



Development of Well Water Quality Model for Obudu Metropolis, Southern Nigeria

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ABSTRACT

Shallow hand-dug wells are the everyday water source for many households in Obudu, Cross River State, but little is known about how their quality changes through the year or how it relates to the way each well is built and sited. We sampled 50 wells every month from January to August 2022 (400 well-month observations; four dry-season and four rainy-season months) and measured fourteen physicochemical and microbiological parameters, with each well's depth, lining, cover and distance to the nearest pollution source. About 49% of the 400 pH readings, and 28 of the 50 wells on their eight-month means, were below the 6.5 lower guideline limit; because pH was read with a visual comparator, these figures are semi-quantitative. Nitrate (maximum 46.5 mg/L), TDS and electrical conductivity stayed below guideline values. Turbidity exceeded 5 NTU in 50.5% of rainy-season readings against 5.5% of dry-season readings, and total coliforms (membrane filtration, CFU/100 mL) were detected in 332 of 400 samples. Because each well was measured eight times, we fitted linear mixed-effects models with a random intercept for each well. Rainy-season water had higher turbidity (+44%), TDS, dissolved oxygen, bicarbonate and calcium, and lower nitrate, magnesium, alkalinity and total coliforms (−32%); pH did not change. After Holm correction, unlined wells were more turbid (lined wells −23%, 95% CI −34 to −10%) and uncovered wells carried higher heterotrophic counts (covered wells −12%, −17 to −6%). Between-well differences accounted for 15–85% of the residual variance, so repeated-measures modelling mattered. In leave-wells-out cross-validation, the models explained at most 19% of the variance in new wells (turbidity), and none for pH. The results support well lining and covering, household disinfection and rainy-season monitoring, and show that well-level characteristics alone do not predict quality well enough for use in screening.

Keywords: groundwater quality; hand dug wells; seasonal variation; mixed effects model; well protection; total coliforms; Obudu; Cross River State

INTRODUCTION

Background

Groundwater supplies a large share of the world's drinking water and a good part of its irrigation, and its importance grows as populations rise and surface sources come under pressure (Foster et al., 2002; Todd and Mays, 2005). Because it sits underground and moves slowly, groundwater is often assumed to be safe. That assumption holds only up to a point. Farming, housing, commerce and industry all leave a footprint on the aquifer below them, and once an aquifer is contaminated it is difficult to monitor and slow, costly and uncertain to clean up.

The problem is sharpest in towns where piped supply is patchy and households dig their own wells A synthesis

of urban groundwater studies across sub-Saharan Africa concluded that shallow sources in cities and towns are frequently of poor quality because waste management and source protection are inadequate, while deeper boreholes more often give acceptable water (Lapworth et al., 2017). Nigerian groundwater chemistry and quality have been reviewed nationally (Edet et al., 2011).

Contamination pathways, regional evidence and the research gap

Contaminants can reach a hand-dug well by three broad routes: infiltration through the soil from nearby sources such as pit latrines, soakaways, refuse and abattoir waste; lateral seepage through unlined walls; and direct entry through an open or poorly sealed top, where runoff, dust and debris can fall in. Lining, cover and distance to the nearest source are therefore the well characteristics most likely to govern what reaches the water. The risk from on-site sanitation is real but poorly quantified: a systematic review found that studies of pit latrines and groundwater are limited, generally focus on a few indicator contaminants, and call for better criteria for siting latrines relative to water sources (Graham and Polizzotto, 2013).

Evidence from Cross River State shows that shallow groundwater quality is a regional concern. In the shale terrain of the Cross River Basin, where water is drawn mainly from hand-dug wells shallower than 20 m, about half of the groundwater samples were acidic and about a quarter exceeded 45 mg/L nitrate, which the authors linked to fertiliser use and poor waste management (Nganje et al., 2017). Groundwater from boreholes in Ikom Local Government Area has been assessed for physicochemical quality (Eni et al., 2025), and the Calabar River has been reported to carry total coliform levels above the acceptable limit at every sampling point (Antigha et al., 2025). Closer to our study area, water quality in the Lower Cross River Basin has been assessed in the Akpabuyo and Odukpani areas (Offiong and Edet, 1998; Edet and Offiong, 2002).

Most of this work consists of single-visit surveys, of boreholes, or from other parts of the state. To our knowledge there are no published monthly records spanning the dry and rainy seasons for hand-dug wells in Obudu, and none that relate such records to well lining, cover and setback distance with a method that respects repeated measurement of the same wells. Without them, decisions on well siting, waste disposal and monitoring are made largely by guesswork, and households have no simple way to tell which wells are most at risk. This study addresses that gap.

Aim and objectives

The aim was to characterise water quality in hand-dug wells in Obudu Metropolis through the dry and rainy seasons and to build and test a repeated-measures model relating it to season and well characteristics. The specific objectives were to:

- (i) quantify fourteen physicochemical and microbiological parameters in 50 wells over eight months;
- (ii) compare the results with the Nigerian Standard for Drinking Water Quality and WHO guidelines;
- (iii) test whether the parameters differ between the dry and rainy seasons;
- (iv) estimate, with linear mixed-effects models that account for repeated measurement of each well, how the parameters relate to season, lining, cover, depth and distance to the nearest pollution source; and
- (v) test how well those models predict water quality in wells that were not used to fit them.

MATERIALS AND METHODS

Study area and well selection

The study was carried out in Obudu Metropolis, Cross River State, southern Nigeria. Fifty sampling points, all hand-dug wells within the town, were chosen to cover a range of land uses, including residential compounds, schools, health facilities, markets, a filling station, abattoirs and farmland. For each well we recorded the street



or compound, the depth, the diameter, whether it was lined, whether it was covered, the distance to the nearest pollution source, and the type of that source (Table 1). Geographic coordinates were not recorded during fieldwork, so wells are identified by street or compound name and well number (Appendix B).

Table 1. Characteristics of the 50 sampled wells

Attribute	Summary
Depth	8–27 m (mean 16.2 m)
Diameter	0.75–1.2 m (mean 0.92 m; one well not recorded)
Lining	23 lined, 26 unlined, 1 not recorded
Cover	36 covered, 14 uncovered
Distance to nearest pollution source	5–40 m (mean 18.1 m)
Nearest pollution source	Soakaway or septic tank (15); refuse or waste dump, including hospital and market waste (15); arable-land waste (8); pit toilet (7); abattoir (4); filling-station waste (1)

Source categories were grouped from the field descriptions.

Sampling schedule and sample handling

Sampling ran from January to August 2022. January to April were treated as the dry season and May to August as the rainy season. Each well was sampled once a month, giving 400 well month observations per parameter. Samples were collected in one-litre plastic containers that were capped immediately after collection, carried to the laboratory, and analysed within 48 hours. Dissolved oxygen was read in the field with a meter shielded from direct sunlight, and temperature was read by immersing a mercury thermometer in the collected sample.

Laboratory analysis and guideline values

Fourteen parameters were measured (Table 2). Turbidity was measured by spectrophotometry at 450 nm and reported in formazin turbidity units, which we treat as equivalent to NTU. Total coliforms were counted by membrane filtration and reported as colony counts per 100 mL of sample (CFU/100 mL); heterotrophs were counted by the pour-plate method, with 1 mL of sample in molten nutrient agar at 45 °C containing nystatin, and reported per mL of sample. Total coliforms were used only as an indicator group: *Escherichia coli* and thermotolerant coliforms were not determined, and no organisms were identified to species. Standard Methods (APHA et al., 2017) is the general reference for these procedures. Guideline values follow the Nigerian Standard for Drinking Water Quality, NIS 554:2015 (SON, 2015), and the WHO guidelines (WHO, 2017).

Table 2. Analytical methods, units and guideline values used

Parameter (unit)	Method	Guideline value (source)
pH	Comparator; two tubes, one with sample and two drops of bromothymol blue, colour matched	6.5–8.5 (NIS 554; WHO)
Temperature (°C)	Mercury thermometer immersed in collected sample	none applied
Dissolved oxygen (mg/L)	DO meter, in situ, shielded from direct sun	None applied
Electrical conductivity (µS/cm)	Temperature compensation/ EC Meter	1000 (NIS 554)
Total dissolved solids (mg/L)	Probe meter, calibrated in air before use	500 (NIS 554)



Turbidity (NTU)	Spectrophotometry at 450 nm, instrument warmed 15 min, calibrated and zeroed	5 (NIS 554)
Ammonium (mg/L)	Nesslerizations; Nessler reagent, 10 min, read at 425 nm against a blank	None applied
Nitrate (mg/L as NO ₃ ⁻)	Cadmium reduction to nitrite, sulphanilic acid and NED, spectrophotometry against a blank; first 25 mL of eluate discarded	50 (NIS 554; WHO)
Bicarbonate (mg/L)	Acid base titration H ₂ SO ₄	None applied
Calcium (mg/L)	Complexometric titration with 0.01 M EDTA after adding NaOH	None applied
Magnesium (mg/L)	EDTA Titrations	None applied
Alkalinity (mg/L)	Complexometric titrations	None applied
Total coliforms (CFU/100 mL)	Membrane filtration, plates incubated at 28–30 °C overnight, colonies counted; volume filtered 100ml	No <i>E. coli</i> or thermotolerant coliforms in 100 mL (WHO); used here as an indicator only
Total heterotrophic count (CFU/mL)	Pour plate, 1 mL in nutrient agar with nystatin, 28–30 °C for 24 h	None applied

Nitrate is expressed as nitrate ion. A guideline expressed as nitrate-nitrogen is lower by a factor of 4.4 (for example 10 mg/L nitrate-N $\approx$ 44 mg/L nitrate).

Quality control and methodological constraints

The project record documents the following controls: the TDS probe was calibrated before use; the spectrophotometer was warmed for 15 minutes, calibrated and zeroed before readings; nitrate and ammonium absorbances were read against a reagent blank; the first 25 mL of eluate from the cadmium reduction column was discarded; the DO meter was shielded from direct sun; sterile pipettes and forceps were used for microbiology; and the pour-plate medium contained an antifungal agent. Detection limits, calibration standards, blank and duplicate frequency and replicate precision were not recorded, and we report that as a limitation (Section 4.7)

Three constraints affect interpretation and are carried through the Discussion. First, bromothymol blue changes colour between roughly pH 6.0 and 7.6, so comparator readings outside that range are extrapolations; we therefore read low and high values as “below” or “above” the guideline range, not as exact figures. Second, total coliforms were incubated at 28–30 °C, below the 35 °C usually specified for the method, and were not confirmed, so counts may differ from those a standard procedure would give. Third, samples were held for up to 48 hours, much longer than is usually advised for microbiological samples (APHA et al., 2017), so bacterial counts may have shifted between collection and analysis.

Data screening

The source tables hold 5,600 values (14 parameters $\times$ 50 wells $\times$ 8 months). Twenty were not used, leaving 5,580. Eleven were missing in the source tables (nine calcium values, comprising all eight months at well 40 and February at well 45, and two nitrate values in April at wells 13 and 37). Three ammonium entries had been recorded without a decimal point (0173, 0250 and 0210) and could not be verified. Six isolated single-month spikes were treated as recording errors because each was far outside the same well’s other seven months: bicarbonate 3010 mg/L (well 42, February) and 90.5 mg/L (well 48, April); magnesium 75.7 mg/L (well 40, February) and 75.5 mg/L (well 6, March); water temperature 39.5 °C (well 36, June); and nitrate 75.9 mg/L (well 38, August). The nitrate value is the one case that matters for guideline compliance: it was 2.4 times the highest value from the same well in the other months (31.6 mg/L), but if it were genuine, it would be the only exceedance of the 50 mg/L limit. We tested the effect of keeping the spikes (Section 3.6). Every exclusion is listed in the supplementary file screening_log.csv.

Statistical analysis

Descriptive and non-parametric tests. Dry-season and rainy-season values were averaged for each well, and the 50 paired averages were compared with the Wilcoxon signed-rank test. Lined and unlined wells, and covered and uncovered wells, were compared on their eight-month mean values with the Mann–Whitney U test, and distance and depth were related to water quality with Spearman rank correlation. These well-level tests use one number per well, so they ignore the within-well replication and serve as a simple cross-check.

Mixed-effects models. Because each well was measured eight times, observations from one well are not independent. For each parameter we fitted a linear mixed-effects model (Laird and Ware, 1982) with a random intercept for well and fixed effects for season (rainy against dry), lining (lined against unlined), cover (covered against uncovered), distance to the nearest pollution source (per 10 m) and well depth (per 5 m). Parameters were fitted by restricted maximum likelihood (Pinheiro and Bates, 2000). Turbidity, ammonium, total coliforms (as log of count + 1) and the heterotrophic count were log-transformed because they were right-skewed, and their effects are reported as percentage changes. Well 7, whose lining was not recorded, was left out of the models. Wald t-tests used between-within degrees of freedom: observations minus wells minus one for season, and wells minus five for the four well-level terms. We report the intraclass correlation (the share of variance between wells after adjusting for the fixed effects) and marginal and conditional R^2 (Nakagawa and Schielzeth, 2013).

Multiplicity and robustness. For each of the five fixed effects, the 14 parameter tests form a family, and we applied Holm’s step-down correction within each family (Holm, 1979). We call an effect significant only when its Holm-adjusted p-value is below 0.05, and flag effects with an unadjusted p-value below 0.05 as suggestive. As a robustness check we refitted each model by ordinary least squares with standard errors clustered by well, and we refitted five models with the screened spikes retained. Software was written in Python using NumPy and SciPy; the code and data are supplied.

Predictive validity. We tested whether the models predict water quality in wells they have not seen using five-fold cross-validation in which all eight months of a well were held out together. Predictions for held-out wells used the fixed effects only, and R^2 was computed against the training-set mean. A cross-validated R^2 near zero or below means the model predicts no better than the average.

RESULTS

Overall water quality

Table 3 summarises all screened observations. Water in the wells was generally dilute and low in dissolved salts. TDS never exceeded 480 mg/L, EC never exceeded 680 $\mu\text{S}/\text{cm}$ and nitrate peaked at 46.5 mg/L (well 21, April), so all three stayed below the guideline values of 500 mg/L, 1000 $\mu\text{S}/\text{cm}$ and 50 mg/L. Nitrate was the closest to its limit: the wells with the highest mean nitrate were wells 21, 22, 23 and 39 (30.5 to 31.9 mg/L), and 57 of 397 readings, 51 of them in the dry months, were 30 mg/L or higher.

Table 3. Summary of all screened observations (50 wells, January–August 2022)

Parameter	n	Min	Max	Mean $\pm$ SD	Guideline
pH	400	3.2	10.5	6.43 $\pm$ 1.11	6.5–8.5
Temperature ($^{\circ}\text{C}$)	399	23.5	32.8	27.6 $\pm$ 1.5	–
Dissolved oxygen (mg/L)	400	3	11.5	6.21 $\pm$ 1.42	–
Electrical conductivity ($\mu\text{S}/\text{cm}$)	400	70	680	276 $\pm$ 88	1000
Total dissolved solids (mg/L)	400	70	480	228 $\pm$ 82	500
Turbidity (NTU)	400	1	8	4.29 $\pm$ 1.88	5
Ammonium (mg/L)	397	0.015	1.05	0.242 $\pm$ 0.126	–

Nitrate (mg/L)	397	6.3	46.5	22.3 ± 7.6	50
Bicarbonate (mg/L)	398	9.1	52.1	27.0 ± 8.0	–
Calcium (mg/L)	391	9.9	44.2	22.6 ± 6.2	–
Magnesium (mg/L)	398	1.3	42.1	18.0 ± 9.1	–
Alkalinity (mg/L)	400	15.8	110.2	59.1 ± 18.7	–
Total coliforms (CFU/100 mL)	400	0	10	2.33 ± 1.89	0 (<i>E. coli</i>)†
Total heterotrophic count (CFU/mL)	400	130	390	248 ± 39	–

† WHO guidance is no detectable *E. coli* or thermotolerant coliforms in 100 mL; total coliforms are used here only as an indicator. Guideline values for pH, TDS, EC and turbidity follow NIS 554:2015; nitrate follows NIS 554 and WHO (2017). No health-based value applies to the other parameters.

Acidity. We report pH at two levels because they answer different questions. Among the 400 individual readings, the mean was 6.43, values ran from 3.2 to 10.5, and 196 (49.0%) were below the 6.5 lower limit, 90 in the dry months and 106 in the rainy months; this describes how often a household could draw acidic water on any given day. Among wells, 28 of the 50 (56%) had an eight-month mean below 6.5, the most acidic being wells 49, 43 and 9 (5.04, 5.21 and 5.58); this describes how many wells are acidic on average. Twelve readings were above 8.5. Because the comparator is reliable only between about pH 6.0 and 7.6 (Section 2.4), we note that 137 of the 196 low readings were below 6.0 and 59 fell between 6.0 and 6.5; the second group is the part that lies within the indicator's working range.

Microbiology. Total coliforms were detected in 332 of 400 samples (83%): 173 of 200 in the dry months and 159 of 200 in the rainy months. Only well 18 was free of them in all eight months. Mean counts were highest at wells 43, 49 and 2 (4.88, 4.50 and 4.25 CFU/100 mL). Counts were modest in absolute terms (mean 2.33, maximum 10 CFU/100 mL), but the drinking-water guideline is the absence of *E. coli* or thermotolerant coliforms in 100 mL, so detection of coliforms in most samples means the water cannot be assumed safe without treatment. Total coliforms alone do not distinguish faecal from environmental sources.

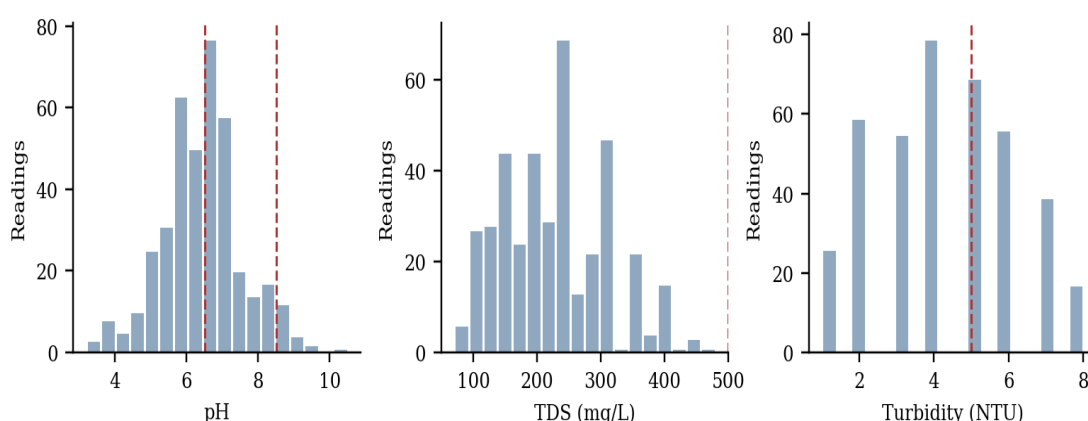


Figure 1. Distribution of all pH, TDS and turbidity readings. Dashed lines mark guideline limits (pH 6.5 and 8.5; TDS 500 mg/L; turbidity 5 NTU).

Monthly and seasonal patterns

Figure 2 and Table 4 show the monthly means. Turbidity rose from 3.3 NTU in January to 5.4 NTU in August, with most of the increase between April and June. Total coliforms moved the other way, from 3.8 CFU/100 mL in January to 1.5 in July and August. Nitrate declined steadily from 26.1 to 16.9 mg/L. TDS, EC, DO and the heterotrophic count crept upward through the rainy months. pH stayed between 6.1 and 6.7 throughout, with its lowest monthly mean (6.08) in May.

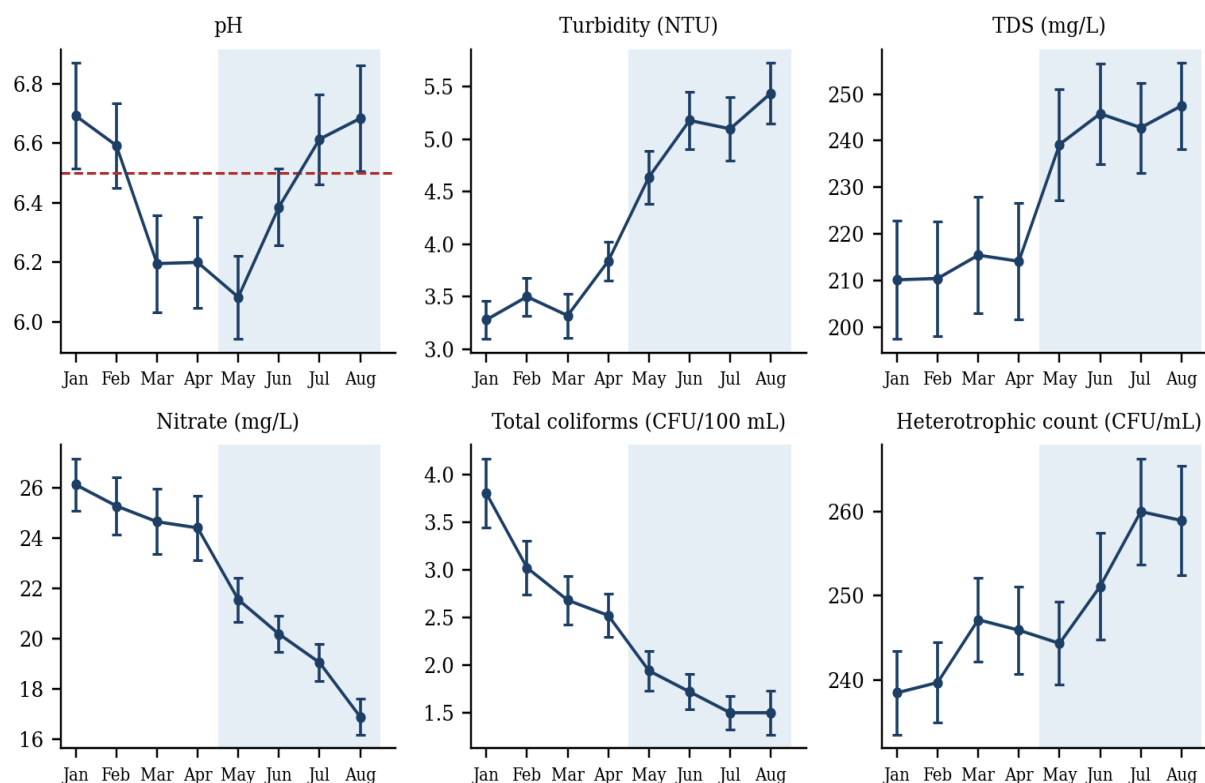


Figure 2. Monthly mean $\pm$ standard error of six parameters across the 50 wells. The shaded band marks the rainy season. The dashed line on the pH panel is the 6.5 lower guideline limit.

Table 4. Monthly mean values across the 50 wells

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
pH	6.69	6.59	6.20	6.20	6.08	6.39	6.61	6.68
Temp (°C)	27.5	27.9	28.1	28.1	27.3	27.4	27.4	27.3
DO (mg/L)	5.89	5.77	5.73	5.97	6.22	6.55	6.72	6.83
EC (μ S/cm)	278	258	261	267	280	282	283	299
TDS (mg/L)	210	210	215	214	239	246	243	248
Turbidity (NTU)	3.28	3.50	3.32	3.84	4.64	5.18	5.10	5.44
Nitrate (mg/L)	26.1	25.3	24.7	24.4	21.6	20.2	19.0	16.9
TCC (CFU/100 mL)	3.80	3.02	2.68	2.52	1.94	1.72	1.50	1.50
THC (CFU/mL)	238	240	247	246	244	251	260	259

Comparing dry and rainy seasons well by well (Table 5), ten of the fourteen parameters changed significantly, and nine remained significant after Holm correction. Turbidity, TDS, bicarbonate, calcium, DO and heterotrophic count were higher in the rainy season, and nitrate, alkalinity and total coliforms were lower. Magnesium was lower in the rains ($p = 0.012$) but did not survive correction. pH, EC, temperature and ammonium did not differ significantly between seasons on this simple test. The turbidity shift was large in practical terms: 5.5% of dry-season readings exceeded 5 NTU against 50.5% of rainy-season readings, and no well averaged above 5 NTU in the dry months whereas 26 did in the rainy months.

Table 5. Dry-season (Jan–Apr) and rainy-season (May–Aug) means of the 50 wells

Parameter	Dry (mean ± SD)	Rainy (mean ± SD)	p	p (Holm)	Higher in
pH	6.42 ± 0.96	6.44 ± 0.86	0.77	0.77	no clear difference
Temperature (°C)	27.9 ± 1.3	27.4 ± 0.9	0.08	0.34	no clear difference
Dissolved oxygen (mg/L)	5.84 ± 0.84	6.58 ± 1.39	0.002	0.01	rainy season
Electrical conductivity (µS/cm)	266 ± 82	286 ± 78	0.23	0.45	no clear difference
Total dissolved solids (mg/L)	213 ± 77	244 ± 57	<0.001	0.003	rainy season
Turbidity (NTU)	3.48 ± 0.87	5.09 ± 1.69	<0.001	<0.001	rainy season
Ammonium (mg/L)	0.236 ± 0.082	0.249 ± 0.089	0.12	0.36	no clear difference
Nitrate (mg/L)	25.1 ± 7.9	19.5 ± 4.7	<0.001	<0.001	dry season
Bicarbonate (mg/L)	23.7 ± 4.8	30.3 ± 6.1	<0.001	<0.001	rainy season
Calcium (mg/L)	21.3 ± 4.6	23.9 ± 6.3	<0.001	<0.001	rainy season
Magnesium (mg/L)	19.1 ± 10.2	16.9 ± 7.1	0.01	0.06	no clear difference
Alkalinity (mg/L)	62.9 ± 22.1	55.2 ± 8.4	0.007	0.04	dry season
Total coliforms (CFU/100 mL)	3.00 ± 1.63	1.67 ± 1.00	<0.001	<0.001	dry season
Total heterotrophic count (CFU/mL)	243 ± 26	254 ± 37	0.002	0.01	rainy season

SD is the standard deviation of the 50 well-level seasonal means (49 for calcium). p is from the Wilcoxon signed-rank test on paired wells; Holm correction across 14 tests.

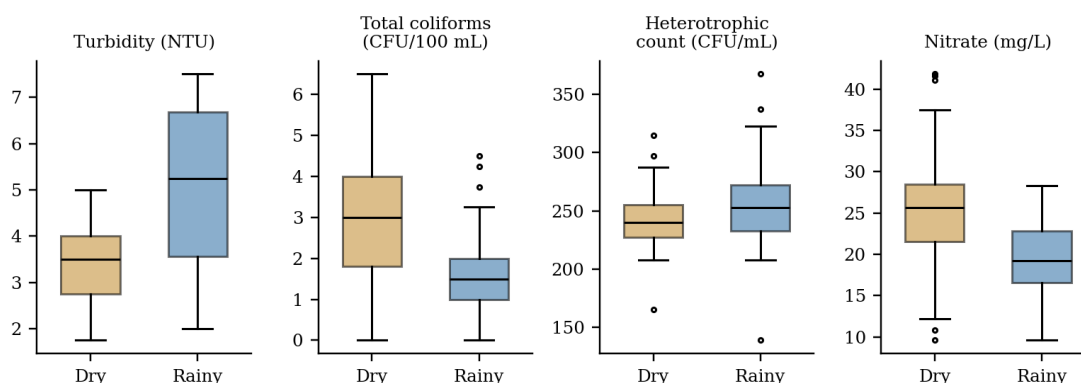


Figure 3. Well-level means in the dry and rainy seasons for turbidity, total coliforms, heterotrophic count and nitrate. Boxes show the interquartile range, the line the median.

Well condition and setting: simple well-level comparisons

Table 6 relates eight-month well means to how each well is built and where it stands. Unlined wells were more turbid than lined wells (4.75 against 3.81 NTU, $p = 0.003$). Uncovered wells had higher heterotrophic counts than covered ones (268 against 240 CFU/mL, $p = 0.009$) and higher EC (308 against 264 µS/cm, $p = 0.049$). Turbidity fell with distance from the nearest pollution source (Spearman $\rho = -0.35$, $p = 0.012$; Figure 4), whereas EC rose with distance ($\rho = 0.31$, $p = 0.028$). Coliform count and nitrate did not differ between lined and unlined or covered and uncovered wells, and pH was unrelated to lining, cover, depth or distance (all $p > 0.6$). Deeper wells did not hold more dissolved minerals (depth against TDS, $\rho = -0.01$, $p = 0.93$).

Table 6. Eight-month well means by lining and cover, and Spearman correlation with distance to the nearest source

Parameter	Lined / unlined	p	Covered / uncovered	p	ρ (distance)	p
Turbidity (NTU)	3.81 / 4.75	0.003	4.11 / 4.74	0.1	-0.35	0.01
Total heterotrophic count (CFU/mL)	238 / 256	0.1	240 / 268	0.009	0.04	0.8
Total coliforms (CFU/100 mL)	2.14 / 2.49	0.26	2.25 / 2.54	0.75	0.05	0.74
Nitrate (mg/L)	21.7 / 23.1	0.48	21.5 / 24.3	0.16	0.21	0.15
Electrical conductivity (μ S/cm)	282 / 271	0.26	264 / 308	0.05	0.31	0.03

Mann–Whitney U test for 23 lined against 26 unlined wells and 36 covered against 14 uncovered wells; one well had no lining record. Spearman coefficients use all 50 wells. Holm correction across these 15 tests leaves only the lining–turbidity difference significant (adjusted $p = 0.046$).

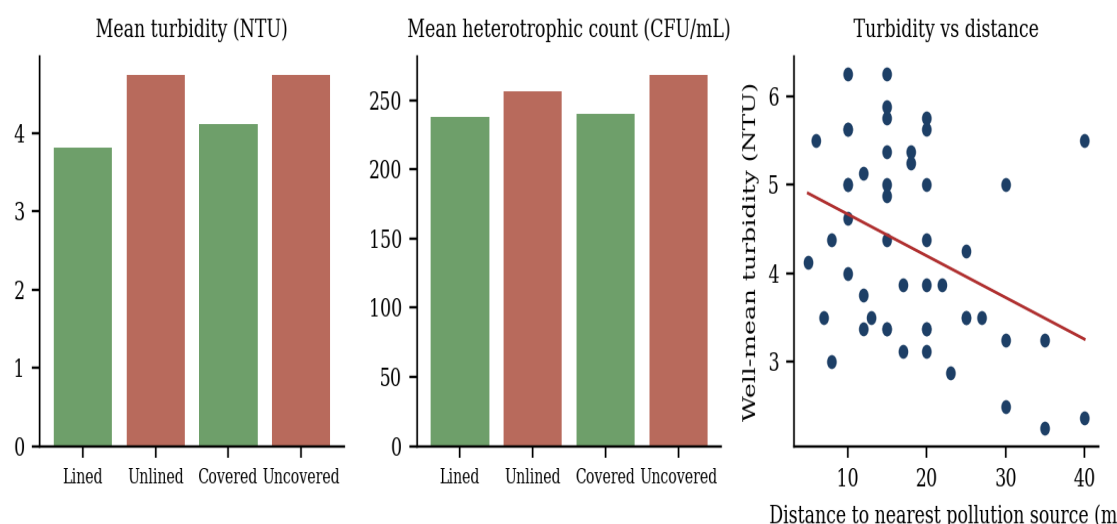


Figure 4. Mean turbidity and heterotrophic count by lining and cover, and the relationship between turbidity and distance to the nearest pollution source.

Mixed-effects models

Table 7 and Figure 5 give the fixed effects from the random-intercept models, which use all 400 well-month observations. Season had the clearest effect. Compared with the dry months, rainy-season water was more turbid (+44%, 95% CI 32 to 57%), had higher TDS (+30.6 mg/L), dissolved oxygen (+0.78 mg/L), bicarbonate (+6.4 mg/L), calcium (+2.6 mg/L) and heterotrophic count (+4%), and was lower in nitrate (−5.8 mg/L), magnesium (−2.3 mg/L), alkalinity (−8.3 mg/L), temperature (−0.55 °C) and total coliforms (−32% in count + 1). EC was also higher in the rains (+16.7 μ S/cm). pH did not change (+0.04, 95% CI −0.15 to 0.24). Ammonium rose by about 10% in the rains but was only suggestive after correction ($p = 0.04$, Holm $p = 0.08$). All of these season effects remained at $p < 0.05$ with well-clustered robust standard errors except those for EC ($p = 0.13$) and ammonium ($p = 0.06$), so the EC and ammonium results should be treated as less secure.

Three well-level effects passed Holm correction. Lined wells were 23% less turbid than unlined wells (95% CI −34 to −10%; Holm $p = 0.024$), and covered wells had 12% lower heterotrophic counts than uncovered wells (−17 to −6%; Holm $p = 0.006$). EC rose with distance from the nearest pollution source by 39 μ S/cm per 10 m

(+17 to +61; Holm $p = 0.011$), which is the opposite direction from what contamination from nearby sources would suggest (Section 4.5). Covered wells were also less turbid (-18% , $p = 0.014$) and had lower EC and calcium, and turbidity fell by 10% per 10 m from the source ($p = 0.016$), but none of these survived correction and they are suggestive only. Total coliforms, nitrate, ammonium, pH, alkalinity and magnesium showed no well-level effect, and well depth was unrelated to any parameter.

Table 7. Fixed effects from the random-intercept mixed models (estimate and 95% CI)

Parameter	Rainy vs dry	Lined vs unlined	Covered vs uncovered	Per +10 m from source	Per +5 m depth
pH	0.04 [-0.15, 0.24]	-0.09 [-0.53, 0.34]	0.14 [-0.29, 0.58]	0.02 [-0.22, 0.26]	0.04 [-0.17, 0.26]
Temperature	-0.55 [-0.82, -0.28] *	0.17 [-0.30, 0.64]	0.22 [-0.26, 0.70]	-0.33 [-0.59, -0.07]	-0.17 [-0.41, 0.06]
Dissolved oxygen	0.78 [0.57, 0.99] *	-0.05 [-0.65, 0.55]	-0.39 [-1.00, 0.22]	-0.23 [-0.56, 0.11]	0.12 [-0.18, 0.41]
Electrical conductivity	16.7 [5.5, 27.9] *	1.91 [-37.46, 41.28]	-46.2 [-86.0, -6.4]	39.4 [17.5, 61.4] *	-10.6 [-30.1, 9.0]
TDS	30.6 [19.1, 42.0] *	-16.2 [-55.4, 23.0]	-7.48 [-47.08, 32.12]	-18.1 [-40.0, 3.7]	8.33 [-11.12, 27.78]
Turbidity	44% [32, 57] *	-23% [-34, -10] *	-18% [-30, -4]	-10% [-18, -2]	1% [-7, 9]
Ammonium	10% [0, 20]	9% [-7, 29]	-6% [-21, 11]	11% [1, 22]	-5% [-12, 3]
Nitrate	-5.80 [-6.71, -4.88] *	-2.87 [-6.38, 0.64]	-3.14 [-6.69, 0.41]	1.07 [-0.89, 3.02]	0.93 [-0.81, 2.67]
Bicarbonate	6.38 [5.11, 7.64] *	-0.39 [-3.03, 2.26]	-0.76 [-3.43, 1.92]	0.68 [-0.80, 2.15]	-0.31 [-1.62, 1.00]
Calcium	2.57 [1.92, 3.22] *	-2.37 [-5.46, 0.72]	-3.98 [-7.18, -0.78]	-0.61 [-2.37, 1.15]	-0.73 [-2.30, 0.84]
Magnesium	-2.30 [-3.00, -1.59] *	-0.67 [-6.23, 4.90]	-0.44 [-6.07, 5.19]	-1.61 [-4.72, 1.49]	0.37 [-2.39, 3.14]
Alkalinity	-8.31 [-11.03, -5.60] *	-3.21 [-11.83, 5.41]	-4.67 [-13.39, 4.04]	-1.06 [-5.87, 3.74]	-0.05 [-4.33, 4.23]
Total coliforms	-32% [-38, -25] *	-10% [-30, 15]	-11% [-31, 13]	-0% [-13, 14]	-4% [-15, 9]
Heterotrophic count	4% [2, 7] *	-7% [-13, -1]	-12% [-17, -6] *	3% [-1, 7]	-2% [-5, 1]

Estimates are in the unit of each parameter, except for turbidity, ammonium, total coliforms (count + 1) and heterotrophic count, which were log-transformed and are shown as % change. * Holm-adjusted $p < 0.05$ within each column. 49 wells (48 for calcium) and 383–392 observations per model.

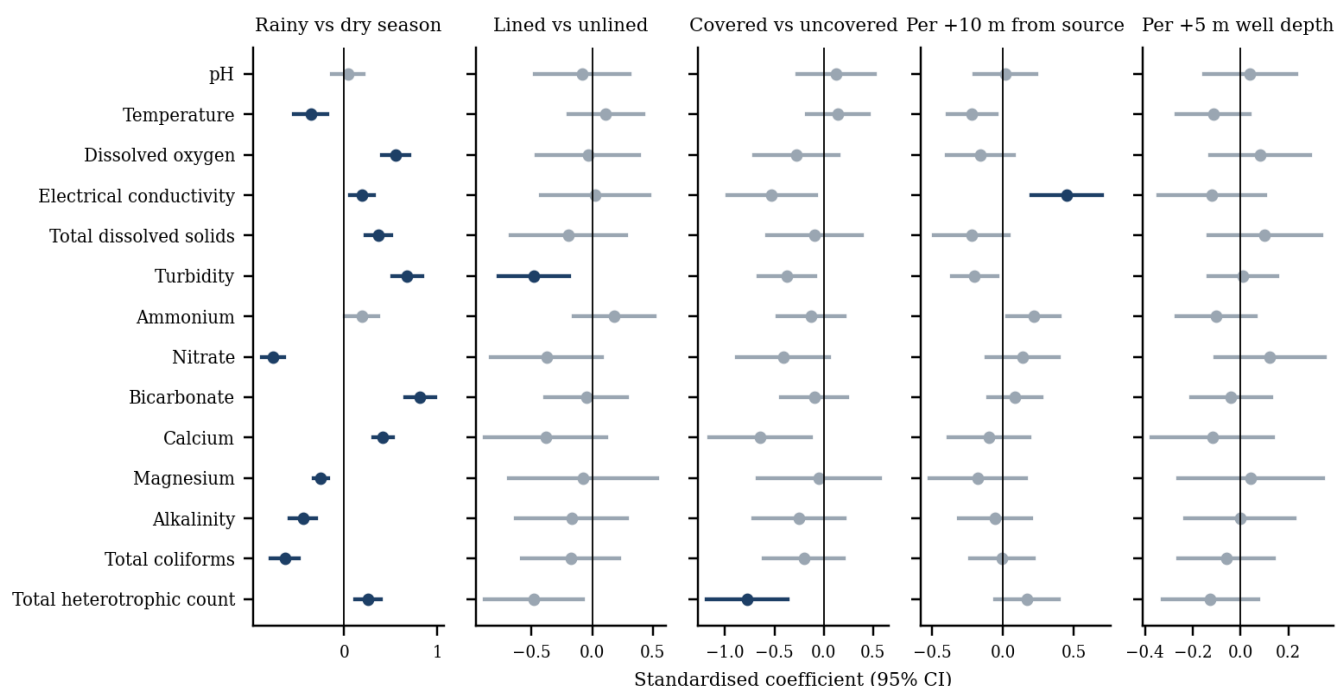


Figure 5. Standardised fixed effects (coefficient divided by the standard deviation of the response) with 95% confidence intervals. Dark symbols are significant after Holm correction; grey symbols are not.

Between-well variance and predictive performance

Well identity accounted for a large part of the variation (Table 8). After adjusting for the fixed effects, the intraclass correlation was highest for magnesium (0.85), calcium (0.68), nitrate (0.57), EC (0.52) and TDS (0.50), meaning that these parameters are largely a property of the well, and lowest for turbidity (0.15) and temperature (0.15), which vary mostly from month to month within a well. A model that ignored this clustering would overstate the effective sample size for the well-level effects.

The fixed effects explained little of the total variance: marginal R^2 was highest for turbidity (0.23), nitrate, calcium and the heterotrophic count (0.20 each) and was 0.01 for pH. In leave-wells-out cross-validation, cross-validated R^2 was 0.19 for turbidity, 0.16 for the heterotrophic count, 0.11 for nitrate and bicarbonate, 0.09 for EC and calcium and 0.06 for total coliforms. It was zero or negative for pH, TDS, ammonium, magnesium and alkalinity, meaning that for those parameters the model predicted new wells no better than the overall mean. Season and the four well characteristics therefore describe how quality changes, but they are not enough to predict the quality of an individual new well.

Table 8. Variance components and predictive performance of the mixed models

Parameter	ICC	Marginal R^2	Conditional R^2	Leave-wells-out R^2
pH	0.27	0.01	0.27	-0.03
Temperature	0.15	0.09	0.22	0.02
Dissolved oxygen	0.4	0.11	0.46	0.02
Electrical conductivity	0.52	0.18	0.61	0.09
TDS	0.5	0.07	0.54	-0.02
Turbidity	0.15	0.23	0.35	0.19
Ammonium	0.18	0.05	0.22	-0.08
Nitrate	0.57	0.2	0.65	0.11
Bicarbonate	0.23	0.17	0.36	0.11



Calcium	0.68	0.2	0.74	0.09
Magnesium	0.85	0.04	0.86	−0.09
Alkalinity	0.46	0.07	0.49	−0.04
Total coliforms	0.35	0.12	0.43	0.06
Heterotrophic count	0.41	0.2	0.53	0.16

ICC: intraclass correlation after adjusting for fixed effects. Marginal R^2 : variance explained by fixed effects; conditional R^2 : by fixed effects and well. Leave-wells-out R^2 : five-fold cross-validation with all months of a well held out together; values at or below zero mean no gain over the overall mean.

Sensitivity to the excluded values

Keeping the six screened spikes changed the season effects little where the effect could be estimated. The rainy-season effect on nitrate was -5.5 mg/L (against -5.8 with screening), on magnesium -2.9 mg/L (against -2.3), on temperature -0.49 °C (against -0.55), and on ammonium (log scale) 0.09 (against 0.09). For bicarbonate the 3010 mg/L entry dominated the fit (season effect -9.2 mg/L, standard error 15.2), which is why it was excluded.

DISCUSSION

Acidity

Slightly acidic groundwater is common in humid tropical settings, where rain is only weakly buffered and decaying organic matter produces carbon dioxide and organic acids in the soil (Hem, 1985). Acidic groundwater has also been reported elsewhere in the Cross River Basin (Nganje et al., 2017); we did not test the cause in Obudu. What is notable here is how many readings and wells fell below 6.5. Low pH matters in practice because it makes water more corrosive to buckets, pumps and fittings and can raise the solubility of metals. The comparator limits what we can say about the lowest readings (down to 3.2), which lie well outside its working range, so we treat them as indicating acidity below the guideline, not as exact values, until they are confirmed with a calibrated meter. Even so, 59 readings fell within the working range and were still below 6.5. Neither season, lining, cover, depth nor distance explained the acidity, and pH was the least predictable parameter in the cross-validation, which suggests that its variation is driven by local geology or soil conditions that we did not measure.

Rainfall effects

The seasonal pattern is consistent with rain doing two things at once. It flushes particles from the surface and from the ground around the well, and it adds fresh water. The flushing shows up as higher turbidity, higher TDS, bicarbonate and calcium, and higher heterotrophic counts in the rainy months. The dilution and the shorter residence time show up as lower nitrate and alkalinity. Rising TDS in the rains is less intuitive, since dilution should lower it. A possible explanation is leaching of salts from waste deposits and soil as the water table rises, though we did not measure the ions needed to test this. The mixed models confirm that these season effects hold when repeated measurement of the same wells is taken into account, and they remain with robust standard errors, except for EC. Rainfall and water-table depth were not recorded, so season is only a proxy for these drivers.

Microbiological quality

The coliform result runs against what one might expect. Total coliforms were more frequent and more numerous in the dry months (mean 3.0 against 1.7 CFU/100 mL), and the model estimates a 32% lower count in the rains, while the heterotrophic count rose slightly. Our data cannot separate the possible causes, which include real dilution, the lower water table and drawn-down, stirred wells in the dry season, and the methodological constraints in Section 2.4 (low incubation temperature and a 48-hour holding time), which could affect dry and rainy samples differently. Whatever the explanation, the practical message does not



change. Coliforms were present in about 83% of samples and only one well stayed free of them. WHO guidance calls for no detectable *E. coli* or thermotolerant coliforms in 100 mL of drinking water (WHO, 2017), and we did not test for those specifically. The sensible reading is that most of these wells should not be assumed safe to drink without treatment, in either season. No well characteristic explained the coliform counts, which is consistent with contamination arriving by several routes at once.

Nitrate

Nitrate stayed below 50 mg/L in every retained reading, but 11 readings of 40 mg/L or more at wells 21 to 24 and 39, all in the dry months, deserve attention. Epidemiological studies have reported adverse outcomes, including colorectal cancer, thyroid disease and neural tube defects, in association with drinking-water nitrate, with some effects observed at levels below regulatory limits (Ward et al., 2018), so compliance with the limit does not by itself mean there is no concern. The fall in nitrate through the rains (-5.8 mg/L) suggests that dilution matters and that dry-season wells are the more exposed. The excluded 75.9 mg/L reading at well 38 in August would, if genuine, be an exceedance, and we recommend that this well be re-sampled. Soakaways, septic tanks, refuse and fertiliser are the usual sources in settings like this one (Foster et al., 2002; Nganje et al., 2017). Nitrate did not differ significantly with lining, cover or distance, and the intraclass correlation of 0.57 indicates that it is mostly a property of the well's surroundings, so we cannot link it to a single source type.

Well construction and siting

The well-condition results are the most directly useful, and two of them are robust to multiple testing. Unlined wells were more turbid, and uncovered wells carried higher heterotrophic counts. These are the relationships one would expect if surface water and particles enter open or porous wells, which is the pathway described in Section 1.2, and they point to inexpensive fixes: lining, a sealed cover and a raised well head. Turbidity also tended to fall with distance from waste (-10% per 10 m), in line with the call for better siting criteria for latrines (Graham and Polizzotto, 2013), but this did not survive correction and should be read as suggestive. The positive relationship between EC and distance runs the other way. We offer no mechanism and treat it with caution: distance was recorded once for the single nearest source, source type varied from soakaways to abattoirs, and wells farther from a source may sit in different parts of town with different soils or land use. The finding that depth did not predict mineral content differs from the common expectation that deeper wells draw on water with a longer contact time with the aquifer (Hem, 1985). The wells spanned only 8 to 27 m, and local conditions may simply have swamped any depth effect.

What the model can and cannot do

A first version of this work fitted a seven-predictor regression to the eight monthly means, which leaves no residual degrees of freedom, so the fit is exact by construction and says nothing about prediction (Montgomery et al., 2012); it is kept in Appendix A for the record only. The mixed-effects models replace it. They use all 400 observations, treat each well as a cluster, and test season and well characteristics together. Two features of the results matter for how they are used. First, the clustering was strong: the intraclass correlation exceeded 0.5 for five parameters, so ignoring the repeated measurements would have inflated confidence in the well-level effects. Second, the models describe more than they predict. Even for turbidity, the best case, the fixed effects explained 23% of the variance and predicted 19% in new wells, and for pH they predicted nothing. A screening tool that scores a new well from its lining, cover, depth, distance and the season would therefore be unreliable on this evidence. The models are better read as estimates of how much lining, covering and season shift water quality on average. Improving prediction would probably need more wells, a full year or more, rainfall and water-table data, soil and geology, and a defined water quality index as a composite response (Brown et al., 1970).

Limitations

The study covers one town and eight months, so year-to-year variation is not captured, and rainfall and water-table depth were not measured. Season and month are confounded with any trend over the eight months, so



“season” effects are differences between the first and second halves of the study period. Several parameters were measured with simple methods: pH by visual comparator (reliable only over a narrow range), and turbidity by spectrophotometry in formazin units. Total coliforms were incubated below the usual temperature, not confirmed, and analysed after up to 48 hours, and *E. coli* was not measured. Detection limits, calibration standards, blanks, duplicates and other quality-control results were not recorded, and geographic coordinates were not taken. Only 50 wells were studied, with unequal groups (14 uncovered wells, 23 lined and 26 unlined), so the well-level effects are associations, not proof of cause, and distance and source type were recorded once and may not reflect all nearby sources. Twenty of 5,600 values were excluded (Section 2.5). Trace metals, radioactive elements and volatile organic compounds were not measured, and other water sources in the area were not sampled.

CONCLUSIONS AND RECOMMENDATIONS

Monthly monitoring of 50 hand-dug wells in Obudu Metropolis between January and August 2022 showed water that is low in dissolved salts and within guideline limits for TDS, EC and nitrate, but frequently acidic, often turbid in the rains, and widely positive for coliforms. Mixed-effects models that account for repeated measurement of each well showed that season has a large and consistent effect: rainy-season water was more turbid (+44%) and higher in TDS, DO, bicarbonate, calcium and heterotrophic count, and lower in nitrate, magnesium, alkalinity and total coliforms. Lining reduced turbidity by about 23% and covering reduced heterotrophic counts by about 12%, and both effects survive correction for multiple testing. These models describe average effects well but predict the quality of individual new wells poorly (cross-validated R^2 of 0.19 at best, and none for pH), so they are not suitable as a screening tool.

On the evidence of this study, we recommend that:

- **Wells are lined and covered.** Households and local government should prioritise sealing, lining and raising the heads of existing wells, starting with those near latrines, soakaways, dumps and abattoirs.
- **Water is treated before drinking.** Given the frequency of coliforms and the rise in turbidity in the rains, households using these wells should disinfect water, especially in the rainy season.
- **Monitoring is routine.** Regular testing of wells for pH, turbidity and microbial indicators, including *E. coli*, should be institutionalised, with extra attention at the start of the rains, and well 38 should be re-sampled for nitrate.
- **Setback distances are respected.** New wells should be sited well away from pit toilets, soakaways, refuse dumps, abattoirs and arable-waste areas, although this study could not show a robust distance effect.
- **The study is extended.** Future work should cover a full year or longer, record rainfall, water level and well coordinates, report detection limits and quality control, measure *E. coli* and pH with calibrated instruments, and add trace metals, radioactive elements and volatile organic compounds.

SUPPLEMENTARY MATERIAL AND DATA AVAILABILITY

The screened data set (wells_long.csv), the log of excluded values (screening_log.csv), the full mixed-model output (mixed_model_results.csv) and the analysis code (analysis_obudu_wells.py) accompany this manuscript and reproduce every table and figure in Section 3.

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APPENDIX A. EXPLORATORY REGRESSION ON MONTHLY MEANS (NOT FOR INFERENCE)

An earlier analysis fitted a multiple linear regression by least squares in SPSS version 22.0 (Draper and Smith, 1998) with pH, temperature, DO, EC, turbidity, TCC and TDS as predictors. The ANOVA output lists 7 degrees of freedom for regression and none for the residual, so the model was fitted to eight observations,

apparently the eight monthly means. It therefore has no residual degrees of freedom, no standard errors and no significance tests, and the equation below is an exact algebraic fit to those eight points. The response, labelled “WHO” in the SPSS output, is not defined in the project record. The coefficients are listed for transparency only and must not be interpreted as validated relationships or used to predict the quality of any well. The mixed-effects models in Section 3.4 supersede it.

$$Y = 27767 - 635.5 \text{ pH} - 714.4 \text{ Temp} + 195.8 \text{ DO} - 15.98 \text{ EC} - 762.0 \text{ Turb} - 459.0 \text{ TCC} + 16.0 \text{ TDS}$$

The project record gives the pH coefficient as -635.5 in the equation and -665.5 in the accompanying text; the equation value is used here.

APPENDIX B. SAMPLED WELLS (IDENTIFICATION IN PLACE OF COORDINATES)

Geographic coordinates were not recorded. Wells are identified by street or compound as recorded in the field.

Well	Street / compound	Depth (m)	Lining	Cover	Distance (m)	Nearest source
1	Bishiri Road	15	Unlined	Covered	10	Soakaway or septic tank
2	Girls Sec Road	10	Lined	Covered	12	Refuse or waste dump
3	Calabar road	20	Lined	Covered	17	Soakaway or septic tank
4	Calabar line	8	Lined	Covered	15	Soakaway or septic tank
5	Guest house	25	Lined	Uncovered	20	Refuse or waste dump
6	Prison road	8.6	Unlined	Uncovered	5	Arable-land waste
7	Anders on street	15	Not recorded	Covered	20	Abattoir
8	Uquare street	10	Unlined	Covered	15	Soakaway or septic tank
9	Hospital road	18	Lined	Covered	25	Refuse or waste dump
10	Andor compound	20	Unlined	Covered	22	Soakaway or septic tank
11	Banana park	18.5	Unlined	Uncovered	27	Soakaway or septic tank
12	Ranch road	20	Unlined	Covered	30	Pit toilet
13	Prison lined	12	Lined	Uncovered	23	Arable-land waste
14	Hospital lined	17	Unlined	Covered	7	Abattoir
15	Bebuabong player ground	20	Lined	Uncovered	35	Pit toilet
16	Barr. Ititim compound	16	Unlined	Covered	12	Arable-land waste
17	Abonkib player ground	15	Lined	Uncovered	30	Arable-land waste
18	Atiekpe road	19.3	Lined	Covered	35	Arable-land waste
19	Bebuagam road	22.5	Lined	Covered	8	Arable-land waste
20	Bebuawawhun	21.3	Lined	Covered	40	Pit toilet
21	Bishiri road	20	Unlined	Covered	30	Refuse or waste dump
22	Girls school	10	Unlined	Covered	40	Arable-land waste
23	Secret Heart Hospital	25	Lined	Covered	25	Refuse or waste dump
24	St. Charles Parish	22	Unlined	Covered	15	Soakaway or septic tank
25	Mr. Odey's compound	15	Unlined	Covered	20	Refuse or waste dump
26	Market road	16	Unlined	Covered	10	Refuse or waste dump
27	Ikew Ogar	20	Lined	Uncovered	20	Abattoir



28	Aohalikwo street	10	Unlined	Covered	15	Soakaway or septic tank
29	Market road	12	Unlined	Covered	15	Refuse or waste dump
30	Police station	14	Lined	Covered	20	Soakaway or septic tank
31	LGA office	27	Lined	Covered	25	Refuse or waste dump
32	Calabar street	15	Unlined	Uncovered	10	Pit toilet
33	Ranch road	17	Lined	Covered	15	Soakaway or septic tank
34	Adie compound	10	Unlined	Uncovered	18	Pit toilet
35	Eye clinic	8	Unlined	Covered	12	Refuse or waste dump
36	Ogar's compound	14	Unlined	Covered	10	Arable-land waste
37	Prison quarters	18	Lined	Covered	13	Soakaway or septic tank
38	Timber shed	24	Lined	Covered	20	Pit toilet
39	Anderson street	18	Unlined	Covered	20	Abattoir
40	Adie Agiopu street	23	Lined	Uncovered	10	Refuse or waste dump
41	Uqwart street	9	Unlined	Covered	15	Soakaway or septic tank
42	Agba's compound	8	Lined	Covered	10	Soakaway or septic tank
43	Agim road	12	Unlined	Uncovered	15	Refuse or waste dump
44	St. Chark primary school	18	Unlined	Covered	18	Refuse or waste dump
45	Obudu Club	25	Lined	Covered	20	Soakaway or septic tank
46	Chief Odey's compound	14	Unlined	Covered	8	Refuse or waste dump
47	Sunny song filling station	15	Lined	Uncovered	6	Filling-station waste
48	Noio Calabar Line	16	Lined	Uncovered	10	Refuse or waste dump
49	No 44B Bishiri road	12	Unlined	Uncovered	15	Soakaway or septic tank
50	Chief Unclies compound	10	Unlined	Covered	17	Pit toilet