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Research Paper

Associations between seasonality and faecal contamination of self-supply sources in urban Indonesia

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ABSTRACT

Water quality monitoring that accounts for seasonal variability is crucial to ensure safe water services at all times, including groundwater self-supply, which provides drinking water for more than 40 million people in urban Indonesia. Seasonal variation of self-supply water quality remains a key evidence gap in Indonesia and elsewhere; therefore, this study investigated the associations between seasonality and faecal contamination of groundwater self-supply in the Indonesian cities of Bekasi and Metro. The study demonstrated mixed results in terms of associations between seasonality and microbial water quality. McNemar's test showed that high concentrations of *Escherichia coli* (*E. coli*) (≥100 MPN per 100 mL) were significantly more likely during the wet season than during the dry season in Bekasi ($p = 0.050$), but not in Metro ($p = 0.694$). There was no statistically significant association between the season and the presence of *E. coli* in self-supply sources for both study sites, nor was there a significant association between the season and the presence of high concentrations of *E. coli* at the point-of-use. At both study sites, presence and high concentrations of *E. coli* during the dry season significantly increased the risk of contamination in the wet season, but the predictive power was weak. Regular water quality testing complemented by sanitary inspection is required to understand the contamination risks of self-supply sources.

Key words: drinking water quality, faecal contamination, groundwater, seasonality, self-supply, urban Indonesia

HIGHLIGHTS

- Insights into the relationship between seasonality and water quality of self-supply.
- Implications for self-supply water quality monitoring in urban Indonesia.
- Highlighting the need for regular water quality testing, complemented with sanitary inspections.

INTRODUCTION

Groundwater self-supply provides drinking water to hundreds of millions of households in low-and middle-income countries (LMICs), including more than 40 million people in urban Indonesia (Foster *et al.* 2021). Household self-supply relying on groundwater refers to on-premises boreholes or dug wells that are typically self-financed and self-managed by individual households (Grönwall & Danert 2020). Being located on a user household's premises, self-supply could have the potential to provide a safely managed water service, which is defined as an improved water source accessible on-premises, available in sufficient quantities when needed and free from faecal and chemical contamination (WHO and UNICEF 2017). However, self-supply services are generally unregulated and unmonitored (Grönwall *et al.* 2010; Grönwall & Danert 2020; Foster *et al.* 2022), resulting in insufficient knowledge of water quality risks such as faecal contamination.

Faecal contamination of unregulated self-supply services remains a prime concern in urban Indonesia, and elsewhere. A systematic review of 30 studies in different LMIC contexts found that faecal indicator bacteria were present in 36% of self-supply sources, including 28% of samples from boreholes, 81% of samples from unprotected wells, and 77% of samples from protected wells (Genter *et al.* 2021). Among the 15 studies conducted in urban areas, faecal indicator bacteria were reported in 34% of self-supply sources (Genter *et al.* 2021). A recent study from urban Indonesia assessed sanitary and socio-economic risk factors of microbial contamination of groundwater self-supply and detected faecal contamination in 66% of household groundwater self-supply sources in two cities, with unprotected dug wells being more prone to contamination than boreholes (Genter *et al.* 2022). Despite widespread boiling practices in the study sites, faecal contamination was detected in 30% of the drinking water samples at point-of-use (Genter *et al.* 2022).

Monitoring of faecal contamination of drinking water is usually based on faecal indicator bacteria. The presence of *Escherichia coli* (*E. coli*) in a 100 mL water sample is the recommended measure of faecal contamination by the World Health Organization (WHO) (WHO 2022). The WHO states as a guideline value that no *E. coli* should be detected in any 100 mL sample (WHO 2022). Water quality monitoring relies often on a single or infrequent test of water for *E. coli* due to limited resources (Kostyla *et al.* 2015; Charles *et al.* 2020). Considering only one season (e.g. wet or dry season) in testing is a particular concern for evaluating water safety (Kostyla *et al.* 2015), as understanding variability (seasonal or otherwise) in occurrence and detection of *E. coli* is necessary to identify and manage threats (Charles *et al.* 2020). Information on the relationship between *E. coli* data from the dry and wet seasons can also provide insight into seasonal bias in sampling at individual time points.

It is known that seasonal effects can impact water quality (Kostyla *et al.* 2015; Bain *et al.* 2021; Nijhawan & Howard 2022), however most studies on water quality are cross-sectional, especially those focusing on self-supply. This may lead to seasonal bias, meaning contamination risks may be under- or overestimated (Bain *et al.* 2014; Genter *et al.* 2021). In a systematic review of faecal contamination of groundwater self-supply in LMICs (Genter *et al.* 2021), only five of the 30 self-supply studies distinguished between water quality in the wet and dry season (Potgieter *et al.* 2006; Pujari *et al.* 2012; Butterworth *et al.* 2013; Knappett *et al.* 2013; Adams *et al.* 2016) and six covered water quality measurements during both seasons but did not differentiate between the seasons (Nogueira *et al.* 2003; Vollaard *et al.* 2005; Van Geen *et al.* 2011; Ravenscroft *et al.* 2017; Davoodi *et al.* 2018; Ebner *et al.* 2018). Other included studies either focused on one season or did not document the season in which data collection took place (Genter *et al.* 2021). Similarly, in the aforementioned study on urban Indonesia, seasonality could not be directly assessed as a risk factor since water quality of self-supply sources was tested during the wet season in one city, and during the dry season in the other city (Genter *et al.* 2022). With climate change leading to more intense rainfall and dry periods (IPCC 2021), there is an urgent need to consider seasonal variability and its influence on faecal contamination and to improve long-term monitoring with more strategically planned water testing to inform drinking water safety (Nijhawan & Howard 2022). Therefore, this study aims to assess the seasonality aspect of microbial water quality in groundwater self-supply sources in urban Indonesia.

METHODS

The study was undertaken in the Indonesian cities of Bekasi and Metro (Supplementary material, Figure S1). Data were collected during the wet season (Bekasi: February–March 2020, Metro: February–March 2022), and during the dry season (Bekasi: October 2021, Metro: October–November 2020).

During the months in which the dry season sampling took place in Metro (October–November 2020), 12 rainy days were recorded with precipitation totalling 163 mm (BPS Kota Metro 2021). In comparison, Metro recorded a total of 22 rainy days with precipitation totalling 604 mm in the wet season months of February and March of the same year (BPS Kota Metro 2021). During the months in which the wet season sampling took place in Bekasi (February–March 2020), 60 rainy days were recorded with precipitation totalling 2,553 mm (BPS Kota Bekasi 2021). In comparison, the preceding dry season months of October and November 2019 yielded 16 rainy days with precipitation totalling 332 mm (BPS Kota Bekasi 2020, 2021).

Concentration of faecal indicator bacteria *E. coli* was quantified for self-supply sources and at point-of-use using IDEXX Colilert-18 and the IDEXX Quanti-Tray®/2000 system based on the most probable number (MPN) approach according to manufacturer's instructions (IDEXX Laboratories, 2015). Matched samples for wet and dry seasons included 204 and 217 self-supply sources, respectively (Supplementary material, S1). These self-supply sources included private boreholes (Bekasi: $n = 186$, Metro: $n = 58$) and dug wells (Bekasi: $n = 18$, Metro: $n = 159$). The majority of dug wells were unprotected (>85%). At point-of-use, 41 and 50 drinking water samples in Bekasi and Metro were from self-supply sources.

See Genter *et al.* (2022) for more information on the study sites, data collection, water quality testing, and quality control procedures.

Water quality samples for wet and dry season were matched considering the household ID and water source type using Microsoft Office Excel 2016. Source types categorized as unprotected and protected dug wells were considered as dug wells. In Bekasi, 39 and 51 samples and in Metro, 61 and 60 samples for wet and dry season, respectively, could not be assigned and were excluded due to the use of different water sources in the wet and dry seasons. *E. coli* concentration for each self-supply source type and season were classified into WHO health risk classes of 'safe or low', 'intermediate', 'high', or 'very high' for water samples with <1, 1–9, 10–99, ≥ 100 *E. coli* counts per 100 mL, respectively. Statistical analysis software R (version 1.2.5001, R Foundation for Statistical Computing, Vienna, Austria) was used for analysis. To determine whether microbial water quality differs between wet and dry seasons, *E. coli* concentration was comparatively assessed using paired samples Wilcoxon test and McNemar's test. Wilcoxon test assesses *E. coli* as a continuous variable, while McNemar's test assesses it as a dichotomous variable. Effect size (r) for Wilcoxon test was calculated by dividing the test statistic (Z) by the square root of the number of observations (n) (Pallant 2007). The proportion of samples with the presence of *E. coli* and high concentrations (≥ 100 MPN per 100 mL) of *E. coli* were calculated.

To investigate whether single time-point water samples are adequate, logistic regression analysis was performed to predict whether *E. coli* contamination present in dry season increases risk in the wet season (Supplementary material, S2). Presence/absence of *E. coli* and high concentration of *E. coli* (cut-off value 100 MPN) during dry season was used to build a logistic regression model (R package: tidyverse) predicting the probability of *E. coli* being present during the wet season. Spearman's rank correlation rho was calculated to assess the correlation between *E. coli* counts from wet and dry season samples (R package: ggpubr)

Information on whether households had recently experienced flooding was obtained from the household survey (Genter *et al.* 2022). Households in Bekasi ($n = 300$) and Metro ($n = 300$) were asked (yes/no) if there has been any flooding in or around the house in the last 12 months in Bekasi and in the last month in Metro. Paired samples Wilcoxon test and McNemar's test were used to assess whether *E. coli* concentration and presence in self-supply sources differs between wet and dry seasons specifically for households that experienced flooding in the past months during rainy season.

RESULTS

E. coli was frequently detected in self-supply sources in Bekasi and Metro during wet and dry seasons. Self-supply sources in Bekasi were dominated by boreholes ($n = 186$), while dug wells ($n = 159$) were common in Metro (Table 1). In Bekasi, *E. coli*

Table 1 | *Escherichia coli* contamination in self-supply sources and drinking water from households in Bekasi and Metro

	Bekasi					Metro				
		Wet season		Dry season			Wet season		Dry season	
	Total n	≥1 MPN/100 mL, *n* (%)	≥100 MPN/100 mL, *n* (%)	≥1 MPN/100 mL, *n* (%)	≥100 MPN/100 mL, *n* (%)	Total, *n*	≥1 MPN/100 mL, *n* (%)	≥100 MPN/100 mL, *n* (%)	≥1 MPN/100 mL, *n* (%)	≥100 MPN/100 mL, *n* (%)
Sources										
Borehole	186	97 (52.2)	35 (18.8)	92 (50.5)	23 (12.4)	58	34 (58.6)	10 (17.2)	30 (51.7)	6 (10.3)
Dug well	18	16 (88.9)	6 (33.3)	12 (66.7)	4 (22.2)	159	128 (80.5)	56 (35.2)	126 (79.2)	64 (40.3)
All self-supply sources	204	113 (55.4)	41 (20.1)	104 (51.0)	27 (13.2)	217	162 (79.4)	66 (30.4)	156 (71.9)	70 (32.3)
All sources (including public sources)	219	124 (56.6)	46 (21.0)	115 (52.5)	30 (13.7)	236	171 (72.5)	67 (28.4)	166 (70.3)	71 (30.1)
Point-of-use										
Borehole	33	11 (33.3)	1 (3.0)	9 (27.3)	1 (3.0)	19	6 (31.6)	0 (0.0)	5 (26.3)	2 (10.5)
Dug well	8	3 (37.5)	0 (0.0)	1 (12.5)	0 (0.0)	31	9 (29.0)	2 (6.5)	15 (48.4)	4 (12.9)
All self-supply sources	41	14 (34.1)	1 (2.4)	10 (24.4)	1 (2.4)	50	15 (30.0)	2 (4.0)	20 (40.0)	6 (12.0)
All sources (including refill and bottled water)	55	17 (30.9)	1 (1.8)	14 (25.5)	1 (1.8)	69	22 (31.9)	4 (5.8)	23 (33.3)	6 (8.7)

was present in 55% ($n = 113$) and 51% ($n = 104$) of all self-supply sources during wet and dry seasons, respectively. In Metro, *E. coli* was detected in 79% ($n = 162$) of self-supply sources during the wet season and 72% ($n = 156$) of self-supply sources during the dry season (Table 1). In Bekasi, the proportion of dug wells with high concentrations of *E. coli* (≥100 MPN) was 33% ($n = 6$) in the wet season and 22% ($n = 4$) in the dry season; while the proportion of boreholes with high concentrations of *E. coli* (≥100 MPN) was 19% ($n = 35$) in the wet season and 12% ($n = 23$) in the dry season (Figure 1). Similarly, in Metro, 35% ($n = 56$) of dug wells and 17% ($n = 10$) of boreholes were in the high risk category during the wet season and 40% ($n = 64$) of dug wells and 10% ($n = 6$) of boreholes during the dry season (Figure 2).

Self-supply sources were more frequently contaminated in the wet season than in the dry season, with a statistically significant difference for high levels of contamination in Bekasi, but not in Metro. Paired samples of Wilcoxon test and McNemar's test (≥1 MPN) showed no significant difference of water quality between wet and dry seasons (Table 2). However, when applying the Wilcoxon test to water sources in Bekasi, *E. coli* concentrations were higher in wet season samples, with p-values less than 0.1 ($p = 0.054$ for all water sources including public sources, 0.078 for all self-supply samples and 0.083 for private boreholes). Applying a high level of contamination of ≥100 MPN as the cut-off, McNemar's test showed a statistically significant difference in water quality of self-supply sources between wet and dry season in Bekasi ($p = 0.050$). No statistically significant difference in water quality was found in Metro. Of the 204 and 217 households relying on self-supply in Bekasi and Metro, respectively, 8 and 12 reported having recently experienced flooding. There was no statistically significant difference in water quality between wet and dry season of self-supply water sources of households experiencing flooding (Supplementary material, S3).

At the point-of-use, *E. coli* was present in drinking water during both seasons, but at lower levels compared to the source. At the point-of-use in Bekasi, *E. coli* was detected in 31% ($n = 17$) of drinking water samples (derived from self-supply, refill and bottled water) during the wet season, and in 26% ($n = 14$) during the dry season (Table 1). Similarly, in Metro, *E. coli* was present in 32% ($n = 22$) and 33% ($n = 23$) of drinking water sources during wet and dry seasons, respectively (Table 1). There was no statistically significant difference between wet and dry seasons for both study sites (Table 2).

Presence and high concentrations of *E. coli* in self-supply sources during the dry season were a significant predictor for risk of contamination during wet season in Bekasi and Metro; however, the power of prediction was weak. The presence of *E. coli* (≥ 1 MPN) during the dry season increased the odds of contamination during the wet season by 2.51 ($p = 0.001$) in Bekasi and 3.63 ($p < 0.001$) in Metro.

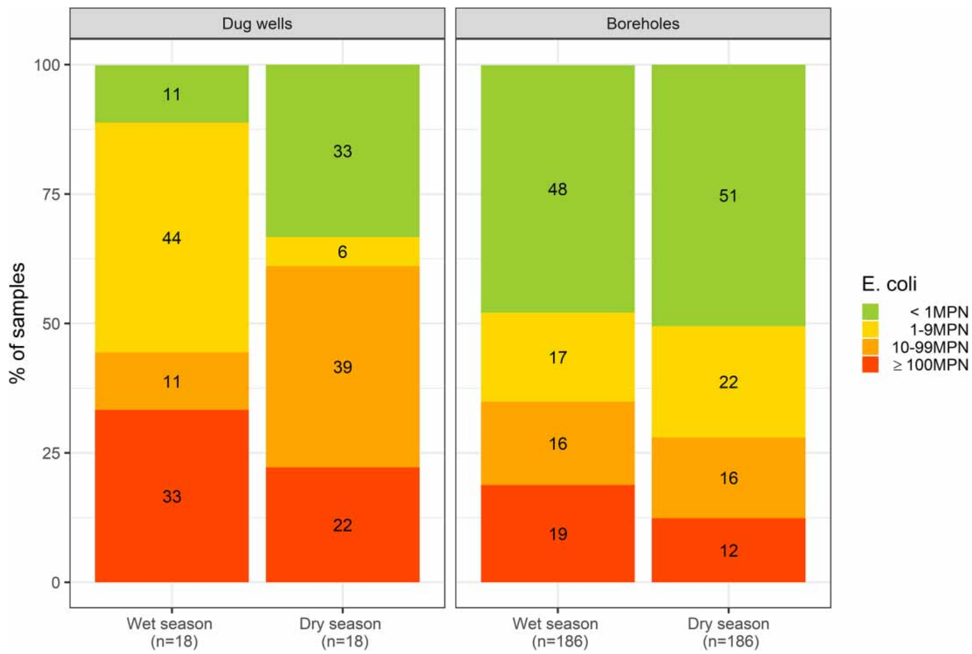

Figure 1 | Risk classification of *Escherichia coli* in self-supply sources in Bekasi City.

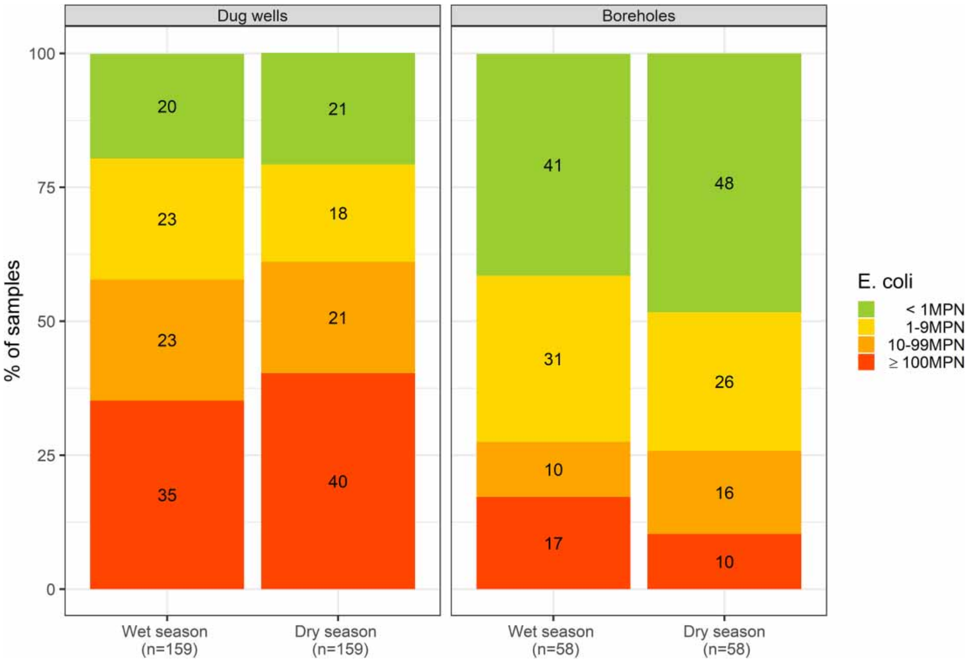

Figure 2 | Risk classification of *Escherichia coli* in self-supply sources in Metro City.

Table 2 | Comparison of *Escherichia coli* concentration using paired samples Wilcoxon and Mc Nemar's test between wet and dry seasons

	Bekasi								**Metro**							
		Paired samples Wilcoxon			**McNemar**					**Paired samples Wilcoxon**			**McNemar**			
					≥ 1 MPN		**≥ 100 MPN**						**≥ 1 MPN**		**≥ 100 MPN**	
	n	***p*-value (greater)**	***z***	***r*[a]**	X^2	***p*-value**	X^2	***p*-value**	***n***	***p*-value (greater for sources, smaller for point-of-use)**	***z***	***r*[a]**	X^2	***p*-value**	X^2	***p*-value**
Sources																
Borehole	186	0.083	1.1	0.1	0.2	0.635	3.0	0.082	58	0.399	0.4	0.1	0.4	0.540	0.9	0.343
Dug well	18	0.467	0.8	0.2	1.1	0.289	0.3	0.617	159	0.423	0.2	0.0	0.0	0.871	1.0	0.312
All self-supply sources	204	0.078	1.3	0.1	0.8	0.368	**3.8**	**0.050**	217	0.378	0.3	0.0	0.4	0.525	0.2	0.694
All sources (including public sources)	219	0.054	1.5	0.1	0.7	0.391	**4.5**	**0.034**	236	0.382	0.3	0.0	0.2	0.635	0.2	0.699
Point-of-use																
Borehole	33	0.568	0.1	0.0	0.1	0.773	–	–	19	0.383	0.1	0.0	0.0	1.0	–	–
Dug well	8	0.091	1.7	0.6	0.5	0.480	–	–	31	0.154	−1.2	−0.2	2.1	0.149	0.3	0.617
All self-supply sources	41	0.380	0.8	0.1	0.6	0.423	–	–	50	0.125	−1.0	−7.7	0.8	0.359	1.5	0.221
All sources (including refill and bottled water)	55	0.470	0.5	0.1	0.2	0.628	–	–	69	0.359	−0.1	−0.0	0.0	1.0	0.1	0.724

[a]Effect size with small effect for $r = 0.1 < 0.3$, moderate effect for $r = 0.3– < 0.5$ and large effect for $r \geq 0.5$.
Bold values indicate statistical significance ($p < 0.05$)

High concentrations of *E. coli* (≥100 MPN) during the dry season significantly increased the presence of *E. coli* during the wet season by 5.56 ($p = 0.002$) in Bekasi and by 5.33 ($p < 0.001$) in Metro.

McFadden pseudo-R^2 indicated weak predictive power with pseudo-R^2 values for the presence and high levels of *E. coli* of 0.04 and 0.04 in Bekasi and 0.06 and 0.07 in Metro.

Spearman's rank test indicated a weak positive correlation between *E. coli* counts from wet and dry season samples in Bekasi ($\rho = 0.31$, $p < 0.001$) and Metro ($\rho = 0.55$, $p < 0.001$).

DISCUSSION

This study did not find any significant seasonal differences in the presence of faecal contamination in either Kota Bekasi or Kota Metro. A possible explanation for the lack of a significant association between the *E. coli* presence and the season could be the dominance of contamination sources that are unaffected by rainfall. For instance, several risk factors such as on-site sanitation, a lack of well protection, and manual water lifting devices (e.g. rope and bucket) can lead to faecal contamination of self-supply systems irrespective of rainfall. The findings from this study stand as a contrast to a recent systematic review of 22 studies in LMICs which showed a statistically significant seasonal trend of greater contamination in improved drinking water sources during the wet season (Kostyla *et al.* 2015). Despite the non-significant difference between seasons, our study showed that self-supply sources were frequently contaminated in both the wet and dry seasons, highlighting the need to better understand the complexity of the various risk factors of faecal contamination in self-supply sources.

A significantly increased risk of a high level of *E. coli* contamination during the wet season was observed in Bekasi, but not in Metro. Self-supply in Bekasi consists primarily of boreholes, which are improved water sources and less susceptible to contamination than shallow dug wells, which were more commonly found in Metro and are at higher risk of faecal contamination irrespective of rainfall. The results may suggest that seasonality plays a greater role for certain infrastructure types such as boreholes, while in dug wells, faecal contamination can easily enter the well and therefore the risk of contamination is high irrespective of seasonality. Seasonality might also affect the association between water quality and sanitary risks with some sanitary risks becoming more prominent in the wet season and others in the dry season. Although the same contamination sources and infrastructure failures may be present during the wet and dry seasons, rainfall may accelerate contamination pathways and result in increased pollution and contamination risks (Levy *et al.* 2016; Kelly *et al.* 2020). Rainfall and the resulting saturation of the subsurface can facilitate the transport of pathogens from human and/or animal excreta in the soil, environmental surfaces, or subsurface, causing groundwater contamination (Levy *et al.* 2016). In our previous study, shallow borehole depth was identified as a significant risk factor for faecal contamination in Bekasi during the wet season; while in Metro during the dry season, the lack of a concrete platform for boreholes and the use of a rope and bucket for dug wells were significant risk factors (Genter *et al.* 2022). The differing risk factors support the notion that in sanitary inspections a summative sanitary risk score alone is not sufficient to predict water quality (Kelly *et al.* 2020). However, sanitary inspection as a complementary tool in water quality monitoring, with consideration of seasonality, could facilitate understanding the complexity of the multiple pathways of faecal contamination as well as addressing the vulnerability of a system to contamination.

The weak predictive power of the presence and high concentrations of *E. coli* in self-supply sources during the dry season for the risk of contamination during the wet season suggests that single one-time water quality results are insufficient to represent safety of self-supply sources. The study found that the presence and high concentrations of *E. coli* in self-supply sources during the dry season significantly increased the likelihood of contamination during the wet season at both study sites; however, the predictive power and the correlation were weak. The results suggest that infrequent tests of water for *E. coli* are inadequate to represent the safety of self-supply services, as risk factors for faecal contamination of groundwater self-supply are influenced by a diversity of environmental conditions and possible contamination sources and pathways (Genter *et al.* 2021, 2022). The weak predictive power may indicate varying degrees of pronounced contamination pathways in the wet and dry seasons. This is consistent with other studies that emphasize the need for water quality monitoring to go beyond a single water quality test to make a statement about water safety (Kostyla *et al.* 2015; Charles *et al.* 2020). For example, Kostyla *et al.* (2015) suggest addressing seasonal variation of contamination by both monitoring guidelines for sampling timing and implementation of sanitary inspections and water safety plans to avoid misrepresenting safety of drinking water sources. To overcome the effects of seasonal bias in water quality results, water quality monitoring in self-supply sources should be conducted on a regular basis.

While single, one-time water quality results are inadequate to understand contamination risks, comprehensive spatiotemporal studies could improve the understanding. Future research that incorporates factors such as rainfall data, regular *E. coli* monitoring, and sanitary inspections into spatiotemporal studies has the potential to improve understanding of the complexities of contamination dynamics. A holistic approach encompassing these elements would provide a more robust basis for predictive models, and furthermore inform the development of appropriate water quality monitoring approaches. Additionally, while we considered flood-affected households in our analysis, our study was constrained by a lack of data concerning the interaction between surface water and groundwater. To address this limitation, future research could encompass hydrogeological analyses.

CONCLUSIONS

This work is significant as it provides insights into the relationship between seasonality and groundwater quality of self-supply services and has implications for self-supply water quality monitoring in urban Indonesia. This study demonstrated mixed results regarding the association between water quality and seasonality. There was a statistically significant difference of high levels of faecal contamination between wet and dry season in Bekasi, but not in Metro. The presence of faecal contamination did not show any significant seasonal difference at both study sites. Presence and high concentrations of *E. coli* in self-supply sources during the dry season were significant but are weak predictors for the risk of contamination during the wet season at both study sites. The complexity of faecal contamination risk factors and the influence of seasonal changes highlight the need for regular water quality testing complemented by sanitary inspections to ensure sustainable water safety for self-supply systems.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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