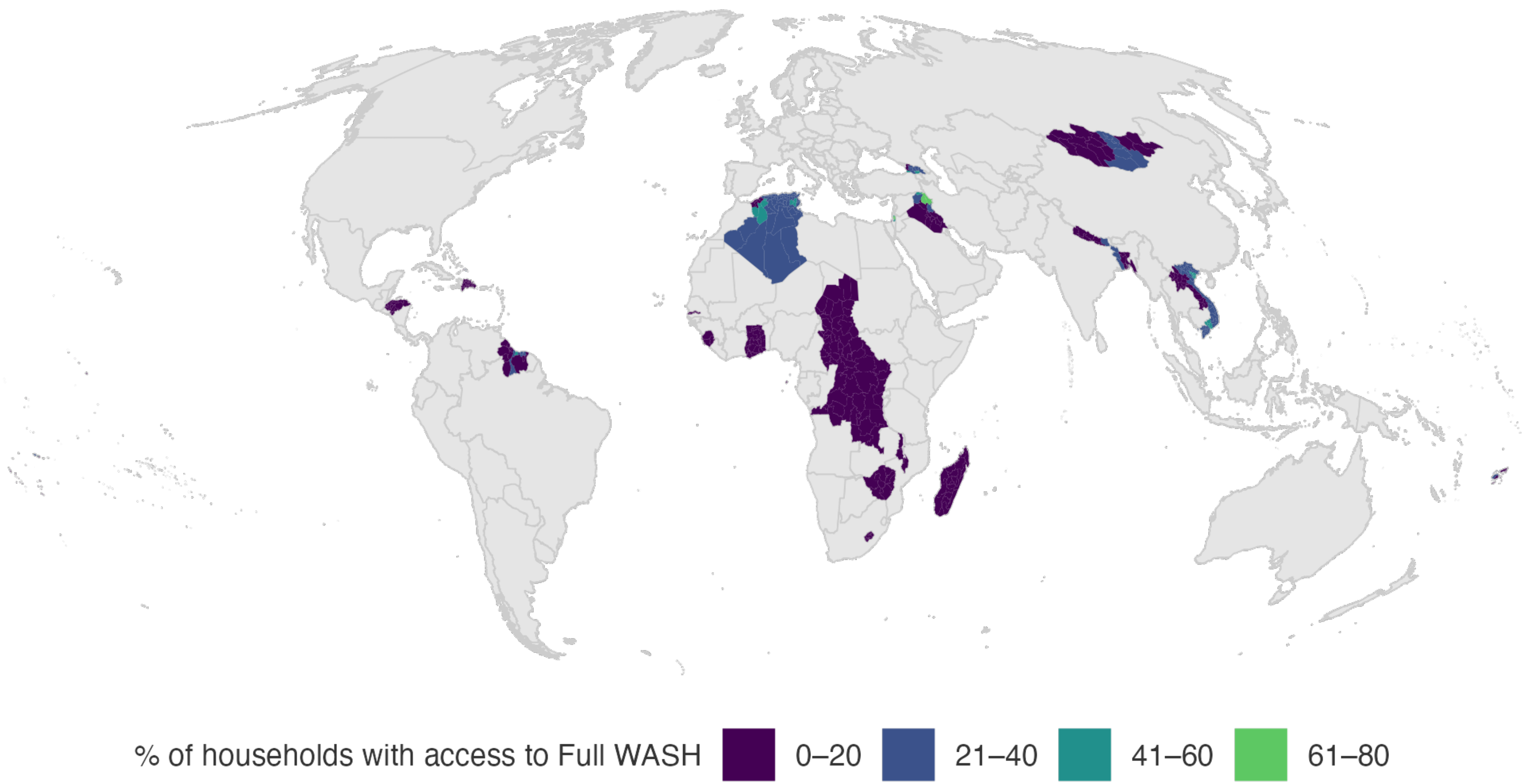
Supplementary Figure S6 – Percentage of households with access to safely managed water according to wealth quintiles. The p value of the Wald test of heterogeneity between quintiles is presented on the right. Darker text colors indicate statistically significant results ($p < 0.05$).



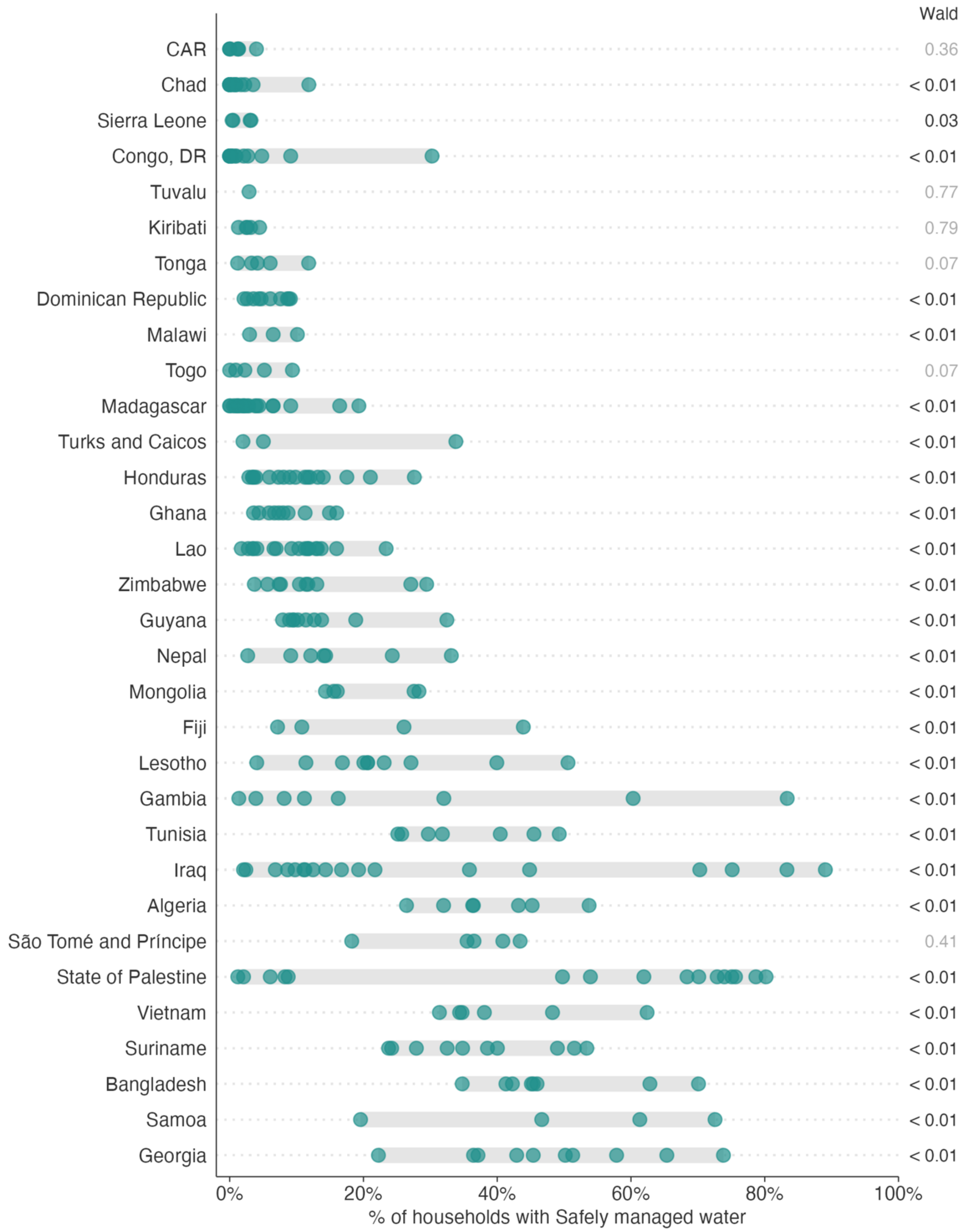
Supplementary Figure S7 – Percentage of households with access to safely disposed sanitation according to wealth quintiles. The p value of the Wald test of heterogeneity between quintiles is presented on the right. Darker text colors indicate statistically significant results ($p < 0.05$).



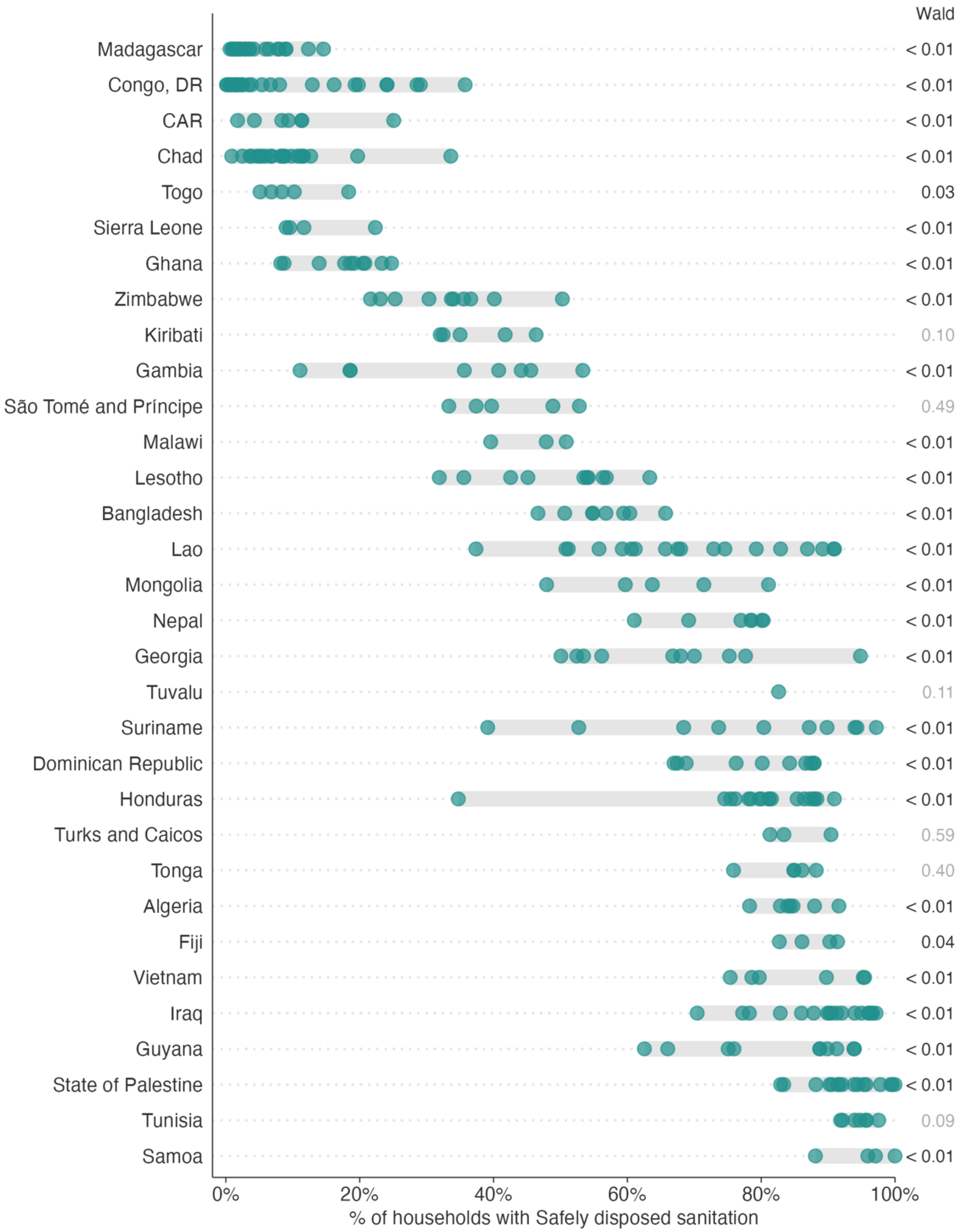
Supplementary Figure S8 – Percentage of households with access to basic hygiene according to wealth quintiles. The p value of the Wald test of heterogeneity between quintiles is presented on the right. Darker text colors indicate statistically significant results ($p < 0.05$).



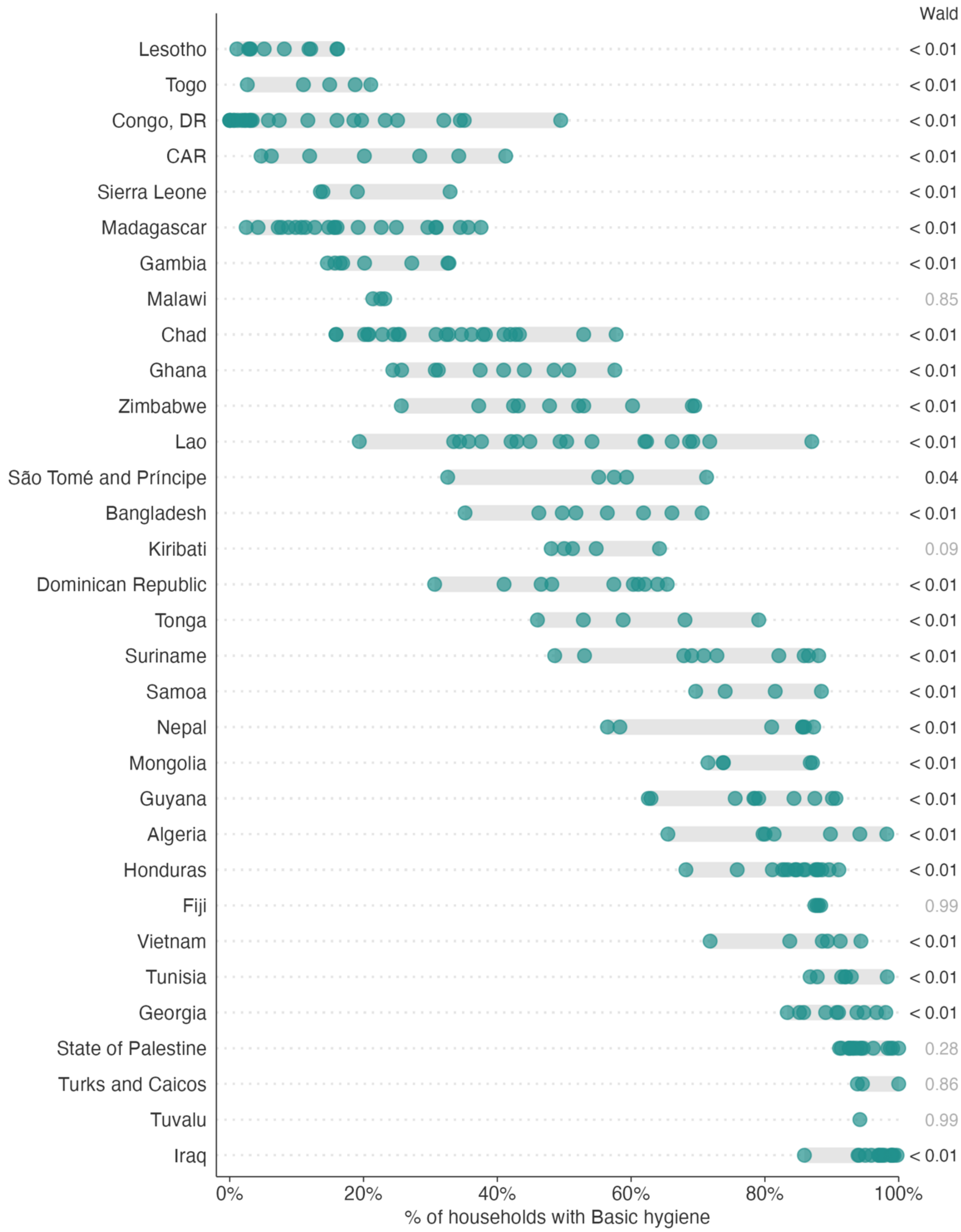
Supplementary Figure S9 – Map of the percentage of households with access to full WASH according to subnational region.



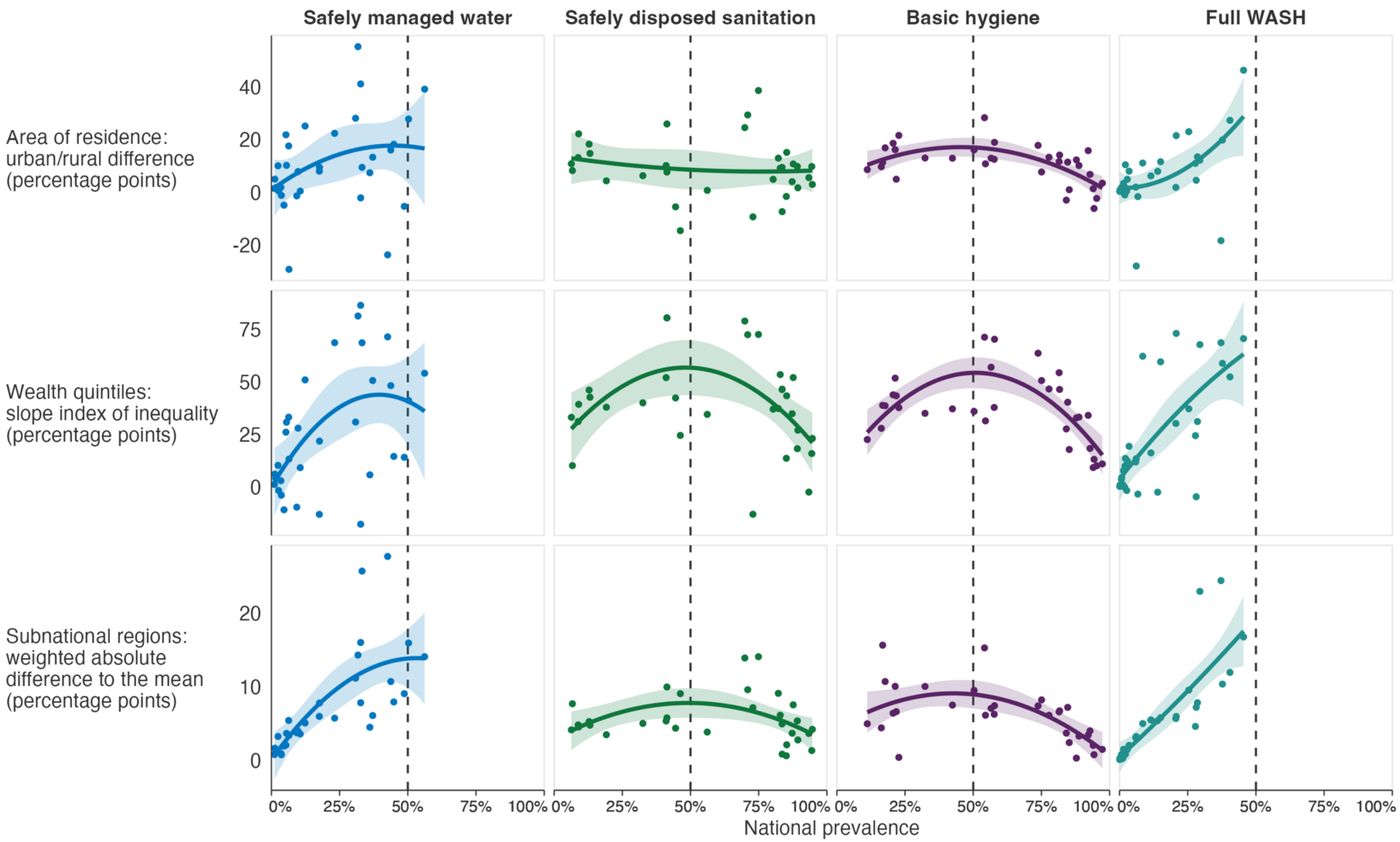
Supplementary Figure S10 – Percentage of households with access to safely managed water according to subnational regions. Each dot represents a region. The p value of the Wald test of heterogeneity between regions is presented on the right. Darker text colors indicate statistically significant results ($p < 0.05$).



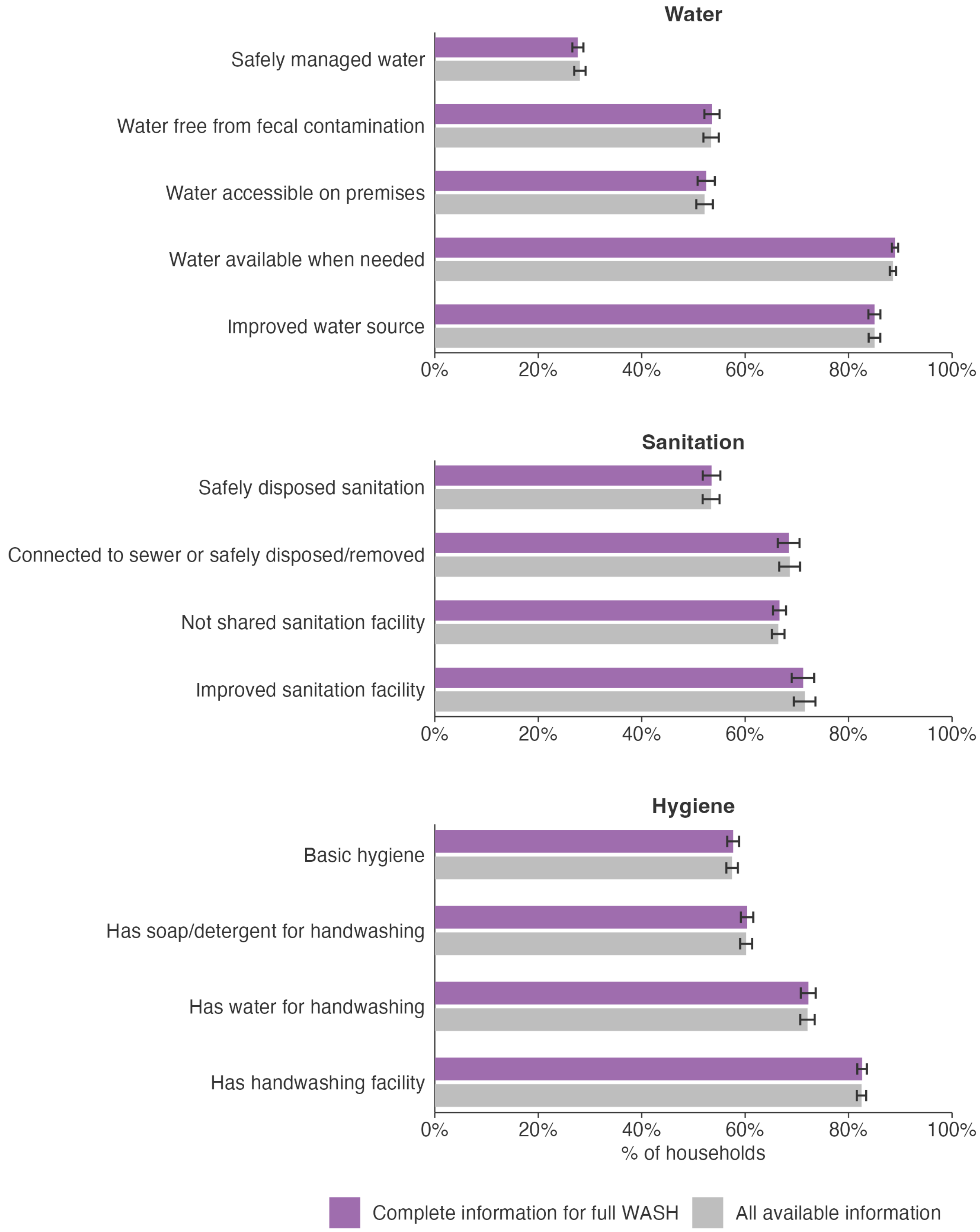
Supplementary Figure S11 – Percentage of households with access to safely disposed sanitation according to subnational regions. Each dot represents a region. The p value of the Wald test of heterogeneity between regions is presented on the right. Darker text colors indicate statistically significant results ($p < 0.05$).



Supplementary Figure S12 – Percentage of households with access to basic hygiene according to subnational regions. Each dot represents a region. The p value of the Wald test of heterogeneity between regions is presented on the right. Darker text colors indicate statistically significant results ($p < 0.05$).



Supplementary Figure S13 – Association between absolute inequality (in terms of area of residence, wealth quintiles and subnational regions) and the national prevalence of safely managed water, safely disposed sanitation, basic hygiene, and full WASH. For area of residence, we calculated the absolute difference in prevalence between the urban and rural areas. For wealth quintiles, we calculated the slope index of inequality. For subnational regions, we calculated the weighted absolute difference to the mean, using the weighted sample size as the weight. We used quadratic models for the fitted curves.



Supplementary Figure S14 – Pooled prevalence of the fourteen WASH indicators. Water contamination refers to contamination at the source where water is collected. Purple bars indicate the prevalence using only households with information available for all indicators (main analysis). Gray bars indicate the prevalence calculated using all the available information for each specific indicator, regardless of missing data for other indicators.

7. Press release

Português

Água, saneamento e higiene: ainda há uma longa estrada pela frente, mas o empoderamento feminino pode nos ajudar ao longo do caminho

No mundo todo, 2,2 bilhões de pessoas ainda não têm água segura para beber, 3,4 bilhões não têm saneamento adequado e 2 bilhões não têm serviços básicos de higiene em suas casas. O progresso na maioria dos países é lento, e a falta de água, saneamento e higiene – conhecida pela sigla WASH, em inglês – tem um efeito desproporcional sobre mulheres e meninas em todo o mundo. Investigar desigualdades no acesso a serviços WASH e sua relação com o empoderamento econômico das mulheres foram os objetivos da tese de doutorado desenvolvida por Thiago Melo Santos, sob a supervisão do Professor Aluísio Barros da Universidade Federal de Pelotas (Brasil) e da Professora Associada Meghan Bohren, da Universidade de Melbourne (Austrália).

Focando em um grupo de países de baixa e média renda, seus resultados descrevem um cenário trágico. Eles mostraram que 7 em cada 10 domicílios tinham água potável contaminada por matéria fecal. "Em países como o Chade (na África), praticamente todos os domicílios tinham água contaminada. Sem mencionar o fato de que muitas fontes de água que consideramos 'melhoradas', como a água da chuva, também apresentavam níveis inaceitáveis de contaminação", disse o autor principal. Quando olhamos para água, saneamento e higiene combinados, a situação é ainda pior: apenas 17% dos domicílios tinham o que os autores chamam de WASH completo. "WASH completo é o que a maioria das pessoas em países de alta renda está acostumada em suas vidas diárias. Você tem água potável limpa, em sua casa, e sempre disponível. É uma instalação sanitária, como um banheiro, que você pode usar, e os resíduos são separados de você e do seu entorno. E um local para lavar as mãos que tem água e sabão", explicou Thiago. Apesar disso, em cerca de metade dos países estudados – a maioria deles na África Subsaariana e em nações insulares (ilhas ou grupos de ilhas) – quase ninguém tinha WASH completo. Na outra metade, o acesso era altamente desigual, com domicílios mais pobres e rurais frequentemente sendo deixados para trás.

Estes resultados podem parecer desanimadores, mas também apontam para uma possível solução. Os pesquisadores descobriram que em domicílios onde as mulheres são mais economicamente empoderadas (ou seja, onde elas participam das decisões econômicas do domicílio, têm empregos remunerados, contas bancárias, etc.), a infraestrutura WASH era melhor. "Ainda estamos nos estágios iniciais da pesquisa, mas os resultados são muito promissores e estão alinhados com o que outros estudos estão mostrando. Parece haver um ciclo positivo: mais empoderamento feminino pode levar a um melhor WASH, e um melhor WASH pode levar a mais empoderamento feminino. Outros tipos de estudos ainda são necessários para confirmar isso, mas estamos muito animados com as possibilidades. Poderia ser um caminho para abordar ao mesmo tempo a igualdade de gênero e o WASH", conclui.

English

Water, sanitation, and hygiene: still a long road ahead, but women's empowerment might help us along the way

Globally, 2.2 billion people still lack safe water, 3.4 billion lack adequate sanitation, and 2 billion lack basic hygiene services in their houses. Progress in most countries is slow, and the lack of water, sanitation, and hygiene – known by the handy acronym WASH – has a disproportionate effect on women and girls worldwide. Investigating inequalities in access to WASH services and their relationship with women's economic empowerment were the goals of the PhD Thesis developed by Thiago Melo Santos, under the supervision of Professor Aluísio Barros from the Universidade Federal de Pelotas (Brazil) and Associate Professor Meghan Bohren, from the University of Melbourne (Australia).

Focusing on a group of low- and middle-income countries, their results paint a dire picture. They found that 7 out of 10 households had drinking water that was contaminated by fecal matter. "In countries like Chad (in Africa), virtually all households had contaminated water. Not to mention that fact that many water sources that we consider 'improved', like rainwater, also had unacceptable levels of contamination", said the lead author. When looking at water, sanitation, and hygiene combined, the situation is even worst: only 17% of the households had what the authors call *full WASH*. "Full

WASH is what most people in high income countries are used to in their daily lives. You have drinking water that is clean, in your house, and always there. It's a sanitation facility, like a toilet, that you can use, and the waste is separated from you and your surroundings. And a place to wash your hands that has water and soap" explained Thiago. Despite this, in around half the countries they studied – most of them from Sub-Saharan Africa and island nations – almost no one had full WASH. In the other half, access was highly unequal, with poorer and rural households often being left behind.

Their results may seem discouraging, but they also point to one possible solution. They found that in households where women are more economically empowered (i.e., where they participate in the house's economic decisions, have paying jobs, bank accounts, etc.), the WASH infrastructure was significantly better. "We are still in the early stages of research, but the results are very promising and in line with what other studies are showing. There appears to be positive feedback loop: more women's empowerment could lead to better WASH, and better WASH could lead to more women's empowerment. Other types of studies are still necessary to establish this, but we are very excited with the possibilities. It could be a path to tackle both gender equality and WASH at the same time" he concludes.