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Estimating the Risk of Domestic Water Source Contamination following Precipitation Events

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Abstract. Climate change is expected to increase precipitation extremes, threatening water quality. In low resource settings, it is unclear which water sources are most vulnerable to contamination following rainfall events. We evaluated the relationship between rainfall and drinking water quality in southwest Guatemala where heavy rainfall is frequent and access to safe water is limited. We surveyed 59 shallow household wells, measured precipitation, and calculated simple hydrological variables. We compared *Escherichia coli* concentration at wells where recent rainfall had occurred versus had not occurred, and evaluated variability in the association between rainfall and *E. coli* concentration under different conditions using interaction models. Rainfall in the past 24 hours was associated with greater *E. coli* concentrations, with the strongest association between rainfall and fecal contamination at wells where pigs were nearby. Because of the small sample size, these findings should be considered preliminary, but provide a model to evaluate vulnerability to climate change.

Climate change is expected to compromise drinking water quality, due, in part, to heavy rainfall washing contaminants into water supplies.[1] Approximately 750 million people lack access to safe drinking water, relying on unprotected water sources such as hand-dug wells and surface water that are vulnerable to contamination following precipitation events.[2] We suspect the risk of drinking water contamination following rainfall is variable, and the location of water sources within the watershed, their physical condition, and the presence of nearby contamination hazards (e.g., latrines, domestic animals) are important determinants. The ability to identify high-risk domestic water sources can aid in designing adaptation programs.

We conducted our study in the lowlands of rural southwest Guatemala, a region that experiences precipitation extremes and where residents generally lack access to improved drinking water sources. From 2005 to 2014, dry season (December–April) monthly rainfall rarely exceeded 60 mm (Figure 1A), whereas rainy season (May–November) rainfall was typically > 200 mm, with > 300 mm common in peak months (June, September, October). We surveyed domestic water sources during the rainy season in June and July 2014 in two communities, Los Encuentros and Colonia Los Dias. The villages have a history of failed piped water systems, and residents rely primarily on hand-dug wells and bottled water for domestic needs.[4]

As wells were usually associated with households, stratified random sampling was used to select wells within each village from a roster obtained from government health posts. We selected 24 households in Colonia Los Dias and 45 in Los Encuentros (of 267 and 620 households, respectively), replacing vacant households with the nearest occupied household whenever possible (13 households). We excluded seven households because the structures were vacant, isolated, or nonexistent and no replacement was available due to the secluded nature of the houses, and one because it shared a well with another in the sample. In one house, residents reported using two wells, so both were sampled. Three wells were excluded from our analysis because field data collection sheets were lost.

Domestic well contamination was measured using the fecal indicator bacteria, *Escherichia coli*, as recommended by the World Health Organization (WHO).[5] One water sample was collected from each well using an aseptic technique into 100-mL Whirl-Pak bags (Nasco, Fort Atkinson, WI), and kept on ice until being processed the same day. Five 1-mL aliquots were taken per sample and cultured for *E. coli* using Petrifilms (3M, St. Paul, MN). Each aliquot was plated and incubated for approximately 24 hours in stacks of up to 15 Petrifilms at 37°C. Because of electrical outages that occurred during incubation of 29% of samples, incubation temperatures ranged from 24 to 41°C. Although power loss led to lower *E. coli* counts, adjusting models for electrical outages did not meaningfully alter results (Supplemental Table 1). Two trained technicians independently counted blue (galactosidase-containing) gas-producing (lactose-fermenting) colony-forming units (CFUs) as presumed *E. coli*.[6] *Escherichia coli* concentration (CFU/100 mL) was estimated using the total CFUs on the five Petrifilms. Samples below the limit of detection were assigned half the lower detection limit.

Daily rainfall was measured using a rain gauge (Onset Corporation RG3, Bourne, MA) located between the two communities (Figure 1B). Recent rainfall was defined as > 1 mm of precipitation from 8:00 AM on the day before sampling to 7:59 AM on the day of sampling. All water samples were collected between 8:00 AM and 1:00 PM. As 99% of rain fell between 1:00 PM and 6:00 PM, small variations in the definition of the 24-hour rainfall window are not expected to impact the results.

Well condition and the presence of potential fecal contamination sources were assessed during sample collection using a standard WHO survey instrument.[7] Bucket-drawn (31%) and mechanical pump (69%) wells were sampled. Wells were overwhelmingly in poor condition: 97% had one or more problems including cracked cement floor (75%), unsanitary or absent well cover (66% of mechanical pump wells), and low or cracked headwalls (17% of bucket-drawn wells). Because of this, we included well type in our analysis but not well condition.

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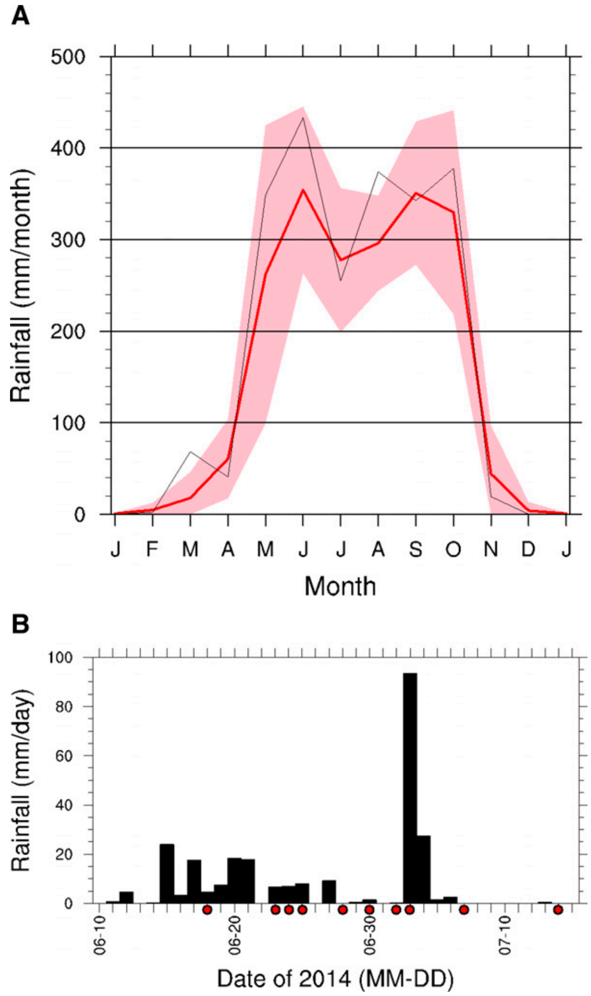

FIGURE 1. Precipitation at the study site in southwest Guatemala. (**A**) Monthly 2005–2014 average precipitation (red line) and standard deviation (pink shading) for the study region, based on analysis of precipitation data from the Climate Prediction Center Morphing Technique.[3] The black line shows the 2014 monthly precipitation. (**B**) Daily precipitation during the study period in June–July 2014, measured using a data logging rain gauge placed between the two study villages. Daily precipitation is defined as total rainfall from 8:00 AM to 7:59 AM the following day. Red dots indicate sampling dates.

A 30-m resolution digital elevation model (DEM) derived from NASA's Satellite Radar Topography Mission and obtained from the U.S. Geological Survey Earth Explorer (http://earthexplorer.usgs.gov) was used to estimate the specific catchment area[8] (α) of the watershed draining at each well site through a method described elsewhere[9] (Figure 2). In brief, α of a grid cell is the sum of the cell's own area plus the area of all upslope cells that drain partially or fully through it, providing an estimate of the land surface area that drains through each well site. We expect α to be an indicator of the surface and shallow subsurface flows that influence a raster cell. Watershed analyses were performed in ArcGIS 10.2 (ESRI, Redlands, CA) using TauDEM 5.0 (David Tarboton, Utah State University, Logan, UT). The coordinates of each well were recorded using a handheld global positioning system (GPS) device (GPSMAP 64ST, Garmin International, Olathe, KS).

We estimated δ, the ratio of *E. coli* concentration at wells where recent rainfall had occurred versus had not occurred. First, we used a simple linear regression model to generate an estimate of δ. We then added statistical interaction terms to our model to evaluate variability in δ. This approach allows estimates of the parameter of interest under different conditions and can be useful for identifying populations vulnerable to climate change (e.g., see refs. 10 and 11). *Escherichia coli* concentration was log transformed and rainfall was evaluated as a binary variable. Because well type was strongly associated with *E. coli* concentration, adjusted models included well type as a covariate. Details of the statistical analysis, including modeling equations, are provided in the Supplemental Appendix. Statistical analyses were conducted in Stata 14 (StataCorp, College Station, TX).

Escherichia coli levels were below the limit of detection (< 20 CFU/100 mL) in 12 wells and exceeded 100 CFU/100 mL in 28 wells. Median *E. coli* concentration was 80 CFU/100 mL (range 0–3,370). Recent rainfall occurred before collection of 31 (53%) samples and was associated with 2.79-fold higher *E. coli* concentrations (95% confidence interval [CI] = 1.17–6.67) using the adjusted, simple linear regression model. In models that allowed for variability in δ, recent rainfall was associated with the greatest *E. coli* concentrations at wells with a large catchment area and where pigs were observed nearby (Table 1). Compared with wells having a latrine nearby, δ was larger at wells where no latrines were located within 10 m, a surprising finding since we observed no evidence of open defecation. δ was similar for bucket-drawn wells and mechanical pump wells, perhaps due to considerable overlap between well types: many electrical pump wells could be converted to bucket-drawn wells in the event of a power outage. Interaction terms were not statistically significant ($P > 0.05$) and the CIs for estimates of δ are wide—thus, the observed differences in δ may be due to chance. Results were not meaningfully changed when rainfall was modeled as a continuous variable (Supplemental Table 2).

The poor condition of the wells, seasonal flooding patterns, and association between rainfall and *E. coli* concentrations, suggest that well water sources in the study region may be vulnerable to surface water contamination during rainfall events.[12,13] Our findings suggest that this vulnerability may vary by local hydrological conditions and the presence of fecal hazards. The specific catchment area of a site provides one means of examining this vulnerability: a well connected to a large catchment area may be at greater risk of contamination, as surface and subsurface water funneled through the site may have a higher likelihood of interacting with a source of contamination in the upstream zone, compared with a well connected to a small catchment area.[14] Herein, we find evidence supporting this hypothesis, while acknowledging that accounting for precise subsurface or overland flow dynamics through the sites could provide greater insights into the mechanisms that underlie the relationship between catchment area and water quality.

Although none of the tests of statistical interaction were significant, the large variability in estimates of δ under different conditions suggest that the use of a single, static parameter, to describe the association between rainfall and domestic water source contamination may not be appropriate. These analyses should be considered exploratory due to the limited

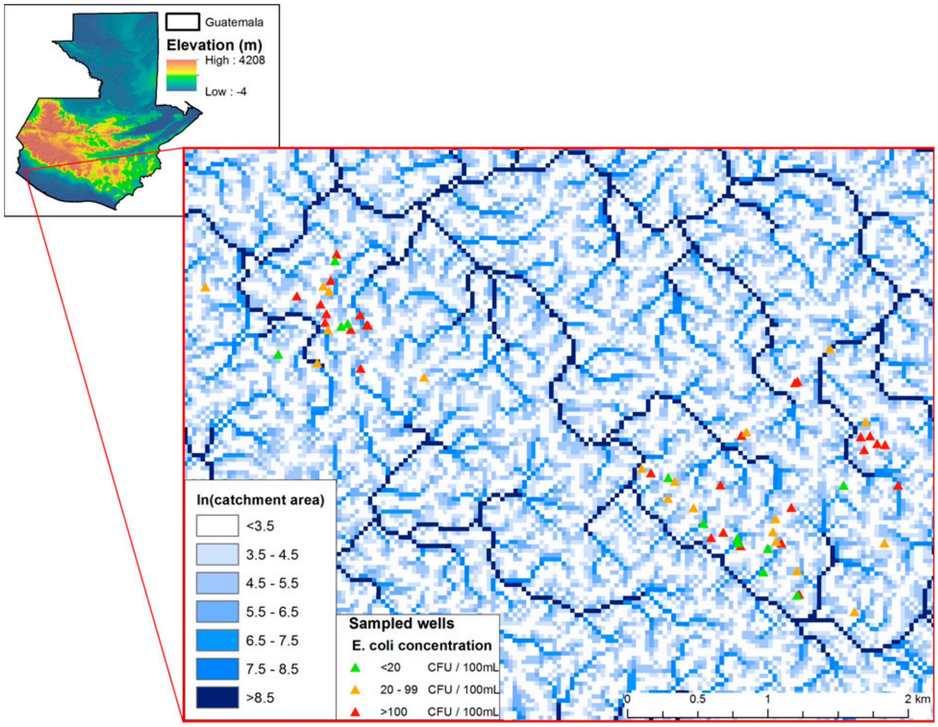

FIGURE 2. Sampled well sites, fecal contamination levels, and natural log-transformed specific catchment area (α) at the study site in the lowlands of southwest Guatemala. Measured in m^2, α estimates the amount of upland area expected to drain through a particular raster cell based on a flow direction grid derived from a 30-m digital elevation model.

number of wells sampled. Extension of this analysis into new contexts and a larger sample would raise confidence in these findings and improve our ability to identify vulnerable water sources. We used a cross-sectional design, that can provide more precise parameter estimates than longitudinal sampling when spatial variation is greater than temporal variation[15]; however, larger, longitudinal studies could allow us to evaluate changes in *E. coli* before and after rainfall events, capture more

TABLE 1

Variations in the association between recent rainfall and fecal contamination of shallow wells by well type, local hydrology, and the presence of fecal contamination hazards

		Unadjusted			Adjusted‡		
	No. of wells	δ*	95% CI	*P* value†	δ*	95% CI	*P* value†
Overall		3.82	(1.57–9.30)		2.79	(1.17–6.67)	
Well type							
Bucket	18	2.52	(0.45–14.01)	0.892			
Mechanical	41	2.89	(1.04–8.06)				
Latrine near well§							
No	29	4.98	(1.37–18.17)	0.571	4.44	(1.31–15.00)	0.269
Yes	30	2.98	(0.84–10.56)		1.70	(0.49–5.92)	
Chickens near well§							
No	21	2.66	(0.60–11.77)	0.492	2.49	(0.59–10.50)	0.756
Yes	38	5.03	(1.68–15.03)		3.30	(1.08–10.14)	
Pigs near well§							
No	43	2.25	(0.80–6.31)	0.062	1.74	(0.64–4.71)	0.069
Yes	16	14.78	(2.72–80.42)		9.93	(1.94–50.87)	
Dogs near well§							
No	24	2.05	(0.50–8.38)	0.249	1.57	(0.41–5.96)	0.244
Yes	35	5.96	(1.84–19.24)		4.31	(1.40–13.29)	
Specific catchment area‖							
Small	29	2.38	(0.67–8.46)	0.274	1.44	(0.43–4.90)	0.126
Large	30	6.33	(1.84–21.86)		5.22	(1.64–16.64)	

CI = confidence interval.
*δ is the ratio of *Escherichia coli* concentration at wells where recent rainfall (> 1 mm in a 24-hour period) had occurred versus had not occurred estimated using linear regression. Interaction models were fit for each variable of interest and used to estimate δ for each value of the conditions listed in the left-hand column.
†We tested the hypothesis that the variable of interest modifies the association between rainfall and *E. coli* concentrations by examining the significance of the interaction term in each model.
‡Adjusted models include well type as a covariate.
§Observed within 10 m of the well. The presence of cats, cows, and horses were also recorded for each well, but because these domestic animals were rarely observed within 10 m of a well (7%, 2%, and 0% of wells, respectively), they were not included in the analysis.
‖Wells lying in a grid cell not expected to receive drainage from additional upslope cells were considered to have a small catchment area and all others were considered to have a large catchment area.

extreme rainfall events and evaluate associations between precipitation and water quality across wet and dry seasons.

Most residents faced major challenges in obtaining safe and sufficient water for household needs: wells were in disrepair and often near sources of contamination including machinery, domestic animals, and standing water. Frequent power outages made electrically powered mechanical wells unreliable, prompting many residents to store water in open containers that are vulnerable to contamination.[16] Precipitation events threaten water quality in such environments. Our findings suggest that risk is not distributed equally, and research to understand vulnerability to climate change should evaluate sources of variability in risk parameters.

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