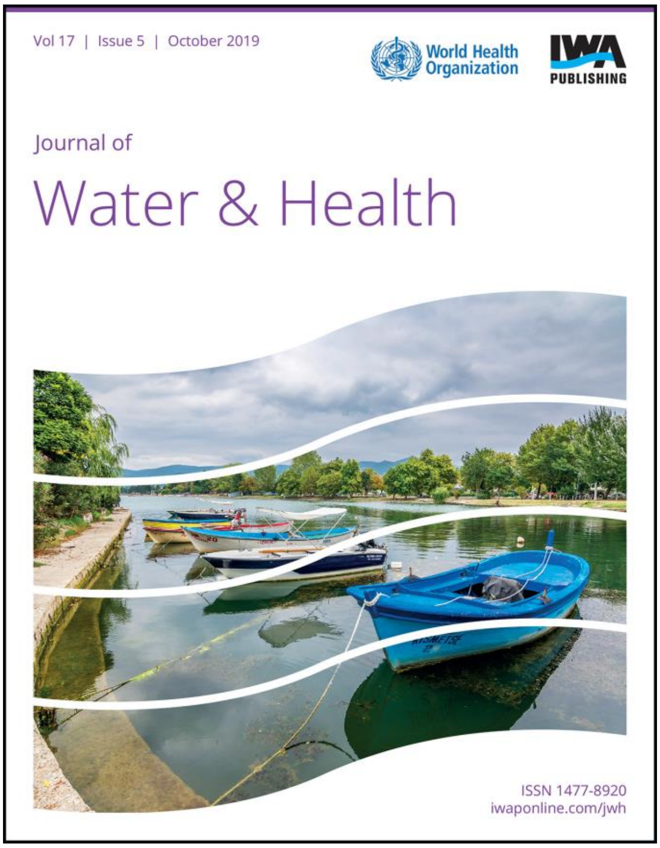
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Faecal contamination of groundwater in rural Vanuatu: prevalence and predictors

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ABSTRACT

Groundwater is an important source of water for coastal communities in Pacific Island Countries. This study assessed the prevalence and predictors of faecal contamination in groundwater sources across 11 islands in Vanuatu. *Escherichia coli* was detected in 49% of sources and *E. coli* concentration exceeded 10 MPN (most probable number)/100 mL for 23% of sources. When adjusting for other variables, the detection of *E. coli* was significantly associated with severe pump stand corrosion, suggestive of contaminated run-off directly entering boreholes. *E. coli* concentration >10 MPN/100 mL was also significantly associated with: (i) hand-dug wells (as compared to drilled boreholes); (ii) severe pump stand corrosion; (iii) water points underlain by volcanic rocks (as compared to coral limestone); and (iv) rainfall in the previous 24 h. Encasing pump stands in concrete – as some communities had done – was found to have a significant protective effect. While baseline statistics for Sustainable Development Goal target 6.1 suggest that 87% of Vanuatu's rural population have access to at least a basic (improved) water source, the results from this study point to extensive microbial water quality concerns linked to degraded water supply infrastructure in need of rehabilitation.

Key words | faecal contamination, groundwater, Pacific Island Country, rural water supply, Vanuatu

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INTRODUCTION

Groundwater is an important source of water for rural households in coastal communities in the Pacific Islands. In Vanuatu, 15% of rural households obtain drinking water from wells and boreholes (VNSO 2017), with dependence highest in dry periods when stored rainwater becomes depleted (Foster & Willetts 2018). However, little has been documented on the microbial quality of these groundwater sources. This study sought to understand the extent to which faecal contamination affects Vanuatu's groundwater sources by assessing levels of *Escherichia coli*, a widely accepted faecal indicator bacteria (Edberg *et al.* 2000). It also aimed to identify the factors associated with *E. coli* levels in order to inform remedial measures for improving the safety of groundwater sources.

According to Vanuatu's national water supply inventory, groundwater is most commonly lifted by handpump, with around 250 installations across rural areas of the archipelago (Foster & Willetts 2018). The standard handpump in Vanuatu is the Nira AF-85 (Mourits & Depledge 1995), a private domain direct action handpump which is capable of a pumping lift of up to 20 m (see Supplementary Figure S1, available with the online version of this paper). The handpump is also found in a number of African countries (Hoffman 1992; Mtunzi & Lombardi 1993; Harvey & Drouin 2006; Macarthur 2015). Although still outnumbered by handpumps, motorised pumps are also being increasingly used to lift groundwater in Vanuatu, particularly in areas with a reliable supply of electricity (Foster & Willetts 2018).

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There is a paucity of empirical evidence on groundwater quality in rural areas of Vanuatu. Data from the country's water supply inventory suggest that water quality testing is the exception rather than the norm. Of the more than 400 water supply systems drawing on groundwater, just 4% are reported to have been tested at some point. A recent study pairing groundwater sources with rainwater sources in 32 communities detected *E. coli* in 56% of groundwater sources tested (Foster & Willetts 2018). Similarly, testing of 181 rural water supply systems by String *et al.* (2017) found 52% of samples contained *E. coli*; however, the specific contribution of groundwater-based systems to this figure was not reported.

Given the dearth of information on the microbiological quality of groundwater in rural Vanuatu, little is known about contamination sources and routes. Both hazard and pathway factors are potential contributors to faecal contamination of groundwater-based rural water supplies (Howard 2002; MacDonald *et al.* 2005). Studies from elsewhere have commonly shown a link between proximate sanitation facilities and faecal contamination of groundwater (Graham & Polizzotto 2013), although the relationship is mediated by a range of contextual factors such as soil and aquifer characteristics. Other factors shown to contribute to faecal contamination of groundwater in low- and middle-income countries include water point design, construction quality, topography, groundwater depth, population density, rainfall, and overall sanitary inspection score (Howard *et al.* 2003; Cronin *et al.* 2006; Knapett *et al.* 2012; Mushi *et al.* 2012; Engström *et al.* 2015; Kostyla *et al.* 2015; Dey *et al.* 2017; Elisante & Muzuka 2016; Martínez-Santos *et al.* 2017; Nienie *et al.* 2017). However, the degree to which these findings translate to the Vanuatu context has not been empirically tested. Thus, the purpose of this study was to clarify these relationships in Vanuatu by assessing the prevalence of faecal contamination and identifying associated risk factors for 149 groundwater-based water supply systems across 11 islands.

METHODS

In order to evaluate the prevalence and predictors of faecal contamination in groundwater sources in rural Vanuatu, microbial water quality testing and sanitary inspections were carried out for 149 groundwater sources (Figure 1).

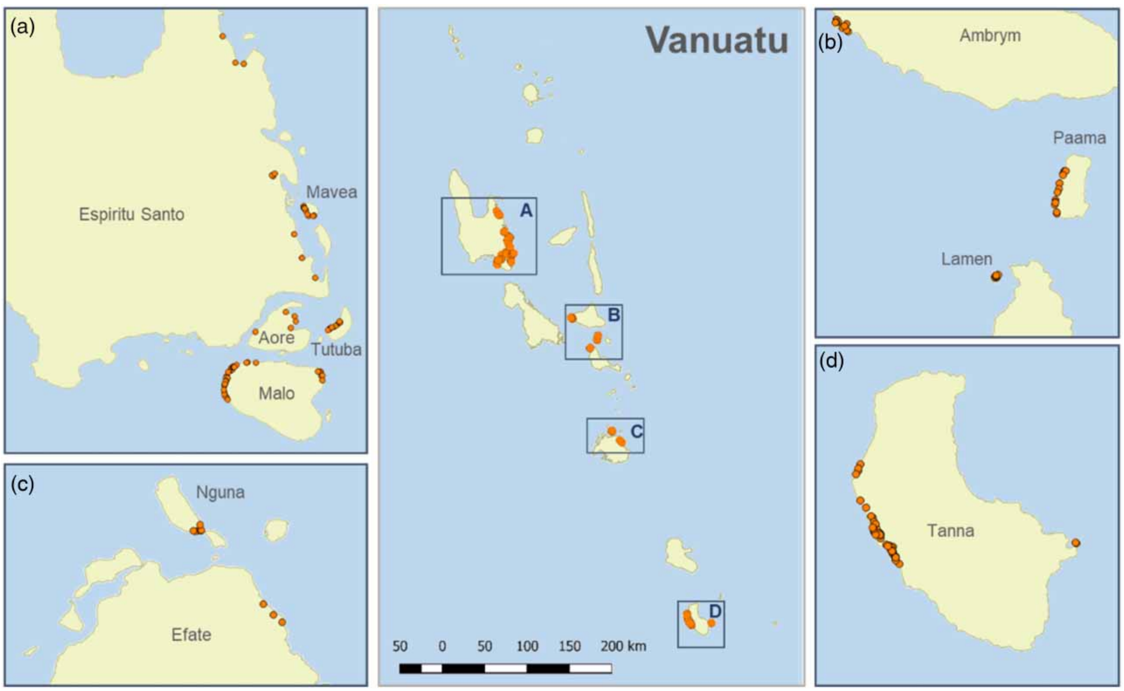

Figure 1 | Distribution of water sources assessed.

Figure 2 | Pump types included in the assessment.

This included 124 Nira AF-85 handpumps, seven India Mark II handpumps and 18 motorised pumps (Figure 2). The data collection took place across 11 islands during August and September 2017, which are typically the driest months of the year in Vanuatu. Data from the country's rural water supply inventory were used as the basis for locating the groundwater sources to be included in the study.

A sanitary inspection was carried out for each water supply system. A questionnaire was developed to gather information on the condition of each water point, including hazard factors that represented possible sources of faecal contamination and pathway factors that could facilitate the localised entry of faecal contamination. Hazard factors assessed were (a) the presence of a sanitation facility within 30 m of the water point and (b) the presence of an animal pen within 30 m of the water point. Thirty metres was chosen as the threshold distance based on the 2014 edition of Vanuatu's National Drinking Water Quality Standards, which proposed 30 m as the point at which the risk of groundwater contamination becomes high (DGMWR & MoH 2014). This guideline also corresponds with global Sphere standards (The Sphere Project 2011). Three localised contamination entry points were identified for the Nira AF-85 handpump: (i) damaged spout, (ii) damaged base plate (pump stand), and (iii) damaged sleeve bearing (Figure 3). The coverage of the water point concrete apron was also measured in order to determine the minimum distance between the outer edge of the apron and the casing of the borehole or well. Given the well-established link between rainfall and microbial water quality (Kostyla *et al.* 2015), at each water point, a respondent was also asked if the rain had fallen within the previous 24 h.

At each location, water was tested for *E. coli* using Aquagenx Compartment Bag Tests (CBTs). CBTs produce a quantitative estimate of *E. coli* concentration based on a most probable number (MPN) per 100 mL (Stauber *et al.* 2014; Gronewold *et al.* 2017). Standard protocols with respect to sample collection, storage, testing, incubation, and measurement were adhered to (Aquagenx 2018). CBTs were kept at temperatures above 25°C for up to 48 h, and a data logger was used to monitor incubation temperatures and ensure compliance with recommended incubation times. Results were determined by matching the colour sequence of the CBT's five compartments with a 32-row MPN table. At the time samples were collected, basic physico-chemical parameters (electrical conductivity and pH) were also measured at each water point using a multiparameter meter (Hanna Instruments, HI98195).

Following data collection, results from the water quality testing were linked with sanitary inspection information as well as two additional variables relating to the water point's elevation and underlying geology. Elevation was used as a proxy for groundwater depth, which in turn may influence microbial water quality. Because groundwater depth measurement, in most cases, would have required the pump to be dismantled, it was not feasible to systematically record depth information. The validity of using elevation as a proxy for groundwater depth was confirmed

Figure 3 | Aspects of the pump condition considered in the assessment of Nira AF-85 handpumps.

by the identification of a statistically significant relationship between these two variables based on a subset of 62 water points where groundwater depth could be measured (one-way analysis of variance (ANOVA), $p < 0.001$) (Figure 4).

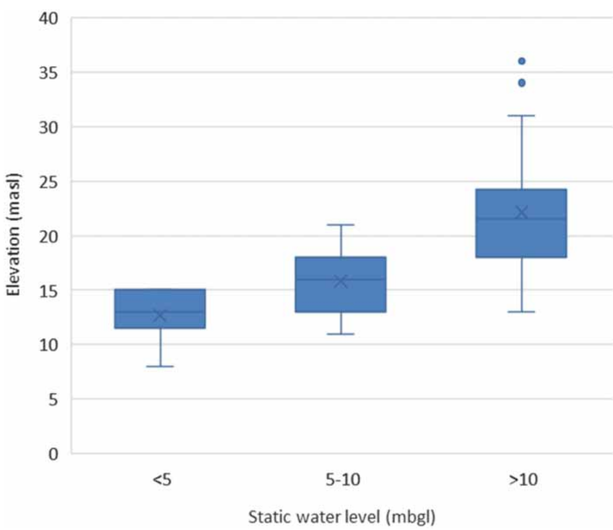

Figure 4 | Relationship between static water level and elevation at points where groundwater depth could be measured.

Elevation data were obtained from the digital elevation model derived from the Shuttle Radar Topography Mission (Reuter *et al.* 2007; Jarvis *et al.* 2008). Geological information was deemed relevant as it can influence the distance and speed at which microbes might be transported within an aquifer (MacDonald *et al.* 2005). Geological data for Vanuatu were obtained from digitised geological maps (IRD 2014; Zaiss 2014).

Simple descriptive statistics were first computed in order to characterise the water supply systems, as well as quantify the prevalence and levels of faecal contamination observed. In doing so, *E. coli* concentrations were converted to decimal categories corresponding to the World Health Organization guidelines: (i) <1 MPN/100 mL, (ii) 1–10 MPN/100 mL, (iii) 10–100 MPN/100 mL, and (iv) >100 MPN/100 mL (WHO 2011). Multivariable logistic regression analysis was then performed to identify significant predictors of *E. coli* concentration. Three binary outcome variables were assessed based on the following *E. coli* thresholds: (i) ≥1 MPN/100 mL, (ii) >10 MPN/100 mL, and (iii) >100 MPN/100 mL. Two sets of models were run: one for all pump types and one for only Nira AF-85 handpumps. All analysis was performed with the statistical software package IBM SPSS Statistics (version 24).

RESULTS

The characteristics of water supply systems assessed are presented in Tables 1 and 2. The majority of pumps were installed on drilled boreholes (97%) and were underlain by coral limestone (85%). A minority of systems were located within 30 m of a sanitation facility (21%) or an animal pen (6%). Only a small proportion of water points (9%) had received rainfall in the 24 h prior to testing. Among the Nira AF-85 handpumps, 31% had base plate damage, 35% had spout damage, and 44% had a damaged sleeve bearing. The average pH was 7.5 for all groundwater sources and 7.4 for Nira AF-85 handpumps, while electrical conductivity averaged 1,335 μS/cm for all groundwater sources and 957 μS/cm for Nira AF-85 handpumps.

Overall, *E. coli* was detected in 49% of groundwater sources and 51% for Nira AF-85 handpumps (Figures 5 and 6). The percentage of sources with detectable *E. coli* was higher for systems that were; (i) underlain by coral limestone, (ii) located within 30 m of a sanitation facility or an animal pen, (iii) situated at a lower elevation, (iv) installed on shallow wells, and (v) visited within 24 h of rainfall.

Table 1 | Characteristics of all groundwater sources tested ($n = 149$)

Characteristics	*N* (%)
Geology	
Coral limestone	126 (85%)
Volcanic	23 (15%)
Sanitation facility	
<30 m away	31 (21%)
>30 m away	118 (79%)
Animal pen	
<30 m away	9 (6%)
>30 m away	140 (94%)
Pump type	
Nira AF-85 handpump	124 (83%)
India Mark II handpump	7 (5%)
Motorised pump	18 (12%)
Elevation	
<15 m	44 (30%)
>15 m	105 (70%)
Well type	
Borehole	145 (97%)
Shallow well	4 (3%)
Rainfall in previous 24 h	
Yes	12 (9%)
No	137 (91%)

Table 2 | Characteristics of Nira AF-85 handpumps tested ($n = 124$)

Characteristics	*N* (%)
Geology	
Coral limestone	108 (87%)
Volcanic	16 (13%)
Sanitation facility	
<30 m away	28 (23%)
>30 m away	96 (77%)
Animal pen	
<30 m away	8 (6%)
>30 m away	116 (94%)
Base plate	
Intact	85 (69%)
Damaged	39 (31%)
Sleeve bearing	
Intact	69 (56%)
Missing	55 (44%)
Spout	
Intact	80 (65%)
Damaged	44 (35%)
Minimum apron coverage	
<35 cm	61 (49%)
≥35 cm	63 (51%)
Elevation	
<15 m	42 (34%)
≥15 m	82 (66%)
Well type	
Borehole	120 (97%)
Shallow well	4 (3%)
Rainfall in previous 24 h	
Yes	11 (9%)
No	113 (91%)

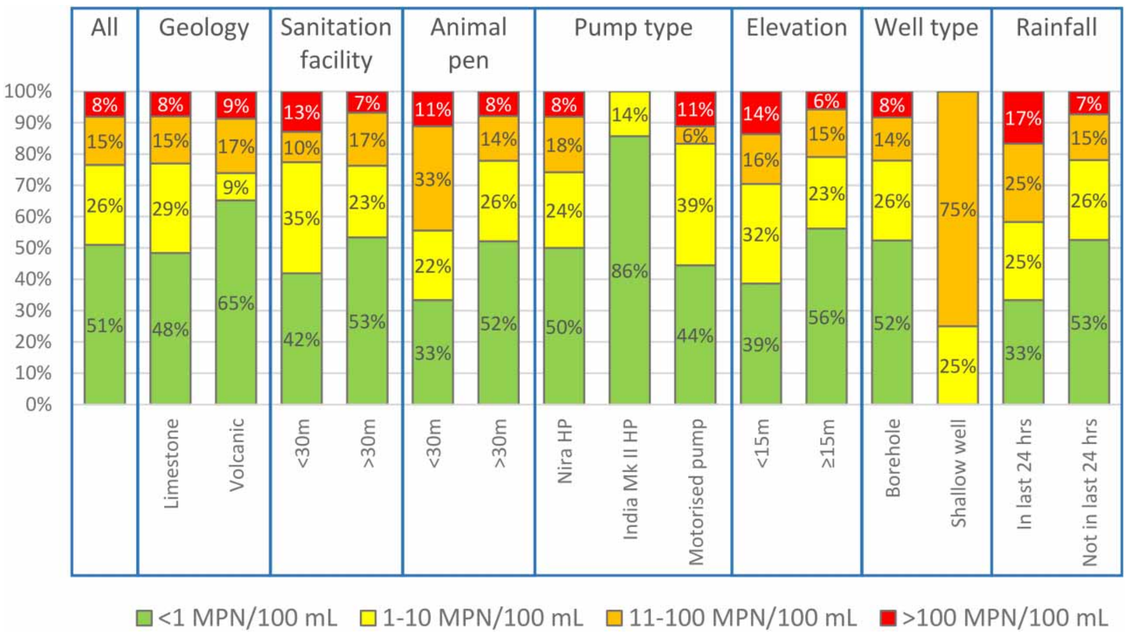

Figure 5 | *E. coli* concentrations in all groundwater sources.

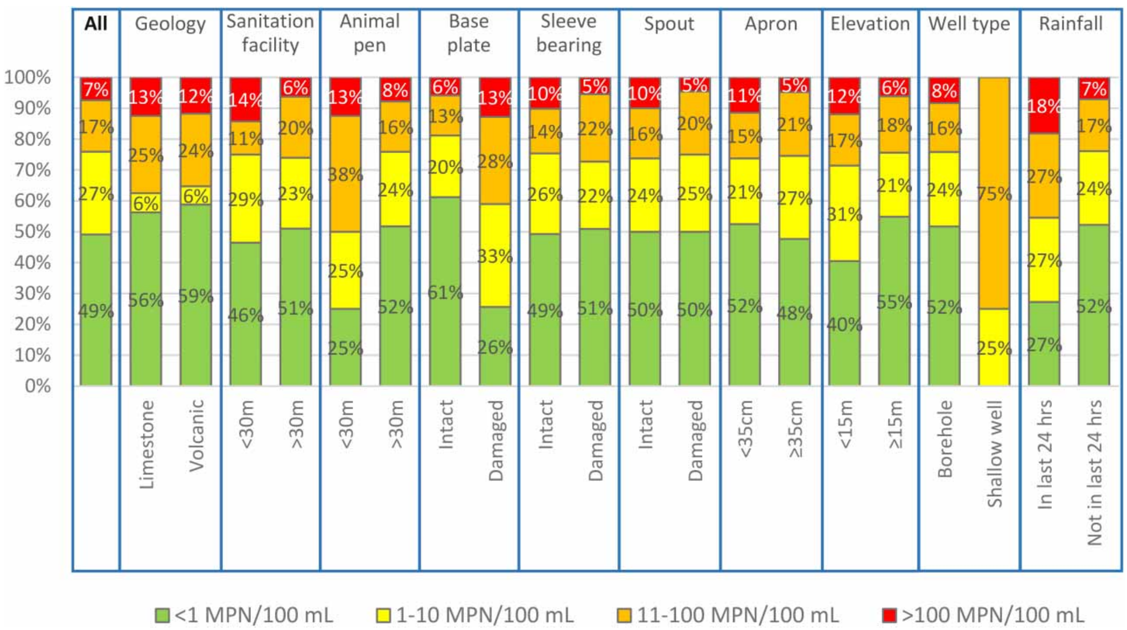

Figure 6 | *E. coli* concentrations in water supplied by Nira AF-85 handpumps.

For the three regression models that incorporated all pump types, only one explanatory variable had a statistically significant association with the *E. coli* level (Table 3). Hand-dug wells had significantly higher adjusted odds of supplying water with *E. coli* exceeding 10 MPN/100 mL as compared to drilled boreholes. When narrowing the analysis to Nira AF-85 handpumps (Table 4), a damaged base plate was significantly associated with *E. coli* being detected

Table 3 | Multivariable logistic regression results for *E. coli* contamination of groundwater supplied by any pump type

	≥1 MPN/100 mL		>10 MPN/100 mL		>100 MPN/100 mL	
	aOR (95% CI)	***p*-value**	**aOR (95% CI)**	***p*-value**	**aOR (95% CI)**	***p*-value**
Geology						
Volcanic	Ref.					
Limestone	1.68 (0.57–4.97)	0.350	0.46 (0.14–1.50)	0.199	0.53 (0.09–3.01)	0.478
Sanitation facility						
<30 m away	Ref.		Ref.		Ref.	
>30 m away	1.65 (0.71–3.83)	0.243	0.74 (0.27–2.05)	0.558	1.62 (0.42–6.25)	0.486
Animal pen						
<30 m away	Ref.		Ref.			
>30 m away	3.15 (0.67–14.8)	0.145	3.45 (0.738–16.4)	0.119	2.18 (0.21–22.6)	0.513
Elevation	1.00 (0.95–1.06)	0.861	0.95 (0.88–1.02)	0.172	0.91 (0.80–1.04)	0.156
Pump type						
Nira AF-85 HP	Ref.	0.467	Ref.		Ref.	
India Mark II HP	0.25 (0.022–2.85)	0.265	–	–		
Motorised pump	1.30 (0.47–3.61)	0.610	0.88 (0.22–3.41)	0.849	2.29 (0.40–13.0)	0.348
Well type						
Borehole	–	–	Ref.		–	–
Hand-dug well	–	–	**10.8 (1.04–113)**	**0.046**	–	–
Rainfall in previous 24 h						
No	Ref.		Ref.		Ref.	
Yes	1.81 (0.51–6.50)	0.361	2.94 (0.82–10.5)	0.097	2.60 (0.46–14.6)	0.279

aOR, adjusted odds ratio; CI, confidence interval; HP, handpump; Ref., reference category.
Bold values indicate statistically significant result.

(>1 MPN/100 mL) and *E. coli* exceeding 10 MPN/100 mL. *E. coli* in excess of 10 MPN/100 mL was also significantly associated with hand-dug wells (as compared to drilled boreholes), volcanic geology (as compared to coral limestone), and rainfall in the previous 24 h.

DISCUSSION

The results suggest that faecal contamination of groundwater-based water supplies is widespread in Vanuatu, with *E. coli* detected in 49% of water sources tested. This proportion is not dissimilar to groundwater sources in other low- and middle-income countries, with a systematic review reporting *E. coli* in 45% and 70% of boreholes and shallow wells, respectively (Shields *et al.* 2015). It is also consistent with other results of microbial water quality testing of rural water supplies in Vanuatu (String *et al.* 2017). This points to the need for a systematic approach to water quality monitoring in rural areas of Vanuatu. While baseline statistics for Sustainable Development Goal target 6.1 suggest that 87% of Vanuatu's rural population have access to at least a basic (improved) water source (WHO/UNICEF 2017), the results reinforce the notion that 'improved' is not synonymous with 'safe' (Shaheed *et al.* 2014; Martínez-Santos 2017). With 15% of Vanuatu's rural population using groundwater sources for drinking, the findings could have important public health implications. Diarrhoeal disease remains a major cause of premature death in Vanuatu, accounting for approximately 6% of deaths among children under 5 years (Carter *et al.* 2016).

This study was conducted in a relatively dry time of the year, so the prevalence of faecal contamination is likely to be higher in other parts of the year when rainfall

Table 4 | Multivariable logistic regression results for *E. coli* contamination of groundwater supplied by Nira AF-85 handpumps

	≥ 1 MPN/100 mL		> 10 MPN/100 mL		> 100 MPN/100 mL	
	aOR (95% CI)	*p*-value	aOR (95% CI)	*p*-value	aOR (95% CI)	*p*-value
Geology						
Volcanic	Ref.		Ref.		Ref.	
Limestone	0.95 (0.27–3.33)	0.929	**0.16 (0.034–0.72)**	**0.017**	0.56 (0.069–4.53)	0.588
Sanitation facility						
<30 m away	Ref.		Ref.		Ref.	
>30 m away	1.11 (0.43–2.89)	0.832	0.80 (0.26–2.45)	0.691	2.13 (0.45–10.0)	0.336
Animal pen						
<30 m away	Ref.		Ref.			
>30 m away	3.13 (0.55–17.9)	0.200	3.71 (0.58–23.8)	0.166	2.62 (0.23–30.1)	0.440
Elevation	0.98 (092–1.04)	0.504	0.95 (0.87–1.03)	0.232	0.91 (0.79–1.05)	0.208
Well type						
Borehole	–	–	Ref.		–	–
Shallow well	–	–	**54.8 (2.87–1,046)**	**0.008**	–	–
Base plate						
Intact	Ref.		Ref.		Ref.	
Damaged	**5.82 (2.26–15.0)**	**<0.001**	**7.17 (2.25–22.9)**	**0.001**	4.77 (0.89–25.5)	0.068
Sleeve bearing						
Intact	Ref.		Ref.		Ref.	
Damaged	0.81 (0.34–1.92)	0.639	1.77 (0.59–5.31)	0.308	0.95 (0.18–4.99)	0.949
Spout						
Intact	Ref.		Ref.		Ref.	
Damaged	0.77 (0.30–1.97)	0.590	0.95 (0.29–3.08)	0.930	0.39 (0.055–2.80)	0.353
Minimum apron distance	1.00 (0.98–1.02)	0.823	0.99 (0.97–1.02)	0.707	0.97 (0.92–1.02)	0.239
Rainfall in previous 24 h						
No	Ref.		Ref.		Ref.	
Yes	3.54 (0.76–16.5)	0.108	**7.29 (1.40–37.8)**	**0.018**	1.93 (0.23–16.2)	0.545

aOR, adjusted odds ratio; CI, confidence interval; Ref., reference category.
Bold values indicate statistically significant result.

intensifies. August and September – the months in which data were collected – are typically the two driest months in Vanuatu (VWGHD 2019). A systematic assessment of the literature has shown that rainfall is associated with increased faecal contamination of water sources (Kostyla *et al.* 2015). The relationship between rainfall and *E. coli* of >10 MPN/100 mL observed in this study indicates that this relationship holds for groundwater sources in Vanuatu.

The results suggest that water from drilled boreholes is safer to drink than water from hand-dug wells. This is consistent with findings from a meta-analysis of previous studies (Shields *et al.* 2015). In the case of Vanuatu, it is unclear whether hand-dug wells are more susceptible to faecal contamination because their large diameter design means that there are additional entry points (e.g. inclusion of a manhole in the concrete apron) or simply because they tend to be constructed where groundwater is shallow and therefore more liable to aquifer contamination.

The relationship between the condition of the pump stand (specifically the base plate) and *E. coli* provides strong evidence that inadequate maintenance is compromising the safety of drinking water supplied. Almost a third of Nira handpumps had base plates that were significantly corroded or missing altogether, allowing run-off to flow directly into the borehole. With an average age of 17 years, most of the Nira AF-85 handpumps inspected were approaching the end of their expected lifespan of 25–30 years (World Bank 1994). There was a clear link between handpump age and pump condition: of those installed in the 1990s, 52% had intact base plates. This compares with 83% of those installed between 2000 and 2009 and 100% of those handpumps installed from 2010 onwards ($p = 0.005$). Hydrochemical properties may also be influencing the condition of the pump stand. While pH of water supplied was similar for those handpumps with and without pump stand corrosion (average of 7.5 vs. 7.4, respectively), there was a significant association between electrical conductivity of groundwater and discernible damage to the base plate ($p = 0.031$; 1,052 μS/cm with pump stand corrosion vs. 750 μS/cm without pump stand corrosion).

Figure 7 | Example of a Nira AF-85 pump stand encased in concrete.

In the immediate term, there is an urgent need to repair and rehabilitate the handpumps with damaged base plates. Community-based committees are generally responsible for managing the maintenance of communal water points in Vanuatu. However, when it comes to the Nira AF-85, the absence of spare part supply chains renders it impossible for communities to coordinate repair activities when replacement parts are needed. In response to this constraint, 11 communities had encased their pump stand in concrete (Figure 7). This measure exhibited a significant protective effect, reducing the adjusted odds of *E. coli* by 97% (AOR 0.026, 95% CI 0.0026–0.25, $p = 0.002$). Encouraging and supporting other communities to replicate this strategy could yield substantial water quality improvements and health benefits at a relatively low cost. However, such stopgap measures do not obviate the need to confront the longer-term challenge of managing and maintaining rural water supply infrastructure across Vanuatu's many islands and strengthening the enabling environment upon which sustainable water services depend.

A coordinated effort to rehabilitate ageing water supply infrastructure in rural Vanuatu may provide an opportunity to improve service levels beyond just water quality improvements. It is notable that the 18 motorised pumps included in the study had all been installed on boreholes that were originally equipped with Nira AF-85 handpumps. These historical upgrades had capitalised on the significant value of a pre-existing drilled borehole, which far outweighs the cost of new pumping equipment. Replacing handpumps with motorised pumps coupled with a small-scale distribution system offers the possibility of piping water onto the premises of water users. As well as delivering health gains (Overbo *et al.* 2016) and time savings, the availability of water on-premises is a key criterion of the safely managed water service standard that will guide efforts towards Sustainable Development Goal target 6.1. This course of action might only be viable under certain conditions though, with the availability of power evidently a key determinant of such schemes in Vanuatu. All but one of the motorised pumps located in this study were situated on the islands of Tanna and Espiritu Santo, specifically in areas where mains electricity is readily accessible. It should also be noted that more advanced systems increase the complexity of operation and maintenance, while the need for a reliable energy source also presents new challenges in terms of continuity of supplies, which in turn may undermine the 'available when needed' requirement of a safely managed service. Solar-powered pumps may obviate dependence on a reliable supply of electricity, though only one such system was observed throughout the course of this investigation.

Although studies have shown an inverse relationship between the distance to a latrine and risk of faecal contamination (Graham & Polizzotto 2013), this investigation did not identify a significant effect for on-site sanitation facilities based on a 30 m cut-off. This may, in part, be because travel distances of microbes are mediated by other factors such as latrine design and construction quality, topography, soil conditions, and geology. To illustrate the point, this study found that the adjusted odds of *E. coli* exceeding 10 MPN/100 mL was sixfold higher for pumps underlain by volcanic rocks in comparison with those underlain by coral limestone.

This study provides a number of important insights; however, it does suffer from several limitations. Firstly, certain variables were defined simplistically by virtue of data limitations. For example, there was little detail available about the substructure of nearby pit latrines, no direct and comprehensive assessment of groundwater depth was possible, and a binary rather than a continuous indicator of rainfall was relied upon. Second, faecal contamination levels tend to vary seasonally. As the results of this study reflect the situation in the driest months of the year (August and September), they may not hold in wetter periods. For example, rainfall levels in the months of February and March are typically three to four times greater than those during August and September (see Supplementary Figure S2 for monthly rainfall in Vanuatu, available with the online version of this paper). Likewise, microbial contamination generally increases during transport and storage of water from off-plot water sources (Bain *et al.* 2014; Shields *et al.* 2015), and so, the associations between explanatory variables and *E. coli* at the source may not necessarily hold for water quality at the point of use. Finally, although *E. coli* is a widely employed and accepted indicator bacteria from which faecal contamination can be inferred, its detection does not reveal the presence of specific pathogens. Different pathogens may exhibit different characteristics in terms of their fate and transport (Mills *et al.* 2018), and hence, health impacts may not align with water quality results based on *E. coli*.

CONCLUSION

This study assessed the prevalence and predictors of faecal contamination in groundwater sources across 11 islands in Vanuatu. *E. coli* was detected in 49% of sources and was significantly associated with severe pump stand corrosion. Other predictive factors for *E. coli* >10 MPN/100 mL included well type, geology, and rainfall. While headline statistics suggest that a high proportion of households use an improved water source in Vanuatu, the results from this study show that the poor condition of handpumps is leading to widespread microbial water quality concerns. With many handpumps approaching the end of their expected service life – combined with an absence of spare part supply chains – there is an urgent need to rehabilitate or replace existing water supply infrastructure. Communities have shown that makeshift and low-cost remedial actions can reduce water quality risks and this could yield important health benefits if replicated more broadly. However, more sustainable and systems-wide solutions are needed in the longer term to prevent slippage in the gains made in water service coverage.

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