ADVANCING EARTH AND SPACE SCIENCE

Water Resources Research

RESEARCH ARTICLE
10.1029/2021WR031843

Microbial Contamination of Groundwater Self-Supply in Urban Indonesia: Assessment of Sanitary and Socio-Economic Risk Factors

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Key Points:

- Risk factors for fecal contamination of groundwater self-supply assessed in two Indonesian cities
- Contamination associated with lower socio-economic status, proximity to sanitation, and lack of well protection
- Widespread boiling of self-supplied water significantly improves microbial quality between source and point-of-use

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Genter, F., Putri, G. L., Pratama, M. A., Priadi, C., Willetts, J., & Foster, T. (2022). Microbial contamination of groundwater self-supply in urban Indonesia: Assessment of sanitary and socio-economic risk factors. *Water Resources Research*, *58*, e2021WR031843. https://doi.org/10.1029/2021WR031843

Received 17 DEC 2021
Accepted 2 OCT 2022

Abstract In urban Indonesia, more than 40 million people rely on groundwater self-supply, but the extent to which self-supply delivers safe water and the associated risk factors for fecal contamination remain unclear. This study quantified *Escherichia coli* (*E. coli*) for 511 self-supply sources and at point-of-use for 173 households in the Indonesian cities of Bekasi and Metro. A structured questionnaire collected information about the household, water sources, and potential contamination sources. Univariate and multivariate logistic regression analysis examined risk factors for fecal contamination. *E. coli* was detected in 66% of sources, including 55% of boreholes, 64% of protected dug wells, and 82% of unprotected dug wells. Widespread boiling of water meant microbial quality improved significantly between source and point-of-use, with *E. coli* detected in 30% of self-supply samples at point-of-use. Unprotected dug wells were significantly more likely to be contaminated than boreholes. In Bekasi, the analysis found a significant association between presence of *E. coli* and sanitation systems located within 10 m of the groundwater source. In Metro, poorer households had significantly higher odds of contamination than wealthier households. Other significant factors included shallower borehole depths in Bekasi, use of a rope and bucket, and absence of a concrete platform in Metro. In Bekasi, *E. coli* concentration at source was significantly associated with water quality at point-of-use. Risk of fecal contamination could be reduced by supporting households to invest in improved protection, and by facilitating promotion for safe household water treatment. Support for self-supply improvements should be weighed against the expansion and improvement of piped water services.

1. Introduction

Many countries are facing challenges in extending water services to poor and vulnerable communities that are most at risk of being left behind (WHO & UNICEF, 2021). The world is not on track to achieve the Sustainable Development Goal (SDG) target 6.1, which calls for universal and equitable access to safe and affordable drinking water for all by 2030 (WHO & UNICEF, 2021). To meet the criteria of a safely managed drinking water service, households must use an improved water source that is accessible on-premises, available in sufficient quantities when needed and free from fecal and chemical contamination (WHO & 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 & UNICEF, 2017). In 2020, two billion people still lacked access to a safely managed water service (WHO & UNICEF, 2021). The lack of access to safe drinking water is felt disproportionately by disadvantaged households (Ezbakhe et al., 2019; Flores Baquero et al., 2016; WHO & UNICEF, 2019).

Self-supply plays an important role in providing water for households in low- and middle-income countries (LMIC) and has implications for progress toward SDG target 6.1 (T. Foster et al., 2021). Household self-supply commonly refers to an on-premises water source, usually relying on groundwater or rainwater, that is privately owned and managed by an individual household or family (Grönwall & Danert, 2020). Self-supply exists in a range of contexts in urban and rural settings and can be found in households which are beyond the reach of utility- or community managed water supplies or in households that need to complement an inadequate supply (Adeniji-Oloukoi et al., 2013; Allen et al., 2006; Grönwall, 2016; Grönwall & Danert, 2020; Komakech & de Bont, 2018; Kulabako et al., 2010; Liddle et al., 2016; Sutton, 2009). Self-supply services are generally unregulated and unmonitored (S. Foster et al., 2022; Grönwall & Danert, 2020; Grönwall et al., 2010). In the

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Asia-Pacific, it is estimated that over 700 million people depended on self-supply across rural and urban areas in 2018 (T. Foster et al., 2021).

In urban Indonesia, nearly one third of the urban population—or more than 40 million people—self-supply their drinking water (T. Foster et al., 2021). Self-supply has the potential to provide a safely managed water service as it is located on the premises of a user household. However, in Indonesia little is known about the extent to which self-supply provides drinking water that is free from contamination (Genter et al., 2021). In 2020, 57% of the Indonesian population were living in urban regions, which corresponds to a population of 156 million people. Indonesia is in the bottom 15 countries globally in terms of urban use of piped water for drinking, with a coverage of 12% (National Population and Family Planning Board (BKKBN) 2018). Yet 72% were using improved water supplies accessible on premises in 2020 (WHO & UNICEF, 2021), a statistic which is largely driven by widespread reliance on self-supply. Self-supply in Indonesia 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 (Cronin et al., 2017; Furlong & Kooy, 2017; Hadipuro, 2010; Kooy et al., 2018; Kurniasih, 2008). Despite the ubiquity of self-supply in urban Indonesia, data on the "free from contamination" criterion for safely managed water are lacking (WHO & UNICEF, 2021), and there is an urgent need to address this evidence gap.

Few studies have rigorously assessed fecal contamination risks of groundwater self-supply. Risk factors for fecal contamination of groundwater self-supply likely vary across contexts, influenced by a diversity of environmental conditions and possible contamination sources (Genter et al., 2021). Risk factors can be categorized as hazard factors, pathway factors, and indirect factors (Howard, 2002). Hazard factors include pollution sources, such as sanitation systems or animal feces. Pathway factors allow microbial pollution to enter the groundwater supply, such as poor construction of water systems. Indirect factors enhance the development of pathway factors, but do not directly allow contamination into the supply, nor form a contamination source. Risk factors for fecal contamination of self-supply have been identified in various contexts, including on-site sanitation as hazard factors (Kumpel et al., 2016, 2017; Martínez-Santos et al., 2017; Ngasala et al., 2019) or poor condition of wells and inadequate protection as pathway factors (Ali et al., 2019; Butterworth et al., 2013; MacCarthy et al., 2013; Vaccari et al., 2010). Household wealth as an indirect determinant of self-supply contamination has not been rigorously assessed, either in Indonesia or elsewhere. This is an important evidence gap to address given the poorest may be less able to invest in safer forms of self-supply.

Understanding the extent to which self-supplied water is affected by contamination risk factors is crucial for people's health and wellbeing in urban Indonesia. This study aims to address this evidence gap by examining the extent and predictors of fecal contamination of groundwater self-supply in two Indonesian cities. Specifically, the study seeks to (a) understand the extent to which groundwater self-supply is free from fecal contamination at both source and point-of-use and (b) identify risk factors of fecal contamination in self-supply at the source and point-of-use.

2. Methods

2.1. Study Area

The study was undertaken in the Indonesian cities of Bekasi and Metro. The two study sites were selected based on widespread use of self-supply, the lack of access to piped water, and high population density. Kota Bekasi is one of Indonesia's most populous cities and is located in West Java on the eastern border of Indonesia's capital Jakarta. In 2017, the population density in Kota Bekasi was 13,841 people/km^2 (BPS, 2021). In 2019, the population of Kota Bekasi had reached approximately three million inhabitants (BPS Kota Bekasi, 2021). Kota Bekasi is divided into 12 districts, three of which were the focus of this study. Kota Bekasi's local water utility is only able to serve 26.8% of the total population, with the marginal areas of the city remaining unserved (Bappeda Kota Bekasi, 2018). Previous census data from 2010 suggested more than 40% of households in Kota Bekasi were dependent on groundwater for drinking water (BPS Kota Bekasi, 2010). Kota Bekasi is served by two groundwater systems: a phreatic/semi-confined system associated with volcanic/alluvial-fan deposits and a confined system with recharge (Dirks et al., 1988). The study sites in Kota Bekasi are served by the phreatic/semi-confined system, where the water level is typically at a depth of four to eight m below ground level.

Kota Metro is a city in the Indonesian province of Lampung on Sumatra Island. In 2018, the population of Kota Metro reached 162,976 people, with a population density of 2,371 people/km^2. The city is divided into five districts, namely Metro Barat (West), Pusat (Central), Selatan (South), Timur (East), and Utara (North). According to official statistics, only 2,134 households were connected to the piped municipal water system in 2018 (1.3% of Metro's population), with most customers from the districts of Metro Pusat (1032 customers) and Metro Timur (920 customers), whereas in Metro Utara no communities used water from Indonesian's water supply company (BPS Kota Metro, 2019). Geologically, Kota Metro is dominated by young volcanic deposits (ESDM, 2021).

2.2. Data Collection

The data collection was carried out during wet season in Bekasi (February–March 2020) and during dry season in Metro (October–November 2020). For the months of data collection, 60 and 12 rainy days were recorded with a precipitation of 2553 mm and 163 mm for Bekasi and Metro, respectively (BPS Kota Bekasi, 2021; BPS Kota Metro, 2021). Data were collected from 300 randomly selected households in both Bekasi and Metro. In Bekasi, participating households were randomly selected across three sub-districts (*Kelurahan*) (Jatiluhur, Sumur Batu, and Jatirangga) from three different districts (*Kecamatan*) in Bekasi (Jatiasih, Bantar Gebang, and Jatisampurna). In Metro, the participating households were randomly selected across five sub-districts (Karangrejo, Hadimulyo Barat, Ganjarasri, Iringmulyo, and Rejomulyo) from the five different districts in Metro (Figure 1). In Bekasi and Metro, districts and sub-districts were selected purposively based on the same criteria, such as self-supply prevalence, lack of access to piped water, and poverty status, with information obtained from secondary data and local government. Although the same selection criteria were applied, all five districts were selected in Metro, while only three were selected in Bekasi. The hamlets (*RW Rukun Warga*), which consist of several neighborhoods (*RT Rukun Tetangga*), were selected in consultation with the heads of the selected sub-districts. After further consultations with the respective head of the selected hamlets, the neighborhoods to be surveyed were chosen. All households of the selected neighborhoods were listed and then randomly selected using the randomization formula in Microsoft Office Excel 2016. The target number of households to be surveyed in each neighborhood was determined in proportion to the population size (Table S1 in Supporting Information S1). Based on the randomization output, households were sorted from smallest to largest randomization output number and then divided into a priority list and a reserve list. The households in the reserve list were only interviewed if the households on the priority list could not be visited or were not willing to be interviewed. Data collection included a household questionnaire, sanitary inspection of self-supply sources, and water quality testing. Prior to the data collection, informed consent was obtained in local language from heads of neighborhoods and from all participants. Ethical approval to conduct the research was provided by the Research Ethics Committee of University of Technology Sydney as well as the Universitas Indonesia.

2.3. Water Quality

Water samples were collected in sterile Whirl-Pak® bags (120 mL capacity, Nasco, Fort Atkinson, WI, USA) from 287 to 296 randomly selected households in Bekasi and Metro, respectively. Samples included 240 and 271 self-supply sources and at point-of-use 81 and 92 drinking water samples (including bottled and refill water) in Bekasi and Metro, respectively. Point-of-use samples were collected for every fifth household. At point-of-use, water was collected as household members would typically do when drinking (e.g., pouring water into a glass or cup, or directly from the storage container). Samples were stored at 2–8°C for transport and processed within 6 hours at a field laboratory in close proximity to the study area. Fecal indicator bacteria *Escherichia coli* (*E. coli*) was quantified with IDEXX Colilert-18 using the IDEXX Quanti-Tray®/2000 system with the Quanti-Tray® sealer model 2X according to manufacturer's instructions (IDEXX Laboratories, 2015). Samples were incubated at 35°C for 18–20 hr. *E. coli* cells were enumerated according to the manufacturer's instructions using an ultraviolet source (365 nm) and the Most Probable Number (MPN) table for the Quanti-Tray®/2000 system. The number of *E. coli* was reported as MPN per 100 mL with lower and upper 95% confidence limits. The Quanti-Tray®/2000 system is capable of quantifying the number of *E. coli* in 100 mL water samples over a range of 1–2419.6 MPN per 100 mL. Data falling outside the detection range were set to half the lower limit of detection (LOD) or to the upper LOD according to Cole et al., 2009.

Figure 1. Study sites in Metro (1: Karangrejo, 2: Hadimulyo Barat, 3: Ganjarasri, 4: Iringmulyo, and 5: Rejomulyo) and Bekasi (1: Jatiluhur, 2: Sumur Batu, and 3: Jatirangga) (QGIS, version 3.24.1).

2.4. Household Survey

A structured household survey was conducted in local language by trained enumerators simultaneously with the water sampling. The main household questionnaire covered a range of themes about the household and water sources used. Questions about the household included themes on health and socio-economic status, water management and decision-making. Self-supply water sources were defined as groundwater sources (boreholes, protected dug wells, or unprotected dug wells) that were privately owned by a household (Text S1 in Supporting Information S1).

2.5. Sanitary Inspection

The household survey questionnaire included a sanitary inspection module with observations on water supply and sanitation infrastructure. Observational questions of the WHO sanitary inspection form were adapted to the local context and included questions on the construction of the well, water lifting device, sanitation facilities, and household water storage and treatment (WHO & UNICEF, 2017). The borehole depth (to bottom of borehole) was determined based on the respondent's information. Further observations were made on borehole infrastructure such as the headworks and the presence of a concrete platform. For dug wells it was recorded whether water was delivered through a pump or a rope and bucket. Potential contamination sources were identified such as the number and proximity of sanitation systems and ownership of animals. Number of on-site sanitation facilities within a radius of 20 m and the lateral distance to the closest sanitation facility were considered and based on surveyed household responses and enumerator estimates. Type and protection of storage container as well as treatment method were recorded for point-of-use water samples (Text S1 in Supporting Information S1).

3. Data Analysis

3.1. Descriptive Analysis

Descriptive analysis was performed using water quality data of self-supply water sources. Due to the focus on self-supply, collected data from public sources were excluded from analysis in Bekasi (Source: $n = 47$, Point-of-use: $n = 3$) and Metro (Source: $n = 25$, Point-of-use: $n = 2$). Refill and bottled (packaged) water were considered for households that only used packaged water at point-of-use and no self-supplied water (Bekasi: $n = 27$, Metro: $n = 26$). Missing data were excluded from the analysis.

3.2. Conceptual Model of Fecal Contamination

To understand risk factors for fecal contamination of self-supply, potential predictors were categorized as hazard factors, pathway factors, and indirect factors (Howard, 2002). The pathway factors were further divided into source and point-of-use (Text S2, Figure S1 in Supporting Information S1, Data Set S1 and Data Set S2).

- Hazard factors: Sanitation systems (number of sanitation systems within 20 m, distance to closest sanitation facility) and animals (ownership)
- Pathway factors:
  - Source: Source type (borehole, unprotected, and protected dug well), infrastructure attributes (borehole depth, borehole concrete platform, and dug well water lifting device)
  - Point-of-use: Infrastructure (piped conveyance vs. manual collection), storage (covered or uncovered storage container)
- Indirect factors: Multidimensional wealth index

3.3. Statistical Analysis

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 source and point-of-use, *E. coli* concentration at source and point-of-use was comparatively assessed using paired samples Wilcoxon and McNemar's test. Paired samples Wilcoxon assesses *E. coli* as a continuous variable, while McNemar's test assesses it as dichotomous variable. R packages "tidyverse," "rstatix," and "coin" were used for calculation. Effect size (r) for Wilcoxon test was calculated based on Pallant, 2007 by dividing the test statistic (Z) by the square root of the number of observations (n). Further, *E. coli* concentration for each water source type and wealth quintile 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, or ≥ 100 *E. coli* counts per 100 mL, respectively. The association between wealth and water quality was investigated using Spearman's rank correlation. The "aod" package in the statistical analysis software R was used to calculate crude odds ratio (OR) and adjusted odds ratio (aOR) based on univariate and multivariate analysis. To assess whether the use of the water type varied by wealth, ORs were calculated based on univariate analysis. At source, the self-supply source type was considered and at point-of-use the water type used for drinking (including refill and bottled water). The analysis considered if multiple sources for drinking were tested for water quality at the household (Bekasi: $n = 6$, Metro: $n = 0$), and distinguished between the water types used

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for drinking. To examine the influence of risk factors at source and point-of-use, ORs and aORs were calculated based on univariate and multivariate analysis. At the source, multivariate analyses were performed including all self-supply source types, and separately for boreholes and dug wells only including type-specific variables such as borehole depth or dug well lifting device. The distance to the closest sanitation facility was considered as a dichotomous variable based on the presence/absence of sanitation system within less or more than 10 m from the water source and as a continuous numerical variable for the estimated distance in the supplementary material. The distance of 10 m between the sanitation systems and the water sources was chosen based on the government construction standards (Apendix III of Minister of Public Works Reg. 33/PRT/M/2016). At the point-of-use, multivariate analyses were performed with and without considering refill and bottled water. The variable treatment was excluded from univariate and multivariate analysis since almost all households reported treating their drinking water. For a summary of the explanatory variables used, see the supplementary material (Text S2, Figure S1, Table S13 in Supporting Information S1, Data Set S1, and Data Set S2).

For each multivariate model, a full model that included all independent variables was adopted rather than a stepwise model selection. This was because the intent of the analysis was to identify variables that were significantly associated with the outcome of interest rather than to find the "best" model for predictive purposes. Chi-Square statistic was used to indicate the fit of the multivariate models. Explanatory variables were tested for multi-collinearity by assessing variance inflation factors using the R package "car."

3.4. Wealth Index

To determine wealth status of households, information on 23 indicators such as household asset ownership, dwelling structure, type of cooking fuel, and household composition were collected in the household survey. A wealth index was constructed for Bekasi and Metro using the same approach as the 2017 Indonesian Demographic and Health Survey (DHS) based on the relevant variables and corresponding indicator values generated from principal component analysis (National Population and Family Planning Board (BKKBN) 2018). Wealth quintiles (Q) were calculated based on the wealth index and the number of household members. The wealth index scores in Bekasi ranged from −1.314 to 1.470 and were divided into quintiles Q1 (−1.314-0.019) reflecting poorest households, Q2 (0.026–0.321), Q3 (0.326–0.518), Q4 (0.519–0.702), and Q5 (0.714–1.470) reflecting wealthiest households. For Metro, wealth index scores ranged from −1.478 to 1.611 and were divided into Q1 (−1.478 to −0.224), Q2 (−0.218-0.068), Q3 (0.073–0.330), Q4 (0.351–0.612), and Q5 (0.617–1.611). Spearman's rank correlation was performed considering wealth as a continuous index variable, while wealth quintiles as categorical variables were used for descriptive analysis. Multivariate analyses were performed considering wealth as a continuous index variable and considering wealth as categorical quintile variable. Univariate and multivariate analyses considering wealth as a categorical quintile variable are included in the supplementary material. A histogram was created using the "ggplot 2" package in the statistical analysis software R (version 1.2.5001, R Foundation for Statistical Computing, Vienna, Austria) to compare the calculated wealth index scores from Metro and Bekasi with the wealth index scores from urban Indonesia more broadly (Figure S2 in Supporting Information S1, Data Set S3, and Data Set S4).

3.5. Quality Control

Alongside collected water samples, one field and one laboratory negative control (sterilized water) were processed as quality control on each sampling day. Duplicates were processed for more than 5% of samples in Bekasi ($n = 20$) and Metro ($n = 20$). Precision of water quality testing was assessed first by calculating the relative percent difference $\mathrm{RPD} = \frac{|C_1 - C_2|}{\left(\frac{C_1 + C_2}{2}\right)} \cdot 100$, where C_1 and C_2 represent duplicate pairs, second by the proportion of pairs indicating equal risk, and third by linear regression between log-transformed microbial counts (Text S3, Figure S3, and S4 in Supporting Information S1). Scatter plots were generated using Microsoft Office Excel 2016.

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4. Results

4.1. Water Quality of Self-Supply

Self-supply was commonly contaminated with *E. coli* at source, but lower levels of contamination were detected at the point-of-use. Self-supply in Bekasi was dominated by boreholes ($n = 215$), while unprotected dug wells ($n = 187$) were more prevalent in Metro. Protected dug wells were rarely present at both study sites. In Bekasi, *E. coli* was detected in 59% ($n = 142$) of all self-supply sources and in 28% ($n = 23$) of all self-supply samples at point-of-use. Similarly, in Metro, *E. coli* was present in 72% ($n = 195$) of all self-supply sources and 32% ($n = 29$) of all self-supply samples at point-of-use (Table 1 and Table 2). In Bekasi, 23% ($n = 55$) of source samples fell into the high risk class of ≥100MPN per 100 mL (Table 1 and Figure 2). However, only one borehole sample and one bottled water sample were in the high risk category at point-of-use (Table 2). In Metro, 35% ($n = 96$) of source samples and 8% ($n = 7$) of point-of-use samples showed high risk (Tables 1 and 2, and Figure 3). Paired samples Wilcoxon and McNemar tests showed significant improvement of water quality between source and point-of-use for all self-supply sources ($p < 0.001$) (Table 3). Point-of-use samples were mostly treated: no treatment was reported for only one and three point-of-use samples in Bekasi and Metro, respectively. Survey results also showed that households usually treat their self-supplied water at the point-of-use.

4.2. Socio-Economic Status

4.2.1. Water Quality Varies by Wealth

Self-supply of poorer households was more frequently contaminated than that of wealthier households. There was a statistically significant correlation between wealth and water quality in Metro, but not in Bekasi. Spearman's rank test showed no statistical significant correlation between wealth and water quality in Bekasi at source (rho = 0.029, $p = 0.643$) and point-of-use (rho = −0.043, $p = 0.705$). The level of contamination at source was similar across all wealth quintiles in Bekasi (Figure 4). In each wealth category, between 17% and 33% of the source samples showed high *E. coli* contamination greater than ≥100 MPN per 100 mL. In Metro, self-supply sources of poorer households were more likely to be contaminated than of wealthier households. The relationship between wealth and water quality at source was statistically significant (rho = −0.240, $p < 0.001$), but there was not a statistically significant relationship between wealth and water quality at point-of-use (rho = −0.150, $p = 0.150$). In Metro, the level of contamination was highest in samples from self-supply sources of the poorest households, with 50% of samples from households categorized in Q1 ($n = 29$) showing *E. coli* contamination greater than ≥100 MPN/100 mL (Figure 5).

4.2.2. Water Source Type Varies by Wealth

Wealth was a significant predictor of water source type in both Metro and Bekasi. In Metro, wealthier households were more likely to own a borehole and poorer households were more likely to own an unprotected well (Figure 6). In Bekasi, univariate analysis indicated no statistically significant association between wealth and ownership of an unprotected well or borehole. The use of refill and bottled water at the point-of-use was associated with wealth in Bekasi. Wealthier households were more likely to buy bottled water ($p = 0.021$), while poorer households were more likely to buy refill water ($p = 0.075$) (Figure 6). In Metro, no statistically significant association between wealth and drinking water type at the point-of-use was found.

4.3. Risk Factors—Univariate and Multivariate Analysis

4.3.1. Quality at Source

Univariate analysis indicated that unprotected wells were significantly more likely to be contaminated than boreholes with odds of contamination (≥1 MPN per 100 mL) being 11.65 times higher in Bekasi ($p = 0.018$) and 4.08 times higher in Metro ($p < 0.001$) (Table 4). Likewise, the likelihood of a high level of microbial contamination (≥100 MPN per 100 mL) was greater for unprotected dug wells (Bekasi: OR = 2.86, $p = 0.048$, Metro: OR = 5.62, $p < 0.001$). In Metro, households in the wealthier quintiles had significantly lower likelihood of contamination than households in the lowest wealth quintile (Table S2 in Supporting Information S1).

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Table 1
Escherichia coli Contamination in Self-Supply Sources From Households in Bekasi and Metro

E. coli presence	Bekasi			Metro		
	Total	≥1 MPN/100 mL	≥100 MPN/100 mL	Total	≥1 MPN/100 mL	≥100 MPN/100 mL
Source	n	n (%)	n (%)	n	n (%)	n (%)
All self-supply sources	240	142 (59.2)	55 (22.9)	271	195 (72.0)	96 (35.4)
Self-supply source types						
Boreholes	215	121 (56.3)	46 (21.4)	71	36 (50.7)	9 (12.7)
Protected wells	9	6 (66.7)	2 (22.2)	13	8 (61.5)	3 (23.1)
Unprotected wells	16	15 (93.6)	7 (43.8)	187	151 (80.7)	84 (44.9)
Wealth						
Q1	47	23 (48.9)	8 (17.0)	58	50 (86.2)	29 (50.0)
Q2	52	34 (65.4)	13 (25.0)	53	39 (73.6)	21 (39.6)
Q3	48	28 (58.3)	9 (18.8)	57	40 (70.2)	19 (33.3)
Q4	43	26 (60.5)	14 (32.6)	52	35 (67.3)	14 (26.9)
Q5	50	31 (62.0)	11 (22.0)	51	31 (60.8)	13 (25.5)
Sanitation systems						
Number: 0	15	4 (26.7)	3 (20.0)	9	5 (55.6)	2 (22.2)
Number: 1–2	156	96 (61.5)	34 (21.8)	168	122 (72.6)	63 (37.5)
Number: 3–4	56	35 (62.5)	15 (26.8)	74	53 (71.6)	23 (31.0)
Number: ≥5	4	1 (25.0)	0 (0.0)	4	2 (50.0)	2 (50.0)
Distance ≤10m[a]	143	90 (62.9)	34 (23.8)	182	130 (71.4)	71 (39.0)
Distance >10m[a]	33	14 (42.4)	7 (21.2)	65	47 (72.3)	17 (26.2)
Animals present						
Animals present	55	30 (54.4)	11 (20.0)	106	80 (75.5)	36 (34.0)
Animals absent	185	112 (60.5)	44 (23.8)	163	113 (69.3)	59 (36.2)
Chicken	53	30 (56.6)	11 (20.8)	101	77 (76.2)	36 (35.6)
Livestock	4	1 (25.0)	0 (0.0)	23	17 (73.9)	5 (21.7)
Infrastructure						
No borehole concrete platform	83	47 (56.6)	18 (21.7)	33	17 (51.5)	6 (18.2)
Borehole concrete platform	119	67 (56.3)	26 (21.8)	29	11 (37.9)	1 (9.1)
Borehole depth <10m	121	75 (62.0)	32 (26.4)	27	17 (63.0)	4 (14.8)
Borehole depth ≥10m	94	46 (48.9)	14 (14.9)	44	19 (43.2)	5 (11.4)
Borehole top open	92	54 (58.7)	18 (19.6)	6	1 (16.7)	0 (0.0)
Borehole top sealed	108	59 (54.6)	26 (24.1)	55	27 (49.1)	7 (12.7)
Motorized pump	220	128 (58.2)	48 (21.8)	101	77 (76.2)	41 (40.6)
No pump	5	3 (60.0)	2 (40.0)	-	-	-
Rope and bucket	0	-	-	41	38 (92.7)	25 (61.0)
Motorized pump and Rope and bucket (~pump)	0	-	-	52	39 (75.0)	18 (34.6)

[a]Minimum distance between shallow wells and pollution source based on construction standards (Apendix III of Minister of Public Works Reg. 33/PRT/M/2016).

Table 2
Escherichia coli Contamination in Self-Supply Samples From Households in Bekasi and Metro at Point-Of-Use

E. coli presence	Bekasi			Metro		
	Total	≥1 MPN/100 mL	≥100 MPN/100 mL	Total	≥1 MPN/100 mL	≥100 MPN/100 mL
Point-of-use	n	n (%)	n (%)	n	n (%)	n (%)
All	81	23 (28.4)	2 (2.5)	92	29 (31.5)	7 (7.60)
Self-supply water						
Boreholes	42	13 (31.0)	1 (2.4)	24	6 (25.0)	2 (8.3)
Protected wells	3	0 (0.0)	0 (0.0)	2	1 (50.0)	1 (50.0)
Unprotected wells	9	4 (44.4)	0 (0.0)	40	17 (42.5)	3 (7.5)
All self-supply	54	17 (31.5)	1 (1.9)	66	24 (36.4)	6 (9.1)
Packaged water						
Refill water	14	2 (14.3)	0 (0.0)	20	3 (15.0)	0 (0.0)
Bottled water	13	4 (30.8)	1 (7.7)	6	2 (33.3)	1 (16.7)
All packaged	27	6 (22.2)	1 (3.7)	26	5 (19.2)	1 (3.8)
Wealth[a]						
Q1	9	0 (0.0)	0 (0.0)	19	10 (52.6)	4 (21.1)
Q2	22	8 (36.4)	0 (0.0)	19	5 (26.3)	2 (10.5)
Q3	17	6 (35.3)	0 (0.0)	18	3 (16.7)	0 (0.0)
Q4	17	6 (35.3)	1 (5.9)	18	6 (33.3)	0 (0.0)
Q5	16	3 (18.8)	1 (6.3)	18	5 (27.8)	1 (5.6)
Treatment self-supply water						
No treatment	1	0 (0.0)	0 (0.0)	3	1 (33.3)	0 (0.0)
Boiling	48	15 (31.3)	1 (2.1)	62	23 (37.1)	6 (9.7)
Bleach/chlorine	1	0 (0.0)	0 (0.0)	0	-	-
Other	1	0 (0.0)	0 (0.0)	0	-	-
Storage type[a]						
Gallon/Dispenser	17	5 (29.4)	1 (5.9)	23	5 (21.7)	1 (4.3)
Bottle	3	1 (33.3)	0 (0.0)	5	2 (40.0)	0 (0.0)
Kettle/teapot	20	4 (20.0)	0 (0.0)	19	6 (60.0)	0 (0.0)
Jug	31	9 (29.0)	1 (3.2)	29	11 (37.9)	3 (10.3)
Bucket	1	0 (0.0)	0 (0.0)	7	3 (42.9)	1 (14.3)
Pot	3	1 (33.3)	0 (0.0)	4	1 (25.0)	1 (25.0)
Kedi/barrel	1	1 (100.0)	0 (0.0)	2	0 (0.0)	0 (0.0)
Storage protection[a]						
Storage container covered	71	20 (28.2)	1 (1.4)	89	28 (31.5)	6 (6.7)
Storage container uncovered	5	0 (0.0)	0 (0.0)	0	-	-

[a]Including all water types.

Similarly, wealth index was a significant predictor of *E. coli* with odds of contamination (≥1 MPN per 100 mL) more than doubling with a unit decrease in wealth index score ($p = 0.003$). In Bekasi, there was no statistically significant association between water quality and wealth. The analysis did, however, find a significant association between presence of *E. coli* and proximity to sanitation systems in Bekasi. Water sources were more frequently contaminated if they were located within 10 m of a sanitation system. There was no association

10.1029/2021WR031843

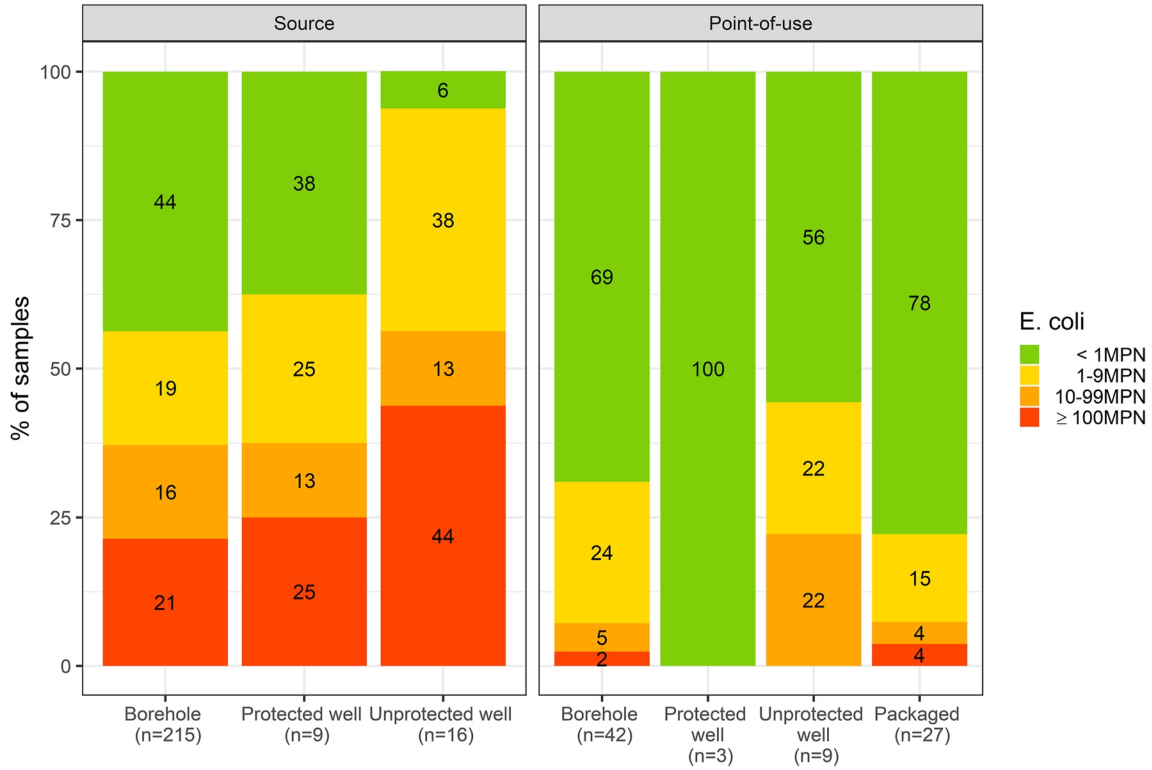

Figure 2. *Escherichia coli* risk classification of water sources in Bekasi City at source and point-of-use.

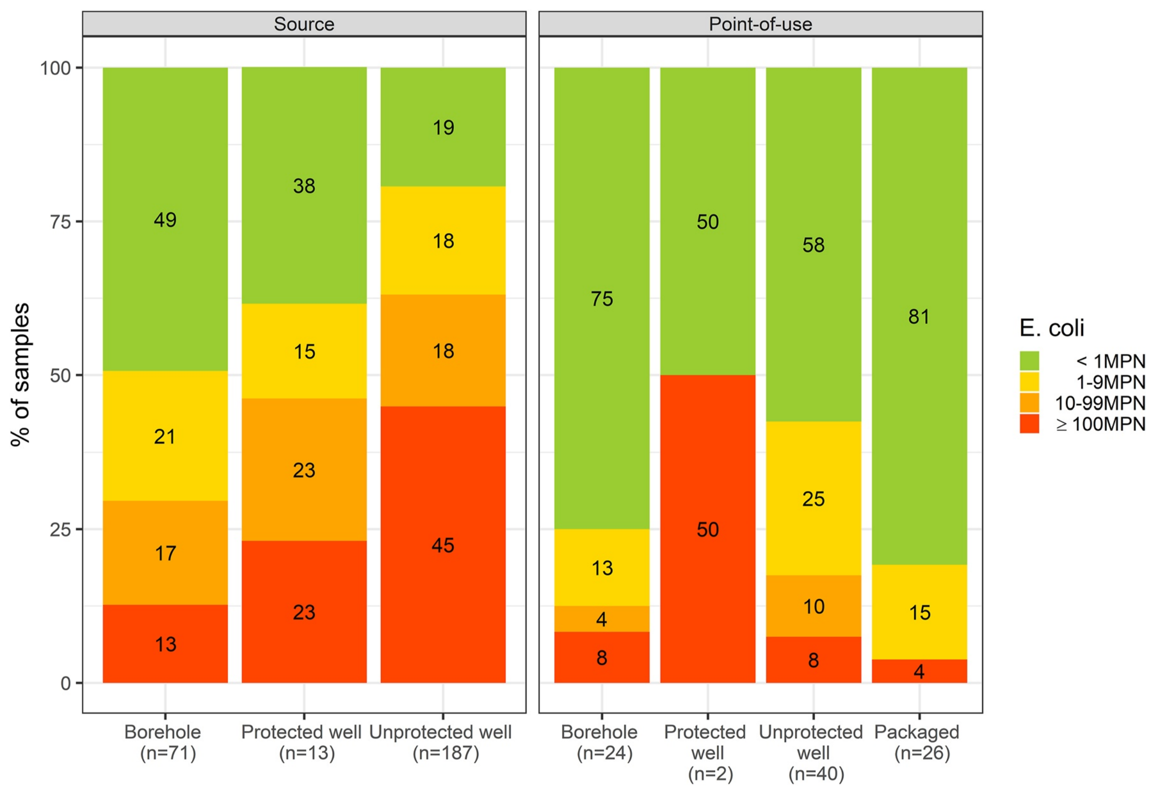

Figure 3. *Escherichia coli* risk classification of water sources in Metro City at source and point-of-use.

Table 3
Paired Samples Wilcoxon and McNemar Tests for Differences in Water Quality Between Source and Point-Of-Use

	Bekasi						Metro					
		Paired samples wilcoxon			McNemar			Paired samples wilcoxon			McNemar	
	n	P-value (greater)	Z	r[a]	Chi-square	P-value	n	P-value (greater)	Z	r[a]	Chi-square	P-value
Borehole	42	**<0.001**	3.5	0.5	5.04	**0.025**	24	0.143	1.2	0.2	2.4	0.121
Protected well	3	0.186	1.4	0.8	-	-	2	0.977	-	-	-	-
Unprotected well	9	**0.007**	2.6	0.9	-	-	40	**<0.001**	3.8	0.6	7.6	**0.001**
All self-supply sources	54	**<0.001**	4.5	0.6	11.1	**<0.001**	66	**<0.001**	3.5	0.4	25.4	**<0.001**

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

between presence of *E. coli* and ownership of chickens or livestock in either study site. In Metro, water from dug wells was more likely to be contaminated and to a higher level when a rope and bucket was used to withdraw water as compared to a pump (≥1 MPN per 100 mL: OR = 3.88, $p = 0.036$, ≥100 MPN per 100 mL: OR = 2.27 $p = 0.032$). In Bekasi, the odds of a high level of contamination (≥100 MPN per 100 mL) decreased with well depth (OR = 0.94, $p = 0.025$).

Multivariate analysis showed that hazard, pathway, and indirect factors are risks for fecal contamination. Consistent with the univariate analysis, multivariate analysis showed that unprotected wells were significantly more likely to be contaminated with *E. coli* and at higher levels than boreholes, with this relationship evident in both study sites (Table 5 and Table S3 in Supporting Information S1). In Bekasi, water sources within 10 m of a sanitation system were more likely to be contaminated than those more than 10 m away (adjusted odds ratio (aOR) = 2.46, $p = 0.035$). In Metro, wealthier households using self-supply had significantly lower odds of *E. coli* concentration exceeding ≥100 MPN per 100 mL (aOR = 0.50, $p = 0.020$) (Table 5 and Table S3

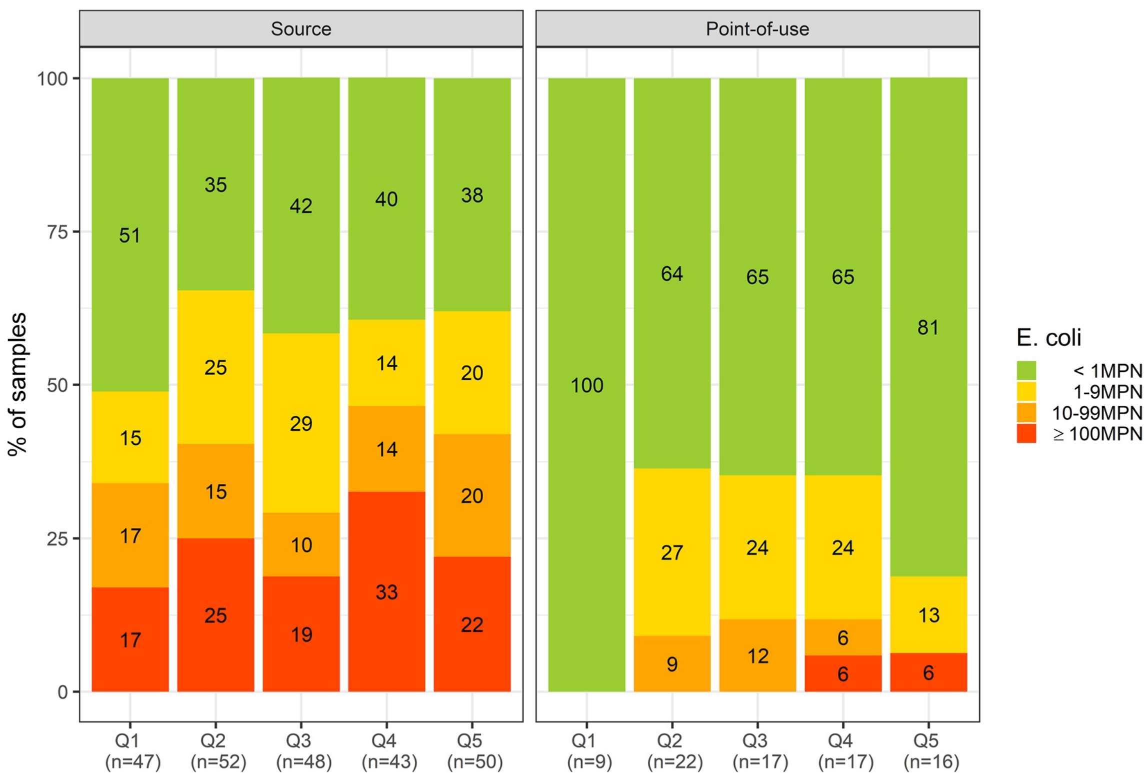

Figure 4. *Escherichia coli* risk classification of self-supply by wealth quintiles in Bekasi, with poorest households categorized in wealth quintile Q1.

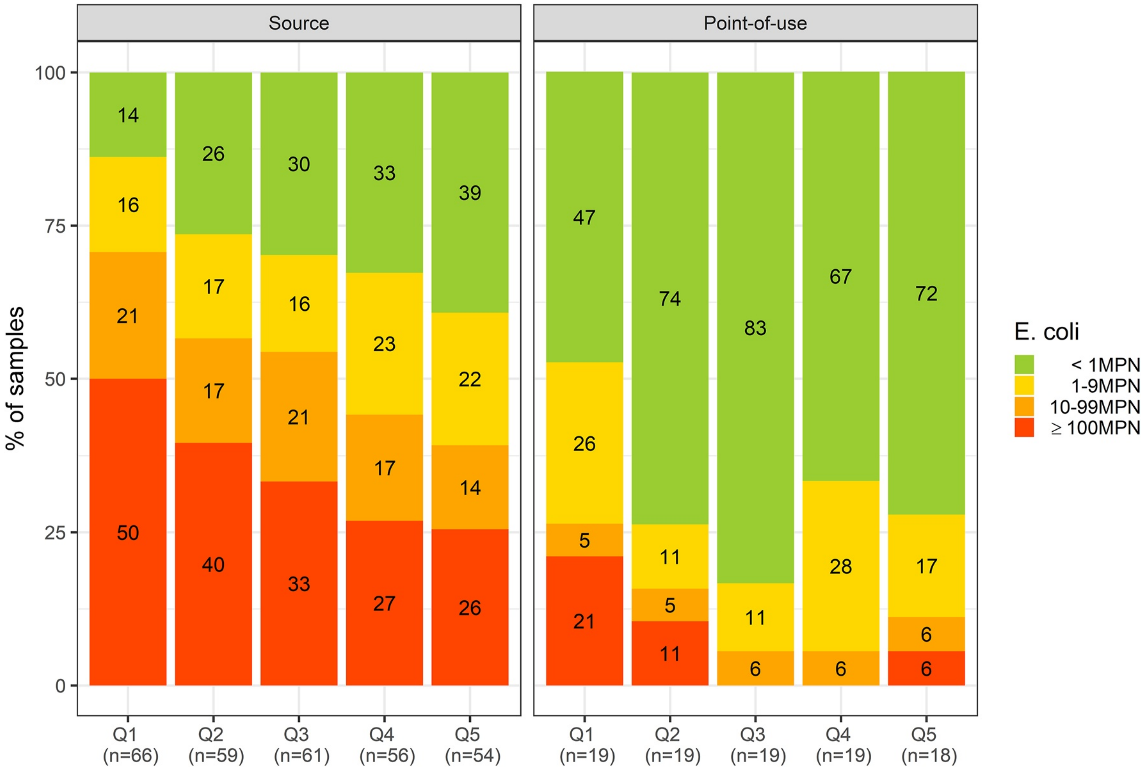

Figure 5. *Escherichia coli* risk classification of self-supply by wealth quintiles in Metro, with poorest households categorized in wealth quintile Q1.

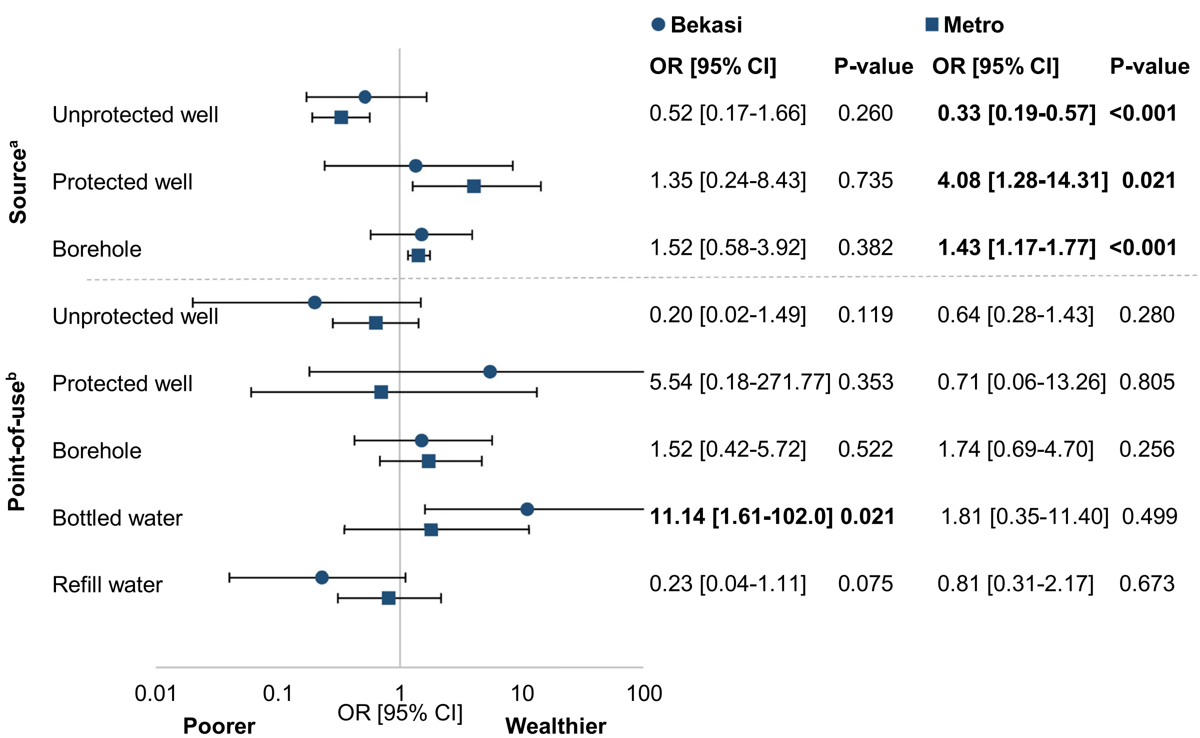

Figure 6. Calculated Odds Ratios show that use of water source types vary by wealth status, with wealthier households in Metro being significantly more likely to have improved self-supply sources and wealthier households in Bekasi being significantly more likely to purchase bottled water. *Note*. (a) For n values refer to Table 1, (b) for n values refer to Table 2, bold values indicate statistical significance ($p < 0.05$).

Table 4

Crude Odds Ratios of Risk Factors for Self-Supply Water Quality at Source in Bekasi and Metro

	Bekasi				Metro			
	≥1 MPN per 100 mL		≥100 MPN per 100 mL		≥1 MPN per 100 mL		≥100 MPN per 100 mL	
Variable[a]	OR [95% CI]	P-value	OR [95% CI]	P-value	OR [95% CI]	P-value	OR [95% CI]	P-value
Wealth[b]								
Wealth index	1.27 [0.70–2.32]	0.436	1.23 [0.61–2.52]	0.566	**0.43 [0.24-0.74]**	**0.003**	**0.44 [0.26-0.72]**	**<0.001**
Source type								
Protected well versus borehole	1.55 [0.40–7.51]	0.541	1.05 [0.15–4.52]	0.953	1.56 [0.47–5.58]	0.474	2.07 [0.41–8.41]	0.332
Unprotected well versus borehole	**11.65 [2.30-212.60]**	**0.018**	**2.86 [0.97-8.08]**	**0.048**	**4.08 [2.27-7.41]**	**<0.001**	**5.62 [2.76-12.72]**	**<0.001**
Protected well versus unprotected well	0.13 [0.01–1.27]	0.107	0.37 [0.04–2.13]	0.290	0.38 [0.12–1.33]	0.108	0.37 [0.08–1.25]	0.138
Sanitation systems								
Number	1.00 [0.80–1.23]	0.971	0.94 [0.73–1.21]	0.626	0.92 [0.76–1.11]	0.383	0.98 [0.82–1.16]	0.787
Closest distance	1.01 [0.97–1.05]	0.577	1.02 [0.98–1.07]	0.315	1.03 [0.99–1.07]	0.170	1.03 [1.00–1.07]	0.074
Sanitation system ≤10m versus >10m	**2.30 [1.07-5.05]**	**0.033**	1.16 [0.48–3.10]	0.754	0.94 [0.49–1.74]	0.841	1.71 [0.93–3.23]	0.090
Animals								
Chicken present versus absent	0.87 [0.47–1.63]	0.667	0.85 [0.39–1.75]	0.672	1.44 [0.83–2.56]	0.206	1.02 [0.61–1.71]	0.931
Livestock present versus absent	0.22 [0.01–1.78]	0.199	-	-	1.13 [0.45–3.23]	0.809	0.48 [0.15–1.25]	0.162
Animals total present versus absent	0.78 [0.43-0.144]	0.428	0.80 [0.37–1.64]	0.558	1.36 [0.79–2.39]	0.275	0.91 [0.54–1.51]	0.708
Infrastructure								
Borehole depth	0.97 [0.93–1.00]	0.076	**0.94 [0.89-0.99]**	**0.025**	0.93 [0.87–1.00]	0.065	1.02 [0.92–1.14]	0.700
Borehole top open versus sealed	1.18 [0.67–2.08]	0.563	0.78 [0.38–1.50]	0.444	0.21 [0.01–1.40]	0.163	-	0.995
Borehole concrete platform present versus absent	0.99 [0.56–1.74]	0.964	1.03 [0.52–2.04]	0.943	0.58 [0.20–1.57]	0.285	0.16 [0.00–1.03]	0.101
Dug well rope and bucket versus pump	-	-	-	-	**3.88 [1.25-17.10]**	**0.036**	**2.27 [1.08-4.85]**	**0.032**
Dug well rope and bucket and pump versus rope and bucket	-	-	-	-	**0.22 [0.05-0.77]**	**0.028**	**0.33 [0.14-0.77]**	**0.011**
Dug well rope and bucket and pump versus pump	-	-	-	-	0.87 [0.40–1.95]	0.734	0.75 [0.36–1.51]	0.421

Note. Bold values indicate statistical significance ($p < 0.05$).

[a]For *n* values please refer to Table 1. [b]Q1 refers to the poorest quintile of households and Q5 refers to the wealthiest quintile of households.

Table 5

Multivariate Analysis of Water Quality for Self-Supply Sources in Bekasi and Metro

	Bekasi				Metro			
	≥1 MPN per 100 mL		≥100 MPN per 100 mL		≥1 MPN per 100 mL		≥100 MPN per 100 mL	
Variable[a,b]	aOR [95% CI]	P-value	aOR [95% CI]	P-value	aOR [95% CI]	P-value	aOR [95% CI]	P-value
Wealth index	1.75 [0.83–3.75]	0.142	1.26 [0.53–3.06]	0.598	0.62 [0.33–1.16]	0.139	**0.50 [0.28-0.89]**	**0.020**
Protected well versus borehole	2.21 [0.43–16.88]	0.374	1.40 [0.19–7.03]	0.700	2.10 [0.61–7.83]	0.247	2.32 [0.44–10.12]	0.278
Unprotected well versus borehole	**9.03 [1.62-169.60]**	**0.040**	2.23 [0.54–8.14]	0.233	**4.58 [2.34-9.08]**	**<0.001**	**4.73 [2.14-11.70]**	**<0.001**
Sanitation system ≤10m versus >10m	**2.46 [1.08-5.81]**	**0.035**	1.22 [0.47–3.47]	0.692	0.95 [0.46–1.91]	0.886	1.77 [0.92–3.51]	0.093
Number of sanitation systems	0.92 [0.66–1.26]	0.595	0.83 [0.56–1.20]	0.333	1.03 [0.78–1.38]	0.839	0.97 [0.74–1.27]	0.845
Animals present versus absent	0.55 [0.25–1.21]	0.139	0.50 [0.16–1.30]	0.185	1.23 [0.65–2.35]	0.521	0.83 [0.46–1.48]	0.538

Note. Bold values indicate statistical significance ($p < 0.05$).

[a]For *n* values please refer to Table 1. [b]Chi-Square and p-value: Bekasi ≥1 Most Probable Number (MPN): $X^2 = 16.40$, $p = 0.012$; Bekasi ≥100 MPN: $X^2 = 4.77$, $p = 0.574$; Metro ≥1 MPN: $X^2 = 30.63$, $p < 0.001$; Metro ≥100 MPN: $X^2 = 32.37$, $p < 0.001$.

Table 6
Multivariate Analysis of Water Quality for Private Boreholes in Bekasi and Metro

	Bekasi				Metro			
	≥1 MPN per 100 mL		≥100 MPN per 100 mL		≥1 MPN per 100 mL		≥100 MPN per 100 mL	
Variable[a,b]	aOR [95% CI]	P-value	aOR [95% CI]	P-value	aOR [95% CI]	P-value	aOR [95% CI]	P-value
Wealth index	1.88 [0.81–4.45]	0.145	1.19 [0.44–3.30]	0.737	0.43 [0.09–1.66]	0.238	**0.004 [0.00-0.18]**	**0.025**
Number of sanitation systems	0.96 [0.68–1.34]	0.809	1.02 [0.67–1.53]	0.942	0.95 [0.56–1.57]	0.839	0.31 [0.04–1.42]	0.172
Sanitation system ≤10m versus >10m	**3.18 [1.26-8.52]**	**0.012**	1.51 [0.48–5.89]	0.504	0.59 [0.11–2.90]	0.519	0.37 [0.00–17.44]	0.628
Animals present versus absent	0.65 [0.26–1.58]	0.337	0.55 [0.15–1.65]	0.324	0.52 [0.12–1.94]	0.346	0.14 [0.00–1.67]	0.166
Borehole depth	0.97 [0.93–1.02]	0.279	**0.93 [0.87-0.99]**	**0.020**	0.98 [0.89–1.08]	0.694	1.21 [1.00–1.61]	0.087
Concrete platform present versus absent	0.77 [0.37–1.60]	0.485	1.76 [0.76–4.27]	0.198	**0.29 [0.08-1.00]**	**0.057**	**0.001 [0.00-0.09]**	**0.033**
Borehole top open versus sealed	1.42 [0.69–2.99]	0.342	0.79 [0.34–1.82]	0.583	0.20 [0.01–1.67]	0.184	-	0.996

Note. Bold values indicate statistical significance ($p < 0.05$).
[a]For n values please refer to Table S10 in Supporting Information S1. [b]Chi-Square and p-value: Bekasi ≥1 Most Probable Number (MPN): $X^2 = 13.42$, $p = 0.063$; Bekasi ≥100 MPN: $X^2 = 15.21$, $p = 0.033$; Metro ≥1 MPN: $X^2 = 4.04$, $p = 0.775$; Metro ≥100 MPN: $X^2 = 11.26$, $p = 0.128$.

in Supporting Information S1). Multivariate analysis of private boreholes showed that borehole depth had a significant association with water quality in Bekasi, with deeper boreholes less likely to have high levels (≥100 MPN per 100 mL) of *E. coli* contamination (aOR = 0.93, $p = 0.020$) (Table 6 and Table S4 in Supporting Information S1). In Metro, high levels of *E. coli* contamination (≥100 MPN per 100 mL) in private boreholes were again significantly associated with lower wealth status (aOR = 0.004, $p = 0.025$) and the absence of a concrete platform (aOR = 0.001, $p = 0.033$). Water from dug wells lifted with a rope and bucket was more likely to be contaminated and at higher levels than water lifted with a pump (Table 7, Table S5 and Table S6 in Supporting Information S1).

4.3.2. Quality at Point-Of-Use

Univariate analysis found that source type and wealth were significantly related to water quality at point-of-use in Metro, but not in Bekasi (Table 8 and Table S7 in Supporting Information S1). In Metro, refill water was significantly less likely to be contaminated than water from unprotected wells at the point-of-use with a crude OR of 0.24 ($p = 0.042$) (Table 8). In Metro, water at the point-of-use from household members categorized in the middle wealth quintile (Q3) was significantly less likely to be contaminated with *E. coli* compared with households in the poorest quintile (Q1) (OR = 0.18, $p = 0.028$) (Table S7 in Supporting Information S1). In Bekasi, no statistically significant association between wealth and water quality at the point-of-use was

Table 7
Multivariate Analysis of Water Quality for Dug Wells in Metro

	Metro			
	≥1 MPN per 100 mL		≥100 MPN per 100 mL	
Variable[a,b]	aOR [95% CI]	P-value	aOR [95% CI]	P-value
Wealth index	0.76 [0.32–1.78]	0.528	0.70 [0.36–1.34]	0.118
Unprotected versus protected	1.78 [0.48–6.05]	0.360	2.07 [0.57–9.83]	0.300
Number of sanitation systems	0.99 [0.68–1.49]	0.961	1.03 [0.75–1.39]	0.871
Sanitation system ≤10m versus >10m	1.02 [0.43–2.33]	0.954	1.72 [0.85–3.58]	0.137
Animals present versus absent	1.58 [0.71–3.63]	0.272	0.82 [0.44–0.54]	0.539
No pump versus pump[c]	**5.08 [1.34-33.58]**	**0.038**	1.88 [0.85–4.22]	0.119

Note. Bold values indicate statistical significance ($p < 0.05$).
[a]For n values please refer to Table S11 in Supporting Information S1. [b]Chi-Square and p-value: Metro ≥1 Most Probable Number (MPN): $X^2 = 170.31$, $p = 0.061$ and Metro ≥100 MPN: $X^2 = 12.71$, $p = 0.048$. [c]Households with rope and bucket and pump are considered as households using a pump. No pump refers to households using rope and bucket as water lifting device.

Table 8
Crude Odds Ratios of Risk Factors for Water Quality at the Point-Of-Use in Bekasi and Metro Including Refill and Bottled Water

	Bekasi		Metro	
	≥1 MPN per 100 mL		≥1 MPN per 100 mL	
Variable[a]	OR [95% CI]	P-value	OR [95% CI]	P-value
Wealth				
Wealth index	1.66 [0.40–7.41]	0.490	0.59 [0.24–1.38]	0.224
Water type				
Protected well versus borehole	-	0.991	3.00 [0.11–84.29]	0.461
Unprotected well versus borehole	1.78 [0.39–7.86]	0.440	2.22 [0.75–7.20]	0.162
Refill water versus borehole	0.37 [0.05–1.63]	0.440	0.53 [0.10–2.35]	0.417
Bottled water versus borehole	0.99 [0.23–3.68]	0.990	1.50 [0.18–9.99]	0.681
Protected well versus unprotected well	-	0.991	1.35 [0.05–35.87]	0.835
Refill water versus unprotected well	0.21 [0.02–1.42]	0.123	**0.24 [0.05-0.85]**	**0.042**
Bottled water versus unprotected well	0.55 [0.09–3.29]	0.514	0.68 [0.09–3.89]	0.672
Refill water versus protected well	-	0.991	0.18 [0.01–5.27]	0.262
Bottled water versus protected well	-	0.991	0.50 [0.01–17.47]	0.676

Note. Bold values indicate statistical significance ($p < 0.05$).
[a]For *n* values please refer to Table 2.

found. Whether or not self-supplied water was piped to a tap (as compared to being manually collected from the well/borehole) did not have a significant influence of water quality at the point-of-use (Table 9 and Table S9 in Supporting Information S1). Univariate and multivariate analysis showed that self-supply water quality at the source had a significant influence on water quality at the point-of-use in Bekasi, but not in Metro (Tables 9 and 10).

Table 9
Crude Odds Ratios of Risk Factors for Self-Supply Water Quality at the Point-Of-Use in Bekasi and Metro Excluding Refill and Bottled Water

	Bekasi		Metro	
	≥1 MPN per 100 mL		≥1 MPN per 100 mL	
Variable[a]	OR [95% CI]	P-value	OR [95% CI]	P-value
Wealth				
Wealth index	1.02 [0.17–6.11]	0.982	0.96 [0.22–2.76]	0.939
Infrastructure				
Manual collection versus piped conveyance[b]	-	-	1.10 [0.12–7.36]	0.936
Rope and bucket and pump versus rope and bucket only[b]	-	-	2.29 [0.33–20.42]	0.413
Rope and bucket and pump versus pump only[b]	-	-	2.48 [0.62–10.57]	0.205
Treatment and storage				
E. coli concentration (MPN/100 mL)	**1.00 [1.00-1.00]**[c]	**0.036**	1.00 [0.99–1.01]	0.940
>100 MPN/100 mL	2.82 [0.74–10.92]	0.125	1.03 [0.22–3.08]	0.959
Storage container covered versus uncovered	-	0.994	-	-

Note. Bold values indicate statistical significance ($p < 0.05$).
[a]For *n* values please refer to Table 2 and Table S12 in Supporting Information S1. [b]Households with rope and bucket and pump considered as households using a pump (piped conveyance), boreholes and dug wells included in analysis. [c]For every 100 Most Probable Number increase in source quality, odds of *E. coli* detection at the point-of-use increases by 20%.

Table 10
Multivariate Analysis for Self-Supply Water Quality at Point-Of-Use

	Bekasi		Metro	
	≥1 MPN per 100 mL		≥1 MPN per 100 mL	
Variable[a,b]	aOR [95% CI]	P-value	aOR [95% CI]	P-value
Wealth				
Wealth index	1.55 [0.23–12.17]	0.658	1.23 [0.26–6.17]	0.797
Manual collection versus piped conveyance[c]	-	-	0.79 [0.10–4.99]	0.804
E. coli source concentration (MPN/100 mL)	**1.00 [1.00-1.00]**[d]	**0.031**	1.00 [1.00–1.00]	0.652

Note. Bold values indicate statistical significance ($p < 0.05$).
[a]For n values please refer to Table 2. [b]Chi-Square and p-value: Bekasi ≥1 Most Probable Number (MPN): $X^2 = 10.75$, p = 0.005; Metro ≥1 MPN: $X^2 = 0.39$, p = 0.942. [c]Households with rope and bucket and pump considered as households using a pump (piped conveyance), boreholes and dug wells included in analysis. [d]For every 100 MPN increase (per 100 mL) in source quality, odds of *Escherichia coli* detection at the point-of-use increases by 20%.

4.4. Discussion

This study shows groundwater self-supply in Bekasi and Metro is commonly contaminated with *E. coli*. Fecal contamination was detected in 66% of self-supply sources across the two study sites. Previous studies in other contexts have typically found lower frequency of fecal contamination for self-supply sources (Genter et al., 2021). A pooled estimate from 30 studies in LMICs found fecal indicator bacteria were reported 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). Of the 15 urban specific studies included, fecal indicator bacteria were reported in 34% of self-supply sources (Genter et al., 2021). The variation in water quality across studies indicates that fecal contamination of self-supply and corresponding pathways are site-specific and depend on local conditions, such as aquifer type, soil type, and standard of infrastructure.

However, reduced levels of fecal contamination were detected at the point-of-use compared to the source. At the point-of-use, *E. coli* was present in 34% of self-supply water samples. This contrasts with findings from numerous previous studies, which have instead observed a deterioration in water quality after collection, which in turn has been attributed to several factors such as water storage conditions and post handling practices (Clasen & 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). In Bekasi and Metro, households reported treating their self-supplied water frequently and almost all households (98%) covered their water storage containers. Boiling to disinfect drinking water has also been shown to effectively reduce fecal contamination despite the high source concentration in rural Vietnam (Clasen et al., 2008). Notwithstanding widespread boiling practices in Bekasi, contaminated source water still had a significant influence on water quality at the point-of-use. This highlights that proper household water treatment and measures to improve source quality are simultaneously important in order to reduce health risks. In contrast, source quality in Metro exhibited no relationship with point-of-use quality, indicating that testing the source water is not necessarily representative of the safety of water at the point-of-use. Monitoring of self-supply source quality might overstate the risk for households in urban Indonesia. This raises questions about the suitability of source quality as an indicator of self-supply water quality and whether the point-of-use water quality should be considered in monitoring programs.

Wealth of households had a significant negative association with fecal contamination of source water, even when adjusting for other sanitary factors. Results from Metro showed that poorer households were at higher risk than wealthier households when considering all self-supply types and boreholes separately, but not when only dug wells were included in the multivariate analysis. In Metro, wealth might reflect unaccounted contamination pathway factors or limitations in the sanitary risk factors assessed. Categorical measures of sanitary conditions may be overly simplistic and well condition might be more of a spectrum, with poorer household relying on unprotected wells that lie at the higher-risk end of the spectrum. Wealth also had an influence on which water sources were used by households. In Bekasi, bottled water was more common in wealthier households, suggesting that poorer household may be unable or unwilling to pay for it. In Metro, poorer households were more likely to own an unprotected well as compared to wealthier households, who instead were more likely to own a borehole.

These outcomes are consistent with the findings of Sugiyono and Dewancker (2020), who reported that private dug wells were the preferred main domestic water source for the poorest households in Metro.

Various sanitary risk factors emerged as significant predictors of water quality in both Bekasi City and Metro City. Well type was a significant determinant of self-supply water quality. The analysis demonstrated that unprotected wells were more likely to be contaminated with *E. coli* than boreholes. These findings are consistent with previous studies from LMICs that compared microbial water quality between improved and unimproved groundwater sources (Bain et al., 2014; Genter et al., 2021). However, high levels of contamination were still detected in boreholes and protected wells across both study sites, reinforcing previous findings that protected sources do not ensure that the water is free of contamination (Bain et al., 2014; Genter et al., 2021).

Water abstraction system for dug wells was related to water quality, with high levels of fecal contamination occurring more frequently when water was abstracted by rope and bucket than when a motorized pump was used. Improving the water abstraction system by replacing a rope and bucket with a pump (manual or motorized) could therefore reduce frequency and magnitude of contamination (Ali et al., 2019; Bazaanah & Dakurah, 2021; Gorter et al., 1995). A shift of private investment toward motorized pumps would also enable self-supplying households to have the convenience of water being piped into the house.

The absence of a borehole concrete platform had a significant association with more frequent high levels of fecal contamination in Metro, highlighting the need for appropriate well protection. In the context of urban Indonesia, the presence of a concrete platform may often indicate that the borehole is present inside the house, meaning contaminated run-off is less likely to enter the boreholes. Other studies on self-supply also found that appropriate well protection is important to improve microbial water quality, such as sealing of the annulus (Knappett et al., 2013) and proper condition of protected borehole casings (Potgieter et al., 2006).

Deeper boreholes were less likely to have high *E. coli* concentration in Bekasi, suggesting deeper groundwater is less liable to contamination from fecal sources. This finding aligns with the results of Kazama and Takizawa (2021) who reported elevated contamination levels in areas with a higher water table in Yogyakarta (Kazama & Takizawa, 2021). Bacterial transfers to aquifers depend on the attenuation potential and the natural travel time to the saturated zone (ARGOSS, 2001; Banerjee, 2011; Voisin et al., 2018), with greater depths resulting in longer travel time and greater attenuation. The study sites in Bekasi are situated in a flat alluvial terrain, suggesting little bacterial transfer through the aquifer.

Fecal contamination of groundwater supplies due to inadequate spacing between sanitation facilities and wells is perceived as a major threat to water quality (Graham & Polizzotto, 2013). A statistically significant relationship between contaminated wells and nearby sanitation systems was found in Bekasi, but not in Metro. In Bekasi, the most prevalent on-site sanitation types were cubluks (a single tank without a concrete base) (47%, $n = 226$), followed by "empangs" (flush to ponds) (19%, $n = 93$), septic tanks (15%, $n = 72$), and pit latrines (6%, $n = 27$). In Metro, household members usually use septic tanks or cubluks (94%, $n = 280$) and to a less extent pit latrines (4%, $n = 13$). Several studies on self-supply in urban areas in low income settings have found significant associations between fecal water contamination and proximity of the well to a sanitation system (Kumpel et al., 2017; Martínez-Santos et al., 2017; Ngasala et al., 2019). The studies reported the use of poorly constructed pit latrines and septic tanks, which leads to the contamination of groundwater wells in close proximity. Ngasala et al., 2019 reported a significant correlation between well depths along with lateral distance to sanitation systems in sand aquifers in Tanzania. In contrast, a study by Ravenscroft et al. (2017) concluded that pit latrines are a minor contributor to fecal contamination of drinking water in alluvial-deltaic terrains and attention should be given to reduce contamination around the well-head. The findings of Ravenscroft et al. (2017) are in line with our results in Metro, but provide a contrast to the results in Bekasi.

Results from Bekasi suggest that lateral separation between sanitation systems and self-supply wells may be insufficient to prevent transport of fecal indicator bacteria through the aquifer pathway. Out of 176 and 247 wells analyzed in Bekasi and Metro, 81% and 74% were located ≤10 m from sanitation systems, respectively. Based on construction standards in Bekasi and Metro, a minimum distance between shallow wells and a pollution source of 10 m is required (Appendix III of Minister of Public Works Reg. 33/PRT/M/2016). The results show that these regulations are not respected in the case of self-supply. Appropriate siting of sanitation systems to ensure low risk of fecal contamination to groundwater sources highly depends on the soil and aquifer properties in the particular

10.1029/2021WR031843

environment. Studies in other environments reported distances from the well to on-site sanitation systems have to be at least 12 or 15 m (Graham & Polizzotto, 2013).

Further investigation is needed to confirm the risk to groundwater from on-site sanitation in Bekasi and Metro, and urban Indonesia more broadly. Results from this study should be interpreted with caution since some data on sanitation systems such as setback distance and sub-surface design attributes were self-reported by households or estimated by enumerators. Further studies into sanitation-groundwater interactions in urban Indonesia might also consider groundwater flow and transport modeling (Ngasala et al., 2021), monitoring networks with new installed sanitation systems and piezometers (Ravenscroft et al., 2017), and spatial GIS databases (Martínez-Santos et al., 2017).

This study was subject to a number of other limitations related to the measure of self-supply water safety. Water quality was determined by the single measure of *E. coli* contamination during wet season in Bekasi and dry season in Metro, thereby providing only a point-in-time snapshot. Conclusions on the water quality should be also drawn with caution since fecal indicator bacteria do not represent pathogens such as viruses, which might survive for longer travel times in the subsurface. Charles et al., 2020 highlights the need to shift from a focus on direct water quality measurements toward a prospective safety perspective to ensure the sustainability and security of water services. Frequent water testing accompanied by understanding of risks from sanitary inspections, systematic management concepts, and routine monitoring are essential for water safety.

Additional factors not considered in the study may have an impact on water quality. For example, indirect factors such as flooding, lack of fencing, or poor surface drainage are not considered. It was not possible to measure the depth to groundwater on-site. Furthermore, generalizations should be made with caution, as the quality of self-supply may vary greatly by region, due to temporal and spatial heterogeneity of water quality and varying hydrogeological conditions. Moreover, the sampling frame was based on areas with a high prevalence of self-supply, which is not necessarily representative for urban Indonesia as a whole. Finally, household use of multiple water sources might not be fully captured, since water quality was tested on water sources that were available at the time of the visit. However, consideration of the use of multiple water sources to meet daily household needs is beneficial to understand household water management and safety (Elliott et al., 2017).

Questions remain on how policy and practice need to respond to water quality concerns of self-supply in urban Indonesia. The cost-benefit of supporting self-supply improvements needs to be assessed in relation to other strategies such as investing in safe and reliable piped services. Financial and technical support for households is needed where piped networks are not feasible and where households cannot afford to invest in safer forms of self-supply. The improvement of self-supply source protection and water abstraction systems is required to improve groundwater quality of self-supply sources. This is especially true in Metro, where many households rely on unprotected dug wells, and where the poorest households are at higher risk of relying on drinking water with fecal contamination. In Bekasi, despite water treatment, source water quality was still related to water quality at the point-of-use, and poorer households were more likely to rely on refill water for drinking. This highlights the need for household education on water quality and associated safe water treatment and storage. Water quality monitoring and awareness raising could encourage households to choose safer water sources and to properly treat their self-supply water.

5. Conclusions

This study is of importance as it provides new evidence on the microbial quality of self-supplied water and contamination risk factors in urban Indonesia, which have hitherto been a major knowledge gap. The findings have significant implications for government decisions on how to respond to self-supply in urban areas of Indonesia and elsewhere in Asia. This study found that groundwater self-supply in Bekasi and Metro commonly contains *E. coli*, with fecal contamination in 66% of self-supply sources and 30% of samples at the point-of-use. At the source, contamination risks were related to infrastructure, proximity to sanitation systems, and wealth. Unprotected dug wells were at greater risk of contamination than boreholes. Water from dug wells equipped with a pump was less likely to be contaminated than dug wells with a rope and a bucket. The presence of a concrete platform around the borehole and greater borehole depth reduced the risk of contamination. Poorer households were at greater risk of fecal contamination in Metro. The distance of sanitation systems, which were based on households' estimates, were related to the risk of fecal contamination in Bekasi, but not in Metro. Households frequently boiled their water before consumption, and this significantly reduced likelihood of *E. coli* contamination. However, a higher *E. coli* concentration at the source was still associated with a higher risk of contamination at the point-of-use in Bekasi. To increase the safety of self-supply, the following recommendations can be concluded from this study: (a) financial support for households to invest in better self-supply infrastructure, such as improved well protection and replacement of rope and bucket systems with pumps; (b) education provided to households to raise awareness regarding proper water treatment and storage; and (c) source water quality of self-supply does not necessarily provide information about the quality water that households consume, and monitoring should also consider quality at the point-of-use. However, these recommendations must be weighed against other strategies such as expansion of municipal piped systems that deliver reliable and high quality water.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Data sets for this research are available in the supporting information files and at https://doi.org/10.26195/72rj-ey57.

Acknowledgments

This study was supported by Australia's Department for Foreign Affairs and Trade (DFAT) through the Water for Women Fund (Grant WRA 1004). The authors gratefully acknowledge the Swiss Ausbildungs-Stiftung Kanton Schwyz, Kanton St. Gallen. We also thank the enumerators of Universitas Indonesia and Universitas Muhammadiyah Metro, faculty members of Universitas Muhammadiyah Metro, Mitsunori Odagiri from UNICEF Indonesia, Angela Harris from NCSU, Bekasi and Metro local government, Indonesian Ministry of National Development Planning (Bappenas), and all participating households in Bekasi and Metro. Open access publishing facilitated by University of Technology Sydney, as part of the Wiley - University of Technology Sydney agreement via the Council of Australian University Librarians.

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