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Risk factors for well contamination in urban Indonesia: evidence to inform siting of wells and sanitation systems

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ABSTRACT

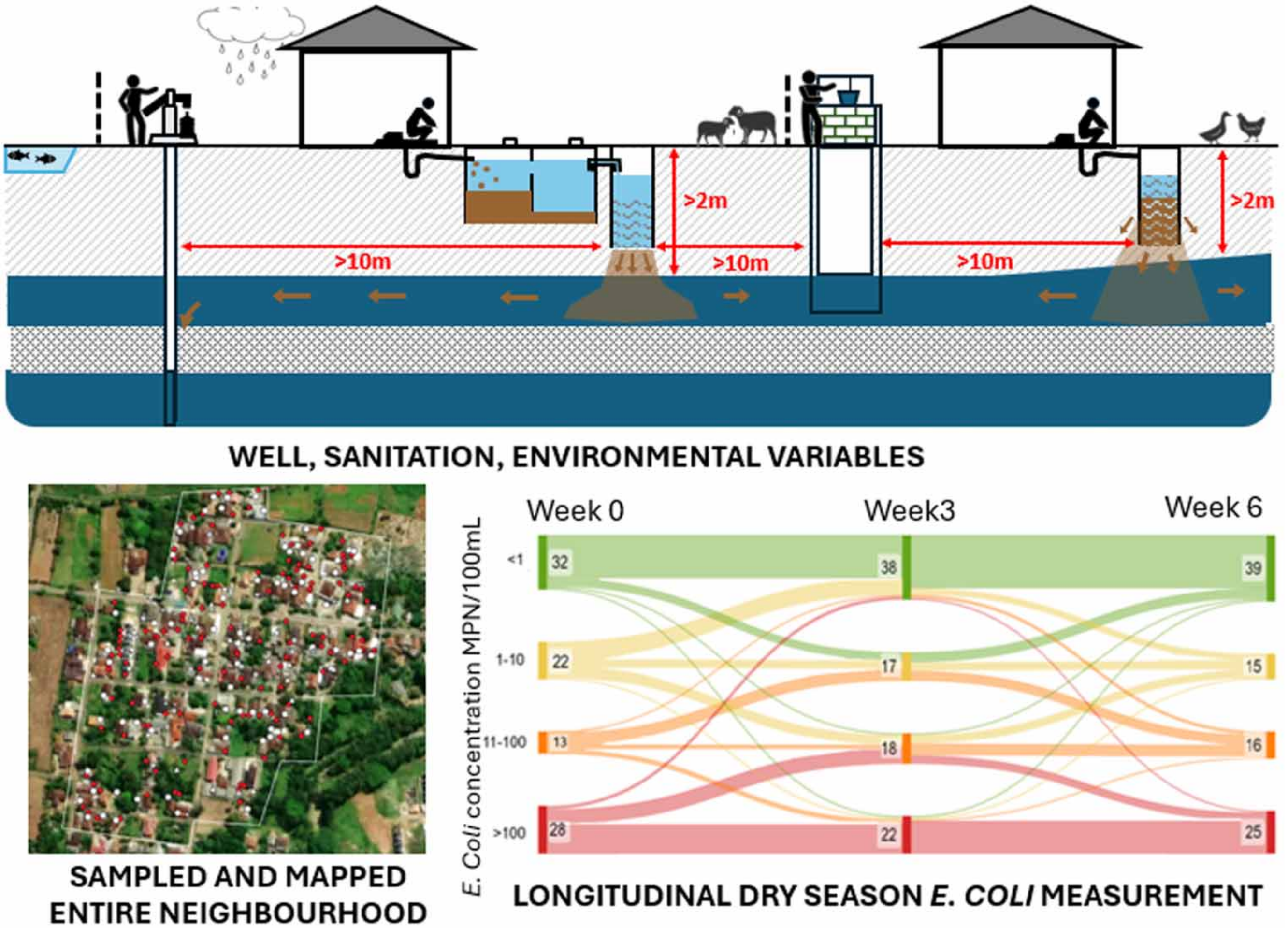
In Indonesia and many urban areas, the coexistence of on-site sanitation and groundwater supply poses faecal contamination risks. Indonesian standards recommend a minimum 10-m horizontal separation and 2-m groundwater depth for siting sanitation systems. This study evaluated the effectiveness of these criteria in Metro City by mapping wells and sanitation systems, controlling for other risk factors, and repeat measurements of groundwater depth and well contamination. E. coli was detected in 70% of wells, with a median concentration of positive samples of 47 MPN/100 mL (interquartile range 6 -727 MPN/100 mL). Although 60% of wells were within 10-m of a sanitation system, horizontal separation was not significantly associated with contamination. Shallower groundwater was significantly associated with an increased presence and high concentrations of *E. coli*. The 2-m threshold was associated with high contamination but not *E. coli* presence. Water quality and groundwater depth varied over the 2-month dry season sampling period, and associations with risk factors varied between repeat and single sample analyses. Other factors also contributed to contamination, including uncovered wells, presence of livestock and rainfall. The findings highlight the limitations of standardised siting criteria, suggesting that site-specific risk assessments may be more effective in managing water and sanitation risks.

Key words: groundwater contamination, on-site sanitation, risk assessment, sanitation siting criteria, well water quality

HIGHLIGHTS

- Shallow groundwater was significantly associated with high contamination, underscoring the importance of vertical separation but questioning the 2 m depth threshold.
- The 10 m horizontal separation criterion was not significantly associated with well contamination.
- Repeat sampling is valuable to account for quality and groundwater variability.
- Local risk assessments are preferable to standardised siting criteria.

GRAPHICAL ABSTRACT



INTRODUCTION

Groundwater supplies approximately half of the global water for domestic use, which is predicted to increase with climate change (UN Water 2022). However, the faecal contamination of groundwater is a major issue, contributing to millions of cases of gastrointestinal illness annually (Murphy *et al.* 2017; Genter *et al.* 2021; Santos *et al.* 2023). Over half of the global population uses on-site sanitation, which is increasing more rapidly than access to sewerage (UNICEF & WHO 2023). On-site sanitation systems have often been considered a principal cause of well contamination (Graham & Polizzotto 2013; Murphy *et al.* 2020), with studies linking increased use with declining water quality (Templeton 2015; Daniels *et al.* 2016). However, other research suggests that local factors, such as well design and maintenance, may play a more significant role in contamination, challenging the extent to which on-site sanitation contributes to groundwater contamination (Sorensen *et al.* 2016; Ravenscroft *et al.* 2017).

Public health authorities often mandate horizontal spacing criteria (i.e. setback distances) between sanitation systems and wells to mitigate contamination risks (Graham & Polizzotto 2013; Nenninger *et al.* 2023). However, implementing these guidelines is particularly challenging in dense urban areas, and transitioning to piped solutions presents its own economic and logistical barriers (Mitlin *et al.* 2019). In Indonesia, where improving water and sanitation safety is a national priority, this study explored the effectiveness of compliance with the sanitation siting criteria in improving well water quality in an urban area with shallow groundwater.

Despite the common use of siting criteria globally, research findings about their effectiveness are inconsistent. A review of sanitation siting criteria revealed horizontal separation distances ranged from 10 to 50 m and often applied a ‘one-size-fits-all approach', failing to consider site-specific conditions such as soil permeability or groundwater depth (Nenninger *et al.* 2023). The most widely used guidelines recommend a 15 m setback distance, reportedly based on four studies, including two from the 1930s, that observed contamination at distances between 25 and 50 m (Nenninger *et al.* 2023). Some studies have found correlations between distance and faecal contamination (Daniels *et al.* 2016; Islam *et al.* 2016; Sclar *et al.* 2016; Ngasala *et al.* 2019). However, others report no significant relationship with horizontal separation (Howard *et al.* 2003; Graham & Polizzotto 2013; Ravenscroft *et al.* 2017). Graham & Polizzotto (2013) emphasised the importance of empirically testing these guidelines under local conditions, while Nenninger *et al.* (2023) advocate for using modelling approaches to incorporate site-specific variables and uncertainties.

Beyond the horizontal pathway, multiple factors can influence the transmission of pathogens from on-site sanitation to wells, including vertical separation, sanitation type and system density. The depth to groundwater is another critical factor in siting on-site sanitation, yet of the four commonly used guidelines, only Lewis *et al.* (1982) included vertical separation criteria (Nenninger *et al.* 2023). Studies have shown that shallow groundwater increases the risk of contamination and horizontal pollutant travel (Caldwell 1938; Cogger *et al.* 1988; Islam *et al.* 2016). Sanitation system density is another potential factor. For example, research in Malawi found that pit latrine density was positively associated with high *E. coli* contamination, controlling for population density (Hinton *et al.* 2024), while studies in less densely populated areas reported no such relationship (Back *et al.* 2018). The type of toilet or containment is rarely assessed, however can contribute very different hydraulic loads to the soil. For instance, wet pit latrines were found to allow bacteria to travel greater distances compared with dry latrines (Caldwell 1938), yet many studies do not adequately specify the type of sanitation systems assessed (Nenninger *et al.* 2023).

Compounding the challenge of evaluating sanitation's role in well contamination are other possible contamination sources, such as localised pathways through poorly designed or maintained wells and broader aquifer pathways (Lawrence & Macdonald 2001). Review papers have criticised the failure of many studies to adequately control for confounding variables (Lawrence & Macdonald 2001; Sclar *et al.* 2016). Various studies found that local factors, particularly well infrastructure, pose greater faecal contamination risks than on-site sanitation systems (Sorensen *et al.* 2016; Ravenscroft *et al.* 2017; Ferrer *et al.* 2020).

Water quality variability further complicates assessments, as single sample testing may fail to capture seasonal or temporal fluctuations. Seasonal changes can impact water quality, particularly for dug wells, though few studies have investigated variability within the same season (Bain *et al.* 2014). Research in the USA and Ireland demonstrated that single samples substantially overestimated *E.coli* contamination compared with repeat sampling (Gill *et al.* 2018; Murphy *et al.* 2020). Studies that collect repeat samples often average seasonal variations, obscuring the fluctuations (Escamilla *et al.* 2013; Diaw *et al.* 2020). In Thailand, biweekly monitoring of wells over a year found significantly greater variability in *E. coli* concentrations for dug wells compared with boreholes, as well as identifying four archetypal contamination responses associated with rainfall and water table fluctuations (Chuah & Ziegler 2018).

In urban Indonesia, 30% of the population uses wells for drinking water, with usage increasing to 66% for non-drinking water purposes, yet recent monitoring found high rates of faecal contamination (Genter *et al.* 2022; Priadi *et al.* 2022). Studies investigating sanitation's impact on well contamination in Indonesia have produced mixed results. High contamination levels ($>$100 MPN/100 mL) have been associated with unimproved sanitation systems located within 10 m of wells (Cronin *et al.* 2017; Genter *et al.* 2022). Conversely, other studies found no significant association between contamination and proximity to sanitation systems (Indrastuti & Takizawa 2021). Indonesian national guidelines recommend on-site sanitation systems in areas with groundwater depths greater than 2 m, low porosity soil ($<5 \times 10^{-4}$ m/s) and a population density below 15,000 pp/km^2 (Pokja PPAS 2017). National sanitation regulations also require that septic tanks have at least 10 m horizontal separation from wells, and unsealed systems (soak pits) are only used when the depth to groundwater is more than 2 m in the rainy season (Ministry of Public Works 2017).

Given the rapid expansion of on-site sanitation systems in urban areas and the growing evidence of faecal contamination of wells, further research is needed to validate whether stricter enforcement of sanitation siting standards can mitigate contamination risks. This study builds on previous recommendations to improve data collection and analysis methods to examine compliance with Indonesian standards, focusing on horizontal and vertical separation between water-flush on-site sanitation systems and wells in urban areas with shallow groundwater. Using mixed methods, including inspections, mapping and repeat *E. coli* measurements during the dry season, this research aims to assess whether adherence to these criteria is associated with reduced faecal contamination.

METHODS

Study area

The research was conducted in Kota Metro, a small city in Lampung Province, Sumatra Island, Indonesia, with a population of over 170,000 (BPS Kota Metro 2024a). The site was selected due to very high use of on-premise wells, one of the highest users of self-supply in Indonesia, with only 5% of residents connected to piped water, as well as the prevalence of on-site sanitation, as there is no centralised sewage system (BPS Kota Metro 2024b). Most households use flush toilets connected to an on-site sanitation system and on-premises dug wells (i.e. large diameter wells) and boreholes (i.e. drilled wells). The district of Iringmulyo was chosen due to its high rates of stunting, previous findings of poor water quality (Genter *et al.* 2022), and the presence of a piped water network (providing a possible future alternative), though most households remain unconnected. The study focused on a single area with relatively homogeneous geophysical characteristics to reduce hydrogeological variability's influence on contamination patterns. A census sampling approach was adopted to enable a detailed, localised assessment of a typical locality. The study area covered 8.7 ha across four adjacent neighbourhoods with relatively uniform housing density (see Supplementary Figure S1). All 132 properties in this area were included in the sampling. Insights from local government, university staff and well drillers identified clayey sands as the predominant soil type. Groundwater in Metro City ranges from 1 to 5 m below the surface, underlain by a clay aquitard at depths of 10–20 m, with a semi-confined gravel aquifer at greater depths supplying boreholes.

Data collection

A mixed methods approach combined household questionnaires, infrastructure mapping, sanitary inspections, depth measurement and water quality sampling. All 132 households in the study area were sampled, and a response rate of 85% was achieved (Supplementary Table S1). Questionnaires, administered in Indonesian by trained enumerators using Survey CTO version 2.71.5, collected data on water supply and sanitation types, usage and emptying practices. Visual inspections observed features and sanitary risks of wells and sanitation systems, followed by detailed mapping of all used and abandoned wells and sanitation systems onto high-resolution printed maps, later digitised in QGIS version 3.22.10 to calculate horizontal and vertical separation distances.

Groundwater samples were collected from all household wells across three sampling phases between August and September 2022 (dry season). Samples were taken directly at the source, either from taps for pumped systems or buckets from uncovered wells, prior to any household treatment. Samples were transported in sterile Whirl-Pak® bags at 2–8 °C in cooler bags for analysis at the Universitas Muhammadiyah Metro for *E. coli* and total coliform using IDEXX Colilert-18 using the IDEXX Quanti-Tray®/2000. Samples were incubated at 35.5 °C for 18–20 h. *E. coli* cells were enumerated using ultraviolet light and the most probable number (MPN) tables. Water quality analysis methods paralleled those explained in Genter *et al.* (2022).

Groundwater depth was measured in all accessible dug wells ($n = 59$) after each of the three water quality samples using a weighted measuring tape to determine the depth from the ground surface to the water level. Depths of sanitation systems were measured in 31 accessible systems using a metal rod inserted into openings, such as lids or ventilation pipes, to calculate the depth to the system base. Qualitative data on-site geology and hydrogeology were gathered from interviews with local well drillers, environmental and public works officers and university staff.

Analysis

Water quality analysis

Given that *E. coli* concentrations were not normally distributed, analysis was based on logistic regression with two binary outcome variables: (a) *E. coli* presence (equal to or greater than 1MPN/100 mL) and (b) high contamination (*E. coli* greater than 100 MPN/100 mL). The variation in water quality across the three sample rounds was assessed first through changes in *E. coli* risk categories and graphed as a Sankey diagram (Figure 1), as well as analysis of the difference in proportions of positive outcomes between sampling rounds using Cochran's Q test with a significance level of $p < 0.05$.

Mapping and spatial analysis

All wells and sanitation systems were mapped into QGIS v3.22.10. The depth to groundwater at sanitation systems was calculated as the difference between a surface layer created from the Indonesian National DEM 5 m elevation data (Badan Informasi Geospasial 2018) and a groundwater depth mesh generated from the measured depth to groundwater in 59 dug

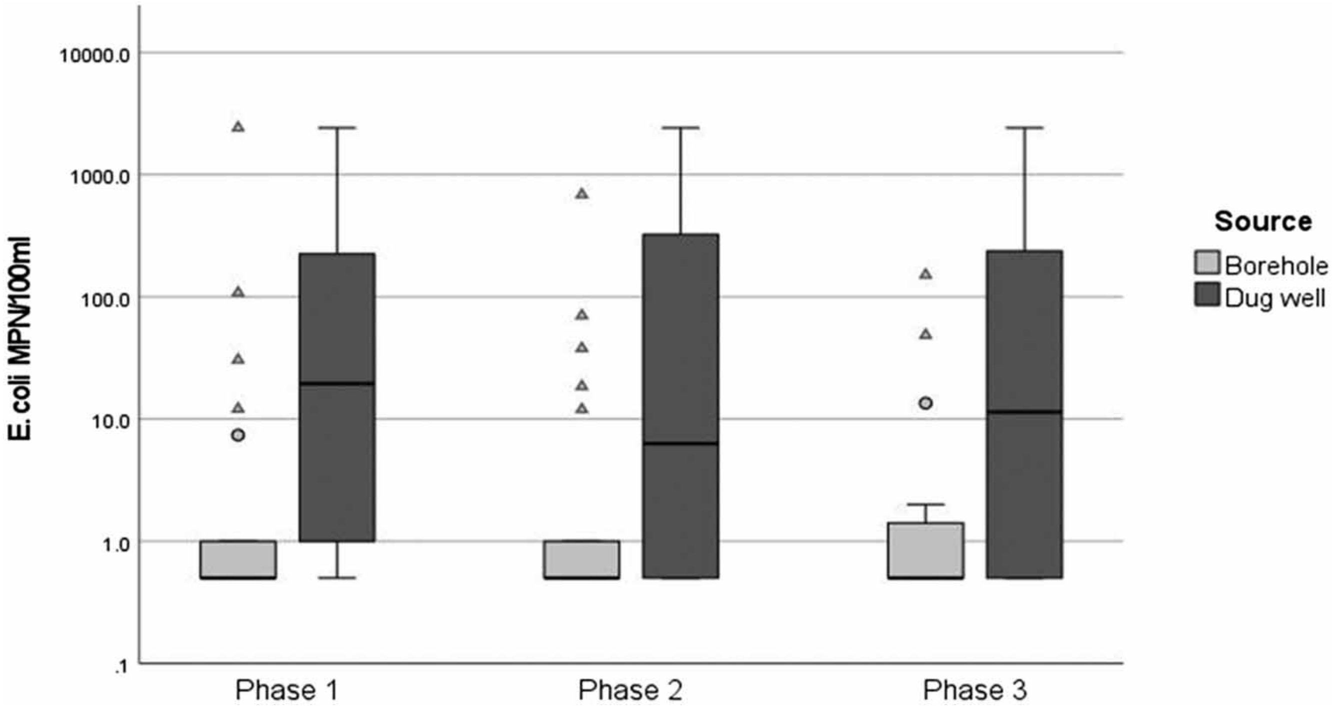


Figure 1 | Comparison of *E. coli* concentration in dug wells and boreholes across the three sampling rounds.

wells for each sampling round. The depth of sanitation systems was measured for 31 sanitation systems, and the infiltration depth was calculated as the estimated depth to groundwater at the sanitation system minus the containment depth.

Analysis of risk factors

Risk factors for groundwater contamination were based on commonly assessed factors (Howard 2002; Kelly *et al.* 2020; Genter *et al.* 2022) and assessed through data from water and sanitation system inspections, household questionnaires, mapping and measurements. Well-related variables included categorical well type (borehole, covered well, uncovered well), dug well type (covered, uncovered without a bucket, uncovered with bucket), binary variables for cracked/missing slab, absence of headwall and borehole depth as a continuous variable. Some variables (e.g. soil type and population density) were assessed as constant due to the localised study area.

Environmental variables included binary measures of the presence of livestock, unlined ponds or stagnant water within 10 m of wells, and other pollution sources within 20 m. Depth to groundwater was analysed as a continuous variable and as a binary variable (greater or less than 2 m), following Indonesian siting criteria. Groundwater flow direction could not be determined, potentially due to the influence of pumped-dug wells and boreholes. Rainfall data were obtained from a nearby meteorological station (BMKG Stasiun Klimatologi Lampung station 96291, https://dataonline.bmkg.go.id/data_iklim) and categorised into binary variables: heavy rainfall for Phase 2 (51 mm rainfall over 7 days prior) and light rainfall for Phases 1 and 3 (9 and 15 mm, respectively).

Sanitation-related variables beyond the binary 10 m separation distance were assessed to monitor the potential interactions and pathogen flows between sanitation systems and wells. These included factors related to horizontal separation distance, density and sanitation type. Calculation in QGIS determined the presence of one or multiple sanitation systems within 10 m of the well, the average distance to the closest sanitation system, the number of sanitation systems within 10 m and the sum of the reciprocal distance of all sanitation systems within 30 m to indicate the impact of multiple sanitation facilities with greater risk of closer distances (adapted from Back *et al.* (2018)).

Correlation between risk factors was assessed using Pearson's bivariate correlation in SPSS v28, focusing on significant correlations (two-tailed $p < 0.005$) and real-world variable interactions. Supplementary Table S4 details these results, highlighting collinearity between well cover and bucket use, livestock and other pollution, and unlined ponds and stagnant water.

Statistical analysis of factors associated with well contamination

Generalised estimating equations (GEEs) in SPSS v28 were used to assess the association between risk factors and well contamination, accounting for the within-subject correlation of repeat measures. Binary logistic regression with a first-order autoregressive relationship (AR1) correlation matrix evaluated the effects of water, environmental and sanitation factors on the outcome variables (a) *E. coli* presence and (b) high contamination, with ordinal phase number as a within-subject variable. Four base models were developed: (1) combined wells (borehole and dug wells), (2) dug wells only, (3) boreholes only and (4) combined wells, yet analysis of single samples and not repeats. See Supplementary Table S5 for specific factors included in each base model. Sanitation and groundwater variables were then assessed by including different individual factors within the model. Significance was assessed at $p < 0.05$, with Bonferroni corrections for the multiple comparisons of sanitation and groundwater variables. Corrected thresholds were $p < 0.013$ for horizontal separation, vertical separation and sanitation type, and for density, it was $p < 0.08$ (three variables for two outcomes) (Perrett & Mundfrom 2010).

RESULTS

Study area

This section summarises the overarching findings of the household questionnaire and inspection results, including the type of water and sanitation facilities. The study area included 112 households with 428 residents, with 96% of households using groundwater as their primary domestic water source, while all used on-site sanitation systems (Supplementary Table S1). Shared facilities were common, with 12% of households sharing wells and 4% sharing on-site systems, while 14% had multiple systems (Supplementary Table S1). Of the 96 wells in use and able to be sampled, 76% were dug wells (shallow/large diameter wells) and 24% were boreholes (drilled wells). Relating to sanitation systems, flush toilets were universally used, with 23% cistern flush and 77% pour flush. Inspections identified that 75% of on-site systems were cesspools (locally known as '*cubluk*'), while 21% were septic tanks.

Water quality results

E. coli was frequently detected in well water, with contamination levels varying across sampling rounds. On average, 61% of samples tested positive for *E. coli*, ranging from 58 to 66% across sampling rounds, resulting in 70% of wells testing positive at least once. Contamination was more common for dug wells (75% tested positive at least once) compared with boreholes (52%) (Supplementary Table S2 and Figure S2). Across sampling rounds, 36% of wells had *E. coli* concentrations exceeding 100 MPN/100 mL at least once, with the median *E. coli* concentration of positive samples ranging from 39 to 62 MPN/100 mL between sampling rounds. As shown in Figure 1, most of the highly contaminated samples (95%) came from dug wells. Water quality of individual wells varied over the 2-month monitoring period (Figure 2), with only 43% of wells remaining in the same contamination category across the three sampling phases. Variation in contamination occurred between samples, with eight dug wells and one borehole shifting between *E. coli* absence to high contamination within the 3-week period. Despite these variations, Cochran's Q test showed no statistically significant differences in the proportion of samples positive for *E. coli* ($\chi^2(2) = 2.583$, $p = 0.275$) or that had high contamination ($\chi^2(2) = 2.842$, $p = 0.241$) across the sample rounds.

Risk factors

Compliance with Indonesia's groundwater depth criteria was high, but adherence to horizontal separation standards was low. Groundwater depth at sanitation systems averaged 2.7–3.14 m below ground across sampling periods and ranged from 1 to 5 m depths overall (Table 1). Most sanitation systems met the 2 m depth to groundwater criterion, with 85, 78 and 87% compliance rates across the three phases. Repeat measures ANOVA showed significant differences in groundwater depths between rounds (F (1.85–175.87) $= 74.925$, $p < 0.001$) based on Huynh-Feldt correction. The average depth of septic tanks ($n = 31$ measured) was 2.04 m, ranging from 1 to 3.4 m, resulting in an average infiltration depth (from the base of the sanitation system to groundwater) of 0.83 m. The range of infiltration depths was -1.87 m (base of tank submerged in groundwater) to 2.92 m, and 25% of sanitation systems were submerged in Phase 2 when groundwater was shallowest, compared with 11% in Phases 1 and 3. Horizontal separation compliance was poor, as 61% of wells had a sanitation system within 10 m, 17% had multiple systems within 10 m, and 92% had at least one system within 15 m (Table 1). The average separation distance was 9.8 m, ranging from 2.9 to 26 m. Most sanitation systems were a single wet pit or cesspool (80%), with the remainder classified as septic tanks discharging to soak pits.

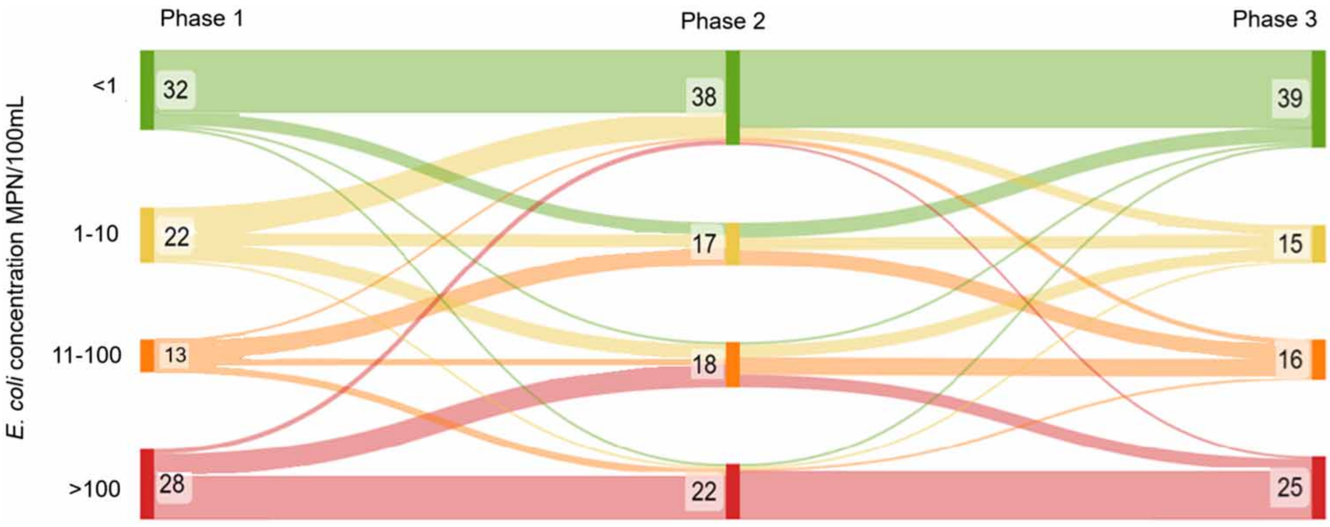


Figure 2 | Variations in *E. coli* concentration categories (MPN/100 mL) between sampling rounds (Phases 1, 2 and 3). Green represents the absence of *E. coli*, and red represents concentrations greater than 100 MPN/100 mL.

Table 1 | Summary of factors related to sanitation type, groundwater depth and separation distances

Sanitation variables	*n* (%)	Horizontal separation variables between well and sanitation system	*n* (%)
Sanitation type: Septic tank	19 (20%)	Ave. distance well to closest on-site sanitation (SD)	9.6 (SD 4.0)
Sanitation type: Pit	77 (80%)	One sanitation <10 m from well	58 (60%)
Toilet type: Cistern flush	18 (19%)	One sanitation <15 m from well	88 (92%)
Toilet flush: Pour flush	76 (81%)	More than one sanitation <10 m from well	16 (17%)
Previously emptied	12 (13%)	Sanitation density within 30 m sum of the reciprocal distance)[a]	0.40 (SD 0.18)
		Average depth of septic tanks m (SD)	2.04 (SD 0.57)

Depth to groundwater (m) at sanitation system (n = *96*)

Phase	Average depth (m) (SD)	% >2 m
Overall	2.94 (0.79)	83%
Phase 1	2.99 (0.76)	85%
Phase 2	2.70 (0.80)	78%
Phase 3	3.14 (0.77)	87%

Infiltration depth (m) between base of sanitation system and groundwater (n = *28*)

Phase	Average depth (m) (SD)	% >2 m
Overall	0.83 (0.87)	5%
Phase 1	0.92 (0.85)	4%
Phase 2	0.57 (0.87)	7%
Phase 3	1.01 (0.87)	4%

[a]Sanitation density refers to the sum of the reciprocal distance between the well and the number of sanitation systems within a 30 m radius of that well, accounting for a higher risk of closer systems (Back *et al.* 2018).

Multiple other risk factors were also present, including poor well infrastructure, local environmental hazards and rainfall effects. For dug wells ($n = 73$), key risks were the lack of a full cover (80%) and the use of buckets for extraction (25%, Table 2). Boreholes ($n = 23$) had an average reported depth of 40 m. Across both types of wells, 17% lacked a protective slab at the base of the well, and 8% had cracked slabs. Of the environmental hazards within 10 m of the well, livestock was the most common, followed by other pollution and unlined ponds (e.g. fishponds, greywater storage). The average rainfall 7 days prior to sampling was much higher in Phase 2 (52 mm) compared with Phases 1 and 3 (9 and 15 mm, respectively), which corresponded with the shallowest groundwater level.

Table 2 | Summary of well and environmental risk factors

Water infrastructure variables	*n* (%)	Environmental variables	*n* (%)
Well type – dug well	73 (76%)	Livestock within 10 m	41 (43%)
Well type – borehole	23 (24%)	Other pollution within 10 m	26 (38%)
Dug well – uncovered	58 (80%)	Unlined pond within 20 m	26 (27%)
Dug well – uses bucket	18 (25%)	Stagnant water near well	15 (16%)
Dug well – no headwall	8 (11%)		
Borehole – reported depth of well	40 m (SD 13)	**Rainfall – Previous 7-day rainfall total** - Phase 1	9.0 mm
All wells – slab cracked or missing	25 (26%)	- Phase 2	52 mm
		- Phase 3	15 mm

Variables for the analysis of risk factors accounted for co-dependence and real-world interactions between factors. Significant correlations were found between uncovered wells, bucket use and lack of a raised wall (Supplementary Table S3). A combined categorical well variable was created for well type to avoid confounding and included borehole (0), dug well with cover (1) and dug well without cover (2). Regarding environmental factors, livestock presence is correlated with other pollution, unlined ponds and stagnant water (Supplementary Table S4), and the correlation is also significant between unlined ponds and stagnant water. Livestock and unlined pond variables were included in the analysis.

Analysis of factors increasing the likelihood of *E. coli* contamination

The analysis explored associations between sanitation variables and well contamination, and this section presents the results of the combined model, the comparison of separate dug and borehole models, and the comparison between repeat and single sample findings.

GEEs revealed that compliance with the horizontal separation criteria of more than 10 m between the well and sanitation system was not significantly associated with reduced contamination risk (Table 3). However, wells with multiple sanitation systems within 10 m had an increased likelihood of high contamination levels, although this was not significant after the Bonferroni correction (Table 4). The criteria of groundwater depth greater than 2 m was associated with a reduced risk of high contamination (adjusted odds ratios (AOR) 0.28, $p = 0.001$), but the association with *E. coli* presence was not significant after correction (Table 4). Treating groundwater depth as a continuous variable, as included in the base model in Table 3, showed

Table 3 | Adjusted odds ratios of the base model binary logistic analysis using GEEs comparing the association of base case risk factors with well contamination, considering (a) presence of *E. coli* and (b) high contamination (>100 MPN/100 mL)

	(a) Presence of *E. coli* (>1 MPN/100 mL)			(b) High contamination (*E. coli* >100 MPN/100 mL)		
Parameter	**Adjusted OR**	**95% CI**	***p***	**Adjusted OR**	**95% CI**	***p***
Dug well uncovered (2)	**7.370**	**2.49–21.84**	**0.000**	**9.140**	**1.52–55.09**	**0.016**
Dug well covered (1)	3.295	0.98–11.05	0.053	3.343	0.46–24.33	0.233
Borehole (0)						
Presence of unlined pond	1.069	0.40–2.84	0.893	0.811	0.3–2.18	0.677
Presence of livestock	1.681	0.68–4.13	0.257	**3.872**	**1.43–10.49**	**0.008**
Heavy rainfall phase	0.670	0.44–1.03	0.068	**0.382**	**0.21–0.71**	**0.002**
One sanitation facility within 10 m of well	0.755	0.3–1.87	0.544	1.276	0.42–3.87	0.666
Depth to groundwater (m)	**0.559**	**0.36–0.88**	**0.012**	**0.226**	**0.12–0.41**	**0.000**

Note: Bold demonstrates results are significant ($p < 0.05$).

Table 4 | Adjusted odds ratios of the association of different sanitation and groundwater variables when added to the base model binary logistic analysis using GEEs, considering (a) presence of *E. coli* and (b) high contamination (>100 MPN/100 mL)

	> 1 MPN/100 mL			> 100 MPN/100 mL		
Parameter[a]	**Adjusted OR**	**95% CI**	***p***	**Adjusted OR**	**95% CI**	***p***
Horizontal distance between the sanitation system and well ($n = 96$, $p < 0.013$)						
One sanitation facility within 10 m of well	0.755	0.3–1.87	0.544	1.276	0.42–3.87	0.666
Distance from well to closest sanitation system (m)	0.977	0.9–1.06	0.575	0.942	0.85–1.04	0.237
Density of sanitation systems around wells ($n = 96$, $p < 0.008$)						
Two or more sanitation facilities within 10 m of well	2.274	0.76–6.82	0.143	3.098	1.15–8.36	0.026
Count of sanitation facilities within 10 m of well	1.174	0.7–1.96	0.538	1.570	0.89–2.78	0.123
Density of sanitation systems within 30 m of well	1.680	0.44–6.38	0.446	2.113	0.3–14.74	0.451
Sanitation type ($n = 96$, $p < 0.013$)						
Septic tank (not pit latrine)	0.459	0.16–1.32	0.149	0.416	0.11–1.65	0.211
Cistern flush (not pour flush)	0.570	0.19–1.73	0.320	0.716	0.18–2.81	0.632
Groundwater depth ($n = 96$, $p < 0.013$)						
Depth to groundwater (m)	**0.559**	**0.36–0.88**	**0.012**	**0.226**	**0.12–0.41**	**0.000**
Groundwater depth >2 m	0.561	0.34–0.92	0.021	**0.279**	**0.13–0.6**	**0.001**
Infiltration depth[b] ($n = 28$, $p < 0.013$)						
Depth of sanitation system (m)	0.736	0.19–2.84	0.656	NA		
Infiltration depth (m)	0.799	0.33–1.93	0.618	NA		

[a]Each sanitation and groundwater variable was adjusted for Bonferroni correction based on the number of factors assessed and an initial significance of $p < 0.05$. The findings in bold are those that are significant.

[b]The infiltration assessment included one model with depth to sanitation and the standard groundwater depth variable; the other model included infiltration depth (groundwater depth – sanitation depth) and excluded the standard groundwater variable.

significant associations with both *E. coli* presence (AOR 0.56) and high contamination (AOR 0.23, $p < 0.013$). Uncovered dug wells were associated with a 7.3 times higher likelihood of *E. coli* presence and a 9.1 times higher likelihood of high contamination than boreholes. Livestock near wells significantly increased the risk of high contamination (AOR 3.9), while sampling during heavy rainfall reduced this likelihood (AOR 0.38).

Recognising different approaches to quantifying sanitation proximity and groundwater depth, alternative variables such as distance to the nearest sanitation system, sanitation density, sanitation type and infiltration depth were also assessed. Aside from the groundwater depth indicators discussed above, this analysis did not find significant associations between alternative sanitation variables and well contamination (Table 4). Multiple sanitation facilities within 10 m may be associated with an increased likelihood of high contamination (AOR 3.1, $p = 0.026$), yet this was not significant after Bonferroni correction.

Separate models for dug wells and boreholes highlighted differing risk factors, possibly due to variations in contamination pathways and drawing from different aquifers. For dug wells, there was no significant difference in well contamination for covered, uncovered and uncovered wells using buckets (Supplementary Table S5). However, heavy rainfall was significantly associated with a reduced likelihood of both *E. coli* presence and high contamination. Increasing infiltration depth was associated with a reduced likelihood of high contamination (AOR 0.140, $p = 0.014$), but this was not significant after correction ($p < 0.013$) (Supplementary Table S5). In boreholes, missing or cracked slabs were significantly associated with increased *E. coli* presence, yet groundwater depth, borehole depth and livestock were not (Supplementary Table S6).

Analysis of individual sampling rounds highlighted the variability of risk factors and limitations of one-off sampling. Unlike the repeat sample model, single sample models no longer identified uncovered wells as a significant factor for high contamination across all phases, although they remained significantly associated with an increased likelihood of *E. coli* presence compared with boreholes (Supplementary Table S7). Conversely, the continuous groundwater depth variable was no longer associated with *E. coli* presence across all phases but remained a significant factor for high contamination. The binary groundwater variable (>2 m depth) was only significantly associated with high contamination in two of the three phases (Supplementary Table S7). While factors such as multiple sanitation facilities within 10 m, pit latrines and higher sanitation density increased the likelihood of high contamination in some phases, these associations were not significant after correction (Supplementary Table S8). These findings underscore the importance of repeated sampling and comprehensive risk assessments, as contamination pathways and risk factors vary by well type, environmental conditions and sampling period.

DISCUSSION

This study investigated the associations between sanitation siting criteria and faecal contamination of wells in a densely populated urban neighbourhood in Metro City, Indonesia. By mapping wells and sanitation systems, collecting repeat measurements of well water quality and groundwater depth, and assessing environmental and well-specific risk factors, the findings highlight critical limitations of current horizontal and vertical setback criteria in managing water and sanitation risks.

Indonesian standards recommend a minimum horizontal separation of 10 m between wells and sanitation systems and a depth to groundwater from the surface of more than 2 m for safe use of on-site sanitation. While 60% of wells had a sanitation system within 10 m and 17% had multiple sanitation systems within this range, horizontal distance alone was not significantly associated with *E. coli* contamination. However, multiple sanitation systems within 10 m showed an increased likelihood of high contamination, although this association was not significant after the Bonferroni adjustment. Groundwater depth ranged from 1 to 5 m; only 22% of sanitation systems did not meet the 2 m depth to groundwater criteria. Non-compliance with this criterion was significantly associated with an increased likelihood of high *E. coli* concentrations in well water, although not for *E. coli* presence after Bonferroni correction. However, when assessed as a continuous variable, deeper groundwater had a significant association with both a reduced likelihood of *E. coli* presence and a reduced likelihood of high contamination. This suggests that the 2 m threshold may have limited effectiveness in reducing the likelihood of contamination. Siting guidance used in other countries focuses on the infiltration depth or separation distance between the base of the sanitation system and groundwater (Lewis *et al.* 1982; Lawrence & Macdonald 2001; Nenninger *et al.* 2023). The average infiltration depth was 0.83 m, with all distances less than 5 m, which, according to Lawrence & MacDonald (2001), would pose a significant risk of microorganisms reaching groundwater. While infiltration depth was significantly associated with high contamination of dug wells (model 2), it was not significant in other models. However, the analysis was limited due to the small sample size and difficulty accessing and measuring containment depths.

The findings align with studies that report greater contamination risks in shallow groundwater but found mixed results for horizontal separation. Our findings are most comparable to studies in dense urban areas with shallow groundwater. Research in Dar es Salaam found a strong correlation between sanitation proximity and shallow well contamination (Ngasala *et al.* 2019), while in India, 10 m was considered an adequate separation distance (Banerjee 2011), and in Kampala, there was no association between latrine presence and contamination (Howard *et al.* 2003). The increased risk of contamination for shallow groundwater aligns with previous studies (Katz *et al.* 2010; Diaw *et al.* 2020; Nenninger *et al.* 2023). As noted in Mbae *et al.* (2024), the variability of methods to assess groundwater risk, the factors assessed and the local contexts complicate comparisons.

Contamination in household wells was also influenced by risk factors associated with the well infrastructure and its use. Uncovered dug wells were associated with a significantly increased risk of *E. coli* presence and high contamination compared with boreholes. No significant difference was found between covered wells and boreholes. Although boreholes showed better water quality than dug wells, 52% still tested positive for *E. coli* in at least one sample. Cracked or missing slabs significantly increased the likelihood of contamination in the borehole-only model. This aligns with previous research highlighting that while boreholes are an improved supply, they do not guarantee water free from contamination (Bain *et al.* 2014; Genter *et al.* 2021). While the boreholes intercept a semi-confined aquifer, the findings align with studies that indicate poor well infrastructure may allow surface water to enter boreholes (Escamilla *et al.* 2013; Daniels *et al.* 2016). These findings suggest that improvements to well infrastructure could reduce risks, particularly by covering wells. While this is already a criterion for the SDG target of improved water supplies, it is not well captured in Indonesian monitoring, as a protected well is defined in monitoring systems by the height of the headwall, depth of lining and surrounding slab, but not the presence of a cover (BPS 2016). Upgrading to boreholes or connecting households to piped supply could mitigate contamination risks, although neither source is guaranteed to be free from contamination, and the population connected to piped water is low in Indonesia (23%) and Metro City (5%) (UNICEF & WHO 2023; BPS Kota Metro 2024b; Zikrina *et al.* 2024).

Local and environmental factors, including livestock presence and rainfall, also influenced well contamination. The presence of livestock near wells was significantly associated with an increased likelihood of high contamination, as has previously been reported in India, Bangladesh and Timor Leste (Odagiri *et al.* 2016; Wardrop *et al.* 2018). Interestingly, the heavy rainfall period was associated with a reduced likelihood of high contamination, contrasting with previous studies reporting increased contamination with rainfall (Kostyla *et al.* 2015; Murphy *et al.* 2020). In our study, this effect is likely to be due to dilution from rainfall. Our study observed heavy rainfall events in the dry season and controlled for groundwater depth, whereas earlier studies typically compared contamination in wet and dry seasons and did not adjust for groundwater depth. The processes influencing contamination transport are dynamic, with complex interactions between surface infiltration, groundwater flow and rainfall; our findings are associated with rainfall during the dry season, and different associations might be observed in the wet season.

Temporal variability was also evident, with *E. coli* contamination levels and groundwater depth fluctuating between sampling rounds. Comparing the repeat and single sample models highlighted variations in the significance of risk factors associated with well contamination. Groundwater depth showed weaker associations with contamination in the single sample models, and the association of well type and sanitation factors with contamination varied across sample rounds. While the temporal variability in well quality is widely recognised, few studies have collected and analysed repeat samples, and those that do often compare wet and dry seasons, which can present substantially different conditions (Howard *et al.* 2003; Wright *et al.* 2013; Gill *et al.* 2018; Murphy *et al.* 2020). Repeat analysis allows a more nuanced understanding of the dynamic interactions between containment pathways, groundwater and wells. GEE provides population-averaged results, and using repeat measures provides a more robust analysis that accommodates the real-world variations in water quality and the complex effects of groundwater and rainfall interactions, providing insights beyond those achieved with one-off sampling and analysis.

These findings question the effectiveness of a one-size-fits-all approach to sanitation siting to inform the suitability of on-site sanitation and mitigate risks to groundwater supplies. Horizontal separation from sanitation facilities was not significantly associated with well contamination at this site under the methods applied. While some sanitation density factors showed weak association in some models, groundwater flow direction may increase horizontal transmission in certain directions, yet the direction was inconsistent at this site. While larger separation distances are recommended by some guidelines, they would be impractical in densely populated areas like Metro City, where 98% of wells had a sanitation system within 15 m. The adequacy of the 2 m depth to groundwater criterion also requires reassessment considering local soil characteristics (Lawrence & Macdonald 2001; Henneman 2020). While it may be sufficient in Metro's clayey soils, it may be insufficient in areas with more permeable sandy soils, which are prevalent across Indonesia. Many studies also highlight the influence of depth to groundwater on horizontal travel distance, further adding to the complexity of single setback distances (Nenninger *et al.* 2023). The simplicity of these separation criteria means that the influence of local conditions on pathogen transport is not adequately considered (Graham & Polizzotto 2013).

To better manage these risks, water and sanitation safety planning and routine sanitary inspections are promising alternatives (Twinomucunguzi *et al.* 2020; WHO 2024a, b). Inspection-based risk assessments could target high-risk areas, such as those with shallow groundwater, poor water quality or lacking piped supplies, to identify common hazards in well and sanitation systems and inform localised risk management strategies. These approaches could build on existing environmental health risk assessments or be integrated into local inspection programs, such as those conducted by sanitarians as part of national ending open defaecation initiatives. Immediate water quality improvement recommendations include increasing efforts to ensure wells are covered, which may require a review of how improved wells are assessed in national monitoring. Where possible, sanitation systems should be built to maximise vertical separation with groundwater, for example, prioritising septic tanks and leach fields or twin pits over deep single pits. Monitoring of water quality must also recognise that an one-off sample may provide only a partial understanding of safety, given the variability shown over a 2-month period. While modelling has proven valuable for understanding the complex dynamics of groundwater contamination (Back *et al.* 2018; Nenninger *et al.* 2023), scaling modelling assessments in Indonesia would be challenging due to limited local government capacity. Although it could be argued that on-site sanitation and on-premises wells are incompatible in urban areas and piped water systems should be prioritised, the slow expansion of piped connections in Indonesia underscores the ongoing need for solutions to manage the risks associated with on-site systems and wells.

Several methodological and site-specific constraints limited this assessment of sanitation separation criteria on well contamination. The census approach was effective in controlling for many environmental variables; however, an ideal site would have avoided major known contamination risks such as uncovered wells and livestock to prioritise the assessment of sanitation pathways. Dedicated piezometers could provide a clearer picture of the sanitation to groundwater transmission pathway and avoid issues with local well contamination, although building piezometers in built-up residential areas is complex. Similarly, using rainfall gauges, rather than relying on data from the nearby weather station, could provide a more accurate and time-sensitive assessment of rainfall. Viruses and other faecal indicators from on-site sanitation may exhibit different transport behaviours in soil and groundwater, and analyses of multiple parameters could yield different results or provide a broader understanding of contamination pathways. Selection of other parameters should, however, account for local constraints such as proximity to agriculture and diagnostic capacity. The inability to differentiate between human and animal sources of faecal contamination limits the specificity of the findings. However, methods to differentiate these sources are often unavailable in small towns such as Metro City. (e.g. Odagiri *et al.* 2016; Fuhrmeister *et al.* 2019), although future studies could consider how to filter and transport samples to another location for analysis to enable analysis of a range of contamination markers (Demeter *et al.* 2023). In addition, larger samples would be beneficial, particularly for infiltration depths, given the stricter statistical thresholds required for multiple-hypothesis testing. Lastly, the study's focus on the dry season may not represent the issues in the wet season, given that prolonged rainfall and raised groundwater levels may alter contamination pathways.

CONCLUSION

The interactions between on-site sanitation and groundwater supply are complex, and simple separation distances or depth criteria may be insufficient to effectively manage contamination risks. Depth to groundwater was a critical factor, with contamination risks decreasing at greater depths. While the binary 2 m depth criterion was associated with reduced high contamination levels in the clayey soils in Metro, it may be inadequate in sandy, more permeable soils, as are common in Indonesia. Horizontal separation of sanitation systems was not significantly associated with well contamination in this study, and the findings emphasise the need for a nuanced understanding of the many local factors influencing contamination pathways in urban areas. Building on previous studies, our risk factor assessment was made more robust by the census sampling and repeated measures of water quality and groundwater depth, capturing real-world variability and strengthening the analysis of contamination risks. Given that multiple factors were assessed to reflect the varied contamination pathways, a larger sample could give more explanatory power to this approach. While models provide valuable insights into the complex factors contributing to contamination, it is challenging to scale such assessments. Given compliance with siting criteria alone is likely insufficient to minimise well contamination risks, local risk assessment approaches, such as safety planning or targeted inspections in high-risk areas, are recommended to identify locally relevant hazards and improvement options. While transitioning to piped water, boreholes or sewer systems may reduce risks, immediate measures are needed to manage the ongoing use of dug wells and on-site sanitation in urban Indonesia. Increasing urbanisation and climate hazards are expected to exacerbate well contamination risks, making localised integrated water and sanitation risk management essential for ensuring safe and sustainable services.

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ETHICS STATEMENT

Free and informed consent was obtained from the participants. The study protocol was approved by the UTS Human Research Ethics Committee at the University of Technology Sydney, NSW, Australia, Protocol # UTS HREC ETH20-5620, approved 6 July 2021.

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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