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Review

Faecal contamination of groundwater self-supply in low- and middle income countries: Systematic review and meta-analysis

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ABSTRACT

Self-supply is a ubiquitous response by households to the public water supply inadequacies found worldwide. Self-supply is invested in and managed by an individual household, accessible on-premises and unregulated. Vulnerability to faecal contamination is a concern due to reliance on low-cost technologies and shallow groundwater. This review aims to evaluate the evidence base on the safety of groundwater self-supply in low- and middle income countries in relation to faecal contamination. Differences in microbial water quality between source types, settings, countries and ownership were investigated. A search of peer-reviewed studies in low- and middle income countries was conducted in online databases, including PubMed, Web of Science, ProQuest and Environmental Complete. Studies were included if they had sufficient detail about the water samples to be related to groundwater self-supply, contained extractable data on faecal indicator bacteria (FIB) including thermotolerant coliform or *Escherichia coli* and were published in English between 1990 and April 2020. A total of 30 studies were included, resulting in 100 datasets and 26,981 water samples across the studies. FIB were present in 36% self-supply samples. The odds of FIB being detected was significantly higher for unimproved sources (OR=8.19, 95% CI [4.04–16.59], $p<0.001$) and for sources in low income countries (OR=3.85, 95% CI [1.85–7.69], $p<0.001$). Self-supply was significantly more likely to be contaminated than piped supply (OR=3.45, 95% CI [1.52–7.82], $p=0.003$). However, water quality was highly heterogeneous ($I^2=90.9\%$). Egger's test found no evidence of small study publication bias for self-supply compared to public supply. No evidence of bias due to lack of randomization or season was found, but study design and quality could potentially bias the results. To achieve Sustainable Development Goal 6.1 on safe drinking water for all, more attention is needed from governments to engage with self-supply and formulate balanced policy responses.

1. Introduction

Sustainable Development Goal (SDG) 6.1 calls for universal and equitable access to safe and affordable drinking water for all by 2030. To meet the criteria of a safely-managed drinking water service, households must use an improved water source that is accessible on-premises, sufficiently available when needed and free from faecal and chemical contamination (WHO and UNICEF, 2017). An improved water facility includes sources that are protected from outside contamination by nature of their construction, such as boreholes, protected dug wells or rainwater harvesting (WHO and UNICEF, 2017). Although billions of people have gained access to basic water services and much progress has been made towards reaching SDG 6.1, more extensive efforts are needed to fully realize the SDG ambition to achieve universal access for all. In 2017, more than 2.2 billion people still lacked access to a safely managed water service (WHO and UNICEF, 2021). The lack of access to safe drinking water is felt disproportionately by disadvantaged community groups (WHO and UNICEF, 2019).

Household self-supply has become essential for people who are beyond the reach of utility- or community managed water supplies, and for those who need to complement an inadequate supply (Grönwall et al., 2010). Self-supply is a service delivery model usually relying on groundwater or rainwater. It is characterized as an on-premises water supply that is invested in, and maintained by, a household and therefore based on affordable technologies (Grönwall and Danert, 2020). Self-supply exists all over the world in both rural and urban settings. One third of the total urban population in continental Africa are likely to rely on self-supply (Chávez García Silva et al., 2020). In Asia-Pacific, over 700 million people depend on self-supply across rural and urban areas (Foster et al., 2021). Rural areas with low population density are often

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difficult or expensive to reach with public or centralised water supply systems (Adeniji-Oloukoi et al., 2013; Allen et al., 2006; Sutton, 2009). In urban areas, cities are expanding rapidly so that individual households in outskirts choose to go off-grid and organize their own drinking water access when there is no reliable and convenient public supply (Grönwall, 2016; Grönwall and Danert, 2020; Komakech and de Bont, 2018; Kulabako et al., 2010; Liddle et al., 2016).

Self-supply has the potential to provide a safely managed water service as it is located on the premises of a user household. However, self-supply services are generally unregulated and unmonitored (Grönwall and Danert, 2020; Grönwall et al., 2010). Therefore, little is known about the extent to which self-supply provides drinking water that is free from contamination, and poor water quality and its associated health risks remain a prime concern (Sutton, 2009). Many self-supply services rely on shallow groundwater sources, which are highly vulnerable to contamination from human activities (Grönwall et al., 2010). Moreover, groundwater self-supply often relies on simple construction and lifting technologies. Faecal contamination from various sources such as sanitation systems, solid waste dumps, household sullage, stormwater drains and animals also poses a risk (ARGOSS, 2001).

Contamination of drinking water constitutes a major burden on public health in low-income countries due to water-related disease such as diarrhoeal diseases (Bain et al., 2014b). The World Health Organization (WHO) drinking water guidelines include criteria for assessing health risks and setting targets for improving water safety (WHO, 2011). The recommended measure for assessing faecal contamination by the WHO is the presence of faecal indicator bacteria (FIB) such as *Escherichia coli* (*E. coli*) or alternatively thermotolerant coliform (TTC) (WHO and UNICEF, 2010). The concentration of faecal indicator bacteria is suggested to be an indicator of health risks. However, FIB are imperfect in representing risk and monitoring is required that goes beyond the single measurements of indicators or contaminants to interpreting health hazards (Charles et al., 2020). Nevertheless, even using imperfect methods, there is an urgent need to understand and address the risks and benefits related to self-supply in order to guide policy and practice towards safely-managed services that meet the needs of disadvantaged populations.

This systematic review with meta-analysis aims to provide insight on the safety of groundwater self-supply in LMIC regarding faecal contamination. Amongst selected studies, this study seeks to understand the extent to which groundwater self-supply is free from faecal contamination and addresses three research questions:

1. To what extent is groundwater self-supply contaminated with FIB in LMIC?
2. How does faecal contamination vary between source types, countries, rural and urban areas, seasons and study designs?
3. How does self-supply compare to public supply in terms of faecal contamination?

The focus of the study is self-supply based on groundwater sources. Further, the literature review focuses on microbial water quality as reported by FIB.

2. Methods

The systematic review of studies including faecal contamination of groundwater self-supply in LMICs was conducted according to the PRISMA guidelines (Moher et al., 2009). Methods for search strategy, study eligibility and data extraction were adapted from Bain et al. (2014b) and are described in the protocol (S1).

2.1. Search strategy

Studies were identified from peer-reviewed literature. Online databases were searched including PubMed, Web of Science, ProQuest and Environmental Complete. Search terms regarding water quality were combined with self-supply terms and restricted to LMICs using a list of country names (Bain et al., 2014b). Searches were conducted between April and June 2020.

2.2. Eligibility and selection

Studies were included in the review provided they: (i) had sufficient detail about the water samples to be related to self-supply groundwater sources; (ii) contained extractable data on TTC or *E. coli*; (iii) were published between 1990 and April 2020, (iv) included at least 10 separate water samples; (v) fell into the classification of LMIC (World Bank, 2020) and, (vi) were published in English. Studies were selected by screening of titles and abstracts followed by screening of full texts for selected studies. Duplicates were identified and removed.

2.3. Data extraction and matching

Basic descriptive data from eligible studies (e.g. author, year of publication), water quality information and additional study characteristics thought to influence water quality were extracted into a Microsoft Office Excel 2016 spreadsheet (S2). Where possible, the following water quality information for each source type in the studies were extracted: non-compliance (presence of *E. coli* or TTC); mean, geometric mean and/or median level of contamination (*E. coli* or TTC per 100 ml); standard deviation, variance or standard errors (*E. coli* or TTC per 100 ml); risk categories of microbial contamination (<1, 1–10, 10–100, 10–50, >50 and >100 *E. coli* or TTC per 100 ml); number of samples tested; analytical method used to detect faecal indicator bacteria.

To explore the influence of seasons, those studies that refer to water quality during “wet”, “rainy” or “dry” periods or equivalent were recorded. The country income group was identified as “low”, “lower-middle” and “upper-middle” income using the World Bank classification (World Bank, 2020). Where possible, level of urbanization was identified as urban or rural. To investigate the influence of source type on water quality, each type of water source was recorded and matched with the corresponding Joint Monitoring Programme (JMP) source definition and classified as improved or unimproved (WHO and UNICEF, 2017). Groundwater sources from studies that did not distinguish between protected and unprotected wells were categorised as unclassified dug well. Groundwater sources that did not distinguish between borehole and dug wells were categorised as unclassified.

2.4. Study quality and risk of bias

Each study was rated for quality based on a quality score between 0 and 10 for specified criteria (Table 1). Quality criteria are based on those used by Bain et al. (2014b). Quality control criteria extracted included information on the selection (selection described, selection randomized, randomized selection described), region described, season reported, quality control, method described, point of sampling defined, handling described, handling minimum criteria met. Higher and lower quality was determined by the median of quality scores of the studies. No study was excluded based on a low quality score. Study designs were identified and categorized as either cross-sectional, longitudinal (study >6 months), cohort, intervention or diagnostic study. The influence of study design and quality on bias between studies was investigated using meta-regression with study design type and quality criteria as subgroups as described in the analysis section (2.5.3 Between study analysis).

2.5. Analysis

2.5.1. Data for analysis

Only studies reporting noncompliance results were used for meta-

Table 1
Quality criteria and description.

Quality Criterion	Description
Selection described	Description of how the water samples were chosen, including how either the types of water source or their users were selected
Selection representative	Description of an approach that provides a representative picture of water quality in a given area
Selection randomized	Randomized sampling over a given study or population
Region described	Description of the geographic region within the country where the study was conducted
Season reported	Report of seasons or months of sampling
Quality control	Specification or reference of quality control procedures
Method described	Description or reference of well-defined and appropriate methods of microbial analysis
Point of sampling	Description of the point at which water was sampled
Handling described	Description of sample handling procedures, including sample collection, transport method and duration
Handling minimum criteria	Fulfilment of handling minimum criteria for sample handling and processing: transport on ice or between 2 and 8 °C, analysis within 6 h of collection, and specified incubation temperature

analysis. Measures of central tendency from studies were not included in the meta-analysis because of limited reporting. For studies reporting both *E. coli* and TTC data, only the *E. coli* results were used. For studies reporting summarised results from sub-results, only the sub-results were used. For studies which assessed water quality at both source and point-of-use, only results from the water source were included in the analysis. For the intervention study, only the dataset several years after the emergency event and intervention was used for analysis (Ali et al., 2019).

2.5.2. Qualitative synthesis

To qualitatively assess the proportion of studies reporting frequent and high levels of microbial contamination, cumulative density functions (CDFs) of the proportion of samples with ≥1 FIB per 100 mL and >100 FIB per 100 mL were plotted for each water source type using the "ggplot2" function in the statistical analysis software RStudio (version 1.2.5001, R Foundation for Statistical Computing, Vienna, Austria). Results of unclassified water sources were not included in the CDFs. FIB concentrations from datasets reporting results in risk classification were plotted using Microsoft Office excel 2016. The extent of FIB contamination of self-supply was calculated based on the included datasets used for meta-analysis.

2.5.3. Between study analysis

To investigate heterogeneity between studies in faecal contamination, random effects meta-regression was used to test *a priori* defined subgroups such as setting, season, source type and other study characteristics as possible explanations. Continuity correction of 0.5 was employed in Microsoft Office Excel 2016 for proportions of 0 or 1 (Sweeting et al., 2004). For studies with zero positive samples, 0.5 was substituted for the number of positive samples and for studies where all samples were positive, 0.5 was subtracted from the total number of positive samples. The "metafor" package in the statistical analysis software R (version 1.2.5001, R Foundation for Statistical Computing, Vienna, Austria) was used for meta-regression (Viechtbauer, 2010). A logit transformation for the analysis of proportion was applied to the proportion of samples with >1 FIB per 100 mL and >100 FIB per 100 mL using the "escalc" function. To compare the faecal contamination with the defined subgroups, random effects pooled odds ratio were calculated using the "rma" function. The DerSimonian-Laird estimator was used to estimate the amount of heterogeneity (DerSimonian and Laird, 1986).

2.5.4. Within study analysis

Studies that included extractable water quality data from both self-supply and public water sources were combined using meta-analysis with the odds ratio as the effect measure to compare the faecal contamination based on the proportion of samples >1 FIB per 100 mL. Pooled estimates were calculated using the "escalc" and "rma" function in the R "metafor" package. Heterogeneity was estimated using Higgins I^2 (Higgins and Thompson, 2002). Here, heterogeneity refers to the variation in faecal contamination levels between the studies. Forest plots were created using the "forest" function for self-supply compared to public water sources, self-supply compared to public piped water sources and improved self-supply water sources compared to improved public water sources. The influence of small study bias was assessed with the funnel plot method and Egger's regression test for odds ratio and standard error using the "funnel.rma" and "regtest" functions (Egger et al., 1997).

3. Results

3.1. Search results

In total 677 records were identified through database searches and additional three reports through snowball searching (Fig. 1). Most studies were excluded because water sources were not related to self-supply or there were no extractable *E. coli* or TTC data. Several studies did not mention the ownership of the water source or did not differentiate the FIB results between public and self-owned water sources. An adequate description of the water source to allow them to be matched to the JMP source was missing in numerous studies. For example, some studies described water sources as "wells" but did not provide information about the construction (e.g. protected or unprotected dug well). In total 30 studies were incorporated in the review resulting in 100 datasets and 26,981 water samples (Tables 2 and S2).

3.2. Study characteristics

Characteristics of the included studies are presented in Table 3. Studies report water quality information from self-supply sources in urban ($n = 15$, 50%), rural ($n = 12$, 40%) or both ($n = 2$, 7%) settings. One study described the region but did not classify the level of urbanization (Ali et al., 2019). In half of the selected studies, self-supply sources were classified as boreholes ($n = 15$) and less commonly as protected and unprotected dug wells ($n = 6$ and $n = 2$). In 40% ($n = 12$) of the selected studies, the self-supply source type was not clearly described and could not be classified. The majority of the studies described the season, with reported water sample collection during wet ($n = 11$, 37%), dry ($n = 14$, 47%) and both ($n = 5$, 17%) season. Some studies ($n = 4$, 13%) did not describe the season or not differentiate between wet and dry season ($n = 6$, 20%).

The review was dominated by cross-sectional studies ($n = 24$, 80%) with fewer longitudinal surveys ($n = 5$, 17%). Sample size of the datasets ranged from three to 4834 samples with a median of 43 samples. Randomized water source or household selection was reported in a minority of studies ($n = 12$, 40%). The majority of the studies reported FIB results as noncompliance ($n = 27\%$, 90%) using *E. coli* ($n = 16$, 53%) and TTC ($n = 16$, 53%) as parameters. One intervention study took place after an emergency (Ali et al., 2019). In addition to the water quality testing, household and sanitary surveys were conducted in 30% ($n = 9$) and 37% ($n = 11$) of the selected studies, respectively.

Study quality ranged from a quality score of 4 to 10 with an interquartile range of 7 to 8 and a median of 7 (Fig. S3). In all studies the region was specified where it was conducted. Most studies described the method ($n = 28$, 93%), the handling ($n = 28$, 93%) and specified the point of sampling ($n = 22$, 73%). Fewer studies met the handling minimum criteria ($n = 19$, 63%), described the selection ($n = 18$, 60%) or randomized selection ($n = 12$, 40%) and the minority specified quality control procedures ($n = 5$, 17%) (Fig. S4).

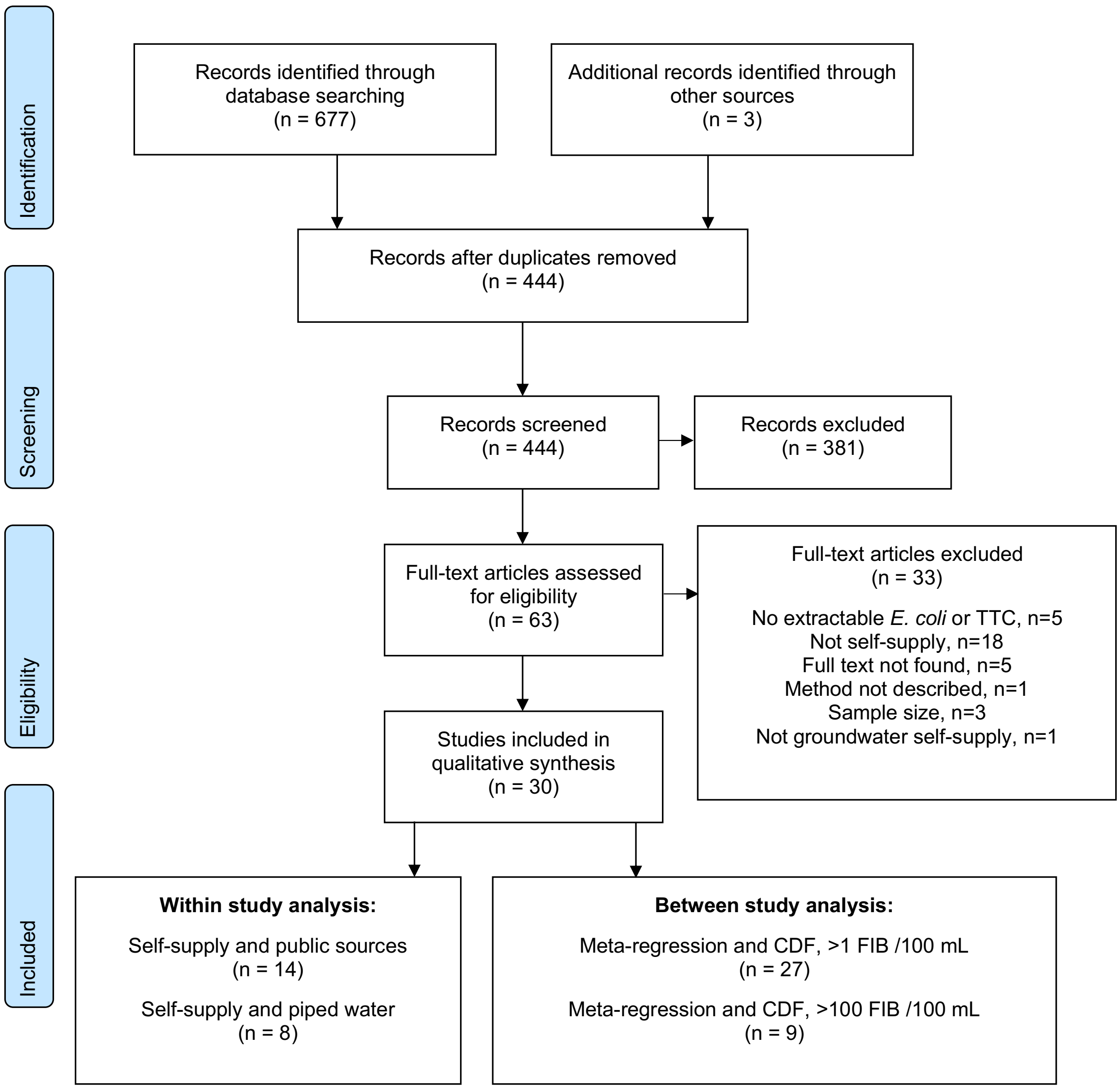

Fig. 1. Flowchart for a review of microbial water quality from self-supply sources.

3.3. Qualitative synthesis

Likelihood and level of microbial contamination varied between study and source type (Fig. S5). FIB were detected in 36% samples ($n_{pos} = 5066$) from self-supply sources, including 28% of samples ($n_{pos} = 1973$) from boreholes, 77% of samples ($n_{pos} = 143$) from protected dug wells, and 81% of samples ($n_{pos} = 777$) from unprotected wells. Studies reporting results in FIB risk classifications showed that FIB were detected in all datasets ($n = 22$) and exceeded levels of 50 and 100 FIB per 100 mL in 95% of the datasets. Although the proportion of samples in which FIB were detected were higher for unimproved sources such as unprotected dug wells, samples from improved sources such as boreholes still exceeded levels of 100 FIB per 100 mL in nine of ten datasets. Samples from protected dug wells exceeded levels of 50 FIB per 100 mL in both of the datasets. The results are in agreement with a comparison to CDFs by source type showing a similar pattern to those from the FIB risk classification (Figs. 2 and S6). FIB were detected in a lower proportion of samples from boreholes and in a higher proportion of samples in unprotected and protected dug wells.

3.4. Between study analysis

The likelihood of self-supply contamination was significantly higher when sources were unimproved and for low-income settings. Meta-regression showed that self-supply sources classified as unimproved were significantly more likely to be contaminated with FIB than improved sources (OR = 8.19, 95% CI [4.04–16.59], $p<0.001$) (Table 4). The odds of microbial contamination were 9.18 times (95% CI [5.00–16.84], $p<0.001$) higher for dug wells compared with boreholes. Similarly, the likelihood of a high level of microbial contamination (>100 FIB per 100 mL) was significantly greater in unimproved compared to improved sources (OR = 27.72, 95% CI [3.80–202.12], $p = 0.001$) and in dug wells compared to boreholes (OR = 19.31, 95% CI [3.26–114.23], $p = 0.001$). Protected dug wells were significantly more frequently contaminated with >1 FIB per 100 mL than boreholes (OR = 9.68, 95% CI [2.92, 32.04], $p<0.001$). Country-level of income status was a significant predictor of microbial contamination, with odds of contamination (>1 FIB per 100 mL) being 3.85 (95% CI [1.85–7.69], $p<0.001$) higher for low-income countries compared with wealthier countries. Odds of a high level contamination (>100 FIB per 100 mL) were 5.26 (95% CI [1.30–33.33], $p = 0.092$) higher for low-income countries. No statistically significant results were found comparing FIB

Table 2
Self-supply studies incorporated in the systematic literature review.

Study	Region	Setting	Self-supply type	FIB parameter
Korfali and Jurdi (2009)	Lebanon	Urban	Borehole	*E. coli*
Korfali and Jurdi (2007)	Lebanon	Urban	Borehole	*E. coli*
Nogueira et al. (2003)	Brazil	Urban and rural	Unclassified well	TTC
Kumpel et al. (2017)	Nigeria	Urban	Borehole	*E. coli* and TTC
Kumpel et al. (2016)	Nigeria	Urban	Borehole	TTC
Ngasala et al. (2019)	Tanzania	Urban	Unclassified	*E. coli*
Knappett et al. (2013)	Bangladesh	Rural	Borehole	*E. coli*
Mukhopadhyay et al. (2012)	India	Urban and rural	Unclassified dug well	*E. coli*
Potgieter et al. (2006)	South Africa	Rural	Borehole	TTC
Martínez-Santos et al. (2017)	Mali	Rural	Unclassified dug well	TTC
MacCarthy et al. (2013)	Madagascar	Urban	Borehole	TTC
Ejechi and Ejechi (2008)	Nigeria	Urban	Borehole	TTC
Gorter et al. (1995)	Nicaragua	Rural	Unprotected and protected dug well	TTC
Vaccari et al. (2010)	Thailand	Rural	Unclassified dug well	*E. coli* and TTC
Metwali (2003)	Yemen	Urban	Unclassified	TTC
Ebner et al. (2018)	Afghanistan	Urban	Unclassified	*E. coli*
Maran et al. (2016)	Brazil	Urban	Borehole and unclassified	*E. coli*
Ali et al. (2019)	Pakistan	Unclassified	Unprotected dug well	TTC
Schram and Wampler (2018)	Haiti	Rural	Unclassified dug well	*E. coli*
Butterworth et al. (2013)	Ethiopia	Rural	Unprotected and protected dug well	TTC
Ravenscroft et al. (2017)	Bangladesh	Rural	Borehole	TTC
Vollaard et al. (2005)	Indonesia	Urban	Borehole and unprotected dug well	TTC
Díaz-Alcaide and Martínez-Santos (2019)	Mali	Rural	Unprotected and protected dug well	TTC
Adams et al. (2016)	Nigeria	Urban	Borehole	*E. coli*
Baloyi and Diamond (2019)	South Africa	Rural	Borehole and unclassified dug well	*E. coli*
Davoodi et al. (2018)	Iran	Urban	Unclassified	*E. coli*
Eisenhauer et al. (2016)	Guatemala	Rural	Unprotected dug well	*E. coli*
Van Geen et al. (2011)	Bangladesh	Rural	Borehole	*E. coli*
Pujari et al. (2012)	India	Urban	Unclassified	TTC
Luby et al. (2008)	Bangladesh	Urban	Borehole	*E. coli* and TTC

contamination in urban versus rural settings and in wet versus dry season.

3.5. Within study analysis

Significantly higher likelihood of FIB contamination was found for self-supply water sources compared to public water sources. Meta-analysis of studies containing water quality FIB data from both self-supply and alternative public sources showed that self-supply is more likely to be contaminated (pooled OR = 3.29, 95% CI [1.79–6.04], $p<0.001$) (Fig. 3 and Table 5). Heterogeneity was high ($I^2 = 90.9\%$), indicating that contamination varies across settings. Similarly, comparing self-supply with piped public sources indicated that self-supply was more likely to be contaminated than public piped sources (pooled OR = 3.45, 95% CI [1.52–7.82], $p = 0.003$). Heterogeneity was relatively high with $I^2 = 83.1\%$. Self-supply source types included both improved and unimproved sources. Public source types were dominated by piped water followed by other improved public sources and included only one unimproved water source. For a small number of studies the OR was smaller than one, indicating that in some settings self-supplied water is less likely to contain FIB than the public water sources (Ejechi and Ejechi, 2008). When comparing improved self-supply sources with improved public sources, odds of faecal contamination were again higher for self-supply (OR = 3.55, 95% CI [1.46–8.66], $p = 0.005$, $I^2 = 77.8\%$) (Fig. 3).

Table 3
Characteristics of included studies.

Characteristics	Studies	Datasets	Samples
	Number (%)	Number (%)	Number (%)
Setting			
Urban	15 (50.0)	28 (28)	7694 (28.5)
Rural	12 (40.0)	65 (65)	9370 (34.7)
Urban and rural	2 (6.7)	2 (2)	430 (1.6)
Unclassified setting	1 (3.3)	5 (5)	9561 (35.4)
Income group			
Upper-middle	8 (26.7)	20 (20)	7006 (26.0)
Lower-middle	15 (50.0)	72 (72)	19,313 (71.6)
Low	7 (23.3)	8 (8)	662 (2.5)
Source type			
Borehole	15 (50.0)	35 (35)	8953 (33.2)
Protected dug well	2 (6.7)	9 (9)	468 (1.7)
Unprotected dug well	6 (20.0)	36 (36)	11,662 (43.2)
Unclassified dug well	5 (16.7)	8 (8)	297 (1.1)
Unclassified	7 (23.3)	12 (12)	5601 (20.8)
Design			
Cross-sectional survey	24 (80.0)	50 (50)	8038 (29.8)
Longitudinal survey	5 (16.7)	18 (18)	10,248 (38.0)
Cohort study	1 (3.3)	27 (27)	1523 (5.6)
Intervention	1 (3.3)	5 (5)	9561 (35.4)
Randomized	12 (40.0)	47 (47)	13,512 (50.1)
Parameter			
E. coli	16 (53.3)	29 (29)	8878 (32.9)
TTC	16 (53.3)	72 (72)	18,103 (67.1)
Results FIB			
Noncompliance	27 (90.0)	70 (70)	24,266 (89.9)
Risk classification	13 (43.3)	31 (31)	12,311 (45.6)
Other (Mean, Median, Range)	13 (43.3)	71 (71)	6709 (24.9)
Surveys			
Household survey	9 (30.0)	49 (49)	3456 (12.8)
Sanitary survey	12 (40.0)	33 (33)	12,159 (45.1)
Seasons			
All (differentiated)	5 (16.7)	NA	NA
All (not differentiated)	6 (20.0)	19 (19)	10,885 (40.3)
Wet	11 (36.7)	20 (20)	2467 (9.1)
Dry	14 (46.7)	51 (51)	3828 (14.2)
Not mentioned	4 (13.3)	10 (10)	9801 (36.3)
Sample size[a]			
Smaller (n = 3–43)	NA	50 (50)	1018 (3.8)
Larger (n = 44–4834)	NA	50 (50)	25,963 (96.2)
Quality[b]			
Lower (1–6)	15 (50.0)	30 (30)	7908 (29.3)
Higher (7–10)	15 (50.0)	70 (70)	19,073(70.7)
Total	30 (100.0)	100 (100.0)	26,981 (100)

[a] Median by datasets of the total sample number.
[b] Median by studies of the total quality score.

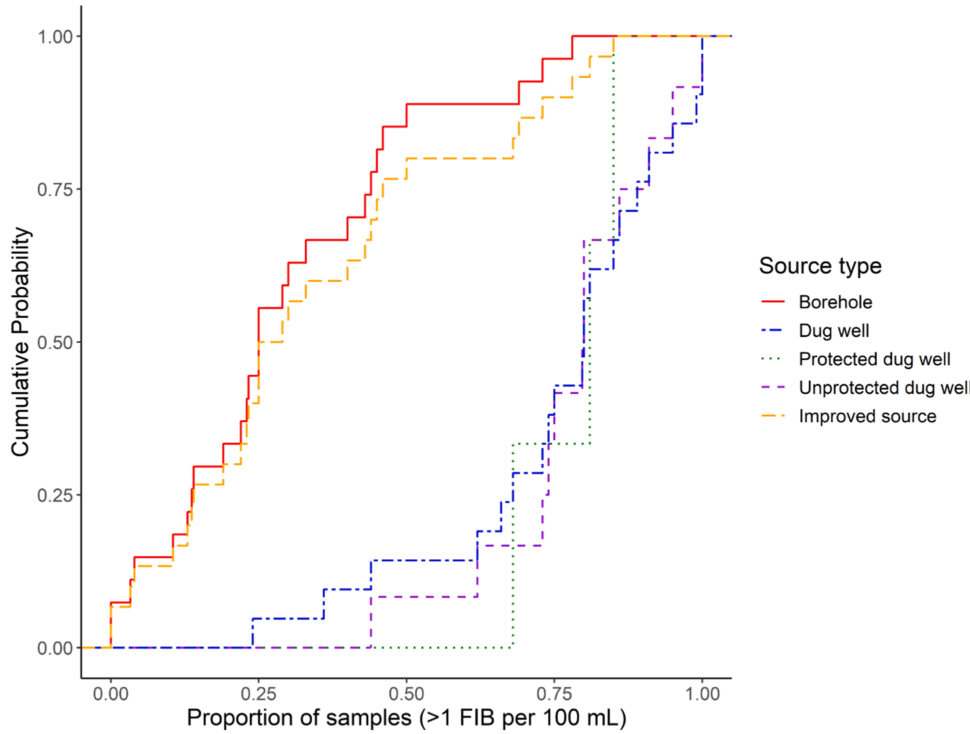

Fig. 2. CDF shows higher proportion of samples with >1 FIB per 100 mL for dug wells.

Table 4
Between study meta-regression.

Variables	Proportion of Samples > 1 FIB per 100 mL			Proportion of samples > 100 FIB per 100 mL		
	Obs.	OR [95% CI]	p-Value	Obs.	OR [95% CI]	p-Value
Setting						
Urban versus rural	54	0.64 [0.33–1.24]	0.184	15	2.25 [0.53, 9.62]	0.275
Low-income versus Other (Upper-middle and lower-middle)	57	**3.85 [1.85–7.69]**	**<0.001**	15	5.26 [1.30, 33.33]	0.092
Source type						
Dug well versus Borehole	48	**9.18 [5.00–16.84]**	**<0.001**	12	**19.31 [3.26, 114.23]**	**0.001**
Protected versus Unprotected dug well	15	0.93 [0.32–2.75]	0.901	–	–	–
Unimproved versus Improved	42	**8.19 [4.04–16.59]**	**<0.001**	11	**27.72 [3.80, 202.12]**	**0.001**
Protected dug well versus Borehole	30	**9.68 [2.92–32.04]**	**<0.001**	–	–	–
Study characteristics						
Wet versus dry	34	1.34 [0.50, 3.54]	0.562	7	1.02 [0.07, 13.94]	0.987
TTC versus *E. coli*	57	**1.92 [1.09, 3.38]**	**0.025**	15	1.08 [0.22, 5.37]	0.929
Random versus non-random selection	57	1.19 [0.63, 2.25]	0.588	15	0.71 [0.19, 2.61]	0.610

3.6. Assessment of bias

Egger's test found no evidence of small study publication bias for the meta-analysis of self-supply compared to alternative public water sources ($p = 0.964$, Figs. S7 and S8), self-supply compared to public piped water sources ($p = 0.293$, Fig. S9) or improved self-supply compared to improved public sources ($p = 0.170$, Fig. S10). Meta-regression did not find significant evidence of bias due to lack of randomization or season (Table 4). TTCs were significantly more likely to be reported as a FIB parameter in studies where water was more contaminated (OR = 1.92, 95% CI [1.09–3.38], $p = 0.025$) and therefore may exaggerate comparisons between studies reporting results in *E. coli* and TTC. Studies classified with lower quality ranking scores below 7 were significantly more likely to report faecal contamination (OR = 3.19, 95% CI [1.75–5.80], $p<0.001$) than higher ranked studies. Studies which did not describe selection or handling and did not meet handling minimum criteria reported were significantly more likely to report presence of FIB per 100 mL (Table S11). Study design might also influence bias in estimates of non-compliance, with significantly higher odds of FIB detection for cross-sectional studies (OR = 4.22, 95% CI [2.43–7.34], $p<0.001$).

4. Discussion

This systematic review of studies shows groundwater self-supply in LMICs is commonly contaminated with FIB. Meta-analysis between studies demonstrated that unimproved groundwater self-supply (i.e. unprotected dug wells) was more likely to be contaminated with FIB than improved sources such as boreholes or protected dug wells (OR = 8.19, 95% CI [4.04–16.59], $p<0.001$). Likewise, CDFs and FIB risk classification showed more frequent FIB contamination for unimproved self-supply sources. These findings are consistent with previous analysis of microbial contamination in groundwater sources more broadly (Bain et al., 2014b). Nonetheless, faecal contamination was still frequently reported for self-supply in the form of boreholes (28% of samples) and protected dug wells (77% of samples), suggesting well protection alone does not fully address water quality problems for self-supply sources. Even with protection, self-supply systems often rely on low-cost technologies and construction techniques, and draw on shallow groundwater sources, which may make them vulnerable to contamination from

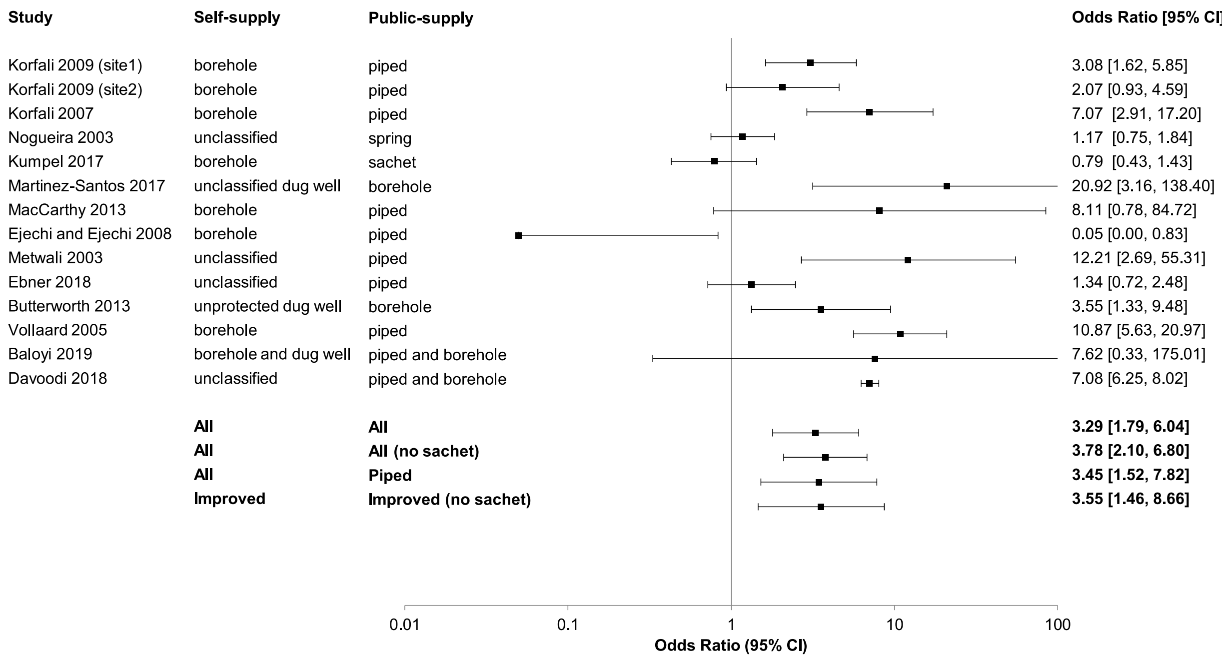

Fig. 3. Forest plot showing higher odds of faecal contamination for self-supply versus public sources.

Table 5
Meta-analysis for self-supply versus public water sources with higher odds ratio for FIB contamination for self-supply sources.

Study	Proportion of Samples > 1 FIB per 100 mL		
	Obs.	OR [95% CI]	p-Value
Self-supply versus public (excluding sachet water)	13	**3.78 [2.10–6.80]**	**<0.001**
Self-supply versus public (including sachet water)	14	**3.29 [1.79–6.04]**	**<0.001**
Self-supply versus piped	8	**3.45 [1.52–7.82]**	**0.003**
Self-supply improved versus public improved	7	**3.55 [1.46–8.66]**	**0.005**

human activities (Grönwall and Danert, 2020). However, previous studies have found similarly widespread FIB contamination for boreholes and protected wells generally (Bain et al., 2014b), and so these water quality risks are not necessarily unique to self-supply.

The reviewed studies reported a range faecal contamination risks including on-site sanitation systems and poor well condition, however few studies rigorously assessed contamination pathways. Sanitary risk inspections are recommended by the WHO drinking water guidelines as a technique to identify poor hygiene and inadequate sanitation as potential risks of faecal contamination (WHO, 2011). Less than half of the reviewed studies conducted sanitary inspections ($n = 12$, 40%), and only three of the reviewed studies conducted sanitary risk inspections according to the WHO guidelines (Kumpel et al., 2017; Luby et al., 2008; Vaccari et al., 2010). Limited data are available on the relationship between contamination of self-supply and sanitary score, suggesting more research is needed to identify important sanitary risk factors.

This study provides evidence that risk of faecal contamination of groundwater self-supply varies across contexts. Microbial water quality was highly heterogeneous ($I^2 = 90.9\%$) between studies, with higher risk of faecal contamination in low-income settings (OR = 3.85, 95% CI [1.85–7.69], $p<0.001$). While Bain et al. (2014a) found rural water sources were at higher risk of contamination, between study analysis of self-supply sources did not find a significant difference in the odds of contamination for rural versus urban locations. The heterogeneity observed may reflect a diversity of environmental conditions and possible contamination sources, including on-site sanitation (Díaz-Alcaide and Martínez-Santos, 2019; Kumpel et al., 2017, 2016; Martínez-Santos et al., 2017; Ngasala et al., 2019) or poor condition of wells and inadequate protection (Ali et al., 2019; Butterworth et al., 2013; Knappett et al., 2013; MacCarthy et al., 2013; Vaccari et al., 2010). The variety of self-supply sources in purpose and form, along with the different risks and benefits in different contexts, means that government policies, regulation and support need to be designed to meet a range of local conditions (Sutton and Butterworth, 2021).

Meta-analysis demonstrated that faecal contamination was less common in piped water. Even when self-supply was improved, piped water was still less likely to be contaminated (Fig. 3). These results suggest that, in general, households should be encouraged and supported to switch to piped supply where possible. However, this differential does not always hold, with Ejechi and Ejechi (2008) reporting significantly lower odds of *E. coli* contamination in borehole water as compared to piped water in urban Nigeria. It should be considered that faecal contamination affects all types of water sources, including piped water (Bain et al., 2014a, 2014b). Due to the limited number of studies that included both self-supply and communal groundwater sources, it was not possible to draw conclusions from the meta-analysis on whether the likelihood of contamination differs between self-supplied and communal groundwater sources. Notably, some studies showed that in areas where piped systems provide safer water, there were households that still preferred to self-supply their drinking water. Further research is needed to understand why in some contexts households might prefer self-supply over piped water, and how these preferences vary across different contexts. Possible reasons why people may prefer self-supply over piped water include convenience and reduced travel time to collect water (compared with public taps), increased water availability (where piped systems provide an intermittent supply), organoleptic properties, and enhanced status and reputation (Capstick et al., 2017; Sutton and Butterworth, 2021).

In areas where piped networks are not possible, supporting households to invest in safer forms of self-supply could reduce the risk of faecal contamination. Piped systems are not always feasible, particularly in sparsely populated rural areas, and self-supply may provide a critical stepping stone or stopgap for households. The meta-analysis indicated significantly lower risk of contamination for improved sources compared with unimproved sources. Similarly, boreholes were significantly less likely to be contaminated than both protected dug wells and unprotected wells. Where piped services remain infeasible, policy and practice should look to support investments in safer forms of self-supply. For example, an incremental approach to self-supply source protection has been implemented in parts of rural Africa (Butterworth et al., 2013; Sutton, 2011).

The results of the meta-analysis may reflect socio-economic inequalities. On a broad scale, the meta-analysis reveals that the risk of contaminated self-supply is higher in low-income countries. On a local scale, self-supply is often seen as a result of socio-economic inequality linked to a lack of water service expansion or poor service quality for the poorest (Furlong and Kooy, 2017; Hadipuro, 2010; Kooy et al., 2018; Kurniasih, 2008). Moreover, the poorest may be less able to invest in safer forms of self-supply, and may be more reliant on shallow groundwater that is vulnerable to contamination. Thus there is a need for reliable provision of piped services and inclusive approaches to increase equity of access. Financing strategies for water quality improvements through source protection and household water treatment could also help address these inequalities (Sutton and Butterworth, 2021).

Notwithstanding water quality concerns, availability and reliability of water is an important consideration when evaluating the role of self-supply in securing water for domestic needs. Water from self-supply can be used for different purposes beyond just drinking – including productive uses – and can supplement other sources that might provide higher quality water for drinking. For example, a study in Kenya reports that residents use private hand-dug wells that provide substantial volumes of water for purposes other than drinking and cooking (Okotto et al., 2015). When considering to what extent self-supply water is available in sufficient quantities when needed, it is important to factor in different water uses. There is also evidence to suggest in certain contexts self-supply can be more reliable than public sources (Butterworth et al., 2013; Foster et al., 2018). Investing in self-supply and being the primary beneficiary are seen as powerful motivators to ensure systems are sustained (Sutton and Butterworth, 2021).

A limitation of the meta-analysis is the variability in study design reported by the included papers. Studies were combined that used *E. coli* and TTC as a faecal indicator, and studies reported different handling and microbiological analytical methods. Meta-analysis showed significantly higher odds of faecal contamination for studies measuring TTC as compared to *E. coli* (OR = 1.92, 95% CI [1.09, 3.38], $p = 0.025$). Moreover, FIB - whether TTC or *E. coli* – are an indicator for faecal contamination and the presence or absence of FIB does not definitively confirm the presence or absence of pathogens (Charles et al., 2020). Further, only one-third of the reviewed studies ($n = 11$) tested the water quality considering both seasons. To ensure water safety, infrequent testing of water for FIB and subsequent interpretation of the health hazard is not sufficient to identify and manage risks.

The quality of the included studies was mixed. In the included studies, sample selection was often not described, representative or randomized, and quality control was not often mentioned. Method and sampling was mostly described, however handling minimum criteria was only reported to be met by 63% of the studies. Studies with a lower quality ranking score reported significantly higher odds of faecal contamination and thus might have caused bias. Meta-analysis resulted in significantly higher odds for FIB positive samples in cross-sectional studies (OR = 4.22, 95% CI [2.43–7.34], $p<0.001$). One possible explanation is that cross-sectional studies were more likely to be conducted in low-income countries. It is also important to note that study sites may have been biased towards locations where faecal contamination of groundwater supplies is perceived to be a problem. This could lead to an overestimation of the extent of faecal contamination in self-supply sources.

The review revealed a relatively small number of studies that have examined microbial quality of self-supplied groundwater in low- and middle-income countries. Within those studies that were identified, very few have rigorously assessed the links between groundwater quality and contamination risks. There is a need to understand water quality and associated contamination risks of self-supply services specifically. Further, studies included in this review focused on measuring water quality at source, neglecting the point-of-use. There is also a lack of information regarding management, storage and treatment practices in households using groundwater self-supply water services and how it relates to the water quality at point-of-use. It is known that the quality of water from improved sources deteriorates significantly after collection, due to different factors such as water storage conditions and post handling practices, and is not necessarily safe at point-of-use (Clasen and Bastable, 2003; Gundry et al., 2006; Lechevallier et al., 1996; McGuinness et al., 2020; Meierhofer et al., 2018; Shaheed et al., 2014; Shields et al., 2015; Trevett et al., 2005; Wright et al., 2004). Considering water quality of self-supply at point-of-use is crucial, since self-supply is on-premises and transport, distribution and storage practices might differ from other water supply types. There is a need to understand water management and treatment practices of self-supply users as well as assessing the microbial water quality at point-of-use during distribution, storage and before consumption. Studies also rarely compared self-supply sources with alternative public service delivery models, which is crucial to evaluate risk and benefits of self-supply as a potential service delivery model. More research is needed in different contexts to understand how self-supply compares to public water sources.

Self-supply is largely unmonitored and unregulated and hence the quality of self-supplied water has been rarely if ever systematically tracked. This has direct implications for monitoring progress towards SDG target 6.1 (universal access to safely managed water services). Self-supplied water is accessible on-premises and hence may contribute to one part of a country's 'safely-managed water' statistic. However, in many countries the data used to inform the 'free from contamination' dimension are derived from utilities providing a treated piped supply to households (WHO/UNICEF, 2018). According to WHO and UNICEF (2018), water quality data for piped supplies is applied towards the entire population using improved supplies as long as the population to which the data relate is at least 80% of the population of interest . When deriving national estimates, the Joint Monitoring Programme treats the safely managed water criteria independently, with the minimum value across the three indicators used to estimate the proportion of the population using a safely managed water service (WHO, 2017). Thus if self-supply counts towards the 'on premises' criterion, but is excluded from the 'free from contamination' calculation, it could lead to an overestimation in the proportion of households that truly have access to safely managed water services. The incorporation of water quality testing into nationally representative surveys (e.g. Multiple Indicator Cluster Surveys) that cover all types of water sources, including self-supply, is one way in which this bias can be addressed.

Policy and practice need to respond to water quality concerns of self-supply. Government and non-governmental support for household investment in safer forms of self-supply can improve the quality and sustainability of self-supply (Sutton and Butterworth, 2021). Self-supply should be considered in water safety planning, including necessary parts such as promotion of household water treatment and hygienic practices. Where piped networks are feasible, governments need to weigh the cost-benefit of supporting self-supply improvements with expansion and improvement of piped water supplies. The scale of continued investment in self-supply highlights the need for policy-makers to consider regulatory and monitoring systems for self-supply (Fischer et al., 2020).

5. Conclusion

This literature review and meta-analysis demonstrated that groundwater self-supply in LMICs often contains FIB, with contamination in 36% of samples across the included studies. Unimproved self-supply sources had more frequent and higher levels of faecal contamination than improved sources, while faecal contamination was more likely in self-supply than in piped water sources. Where piped systems are not feasible, supporting households to invest in safer forms of self-supply could reduce the risk of faecal contamination. Self-supply as a service delivery model needs government recognition and differentiated support for the different circumstances in which it is present.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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