



Impact of flooding on microbiological contamination of domestic water sources: a longitudinal study in northern Ghana

Mawuli Dzodzomenyo¹ · Moses Asamoah¹ · Chengxiu Li² · Elvis Kichana³ · Jim Wright²

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Abstract

Flooding is the most frequent natural hazard globally, but evidence of its impact on domestic water point contamination remains limited. This study aimed to assess dam-related flooding's impact on microbiological contamination of rural water points and to evaluate agreement of satellite-derived flood maps with ground-based observations of water point flooding. Fieldwork took place in two Ghanaian districts frequently flooded following dam overspill. Fifty-seven water points were tested for bacterial parameters during and immediately after flooding. Forty water points were resampled in the dry season, with the remainder having run dry. Ground-based observations of flooding were compared with three satellite-derived flood maps. Boreholes were less contaminated than wells or surface waters (geometric mean *E. coli* = 20.2, 175.6, and 590.7 cfu/100 ml, respectively). Among groundwater points, a Wilcoxon signed-rank test indicated significantly greater median *E. coli* and thermotolerant coliform contamination during flooding ($p = 0.025$ and $p < 0.001$, respectively), but *Shigella*, salmonella, and intestinal enterococci counts were not significantly different between seasons. In contrast, among surface water points, *E. coli*, *Shigella*, and *Salmonella* counts were significantly greater in dry season samples ($p < 0.005$ for all parameters), possibly reflecting a “concentration” effect. Satellite-derived flood maps had no or low agreement with ground-based observations of water point flooding. Although groundwater quality deteriorated during and after flooding, surface waters were the most microbiologically contaminated in both seasons. The greatest public health risk thus occurred where households switched to surface water collection during or following flood season. Flood risk should be assessed before borehole installation and existing flood-prone boreholes remediated to mitigate population exposure to contaminated water.

Keywords Flooding · Hydropower · Microbiological contamination · Natural hazards · Remote sensing · Water safety

Introduction

Flooding is the most frequent form of natural hazard globally (Guha-Sapir et al. 2011) and future population exposure to flooding is forecast to increase in tropical regions as rainfall events become more intense (Smith et al. 2014). 2.8 billion people were affected by floods between 1980 and 2013 (Doocy et al. 2013) and in low-income countries, several studies indicate increased gastrointestinal disease

risk following flooding (Alderman et al. 2012). Flooding can increase population exposure to contaminated drinking water through multiple pathways. Flooding may mobilise pathogens both in surface waters and through saturated groundwaters, transporting them into domestic water sources; floodwaters may overwhelm or damage supply infrastructure forcing consumers to use unsafe alternatives; and it may lead to population displacement, again resulting in unsafe water source use (Levy et al. 2016; McCluskey 2001). The effects of such infrastructural damage and pathogen ingress may extend long after inundation recedes.

Most studies of flooding's impact on the microbiological quality of water points have relied on a cross-sectional design. Although the definition of a water point is often ambiguous or unclear (Verplanke and Georgiadou 2017), for our study, we define a water point as a site such as a borehole, well, stream or riverbank location that households regularly visit to fetch water for domestic purposes. With

✉ Jim Wright
J.a.wright@soton.ac.uk

¹ Ghana School of Public Health, University of Ghana, Accra, Ghana

² School of Geography and Environmental Science, University of Southampton, Southampton, UK

³ World Vision International, Tamale, Ghana

few exceptions (Islam et al. 2007), water sampling has taken place alongside retrospective assessment of a water point's inundation history, either through fieldwork or based on the local knowledge of disaster response teams, supply users or managers (Hoque et al. 1993; Luby et al. 2008). Given this reliance on fieldwork, such approaches may be challenging to operationalise at scale. As alternatives to such field-based methods for assessing water point inundation, several satellite-derived flood or transient surface water products now exist with global coverage. These include the moderate-resolution imaging spectroradiometer (MODIS) Global Flood Product, available in near real-time (Lin et al. 2019), and the Joint Research Center (JRC) Global Surface Water dataset based on Landsat imagery available since 1984 (Pekel et al. 2016). Such products could potentially be coupled with national-scale water point or water quality databases, such as those derived water quality modules within national household surveys (Wardrop et al. 2018) or through water point mapping (Garriga et al. 2015). This would enable large-scale evaluation of flooding's impact on water quality or, via the near real-time Modis product, rapid post-flood identification of potentially affected water points for remediation. However, this would require evaluation of their suitability for this purpose.

The characteristics of a flood event affect its impact on water points and supply infrastructure. Aside from flood magnitude, greater horizontal velocity of floodwaters is associated with greater infrastructural damage (McCluskey 2001), surface run-off can transport microbial contamination into water supplies (Mellor et al. 2016), whilst coastal flooding can lead to longer term salinization of groundwaters (Terry and Chui 2012). However, a scoping review of studies of enteric disease and surface water flooding in developed countries found literature focused solely on pluvial or fluvial flood events (Andrade et al. 2018). No studies were identified of water supply impacts of dam-related flooding, despite a conservative estimate of 472 million people globally living downstream of large dams (Richter et al. 2010). Since pluvial flood risk is increasingly mediated by dam overspill regimes, the impacts of this type of flooding remain a knowledge gap. Similarly, since flooding is often unpredictable, many studies of its impact on water points and their use gather post-flooding data only (Andrade et al. 2018), limiting understanding of temporal aspects of causality and contamination patterns. Alongside studies of their impact on health outcomes, there is thus a need to understand the impact of flooding on water source safety and domestic water use, as one of several pathogen transmission pathways that could compromise public health during and after flood events.

The primary objective of this study is therefore to assess the impact of dam-related flooding on microbiological contamination of rural water points. We define dam-related

flooding as arising where the presence of a dam in a catchment mediates downstream riverine flood risk. A secondary objective is to evaluate uncertainty in using remotely sensed data to measure the inundation status of water points. We examine these objectives in two study districts in northern Ghana, which are frequently inundated seasonally following the overspill of a large multi-purpose dam in neighbouring Burkina Faso.

Methods

Study site and flood event

The study formed part of a larger project, looking at the impact of flooding in northern Ghana on water points, outpatient attendance and health, and the livelihoods and life courses of affected communities. Fieldwork took place in 2020 during and following flooding from dam overspill in two case study districts, Savelugu Municipal and Talensi. These are among several Ghanaian districts located in the White Volta basin downstream of the Bagre Dam (Fig. 1). When levels of this multi-purpose dam reach 235 m above sea level, to minimize the risk of dam wall collapse, the operating company (Sonabel) release water, which then flows via the Volta river system into northern Ghana. For the past decade, the combination of such water releases with intense rainfall in northern Ghana and Burkina Faso, typically in August–October, has caused damage to crops, water sources, property and sometimes fatalities in Ghana (Abass et al. 2019). The dam operator forewarns the Ghana National Disaster Management Organisation (NADMO) of scheduled releases, so that NADMO can then issue flood warnings to the public if appropriate. Unlike many other flood events in Sub-Saharan Africa which are unpredictable in nature, NADMO's flood warning system provided the research team with the opportunity to prepare for post-flood water testing fieldwork and thereby to study flooding's impact on microbial contamination of water sources.

Typically, northern Ghana experiences a wet season from April–October when seasonal precipitation totals sometimes exceeds 1000 mm, with a dry season from November to March when seasonal totals average less than 100 mm (Dickinson et al. 2017). Intense rainfall led to dam overspill on 10 August 2020 (the earliest annual spillage event on record), with an exceptionally high release rate of 1108 m³/second on 27 August 2020 (Water Resources Commission 2020). By 3 September, extensive areas of northern districts including Talensi had flooded and the Water Resources Commission initiated emergency channel dredging in the lower reaches of the White Volta sub-basin. By 7 September, however, flooding in multiple districts had resulted in ten fatalities, extensive crop and water infrastructure damage,

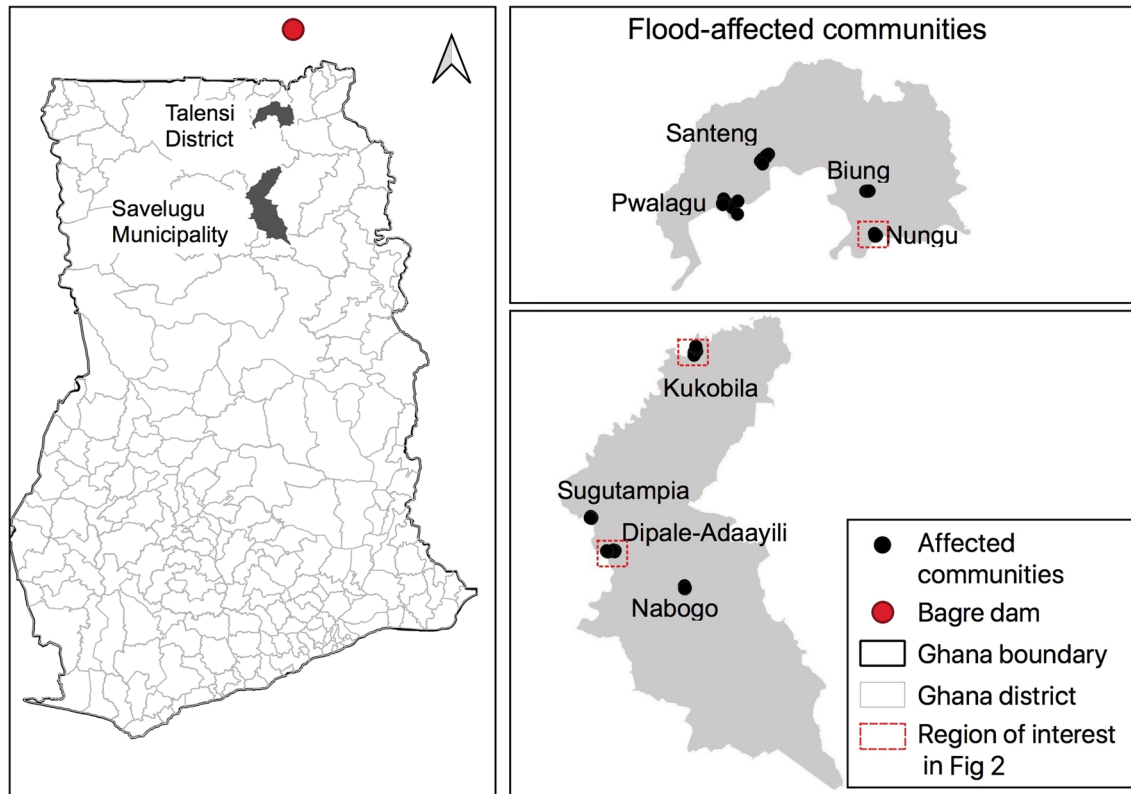


Fig. 1 Maps showing location of Bagre Dam and Talensi and Savelugu Municipality districts in northern Ghana

and travel disruption (West Africa Network for Peace-Building 2020).

The Savelugu Municipality in Northern Region was previously part of Savelugu-Nanton District and had a population of 122,888 in the 2021 census (Ghana Statistical Services 2021). In 2010 in the former Savelugu-Nanton District, 39.6% of households used boreholes for drinking, 18.6% relied on piped water, and 13.2% used surface waters (Ghana Statistical Services 2014a). The White Volta runs through the municipality, providing its predominantly rural residents with opportunities for fishing and farming along the river, much of which is subsistence farming. The Talensi District in Upper East Region had a population of 87,021 in 2021 (Ghana Statistical Services 2021), with most households (64.8%) using boreholes for drinking water in 2010 (Ghana Statistical Services 2014b). Arable agriculture is the main source of employment for 90% of its population. Livestock rearing, poultry raising, fuelwood extraction, food manufacturing, logging, and tourism are other forms of livelihood. From 2014 to 2017, several hundred boreholes, protected well and springs in both Upper East and Northern region were either rehabilitated or installed to mitigate flood risk through donor funding. Measures included raised platforms and reinforced or deepened sanitary seals/linings around shafts (de Veer and Garibie 2018).

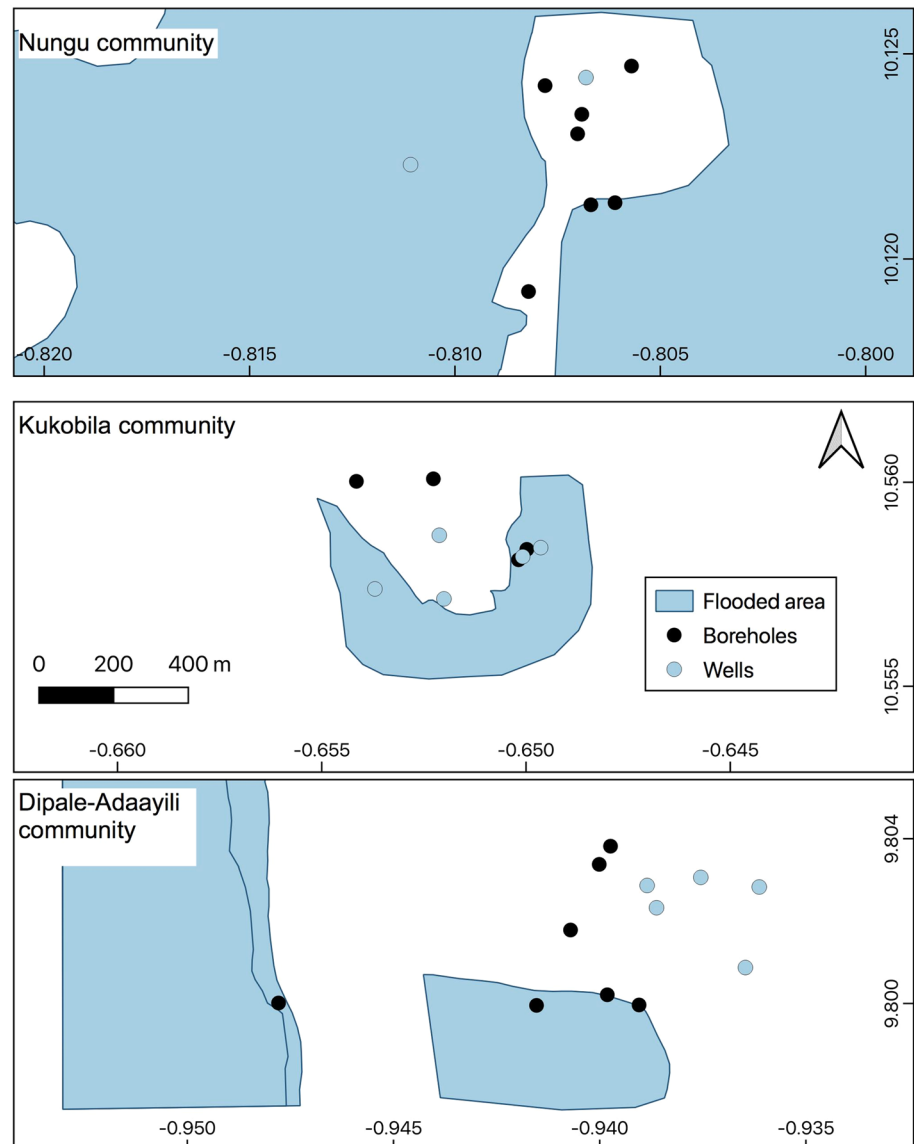
Sample design

Within the two flood-prone districts of Savelugu Municipal and Talensi, four flood-affected communities were identified via preliminary inspection of satellite imagery and stakeholder consultation (Fig. 2). From within these communities, we estimated a total sample size of 114 water samples (comprising 57 flood-free water point samples and 57 flood-affected water point samples) would be required to detect differences in the proportion of microbiologically contaminated flooded versus non-flooded boreholes. This sample size calculation was based on findings from a Bangladeshi study (Luby et al. 2008), which reported 31% of flooded tube wells with detectable thermotolerant coliforms compared to 10% in non-flooded tube wells ($\alpha=0.05$, power=0.8).

Mapping of water points

In each of these eight communities, following seeking of informed consent, the local assembly person (an elected representative) was asked to map the locations of water points, most recent and maximum flood extent on hardcopy A0 basemaps of the area, following consultation with other community members. Initial community liaison revealed that the local assembly person typically has responsibility

Fig. 2 Maps showing inundated areas, with water points in selected communities identified via participatory mapping with local political representatives from Talensi and Savelugu Municipality districts, northern Ghana (showing degrees of latitude and longitude)



for organising communal repairs of water infrastructure, so has detailed knowledge of water point locations. Colour hard copy maps for each community were generated from high spatial resolution Google satellite imagery, acquired between 2016 and 2019. Map scales ranged from 1:5000 to 1:20,000, as recommended for participatory mapping (Forrester and Cinderby 2015). Interviews took place from 14 to 21 September 2020 in or shortly after the flood season. Following the seeking of informed consent, as an orientation exercise, the nature of the maps was explained to participants, who were then asked to identify local landmarks on basemaps, since none had prior experience of participatory mapping. Supported by other participants, the assembly person was asked to map the extent of the most severe flood in living memory using landmarks visible on maps, as well as the most recent flooding in 2020. Via the

basemaps and supported by other participants, the assembly person was then asked to plot water point locations (wells; boreholes; mechanised boreholes; surface waters, e.g. ponds, rivers, dams) within and outside flood zones. Hard copy maps were subsequently georeferenced and mapped features digitised using QGIS.

All water points identified through participatory mapping were selected for sampling. The community representative together with laboratory technician and the field team proceeded to seek the informed consent of participants before taking samples and administering a short questionnaire. Samples were collected from these water points from 15 to 22 September 2020, during or immediately after flooding from the Bagre Dam. Locations of selected water points were more precisely located during the water sampling campaign by use of a non-differential, hand-held Global

Positioning Systems (GPS) receiver. Three 100 mL samples from each water point were taken in bottles containing sodium thiosulfate, to neutralise the effect of chlorine during transport. Although no water points had chlorination units, shock chlorination is occasionally reportedly used for post-flooding supply remediation. Borehole spouts were disinfected through flaming prior to sampling, whilst surface water grab samples were taken approximately 20 cm beneath the surface. Well water samples were drawn with the same container as users before being transferred to sample bottles. Observations on contamination hazards were made and recorded on paper, together with raising of borehole platforms against flooding. Observed hazards included proximity to pit latrines; presence of livestock, faeces or refuse near the water point; damage to concrete aprons or parapets; and presence/absence of fencing. Subsequent post-flood (dry season) sampling of the same water points took place from 15 to 22 February 2021.

Sample processing and laboratory procedures

All samples were transported on ice to a World Vision laboratory in Tamale, which forms part of a regional laboratory quality assurance programme. All samples were then stored at 6 °C and processed within 24 h of collection.

In the laboratory, standard methods were used throughout (Rice et al. 2012). *E. coli* bacteria were enumerated through membrane filtration on Brilliance *E. coli*/coliform medium (Oxoid Ltd., UK), following incubation at 37 °C for 24 h following APHA 2510B. Xylose Lysine in Deoxycholate (XLD) agar (Oxoid Ltd., UK) was similarly used to enumerate *Shigella* and *Salmonella* spp. and enterococci agar used for intestinal enterococci via membrane filtration under the same incubation conditions. Procedures followed methods APHA 9260E, APHA 9260E, and APHA 9230A, respectively. Purple colony-forming units (cfu) on Brilliance medium were considered *E. coli*, red cfu with black centres on XLD agar were enumerated as *Salmonella* spp, and red cfu on XLD agar enumerated as *Shigella* spp. Red colonies on Chromocult enterococci agar (Merck KGaA, Germany) were enumerated as intestinal enterococci. To enumerate thermotolerant coliforms, membrane filtration was again used with m-FC broth without resolic acid (Millipore, USA), with plates incubated for 24 h at 44.5 °C. Blue colonies were considered thermotolerant coliforms. Where plates had more than 200 cfu/100 mL, a duplicate sample was processed (Rice et al. 2012).

Samples were also tested for physico-chemical parameters in the laboratory. Turbidity was measured for 10 mL of each sample via method APHA 2130B and a calibrated HACH turbidimeter (HACH, USA. 2100P), whilst pH and electrical conductivity were measured via a calibrated Mettler Toledo FiveEasy pH Meter and method APHA

2510B. Finally, nitrate in water samples was measured via the Ion-Selective Electrode (ISE) method APHA 4500D (Rice et al. 2012). A Thermo-Scientific Orion 9707BNWP Sure Flow Combination Nitrate Ion-Selective Electrode (ISE) connected to a calibrated Thermo Orion four-star pH meter was used to measure nitrate concentrations.

Flood mapping from satellite imagery

The performance of three satellite-derived flood data products was evaluated using field observations of flooding at water points. Firstly, we used the MODIS Near Real-Time (NRT) flood product, which is available daily from 2000 to 2020 at 250 m spatial resolution (Lin et al. 2019). We created a composite maximum flood area map layer for the 2020 flood season from daily MODIS NRT imagery. Secondly, we used the monthly JRC Global Surface Water dataset, which was generated using Landsat 5, 7, and 8 satellite imagery at a higher spatial resolution of 30 m (Pekel et al 2016). Since the JRC dataset maps seasonal surface water by month, we used seasonal surface water as a proxy for flood coverage in September 2020, when field data was collected. Alongside these two flood products derived from optical satellite imagery, we also derived flood extent based on Synthetic Aperture Radar (SAR) Sentinel-1 C-band satellite images at a spatial scale of 10 m. SAR has been widely used for flood mapping and benefits from more frequent observations since, unlike optical imagery, it can penetrate cloud (Alsdorf et al. 2007; Ward et al. 2014). To classify flooded areas, we combined three commonly used algorithms, namely image thresholding, the Normalised Difference Flood Index and Change Detection and Thresholding (CDAT). Thresholds for these algorithms were derived from the 95th centile of the backscatter coefficient distribution for water bodies detected from optical satellite images (Landsat-8 and Sentinel-2). The algorithms were used to identify maximum flood extent for September 2020, classifying flooding where at least two of the three algorithms were consistent.

Geospatial and statistical analysis

We overlaid water point locations captured via GPS with each of the three satellite-derived flood datasets. We then compared the level of agreement between flood status as recorded through the water point survey and the three satellite-products via the Kappa index of agreement (McHugh 2012).

For water points sampled in both the flood and dry season, for each microbiological parameter, we tested for significant seasonal differences in bacteria count distributions using the Wilcoxon signed-rank test in Stata Version 16 (StataCorp 2019). After examining the distribution of bacteria counts by source type, tests were calculated separately for surface

waters (grouping ponds, rivers and streams) versus groundwater sources (grouping boreholes and wells) since median bacterial counts were similar for these two groups.

Results

In participatory mapping, the most recent flood of 2020 had the greatest extent that participants could recall. In total, 59 water points were located for sampling during the flood period (Table 1), with 29 lying in flood-affected areas (Fig. 2). One water point was a mechanised, solar powered system for abstracting surface water from the Nabogu River that incorporated a reverse osmosis treatment unit. Otherwise, water points did not incorporate any other treatment units. Of 17 flood-affected wells and boreholes, five were inundated at the time of sampling whilst the remainder had recently been flooded. Most boreholes (15 out of 19) had a raised platform at least 0.5 m high to mitigate flooding. Among the 30 water points that were not inundated, two boreholes were non-functional and only repaired subsequently at the start of the dry season. In follow-up dry season fieldwork, many wells and surface water sources had run dry and could not be sampled, leaving communities reliant on boreholes. Sanitary inspection revealed solid waste had been dumped in seven unprotected wells that had run dry in Savelugu District.

Changes in microbiological water source quality during flooding

Table 2 shows the change in median microbiological contamination for those sources that were sampled in both seasons, grouped into surface waters versus groundwater. A Wilcoxon signed-rank test indicated a significant increase in

Table 1 Number and type of water points sampled during and following flooding as a percentage of those selected for sampling

Source type	Flood season	Non-flood, dry season
<i>Improved</i>		
Borehole	16 (89%)	18 (100%)
Mechanized borehole	2 (100%)	2 (100%)
Mechanised river system with reverse osmosis treatment	1 (100%)	1 (100%)
Protected well	6 (100%)	3 (50%)
<i>Unimproved</i>		
Unprotected well	15 (100%)	6 (40%)
Pond	9 (100%)	4 (44%)
River	6 (100%)	6 (100%)
Stream	2 (100%)	0 (0%)
Total	57 (97%)	40 (68%)

median *E. coli* and thermotolerant coliform contamination during flooding, with significantly increased nitrate levels. However, median bacterial counts were similar for Shigella, salmonella, and intestinal enterococci in flood versus non-flood seasons. *E. coli* and thermotolerant coliform counts increased most among flood-affected water points. In contrast, among surface water points, the Wilcoxon signed-rank test indicated significantly greater median *E. coli*, Shigella, and Salmonella counts in dry season samples, alongside greater median turbidity.

Accuracy of remotely sensed assessment of inundation status of water points

When the flood status of the water points as identified in the field was compared with flood status identified through remote sensing (Table 3), generally, the remotely sensed classifications performed poorly. The MODIS flood product failed to identify any of the water points as flooded, whilst the Landsat-8 product correctly identified just one point as flooded. The Sentinel-1 classification performed best, correctly identifying eight water points as flooded. The Kappa index of agreement was thus zero for the MODIS flood product (signifying agreement was no better than chance) and close to zero for Landsat-8 product, whilst agreement for the Sentinel-1 product was better than chance but still minimal at 0.27 (McHugh 2012).

Discussion

Our study is one of very few to examine the effect of flooding on the microbiological quality of water points in developing countries via a longitudinal design. Evidence on the impact of flooding and water point contamination remains scarce worldwide. A scoping review focussed on developed countries found only 14 studies assessing the impact of flooding on groundwater contamination (Andrade et al. 2018), none of which related to flooding from dams. In developing countries, the few studies of flooding and water contamination have often followed a cross-sectional design (Luby et al. 2008; Phanuwat et al. 2006), sampling water points once only after flooding. However, a longitudinal study that repeatedly tested 20 handpumps, vending points, and piped connections in urban Bangladesh found that the proportion with detectable total and thermotolerant coliforms in 100 mL peaked at 95% during the height of flooding, then declined to 60% a fortnight later (Islam et al. 2007). The study did not test for pathogens. Our longitudinal study (Table 2) also found increased faecal indicator bacteria counts (*E. coli* and thermotolerant coliforms) in groundwater sources during or immediately after flooding, consistent with this Bangladeshi study. The World Health Organisation's latest templates for

Table 2 Median microbiological contamination of 40 water points sampled in both flood and non-flood seasons in northern Ghana, showing significance of a Wilcoxon signed-rank test for seasonal distributional differences in bacteria counts

Source type	Parameter	Median (flood season)	Median (non-flood, dry season)	n	p Value (*indicates <0.05 on Wilcoxon signed-rank test and **<0.01)
Boreholes, mechanised river system	<i>E. coli</i> (cfu/100 ml)	14	0	19	0.025 ^{a,*}
Boreholes, mechanised river system	Salmonella (cfu/100 ml)	0	0	19	0.16 ^a
Boreholes, mechanised river system	Shigella (cfu/100 ml)	0	0	19	0.21 ^a
Boreholes, mechanised river system	Intestinal enterococci (cfu/100 ml)	0	0	19	0.82 ^a
Boreholes, mechanised river system	thermotolerant coliforms (cfu/100 ml)	33	0	19	<0.001 ^{a,**}
Boreholes, mechanised river system	Nitrate (mg/L)	1.95	1.78	19	0.009 ^{a,**}
Boreholes, mechanised river system	Turbidity (NTU)	0.66	0.79	19	0.58 ^a
Wells	<i>E. coli</i> (cfu/100 ml)	230	160	9	
Wells	salmonella(cfu/100 ml)	40	80	9	
Wells	Shigella (cfu/100 ml)	20	20	9	
Wells	Intestinal enterococci (cfu/100 ml)	10	40	9	
Wells	thermotolerant coliforms (cfu/100 ml)	360	110	9	
Wells	Nitrate (mg/L)	90.8	8.2	9	
Wells	Turbidity (NTU)	1.39	2.46	9	
Surface water points	<i>E. coli</i> (cfu/100 ml)	120	660	10	0.002 ^{**}
Surface water points	Salmonella (cfu/100 ml)	20	65	10	0.004 ^{**}
Surface water points	Shigella (cfu/100 ml)	40.5	125	10	0.002 ^{**}
Surface water points	Intestinal enterococci (cfu/100 ml)	46.5	30	10	0.90
Surface water points	thermotolerant coliforms(cfu/100 ml)	195	285	10	0.38
Surface water points	Nitrate (mg/L)	1.2	1.2	10	0.58
Surface water points	Turbidity (NTU)	41.1	211	10	0.02 [*]

^aTest for wells and boreholes combined

Table 3 Number of water points classified as flooded through ground survey, compared to their classification via three different remotely sensed flood products (derived from Landsat 8, Sentinel-1, and MODIS), with related accuracy assessment statistics

Statistic	Sentinel-1	Landsat-8	MODIS
Flooded in remotely sensed imagery and in ground survey	8	1	0
Not flood in remotely sensed imagery and ground survey	28	28	28
Flooded in ground survey, but not in remotely sensed imagery	21	28	29
Flooded in remotely sensed imagery, but not in ground survey	0	0	0
% Overall agreement	63.2%	50.9%	49.1%
Kappa	0.27	0.03	0.00

conducting sanitary risk inspection at dug wells and springs specifically record whether such water points lie in flood zones (World Health Organization 2021). Since our findings suggest that some indicator bacteria counts increased significantly in groundwater samples during or immediately following flooding, including flood zones as a contamination hazard checklist item appears justified. However, whilst faecal indicator bacteria counts in groundwater samples increased during and immediately after the flood period, there were no detectable bacterial pathogens (Shigella or Salmonella spp.) in borehole samples in samples from any

season. Similarly, the practice of promoting household water treatment during and following flood events (McCluskey 2001) also seems justified.

In contrast to groundwater sources, counts of *E. coli*, salmonella, and shigella from surface water collection points were significantly higher in the dry, post-flood period. This contrasts with findings of previous studies of surface waters. A study of samples from the Rio Negro, Brazil, for example, found no significant seasonal differences in faecal indicator bacteria, but greater flood season concentrations of viruses such as rotavirus and human adenovirus (Vieira et al. 2017;

Vieira et al. 2016). Flood-related changes in microbiological contamination have previously been attributed to a “run-off effect”, whereby contamination increases as surface run-off flushes micro-organisms into water supplies; a “dilution effect” whereby contamination is diluted by high precipitation during flooding; and a “concentration effect” as micro-organisms accumulate in dry conditions (Mellor et al. 2016). We postulate that surface water point contamination changes reflect this “concentration effect”, whereas groundwater point contamination changes reflect a “run-off effect”. Across both seasons, relative levels of bacterial contamination by source type reflected the known high public health risk of unprotected surface waters (WHO/UNICEF 2019). Lower bacterial contamination of boreholes relative to wells is also consistent with the greater safety of deep aquifers from vertical attenuation of microbiological contamination during subsurface transport in most settings (Lawrence et al. 2001). Similar to observed switching of Kenyan households from boreholes to rainwater harvesting in the wet season (Thomson et al. 2019), our study found evidence that some boreholes were used only in the dry season. Some were allowed to fall into disrepair during the wet season but repaired at the start of the dry season.

Our study related to fluvial flooding, mediated by overspill from the Bagre Dam. Since the impact of flooding from dams depends greater on their predictability, speed of onset and level of destructive force (Lempérière 2017), our findings may not be generalisable to other flood-prone water points downstream of dams or to other types of flooding. By focussing on repeated sampling of water points rather than affected community members, our study also does not consider the potential impact of temporary population displacement away from flooded areas and its effect on population exposure to contaminated drinking water (Levy et al. 2016). Particularly given that we only conducted two rounds of sampling and bacterial counts in surface waters especially can show high temporal variability (Levy et al. 2008), seasonal changes in bacteria counts could potentially relate to other unmeasured seasonal environmental or socio-economic changes apart from flooding.

Given the potential public health consequences of water point inundation, future research should evaluate the effectiveness of potential intervention measures to mitigate this risk. Such studies could include hydrological modelling of the use of the Pwalugu reservoir to retain flood waters and protect districts in the lower White Volta basin, structural flood mitigation measures in the river’s tributaries (Udo et al. 2012), or potentially adjusting the overspill regime of the Bagre Dam itself. They also include assessment of the effectiveness of measures to protect flood-exposed boreholes and wells from contamination, such as raised platforms and strengthened or deepened sealing of shafts (de Veer and Garibie 2018; Sandhu et al. 2018), or post-flooding

rehabilitation measures such as shock chlorination (Luby et al. 2006). In future research, we also recommend testing for both pathogens and faecal indicator bacteria, given that the two groups of organisms exhibited different seasonal behaviours in our study.

Given the risks to field teams sampling water points during flood events, the use of ground-based sensors or satellite imagery to assess flood status of water points remotely should be further investigated. There are now several large-scale, nationally representative data sets that contain georeferenced microbiological data for water points, including from Nigeria (Christenson et al. 2014) and Rwanda (Kirby et al. 2016), as well as other international databases, notably GEMS Water (Robarts et al. 2002). Water point locations in such data sets could potentially be overlaid onto geospatial flood products to quantify the microbiological contamination risk from flooding, without the need for hazardous fieldwork. However, our analysis (Table 3) suggests that the MODIS NRT flood product and Landsat-derived JRC global surface water product largely or wholly failed to detect flooding of sampled water points. When flooding was mapped by classifying Sentinel-1 SAR imagery, this had greater agreement with field observations of water point flooding, but agreement was still low. There are known shortcomings of individual satellite-based sensors such as MODIS NRT, including primarily spectral similarity and thus misclassification of terrain or cloud shadows as inundated areas and vice versa, but also inaccuracies arising from its coarse spatial resolution of 250 × 250 m and poor cloud penetration (Lin et al. 2019; Revilla-Romero et al. 2015). We therefore recommend that any future study that combines remotely sensed imagery of flooding with geospatial databases of water points should use image fusion techniques (Ghassemian 2016) to integrate optical and Sentinel-1 SAR imagery. There would also be scope to use in situ sensors embedded in boreholes to record flood events without putting field personnel at risk. Sensors have already been successfully deployed to understand patterns of borehole use in Kenya (Thomson et al. 2019) and in situ flood sensors are in operational use in parts of Bangladesh (Islam et al. 2014) and elsewhere.

Conclusion

Our study is one of very few that evaluated the effect of flooding on water point quality through sampling in both flood season and the subsequent dry season. We find that faecal indicator bacteria (thermotolerant coliforms and *E. coli*) increased significantly in the flood season for groundwater sources, but bacterial pathogens (*Shigella* and *Salmonella*) were not detectable in borehole samples during either season. In contrast, surface water

deteriorated significantly in the dry season, with *Shigella*, *Salmonella*, *E. coli*, and turbidity levels all significantly greater. Based on these findings, we recommend testing for both pathogens and faecal indicator bacteria in future studies, and further research into mitigation measures such as holding dams, modified dam release schedules, or structural measures to protect water points from flood water ingress. We also recommend screening proposed installation locations for new water points for flood risk. We also find that satellite-derived flood maps have poor agreement with ground-based observations of water point flooding, but that classified Sentinel-1 imagery has better agreement than flood products derived from optical satellite imagery. For future national-scale assessment of flooding's impact on water quality via water point mapping databases, we recommend integration of Sentinel-1 and optical imagery to overcome these limitations.

Author's contribution Mawuli Dzodzomenyo contributed to conceptualisation, writing of original draft, supervision, project administration, and funding acquisition. Moses Asamoah contributed to investigation, data curation, and writing—review and editing. Chengxiu Li contributed to formal analysis, data curation, visualisation, and writing—review and editing. Elvis Kichana contributed to investigation, resources, and writing—review and editing. Jim Wright contributed to conceptualisation, writing of original draft, supervision, project administration, and funding acquisition.

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Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

Ethical approval This study was approved by the Ethics Committee of the Faculty of Environmental and Life Sciences, University of Southampton, UK (Ref No: 48187, Approval date: 2 May 2019) and the Institutional Review Board of the Noguchi Memorial Institute for Medical Research, University of Ghana (04/03/2020, Reference NMIMR-IRB CPN 062/19-20).

Research data Participatory mapping data are available at <https://doi.org/10.5258/SOTON/D1956>. Administrative Boundaries for Ghana can be accessed from the humanitarian data exchange: <https://data.humdata.org/dataset/ghana-administrative-boundaries>. Please note that water quality data is currently being archived by the authors.

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References

- Abass K, Dumedah G, Frempong F (2019) Understanding the physical and human contexts of fluvial floods in rural Ghana. *Int J River Basin Manag*. <https://doi.org/10.1080/15715124.2019.1653310>
- Alderman K, Turner LR, Tong S (2012) Floods and human health: a systematic review. *Environ Int* 47:37–47. <https://doi.org/10.1016/j.envint.2012.06.003>
- Alsdorf DE, Rodríguez E, Lettenmaier DP (2007) Measuring surface water from space. *Rev Geophys*. <https://doi.org/10.1029/2006RG000197>
- Andrade L, O'Dwyer J, O'Neill E, Hynds P (2018) Surface water flooding, groundwater contamination, and enteric disease in developed countries: a scoping review of connections and consequences. *Environ Pollut* 236:540–549. <https://doi.org/10.1016/j.envpol.2018.01.104>
- Christenson E, Bain R, Wright J, Aondoakaa S, Hossain R, Bartram J (2014) Examining the influence of urban definition when assessing relative safety of drinking-water in Nigeria. *Sci Total Environ* 490:301–312. <https://doi.org/10.1016/j.scitotenv.2014.05.010>
- de Veer T, Garibie NM (2018) End of project evaluation: water, sanitation, and hygiene in disaster-prone communities programme in northern Ghana. Nairobi
- Dickinson KL et al (2017) Changing weather and climate in Northern Ghana: comparison of local perceptions with meteorological and land cover data. *Reg Environ Change* 17:915–928. <https://doi.org/10.1007/s10113-016-1082-4>
- Doocy S, Daniels A, Murray S, Kirsch TD (2013) The human impact of floods: a historical review of events 1980–2009 and systematic literature review. *Plos Curr Disasters*. <https://doi.org/10.1371/currents.dis.f4deb457904936b07c09daa98ee8171>
- Forrester J, Cinderby S (2015) A guide to using community mapping and participatory-GIS. University of York, Stockholm Environment Institute, York
- Garriga RG, de Palencia AJF, Foguet AP (2015) Improved monitoring framework for local planning in the water, sanitation and hygiene sector: from data to decision-making. *Sci Total Environ* 526:204–214. <https://doi.org/10.1016/j.scitotenv.2015.04.078>
- Ghana Statistical Services (2014a) 2010 Population and housing census district analytical report: Savelugu-Nanton District. Accra
- Ghana Statistical Services (2014b) 2010 Population and housing census district analytical report: Talensi district. Accra
- Ghana Statistical Services (2021) Ghana 2021 population and housing census: population of regions and districts, vol 3A. Accra
- Ghassemian H (2016) A review of remote sensing image fusion methods. *Inf Fus* 32:75–89. <https://doi.org/10.1016/j.inffus.2016.03.003>
- Guha-Sapir D, Vos F, Below R (2011) Annual Disaster Statistical Review 2010: the numbers and trends. Belgium, Brussels
- Hoque BA, Sack RB, Siddiqi M, Jahangir AM, Hazera N, Nahid A (1993) Environmental-health and the 1991 Bangladesh cyclone. *Disasters* 17:143–152. <https://doi.org/10.1111/j.1467-7717.1993.tb01141.x>
- Islam MA, Islam T, Minhaz Ahmed S, Ahmed N Implementation of flash flood monitoring system based on wireless sensor network

- in Bangladesh. In: 2014 international conference on informatics, electronics & vision (ICIEV), 23–24 May 2014. pp 1–6. <https://doi.org/10.1109/ICIEV.2014.6850752>
- Islam MS et al (2007) Faecal contamination of drinking water sources of Dhaka city during the 2004 flood in Bangladesh and use of disinfectants for water treatment. *J Appl Microbiol* 103:80–87. <https://doi.org/10.1111/j.1365-2672.2006.03234.x>
- Kirby MA, Nagel CL, Rosa G, Iyakaremye L, Zambrano LD, Clasen TF (2016) Faecal contamination of household drinking water in Rwanda: a national cross-sectional study. *Sci Total Environ* 571:426–434
- Lawrence AR, MacDonald DMJ, Howard AG, Barrett MH, Pedley S, Ahmed KM, Nalubega M (2001) Guidelines for assessing the risk to groundwater from on-site sanitation. Nottingham
- Lempérière F (2017) Dams and floods. *Engineering* 3:144–149. <https://doi.org/10.1016/J.ENG.2017.01.018>
- Levy K, Nelson Kara L, Hubbard A, Eisenberg Joseph NS (2008) Following the water: a controlled study of drinking water storage in northern coastal Ecuador. *Environ Health Perspect* 116:1533–1540. <https://doi.org/10.1289/ehp.11296>
- Levy K, Woster AP, Goldstein RS, Carlton EJ (2016) Untangling the impacts of climate change on waterborne diseases: a systematic review of relationships between diarrheal diseases and temperature, rainfall, flooding, and drought. *Environ Sci Technol* 50:4905–4922. <https://doi.org/10.1021/acs.est.5b06186>
- Lin L et al (2019) Improvement and validation of NASA/MODIS NRT global flood mapping. *Remote Sens*. <https://doi.org/10.3390/rs11020205>
- Luby S, Islam MS, Johnston R (2006) Chlorine spot treatment of flooded tube wells, an efficacy trial. *J Appl Microbiol* 100:1154–1158. <https://doi.org/10.1111/j.1365-2672.2006.02940.x>
- Luby SP, Gupta SK, Sheikh MA, Johnston RB, Ram PK, Islam MS (2008) Tubewell water quality and predictors of contamination in three flood-prone areas in Bangladesh. *J Appl Microbiol* 105:1002–1008. <https://doi.org/10.1111/j.1365-2672.2008.03826.x>
- McCluskey J (2001) Water supply, health and vulnerability in floods. *Waterlines* 19:14–17
- McHugh ML (2012) Interrater reliability: the Kappa statistic. *Biochemia Medica* 22:276–282
- Mellor JE et al (2016) Planning for climate change: The need for mechanistic systems-based approaches to study climate change impacts on diarrheal diseases. *Sci Total Environ* 548:82–90. <https://doi.org/10.1016/j.scitotenv.2015.12.087>
- Pekel JF, Cottam A, Gorelick N, Belward AS (2016) High-resolution mapping of global surface water and its long-term changes. *Nature* 540:418. <https://doi.org/10.1038/nature20584>
- Phanuwan C, Takizawa S, Oguma K, Katayama H, Yunika A, Ohgaki S (2006) Monitoring of human enteric viruses and coliform bacteria in waters after urban flood in Jakarta, Indonesia. *Water Sci Technol* 54:203–210. <https://doi.org/10.2166/wst.2006.470>
- Revilla-Romero B, Hirpa FA, Pozo JT, Salamon P, Brakenridge R, Pappenberger F, De Groeve T (2015) On the use of global flood forecasts and satellite-derived inundation maps for flood monitoring in data-sparse regions. *Remote Sens*. <https://doi.org/10.3390/rs71115702>
- Rice EW, Bridgewater L, American Public Health A, American Water Works A, Water Environment F (2012) Standard methods for the examination of water and wastewater. American Public Health Association
- Richter BD, Postel S, Revenga C, Scudder T, Lehner B, Churchill A, Chow M (2010) Lost in development's shadow: the downstream human consequences of dams. *Water Altern- Interdiscip J Water Polit Dev* 3:14–42
- Roberts RD, Fraser AS, Hodgon KM, Paquette GM (2002) Monitoring and assessing global water quality—the GEMS-Water experience. *Int J Ecohydrol Hydrobiol* 02:19–27
- Sandhu C et al (2018) Measures to mitigate direct flood risks at river-bank filtration sites with a focus on India. *Sustain Water Resour Manag* 4:237–249. <https://doi.org/10.1007/s40899-017-0146-z>
- Smith KR et al. (2014) Human health: impacts, adaptation and co-benefits. In: Field CB et al. (eds) *Climate change 2014: impacts, adaptation and vulnerability. Part A: global and sectoral aspects. Contribution of Working Group II to the 5th Assessment Report of the Inter-governmental panel on climate change*. Cambridge University Press, Cambridge, pp 706–754
- StataCorp (2019) *Stata Statistical Software*, 16 edn. Statacorp LLC, College Station, Texas
- Terry JP, Chui TFM (2012) Evaluating the fate of freshwater lenses on atoll islands after eustatic sea-level rise and cyclone-driven inundation: a modelling approach. *Glob Planet Change* 88–89:76–84. <https://doi.org/10.1016/j.gloplacha.2012.03.008>
- Thomson P, Bradley D, Katilu A, Katuva A, Lanzoni M, Koehler J, Hope R (2019) Rainfall and groundwater use in rural Kenya. *Sci Total Environ* 649:722–730. <https://doi.org/10.1016/j.scitotenv.2018.08.330>
- Udo J, Klopstra D, Hartman M, Andah W, van de Giessen N, Termes P, Bijkerk T (2012) North Ghana sustainable development, disaster prevention and water resources management: flood hazard assessment, White Volta. Lelystad, Netherlands
- Verplanke J, Georgiadou Y (2017) Wicked water points: the quest for an error free national water point database. *ISPRS Int J Geo Inf*. <https://doi.org/10.3390/ijgi6080244>
- Vieira CB et al (2017) The impact of the extreme Amazonian flood season on the incidence of viral Gastroenteritis cases. *Food Environ Virol* 9:195–207. <https://doi.org/10.1007/s12560-017-9280-x>
- Vieira CB et al (2016) Viruses surveillance under different season scenarios of the Negro River Basin, Amazonia, Brazil. *Food Environ Virol* 8:57–69. <https://doi.org/10.1007/s12560-016-9226-8>
- Ward DP, Petty A, Setterfield SA, Douglas MM, Ferdinands K, Hamilton SK, Phinn S (2014) Floodplain inundation and vegetation dynamics in the Alligator Rivers region (Kakadu) of northern Australia assessed using optical and radar remote sensing. *Remote Sens Environ* 147:43–55. <https://doi.org/10.1016/j.rse.2014.02.009>
- Wardrop NA, Hill AG, Dzodzomenyo M, Aryeetey G, Wright JA (2018) Livestock ownership and microbial contamination of drinking-water: evidence from nationally representative household surveys in Ghana, Nepal and Bangladesh. *Int J Hyg Environ Health* 221:33–40. <https://doi.org/10.1016/j.ijheh.2017.09.014>
- Water Resources Commission (2020) Addressing the impacts of spillage of the Bagre Dam in the White Volta river basin in Ghana. Water Resources Commission, Accra
- West Africa Network for Peace-Building (2020) Ten dead, several rendered homeless after Bagre Dam Spillage. West Africa Network for Peace-Building, Tamale
- WHO/UNICEF (2019) Drinking water: the new JMP ladder for drinking water. World Health Organization. <https://washdata.org/monitoring/drinking-water>. Accessed 8 Apr 2019
- World Health Organization (2021) Sanitary inspection packages for drinking-water. World Health Organization. <https://www.who.int/teams/environment-climate-change-and-health/water-sanitation-and-health/water-safety-and-quality/water-safety-planning/sanitary-inspection-packages>. Accessed 21 Sept 2021

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