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Quantification of Exposure to Open Drains in Low-Income Neighborhoods in Accra, Ghana: Implications for Microbial Risk Assessment

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B.S., University of Notre Dame, 2011

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An abstract of
A thesis submitted to the Faculty of the
Rollins School of Public Health of Emory University
in partial fulfillment of the requirements for the degree of
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in Epidemiology
2013

Abstract

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By Stephanie Gretsch

In developing countries, high rates of urbanization are adding pressure to already stressed water and sanitation systems that are critical to the health of urban communities. Inadequate access to improved sanitation, coupled with limited sewage collection and treatment can cause widespread fecal contamination of urban environments. Drainage networks, commonly present in these settings, act as the primary outlet for wastewater. Drains are rarely covered completely, allowing residents, especially children, to be easily exposed to their contents. This study used extensive microbiological sampling, behavioral observation, drain characterization, spatial mapping, and exposure assessment to comprehensively examine open drains as a route of exposure to fecal contamination in four low-income neighborhoods in Accra, Ghana. Drains that were originally rivers or lagoons had a mean *E. coli* concentration of 6.99 cfu log_{10}/100ml, while drains that were not, had a mean *E. coli* concentration of 8.44 cfu log_{10}/100ml. All drains had a mean coliphage concentration of 4.61 pfu log_{10}/100ml. After excluding drains that were originally rivers or lagoons, *E. coli* and coliphage concentrations did not differ significantly by neighborhood, drain size, construction type, or coverage. All children were observed entering small drains at a lower rate than large drains, and children under 5 years old were observed entering formally-constructed drains at a lower rate than ecologically-formed drains. A stochastic model of six exposure scenarios was constructed to estimate ingestion of drain water via mouthing of contaminated hands. Pairwise comparisons of exposure dose distributions by child age (under 5 years or 5-12 years) and exposure activity (accidental entry, deliberate entry, or entry to fetch an object) found no differences in doses. High concentrations of microbial contamination in drains were the primary determinant of exposure dose compared to type of exposure activity and child age. Exposure doses calculated in this study were significantly lower than previous estimates that assumed 5mL of drain water was directly ingested. Differences in the drainage network by neighborhood, and drain entry behavior by drain characteristic, suggest that risk of enteric disease from open drains is likely not uniform throughout the city. Drains should be covered to mitigate this serious public health risk.

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ABBREVIATIONS

AMA	Accra Metropolitan Area
cfu	Colony forming units
E. coli	*Escherichia coli*
EPA	United States Environmental Protection Agency
DALY	Disability adjusted life years
GIS	Geographic Information System
GPS	Global Positioning System
MDG	Millennium Development Goals
Noguchi	Noguchi Memorial Institute for Medical Research; University of Ghana, Legon
pfu	Plaque forming units
QMRA	Quantitative microbial risk assessment
TREND	Training Research and Network for Development Group; Accra, Ghana
UN	United Nations
UNICEF	United Nations Children's Fund
UTM	Universal Transverse Mercator
WASH	Water, sanitation, and hygiene
WHO	World Health Organization
WRI	Water Research Institute; Accra, Ghana

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I. BACKGROUND

A. The Global Burden of Diarrheal Disease

Diarrhea is the seventh leading cause of death and the second leading cause of childhood mortality worldwide (1, 2). Globally, diarrhea is attributed to just over ten percent of all childhood deaths. In sub-Saharan Africa diarrhea plays an even greater role in childhood mortality, causing over half of all deaths among children under 5 years (2). Unsafe water, inadequate sanitation, and poor hygiene have been attributed to nearly 90 percent of deaths due to diarrhea, highlighting the importance of water, sanitation, and hygiene (WASH) interventions in reducing childhood mortality (3). WASH interventions are not only proven to reduce childhood death to due diarrhea, but importantly for decision-makers, they are one of most cost effective strategies to reduce childhood mortality (4).

The Millennium Development Goals (MDGs) have named reducing under-five mortality by two-thirds and halving the proportion of people without sustainable access to basic sanitation global priorities, but based on current trends, both of these goals will not be achieved by 2015. Childhood mortality has only been reduced by one third, falling short of the proposed two-thirds reduction (5). These two goals are inherently tied as reductions in childhood mortality follow improvements in access to sanitation systems. Unfortunately, access to improved sanitation facilities[1] still remains elusive for many of those living in sub-Saharan Africa where only 30 percent of those living in the region have access. Inadequate access to improved facilities contributes to fecal contamination

[1] The World Health Organization 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.

of the environment and poses a serious health risk to vulnerable populations including children, the elderly, immunocompromised persons, and pregnant women.

B. Sanitation Challenges in Urban Environments

The global community is becoming more urban, shifting the environments people live in and the pathways by which they are exposed to fecal pathogens. Currently, more of the world's population lives in urban settings than rural settings, and as urban populations continue to grow, it is projected that by 2050 seven out of ten people in the world will live in urban environments (6). Ghana already has a highly urbanized population with 12.6 million people living in urban settings (5). In cities in low-income countries, high rates of urbanization are adding pressure to already stressed water and sanitation systems that are critical to the health of the urban communities. Cities served by piped water, sanitation, drainage, waste removal and a good health care system typically see childhood mortality rates of 10 per 1,000 live births, while the absence of those systems can increase childhood morality 10- to 20-fold (7). A portion of the 121 deaths per 1,000 live births in children under 5 years in sub-Saharan Africa and 74 deaths per 1,000 live births in Ghana could be averted with proper investment in water, sanitation, and drainage systems (2, 5).

People living in urban settings are commonly thought to have better access to sanitation compared to those in rural settings, but regional averages mask disparities in access to improved sanitation. In urban populations in sub-Saharan Africa, the richest residents are over twice as likely to have access to improved or shared facilities compared to the poorest residents (8). Poor urban residents in sub-Saharan Africa also commonly reside in slums that rarely have formal sanitation or drainage systems, and insecure tenure decreases the community's motivation to invest in infrastructure. Additionally, due to land restraints, urban households typically do not have space to install a household latrine and are forced to rely on public latrines. Public latrines are common in Ghana, and the county has the largest percentage of its population relying on shared facilities in the world (8). Shared facilities are often not conducive for young children to use because of the distance required to access them, large pit openings, and poorly maintained conditions (7). As a result, child feces frequently end up contaminating the environment creating a cyclic pattern of exposure to fecal microbes (Appendix A). Children that have become infected with enteric pathogens due to poor sanitation conditions then shed more pathogens into the environment. This creates settings where other children can become exposed and infected. Children are central to this exposure cycle because they engage in activities that expose themselves to fecal microbes, are more vulnerable to enteric infections than adults, and commonly do not have their feces disposed of properly (2).

Lack of access to improved sanitation, dysfunctional water and drainage systems, and crowded conditions create complex webs of fecal exposure pathways in urban environments. A resident of a city in a low-income county can be exposed to fecal pathogens through a variety of pathways and settings: recreational water, drinking water, floodwater, wastewater-irrigated crops, markets, school/nurseries, public latrines, flies, households, and open drains. These pathways can be classified into either the private or public domain (9). For city planning purposes it is most important to understand how exposure is occurring in the public domain because this is where the government can have the most impact. Knowing what the most contaminated pathways are and the numbers and types of people typically exposed to each pathway can help direct decision-makers when deciding how to most effectively invest limited resources.

C. Sanitation in Accra, Ghana: The Role of Open Drains

The availability of proper sanitation is limited for urban residents of Ghana; only 19 percent have access to improved facilities, while 73 percent use shared facilities, 2 percent use other types of unimproved facilities, and 6 percent practice open defecation (8). A large proportion of urban residents live in Accra, a coastal city with a population of 3.9 million people (10). In the Greater Accra Metropolitan Area (AMA), 41.3 percent of the population do not have access to sanitation facilities in their homes and rely on the use of public latrines (11). While reports have determined that only 4.3 percent of the population practices open defecation or uses bucket or pan latrines, observations of “flying toilets” (excreta in plastic bags) and open defecation at beaches suggest this number is much higher (11). In a more recent survey, almost one third of Accra residents reported relying on the pan/bucket system, and 4 percent said they use plastic bags, gutters, outdoor areas, or hole dug in the ground to dispose of feces (12). Regardless of the exact percentage, it is clear many people in Accra do not have access to proper sanitation facilities, and institutionalized open defection still exists.

Water treatment has been largely successful in Accra, but sewage treatment in the city has effectively stopped. The largest sewage treatment plant located at James Town/Korle

Lagoon has been non-functional since 2009, and while private or municipal tanker trucks collect sewage, the three government-sanctioned fecal sludge disposal sites discharge untreated sewage directly into the environment (13). The failure of these systems was reflected in a QMRA of the city that found the dysfunctional sanitation system in Accra accounted for 94 percent of all cases of diarrheal illness and 88 percent of all DALYs attributed to enteric infections resulting from the urban water and sanitation systems (14).

Inadequate access to improved sanitation facilities and the absence of sewage treatment increases the degree of fecal contamination in the city. One of the main outlets for improperly disposed of sewage in urban settings is the open drains network. Accra is comprised of a series of open drainage channels, most of which ultimately run into the Korle Lagoon and later the Atlantic Ocean. Small, tertiary drains run alongside of the roads or between houses. These merge into medium, secondary drains that eventually lead to large, primary drains that can be several meters wide. Recent investments in infrastructure have improved some of the tertiary drains, but the primary and secondary drains have largely been ignored, forcing some citizens to construct drains themselves (12, 13). In illegal settlements, community members construct all of the drains in the neighborhood themselves. Drains constructed by citizens instead of city engineers may be less structurally sound, more prone to blockages, and not built to have the water drain properly making it easier for community members to come into contact with the contents of the drains.

Open drains are intended to collect storm water, but they have also become an outlet for grey water, black water, and solid waste. Grey water from the nearby households and businesses enters the drains via gutters and through direct dumping of grey water into open drains. Over 50 percent of households dump their wastewater in open drains and just under 10 percent of households safely dispose of their wastewater in septic tanks (15). Black water enters the system via open defecation into the drains; by the emptying of children's potties, pan and bucket latrines into drains; and leaky septic tanks. Solid waste is also commonly found in the drainage channels, choking them and causing flooding even during moderate rains. In a survey facilitated by the World Bank in 2010, over 70 percent of citizens in Accra reported that the drains in their neighborhood are "always choked" or "often choked" (12). Given these conditions, it is not surprising that the citizens of Accra are highly dissatisfied with the current drain and gutter service in the city. Fewer than 30 percent of participants reported feeling satisfied with the service; in low service coverage areas, satisfaction fell below 20 percent (12). Drains and gutters were identified as the second highest service priority behind toilets and sanitation in the city outranking refuse and solid waste, water, public markets, basic education, and roads in their perceived priority for improvement (12).

Residents of Accra, especially children, can easily come into contact with the drains because they are rarely covered completely. Seventy percent of households in Accra reported that the drains in their neighborhood are uncovered and this concerns them (12). Very few households hire private companies to come clean the drains, subsequently adults and children clean out their household drain and are exposed to its contents. Direct exposure to open drains is most often experienced by children who may fall into the drains, enter them to retrieve a toy or ball, play in them, or scavenge them for trash or recyclable items.

D. Drainage Systems and Health

The current state of the drainage network in Accra is worrisome because drainage networks have been associated with poor health outcomes. Drainage systems have been associated with increased risk of exposure to fecal pathogens in two respects: 1) the absence of drainage systems increases the extent of environmental contamination, and 2) the presence of open drainage systems create spaces that are accessible to children and concentrate pathogens into one contaminated source.

Absence of drainage systems. The absence of proper drainage systems results in contaminated environments from storm water, grey water, feces, and solid waste (16). In urban neighborhoods in Salvador, Brazil lacking sewage systems, those with covered drainage channels had lower childhood diarrhea incidence rates then communities without drains (17). Communities with covered drains also had lower rates of nematode infections, which are not subject to observer bias as diarrhea is, further supporting the protective role of reduced exposure to drains (18). In both studies, children over one years old who were playing in the public domain were most affected by the absence of drains (17). Insufficient drainage networks have also been shown to elevate the risk of cholera outbreaks further demonstrating the protective role of drainage networks. In

Lusaka, Zambia, drainage networks that had less coverage and total length were associated with a higher incidence of cholera (19).

Presence of an open drainage system. Drainage systems are important to move storm and wastewater out of a neighborhood, but if uncovered and not properly maintained they can lead to poor health outcomes. In a longitudinal study of children living in urban Brazil, the presence of an open sewer near a household was associated with just under a 30 percent increase in the number of diarrhea episodes per child-year (20). The strongest association between number of diarrhea cases per year and the presence of open sewers was for children one to three years old (20). The authors hypothesized that this may be because these children are old enough to play in the public domain, but young enough that they still have poor hygiene. Additionally, in the same region, the presence of a drainage ditch close to a household was associated with a 0.89 day increase in the duration of a diarrheal episode (21).

Together, these results suggest that preschool age children are most affected by contaminated environments and drainage channels in the public domain. Extensive, covered drainage networks would be most effective in reducing childhood diarrheal incidence due to exposure to the drainage pathway.

E. Quantitative Microbial Risk Assessment of Wastewater Exposures

Quantitative microbial risk assessment (QMRA) is one strategy that has been employed to try to quantify the risk of exposure to wastewater. QMRA was developed to determine the risk associated with different exposures, taking into account pathogen concentration and frequency and duration of human exposure activities (22). The strategy is advantageous because it can estimate low levels of risk and disease, enables comparison of different exposure routes, and is a relatively low-cost method (23). However, the validity of QMRA models is contingent on appropriate model inputs, and validated data inputs are often not available for every exposure scenario of concern. Exposure parameters are frequently based on observed behavior and environmental conditions in high-income countries. The application of these inputs to models addressing exposure in low-income countries is problematic and has highlighted the need for exposure data from low-income countries.

Despite its limitations, QMRA is the current WHO-recommended strategy for guiding decision-makers in planning successful and cost-effective sanitation interventions (18). The method has been used to quantify enteric disease risk from drainage channels in numerous settings, usually focusing on occupational hazards to farmers and risks to consumers of wastewater-irrigated produce. Additional studies have also looked at recreational swimming in large canal networks. These studies are expounded upon below.

In Accra, there have been numerous studies documenting the risks associated with urban agriculture. Irrigation water from drains is highly contaminated, and exposure to drain water posed more risk than when streams or piped water was used for irrigation (24). Fecal coliform levels in drain water varied from $9x10^2$ to $1x10^8$ cfu per 100ml (24-27).

This exceeds the WHO recommended level of $1x10^3$ fecal coliforms cfu per 100ml of water for unrestricted irrigation. High levels of contamination in urban drainage channels have also been observed in other cities. In peri-urban Thailand, exposure to the urban cannel network via recreational swimming, farming, and eating raw vegetables grown along the canal's banks were all associated with average yearly risks of Cryptosporidium, Giardia, and diarrhegenic *E. coli* infection over 6000-fold greater than the benchmarked yearly infection rate (<1 infection/10,000 individuals) (28, 29). Additionally, further assessment of the same area examined wastewater exposure from collecting vegetables along the canal banks and bathing in canal water found mean *Giardia lamblia* and *Entamoeba histolytica* infection risks to range from 44-100% for a single exposure (30).

These previous assessments of exposure to wastewater have demonstrated that urban drainage channels are highly contaminated with fecal contam, and exposure from common activities taking place at drains is not negligible. However, exposure activities that children in urban communities participate in have different characteristics than exposure due to urban farming or recreational swimming. Children exposed to drains will rarely have more than their hands or feet exposed to the contents of the drain, unlike in swimming activities that involve full body contact. Additionally, farmers deliberately handle drain water while irrigating crops, but children's exposure to drain contents is usually accidental due to their proximity to drains while playing. Risk assessments that specifically examine children's exposure to drain water in urban communities are needed to determine how much risk open drains pose to this population.

Recently, two QMRAs were conducted to quantify the burden of disease caused by the urban water and sanitation systems in Accra. Open drains were identified as the most hazardous and second most hazardous pathway in these assessments highlighting the importance of the open drains as an exposure pathway (14, 31). Open drains were predicted to cause 64 percent of all cases of diarrheal illness attributed to the water and sanitation system per year (120,468 cases) and 62 percent of all DALYs per year (22,328 DALYs) (14). Covering the open drains was identified as the most cost effective strategy to reduce DALYs. This intervention was predicted to reduce the total number of DALYs each year by about 50 percent and remove all but eight percent of the DALYs attributed to the open drains pathway (14). While the two studies provided a good estimate of the disease burden associated with open drains in Accra, they both made key assumptions about the concentration of pathogens in open drains and to what extent children are exposed to open drains. These limitations are discussed in the paragraphs below.

Limitations in microbe concentration estimation. The Lumani 2007 QMRA did not conduct environmental sampling of open drains and assumed that microbe concentrations in open drains were equal to concentrations in the Odaw River (6.09 $\log_{10}$ cfu/100ml). It is likely that contamination levels in the Odaw River are an underestimation of the microbe concentrations of open drains because in addition to inputs from households, the river also receives naturally occurring environmental inputs that dilute pathogen concentrations in the water. The QMRA by Labite and colleagues collected 36 environmental samples of open drains in two low-income neighborhoods, Nima and Jamestown. Samples were tested for *E. coli*, total coliforms, *Salmonella*, other

Enterobacteriaceae, and helminth eggs. The arithmetic mean of the *E. coli* concentrations from the open drain samples was 8.0 $\log_{10}$ cfu/100ml confirming that the concentration used by Lumani was an underestimation. This may be one reason why the Labite QMRA found open drains to be the most hazardous pathway while the Lumani QMRA found recreational swimming to be most hazardous. Both studies used [*E. coli*]: [pathogen] ratios to estimate the concentration of human pathogens in drain water used for the risk assessment (32, 33). The application of [*E. coli*]: [pathogen] ratios established from studies in other settings, especially those in high-income countries and rural areas, are questionable in a QMRA for an urban area in a low-income setting.

Limitations in exposure assessment. Both QMRAs assumed that children playing near open drainage channels ingested 5ml of water and played by drains four times a year. This assumption was based on a study of children playing near a wetland inlet in Sweden (34). The environment and behavior of children living in a low-income urban environment is likely to be different than that of children in a high-income country where the exposure parameter was determined. Additionally, based on observations of open drains in Accra, drain water is rarely ingested directly, as in recreational swimming, but occurs indirectly via hands or fomites. Failure to consider and account for these transfer events may over estimate the amount of exposure that occurs in this setting.

Limitations in the model structure. The QMRAs by Lumani and Labite et al. used point estimates that do not take into account uncertainty distributions inherent in these estimates. Monte Carlo analysis was recommended for future studies by the researchers.

F. Study Objectives

Previous studies identified the importance of open drains as a fecal exposure pathway in low-income urban settings. Limitations in previous estimates of the risk associated with this pathway motivated this study to examine in more depth the open drains exposure pathway. The goal of the study was threefold:

1) Characterize the drainage networks in four low-resource neighborhoods in Accra, Ghana in terms of size, structural composition, water flow, and spatial configuration in the neighborhood.
2) Determine if the location and type of drain affected the level of fecal contamination in the drain and extent of children's exposure to the drain.
3) Estimate the risk of exposure to fecal contamination via open drains from common activities in the study neighborhoods.

The results of this study can be used to raise awareness about the importance of open drains for the health of urban community members, especially children. The results can also be used by decision-makers to inform development of targeted interventions to reduce exposure to fecal contamination from open drains through the identification of the location and characteristics of high-risk drains.

II. MANUSCRIPT

A. Introduction

The global community is becoming more urban. Currently more of the world's population live in urban settings than rural settings, and by 2050, it is projected that seven out of ten people in the world will live in urban settings (6). Africa in particular is expected to have high urbanization rates (10), adding pressure to already stressed water and sanitation systems that are critical to the health of urban communities. Cities served by piped water, sanitation, drainage, waste removal, and a good health care system typically see childhood mortality rates of 10 per 1,000 live births, while the absence of those systems can increase childhood morality 10- to 20-fold (7). Lack of access to improved sanitation, dysfunctional water and drainage systems, and crowded living conditions create complex webs of fecal exposure pathways in urban environments. Identifying the most contaminated pathways and the numbers and types of people typically exposed to these pathways can help direct decision-makers when considering how to most effectively invest limited resources.

In Accra, Ghana access to improved sanitation is still elusive for many residents, especially those living in low-income neighborhoods (11, 12). The inability of many residents to access improved sanitation facilities, coupled with limited sewage collection and the absence of sewage treatment in the city (13), has resulted in improperly disposed sewage contaminating the urban environment. Open drains have become the main outlet for this waste. The drainage network is intended to collect storm water, but grey water, black water, and solid waste are frequently disposed of in the drains (12, 15). Residents of Accra, especially children, can easily come into contact with the drains because they are rarely covered completely (12). Direct exposure to open drains is most often experienced by children who may fall into the drains, enter them to retrieve a toy, or scavenge in them for trash. The state of the drainage system in Accra is serious public health concern because both the absence of covered drainage systems (17-19) and the presence of uncovered drainage ditches (20, 21) can increase the risk of exposure to fecal contamination and subsequent risk of enteric infection.

Quantitative Microbial Risk Assessment (QMRA) is one strategy that has been employed to try to quantify the risk of exposure to wastewater. Previous QMRAs conducted in Accra have focused on quantifying the occupational hazard to farmers and risks to consumers of wastewater-irrigated produce. These studies have demonstrated that open drains in the city are highly contaminated with fecal microbes and pose an unacceptable level of risk to these two groups (24-27). A recent QMRA identified open drains as the most hazardous exposure in Accra. Open drains were predicted to cause 64 percent of all cases of diarrheal illness and 62 percent of all DALYs attributed to the inadequate water and sanitation system per year (14). While the study provided a solid foundation for the estimate of the disease burden associated with open drains in Accra, key assumptions pertaining to concentrations of fecal microbes and exposure assessment parameters, and the use of a deterministic model, merit further investigation into this environmental health risk. The goal of the study was threefold:

1) Characterize the drainage networks in four low-resource neighborhoods in Accra, Ghana in terms of size, structural composition, water flow, and spatial configuration in the neighborhood.
2) Determine if the location and type of drain affect the level of fecal contamination in the drain and extent of children's exposure to the drain.
3) Estimate the risk of exposure to fecal contamination via open drains from common activities in the study neighborhoods.

B. Methods

The study was conducted from July 2011 to November 2012 in four low-resource neighborhoods in Accra, Ghana. Activities pertinent to this analysis were: 1) a household survey of demographics and WASH practices, 2) mapping of open drains and data collection sites, 3) characterization of open drains, 4) structured observations of children's activities in open drains, and 5) environmental sampling and testing of water samples collected from open drains. The researcher was added to an existing protocol (IRB00051584) previously approved by Emory University's Institutional Review Board.

i. Study Site

Neighborhood Selection

Four low-resource neighborhoods located in the Accra Metropolitan Area (AMA) were selected for study: Alajo, Bukom, Old Fadama, and Shiabu (Figure 2.1). Neighborhoods were selected based on a set of population and physical characteristic criteria described in Table 2.1. Other secondary selection criteria considered included logistics, the receptiveness of community members, and the safety of the study team. All neighborhoods were assumed to have schools, public latrines, and varying levels of latrine coverage.

Neighborhood Characteristics

Alajo, the wealthiest of the neighborhoods studied, is situated the furthest inland of the coastline and is bordered by the Odaw River and one of its tributaries that were cemented by the city government in 2002. Alajo has one small market in the southern part of the community and an industrial area and urban agricultural area in the northern quarter. Bukom is a coastal community situated in downtown Accra. Infrastructure from an English settlement built in the late nineteenth century still remains, although substantial updates have not been made since that time. The streets of Bukom are very crowded and lined with vendors set up over the drains. In addition, activities such as cooking and washing often overflow from the households into the street. The third neighborhood, Old Fadama is an illegal settlement, and as such it has the least developed drainage system. The large Agbogbloshi Market, where many of the residents work, borders the northeast part of the neighborhood. Almost all of the residents have to rely on public latrines and bathhouses. The final neighborhood studied was Shiabu, another costal community west of the city center. The makeup of the community is diverse with informal/squatter housing near the beach and gated houses with piped sewage in the northern region, although the sewage treatment plant for the area is no longer functional.

ii. Data Collection

All data collection was facilitated by community liaisons who had intimate knowledge of the neighborhood and helped guide the selection of sampling sites.

Household Survey:

A household survey was conducted in each neighborhood from August to September 2012 by enumerators at the TREND Group. Survey topics of interest to this study included demographic information, sanitation and hygiene practices, access to WASH facilities, disposal of child feces, and disposal of rubbish (Appendix B). Surveys were given in the afternoon to the household member that was present and willing to participate.

Open Drain Characteristics

Characterization of open drains took place from June to July 2012. Each neighborhood was canvased on foot, and all accessible drains were characterized. A drain characterization tool (Appendix C) was completed at the beginning, ending, merging, and other key points along each drain (e.g. points where water flow changed direction, formal construction of drains ended, etc.). Descriptions recorded were size: small (<0.5m), medium (0.5-1m), large (1-3m), or extra-large (>3m); location of the drain: side of road or between buildings; neighborhood environment surrounding the drain: school, homes, businesses, agriculture, vendor stand, water pipes, latrine, or bathing facility; water level: dry, low (mostly dry, small stream), medium (most contents are suspended in water), high (obviously high water level, near top or overflowing), or unable to see; water flow:

stagnant, moving, or unable to see; cardinal direction of water flow; scale of drain coverage by the city and citizens: uncovered, only a few areas covered, about 50 percent coverage, about 75 percent coverage, almost all of the drain is covered, or completely covered; construction type: ecological (dirt lined with no formal planning), formal by city (cement or stone lined that were intentionally constructed by the city government), or formal by citizens (cement or stone lined that were intentionally constructed by citizens); and composition of the lining: cement, dirt, stone, or mixed. Pictorial examples of drain size, water level, coverage, and construction type are presented in Appendix D.

Structured Observations

Enumerators from the TREND Group conducted structured observations of open drains from March to November 2012. In each neighborhood, enumerators selected a small, medium, and large drain to observe for an hour each. Enumerators were instructed to choose a vantage point away from the drain to minimize the influence their presence may have on the behavior of the community members. The frequencies of children under 5 years old and children 5 to 12 years old observed going inside the drain or defecating into/inside the drain 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 their body went beyond the perimeter of the drain. At the beginning of each hour, drain descriptions were recorded indicating the construction type, water level, water movement, and neighborhood environment as characterized in the drain characterization tool. All drain description and observation data was recorded on the Drain Description and Conditions: Structured Observation Form (Appendix E).

Environmental Samples

Three environmental water samples from open drains were collected once monthly in each neighborhood from March to November 2012 by study staff at the Water Research Institute (WRI). In each sampling round, the study team typically collected a sample from a small, medium, and large drain. Samples were collected using sterile technique in 500mL Whirl-Pak® (Nasco, Fort Atkinson, WI) bags and stored on ice until they were returned to WRI. A Small Volume Environmental Water: Environmental Sample Collection Form was also completed at the time of sampling to record the conditions of the drain at the time of sampling (Appendix F).

iii. Data Management

All paper forms completed in the field were entered into a central Access database (Microsoft, Redmond, WA) managed by the study team. Double entry of 25 percent of all forms was completed to ensure data quality.

iv. Laboratory Methods

Technicians at WRI processed environmental water samples the day of collection. *E. coli* and coliphage assays using 100 μl of three serial dilutions: 10^{-5}, 10^{-6}, and 10^{-7} were tested according to EPA method 1604 (35) and EPA method 1601 (36).

v. Spatial Analysis

A Garmin Global Positioning System (GPS) unit (Etrex Venture HC) with 1-meter resolution and 30 averaged points was used to record the location of each environmental sample and structured observation. The study staff also recorded coordinates of key locations in the neighborhood including public latrines, schools, and markets. Mapping the open drains network in each neighborhood took place in conjunction with the drain characterization survey. GPS coordinates were captured at each location where a characterization form was completed. Additional coordinates were taken as needed to provide the necessary spatial data to reconstruct the drainage networks digitally.

Initially, open drain lines from the drain mapping activity were digitized in Google Earth (Google, Inc., Mountain View, CA). The digitized lines were then transferred into ArcGIS 10.1 (ESRI, Redlands, CA). All other spatial data were directly imported into ArcGIS. All spatial data were projected in Universal Transverse Mercator (UTM), Zone 30 north for analysis. Behavioral and microbial samples were joined to the drain network based on closest Euclidian distance.

ArcGIS was used to characterize the drains in terms of total drain length, neighborhood area, and spatial proximity to key neighborhood locations. Neighborhood area and total drain distance were used to calculate the density of drains (m/km^2) in each neighborhood. Drain characterization data was weighted by the total length of drains in each neighborhood to obtain the percentage of the total drain network with each characteristic (size, construction type, water level and coverage).

vi. Statistical Methods

Statistical analyses were conducted in SAS 9.3 (SAS, Cary, NC). All statistical tests were evaluated at an alpha level of 0.05. The rates of children observed per hour in drains and defecating into/inside of drains were calculated. Each recorded count from the structured observation was assumed to represent a unique child. Poisson regression models of both activities listed above stratified by child's age, neighborhood, drain size, and drain construction type were fitted to determine if there were differences in the rates of children observed doing each activity.

The total volume of the three environmental sample dilutions was used to determine the final microbial indicator concentration of each sample. Indicator concentrations below the limit of detection were given a value of negative square root two. The final *E. coli* and coliphage concentrations were log-transformed, and the geometric mean, standard deviation, minimum, and maximum were calculated. *E.* coli and coliphage concentrations were analyzed with analysis of variance to determine if significant differences among neighborhoods and drain size existed. Indicator concentrations were also analyzed with two-sample t-tests to determine if there were significant differences in drain construction and drain coverage. Kernel density plots of both *E. coli* and coliphage concentrations for each of the above characteristics were constructed.

vii. Exposure Assessment

Exposure Scenarios:

Based on structured observations of open drains conducted in Accra, six exposure scenarios were identified. Exposure scenario A involved children under 5 years old incidentally entering the drain and directly contacting drain water with their hands. Exposure scenario B involved children 5 to 12 years old doing the same activity. Exposure scenario C involved children under 5 years old incidentally entering the drain to retrieve an object. Exposure scenario D involved children 5 to 12 years old also incidentally entering the drain to retrieve an object. Incidental entry scenarios (A–D) were based on observations of children falling into drains or entering drains to retrieve an object that had fallen inside (Figure 2.2). Exposure scenario E involved children under 5 years old purposefully entering a drain for a period of time during which their hands could come into contact drain water. Exposure scenario F involved children 5 to 12 years old doing the same activity. The instrumental entry scenarios (E and F) were based on observations of children playing in the drains or walking in drains to collect trash or recyclable items (Figures 2.3, 2.4). In all scenarios, we assumed ingestion of drain water resulted from hand mouthing events. Direct ingestion of a small volume of drain water was only assumed to occur during instrumental drain entry (Figure 2.5).

Model Parameters:

Model parameters and key assumptions are presented in Table 2.2 for the hand contamination distributions and Table 2.3 for the exposure dose distributions. Model parameters were generated in R 2.14.2 (Vienna, Austria). Point estimates were used to describe the transfer efficiency of microbes from objects to hands and hands to mouth (37). The estimated duration of time spent in a drain was based on a competing hazards model: when a child is in any given state (engaged in a given activity in a given compartment) it remains in that state for a certain period of time. During that period, all other behaviors in its repertoire (the complete set of its behaviors) compete for becoming the next state the child will move into, each with its own hazard rate. These hazard rates were estimated from observed durations of activities (of children less than 5 years old in households/nurseries), assuming a Weibull hazard model with shape factor adjusted (to values greater than two) to prevent very short durations. Hazard rate estimates were stratified by neighborhood and compartment (only drains for the present analysis). Ten thousand simulated durations were generated first by generating random walks through all possible activity states for any individual child and then selecting the durations of play/sit activity in drains. It was assumed that the duration of time a child spent in a drain was the same for all neighborhoods and for children of all ages. The simulated durations for Alajo were used for this analysis.

For the remaining parameters, 10,000 Monte Carlo simulations were generated to describe the distribution of each parameter. A log-normal distribution was used to describe the initial coliphage and *E. coli* concentrations in drain water. The generated concentrations were transformed back to the ordinal scale for the analysis. To describe the frequency of hand contact with drain water per drain entry event during instrumental entry, a Poisson distribution of the period of time spent in the drains calculated above multiplied by an assumed five drain contact events per hour was used. This produced a discrete distribution of the number of hand contact events. To describe the frequency of hand or object contact with drain water per drain entry event during incidental entry, a Poisson distribution with a value of one was fitted. To ensure at least one contact event occurred for each drain entry event, the distribution was resampled until all zero values were replaced.

To determine the volume of drain water loaded on hands, three parameters were used: 1) surface area of hands or object; 2) percent of the hands or object contacted by drain water, hands, and mouth; and 3) thickness of the drain water film on hands or object. The surface area of children's hands were described by a uniform distribution with the lower and upper bound representing the 5th and 95th percentile of body surface area for male and female children (38). A non-porous ball represented the typical object retrieved, and a uniform distribution with the upper bound equal to the surface area of a regulation soccer ball and the lower bound equal to the surface area of a ball half the size of a soccer ball was fitted. The percent of hands that contacted drain water was given a uniform distribution based on observations of children contacting non-dietary water (39). The percent of an object contacting drain water was given a uniform distribution under the assumption that at least 25 percent of the object would come into contact with drain water. The percent of hands contacting an object was given a uniform distribution with the upper and lower bounds determined from observations of children playing with toys outside (39). The thickness of the film of drain water left on the hands or object was assumed to be the same given the hydrophilic properties of hands and non-porous objects. This parameter was described by a uniform distribution with the upper bound representing immersion into water with no wiping afterwards and the lower bound representing immersion into water followed by partial wiping (40).

Finally, parameters used to describe the transfer of microbes between hand and mouth included the percent of the hand contacting the mouth, the frequency of hand mouthing by age group, and the time until hand washing. The percent of the hand contacting the mouth was uniformly distributed based on observations of child hand mouthing in an outdoor setting (41). The final dose was assumed to be additive based on the frequency of hand mouthing events. The frequency of hand mouthing for children under 5 years old and children 5 to 12 years old was described by a Weibull distribution with equal mouthing frequencies for male and female children (42, 43). Lastly, the time until hand washing occurred removing all microbes loaded on hands was given an uniform distribution based on the assumption that children are awake for 16 hours a day and wash their hands 3.9 times a day with hand washing equally likely to occur any time throughout the day (44). The inactivation of microbes on hands or objects was not considered in this analysis nor was the decay of microbes present on hands following mouthing events.

Model Equations:

Three 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 exposure dose for each exposure scenario. These equations were based on equations previously derived to describe surface loading of chemicals on hands (45).

The distribution of hand contamination (number of microbes transferred directly from drain to hand) is proportional to the initial concentration of microbes in drain water (C_x), the frequency of hand contact with the drain ($D_{Is} \times T_x$ for instrumental entry, D_{Ic} for incidental entry), the surface area of the hand contacting the drain water ($A_x \times S_{HDW}$), and the thickness of the water film left on the hand (V).

(1) $$E_x = \begin{bmatrix} C_c \\ \text{or} \\ C_{ec} \end{bmatrix} \times \begin{bmatrix} D_{Is} \times T_{Is} \\ \text{or} \\ D_{Ic} \end{bmatrix} \times \begin{bmatrix} A_5 \\ \text{or} \\ A_{12} \end{bmatrix} \times S_{HDW} \times V$$

The distribution of hand contamination though an object (number of microbes transferred from drain to object to hand) is proportional to the initial concentration of microbes in the drain (C_x), the frequency of object contact with the drain (O_{Ic}), the surface area of the object contacting the drain water ($A_O \times S_{ODW}$), the thickness of the water film left on the object (V), the proportion of the object that the hand contacts ($A_x \times S_{OH}/A_O \times S_{ODW}$), and the transfer efficiency of microbes between the object and hand (TE_{Ox}).

(2) $$E_x = \begin{bmatrix} C_c \\ \text{or} \\ C_{ec} \end{bmatrix} \times O_{Ic} \times A_O \times S_{ODW} \times V \times \left(\frac{\begin{bmatrix} A_5 \\ \text{or} \\ A_{12} \end{bmatrix} \times S_{OH}}{A_O \times S_{ODW}} \right) \times \begin{bmatrix} TE_{Oc} \\ \text{or} \\ TE_{Oec} \end{bmatrix}$$

The hand-to-mouth dose distribution is proportional to the number of microbes on the hand (as determined by the distribution of hand contamination, E_x, calculated in equations 1 and 2), the frequency of hand mouthing (HM_x), the percent of the hand contacting the mouth (S_{HM}), the transfer efficiency of microbes between the hand and mouth (TE_{Hx}), and the time until hand washing (T_{HW}).

(3)
$$D_x = \begin{bmatrix} E_{Ac} & & E_{Aec} \\ \text{or} & & \text{or} \\ E_{Bc} & & E_{Bec} \\ \text{or} & & \text{or} \\ E_{Cc} & & E_{Cec} \\ \text{or} & \text{or} & \text{or} \\ E_{Dc} & & E_{Dec} \\ \text{or} & & \text{or} \\ E_{Ec} & & E_{Eec} \\ \text{or} & & \text{or} \\ E_{Fc} & & E_{Fec} \end{bmatrix} \times \begin{bmatrix} HM_5 \\ \text{or} \\ HM_{12} \end{bmatrix} \times S_{HM} \times \begin{bmatrix} TE_{Hc} \\ \text{or} \\ TE_{Hec} \end{bmatrix} \times T_{HW}$$

For scenarios A-D (incidental drain entry), the final exposure dose was generated by equation 3. For scenarios E and F (instrumental drain entry), it was assumed that all children additionally ingested a droplet of drain water. This residual exposure dose distribution for instrumental entry is proportional to the initial concentration of microbes in drain water (C_x) and the volume of one droplet of water (0.05mL).

(4)
$$R_x = \begin{bmatrix} C_c \\ \text{or} \\ C_{ec} \end{bmatrix} \times 0.05\text{mL}$$

The final exposure dose for these two scenarios was the sum of the hand-mouth dose generated by equation 3 and the residual exposure dose generated by equation 4.

Comparison of Exposure Doses

To compare the exposure dose distributions between different initial microbial concentrations in drain water and different exposure scenarios, pairwise comparisons were made by subtracting the log-transformed exposure dose distributions. This method is equivalent to performing a pairwise non-parametric t-test where the percentage of the differences that are greater than zero indicates the level of significance (46). Six pairwise comparisons of the exposure dose distributions were calculated: 1) *E. coli* concentrations minus coliphage concentrations, 2) *E. coli* concentrations found in drains that were originally rivers/lagoons minus *E. coli* concentrations in all other drains, 3) children under 5 years old minus children 5 to 12 years old, 4) incidental drain entry with direct hand-drain water contact minus incidental drain entry to retrieve an object, 5) incidental drain entry with direct hand-drain water contact minus instrumental drain entry, and 6) instrumental drain entry minus incidental drain entry to retrieve an object..

Comparison of Calculated Exposure Doses to Previous Exposure Estimates

Exposure doses calculated in this study were compared to the exposure doses that would have been used if every child directly ingested 5mL of drain water per exposure event as assumed in previous studies (14, 31). The distributions of exposure doses based on direct ingestion of 5mL of drain water were calculated for *E. coli* and coliphage by multiplying the initial concentration of microbes in drain water (C_x) by 5mL. Pairwise comparisons, as described above, were calculated by subtracting the exposure dose based on previous estimates with each of the three drain exposure activities modeled in this study.

C. Results

i. Neighborhood Demographics and Sanitation Practices

Two hundred household surveys were conducted in each of the four study neighborhoods (Figure 3.1). Reported demographic characteristics for each neighborhood are presented in Table 3.1. Bukom had the highest percentage of respondents reporting homeownership reflective of the old, established nature of the neighborhood. Unlike the other three neighborhoods, homeownership in Old Fadama only indicates the tenant owns the housing structure and not the land the house is built on because the neighborhood is a squatter settlement on government land. The dominant religion in Alajo, Bukom, and Shiabu is Christianity, while Islam dominates in Old Fadama. Old Fadama had the lowest levels of education with over 40 percent of respondents reporting no formal education. In comparison, Alajo and Shiabu had the highest rates of education reported; about 40 percent of the respondents reported completing secondary school or higher. Across all the neighborhoods, reported household size varied between four to five people and on average children under 5 years old and children 5 to 12 years old were reported in at least half of the households. In all neighborhoods, at least 10 percent of the observed children in surveyed households had diarrhea in the past two weeks. The highest percentage of children with reported diarrhea was in Old Fadama where 25 percent of the observed children had diarrhea in the past two weeks.

Access to improved sanitation facilities (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) and practices of child feces disposal varied across neighborhoods

(Table 3.2). Almost no one in Bukom or Old Fadama reported having access to a toilet in her or his housing compound, and very few people reported never using a public latrine. Alternatively, sanitation access in Alajo and Shiabu was varied. An improved toilet was reported in over half of all respondents' housing compounds in Alajo, and just as many respondents reported never using a public latrine. Residents of Shiabu also had greater access to improved toilets in housing compounds; just over 40 percent of households reported having an improved toilet in their compound. In all neighborhoods, the percentage of households with no access to a toilet was greater than the percentage of respondents who reported using a public latrine every day. The location of where people who do not have a compound sanitation facility and do not use public latrines everyday go to take care of their daily sanitation needs is unknown. Feces disposal for the youngest child in the household was most commonly reported to be with the rubbish. Depending on the rubbish disposal practice, child feces may end up in drains, the ocean, or other places in the neighborhood. In every study neighborhood, there were some households that reported disposing child feces directly into a drain; this practice was most commonly reported (11.1%) in Old Fadama.

Households in Old Fadama were at least twice as likely to report not having a drain near their home compared to households in Alajo, Bukom, and Shiabu (Table 3.3). In all study neighborhoods, children were more often seen defecating in drains every day than adults. Defecation in drains was least common in Shiabu where survey respondents reported that both and children and adults were never seen defecating in a household drain. Reported drain defection was most common in Old Fadama; 22.0% and 14.8% of respondents reported seeing children and adults defecating every day in a drain near their household respectively. Similar rates of reported child and adult defection into drains were reported in Bukom (Table 3.3).

ii. Open Drain Characteristics

General characteristics

Alajo had an extensive drainage network, with formal cement lined drains that not only lined all of the streets but penetrated into residential areas as well. The drains that penetrated into the residential areas were constructed by the residents and were usually small in size but were heavily used with multiple bathhouses connected to them. The Odaw River and one of its tributaries bordered the neighborhood on two sides.

In Bukom, colonial English settlement had left an extensive network of drains that lined the streets of the neighborhood. There was one large drain that ran through the neighborhood and terminated into the Korle Lagoon. Excluding the drains near the beach, all of the drains in the community flowed to this large, terminal drain. In the beach area, one terminal drain received all of the other drains and terminated directly into the sea, where offshore fisherman worked. A market area in the neighborhood had drains on either side of the streets. These drains were choked with trash and would occasionally overflow when it rained.

Old Fadama was situated just upstream of the Korle Lagoon where a majority of the drains in Accra terminate. The two large drains that make up the other boundaries of the neighborhood are heavily polluted with solid waste, and feces are commonly observed along their banks. One of these drains is the downstream portion of the Odaw River that borders Alajo. Almost all of the drains were ecologically formed and later enhanced with stones or wood by residents. It was common for drains to be covered up by wooden housing structures as the community grew. There were some cement lined drains in the neighborhood, and those tended to be closer towards the street where the neighborhood was further established.

The Chemu lagoon bordered Shiabu on the east, and the upper region of the river was recently cemented in 2010. The Chemu lagoon was heavy polluted with solid waste, and animal and human feces were commonly seen on its banks. Children had also been observed playing in and around the lagoon. The drainage network in the neighborhood was currently being developed, as evidenced by new and partially completed drains that lined the roads. However, it appeared that many of the drains in the community were not properly constructed, because the water in many of the drains rarely flowed unless it rained heavily. The drains near the beach are usually clogged with sand or silt. Away from the beach, there are many housing compounds and businesses that have connected their wastewater pipes directly to the drains on the street.

Specific characteristics

Observed characteristics of the open drains network in each neighborhood are presented in Table 3.4. Bukom had the densest drain network, followed by Alajo and Shiabu and finally Old Fadama with the fewest drains per square kilometer. The calculated drain density is consistent with reports of how frequently drains were observed near households in the household survey (Table 3.3). In Alajo, Bukom, and Shiabu, drain construction was primarily done by the city, however, in Old Fadama, all but one drain was ecologically formed or constructed by citizens (Figure 3.2).

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 larger in size and shallow. As such, over 50 percent of the drains present in Alajo, Bukom, and Shiabu were medium in size (Figure 3.3). Extra-large drains that were rivers or lagoons bordered three of the neighborhoods: Alajo, Old Fadama, and Shiabu (Figure 3.3).

In all study neighborhoods, citizens were observed to commonly cover drains (Figure 3.4). Drain coverage by the city was most common in Shiabu with 64.7% coverage by the city. This may be a product of the recent government investment in drainage infrastructure in the neighborhood. Old Fadama had the largest percentage of the drainage network with no coverage; over half the entire drain network was left uncovered. Low levels of coverage provide more opportunities for children enter the drains.

In all study neighborhoods, the observed water level was most commonly medium or low (Figure 3.5). High water levels in drains were not commonly observed in Alajo and Shiabu, and these neighborhoods also had the highest percentage of dry drains. In Old Fadama, where the fewest drains were observed, over 35 percent of the drain network was observed to have a high water level, and less than 1 percent of the network had no water in the drains. High water levels may indicate improper construction, blockages, or heavily used areas of the network.

iii. Observed Behavior of Children Around Open Drains

In total, 45 structured observations of children's behavior around open drains were conducted; 33 observations had GPS coordinates (Figure 3.6). Regardless of the age of the child, children were more frequently observed inside a drain than defecting into/inside a drain. The rate of children in drains per hour of observation time was not significantly different based on the estimated age of the child (Table 3.5). However, children under 5 years old were observed defecating into/inside of a drain three times more often than children 5 to 12 years old (p-value=0.002) (Table 3.5). The rate of children under 5 years old that were observed in drains was significantly lower in Alajo, Bukom, and Shiabu compared to Old Fadama (Table 3.6). On average 3.5 children per hour were observed in drains in Old Fadama, while less than one child per hour was observed in Alajo, Bukom, and Shiabu. The rate of children under 5 years old observed in drains was also significantly lower for small and medium drains compared to large drains, and was lower for formal drains compared to ecological drains (Table 3.6). All but one observation of children under 5 years old defecating into/inside of drains took place in large, ecologically formed drains in Old Fadama. One additional observation of defecation occurred in a small, formally constructed drain in Bukom.

The rates of children 5 to 12 years old observed in a drain per hour were significantly lower in Bukom compared to Alajo, Old Fadama, and Shiabu (Table 3.7). One to two children were observed in a drain per hour in Alajo, Old Fadama, and Shiabu while one child was observed in Bukom for every two hours. The rate of children 5 to 12 years old observed in small drains was less than twice the rate of children observed in large drains. There was no difference in the observed rates of drain entry based on drain construction. Defecation into/inside of drains for children 5 to 12 years old was observed only in large drains. No defecation was observed in Shiabu, and rates of observed defecation did not differ between the other three neighborhoods. Observed rates of defecation also did not differ by drain construction type.

iv. Microbial Concentrations in Open Drains

There were 86 water samples from open drains tested for *E. coli*, and 42 water samples tested for coliphage (Figure 3.7). The concentrations of coliphage in the open drain water samples were consistently lower than the *E. coli* concentrations across all categories. The overall geometric mean of the *E. coli* concentration in the open drain water samples was 8.20 cfu $\log_{10}$/100ml, and the overall geometric mean coliphage concentration was 4.61 pfu $\log_{10}$/100ml. Water samples from drains that were originally rivers or lagoons (all of the extra-large drains) had *E. coli* concentrations that were significantly lower than water samples that were taken from drains that only functioned as drains (p-value=0.028) (Figure 3.8). Rivers or lagoons had a geometric mean *E. coli* concentration of 6.99 cfu $\log_{10}$/100ml, while drains that were not rivers or lagoons had a geometric mean *E. coli* concentration of 8.44 cfu $\log_{10}$/100ml (Table 3.8). There was no significant difference in coliphage concentrations between drains that were originally rivers or lagoons and those that were not (Table 3.9).

To assess differences in microbial concentrations between other neighborhood and drain characteristics, samples from drains that were originally rivers or lagoons were removed from the analysis to eliminate any biases those samples might introduce. The resulting 72 drain water samples tested for *E. coli* and 35 drain water samples tested for coliphage were analyzed. For these samples, the *E. coli* and coliphage concentrations of drain water samples did not significantly differ by neighborhood or drain size, construction type, or coverage (Tables 3.8, 3.9).

v. Exposure Assessment

The geometric mean, median, and 95 percent range for the final coliphage and *E. coli* exposure doses are presented in Table 3.10. Scenario A resulted in the greatest exposure to fecal microbes in drain water. The coliphage doses had a median value of 35.46 pfu, while *E. coli* doses had a median value of 1.21×10^5 cfu. Scenario D resulted in the lowest exposure to microbes present in drain water with a median value of 2.88 coliphage pfu ingested and 2.42×10^4 *E. coli* cfu ingested. In general, the log-transformed exposure dose distributions for the three different exposure activities (incidental entry with direct hand-drain water contact, incidental entry to retrieve an object, and instrumental entry) had a normal shape, with the coliphage doses centering around 1.0 log pfu and the *E. coli* doses centering around 4.5 log cfu (Figure 3.9).

Although the coliphage and *E. coli* concentrations in drain water were previously found to be significantly different, the exposure dose distributions for the two microbes differed only by 86.23%. Similarly, while the *E. coli* concentrations in drains that were rivers/lagoons and the *E. coli* concentrations in all other drains had differed significantly, the exposure dose distributions only differed by 65.18%. The final exposure doses for children under 5 years old were slightly higher than the exposure doses for children 5 to 12 years old due to the increased mouthing frequencies in young children, but the differences in the log-transformed exposure doses were not significant (Table 3.11). The log-transformed distributions in the coliphage and *E. coli* exposure doses between incidental entry with hand contact and instrumental entry were almost identical, differing by only 0.04 log pfu and cfu. The log-transformed coliphage and *E. coli* exposure dose distributions for incidental entry with hand-drain water contact were 0.90 pfu and 0.53 cfu logs greater than the log-transformed distribution for incidental entry to retrieve an object, respectively. The log-transformed distributions for these two exposure activities had the greatest difference (89.64% and 79.43% respectively). None these exposure dose distributions determined by different exposure activities differed by more than 95 percent (Table 3.11, Figure 3.10).

The geometric mean of the coliphage exposure dose that would have resulted if we assumed drain exposure resulted in direct ingestion of 5mL of drain water was 3.29 pfu (95% range: 4.60×10^{-2}, 8.90×10^{7} pfu). The geometric mean of the *E. coli* dose was 6.89 cfu (95% range: 339.26, 1.67×10^{11} cfu). The log-transformed exposure dose distributions from direct ingestion of 5mL of drain water were all over 95 percent different than the log-transformed distributions of the exposure doses modeled in this study for the three different types of drain exposure activities (Table 3.12). This suggests previous estimates of children's exposure to drain water in urban areas may have overestimated exposure.

D. Discussion

i. Drain Exposure Model

To our knowledge, this study represents the first attempt to quantify children's exposure to fecal microbes present in open drain water using a stochastic model. Ingestion of drain water was primarily modeled based on indirect ingestion via mouthing of contaminated hands. Based on observations of children's interactions with open drains, we believe this represents a more realistic sequence of events that leads to the ingestion of drain water opposed to assuming some volume of drain water is directly ingested. We also accounted for different types of activities that could exposure children to drain water by modeling three different exposure activities: 1) incidental entry with direct hand-drain water contact, 2) incidental entry for an object with hand contamination occurring though the object, and 3) instrumental 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 age groups (under 5 years old and 5 to 12 years old) of children exposed to drain water were considered to account for differences in hand size and hand mouthing frequencies. This resulted in six exposure scenarios that were assessed.

Incidental entry with direct hand-drain water contact for children under 5 years old resulted in the highest geometric mean exposure dose for both coliphage (1.50 pfu) and *E. coli* (5.05 cfu). Incidental entry to retrieve an object for children 5 to 12 years old resulted in the lowest mean geometric mean exposure dose for coliphage (0.43 pfu) and *E. coli* (4.36 cfu). Given the large amount of uncertainty in our estimates, the log-transformed coliphage and *E. coli* exposure doses only differed by 86 percent. We also found that the log-transformed exposure doses across age groups and exposure activities were not significantly different from each other either. Although children under 5 years old more frequently mouth hands, the log-transformed exposure doses for children under 5 years old and children 5 to 12 years old differed only by a geometric mean of 0.15 microbes. The log-transformed exposure doses for the three different exposure activities assessed also did not differ by more than 95 percent. We hypothesize that the high initial concentration of microbes present in open drains masked the effect that exposure activities and hand mouthing frequencies had on the drain exposure dose. Rather, drain water is so highly contaminated with fecal microbes that any contact children have with drain water results in a high level of exposure to these microbes.

Previous studies that have attempted to quantify children's exposure to open drains have assumed that the child directly ingested 5mL of drain water during each drain entry event (14, 31). Using the same initial concentration of microbes, the exposure dose that resulted from this assumption was significantly greater than the exposure doses estimated for each of the three exposure activities that were modeled in this analysis. This suggests exposure from open drains was previously overestimated because the indirect nature of children's exposure to drain water and the transfer efficiencies between initial contact with drain water and subsequent ingestion were not accounted for. The rate of observed drain entry by children in the study communities also suggests children are likely to enter drains more than four times a year as previously assumed. Future studies about the yearly frequency of drain entry in urban settings would enable better estimates of the risk from this pathway.

The development of this model required a number of assumptions and simplifications. It was not noted in the structured observations conducted if drain entry events observed involved direct or indirect hand contact with the drain water, thus reasonable estimates were used for the exposure assessment. Future observations of children's interactions with open drains should note the frequency of hand or object contact with drain water to help better characterize these types of exposures. We assumed the number of microbes on hands or objects was additive based on the number of contact events with drain water. Future assessments should consider that there may be a point of saturation in the contamination of hand and objects or that subsequent contact with drain water could detach microbes from these surfaces. Inactivation of microbes over time (47) and the decay of microbes on hands following mouthing events (48) were also not considered, though future assessments may find these additional parameters valuable to include. The duration of drain entry used to model instrumental entry was based on observations of children under 5 years old in a household or nursery under the supervision of a caretaker. We expect children playing in the public domain, without caretaker supervision, to spend longer periods of time in drains thus increasing the exposure dose due to instrumental drain entry. We also expect the frequency of hand washing is likely lower in a low-income setting which may increase the length of time a child could mouth contaminated hands (49, 50). Hand washing is also likely not 100 percent effective at removing microbes from hands, especially if no soap or poor quality water is used (51-53).

ii. Microbial Concentrations in and Structured Observations of Open Drains: Implications for Microbial Risk Assessment

Open drain water is highly contained in Accra, with concentrations of fecal microbes on the order of those found in raw sewage. Drains that originally functioned as rivers or lagoons had significantly lower concentrations of *E. coli* (6.99 $\log_{10}$ cfu/100mL) than drains that only functioned to collect storm and wastewater (8.44 $\log_{10}$ cfu/100mL). We attribute these differences to the environmental water still present in river/lagoon drains that dilute the microbial inputs. This is consistent with previous estimates of microbial concentrations in open drains in Accra that have either been based on samples from the rivers or street drains in the city (14, 24, 31). For unknown reasons, the coliphage concentrations (4.61 $\log_{10}$ cfu/100mL) did not mirror the pattern observed with *E. coli* concentrations. However, when the two *E. coli* concentrations were applied to the exposure assessment model, the distributions of the resulting exposure doses differed by only 64.18% indicating they were not significantly different. Among the drains that did not function as rivers or lagoons, there were no significant differences in microbial concentrations by neighborhood despite the differences in reported access to improved sanitation facilities, frequency of public latrine use, child feces disposal practices, and drain defection practices that could all modify the load of fecal microbes entering the drains. Drain size, the type of drain construction, and drain coverage also did not alter microbial concentrations. Importantly, this indicates the extent of exposure to fecal microbes from open drains in Accra is dependent on the frequency of drain entry not the place or type of drain entered.

Although not a common event, drain entry by children under 5 years old and 5 to 12 years old was observed in all neighborhoods, sizes of drains, and in both formally constructed and ecologically formed drains. Furthermore, while microbial concentrations in opens drains were effectively constant across neighborhoods and drain characteristics, there were differences in the rates of children observed in drains and defecating into/inside of drains by neighborhood and drain characteristic. All children were more likely to be observed in large drains compared to small drains, and children under 5 years old in particular were more likely to be observed in ecologically formed drains than formally constructed drains. This suggests children living in neighborhoods with many large and ecologically formed drains more frequently come into contact with the contents of open drains than children living in neighborhoods with small and formally constructed drains.

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 enteric disease infection risk from open drains is likely not uniform throughout the city. In neighborhoods, such as Bukom, where just 7.8% of the drains are completely uncovered, there is less opportunity for drain entry compared to a neighborhood similar to Old Fadama where 54.9% of the drain network is completely uncovered. Additionally, higher rates of children observed entering large and ecologically formed drains indicates children living in areas where those types of drains are present, will more frequently come into contact with the contents of open drains resulting in greater yearly infection risks. Future microbial risk assessments that estimate the burden of diarrheal disease in urban settings should not ignore these differences in infrastructure and drain entry behavior to properly document the disparities in the burden of enteric disease infection associated with exposure to open drains.

E. Conclusions

- The drainage network in Old Fadama, an illegal settlement, was very different from the other three study neighborhoods. In the three formal neighborhoods, the drainage network was primarily built by the city government with some secondary citizen construction and ecologically formed drains. In comparison, Old Fadama had the lowest density of drains per square kilometer, all of the drains were built by citizens or ecologically formed, and a large percentage of drains were completely uncovered. These characteristics, largely the low level of coverage, made drains in Old Fadama more accessible to children living in the neighborhood.
- Open drains in Accra are highly contaminated with fecal microbes, though drains that originally functioned as rivers or lagoons had slightly lower levels of contamination. Despite the different demographic compositions, sanitation practices, and drainage network characteristics documented in the study neighborhoods, no differences in drain microbial levels were observed by neighborhood. This indicates feces are being improperly disposed in all neighborhoods, and open drains are the likely outlet for this improperly disposed waste.

- While contamination levels are consistent across drain types, children were more likely to be observed in certain types of drains than others. In particular, all children entered small drains at a lower rate than large drains, and children under 5 years old entered formally constructed drains at a lower rate than ecologically formed drains. Children living in neighborhoods with large and ecologically formed drains, indicative of areas with modest government infrastructure, are subsequently expected to bear most of enteric disease burden caused by exposure to open drains.
- Common activities observed that expose children to open drains result in doses of fecal microbes that will almost surely cause infection. The high level of fecal contamination in drains rather than the type of hand contact (direct or mediated though an object) with drain water is the primary determinant of exposure dose.
- Although microbial risk assessments involving exposure to water commonly assume some deterministic volume of water is directly ingested, our results demonstrate this assumption overestimates exposures to water that are primarily mediated through hands or objects.

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G. Tables

Table 2.1. Population and physical characteristics for study neighborhoods

Neighborhood	**Population and physical characteristics**					
	Predominant Religion	Immigrant vs. Indigenous	Inland vs. Coastal	Flooding	Density	Older vs. New
Alajo	Christian	Immigrant	Inland	Yes	Medium	Older
Bukom	Christian	Indigenous	Coastal	No	High	Older
Old Fadama	Muslim	Immigrant	Inland	Yes	High	Newer
Shiabu	Christian	Indigenous	Coastal	Yes	High	Newer

Table 2.2. Model parameters used to estimate hand and object contamination distributions

Variable	Symbol	Parameter	Source	Key Assumptions
Microbe concentration (log_{10}/100mL)				Pathogens are suspended homogeneously.
Coliphage	C_C	Normal (4.61, 2.34)	This study	Concentrations are constant across time
E. coli	C_{Ec}	Normal (8.20, 2.25)	This study	given continual input of contaminated sources.
Time spent in the drain per entry event (hr)				
Instrumental entry	T_{Is}	Determined from a hazard model of children's activities.	This study	Durations of time spent in a drain are the same for each neighborhood and for children of all ages.
Frequency of contact with drain (#/drain entry event)				
Incidental entry, hand	D_{Ic}	Poisson (1)	Assumption	At least one contact occurred. Distribution
Incidental entry, object	O_{Ic}	Poisson (1)	Assumption	was resampled until no 0's occurred.
Instrumental entry	D_{Is}	Poisson ($5 \times T_{Is}$)	Assumption	On average 5 contacts per hour occurred.
Area of surface (cm^2)				
Hands, children under 5	A_5	Uniform (244.4, 329.0)	US EPA 2011	Children 2 to <3 years old represent the average age.
Hands, children 5 to 12	A_{12}	Uniform (380.7, 695.6)	US EPA 2011	Children 6 to <11 old represent the average age.
Object	A_O	Uniform (378.8, 1515.5)	FIFA regulations Assumption	A ball ranging from 69.0 to 34.5cm in circumference represents the average object.
Object contacted (%)				
Hand in drain water	S_{HDW}	Uniform (0.08, 1.00)	AuYeung 2008	Contact is equal for all children.
Object in drain water	S_{ODW}	Uniform (0.25, 1.00)	Assumption	At minimum, 25% of the object contacts drain water.
Hand on object	S_{OH}	Uniform (0.08, 0.27)	AuYeung 2008	Contact is equal for all children.

Water film thickness (cm)				
Hand or object	V	Uniform (0.00241, 0.00499)	US EPA 1987	Film thickness is equal for hands and non-porous objects. Thickness ranges from partial wipe to no wipe after immersion in water.
Transfer efficiency, object to hand (%)				
Coliphage	TE_{OC}	0.2759	Rusin 2002	
E. coli	TE_{OEc}	0.6580	Rusin 2002	Transfer efficiency for gram-negative bacteria (*Serratia rubidea*) and *E. coli* is equal.

Table 2.3. Model parameters used to estimate exposure dose distributions

Variable	Symbol	Parameter	Source	Key Assumptions
Object contacted (%)				
Hand in mouth	S_{HM}	Uniform (0.06, 0.33)	AuYeung 2007	Equal for children of all ages.
Frequency of hand mouthing (#/hr)				Based on outdoor mouthing frequencies.
Children under 5	HM_5	Weibull (0.56, 3.41)	Xue 2007	Children 2 to <3 years old represent the average age.
Children 5 to 12	HM_{12}	Weibull (0.49, 1.47)	Xue 2007	Children 6 to <11years old represent the average age.
Time microbes could be ingested (hrs)				
Time to hand washing	T_{HW}	Uniform (0.05, 4.10)	Freeman 2001	All children are equally likely to wash their hands. Children are awake for 16 hrs and wash their hands 3.9 times a day. Hand washing is equally likely to occur at any time throughout the day.
Transfer efficiency, hand to mouth (%)				
Coliphage	TE_{HC}	0.3390	Rusin 2002	
E. coli	TE_{HEc}	0.3397	Rusin 2002	Transfer efficiency for gram-negative bacteria (*Serratia rubidea*) and *E. coli* is equal.

Table 3.1. Reported demographics by neighborhood

	Alajo	Bukom	Old Fadama	Shiabu
Demographics	**n=200**	**n=200**	**n=200**	**n=200**
Homeowner (%)	51.5	80.0	64.5	54.5
Level of education (%)				
No formal education	12.5	13.5	43.5	8.5
Some secondary or less	48.5	70.0	44.0	51.0
Completed secondary or higher	38.0	16.5	12.5	40.5
Religion (%)				
Christian	79.0	88.0	37.5	96.5
Muslim	21.0	8.0	60.5	2.5
Other	0.0	4.0	2.0	1.0
Average HH[1] size (±SD)	5.2 (±3.6)	5.8 (±4.9)	4.1 (±3.0)	4.5 (±2.0)
Average no. children under 5 yrs in HH[1] (±SD)	0.6 (±0.8)	0.7 (±1.0)	0.7 (±0.7)	0.6 (±0.8)
Average no. children 5-12 yrs in HH[1] (±SD)	0.8 (±1.0)	1.1 (±1.2)	0.5 (±0.1)	0.7 (±0.9)
Diarrhea presence	**n=81**	**n=115**	**n=115**	**n=89**
Child with diarrhea in past 2 weeks (%)	12.3	17.4	25.2	10.1

[1]HH denotes household

Table 3.2. Reported sanitation practices by neighborhood

	Alajo	Bukom	Old Fadama	Shiabu
Latrine use (%)	**n=200**	**n=200**	**n=200**	**n=200**
Type of toilet in compound[1]				
None	42.0	92.5	97.5	54.0
Improved	55.0	6.0	1.5	42.0
Unimproved	3.0	0.0	0.5	3.0
No response	0.0	1.5	0.5	1.0
Frequency of public latrine use in last week				
Everyday	30.0	65.0	77.5	45.0
A few times a week	14.0	25.5	21.5	14.0
Once a week	1.0	3.5	0.0	1.0
Never	55.0	3.5	0.5	39.5
No response	0.0	2.5	0.5	0.5
Child feces (%)	**n=79**	**n=89**	**n=108**	**n=88**
Feces disposal for youngest child				
Rubbish	54.4	57.3	44.4	50.0
Drain	6.3	1.1	11.1	8.0
Public latrine	13.9	30.3	38.9	25.0
Private latrine	25.3	2.2	0.0	15.9
Washed diaper	0.0	1.1	0.0	0.0
Other	0.0	0.0	1.9	0.0
Don’t know	0.0	3.5	0.0	0.0

[1]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.

Table 3.3. Reported household drain sanitation practices by neighborhood

	Alajo	Bukom	Old Fadama	Shiabu
Drain presence (%)	**n=200**	**n=200**	**n=200**	**n=200**
No drain near HH[1]	41.5	34.0	82.5	42.0
Drain defecation (%)	**n=116**	**n=132**	**n=27**	**n=115**
Children seen defecating in drain near HH[1]				
Everyday	4.3	15.2	22.2	0.0
Sometimes	3.4	13.6	3.7	8.7
Never	92.2	71.2	74.1	91.3
Adults seen defecating in drain near HH[1]				
Everyday	2.6	12.1	14.8	0.0
Sometimes	7.8	9.1	3.7	6.1
Never	89.7	78.8	81.5	93.9

[1]HH denotes household

Table 3.4. 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
Coverage[1] (%)				
No coverage	33.4	7.8	54.9	24.6
Coverage by citizens	53.9	79.8	45.1	53.1
Coverage by city	33.2	18.6	0.0	64.7
Construction type[1,2] (%)				
Ecological	14.3	0.3	64.8	20.9
Formal by citizens	18.8	19.9	51.3	9.0
Formal by city	70.1	79.8	5.3	74.8
Size[1] (%)				
Small (<0.5m across)	10.2	27.5	5.5	7.2
Medium (0.5-1m across)	52.1	57.4	31.5	73.4
Large (1-3m across)	25.4	15.1	33.4	10.1
Extra-large[3] (>3m across)	15.8	0.0	29.5	9.2
Water level[1,4] (%)				
Dry	12.7	6.4	0.9	10.1
Low	36.1	52.6	21.6	43.7
Medium	50.5	27.5	36.4	39.2
High	0.7	10.1	36.7	7.0
Unable to see	1.6	3.4	4.3	0.0

[1]All percentages are based on total drain length
[2]Ecological drains were dirt lined with no formal planning. Formal drains were cement or stone lined that were intentionally constructed.
[3]All extra-large drains were originally rivers or lagoons.
[4]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 3.5. The rates of children observed in open drains by age[1]

	Children seen in drain[2]				Children seen defecting into/inside drain[2]			
	No. children observed	Hrs[3]	Rate (children/hr)	p-value	No. children observed	Hrs[3]	Rate (children/hr)	p-value
Age (n=45)								
Under 5 years	70	45	1.6	Ref[4]	26	45	0.6	Ref[4]
5 to 12 years	67	45	1.5	0.798	7	45	0.2	**0.002**

[1]Age was estimated by the observer.
[2]Each observation took place for one hour. It was assumed each recorded count represented a unique child.
[3]Total observation hours at drain locations
[4]Reference value for Poisson regression analysis.

Table 3.6. The rates of children under 5 years old[1] observed in open drains by neighborhood and drain characteristics

	Children seen in drain[2]				Children seen defecting into/inside drain[2]			
	No. children observed	Hrs[3]	Rate (children/hr)	p-value	No. children observed	Hrs[3]	Rate (children/hr)	p-value
Neighborhood								
Alajo (n=11)	10	11	0.9	**<0.001**	0	11	0.0	N/A[7]
Bukom (n=11)	7	11	0.6	**<0.001**	1	11	0.1	**0.004**
Old Fadama (n=14)	49	14	3.5	Ref[6]	25	14	1.8	Ref[6]
Shiabu (n=9)	4	9	0.4	**<0.001**	0	9	0.0	N/A[7]
Drain size[4]								
Small (n=15)	10	15	0.7	**<0.001**	1	15	0.1	**0.001**
Medium (n=16)	22	16	1.4	**0.011**	0	16	0.0	N/A[7]
Large (n=14)	38	14	2.7	Ref[6]	25	14	1.8	Ref[6]
Drain construction[5]								
Formal (n=25)	22	25	0.9	**<0.001**	1	25	0.0	**<0.001**
Ecological (n=19)	48	19	2.5	Ref[6]	25	19	1.3	Ref[6]

[1]Age was estimated by the observer.
[2]Each observation took place for one hour. It was assumed each recorded count represented a unique child.
[3]Total observation hours at drain locations
[4]Small drain (<0.5m across), medium drain (0.5-1m across), large drain (>1m across).
[5]Ecological drains were dirt lined with no formal planning. Formal drains were cement or stone lined that were intentionally constructed.
[6]Reference value for Poisson regression analysis.
[7]Unable to run the analysis because no children were observed.

Table 3.7. The rates of children 5 to 12 years old[1] observed in open drains by neighborhood and drain characteristics

	Children seen in drain[2]				**Children seen defecting into/inside drain[2]**			
	No. children observed	Hrs[3]	Rate (children/hr)	p-value	No. children observed	Hrs[3]	Rate (children/hr)	p-value
Neighborhood								
Alajo (n=11)	13	11	1.2	0.073	1	11	0.1	0.306
Bukom (n=11)	6	11	0.5	**0.002**	2	11	0.2	0.602
Old Fadama (n=14)	30	14	2.1	Ref[6]	4	14	0.3	Ref[6]
Shiabu (n=9)	18	9	2.0	0.817	0	9	0.0	N/A[7]
Drain size[4]								
Small (n=15)	13	15	0.9	**0.018**	0	15	0.0	N/A[7]
Medium (n=16)	27	16	1.7	0.624	0	16	0.0	N/A[7]
Large (n=14)	27	14	1.9	Ref[6]	7	14	0.5	Ref[6]
Drain construction[5]								
Formal (n=25)	40	25	1.6	0.634	2	25	0.1	0.155
Ecological (n=19)	27	19	1.4	Ref[6]	5	19	0.3	Ref[6]

[1]Age was estimated by the observer.
[2]Each observation took place for one hour. It was assumed each recorded count represented a unique child.
[3]Total observation hours at drain locations
[4]Small drain (<0.5m across), medium drain (0.5-1m across), large drain (>1m across).
[5]Ecological drains were dirt lined with no formal planning. Formal drains were cement or stone lined that were intentionally constructed.
[6]Reference value for Poisson regression analysis.
[7]Unable to run the analysis because no children were observed.

Table 3.8. *E. coli* concentrations from open drain water samples by neighborhood and drain characteristics

	E. coli **(cfu $\log_{10}$/100ml)**				
	Mean	SD	Min	Max	p-value
Overall (n=86)	8.20	2.25	-0.15	11.17	
River or lagoon[1]					**0.028**
No (n=72)	8.44	2.00	-0.15	11.17	
Yes (n=14)	6.99	3.06	-0.15	8.85	
Neighborhood[2]					0.622
Alajo (n=18)	8.63	0.68	7.49	10.18	
Bukom (n=18)	8.58	2.31	-0.15	10.86	
Old Fadama (n=16)	7.84	2.24	-0.15	9.86	
Shiabu (n=20)	8.60	2.33	-0.15	11.17	
Size[2,3]					0.402
Small (n=13)	8.58	0.67	7.34	9.60	
Medium (n=44)	8.61	2.14	-0.15	11.17	
Large (n=15)	7.81	2.31	-0.15	9.61	
Construction[2,4]					0.947
Formal (n=56)	8.43	2.23	-0.15	11.17	
Ecological (n=16)	8.47	0.86	7.34	9.86	
Coverage[2]					0.306
Some coverage (n=54)	8.58	1.92	-0.15	11.17	
No coverage (n=18)	8.02	2.23	-0.15	10.79	

cfu denotes colony forming units
[1]Drain was originally a river or lagoon but now functions as a large, terminal drain.
[2]Only drains that were not originally rivers or lagoons were included.
[3]Small drain (<0.5m across), medium drain (0.5-1m across), large drain (1-3m across)
[4]Ecological drains were dirt lined with no formal planning. Formal drains were cement or stone lined that were intentionally constructed.

Table 3.9. Coliphage concentrations from open drain water samples by neighborhood and drain characteristics

	Coliphage (pfu log_{10}/100ml)				
	Mean	SD	Min	Max	p-value
Overall (n=42)	4.61	2.34	-0.15	7.30	
River or lagoon[1]					0.816
No (n=35)	4.56	2.39	-0.15	7.30	
Yes (n=7)	4.81	2.25	-0.15	6.34	
Neighborhood[2]					0.367
Alajo (n=6)	4.74	2.51	-0.15	6.43	
Bukom (n=13)	5.08	2.56	-0.15	7.30	
Old Fadama (n=8)	3.08	2.73	-0.15	5.95	
Shiabu (n=8)	5.12	1.05	3.97	6.93	
Size[2,3]					0.451
Small (n=10)	5.15	2.14	-0.15	7.30	
Medium (n=17)	4.05	2.56	-0.15	7.30	
Large (n=8)	4.99	2.33	-0.15	7.28	
Construction[2,4]					0.672
Formal (n=25)	4.69	2.40	-0.15	7.30	
Ecological (n=10)	4.30	2.46	-0.15	6.43	
Coverage[2]					0.987
Some coverage (n=25)	4.57	2.36	-0.15	7.30	
No coverage (n=10)	4.59	2.59	-0.15	6.43	

pfu denotes plaque forming units
[1]Drain was originally a river or lagoon but now functions as a large, terminal drain.
[2]Only drains that were not originally rivers or lagoons were included.
[3]Small drain (<0.5m across), medium drain (0.5-1m across), large drain (1-3m across)
[4]Ecological drains were dirt lined with no formal planning. Formal drains were cement or stone lined that were intentionally constructed.

Table 3.10. Coliphage and *E. coli* exposure doses for six drain entry exposure scenarios

Drain exposure scenario		**Coliphage (pfu)** Geometric mean	Median	95% range	***E. coli* (cfu)** Geometric mean	Median	95% range
Children under 5 years	(A) Incidental, hands[1]	1.50	35.46	2.51×10^{-4}, 2.62×10^{6}	5.05	1.21×10^{5}	0.65, 8.18×10^{9}
	(C) Incidental, object[2]	0.60	4.29	2.87×10^{-5}, 3.55×10^{5}	4.52	3.55×10^{4}	0.22, 2.23×10^{9}
	(E) Instrumental[3]	1.44	29.73	6.93×10^{-4}, 1.04×10^{6}	4.99	9.31×10^{4}	3.31, 3.16×10^{9}
Children 5 to 12 years	(B) Incidental, hands[1]	1.34	22.60	1.72×10^{-4}, 1.92×10^{6}	4.88	8.06×10^{4}	0.51, 7.03×10^{9}
	(D) Incidental, object[2]	0.43	2.88	1.88×10^{-5}, 3.04×10^{5}	4.36	2.42×10^{4}	0.17, 2.17×10^{9}
	(F) Instrumental[3]	1.43	28.53	6.63×10^{-4}, 1.04×10^{6}	4.98	9.01×10^{4}	3.28, 3.28×10^{9}

pfu denotes plaque forming units; cfu denotes colony forming units
() indicates exposure scenario
[1]Incidental drain entry with hand contact describes a scenario where a child accidentally entered a drain (typically by falling), had hand contact with drain water and subsequent hand mouthing events occurred.
[2]Incidental drain entry for an object describes a scenario where a child entered a drain to retrieve an object that fell inside, had contamination of their hands through the object and subsequent hand mouthing events occurred.
[3]Instrumental 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 instrumental entry event.

Table 3.11. Pairwise comparisons of exposure doses by activity and microbe

Comparison exposure doses (microbes) A	B	Geometric mean difference (A - B)	95% range	% of A greater than B
E. coli concentration	Coliphage concentration	3.59	-2.94, 9.88	86.23
E. coli concentrations in other drains[1]	*E. coli* concentrations in river/lagoon drains[1]	1.42	-5.74, 8.57	65.18
Coliphage (pfu)				
Children under 5 yrs	Children 5 to 12 yrs	0.15	-2.81, 3.32	53.77
Incidental, hands[2]	Instrumental[3]	0.04	-2.47, 1.90	52.14
Incidental, hands[2]	Incidental, object[4]	0.90	-0.53, 1.99	89.64
Instrumental[3]	Incidental, object[4]	0.86	-1.05, 3.37	77.53
***E. coli* (cfu)**				
Children under 5 yrs	Children 5 to 12 yrs	0.15	-2.83, 3.23	53.49
Incidental, hands[2]	Instrumental[3]	0.04	-2.52, 1.93	52.25
Incidental, hands[2]	Incidental, object[4]	0.53	-0.93, 1.60	79.43
Instrumental[3]	Incidental, object[4]	0.49	-1.43, 3.06	65.14

pfu denotes plaque forming units; cfu denotes colony forming units

[1]Drains were originally rivers or lagoons but now function as large, terminal drains compared to all other drains in the community.

[2]Incidental drain entry with hand contact describes a scenario where a child accidentally entered a drain (typically by falling), had hand contact with drain water and subsequent hand mouthing events occurred.

[3]Instrumental 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 entry event.

[4]Incidental drain entry for an object describes a scenario where a child entered a drain to retrieve an object that fell inside, had contamination of their hands through the object and subsequent hand mouthing events occurred.

Table 3.12. Pairwise comparisons of previous exposure dose estimates[1] with new calculated exposure doses for three exposure activities

Comparison exposure dose	Geometric mean difference	95% range	% of 5mL dose greater than comparison dose
Coliphage (pfu)			
Incidental, hands[2]	1.84	0.01, 4.52	99.74
Instrumental[3]	1.87	0.68, 2.00	99.63
Incidental, object[4]	2.74	0.89, 5.44	99.93
***E. coli* (cfu)**			
Incidental, hands[2]	1.83	0.01, 4.52	97.57
Instrumental[3]	1.87	0.68, 2.00	97.58
Incidental, object[4]	2.36	0.51, 5.06	99.74

pfu denotes plaque forming units; cfu denotes colony forming units

[1]Previous estimates assumed 5mL of drain water was ingested for each drain exposure event.

[2]Incidental drain entry with hand contact describes a scenario where a child accidentally entered a drain (typically by falling), had hand contact with drain water and subsequent hand mouthing events occurred.

[3]Instrumental 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 entry event.

[4]Incidental drain entry for an object describes a scenario where a child entered a drain to retrieve an object that fell inside, had contamination of their hands through the object and subsequent hand mouthing events occurred.

H. Figures

Figure 2.1. Study area: four low-resource neighborhoods in Accra, Ghana

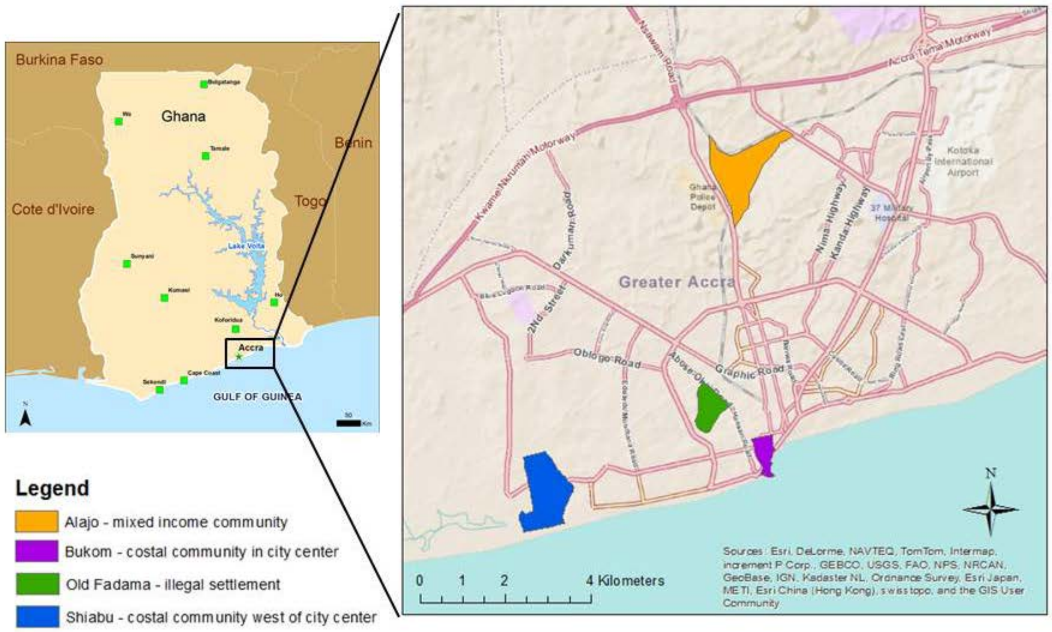


Figure 2.2. Observed incidental drain entry

Photo courtesy of Alexandra Huttinger

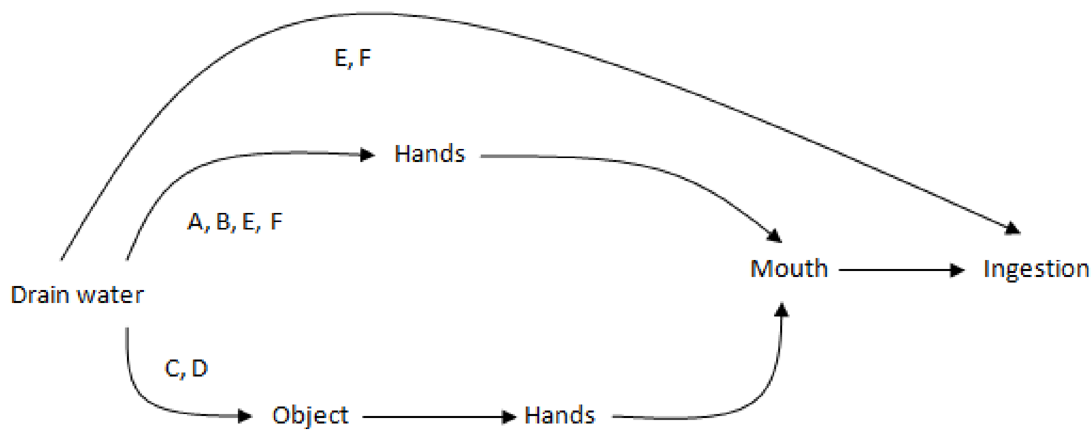
Figure 2.3. Observed instrumental drain entry

Photo courtey of Habib Yakubu

Figure 2.4. Observed instrumental drain entry

Photo courtesy of Stephanie Gretsch

Figure 2.5. Schematic of drain exposure scenarios



A, B denote incidental drain entry with direct hand-drain water contact; C, D denote incidental drain entry to retrieve an object; E, F denote instrumental drain entry.

Figure 3.1. Household survey locations

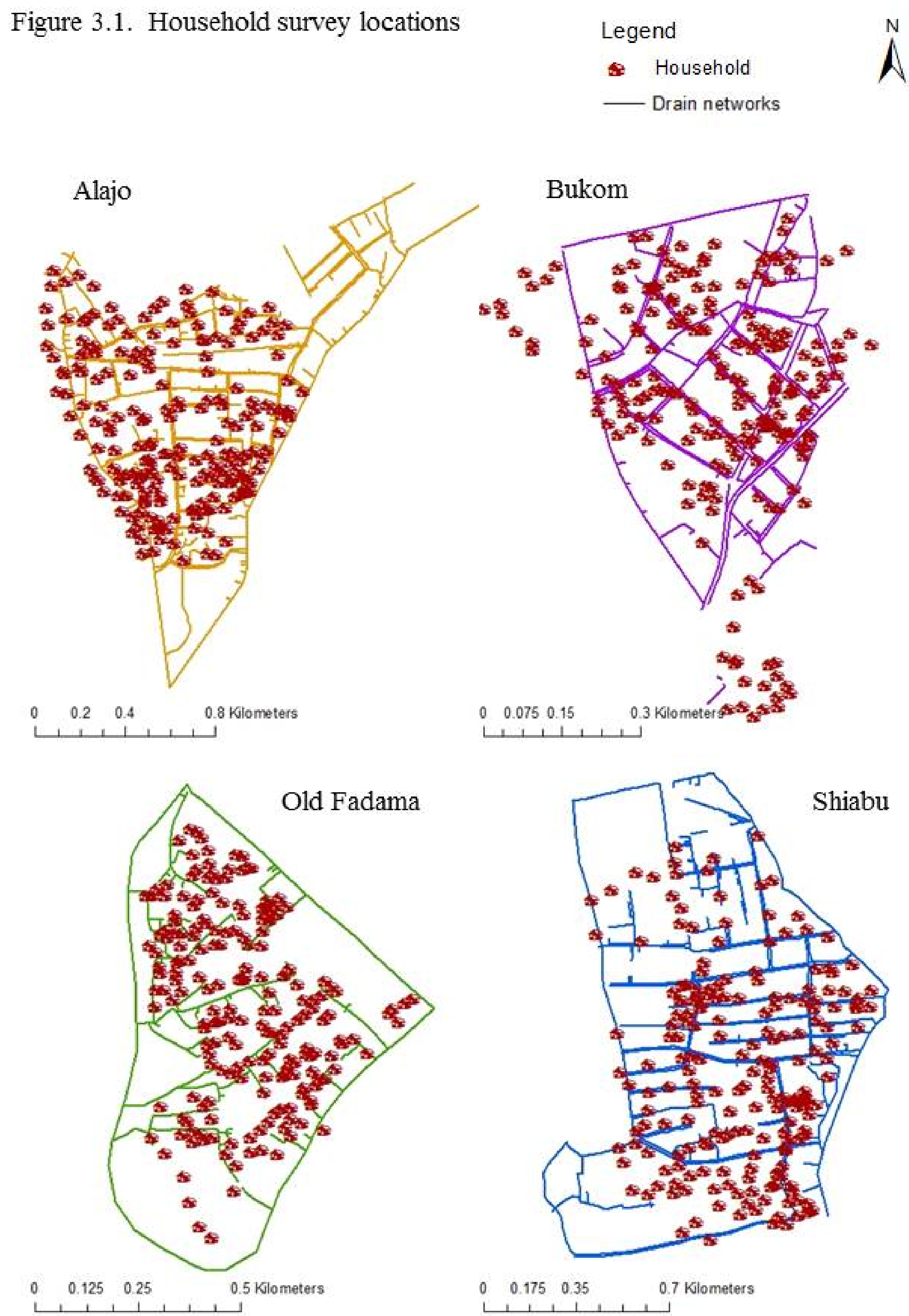


Figure 3.2. Drain construction by neighborhood

Figure 3.3. Drain size by neighborhood

Figure 3.4. Drain coverage by neighborhood

Figure 3.5. Drain water level by neighborhood

Figure 3.6. Structured observation locations

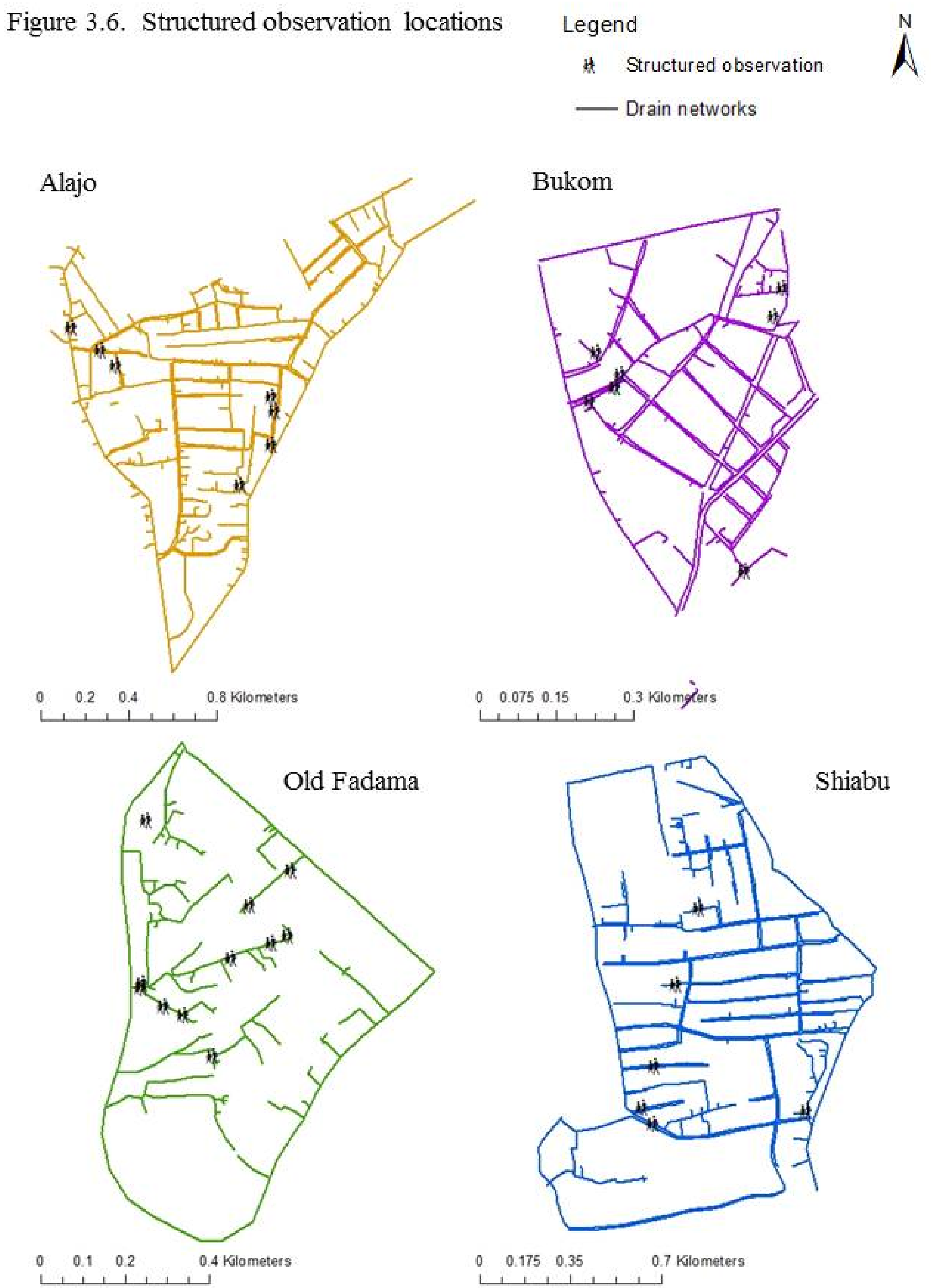


Figure 3.7. Environmental sample locations

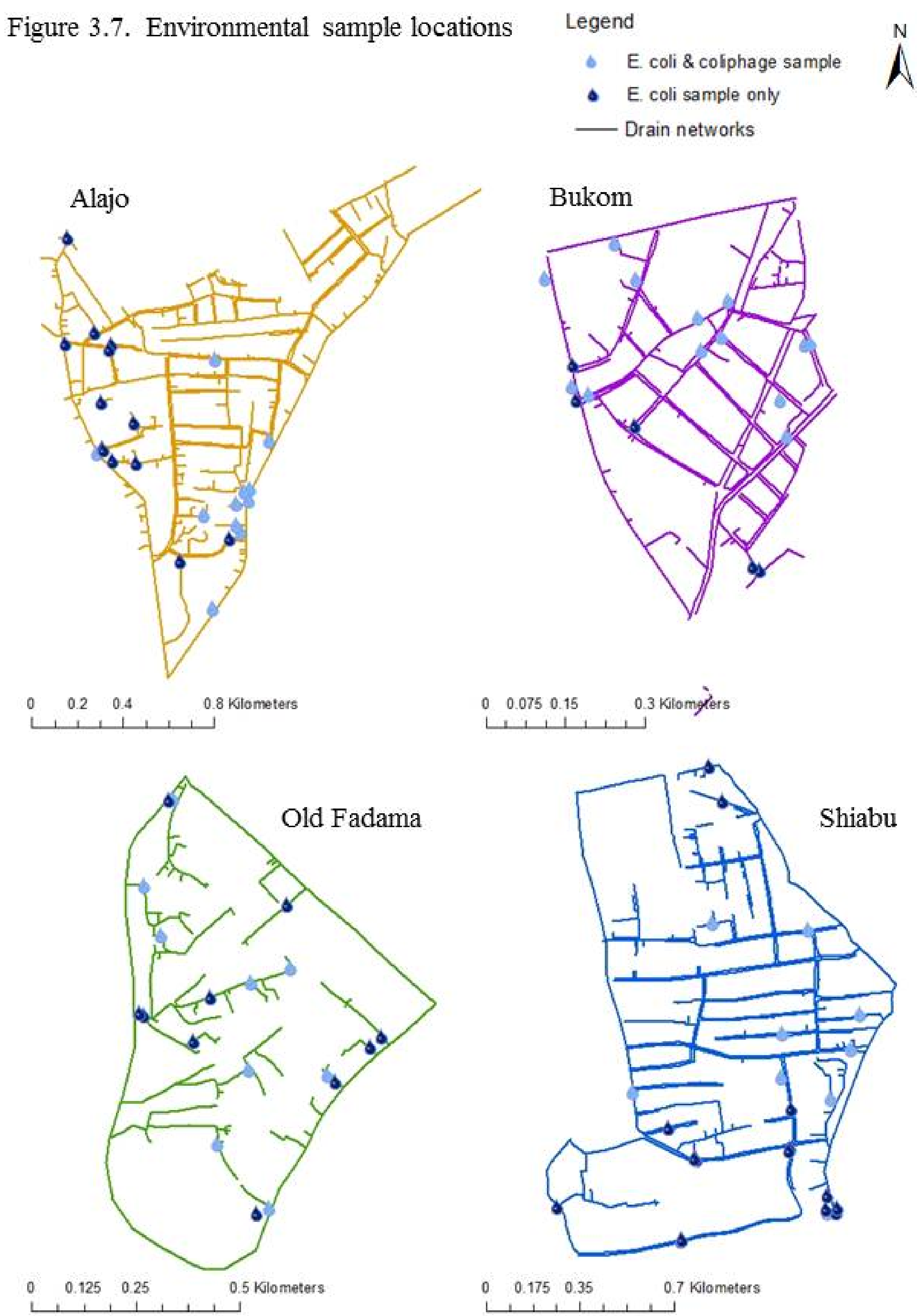


Figure 3.8. Kernel density of drain *E. coli* concentrations comparing drains that were originally rivers and lagoons to those that were not

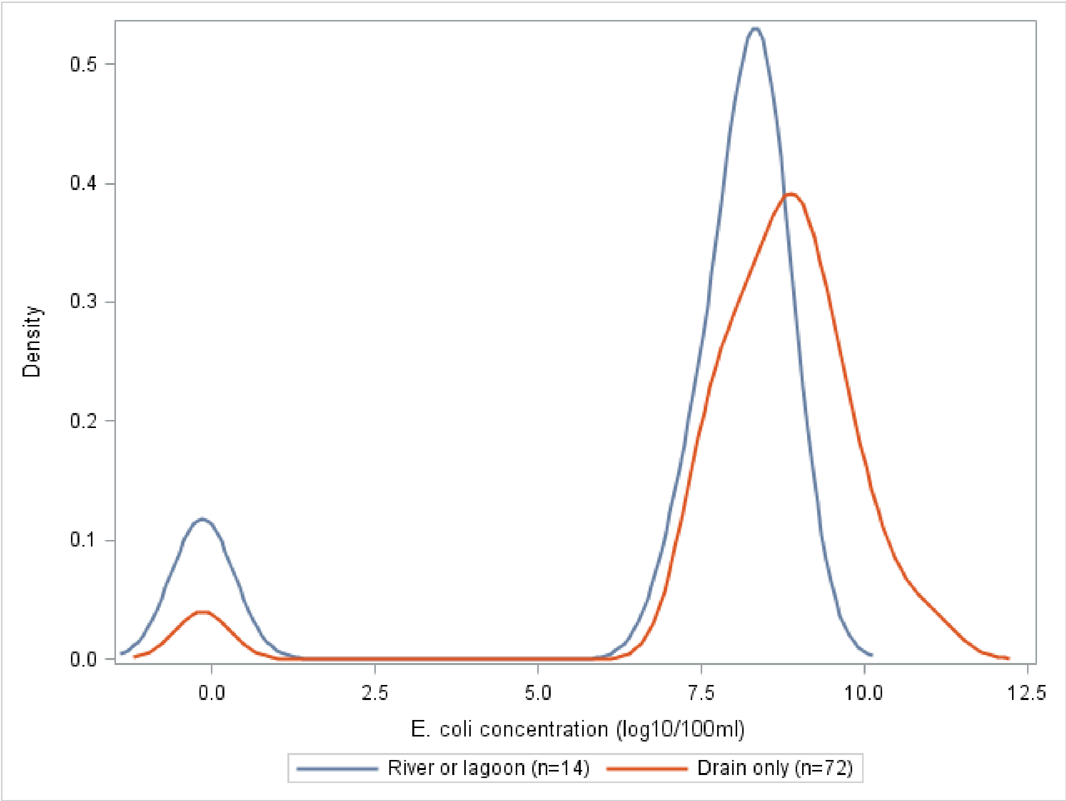
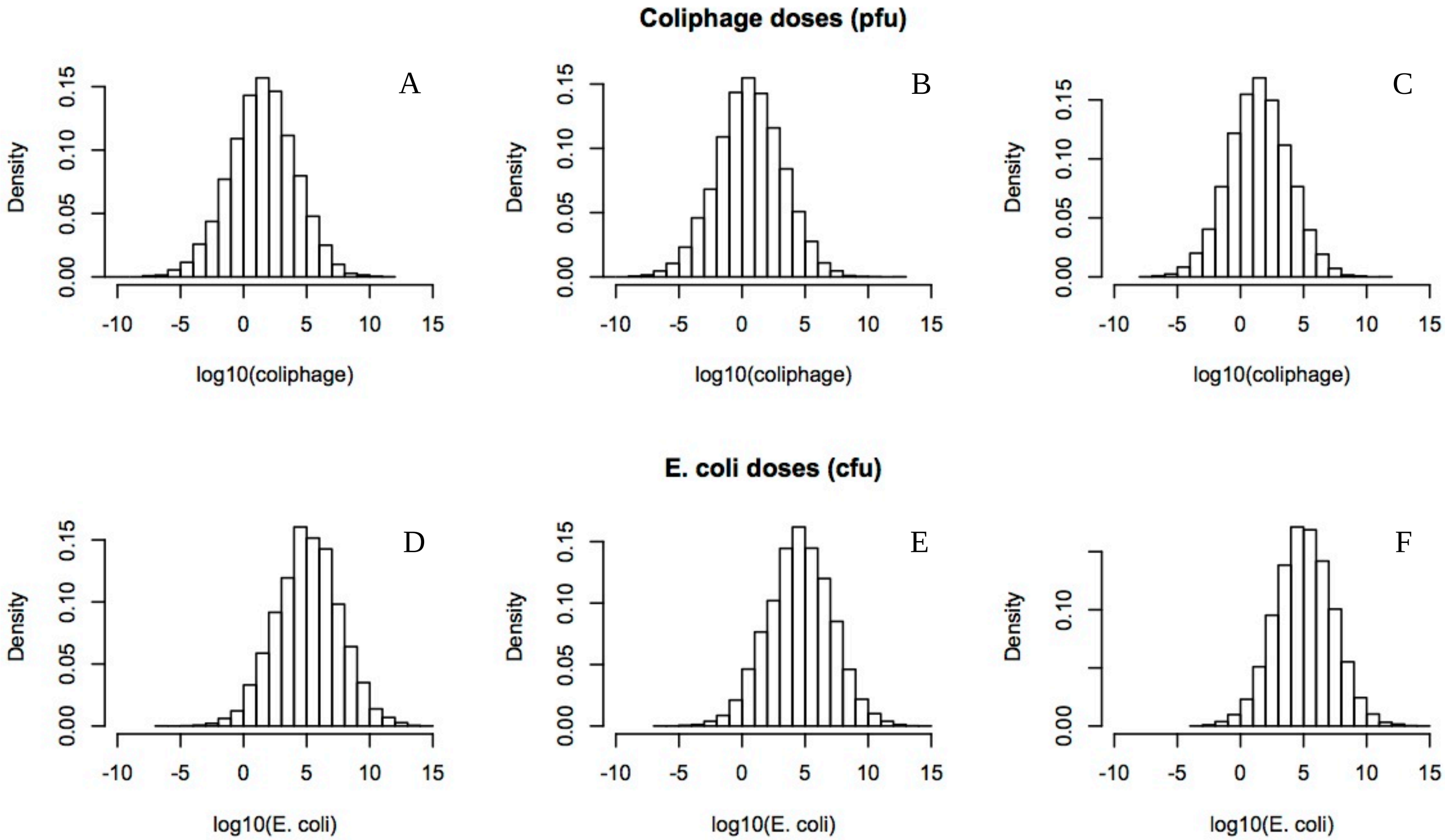
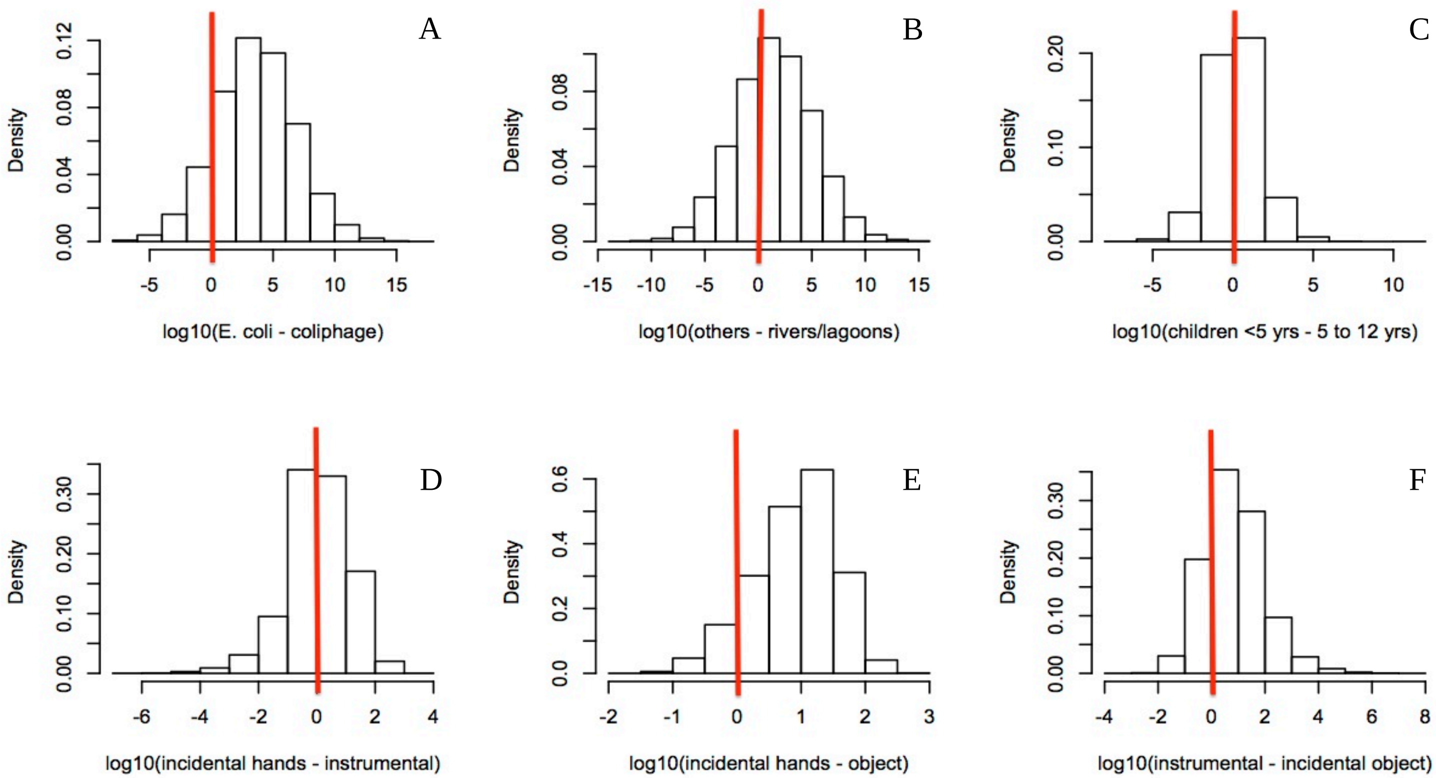


Figure 3.9. Log-transformed exposure dose distributions for children under 5 years old



pfu denotes plaque forming units; cfu denotes colony forming units
Where: A (D) is the coliphage (*E. coli*) exposure dose distribution for incidental drain entry with direct hand contact with drain water. B (E) is the coliphage (*E. coli*) exposure dose distribution for incidental drain entry to retrieve an object. C (F) is the coliphage (*E. coli*) exposure dose distribution for instrumental drain entry.

Figure 3.10. Differences in the log-transformed exposure doses for different initial microbial concentrations and the log-transformed coliphage exposure doses by exposure activities



Where: (A) represents the difference in the initial *E. coli* concentration and coliphage concentration. (B) represents the difference between the initial *E. coli* concentrations found in all other drains and the *E. coli* concentrations found in river/lagoon drains. (C) represents the difference between coliphage doses between children under 5 years and children 5 to 12 years. (D) represents the difference between coliphage doses in incidental entry with hands and instrumental entry. (E) represents the difference between coliphage doses between incidental entry with hands and incidental entry for an object. (F) represents the difference between coliphage doses in instrumental entry and incidental entry for an object.

III. LESSONS LEARNED AND FUTURE ANALYSES

A. Lessons Learned

1. *Recommendation:* As more of the world's population move to urban settings, adding stress to already dysfunction drainage systems, we expect fecal contamination of drains and children's exposure to drains to remain at the levels observed in this study or increase. In order to eliminate this type of exposure, all drains should be covered. If the current practice of building uncovered drains remains unchanged, flooding of the environment will be reduced, but the drains will still be highly contaminated and pose a threat to the children and community members that live next to them. We can see this evidenced by the drainage networks in Alajo, Bukom, and Shiabu that have a large percentage of the network constructed by the government, and yet the drains are just as contaminated with fecal microbes as the drainage network in Old Fadama, where no government infrastructure is present. Covering drains is a low-cost solution that can mitigate this type of exposure to fecal microbes (14).

2. *Recommendation:* Areas, such as parks and soccer fields, should be demarcated in city plans to create areas in the communities that are safe for children to play.

3. *Recommendation:* Assessment of drains in other contexts should focus on areas where children play and large terminal drains where activities such as defection, scavenging for trash and recyclables, or fishing occur.

4. *Recommendation:* In a survey of urban residents in Accra facilitated by the World Bank, very few respondents (10%) reported receiving information from the city about how and why drains should be clean. However, 91 percent of respondents who had received information reported this information was helpful, and they followed some or all of the recommendations (12). I recommend the city create a simple informational handout that can be distributed to community members informing them of the importance of keeping children out of drains, not disposing of feces or solid waste in drains, and the proper way to clean drains if needed. This type of handout would be well received and effective based on this previous survey.

5. Before visiting Accra, I did not realize how connected issues surrounding open drains and solid waste disposal are. Any discussions concerning how exposure to open drains can be mitigated should also be accompanied by discussions about how to ensure solid waste is disposed of properly. If the drains are covered but remain an outlet for solid waste, they will not only continue to overflow, but community members will be unable to clear them. Policies need to be created to ensure solid and liquid wastes are disposed of separately and in a manner that does not contaminate the environment.

6. I would coordinate the completion of the drain characterization form to take place at the same time microbial sampling and structured observations occur. This would ensure the correct drain characterization information is recorded at each

location where samples or observations take place. Given the density of the drainage network and inherent error in GPS systems, matching the digitized drain lines that contained the drain characterization data to the sampling sites based on nearest distance was subject to error.

7. I would create a more specific definition of drain entry to be used in structured observations. I would differentiate between subjects observed that only crossed the drain threshold and subjects that made contact with the drain contents (either by hand, foot, or another body part). The duration of drain entry and the frequency of hand, foot, or other body part contact with open drain contents should also be recorded to better characterize this exposure.

8. Drain defection was expected to be rare and, as such, defection events that occurred into drains and inside of drains were not differentiated in the structured observation tool. In practice, drain defection was observed regularly. It would have been valuable to know which defection events involved drain entry with exposure to drain contents, and which events only involved the subject squatting over the drain with no exposure to the drain contents.

9. Making reasonable assumptions and simplifications are a necessary component of exposure assessment, especially when modeling an exposure that has not been extensively studied. I learned to trust my own judgment, informed by the literature and key informants, when making assumptions that were necessary to model exposure to drains in this assessment.

B. Future Analyses

1. While not included in this thesis, a cluster analysis of reported defection in open drains (as determined by the household survey) is currently under way. This analysis will allow us to determine if there are clusters of drain defection activity. A logistic model is being used to determine what factors, including the distance to different types of drains and access to improved sanitation facilities, predict reported drain defection. This model will be applied to the raw data and to the identified clusters to determine if clusters are better suited to explain reported drain defection. If clusters are identified, they will help us understand where open defection is taking place in the communities. The absence of clusters may indicate that open defection is universally practiced in the neighborhood.

2. A cluster analysis of either reported or observed drain entry would also be valuable to determine if and where clusters of drain entry activity take place. This information could be used to help direct decision-makers to cover a limited number of drains and reduce the greatest areas of exposure.

3. Future studies that do not have the time or resources to conduct extensive household surveys or structured observations may find community mapping valuable to determine more generally where defection and entry into drains take place in the study area.

4. I recommended a sensitivity analysis of selected exposure parameters be completed in the future. In particular, the transfer efficiency parameters that were considered as a point estimates and the time-until-hand-washing parameter, that we suspect is longer than was considered in this analysis, should be assessed.

5. This study only considered exposure to drain water, but sediment samples were also collected from open drains and found to have high levels of fecal microbes. Future exposure assessments could consider the combined exposure dose that would result from exposure to drain water and sediment.

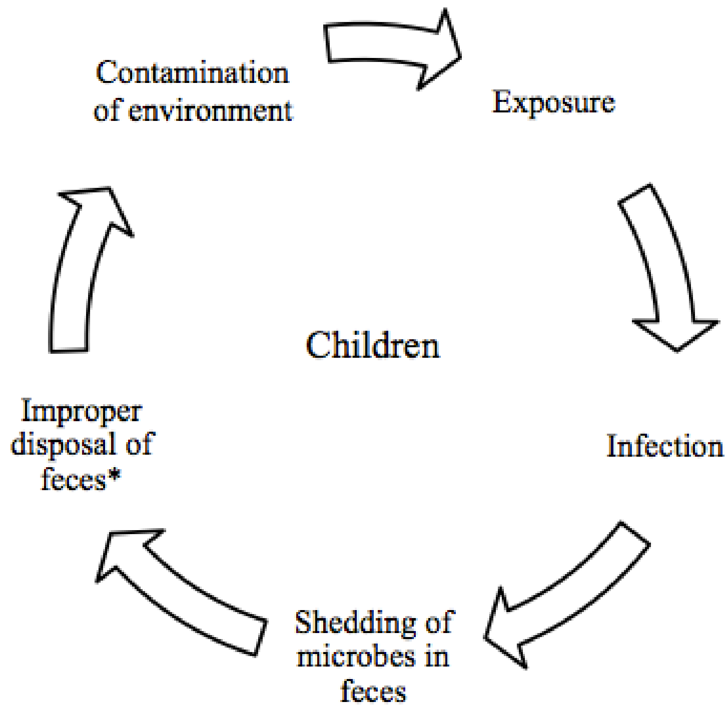
6. Our exposure model assumed that the number of microbes on hands or objects was additive after each contact with drain water. Other assumptions, such as assuming the number of drain water contact events matter only until some saturation point is reached, or that subsequent contact with drain water actually could detach microbes on hands or objects, are also plausible and could be considered.

7. Future exposure assessments may also want to consider: 1) the rates at which microbes become inactivated on surfaces and hands, 2) there may be some decay in the number of microbes present on hands after each hand mouthing event, and 3) hand washing is likely not 100 percent effective at removing/inactivating microbes present on hands, especially if no soap or poor quality water are used.

8. The directionality of drain water flow was collected for each of the drainage channels in the study communities. This allows for a drain network model to be created in ArcGIS that could simulate how water (and subsequently fecal microbes) moves throughout the study neighborhoods. Scenarios, such as breaks in septic tanks, could be modeled to determine what populations in the neighborhood would be affected, and if and where microbial sinks are located in the neighborhood.

IV. APPENDIX

A. Cyclic pattern of exposure to fecal microbes



*One cause being lack of access to improved sanitation facilities

B. Household Survey

Household Survey

Location ID [ ] GPS longitude W000. [ ] Date [ ]

GPS latitude N05. [ ]

1.0 General Information

Ques #	Description
101	Should I describe you as a head of a household or household member? (A household is people sharing a cooking pot) ☐ Female head of household ☐ Male head of household ☐ Female household member ☐ Male household member
102	Tenancy status ☐ Renter ☐ Owner
103	How long have you lived in this household? [ ] months/years
104	What is your highest level of education? ☐ No formal education ☐ Higher than secondary ☐ Some primary ☐ No response ☐ Completed primary ☐ Some secondary ☐ Completed secondary
105	What is your religion? ☐ Christian ☐ No response ☐ Moslem ☐ Traditional/Spiritualist ☐ No religion ☐ Other
106	What is your mother tongue? ☐ Ga ☐ Other ☐ Twi ☐ No response ☐ Fante ☐ Hausa
107	Is a business run from this compound/household? ☐ Yes ☐ No ☐ No response
108	If so, what kind of business? ☐ Food vending ☐ Other
109	How many households are in this compound? A household is people sharing a cooking pot. [ ]
110	How many people live in this compound? [ ]

1

111	How many people are in your household?	
112	How many male adults (18 and older) live in your household?	
113	How many female adults (18 and older) live in your household?	
114	How many children under 5 live in your household?	
115	How many children ages 5 -12 live in your household?	
116	How many young people ages 13-17 live in your household?	
117	Does your household have electricity?	☐ Yes ☐ No ☐ No response
118	Does your household have a radio?	☐ Yes ☐ No ☐ No response
119	Does your household have a television?	☐ Yes ☐ No ☐ No response
120	Does your household have a refrigerator?	☐ Yes ☐ No ☐ No response
121	Does your household have a bicycle?	☐ Yes ☐ No ☐ No response
122	Does your household have a motorcycle?	☐ Yes ☐ No ☐ No response
123	Does your household have a car?	☐ Yes ☐ No ☐ No response
124	Does your household have a domestic worker not related to the head of the household	☐ Yes ☐ No ☐ No response

2

2.0 Water Supply

201	What is your primary source of drinking water? ☐ Sachet/Water bottle ☐ Well ☐ Other Specify other ____ ☐ Tap from pipe network ☐ Water truck ☐ Don't know ☐ Tap form polytank ☐ Harvested Rainwater ☐ No response
202	How often do you replenish this primary source of drinking water? ____ ☐ Everyday ☐ Few times per week ☐ Once per week or less
203	How much water does your child drink every day? ____ ☐ Cups ☐ Sachets
204	What is your primary sources of water for cooking and hygiene? ☐ Sachet/Water bottle ☐ Well ☐ Other Specify other ____ ☐ Tap from pipe network ☐ Water truck ☐ Don't know ☐ Tap form polytank ☐ Harvested Rainwater ☐ No response

3

3.0 Sanitation and Hygiene

301 How many latrines are on this compound? ______ If none -> 303

302 How many households do you share a latrine with? ______

303 Where do children (ages 5-12) in your household typically defecate?

- ☐ Compound latrine
- ☐ Public latrine
- ☐ In a bag/flying toilet
- ☐ Chamber pot
- ☐ Outside
- ☐ CBeach
- ☐ Other Specify othe ______
- ☐ Don't know
- ☐ No response

304 (If single household, then skip) Is this the same for the other children in this compound?

- ☐ Yes
- ☐ No
- ☐ Don't know
- ☐ No response

305 (If respondent has a child under 5) The last time your youngest child defecated, where did they defecate?

- ☐ Compound latrine
- ☐ Public latrine
- ☐ In a potty
- ☐ In a diaper/nappy
- ☐ On ground/outside compound
- ☐ On ground/inside compound
- ☐ In drain/gutter
- ☐ Don't know
- ☐ No response

(If resondent does not have child under 5, skip to 308)

306 What is the age of this child? ______ Months/Years

307 The last time your youngest child defecated, how did you dispose of feces?

- ☐ Combined with rubbish
- ☐ Dumped into drain/gutter
- ☐ Dumped in public latrine
- ☐ Dumped in compound latrine
- ☐ Washed diaper/nappy
- ☐ Left on ground
- ☐ Don't know
- ☐ No response

308 Do other mothers in the compound ever use potties for their children?

- ☐ Yes
- ☐ No
- ☐ Don't know
- ☐ No response

309 Are there ever times when other mothers leave child feces on the compound ground?

- ☐ Yes
- ☐ No
- ☐ Don't know
- ☐ No response

310 How often do you see children defecating in the drain near your house?:

- ☐ Everyday
- ☐ Sometimes
- ☐ Never
- ☐ No drain near house
- ☐ No response

311 How often do you see adults defecating in the drain near your house?:

- ☐ Everyday
- ☐ Sometimes
- ☐ Never
- ☐ No drain near house
- ☐ No response

4

312	How much did members of your household spend on public latrines yesterday, not including showers?	Cedis/Pesewas
313	Where did you last bathe? ☐ In compound ☐ Public bath ☐ Beach ☐ Other Specify othe ☐ No response	
314	How much did members of your household spend on bathing facilities yesterday?	Cedis/Pesewas
315	How much did you spend on drinking water yesterday for your family?	Cedis/Pesewas
316	How much did you spend on water (for all purposes) yesterday for your family?	Cedis/Pesewas
317	How does your household primarily dispose of rubbish? ☐ Disposal pit in compound ☐ Private collection service ☐ Private local collection ☐ Drain ☐ Public dump site ☐ Burned ☐ Other Specify other ☐ Don't know ☐ No response	
318	How much did you spend on rubbish disposal yesterday?	Cedis/Pesewas

5

4.0 Health

401 Has this child had diarrhoea in the past two weeks? (Diarrhoea is 3 or more loose or watery stools within 24 hours)

- ☐ Yes
- ☐ No -> **403**
- ☐ Don't know -> **403**
- ☐ No response -> **403**

402 Was this bloody diarrhoea?

- ☐ Yes
- ☐ No
- ☐ Don't know
- ☐ No response

403 Do you ever de-worm your child?

- ☐ Yes
- ☐ No
- ☐ Don't know
- ☐ No response

404 When did you last de-worm him/her? ______ days/months/years

5.0 Wash facilities on compound

501 What kind of latrine do you have in this compound?

- ☐ No facility/Bush/Field
- ☐ Traditional pit latrine
- ☐ KVIP(double)
- ☐ VIP(single)
- ☐ Bucket/pan
- ☐ Pour flush
- ☐ Flush toilet
- ☐ Other
- ☐ No response

502 Do you have a sink where you wash your hands after defecation?

- ☐ Yes
- ☐ No
- ☐ No response

503 Do you have a container where you store drinking water?:

- ☐ Yes
- ☐ No -> **506**
- ☐ No response -> **506**

504 If so, can you please show this to me?
(What type of drinking water container do they have?)

- ☐ Narrow mouth (<6cm)
- ☐ Wide mouth (>6cm)
- ☐ Not able to see -> **skip 506**

505 Is the container that the drinking water is stored in covered or uncovered?:

- ☐ Covered
- ☐ Not covered
- ☐ Not able to see -> **skip 506**

506 (Observe, don't ask!) Are feces observed around compound grounds?: ☐ Yes ☐ No

507 (Observe, don't ask!) Are animals observed roaming around compound grounds?: ☐ Yes ☐ No-> **skip 50**

6

508	(Observe, don't ask!) If yes, which animals are observed? (check all that apply): ☐ Goats ☐ Dogs ☐ Chickens ☐ Cats ☐ Pigs ☐ Other
509	(Observe, don't ask!) Are food waste observed on compound grounds?: ☐ Yes ☐ No

6.0 Weekly Activities Questions

601	This past week, how many times did you use a public latrine?: ☐ Everyday ☐ Never ☐ A few times a week ☐ No response ☐ Once a week
602	This past week, how many times did you go to the market: ☐ Everyday ☐ Never ☐ A few times a week ☐ No response ☐ Once a week
603	This past week, how many times did you eat raw produce?: ☐ Everyday ☐ Never ☐ A few times a week ☐ No response ☐ Once a week
604	This past week, how many times did you buy food from a vendor?: ☐ Everyday ☐ Never ☐ A few times a week ☐ No response ☐ Once a week

7.0 Beach

701	This past month, how many times did you go to the beach? (This is for any reason, including recreational, buying, selling, etc): ☐ Everyday ☐ 5 to 10 times ☐ 1 to 4 times ☐ Never ☐ No response
702	In a regular week, when there are no restrictions on going to the beach, how often does your youngest child go to the beach?: ☐ Everyday ☐ Once a week ☐ Twice a week ☐ None ☐ Other
703	Do you have a job that puts you in contact with sea water?: ☐ Yes ☐ Don't know ☐ No ☐ No response
704	Does anyone other than you in your household have a job that puts them in contact with sea water?: ☐ Yes ☐ Don't know ☐ No ☐ No response
705	How often do you get into sea water when you go to the beach: ☐ Everytime ☐ Never ☐ Sometimes ☐ No response

7

8.0 Flooding

801 In the past year, has your compound flooded?:

- ☐ Yes
- ☐ Don't know
- ☐ No
- ☐ No response

9.0 Schools **(If no children, End of Survey**

901 Do any children in your household attend nursery school?:

- ☐ Yes
- ☐ Don't know **(End Survey)**
- ☐ No **(End Survey)**
- ☐ No response **(End Survey)**

902 If yes, how many of them?: ______

903 If yes, how many days per week? (If more than one child, ask this question for the youngest of them): ______

904 If yes, how many hours per day? (If more than one child, ask this question for the youngest of them): ______

905 How often does your child purchase food at school:

- ☐ Everytime
- ☐ Sometimes
- ☐ Never
- ☐ No response **Skip to 906**

906 If never, why?:

- ☐ Food carried from home
- ☐ School feeding program

Comments

Enumerator code ______

Data entry code ______

8

C. Drain Characterization Tool

Drain Characterization Tool:

Date (DD/MM/YY): Unique ID:

GPS ID: Pictures taken?:

Neighborhood: Alajo Bukom Old Fadama Shaibu

Time stamp:

Descriptions:

1. Size of drain:

Small	Medium	Large	Extra Large
<0.5m	0.5-1m	1-3m	>3m

2. Where is the drain located:

Side of street (One side / Both sides) Between buildings Terminal to the sea Terminal outside neighborhood

Branching point Merging point Round corner 90° corner

3. What's located "around (within 2 m radius)" the drain (circle all that apply):

Nursery, Primary School Homes Businesses Agriculture

Vendor Stand Water Pipes Latrine Bathing Facility

4. Water level of the drain at time of observation:

Low Medium High Dry Unable to see

5. Water in the drain stagnant or moving:

Moving Stagnant N/A

6. If water is moving, what direction is the water flowing:

N NE E SE S SW W NW N/A

Write in description of direction of flow ______________________________

7. Drain covered or uncovered:

Uncovered Covered by city Covered by citizens Unknown source

8. If covered by city, scale of coverage as far as eye can see:

1	2	3	4	5
only a few areas covered	about 50%	about 75%	Almost all of drain is covered	Completely covered

9. If covered by citizens, scale of coverage as far as eye can see:

1	2	3	4	5
only a few areas covered	about 50%	about 75%	Almost all of drain is covered	Completely covered

9. Drain formally or ecologically constructed:

Formally by city Formally by citizens Ecologically

10. Drain cement lined or dirt lined:

Cement Stones Dirt Mixed

D. Pictorial Examples of Drain Classifications

Figure D.1. Drain size

Small

Medium

Large

Extra-large

Photos courtesy of Stephanie Gretsch

Figure D.2. Drain water level

Photos courtesy of Stephanie Gretsch

Figure D.3. Drain coverage

Coverage by city — Coverage by citizens

Photos courtesy of Stephanie Gretsch

Figure D.4. Drain construction type

Formal by city | Formal by citizens | Ecological

Photos courtesy of Stephanie Gretsch

E. Structured Observation Tool

Drain Description and Conditions Strucured Observation

page 1/2

Observation start time [ ] : [ ]

Observation end time [ ] : [ ]

Date [ ] / [ ] / [ ]

	Small Drain (less than ½ meter across)	Medium Drain (½ to 1 meter across)	Large Drain (more than 1 meter across)
GPS latitude			
GPS longitude			
Photo			

Description

Drain construction type	1) planned/cemented 2) unplanned/dirt ditch	1) planned/cemented 2) unplanned/dirt ditch	1) planned/cemented 2) unplanned/dirt ditch
Environment around drain (within 2m radius). Check all that apply.	1) schools 2) homes 3) businesses 4) market/vendor food 5) urban agriculture site 6) latrine/bathing facilites	1) schools 2) homes 3) businesses 4) market/vendor food 5) urban agriculture site 6) latrine/bathing facilites	1) schools 2) homes 3) businesses 4) market/vendor food 5) urban agriculture site 6) latrine/bathing facilites
Water level of the drain at time of observation	1) low (bottom of drain is dry or partially covered in water, not all contents are suspended in water) 2) medium (bottom of drain is covered in water, all contents are suspended in water) 3) high (high water level, within 3cm of top or overflowing)	1) low (bottom of drain is dry or partially covered in water, not all contents are suspended in water) 2) medium (bottom of drain is covered in water, all contents are suspended in water) 3) high (high water level, within 3cm of top or overflowing)	1) low (bottom of drain is dry or partially covered in water, not all contents are suspended in water) 2) medium (bottom of drain is covered in water, all contents are suspended in water) 3) high (high water level, within 3cm of top or overflowing)
Is the water in the drain stagnant or moving?	1) stagnant 2) moving	1) stagnant 2) moving	1) stagnant 2) moving

Enumerator code [ ]

Location ID [ ]

SANIPATH

Drain Description and Conditions
Strucured Observation

page 2/2

Observations	Small Drain (less than ½ meter across)	Medium Drain (½ to 1 meter across)	Large Drain (more than 1 meter across)
Number of children under 5 inside the drain			
Number of children 5-12 inside the drain			
Number of adults (ages 12+) seen defecating into/inside drain			
Number of children under 5 seen defecating into/inside drain			
Number of children 5-12 seen defecating into/inside drain			
Dumping into drain (sullage, potty contents, poly bags)			

List other activities observed inside drain

Enumerator code

Location ID

SANIPATH

F. Environmental Sample Collection Form

Small Volume Environmental Water
Environmental Sample Collection Form

Barcode

Date

Time

1. GPS latitude N05.

   GPS longitude W000.

2. Select the neighborhood:
   - ☐ Alajo
   - ☐ Old Fadama
   - ☐ Bukom
   - ☐ Shaibu

3. Location ID:

4. Sample source (select one)
   - ☐ Hand-washing buckets
   - ☐ Produce washing water
   - ☐ Other   If "other," specify:
   - ☐ Open drain

   4a. If open drain (select one):
   - ☐ Small drain
   - ☐ Medium drain
   - ☐ Large drain

   4b. Check box if drain is within 3m of HH compound? ☐

   4c. If "Yes", check box:
   - ☐ Exposed to sunlight?
   - ☐ Near prepared food?
   - ☐ Within 3m of feces?
   - ☐ Within 30m of latrine or defecation area?

5. Physiochemical Characteristics

   Turbidity

   Temperature

Notes

Picture taken? ☐

Picture 1

Picture 2

Picture 3

Collector   Data Entry Code: