Quantification of exposure to fecal contamination in open drains in four neighborhoods in Accra, Ghana

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ABSTRACT

In low-income countries, rapid urbanization adds pressure to already stressed water and sanitation systems that are critical to the health of communities. Drainage networks, designed for stormwater but commonly used for disposing of waste, are rarely covered completely, allowing residents to easily come into contact with their contents. This study used spatial mapping, documentation of physical drain characteristics, microbiological analysis of drain samples, and behavioral observation to comprehensively examine drains as a route of exposure to fecal contamination in four low-income neighborhoods in Accra, Ghana. A stochastic model of six likely exposure scenarios was constructed to estimate children's exposure to drain water. Regardless of the age of the child, any exposure scenario considered resulted in exposure to a high level of fecal contamination. Fecal contamination levels in drains were high (*Escherichia coli*: geometric mean (GM), 8.60 cfu $\log_{10}$/100 mL; coliphage: GM, 5.56 pfu $\log_{10}$/100 mL), and did not differ by neighborhood or physical drain characteristics, indicating that frequency of contact with drains, and not drain type or location, drives exposure risk. To mitigate health risks associated with this exposure, drains should be covered, with priority given to large concrete and small to medium dirt-lined drains that children were most commonly observed entering.

Key words | exposure assessment, Ghana, open drains, stochastic modeling, urbanization, wastewater

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INTRODUCTION

Currently, more of the world's population live in urban settings than in rural settings, and by 2050, it is projected that seven out of ten people worldwide will live in urban settings (WHO & UN-Habitat 2010). Africa in particular is expected to continue to have rapid urbanization rates (United Nations 2012), adding pressure to already stressed water and sanitation systems. Cities served by piped water, sanitation, drainage, waste removal, and a good health care system typically have childhood mortality rates of 10 per 1,000 live births, while the absence of those systems can increase childhood mortality 10- to 20-fold (UNICEF 2002). Just 20% of the population in urban Ghana had access to improved sanitation facilities in 2012, and 72% of the urban population relied on shared sanitation facilities (WHO/UNICEF Joint Monitoring Programme 2014). In Accra, Ghana, the inability of many residents to access improved sanitation facilities, coupled with the absence of sewage treatment in the city (Adank *et al.* 2011), has resulted in serious contamination of the urban environment. As in many other cities in developing countries, grey water, black water, and solid waste are frequently disposed of in open drains that are intended to collect storm water (Labite *et al.* 2010; The World Bank 2010). Residents of Accra can easily come into contact with the drains because they are rarely covered completely (The World Bank 2010). Direct exposure to open drains occurs most often to children who may fall into the drains, or enter into the drains to retrieve a toy, or scavenge for trash. The state of the drainage system in Accra is a serious public health concern because both the absence of covered drainage systems (Moraes *et al.* 2003; Sasaki *et al.* 2009; The World Bank 2010) and the presence of uncovered drainage ditches (Genser *et al.* 2006; Santos *et al.* 2012) increases the likelihood of exposure to fecal contamination and subsequent risk of enteric infection.

Quantitative Microbial Risk Assessment (QMRA) is a method that can be used to estimate the risk of exposure to pathogenic microorganisms. Published QMRAs of wastewater conducted in Accra have focused on quantifying occupational hazards to farmers (Obuobie *et al.* 2006; Seidu *et al.* 2008) and risks to consumers of wastewater-irrigated produce (Amoah *et al.* 2005; Obuobie *et al.* 2006; Amoah *et al.* 2007; Drechsel *et al.* 2008; Seidu *et al.* 2008). These studies have demonstrated that open drains in the city are highly contaminated with fecal microbes. Recent QMRAs of the water and sanitation systems in low-income urban neighborhoods identified open drains as the most hazardous exposure source (Labite *et al.* 2010; Katukiza *et al.* 2013). In Accra, exposure to open drains was predicted to cause 64% of all cases of diarrheal illness and 62% of all disability-adjusted life years were attributed to the inadequate water and sanitation systems per year (Labite *et al.* 2010). While open drains have been identified as an important environmental health risk, few studies have focused on the risk this exposure pathway poses to children. Furthermore, the effects of drain-level and neighborhood-level characteristics that could modify both the amount of fecal contamination in drains and the frequency with which children are exposed to drains have not been examined. The goal of this study was two-fold:

1. Determine if physical drain characteristics or neighborhood characteristics are associated with (a) the level of fecal contamination in drain water, and (b) the frequency of children's contact with drain water.
2. Determine if child's age or the type of activity leading to drain exposure significantly affects the dose of fecal contamination (measured as *Escherichia coli* and coliphage) a child would be exposed to.

METHODS

The study was conducted from July 2011 to November 2012 in four low-income neighborhoods in Accra, Ghana: Alajo, Bukom, Old Fadama, and Shiabu (Figure 1). The neighborhoods were selected to be representative of the risk conditions associated with poor sanitation across a variety of low-income urban environments. Alajo, the wealthiest of the neighborhoods studied, is situated furthest inland from the coastline and is bordered by the Odaw River and the Onyasia River. Bukom is a coastal community situated in downtown Accra. Old Fadama is an inland squatter settlement, and as such had the least developed drainage and sanitation infrastructure. Finally, Shiabu is another costal community boarded by the Chemu Lagoon with squatter housing in the southern half of the community and gated wealthier houses in the northern half.

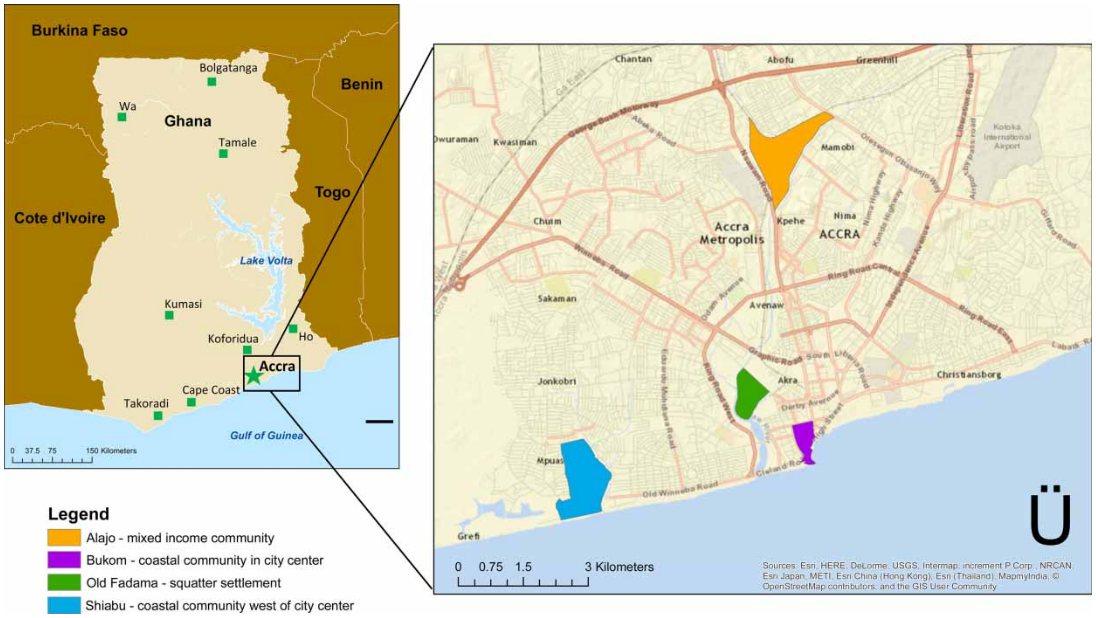

Figure 1 | Study area: four low-resource neighborhoods in Accra, Ghana.

A survey of randomly selected households was conducted in each neighborhood to collect information on household demographics and sanitation and hygiene practices as previously described (Peprah *et al.* 2015). The individual surveyed determined what drain was nearest to their household. Informed consent was obtained from all individuals who participated in the study. Drain characterization was conducted in each neighborhood by onsite inspection, and all accessible drains were characterized. A series of drain characteristics were recorded at the beginning, ending, and merging points of each drain. Characteristics recorded were: (1) width: small (<0.5 m), medium (0.5–1 m), large (1–3 m), or extra-large (>3 m); (2) water level: dry, low (small stream), medium (most contents suspended in water), high (near top or overflowing), or unable to observe; (3) drain cover by the city or citizens; and (4) construction type: ecological (dirt-lined), formal by city (cement- or stone-lined constructed by the city government), or formal by citizens (cement- or stone-lined constructed by citizens).

Additionally, 1-hour periods of structured observations of child behavior around open drains were conducted in all study neighborhoods. The frequencies of drain entry of young children (under 5 years) and older children (5–12 years) were recorded. Determination of age was at the discretion of the enumerator. A child was considered to be inside the drain if any part of his or her body went beyond the perimeter of the drain. Three water samples from open drains were collected monthly in each neighborhood for eight months. Samples were processed for *E. coli* and coliphages using 100 μL of three serial dilutions, 10^{-5}, 10^{-6}, and 10^{-7}, according to EPA methods 1604 (US EPA 2002) and 1601 (US EPA 2001).

A Global Positioning System unit was used to record the locations of each environmental sample, structured observation of behavior, and drain characteristic. Drain lines were digitized in Google Earth (Google, Inc., Mountain View, CA) and then transferred into ArcGIS 10.1 (ESRI, Redlands, CA). Behavioral and microbial data were joined to the drain network based on closest Euclidean distance. ArcGIS was used to calculate each neighborhood's area, total drain length, and density of drains. Drain characterization data were weighted by the total length of drains in each neighborhood to obtain the percentage of the total drain network with each characteristic.

Statistical analyses were conducted in SAS 9.3 (SAS, Cary, NC). All statistical tests were evaluated at an alpha level of 0.05. The contact rates of young and older children observed in drains per hour were calculated. Each record of child contact was assumed to represent a single child. Poisson regression models of drain entry rates were fitted for neighborhood, drain size, and drain construction type to determine if there were differences in the rates of children observed entering drains by each variable. The referent level was set to the category suspected to have the highest entry rate. The final *E. coli* and coliphage concentrations were log-transformed, and the geometric mean and standard deviation were calculated. Samples with no detectable microbial concentrations were assigned a value of 0.5/100 mL of the highest dilution tested. *E. coli* and coliphage concentrations were analyzed by analysis of variance to determine if there were significant differences between neighborhoods and drain size. Two-sample *t*-tests were conducted to determine if microbe concentrations differed by drain construction and drain cover.

EXPOSURE ASSESSMENT

Based on structured observations of open drains conducted in Accra, six likely exposure scenarios were identified involving three exposure activities and two age groups of children (Figure 2). Exposure scenario A (B) involved young (older) children accidentally entering the drain and having direct hand contact with drain water. Exposure scenario C (D) involved young (older) children incidentally entering the drain to retrieve an object and having indirect contact with drain water via the contaminated object. Exposure scenario E (F) involved young (older) children deliberately entering a drain for a period of time (e.g. to play, collect recyclables, or defecate) during which their hands come into contact with drain water.

Equations describing the loading of microbes on hands (directly or through an object) and the transfer of microbes from hand-to-mouth were used to determine the final dose for each exposure scenario (Zartarian *et al.* 2000). Model parameters are presented in Table 1 for the hand contamination distributions and Table 2 for the dose distributions. Model parameters and equations are described further in the Appendix (available with the online version of this paper).

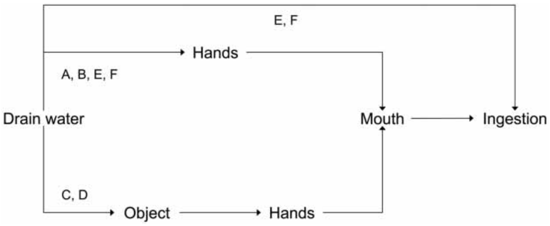

Figure 2 | Schematic of drain exposure scenarios. A, B denote accidental drain entry with direct hand-drain water contact; C, D denote incidental drain entry to retrieve an object; E, F denote deliberate drain entry.

Distribution of hand contamination

$$E_x = C_x \times \left[\begin{matrix} D_D \times T_D \\ \text{or} \\ D_A \end{matrix}\right] \times (A_x \times S_{HDW}) \times V \qquad (1)$$

Distribution of hand contamination via an object

$$E_x = C_x \times D_I \times (A_O \times S_{ODW}) \times V \times \left(\frac{A_x \times S_{OH}}{A_O \times S_{ODW}}\right) \times TE_{Ox} \qquad (2)$$

Distribution of dose from hand-to-mouth contact

$$D_x = E_x \times HM_x \times S_{HM} \times TE_{Hx} \times T_{HW} \qquad (3)$$

For scenarios A–D, the final doses were generated by Equation (3). For scenarios E and F, it was assumed that all children ingested an additional droplet of drain water, which was assumed to have a fixed volume of 0.05 mL.

Distribution of residual dose from direct ingestion

$$R_x = C_x \times 0.05\text{mL} \qquad (4)$$

The final dose for these two scenarios was the sum of the hand-to-mouth dose generated by Equation (3) and the residual dose generated by Equation (4).

To compare the dose distributions between different initial microbial concentrations in drain water and different exposure scenarios, Monte Carlo (MC) simulations of dose distributions were compared pairwise by subtracting log-transformed MC simulations and calculating the fraction greater than zero. This method is equivalent to performing a pairwise non-parametric test where the percentage of the differences that are greater than zero corresponds to the level of significance (Gelman *et al.* 2004). Six pairwise comparisons of the dose distributions were calculated: (1) *E. coli* concentrations vs. coliphage concentrations, (2) *E. coli* concentrations found in drains that were originally rivers/lagoons vs. *E. coli* concentrations in all other drains, (3) young children vs. older children, (4) accidental drain entry vs. incidental drain

Table 1 | Model parameters used to estimate hand and object contamination distributions

Variable	Symbol	Parameter	Source
Microbe concentration ($\log_{10}$/100 mL)			
Coliphage	C_C	Normal (5.56, 1.18)	This study
E. coli	C_{Ec}	Normal (8.60, 1.00)	This study
Time spent in the drain per entry event (hr)			
Deliberate entry	T_D	Determined from a hazard model of children's activities	This study
Frequency of contact with drain (#/drain entry event)			
Accidental entry	D_A	Poisson (1)	Assumption
Incidental entry	D_I	Poisson (1)	Assumption
Deliberate entry	D_D	Poisson ($5 \times T_D$)	Assumption
Area of surface (cm^2)			
Hands, young children[a]	A_Y	Uniform (244.4, 329.0)	US EPA (2011)
Hands, older children[b]	A_M	Uniform (380.7, 695.6)	US EPA (2011)
Object	A_O	Uniform (378.8, 1515.5)	Assumption
Object contacted (%)			
Hand in drain water	S_{HDW}	Uniform (0.08, 1.00)	AuYeung *et al.* (2008)
Object in drain water	S_{ODW}	Uniform (0.25, 1.00)	Assumption
Hand on object	S_{OH}	Uniform (0.08, 0.27)	AuYeung *et al.* (2008)
Water film thickness (cm)			
Hand or object	V	Uniform (0.00241, 0.00499)	US EPA (1987)
Transfer efficiency, object to hand (%)			
Coliphage	TE_{OC}	0.2759	Rusin *et al.* (2002)
E. coli	TE_{OEc}	0.6580	Rusin *et al.* (2002)

[a] Children aged less than 5 years.
[b] Children aged 5–12 years.

entry, (5) accidental drain entry vs. deliberate drain entry, and (6) deliberate drain entry and incidental drain entry. Doses calculated in this study were also compared pairwise to the doses that would result if every child ingested 5 mL of drain water per exposure event as was assumed in a previous QMRA (Labite *et al.* 2010). The distributions of doses based on direct ingestion of 5 mL of drain water were calculated for *E. coli* and coliphage by multiplying the initial concentration of microbes in drain water (C_x) by 5 mL.

RESULTS

Two hundred household surveys were conducted in each study neighborhood. Reported household characteristics for each neighborhood are presented in Table 3. Households without a toilet in the compound must rely on public toilets. Old Fadama had the lowest level of sanitation infrastructure. Almost no one had access to improved sanitation facilities in her or his compound, and many reported not having a drain near the household. While many residents of Bukom also lacked access to sanitation facilities, this community had the highest proportion of households reporting access to drains. In both Alajo and Shiabu, about 50% of households had access to a toilet in the compound, and around 40% reported having a drain near the household. Defecation in drains was least common in Shiabu where respondents reported that both children and adults were never seen defecating in a household drain. Reported drain defecation was most common in Old Fadama; 22% and 15% of respondents reported seeing children and adults defecating every day in a drain near their household, respectively. Similar rates of

Table 2 | Model parameters used to estimate dose distributions

Variable	**Symbol**	**Parameter**	**Source**
Object contacted (%)			
Hand in mouth	S_{HM}	Uniform (0.06, 0.33)	AuYeung *et al.* (2007)
Frequency of hand mouthing (#/hour)			
Young children[a]	HM_Y	Weibull (0.56, 3.41)	Xue *et al.* (2007)
Older children[b]	HM_M	Weibull (0.49, 1.47)	Xue *et al.* (2007)
Time microbes could be ingested (hours)			
Time to hand washing	T_{HW}	Uniform (0.05, 4.10)	Freeman *et al.* (2001)
Transfer efficiency, hand to mouth (%)			
Coliphage	TE_{HC}	0.3390	Rusin *et al.* (2002)
E. coli	TE_{HEc}	0.3397	Rusin *et al.* (2002)

[a] Children aged less than 5 years.

[b] Children aged 5–12 years.

Table 3 | Surveyed household characteristics by neighborhood

	Alajo	**Bukom**	**Old Fadama**	**Shiabu**
General	n = 200	n = 200	n = 200	n = 200
Median HH size (Range)	5 (1–35)	5 (1–50)	3 (1–20)	4 (1–10)
No formal education (%)	13	14	44	9
Sanitation	n = 200	n = 200	n = 200	n = 200
No drain near HH (%)	42	34	83	42
Type of toilet in compound[a] (%)				
None	42	93	98	54
Improved	55	6	2	42
Unimproved	3	0	1	3
No response	0	2	1	1
Defecation in drain near HH	n = 116	n = 132	n = 27	n = 115
Children observed (%)				
Everyday	4	15	22	0
Sometimes	3	14	4	9
Never	92	71	74	91
Adults observed (%)				
Everyday	3	12	15	0
Sometimes	8	9	4	6
Never	90	79	82	94

HH denotes household.

[a] The WHO and UNICEF define improved sanitation as: flush toilet, piped sewer system, septic tank, flush/pour flush to pit latrine, ventilated improved pit latrine (VIP), pit latrine with slab, and composting toilet.

observed child and adult defecation into drains were reported in Bukom.

Characteristics of the open drains network varied by neighborhood (Table 4). Bukom had the densest drain network, followed by Alajo and Shiabu and finally Old Fadama with the fewest drains per square kilometer. Calculated drain density was consistent with how frequently drains were reported near households in the household survey (Table 3). In Alajo, Bukom, and Shiabu, drain construction was primarily carried out by the city; however, in Old Fadama, all but one drain was ecologically formed or constructed by citizens. Drain size was generally a reflection of construction. Drains built by the city were typically medium in size and deep, while drains that were ecologically formed tend to be wider and shallow. As such, over 50% of the drains present in Alajo, Bukom, and Shiabu were medium in size. Extra-large drains that were originally rivers or lagoons bordered all neighborhoods except Bukom. Drain mapping revealed that, excluding these few extra-large drains that bordered the communities, drains rarely flowed between neighborhoods. Old Fadama had the largest percentage of drainage network with no cover; over half the network was completely uncovered.

In total, 45 hours of structured observations of children's behavior around open drains were conducted. The frequency of young children observed in drains was significantly lower in Alajo, Bukom, and Shiabu compared to Old Fadama, which had the largest percentage of drains with no cover (Table 5). On average, three to four young children per hour were observed in drains in Old Fadama, while less than one young child per hour was observed in Alajo, Bukom, and Shiabu. The frequency of young children observed in drains was also significantly lower for small and medium drains compared to large drains, and for formal drains compared to ecological drains. The frequency of older children observed in drains was significantly lower in Bukom compared to Old Fadama, but did not differ significantly when comparing Alajo or Shiabu to Old Fadama (Table 5). One to two children were observed in a drain per hour in Alajo, Old Fadama, and Shiabu while one child was observed in Bukom every 2 hours.

Table 4 | Observed drain characteristics by neighborhood

	Alajo	**Bukom**	**Old Fadama**	**Shiabu**
Linear meters of drains (m)	30,679	10,652	8,393	28,999
Drain density (m/km^2)	19,263	31,715	15,706	19,205
Cover[1] (%)				
No cover	33	8	55	25
Cover by citizens	54	80	45	53
Cover by city	33	19	0	65
Construction type[a,b] (%)				
Ecological	14	0	65	21
Formal by citizens	19	20	51	9
Formal by city	70	80	5	75
Size[a] (%)				
Small (<0.5 m across)	10	28	6	7
Medium (0.5–1 m across)	52	57	32	73
Large (1–3 m across)	25	15	33	10
Extra-large[c] (>3 m across)	16	0	30	9
Water level[a,d] (%)				
Dry	13	6	1	10
Low	36	53	22	44
Medium	51	28	36	39
High	1	10	37	7
Unable to see	2	3	4	0

[a] All percentages are based on total drain length.

[b] Ecological drains were dirt lined with no formal planning. Formal drains were cement or stone lined and were intentionally constructed.

[c] All extra-large drains were originally rivers or lagoons.

[d] Water levels recorded were dry, low (mostly dry, small stream, not all contents are suspended in water), medium (contents are suspended in water, bottom of drain covered with water), high (obviously high water level, near top or overflowing), or unable to see.

Table 5 | Rates of children observed in open drains by neighborhood and drain characteristics

		Children under 5 years old[a]		**Children 5–12 years old[a]**	
	Hours[b]	**Rate (children/hour)**	***P*-value**	**Rate (children/hour)**	***P*-value**
Neighborhood					
Alajo	11	0.9	<0.01	1.2	0.07
Bukom	11	0.6	<0.01	0.5	<0.01
Old Fadama	14	3.5	Ref	2.1	Ref
Shiabu	9	0.4	<0.01	2.0	0.82
Drain size[c]					
Small	15	0.7	<0.01	0.9	0.02
Medium	16	1.4	0.01	1.7	0.62
Large	14	2.7	Ref	1.9	Ref
Drain construction[d]					
Formal	25	0.9	<0.01	1.6	0.63
Ecological	19	2.5	Ref	1.4	Ref

[a] Age was estimated by the observer.

[b] Total observation hours at drain locations. Each observation took place for 1 hour. It was assumed each recorded count represented a single child.

[c] Small drain (<0.5 m across), medium drain (0.5–1 m across), large drain (>1 m across).

[d] Ecological drains were dirt lined with no formal planning. Formal drains were cement or stone lined and were intentionally constructed.

The frequency of older children observed in small drains was less than twice the rate of older children observed in large drains. There were no differences in the observed frequencies of older children entering drains based on drain construction.

There were 86 water samples from open drains tested for *E. coli* and 42 for coliphage. The concentrations of coliphage in the open drain water samples were consistently lower than the *E. coli* concentrations across all drain types (Table 6). Water samples from drains that were originally rivers/lagoons had *E. coli* concentrations that were significantly lower than water samples that were taken from drains that only functioned as drains (geometric mean, 7.93 cfu $\log_{10}$/100 mL vs. 8.72 cfu $\log_{10}$/100 mL; $P < 0.01$). There was no significant difference in coliphage concentrations between drains that were originally rivers/lagoons and those that were not. To assess differences in microbial concentrations between other neighborhood and drain characteristics, samples from drains that were originally rivers/lagoons were removed from the analysis. For remaining samples, *E. coli* and coliphage concentrations in drain water samples did not significantly differ by neighborhood, drain size, construction type, or cover (Table 6).

The geometric mean and 95% range for the final estimated coliphage and *E. coli* doses are presented in Table 7. Exposure to the highest dose of fecal microbes was estimated to occur durning scenario A. The coliphage doses had a mean of 2.44 pfu $\log_{10}$, while *E. coli* doses had a mean of 5.47 cfu $\log_{10}$. Scenario D estimated exposure to the lowest dose of fecal microbes with a mean of 1.39 pfu $\log_{10}$ of coliphage ingested and 4.80 cfu $\log_{10}$ of *E. coli* ingested. Although the *E. coli* concentrations in drains that were rivers/lagoons

Table 6 | Coliphage and *E. coli* concentrations from open drain water samples by neighborhood and drain characteristics

	Coliphage (pfu $\log_{10}$/100 mL)				*E. coli* (cfu $\log_{10}$/100 mL)			
	N	Geo mean	SD	*P*-value	N	Geo mean	SD	*P*-value
Overall	42	5.56	1.18		86	8.60	1.00	
River/lagoon[a]				0.40				<0.01
No	35	5.63	1.17		72	8.72	0.99	
Yes	7	5.21	1.25		14	7.93	0.77	
Neighborhood[b]				0.19				0.08
Alajo	6	5.21	1.45		18	8.62	0.71	
Bukom	13	6.13	1.10		19	8.95	0.98	
Old Fadama	8	5.63	1.01		16	8.23	0.85	
Shiabu	8	5.12	1.06		19	9.01	1.22	
Size[b,c]				0.72				0.05
Small	10	5.42	1.44		13	8.55	0.73	
Medium	18	5.63	1.04		45	8.93	1.03	
Large	7	5.91	1.19		14	8.23	0.92	
Construction[b,d]				0.92				0.15
Formal	25	5.61	1.28		56	8.81	1.00	
Ecological	10	5.66	0.90		16	8.41	0.93	
Cover[b]				0.80				0.05
Some cover	25	5.66	1.16		54	8.85	0.94	
No cover	10	5.54	1.25		18	8.33	1.07	

cfu denotes colony forming units; pfu denotes plaque forming units.

[a] Drain was originally a river or lagoon but now functions as a large, terminal drain.

[b] Only drains that were not originally rivers or lagoons were included.

[c] Small drain (<0.5 m across), medium drain (0.5–1 m across), large drain (1–3 m across).

[d] Ecological drains were dirt lined with no formal planning. Formal drains were cement or stone lined and were intentionally constructed.

were significantly lower than the concentrations in all other drains, practically the concentrations were similar and differed by less than 1 cfu $\log_{10}$. When these two concentrations were applied to the exposure model, the log-transformed doses only differed by 79.6% indicating no significant difference between the two doses.

Estimated doses did not differ significantly by age group or exposure activity. The final doses for young children were slightly higher than the doses for older children because we assumed higher mouthing frequencies in young children; however, due to considerable variation in MC estimates, the differences in the log-transformed doses were not significant. In addition, while the log-transformed coliphage and *E. coli* doses resulting from incidental entry were lower than those for accidental and deliberate entry, this difference was not significant. Overall, within each age group, there was no significant difference in the coliphage and *E. coli* doses that were estimated from the three exposure activities (Figure 3).

The mean of the coliphage dose that was estimated to occur if we assumed drain exposure resulted in direct ingestion of 5 mL of drain water was 4.27 $\log_{10}$ pfu (95% range: 2.00, 6.56 $\log_{10}$ pfu). The mean of the *E. coli* dose was 7.29 $\log_{10}$ cfu (95% range: 5.35, 9.22 $\log_{10}$ cfu). The log-transformed dose distribution for direct ingestion of 5 mL of drain water was significantly different from all log-transformed dose distributions modeled in this study for both fecal indicators (Figure 3).

DISCUSSION

To our knowledge, this study represents the first attempt to quantify exposure of children to fecal microbes present in

Table 7 | Estimated coliphage and *E. coli* doses for six drain entry exposure scenarios

Exposure scenario		$\log_{10}$ (coliphage, pfu)		$\log_{10}$ (*E. coli*, cfu)	
		Geo mean	95% range	Geo mean	95% range
Children under 5 years	(A) Accidental[a]	2.44	–0.99, 5.50	5.47	2.31, 8.22
	(C) Incidental[b]	1.54	–1.88, 4.65	4.94	1.69, 7.75
	(E) Deliberate[c]	2.40	0.05, 4.86	5.43	3.41, 7.57
Children 5–12 years	(B) Accidental[a]	2.29	–1.40, 5.52	5.32	1.87, 8.22
	(D) Incidental[b]	1.39	–2.39, 4.63	4.80	1.33, 7.75
	(F) Deliberate[c]	2.39	0.04, 4.84	5.42	3.40, 7.54

pfu denotes plaque forming units; cfu denotes colony forming units.

(A)–(F) indicates exposure scenario.

[a] Accidental drain entry describes a scenario where a child fell into a drain, had hand contact with drain water and subsequent hand mouthing events occurred.

[b] Incidental drain entry describes a scenario where a child entered a drain to retrieve a fallen object, had contamination of their hands through the object and subsequent hand mouthing events occurred.

[c] Deliberate drain entry describes a scenario where a child purposefully entered a drain for a period of time in which their hands could contact drain water and subsequent hand mouthing events occurred. It was assumed at least a droplet of drain water was ingested per deliberate entry event.

open drain water using a stochastic model. Ingestion of drain water was primarily modeled as indirect ingestion via mouthing of contaminated hands. Based on observations of children's interactions with open drains, we believe this represents a realistic sequence of events that leads to the ingestion of drain water, as opposed to assuming an arbitrary volume of drain water is directly ingested. We also accounted for different types of activities that could cause exposure of children to drain water by modeling three different likely exposure activities: (1) accidental entry with direct hand-drain water contact, (2) incidental entry to retrieve an object, with hand contamination occurring through the object, and (3) deliberate entry with direct hand-drain water contact dependent on the time spent in the drain along with direct ingestion of a droplet of drain water. Two different age groups of children were considered to account for differences in hand size and hand mouthing frequencies. This resulted in six exposure scenarios.

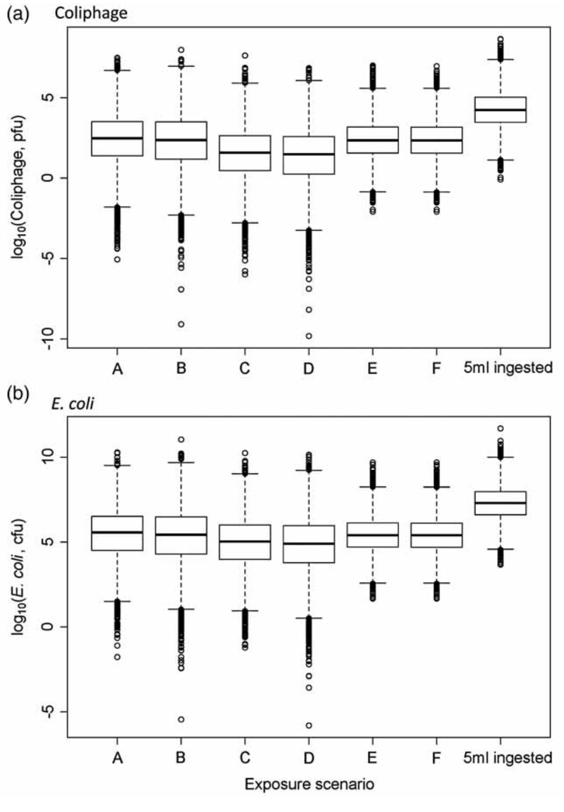

Figure 3 | Distribution of log-transformed doses by exposure scenario. Exposure scenarios A-F refer to child drain exposure scenarios as described in the text. 5 ml ingested refers to a scenario where a child directly ingests 5ml of drain water.

The primary factor that determined dose was the high concentration of fecal microbes present in drain water. No differences were found in the log-transformed doses across age groups even though young children more frequently mouth hands than older children. Exposure activity also did not significantly change the estimated doses. We hypothesize that the highly variable concentration of microbes in open drains masked the effect these behavioral parameters had. In this setting, drain water was so highly contaminated with fecal microbes that any contact resulted in a high level of exposure to these microbes.

Published studies on exposure of children to open drains have assumed that the child directly ingested 5 mL of drain water during each drain entry event and that such events occurred four times a year (Labite *et al.* 2010). Using the same initial concentration of microbes, the dose that resulted from those assumptions was significantly higher than the doses estimated for each of the three exposure activities modeled in this analysis. We suspect previous studies of drain water exposure overestimated the doses because transfer efficiencies between drain water contact and subsequent ingestion were not accounted for. The rates of observed drain entry by children in the present study also suggest that children contact drain water more frequently than previously assumed. Additional behavioral studies of the frequency of drain contact in urban settings would enable better estimates of the risk of exposure to fecal microbes from this pathway.

The development of the present model required a number of assumptions and simplifications. It was not noted in the structured observations if observed drain entry events involved any kind of hand contact with the drain water, thus reasonable estimates were used for the probability of hand contact. More detailed observations of children's interactions with open drains might allow observation of the frequency of hand or object contact with drain water to help better characterize these types of exposures. We assumed that the numbers of microbes on hands or objects were additive, accumulating the results of a number of contact events with drain water. Future assessments should consider that there may be a point of saturation in the contamination of hands and objects or that subsequent contact with drain water could detach microbes from these surfaces. Inactivation of microbes over time (Liu *et al.* 2012) and the decay of microbes on hands following mouthing events (Ozkaynak *et al.* 2011) were also not considered. The duration of presence in a drain used to model deliberate entry was based on observations of young children in a household or nursery under the supervision of a caretaker. We expect children playing in the public domain, without caretaker supervision, would spend longer periods of time in drains thus increasing exposure due to deliberate drain entry. We also expect that hand washing frequencies are lower in developing-country settings, increasing the length of time a child could mouth contaminated hands (Hoque 2003; Pengpid *et al.* 2012). Hand washing is also likely not 100% effective at removing microbes from hands, especially if no soap or poor quality water is used (Hoque *et al.* 1995; Montville *et al.* 2002; Burton *et al.* 2011).

Open drain water is highly contaminated in Accra. Drains rarely flowed between neighborhoods; therefore we can safely assume that contamination levels are primarily impacted by spillage events within a given neighborhood. Among the drains that did not function as rivers/lagoons, there were no significant differences in microbial concentrations by neighborhood, despite differences in reported access to improved sanitation facilities and drain defecation practices that could modify the load of fecal microbes entering drains. Drain size, the type of construction, and cover also were not associated with different microbial concentrations. Additionally, exposure doses did not differ between the six exposure scenarios considered in this study. Taken together, this indicates that the dose of fecal microbes associated with access to open drains is dependent on the frequency of drain entry and not the location, type of drain, or how drain entry occurs.

Consistent with previous studies in Accra that took water samples from drains (Seidu *et al.* 2008; Labite *et al.* 2010), drains that originally functioned as rivers/lagoons had significantly lower concentrations of *E. coli* than drains that only functioned to collect storm and wastewater. Coliphage concentrations did not mirror this pattern, which may be because *E. coli* dies off more quickly than coliphage. We attribute the differences in *E. coli* concentrations in the two different types of drains to the environmental water still present in river/lagoon drains that dilute microbial inputs. However, when the two *E. coli* concentrations were applied to the exposure assessment model, the distributions of the resulting doses did not significantly differ from each other.

Although infection risk was not calculated in this study, differences in the drainage network and drain entry behavior by neighborhood and drain characteristics suggest that the risk of infection by enteric pathogens in open drains is likely not uniform throughout the city. In neighborhoods such as Bukom, where over 90% of drains have some sort of cover, there is less opportunity for drain entry compared to a neighborhood like Old Fadama where over 50% of the drain network is completely uncovered. This may help explain why the rate of young and older children observed in drains was significantly lower in Bukom compared to Old Fadama. Additionally, while microbial concentrations in open drains effectively had the same distribution across neighborhoods and drain characteristics, higher rates of children were observed entering large and ecologically formed drains. This may be because these types of drains can contain fish that older children try to catch and are easier to access when compared to formally constructed drains with steep sides. Children that live in areas with many uncovered drains and large, ecologically formed drains are therefore likely to come into contact with open drain water more frequently, resulting in higher daily infection risks. Our results also demonstrate that in scenarios where exposure is primarily mediated though hands or objects, ingestion volume should be reduced appropriately to account for transfer efficiencies.

CONCLUSIONS

As urbanization continues, we expect fecal contamination of drains and children's exposure to drains to increase, or at least remain at the levels observed in this study. If the current practice of building uncovered drains remains unchanged, flooding of urban environments may decrease, but as long as no sewerage exists, drains will still be highly contaminated and pose a threat to children and other community members that live near them. Support for this conclusion can be found in the similar levels of fecal contamination observed in neighborhoods with many drains built by the government and neighborhoods with no government infrastructure. Given the absence of sewage treatment and safe disposal of feces in many low-income urban settings, an integrated approach involving covering drains, increasing low-cost options to safely dispose of feces, and creating safe places in urban neighborhoods for children to play could mitigate the risk of exposure to these major sources of fecal microbes. To ensure drains can still be accessed to unclog solid waste that may accumulate in them, drains should be covered with a removable covering, like cement tiles. This study and others (Labite *et al.* 2010; Katukiza *et al.* 2013) have demonstrated that open drains pose a great risk of exposure to fecal contamination; therefore, further studies to measure and prevent this risk are critical for the health of urban communities.

ETHICS STATEMENT

Free and informed consent of the participants or their legal representatives was obtained, and the study protocol was approved by the Institutional Review Board at Emory University, GA, USA (Protocol number: IRB00051584. Approval date: 10/20/2010).

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