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Quantitative Microbial Risk Analysis to evaluate health effects of interventions in the urban water system of Accra, Ghana

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ABSTRACT

A quantitative microbial risk assessment was applied to evaluate the microbial risks of the Accra Urban Water System (AUWS). The exposure assessment was based on the count of indicator organisms in waste water from open roadside drains and in water and sand samples from the beach. The predicted total disease burden generated in a representative catchment of the AUWS (Odaw Catchment) was 36,329 Disability Adjusted Life Years (DALYs) per year, of which 12 and 88% are caused by, respectively, shortcomings in the water supply system and inappropriate sanitation. The DALYs per person per year were above the WHO reference value. The open roadside drain had the highest contribution to the disease burden. Of four possible interventions evaluated for health risk reduction, the highest efficiency in terms of DALYs averted per euro invested would be achieved by providing covers for the open roadside drains.

Key words | DALY, disease burden, health benefit, quantitative microbial risk assessment, urban water system

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INTRODUCTION

Lack of proper water supply, sanitation, flood protection and solid waste collection are serious environmental problems escalating in sub-Saharan Africa due to the large growing urban population (Barten *et al.* 2008). Currently, nearly 300 million people in this part of the world do not have access to clean drinking water and 440 million do not have access to basic sanitation (G8 2007). As a result, the urban water system has become a health hazard, especially for vulnerable groups like the elderly, pregnant women and children.

In Ghana, the urban population is 88% of the total population due to population growth and rapid urbanization (Ghana Statistical Service 2005). A large fraction of the urban dwellers do not have access to a reliable piped water supply system and many do not have access to sanitation. According to the Ghana Statistical Service

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(2005), only 44% of the households in Accra have access to pipe-borne water inside the house and as few as 13% are connected to a sewer system. Most Ghanaian households that do have sanitation discharge the black waste water into a septic tank or a soak-away. These septic tank effluents and overflows from soak-aways are often discharged in small roadside stormwater drains. Grey waste water is also discharged into these stormwater drains. The small drains combine into larger drains that finally discharge into the rivers, which ultimately discharge into the sea. One of these large and heavily polluted stormwater drains is the Odaw drain, located in the western part of Accra. Storm events cause regular flooding of the Odaw drain, affecting thousands of mostly poor inhabitants that live alongside it. One of the reasons for the flooding of the drains is the accumulation of solid waste in them, due to the absence of a solid waste collection system.

The current state of the water system is a health hazard for Accra's population. Various projects are underway to improve this situation. However, in Accra, as in most developing countries, the available budgets are not sufficient to address all disease transmission pathways all over the city (Mara 2003). Therefore, it is essential to target investments in the urban water system to maximize the positive health effects of the investments made (Hutubessy *et al.* 2003). Unfortunately, planners and decision makers in many cities have no access to tools to optimize the health benefits of the investments in the urban water system. This paper therefore applied a Quantitative Microbial Risk Assessment (QMRA) (Westrell *et al.* 2004) to quantify the public health risk generated in the Accra urban water system (AUWS). Furthermore, the possible health benefits associated to a selection of interventions to improve the urban water system are compared.

MATERIALS AND METHODS

Description of the study area

This study was undertaken in the Accra Metropolitan Assembly (AMA), the capital city of Ghana, with an estimated population of about 1.6 million people (Ghana Statistical Service 2005). The selected study area was the part of Accra draining into the Odaw catchment and Korle lagoon, comprising about 60% of the total AMA population. The mean annual rainfall in Accra is 887 mm and the mean temperature varies between 20 and 30°C (Ghana Statistical Service 2005). According to Ghana Statistical Service (2005) the population density was estimated to be 896 persons per square kilometre with a growth rate of 4.4% per year according to the 2000 census. High inequality exists in the income level of residents: in the high-income zones with appropriate neighbourhood infrastructure the average annual per capita income was estimated to be 8,000 USD. In contrast, this was estimated to be 410 USD in the lower-class income zones. These areas of the city are mostly unplanned and characterized by poor or non-existent neighbourhood infrastructure and utilities (lack of sanitation infrastructure) (AMA 2007).

Sampling sites and collection

The neighbourhoods of Nima and James Town were selected as the sampling sites as they have heavily polluted open drains, where especially children may come into contact with water. Selection criteria were high population density, low income and poor sanitation. In each site, three sampling points were identified. On three sampling days, samples were collected in the morning (between 7 h 30 and 9 h 30) and in the afternoon (between 14 h and 16 h). A total of 36 grab samples were collected from the six sampling points. 250-ml samples were used for bacteriological analyses and 1-litre samples for helminth eggs count. In addition, samples of sand and seawater were collected at two different beaches on three days: one behind Independence Square and one near Lapalm Beach Hotel. These were selected due to their accessibility and the number of visitors. On each beach, three separate samples were collected and mixed. The composite sand samples were obtained from dry and wet sand.

Sample analysis

All samples for bacterial analysis were transported to the laboratory on ice and processed within three hours. *Escherichia coli*, total coliforms, *Salmonella* and other Enterobacteriaceae were assessed by using the spread plate method with Chromocult Coliform Agar (AWWA 1985). Helminth eggs analysis was done according to Schwartzbrod (1988).

Quantitative microbial risk assessment

To carry out a QMRA, four steps are involved: hazard identification, exposure assessment, dose–response analysis and risk characterization (Haas *et al.* 1999). Four reference pathogens were chosen to represent bacteria, viruses, protozoa and helminths (WHO 2004): *Campylobacter*, Rotavirus, *Cryptosporidium* and *Ascaris*, respectively. *Salmonella* was added due to its easy detection in the field measurements.

The data required for QMRA was partly collected from water sector institutions in Accra, partly from the literature and partly from actual measurements of pathogen concentrations (see above). A comprehensive field survey was done in order to determine the potential exposure pathways and exposed population. This was complemented with interviews with water supply and waste water experts. A small survey was done to estimate the number of bathers exposed and the frequency of visiting.

An *E. coli*: pathogen ratio was used to calculate the concentration of pathogens: the *E. coli*: Rotaviruses, *E. coli*: *Campylobacter* and *E. coli*: *Salmonella* ratio was assumed to be 1: 10^5 and the *E. coli*: *Cryptosporidium* and *E. coli*: *Ascaris* ratio to be 1: 10^6 (Howard *et al.* 2007; Mara *et al.* 2007). The dose was calculated as the product of the concentration of pathogens at a specific exposure route and the volume ingested. From this, the annual probability of developing illness and the annual number of symptomatic cases were calculated as suggested by Haas *et al.* (1999). Table 1 gives the overview of the dose–response parameters used in the QMRA.

Calculation of disease burden

The disability adjusted life year (DALY) is an indicator of the time lived with a disability and the time lost due to premature mortality (WHO 2004). DALYs were calculated for each pathogen according to Havelaar & Melse (2003). The average life expectancy at birth for Ghana (57 years: Ghana Statistical Service 2005) was used in the calculations.

It was assumed that there are no interactions between different exposure events, i.e. exposure to one pathogen does not affect the likelihood of exposure to or infection by other pathogens. For each pathogen, health outcomes, duration and severity weights were identified from the literature (see Table 2 for calculations).

Rotaviruses

The disease outcomes, severity weights and duration of disease due to Rotaviruses were based on Havelaar & Melse (2003). The case fatality ratio for Rotavirus was 0.7% (Howard *et al.* 2006). The mortality burden for both pathogens was based on an average age of death at 1 year.

Cryptosporidium

The disease outcome was taken to be watery diarrhoea with a mean duration of 7.2 days (Havelaar & Melse 2003). Cryptosporidiosis is mild and self-limiting for the population at large but has a high mortality rate among those who test positive for HIV/AIDS (WHO 2004). This group was used to calculate the mortality burden (Howard *et al.* 2006).

Table 1 | Dose–response parameters used in the QMRA

Organisms	Parameters	Type of model	Sources
Campylobacter	$\alpha = 0.145$; $N_{50} = 896$; $P_{DI} = 0.3$	ß Poisson model	Haas *et al.* (1999) and WHO (2004)
Salmonella	$\alpha = 0.3126$; $N_{50} = 23600$; $P_{DI} = 0.3^*$	ß Poisson model	Haas *et al.* (1999) and WHO (2004)
Rotavirus	$\alpha = 0.2531$; $N_{50} = 6.17$; $P_{DI} = 0.5$	ß Poisson model	Haas *et al.* (1999) and WHO (2004)
Cryptosporidium	$r = 0.00419$; $P_{DI} = 0.7$	Exponential	Teunis *et al.* (1996)
Ascaris	$r = 0.0199^{\dagger}$; $P_{DI} = 0.39$	Exponential	Haas *et al.* (1999) and Bitton (2005)

*The P_{DI} value for *Campylobacter* was also used for *Salmonella*.
†Dose–response parameter for *Giardia* was used because *Giardia* and *Ascaris* have the same infective dose (Bitton 2005).

Table 2 | Severity, duration and disease burden per case for pathogens included in the study

Pathogen	Outcomes	Severity*	Duration*,†	Disease burden per case in DALYs‡,§
Campylobacter				
	Gastroenteritis			
	No GP (94%) of all cases	0.067	3.48 days (0.009 years)	$0.94 \times 0.067 \times 0.009 = 6.0 \times 10^{-4}$
	GP only (6%)	0.39	9.72 days (0.026 years)	$0.06 \times 0.39 \times 0.026 = 6.2 \times 10^{-4}$
	Hospitalization (9%)	0.39	14.39 days (0.039 years)	$0.09 \times 0.39 \times 0.039 = 1.3 \times 10^{-3}$
	Fatal (0.1%)	1	56 years	$0.001 \times 1 \times 56 = 0.056$
	Rea (7% of all cases)			
	No GP (85.8%)	0.127	222 days (0.6 years)	$0.071 \times 0.858 \times 0.127 \times 0.6 = 4.6 \times 10^{-3}$
	GP only (22%)	0.21	222 days (0.6 years)	$0.071 \times 0.223 \times 0.21 \times 0.6 = 1.9 \times 10^{-3}$
	Hospitalization (2.20%)	0.37	222 days (0.6 years)	$0.071 \times 0.220 \times 0.37 \times 0.6 = 3.4 \times 10^{-3}$
	Total			0.068
Salmonella				
	Gastroenteritis			
	No GP (94%) of all cases	0.067	5.58 (0.015)	$0.94 \times 0.067 \times 0.015 = 9.6 \times 10^{-4}$
	GP only (6%)	0.393	10.65 (0.029)	$0.06 \times 0.39 \times 0.029 = 6.8 \times 10^{-4}$
	Hospitalization (9%)	0.393	16.15 (0.044)	$0.09 \times 0.39 \times 0.044 = 1.5 \times 10^{-3}$
	Fatal (0.1%)	1	56	$0.001 \times 1 \times 56 = 0.056$
	Rea (8%)			
	No GP (85.8%)	0.127	222 days (0.6 years)	$0.08 \times 0.858 \times 0.127 \times 0.6 = 5.2 \times 10^{-3}$
	GP only (22%)	0.21	222 days (0.6 years)	$0.08 \times 0.223 \times 0.21 \times 0.6 = 2.2 \times 10^{-3}$
	Hospitalization (2.20%)	0.37	222 days (0.6 years)	$0.08 \times 0.220 \times 0.37 \times 0.6 = 3.9 \times 10^{-4}$
	Total			0.067
Rotavirus				
	Mild diarrhoea (85.6% of all cases)	0.1	7 days (0.02 years)	$1 \times 85.6\% \times 0.10 \times 0.02 = 0.002$
	Severe diarrhoea (14.4% of all cases)	0.23	7 days (0.02 years)	$1 \times 14.4\% \times 0.23 \times 0.02 = 7.0 \times 10^{-4}$
	Death	1	56 years	$1 \times 0.7\%$ (death) $\times 56 = 0.392$
	Total			0.39
Cryptosporidium				
	Watery diarrhoea	0.067	7.2 days (0.02 years)	$1 \times 0.067 \times 0.02 = 0.0013$
	Death	1	22.5 years	$1 \times 0.41\%$ (death) $\times 22.5 = 0.09$
	Total			0.09
Ascaris				
	Intestinal obstruction, population	0.024	35 days (0.1 years)	$1 \times 0.024 \times 0.1 = 0.0024$
	Contemporaneous cognitive deficit (5% of all cases)	0.006	28 days (0.08 years)	$1 \times 5\% \times 0.006 \times 0.08 = 2.4 \times 10^{-5}$
	Death	1	56 years	$1 \times 0.08\%$ (death) $\times 56 = 0.045$
	Total			0.05

*The severity weights and duration of disease, Rotavirus and *Cryptosporidium* were from Havelaar & Melse (2003). Severity weights and duration of the outcomes due to *Salmonella* and *Campylobacter* infections were from Kemmeren *et al.* (2006). Duration of disease following *Ascaris* infection was taken from Bundy *et al.* (1997), while the severity weight was taken from Lopez *et al.* (2006).

†The years of life lost following death from *Campylobacter*, Rotavirus and *Ascaris* was taken to be the life expectancy at birth of Ghana – death at age of 1 year ($57 - 1 = 56$ years); as for *Cryptosporidium*, this was calculated from the HIV/AIDS group who already have a reduced life expectancy.

‡The sources of case fatalities included: *Salmonella* and *Campylobacter* (Haas *et al.* 1999), Rotavirus (Howard *et al.* 2006), *Cryptosporidium* (based on the 10% HIV/AIDS prevalence in Accra), *Ascaris* (Crompton 1999).

§DALYs = Number (of symptomatic cases) × severity weight × duration in years.

The HIV/AIDS prevalence rate in Accra was estimated to be 4.1% in 2002 (UNAIDS 2006). The mortality rate among this group was assumed to be 10% (Havelaar & Melse 2003), thus giving a case fatality rate of 0.41%. The years-of-life-lost among this group was calculated in three different groups. NACP (2001) estimate that 89% of HIV/AIDS infections in Ghana occur in the age group 15–49 years, 8% in the age group 50–59 years and 3% in the age group 0–14 years. The mean age of death for each age group was calculated based on the information that a person with full-blown AIDS will die after approximately 1.5 years (NACP 2001). This gave the mean age of death at 33.5 years, 56 years and 8.5 years, respectively. The estimate on the years-of-life-lost due to cryptosporidiosis was based on a weighted average (22.5 years lost).

Ascaris

The disease outcomes following *Ascaris* infection were defined as high intestinal obstruction in children and cognitive deficit (Mathers *et al.* 2003). It is estimated that 5% of the cases will develop contemporaneous cognitive deficit. The mean duration and the severity weights were taken from Bundy *et al.* (1997) and Lopez *et al.* (2006), respectively. Death of some children might occur and, therefore, the mean age of death was assumed to be 1 year with a case fatality of 0.08% (Crompton 1999).

Campylobacter and *Salmonella*

The outcomes of *Campylobacter* and *Salmonella* are mild diarrhoea and severe gastrointestinal illness with a duration between 3 days and lifelong. However, for some patients the disease can be fatal; the fatality ratio for these pathogens is 0.1% (Haas *et al.* 1999). Severe gastrointestinal illness may result in complications. The most important sequela during the complications due to *Campylobacter* and *Salmonella* infections is Reactive Arthritis (ReA) (Kemmeren *et al.* 2006). This could be followed by Inflammatory Bowel Disease (IBD), which is a chronic intestinal disorder. *Campylobacter* may cause also a neurological disease called Guillain–Barré syndrome (GBS). However, IBD and GBS are not included in the disease burden calculation due to the lack of data. It is estimated that 8 and 7% of all cases due to, respectively, *Salmonella* and *Campylobacter* infections would develop sequelae and 22% will need medical help (Kemmeren *et al.* 2006).

RESULTS

Exposure assessment

The field survey and interviews revealed that a significant number of different exposure routes exist in Accra (Tables 3 and 4), which may be grouped under the headings of water supply and sanitation.

Exposure via contaminated water supply

Production of drinking water from surface water in Accra (Weija and Kpong treatment plants) proceeds via the following steps: coagulation/flocculation, slow sand filtration and chlorination. These steps were identified as critical points that could, in the case of malfunctioning, lead to pathogen breakthrough. Interviews at the treatment plants made clear that power outages and filtration errors occurred at the Weija water treatment plants; and coagulation, disinfection and filtration errors at the Kpong treatment plants.

The likely removal of pathogens through different treatment processes was calculated by assigning log removal credits for every treatment step (Tables 5 and 6). Assuming that 95% of the thermotolerant coliforms are *E. coli* (WHO 2006), the *E. coli* concentration of the raw water was estimated at 15.2 microorganisms/100 mL and 7.6 microorganisms/100 mL at the Weija and Kpong treatment plants, respectively (ATMA, unpublished data; Weija Waterworks, unpublished data). The concentration of each pathogen was calculated based on the drinking water quality, the *E. coli:* pathogens ratio and taking into account the frequency of failure events (Table 3).

Besides the treatment procedure, the distribution system was selected as the critical point because the interviews revealed that there is an intermittent water supply in Accra as well as fluctuations in pressure. Therefore, the risk of infection from the distribution network (Table 5) was estimated using data on the microbiological quality of tap water from Cobbina (2004), who found that the *E. coli* concentration in tap water in Accra was 0.23 microorganisms/100 mL.

Table 3 | Ingestion, frequency, exposed population and concentration of pathogens for the water supply pathways

				Microorganisms/100 ml				Cysts/100 ml
Type of exposure[a]	**Volume (ml)**	**Frequency (per year)**	**Exposed population**	***E. coli***	***Campylobacter***	***Salmonella***	**Rotavirus**	***Cryptosporidium***
1. Power outage at Weija treatment plant	2900[b]	3.6	646,986[d]	44[g]	2.62×10^{-7}	2.6×10^{-7}	4.1×10^{-9}	2.6×10^{-7}
2. Filtration error at Weija treatment plant	2900	1	646,986[d]	44[g]	2.62×10^{-9}	2.62×10^{-9}	2.21×10^{-7}	1.52×10^{-6}
3. Disinfection error at Kpong treatment plant	2900	365	348,378[e]	22[g]	6.21×10^{-10}	6.21×10^{-10}	1.31×10^{-7}	7.59×10^{-8}
4. Coagulation error at Kpong treatment plant	2900	365	348,378[e]	22[g]	6.21×10^{-8}	6.2×10^{-8}	1.3×10^{-7}	7.6×10^{-8}
5. Filtration error at Kpong treatment plant	2900	1	348,378[e]	22[g]	2.10×10^{-7}	2.10×10^{-7}	4.14×10^{-6}	2.41×10^{-6}
6. Contaminated distribution system	2900	146[c]	944,678[f]	6.6	2.31×10^{-6}	2.31×10^{-6}	2.31×10^{-6}	2.31×10^{-7}
7. Pollution entering part of system without pressure (108 h per week)[h]	2900	234	298,609	6.6	2.31×10^{-6}	2.31×10^{-6}	2.31×10^{-6}	2.31×10^{-7}
8. Pollution entering part of system without pressure (120 h per week)[i]	2900	260	348,378	6.6	2.31×10^{-6}	2.31×10^{-6}	2.31×10^{-6}	2.31×10^{-7}

[a]Exposure routes 3and 4 were based on normal operations at Kpong while 1, 2 and 5 were based on incidents.
[b]Watanabe *et al.* (2004) cited by Howard *et al.* (2007).
[c]40% of the year, estimated from previous research (Cobbina 2004).
[d]65% of the population of Odaw catchment.
[e]35% of AMA population.
[f]Population of Odaw catchment without the population of Accra New Town (50,685) as it is without water supply.
[g]Concentration of *E. coli* in raw water at Weija and Kpong treatment plants (ATMA, unpublished data; Weija Waterworks, unpublished data).
[h]30% of the population receives water 12 hours a day, five days a week (Wateraid 2006).
[i]35% of the population receives water twice a week (Wateraid 2006).

Table 4 | Volume ingested, frequency, exposed population and concentration of pathogens in the sanitation pathway

				Microorganisms/100 ml				Oocysts/100 ml	Eggs/l
Type of exposure	**Volume ingested (ml)**	**Frequency (per year)**	**Exposed population**	***E. coli***	***Campylobacter*[f]**	***Salmonella***	**Rotavirus**	***Cryptosporidium***	***Ascaris***
1a. Recreational swimming	75	2	42.303	1×10^{4}[a]	0	0[a,e]	1.7×10^{-2}	1.7×10^{-3}	0[a,e]
1b. Beach sand	5	2	52.256	1×10^{6}[a,d]	9×10^{5}	9×10^{5}[a,d]	1.5×10^{1}	1.5	0[a,e]
2a. Unintentional ingestion of flood water	1	1	111,790	1×10^{6}[b]	1.2×10^{1}	1.2×10^{1}	1.2×10^{1}	1.2	1.2×10^{1}
2b. Unintentional immersion at lagoon	30	1	10	1×10^{6}[b]	1.2×10^{1}	1.2×10^{1}	1.2×10^{1}	1.2	1.2×10^{1}
2c. Children playing in flood water	1	1	23,699	1×10^{6}[b]	1.2×10^{1}	1.2×10^{1}	1.2×10^{1}	1.2	1.2×10^{1}
3a. Workers desludging the waste water treatment plant (WWTP)	5	12	10	1×10^{8}[c]	1.2×10^{3}	1.2×10^{3}	1.2×10^{3}	1.2×10^{2}	1.2×10^{3}
3b. Workers removing debris from the WWTP inlet works daily during the rainy season	1	90	10	1×10^{8}[c]	1.2×10^{3}	1.2×10^{3}	1.2×10^{3}	1.2×10^{2}	1.2×10^{3}
3c. Workers taking samples from the WWTP inlet works for laboratory analysis	0.1	1	3	1×10^{8}[c]	1.2×10^{3}	1.2×10^{4}	1.2×10^{3}	1.2×10^{2}	1.2×10^{3}
4a. Septic truck staff handling septage at the faecal septage disposal place	1	317	100	1×10^{8}[c]	1.2×10^{3}	1.2×10^{3}	1.2×10^{3}	1.2×10^{2}	1.2×10^{3}
4b. Children playing with contaminated sand at the faecal septage disposal place (Lavender Hill)	5	2	4.018	1×10^{8}[c]	1.2×10^{3}	1.2×10^{3}	1.2×10^{3}	1.2×10^{2}	1.2×10^{3}
4c. Fishermen ingesting contaminated water at the shore next to the faecal septage disposal point	1	1	10	1×10^{8}[c]	1.2×10^{3}	1.2×10^{3}	1.2×10^{3}	1.2×10^{2}	1.2×10^{3}
5. Children playing near open drainage channels	5	4	52, 624	1×10^{8}[a]	4.31×10^{7}	4.31×10^{7}[a]	1.2×10^{3}	1.2×10^{2}	0.7[a]

[a]Field measurement.
[b]Nana-Amankwaah, unpublished.
[c]Assumption.
[d]In microorganisms per g dry weight.
[e]Not detected.
[f]*Campylobacter* was assumed to be similar to *Salmonella*.

Table 5 | Log reduction of microorganisms in drinking water by various processes*

Process	Bacteria	Viruses	Protozoa
1. Coagulation/flocculation/sedimentation			
Baseline removal	0.2 (30%)	0.2 (30%)	0.2 (30%)
Maximum removal	1 (90%)	0.52 (70%)	1 (90%)
2. Granular high-rate filtration			
Baseline removal	–	–	0.52 (70%)
Maximum removal	2 (99%)	3 (99.9%)	3 (99.9%)
3. Slow sand filtration			
Baseline removal	0.3 (50%)	0.1 (20%)	0.3 (50%)
Maximum removal	2.3 (99.5%)	4 (99.99%)	2 (99%)
4. Chlorination†			
Median and range of removal	3.5 (2.5–5.0)	2.0 (1.5–3.0)	0.4 (0–1)

*Source: adapted from WHO 2004.
†Adapted from Westrell et al. (2003), showing median and range of removal.

Table 6 | Log removal of pathogens at the two treatment plants in the event of failures, based on Table 5

Incidents	*Campylobacter*	Rotavirus	*Cryptosporidium**
Weija treatment plant			
1. Power Outage (disinfection error, coagulation error, filtration error)			
Coagulation/flocculation	0	0	0
Slow sand filtration†	0.3	0.1	0.3
Chlorination	0	0	0
Total log reduction	0.3	0.1	0.3
2. Filtration error			
Coagulation/flocculation	1	0.52	1
Slow sand filtration	0	0	0
Chlorination	3.8	2.3	0
Total log reduction	4.8	2.83	1
Kpong treatment plant			
3. Disinfection error			
Coagulation/flocculation‡	0.5	0.26	0.5
Rapid sand filtration§	1	1.5	1.5
Chlorination¶	1.6	1	0
Total log reduction	3.1	2.76	2
4. Coagulation error			
Coagulation/flocculation‡	0.5	0.26	0.5
Rapid sand filtration§	1	1.5	1.5
Chlorination¶	1.6	1	0
Total log reduction	3.1	2.76	2
5. Filtration error			
Coagulation/flocculation	0.5	0.26	0.5
Rapid sand filtration	0	0	0
Chlorination	1.6	1	0
Total log reduction	2.1	1.26	0.5

*Chlorine was assumed to have no effect on *Cryptosporidium* (WHO 2004).
†If there is no coagulation, slow sand filtration will only achieve baseline removal (Table 5).
‡50% removal was assumed since the required log removal is a combination of both coagulation and filtration (Stanfield et al. 2003). Currently no coagulation takes place at Kpong treatment plant.
§50% removal was assumed since effective filtration depends on effective coagulation (Stanfield et al. 2003; LeChevallier & Au 2004).
¶Using five bags of the disinfectant instead of 12 means that only 42% disinfection is achieved.

Exposure via sanitation

Five major exposure routes were identified in the sanitation system. These are: recreational swimming, flooding of the Odaw drain, waste water treatment plant, faecal septage disposal point and open roadside drains.

The concentration of pathogens in seawater and beach sand is reported in Table 7. In the open roadside drains, the mean concentration of *Escherichia coli*, total coliforms, *Salmonella* and other enterobacter species was above 7 logs microorganisms/100 mL for all pathogens (Table 7). Helminth eggs were also detected in the open roadside drain, but not at the beach. The mean concentration in drainwater from the two locations (Nima and James Town) was 0.7 egg/L with a maximum of 3 eggs/L.

Risk of contamination and risk burden

The total number of infections due to *Salmonella*, *Campylobacter* or Rotavirus was above 5,000 per year (Table 8) and the highest number of infections was due to Rotavirus and *Campylobacter*. The lowest number of infections was due to *Ascaris* (1,163 infections). Among all the pathways under consideration, the highest number of cases was noticed at the open drain, irrespective of the pathogen (Table 9). The second major pathway was recreational swimming. Considering the entire Accra Urban Water System (AUWS), both the water supply and sanitation system could be a major threat to the citizens of Accra. However, sanitation contributed to a higher number of cases (Table 9).

The disease burden (DALYs) per case per pathogen was calculated (Table 2) and multiplied by the total number of

Table 7 | Concentrations of microorganisms in the open roadside drains, seawater and beach sand

Samples location	Units	*E. coli*	Total coliforms	*Salmonella*	Other Enterobacteriaceae	Number of samples
Open roadside drain	Log_{10} microorganisms/100 ml	8.0 ± 0.4	8.8 ± 0.4	7.7 ± 0.4	8.4 ± 0.3	36
Seawater	Log_{10} microorganisms/100 ml	3.6 ± 0.0	4.6 ± 0.4	n.d	5.9 ± 0.7	6
Beach sand	Log_{10} microorganisms/g of dry weight	6.0 ± 0.3	6.7 ± 0.4	4.8 ± 0.5	6.7 ± 0.5	6

n.d.: not detected.

Table 8 | Annual infections from sanitation and water supply pathways

Exposure routes	*Campylobacter*	*Salmonella*	Rotavirus	*Cryptosporidium*	*Ascaris*
Open drain	52587	52610	52280	5117	146
Recreational swimming	48064	43299	21400	321	0
Flooding of Odaw drain	313	2	8347	7	33
Faecal septage disposal	1998	86	3799	280	967
UASB	20	2	21	6	17
Sub-total sanitation	102983	96000	85848	5733	1163
Water treatment	123	1	4227	19	
Water distribution	483	3	13186	4	
Sub-total water supply	606	4	17413	23	
Total	103589	96004	103261	5756	1163

cases per pathogen. The total disease burden from the Accra urban water system was predicted to be 36,329 DALYs and the contribution of the open drain was 61% (Figure 1). The DALYs per person per year from the AUWS due to *Campylobacter*, *Salmonella*, Rotavirus, *Cryptosporidium* and *Ascaris* was, respectively, 4.0×10^{-3}, 4.0×10^{-3}, 3.0×10^{-2}, 4.0×10^{-4} and 2.0×10^{-5} (DALYs per agent/total population in the Odaw catchment of 995, 363 persons). If the reference risk of 1.0×10^{-6} DALYs per person per year (WHO 2004) were to be applied, then the

Table 9 | Number of cases and number of DALYs from the sanitation and water supply system

Exposure routes	Number of cases	Contribution of each exposure route to the number of cases (in %)	Number of DALYs per year	Contribution of each exposure route to the number of DALYs (in %)
Open drain	120468	64	22328	62
Recreational swimming	48396	26	6952	19
Flooding of Odaw drain	4285	2	1635	5
Faecal septage disposal	3878	2	1054	3
UASB	52	0	10	0
Sub-total sanitation	177082	94	31979	88
Water treatment	4559	2	1762	5
Water distribution	6757	4	2588	7
Sub-total water supply	11316	6.0	4350	12
TOTAL	188398		36329	

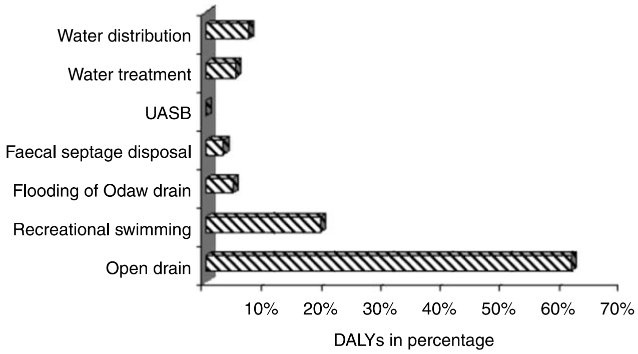

Figure 1 | Contribution of each exposure pathway to the total disease burden from water supply and sanitation.

disease burden from the AUWS is higher than the WHO reference for each pathogen. This is a threat to the citizens of Accra, and efforts should be made to reduce this risk.

DISCUSSION

Disease pathways in the urban water system of Accra

Contrary to most QMRA studies which are applied either to the water supply system or the sanitation system (Howard *et al.* 2006; Schönning *et al.* 2007), this study provides the health risks for the entire urban water system in Accra. The results show that the open roadside drain was the most hazardous disease transmission route, followed by recreational swimming (Figure 1). In Accra, the open drain is carrying not only storm water, but also septic tank overflows from more than 50% of the population (Ghana Statistical Service 2005). Therefore, the open roadside drains pose a serious health risk for Accra's citizens, especially children who may come into contact with the polluted water while playing in the street. Additionally, people eating raw vegetables irrigated by water from the drains are highly exposed. Unfortunately, this practice is common in Accra. Considering *Ascaris* and Rotavirus, the annual health risk due to these pathogens for the average consumer of lettuces irrigated with drainwater was estimated to be 100% (Seidu *et al.* 2008).

Within the water supply system, the risk associated with the water distribution system is larger than that of the water treatment. The same conclusion was drawn by Howard *et al.* (2006) in a study about the risk related to drinking water consumption in Uganda. Geldreich (1996) reported that the main risk from the water supply in developing countries is associated to the distribution network. In Accra, prolonged periods of low pressure in large parts of the distribution network are common, which may lead to intrusion of contaminated groundwater.

Pathogen concentrations in urban water of Accra

The concentration of bacteria in the open roadside drains indicated a high level of pollution (Table 7), which can be explained by the general lack of sanitation and the presence of both black and grey water in the drains (Obuobie *et al.*

Table 10 | Number of DALYs remaining after the interventions*

		Interventions			
Exposure routes	**DALYs per year (baseline)**	**A**	**B**	**C**	**D**
Open drain	22328	(5) 1116	(3) 670	(8) 1786	(100) 22328
Recreational swimming	6952	(100) 6952	(1) 69	(100) 6952	(100) 6952
Flooding of Odaw drain	1635	(10) 163	(8) 131	(2) 33	(100) 1635
Faecal septage disposal	1054	(50) 527	(0) 0	(100) 1054	(100) 1054
UASB	10	(100) 10	(97) 10	(100) 10	(100) 10
Sub-total sanitation	31979	8769	880	9835	31979
Water treatment	1762	(95) 1674	(75) 1321	(100) 1762	(10) 176
Water distribution	2588	(95) 2458	(75) 1941	(100) 2588	(10) 259
Sub-total water supply	4350	4132	3262	4349	435
TOTAL	36329	12901	4142	14184	32414

*The first value in brackets is the number of DALYs remaining, as a percentage of the baseline value; the second value (without brackets) is the expected number of DALYs per year remaining after the implementation of each intervention.

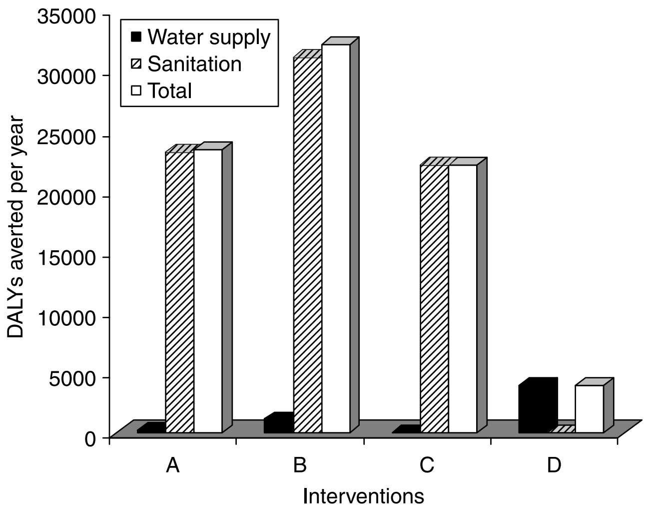

Figure 2 | DALYs averted after the interventions in Accra urban water system.

2006). Gbewonyo (2007) found 2×10^7 faecal coliforms/100 mL in open drains at urban agriculture sites in Accra. A similar value was found by Gbireh (1999): faecal coliform concentrations in various sources of water used for irrigation in Accra (drain and river) ranged from 10^5 to 10^8 microorganisms/100 mL. The values found in this research are at the higher end of this range, which could be explained by the location of the sampling sites (very close to the houses). During the transport of drainwater to the urban agriculture sites, dilution and decay will decrease their concentration. The presence of *Salmonella* in the drainwater was not surprising because at high concentrations of faecal coliforms, *Salmonella* is expected to be present as well (Elmanama *et al.* 2005).

The microbial pollution of the seawater along the shore was not unexpected, since from the roadside drains, the water flows without any treatment into the Odaw River which discharges into the ocean. The microbial pollution of the beach sand was higher than that of the seawater (Table 7). The sand offers a suitable environment for pathogen survival, due to its large area, and it therefore may act as reservoirs for microbial contaminants (Bonilla *et al.* 2007).

Ratio *E. coli* : pathogens

The use of *E. coli* : pathogens ratios to estimate the concentration of pathogens at various exposure routes could under- or overestimate the risk, while the ratio may be different for the various types of water. The ratio may vary due to the variation in environmental conditions, because different pathogens respond differently to certain specific ecosystem conditions. Considering the different exposure routes in Accra, the environmental conditions differ certainly from each other, and as such the uncertainty in the ratios increased the overall uncertainty in the predicted infection rates. Unfortunately no specific information on the ratios is available for Accra.

QMRA for decision making

The inventory of the disease transfer pathways and the quantification of cases likely to originate from those pathways allow the quantification of the positive health effect of interventions that are aimed to block these pathways. By calculating the ratio of positive health effects to the required financial investment, the efficiency of different interventions could be evaluated. The calculations below are based on interventions and associated costs as proposed by the Accra Sewerage Improvement Project (ASIP) (African Development Fund 2005). The following interventions were analysed.

Intervention A: sewerage network and sanitation facilities

The major components of this intervention are rehabilitation and extension of the separate sewerage network, rehabilitation of house connections and construction of a new sewerage network. The investment costs of these interventions are estimated at 17.5 US$ per capita. Operational costs were not considered.

Intervention B: sewage network and sanitation facilities combined with treatment plant

This combines intervention scheme A with sewage transfer facilities and treatment plants to ensure that the sewage will be treated in an appropriate way before it is discharged in the environment. For the implementation of all components of this intervention, the investment required is 35.8 US$ per capita per year. Operational costs were not considered.

Intervention C: coverage of the roadside drains

This intervention is not included in the Accra Sewerage Improvement Project (African Development Fund 2005) but, because of the major contribution of the open roadside drains to the disease burden in Accra (Figure 1), the efficiency of covering them in order to reduce the exposure of the population to the polluted drainwater also needs to be evaluated.

Intervention D: further improvement of water supply system

This intervention is included in this study in order to prioritize investments between improving the sanitation or water supply system.

By implementing the interventions, the percentage reduction of the number of cases for each intervention and exposure route was estimated on expert opinion, since no information is available in the literature (Table 10). The lower the number of remaining DALYs, the better is the intervention for health status improvement. The total number of DALYS averted per year was the highest for intervention B, the separate sewer system connected to a treatment plant (Figure 2). Interventions A (only sewerage) and C (covering roadside drains) would both have a somewhat smaller impact. The number of DALYs averted due to further improvements in the water supply system was very low. Taking into account the cost estimate of ASIP and the population of the study area (Odaw catchment), the implementation of intervention A will require the investment of 742 US$ per DALY averted while 1,105 US$ per DALY averted would be needed for intervention B. Since the health benefit of intervention C (coverage of the drains) is comparable to intervention A, and at the same time probably much cheaper, the achievable health benefits with a given budget are probably maximum for intervention C. In a recent study (Seidu, personal communication) the ratio of investment costs to health benefit of coverage of the drain has been assessed; this was estimated at 516 US$/DALY. Intervention D averts a relatively small number of DALYs. Since cost estimates are not available for this intervention, the efficiency in terms of DALYS averted per US$ invested cannot be evaluated for this option.

CONCLUSIONS

- The applied methodology can be used to compare between the different pathways and between the effects of different interventions.
- Though the results are subject to significant uncertainty, due to uncertainty in *E. coli* : pathogen ratios and because not all pathogens could be included in the analysis, it became clear that the water system is a serious health hazard for the citizens of Accra. The predicted disease burden is above the WHO reference value for each pathogen that was analysed.
- The disease transmission via the sanitation pathway is more important than transmission via the water supply pathway.
- The major transmission routes of waterborne diseases are the ingestion of contaminated water by children, while playing near open roadside drains (64% of DALYs), and the ingestion of polluted seawater or contaminated beach sand (26% of DALYs).
- Provision of a separate sewerage network, sanitation facilities and a waste water treatment plant had the largest impact on the reduction of the disease burden (DALYs averted). The coverage of the roadside drains had the highest efficiency in terms of DALYs averted per US$ invested.

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