Disentangling the Risk Factors and Health Risks Associated with Faecal Sludge and Wastewater Reuse in Ghana

Philosophiae Doctor (PhD) Thesis

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Summary

The reuse of faecal sludge and wastewater in agriculture is widespread worldwide. However, the practice is also associated with significant microbial health risks especially in countries where systems for the treatment and safe agricultural reuse of faecal sludge and wastewater either inadequate or non-existent. Thus, a major challenge is how to reduce the health risks associated with the practice without compromising on its benefits in these countries. Addressing this challenge requires a multi-faceted approach nested in an understanding of the exposure pathways and health risks associated with the practice for the effective development of risk mitigating measures. This thesis assesses the health risks associated with agricultural reuse of wastewater and faecal sludge in Ghana; and further assesses the effectiveness of potential interventions for mitigating the health risks. For this, an integrated methodology encapsulating stochastic and deterministic quantitative microbial risk assessment, epidemiology and cost-effectiveness analysis was employed.

The health risks for farmers irrigating with polluted drain and stream water and consumers of the irrigated lettuce in Ghana were above the WHO tolerable *Ascaris* and rotavirus infection risks. For farmers, on-farm contaminated soil was the most significant health hazard compared with the irrigation water. The infection risk for consumers of the stream and drain irrigated lettuce was not significantly affected by contamination during post-harvest handling. Non-treatment interventions at the farm and in the kitchens of fast-food sellers were both effective and cost-effective in safeguarding the health of consumers' of wastewater irrigated lettuce. The cost-effectiveness ratios (CERs) for the farm based and fast-food sector interventions were US$ 31/DALY (95% CI: 27-35) and US$ 67/DALY (95% CI: 58-76) respectively. A combination of on-farm and post-harvest intervention was also cost-effective, as long as the adoption rates of either farmers or street food sellers did not fall below 70%. The rehabilitation of existing wastewater treatment plants for irrigation was also cost-effective (US$ 31/DALY, 95% CI: 27 - 35); but the construction of a new-treatment plant for irrigation was not cost-effective (US$ 786/DALY, 95% CI: 678 - 893). The study recommends a combination of treatment and non-treatment interventions in safeguarding the health of consumers of wastewater irrigated vegetables.

Two traditional sludge drying methods *random spot spreading* and *pit containment* were employed by farmers to process sludge into 'cakes' before soil incorporation. Sludge dried for ≥60 days in the random spot spread and ≥90 days in the pit methods met the WHO monitoring benchmark for *Ascaris* and *E. coli* with respect to sludge application. By applying quantitative microbial risk assessment, the viral and *Ascaris* infection risks for for these sludge drying times for three exposure pathways a) accidental ingestion of small amounts of cakes; b) accidental ingestion of cake sludge-soil mixture; and c) inhalation of aerosols (for only viral infection) were assessed. The infection risks for the drying times in the three exposure pathways were acceptable given that the tolerable annual infection risks were 10^{-4} for rotavirus and 10^{-2} for *Ascaris*. Seasonality analysis of diarrhoeal disease incidence in sludge applying communities showed a higher diarrhoeal disease incidence (RR= 1.04, 95%CI: 0.61-1.45) in the period of sludge application than the period of non-sludge application (RR=0.99, 95% CI: 0.73-1.24). However, this trend was not statistically significant ($p > 0.05$). Both rainfall and temperature events as well as their lags were associated with the seasonal variations in diarrhoeal disease incidence. Further analysis of diarrhoeal disease incidence in sludge applying households using hierarchical effect decomposition models revealed that public domain risk factors were the most important determinants of diarrhoeal disease incidence in the sludge households. This was followed by domestic domain and distal socio-economic risk factors respectively. The combined population attributable fractions of the public domain risk factors was 24% accounted for by distance to water sources (18%) and sludge drying time (6%). Not washing hands with soap was the main risk factor in the domestic domain and contributed 18% of the diarrhoeal disease incidence. In the distal socio-economic block, the main risk factor was the wealth status of the households, contributing 15% of the diarrhoeal disease incidence. About 70% of the combined effect of the distal and public domain risk factors was mediated by the domestic domain factors in the pathway to diarrhoeal disease transmission. The study recommends an integrated multi-barrier risk management strategy for mitigating diarrhoeal disease transmission in the faecal sludge applying households focusing on the public (including the farm) and domestic domain risk factors.

Sammendrag

Avløpsvann og avløpsslam gjenbrukes i landbruket i store deler av verden, og dette får økt aktualitet. Denne praksisen kan imidlertid også medføre en betydelig helserisiko, spesielt i land hvor systemer for behandling er mangelfulle eller fraværende, og hvor de mangler rutiner for sikker gjenbruk av fekalt slam i landbruket. Det er derfor en hovedutfordring å finne ut hvordan helserisikoen knyttet til gjenbruk av avløpsvann og slam kan reduseres, slik at denne ressursen kan utnyttes videre i disse landene. For å kunne utvikle effektive risikoreduserende tiltak kreves det ulike faglige tilnærminger basert på en forståelse av eksponeringsveier og hvilken helserisiko som er knyttet til gjeldende praksis. I denne avhandlingen vurderes helserisiko ved gjenbruk av avløpsvann og avløpsslam i landbruket i Ghana, samt effektiviteten av potensielle intervensjoner for reduksjon i helserisiko. Vurderingene er gjennomført ved bruk av en integrert metodikk som omfatter stokastisk og deterministisk kvantitativ mikrobiell risikovurdering, epidemiologi og analyser av kostnadseffektivitet.

Helserisikoen for gårdbrukere som vanner med forurenset overvann og elvevann, og konsumenter av vannet salat i Ghana var høyere enn WHO´s anbefalte grenseverdi for akseptabel *Ascaris* og rotavirus infeksjonsrisiko. Stedlig forurenset jord utgjorde en større risiko for gårdbrukerne enn vannings-vann. Infeksjonsrisikoen for konsumenter av salat som var vannet med overvann og elvevann var ikke påvirket av kontaminering grunnet håndtering etter høsting.

Kostnadseffektiviteten for tiltak på gården og i gatekjøkken-sektoren var henholdsvis US $ 31/DALY (95% CI:27-35) og US $67/DALY (95% CI:58-76). En kombinasjon av tiltak på gården og tiltak etter høsting var også kostnadseffektivt, så lenge deltagelsen blant bønder og gatekjøkkenpersonalet ikke var under 70 %. Rehabilitering av eksisterende avløpsrenseanlegg til bruk i vanning var også kostnadseffektivt (US $ 31/DALY, 95% CI 27-35), men etablering av et nytt avløpsrenseanlegg til bruk i vanning var ikke kostnadseffektivt (UD $ 786/DALY, 95% CI:678-893). Studien anbefaler en kombinasjon av avløpsbehandling og tiltak uten behandling for å sikre helsen til konsumenter av grønnsaker som er vannet med avløpsvann.

Gårdbrukerne brukte to tradisjonelle slamtørkemetoder, tilfeldig punktspredning på jordet og avvanning i liten slamlagune, før nedmolding i jorda. Slammet som var tørket ≥ 60 dager ved tilfeldig punktspredning og ≥ 90 dager i slamlaguner, tilfredsstilte WHO´s grenseverdier med hensyn på innhold av *Ascaris* og *E.coli.* Ved hjelp av kvantitativ mikrobiell risikovurdering ble risikoen for virus og *Ascaris* infeksjon ved disse tørkemetodene vurdert for tre ulike eksponeringsveier, a) inntak av små mengder av tørket slam ved uhell; b) inntak av en blanding av tørrslam og jord ved uhell og c) inhalering av aerosoler (bare for virus infeksjon). Infeksjonsrisikoen ved de tre eksponeringsveiene ble vurdert til å være akseptabel, gitt at grensen for akseptabel årlig infeksjonsrisiko er 10^{-4} for rotavirus og 10^{-2} for *Ascaris*. En analyse av sesongvariasjoner i forekomst av diaré-sykdom i de samfunnene som gjenbruker slam viste en høyere forekomst (RR= 1.04, 95%CI: 0.61-1.45) i slamspredningsperioden, sammenlignet med perioden uten slamspredning (RR=0.99, 95% CI: 0.73-1.24). Denne tendensen var dog ikke statistisk signifikant (p >0.05). Både nedbørmengde og temperatur, samt deres forsinkelse bidro til sesongvariasjoner i diarétilfeller. Videre analyse av forekomst av diarésykdommer i ”slam-husholdningene” gjennomført ved hjelp av en hierarkisk dekomponeringsmodell, viste at de samfunnsrelaterte risikofaktorene var de viktigste determinantene for diarésykdom i disse husholdningene. Deretter fulgte risikofaktorer i husholdningen og sosio-økonomiske risikofaktorer. Av de samfunnsrelaterte faktorene var avstanden til vannkilder og slamtørketid de viktigste. Disse faktorene forklarte til sammen 24

% av alle diarétilfellene i husholdningene. Den viktigste risikofaktoren i husholdningen var manglende håndvask med såpe og utgjorde 18 % av dirétilfellene i husholdningen. Den viktigste sosi-økonomiske faktoren var velstandsnivå som forklarte 15 % av tilfellene. Omtrent 70 % av den kombinerte effekten av sosio-økonomiske og samfunnsrelaterte faktorer på overføring av diarésykdommer er påvirket av faktorer i husholdningen. Studien anbefaler et helhetlig rammeverk for risikohåndtering som fokuserer på risikofaktorer på gården, i lokalsamfunnet og i husholdningen, for å redusere forekomsten av diaré.

This work is dedicated to my parents

"*We ourselves feel that what we are doing is just a drop in the ocean. But the ocean would be less because of that missing drop*" **Mother Teresa (1910-1997)**

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List of Papers

This thesis is based on the following papers that will be referred to in the text by their Roman numerals

I. **Razak Seidu**, Arve Heistad, Philip Amoah, Pay Drechsel, Petter D. Jenssen and Thor Axel Stenström (2008) Quantification of the Health Risk Associated with Wastewater Reuse in Accra, Ghana: A contribution toward Local Guidelines *Journal of Water and Health* 06 (4): 461-471.

II. **Razak Seidu** and Pay Drechsel (2010) Cost-Effectiveness Analysis of Treatment and Non-Treatment Interventions for Diarrhoea Disease Reduction Associated with Wastewater Irrigation. In Pay Drechsel et al. (2010) Wastewater irrigation and health: assessing and mitigating risk in low-income countries. Earthscan, UK.

III. **Razak Seidu** and Thor Axel Stenström (2010) Occupational Health Risk of Cake Sludge Application in Northern Ghana. *Journal of Water Research (Submitted).*

IV. **Razak Seidu**, Thor Axel Stenström and Owe Löfman (2010) A Comparative Cohort Study of the Effect of Rainfall and Temperature on Diarrhoea Disease in Faecal Sludge Communities, Northern Ghana. *Journal of Water and Climate (Submitted)*

V. **Razak Seidu**, Owe Löfman, Pay Drechsel, Arve Heistad and Thor Axel Stenström (2010) Risk Factor Analysis of Diarrhoea disease in Faecal Sludge Applying Households using a Hierarchical Effect Decomposition Model. (*Manuscript*)

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Abbreviations

AATSE	Australian Academy of Technological Sciences and Engineering
CER	Cost-Effectiveness ratio
CHOICE	Choosing Interventions that are Cost-Effective
DALY	Disability Adjusted Life Year
FAO	Food and Agriculture Organization of the United Nations
HACCP	Hazard Analysis and Critical Control Points
HED	Hierarchical Effect Decomposition
ICER	Incremental Cost Effectiveness Ratio
IWMI	International Water Management Institute
PAF	Population Attributable Fraction
pppy	Per person per year
QMRA	Quantitative Microbial Risk Assessment
RR	Relative risk
TMA	Tamale Metropolitan Assembly
TS	Total Solids
USEPA	United States Environmental Protection Agency
WHO	World Health Organization
WWTP	Wastewater Treatment Plant
YLD	Years of Life with Disability
YLL	Years of Life Lost

1.0 INTRODUCTION

1.1 Extent and Drivers of Wastewater and Excreta Reuse in Agriculture

Wastewater[1] and excreta[2] reuse in agriculture has been practiced for centuries in different human civilizations. In Far East China, the art of excreta collection and reuse in agriculture was well advanced before 500 B.C; and in Latin America, excreta reuse was a common agronomic practice among the Incas and Aztecs civilizations. Centuries before the advent of advanced wastewater treatment technologies, the agricultural application of wastewater and excreta was widespread in many European countries (AATSE, 2004). Sewage farms were common in Germany and the U.K in the 14th and 16th Centuries respectively (Asano and Levine, 1996). Also, in Sweden, the application of latrine products on farms was common (Tingsten, 1911). More recently, wastewater and excreta reuse has become an inextricable component of sustainable sanitation strategies worldwide and is being promoted through the development and re-configuration of sanitation technologies. According to a previous estimate by Future Harvest (2001), more than 20 million ha of agricultural land were irrigated with untreated, partially treated and diluted wastewater. This figure was recently revised downwards to 4-6 million ha (Jimenez and Asano, 2008); but is expected to increase in the future especially in urban and peri-urban areas of developing countries where presently, in 4 out of 5 cities, wastewater is used for irrigation (Raschid-Sally and Jayakody, 2008). The extent of excreta reuse in agriculture worldwide has not been well documented, but is so far considered significant based on anecdotal evidence gathered from 37 countries (Jimenez *et al.* 2010). This increasing trend is in recognition of wastewater and excreta as a resource that if properly managed can contribute significantly to sustaining livelihoods, food security, and environmental quality (Raschid-Sally *et al.* 2005).

Wastewater and excreta contain vital plant nutrients including phosphorus, with present recoverable reserves estimated to last for less than 200 years (Larsson *et al.* 1997). For instance, 1000 cubic meters of municipal wastewater used to irrigate one hectare can contribute 16 – 62 kg total nitrogen and 4 – 24 kg phosphorus of soil nutrient (Qadir *et al.* 2007). In water stressed regions where there are competing demands for freshwater resources for crop production and other uses, wastewater irrigation has become an integral component of water resource management. In Israel, > 60% of treated wastewater is used for agricultural irrigation (Lawhon and Schwartz, 2006), while in Jordan, 10% of fresh water supply is from reclaimed wastewater (McCornick, 2001). In Australia, several schemes have been developed for the agricultural reuse of treated wastewater (Hamilton *et al.* 2007). Across Mexico, more than 350,000 ha of farmlands particularly in Mezquital (with 90,000 ha of agricultural fields) are irrigated with wastewater (Peasey *et al.* 2000). Examples of wastewater irrigation practices can also be found in several African countries including Tunisia (Shetty, 2004); Ghana (Cornish and Kielen, 2004); South Africa (Grobicki, 2000); Senegal (Gaye and Niang, 2002); and Zimbabwe (Hranova, 2000).

The contribution of irrigation schemes to the food basket and income of poor households, especially in developing countries is immense. For instance, in Hanoi, Vietnam it is estimated

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[1] The term wastewater refers in this thesis to the liquid part of waste from households (black and greywater), farms and industrial establishments which could also be mixed with groundwater, surface water, and storm water (surface runoff) as may be present (Metcalf and Eddy, 2003).

[2] In this section, excreta is used as a generic term and refers to faecal sludge, biosolid, night soil and septage.

that 80% of vegetable production is from wastewater irrigated fields (Lai, 2002). In West Africa, between 50 and 90 per cent of vegetables consumed by urban dwellers are irrigated with wastewater polluted surface water within or close to cities (Drechsel *et al*. 2006). There is presently no countrywide or regional data on the contribution of faecal sludge fertilized fields to food production. Theoretical estimates suggest that the nutrient production from the excreta of a person is sufficiently adequate to meet his/her food needs (Drangert, 1998).

The aforementioned benefits can be eroded by significant health consequences particularly in poor countries where systems for the safe application of wastewater and excreta are either non-existent or inadequate. In these countries, severe gastro-enteric infections have been associated with the reuse of wastewater and excreta in agriculture (Blumenthal and Peasey, 2002). Therefore, for most of these poor countries, a major challenge is how to minimize the health impact associated with the reuse schemes. Minimizing the health impact associated with the practice requires a better understanding of the risk factors driving disease transmission at the farm and community levels.

This thesis, which forms part of a comprehensive health risk assessment and mitigation study for informal reuse schemes, contributes to deepening and widening understanding on the risk factors, health risks and interventions for informal wastewater and sludge reuse schemes in Ghana. Even though the study focuses on Ghana, the approaches as well as findings made here are applicable to other informal reuse schemes elsewhere.

1.2 Wastewater and Faecal Sludge Reuse in Ghana

The wastewater and excreta reuse schemes in Ghana, are the corollary of rapid urbanization with its concomitant problems of endemic poverty, increased food demand and limited access to improved water and sanitation infrastructure. The country's development efforts, over the past decades, have left a vast majority of its urban population without access to improved sanitation infrastructure. About 45% of the country's 20 million people live in environmentally depressing towns and cities characterized by limited or non-existent facilities for the collection, treatment and safe disposal of solid waste, wastewater and faecal sludge (Ghana Statistical Service, 2002). For the remaining proportion with some access, this is skewed towards un-sewered technologies (i.e., latrines and septic tanks) that 'collect and store' human excreta and direct grey water into open spaces, storm water drains and streams without treatment. These un-sewered technologies account for 85% of the excreta generated in urban areas (Eawag-Sandec, 2006). There are about 70 wastewater treatment plants in Ghana, but only about 10% are functional (IWMI, 2009) and sparingly treat 4-5% of the wastewater generated by the urban population (Ghana Statistical Service, 2002). Even if all were functioning, only about 10% of the wastewater generated could be treated. For the large number of un-sewered on-site installations collecting and storing human excreta, the management of the sludge generated thereof remains an intractable challenge (Montangero *et al*. 2002). The cumulative impact of the poor state of wastewater and faecal sludge management systems is that, streams and storm water drains traversing towns and cities have become open sewers for excreta polluted greywater while unused plots, depressions, and the ocean have become receptacles for faecal sludge (Obuobie *et al*. 2006; IWMI, 2009).

Directly linked to the poor sanitation infrastructure and the widespread pollution of surface waters are informal agricultural *reuse schemes* that reclaim urban polluted water for crop production. It is estimated that around Kumasi, there is twice the area irrigated with highly polluted surface water than with freshwater in all of Ghana's public irrigation schemes (Obuobie *et al.* 2006). Most of these 'wastewater' irrigated farms are either downstream of cities or close to stream and drains. They are on lands owned by public institutions and private developers with an average plot size of much less than 0.1 ha per farmer (Obuobie *et al.* 2006). Several types of vegetables are grown on these irrigated sites including cabbage, lettuce, spring onions, cauliflower, green pepper and okra. Wastewater irrigation is all year round, but is more pronounced in the dry season, when some rain-fed farmers also join. For instance, it has been shown that, around the second largest city of Ghana, some 10,000 farmers are engaged in wastewater irrigation in the dry season (IWMI, 2009).

Compared to the wastewater irrigation schemes, there is paucity of data on the extent of faecal sludge use in Ghana. However, the practice is reported to be widespread in peri-urban communities in the Northern regions of the country (Cofie *et al*. 2005). The dominance of faecal sludge reuse in these regions is the consequence of a number of factors. Salient among these, are severe poverty and depleting soil nutrients. According to the *Ghana Poverty Reduction Strategy Document,* more than 70% of the population in the Northern regions of Ghana, mostly from farming households, lives below the poverty line (Government of Ghana, 2002). Soils in the Northern regions are also generally poor in nutrients (Cofie *et al*. 2005), thus making poor farmers who cannot afford chemical fertilizers resort to sludge from un-sewered public latrines and septic tanks as soil ameliorants. Two types of sludge are applied by farmers, high strength (public toilet or bucket latrine) and low strength (septage) (Heinss *et al*. 1998). Sludge is collected and transported to farms by suction truck drivers, paid a fee by farmers. Treatment of the sludge is undertaken by farmers using two drying methods, pit containment and random spot spreading (**Figure 1**). Under the random spot spreading method, sludge is discharged at various random spots on farmers' plots and allowed to dry. In the pit method, pits are dug closer to the farms or on-farm and the bottoms of the pits lined with straw. Faecal sludge is discharged into the pit, which is large enough to take several trips of the suction truck loads. Layers of bran and straw are placed in between subsequent trips. The process is repeated until the pit is full. This is then left to dry. The drying methods produce sludge cakes that are collected and incorporated into the soil by farmers. Both sludge drying and soil incorporation occur during the dry season prior to the start of the rainy season that also coincides with the farming season. However, farmers do not follow any specific time lines in the treatment of the sludge; and only collect the cake sludge as and when they perceive it to pose no health risk. Unlike the wastewater irrigation schemes, crops grown in the sludge farms are mainly cereals and tubers with a large proportion consumed by the farming households.

Figure 1: Random spot and pit methods of sludge treatment in Northern Ghana

	Random Spot Spread	Pit
Raw Sludge		
	↓	↓
Cake Sludge		

Photo: R. Seidu

1.3 Microbial Hazards Associated with the Reuse Schemes in Ghana

1.3.1 Microbial Hazards in Irrigation water and Faecal Sludge

All the major groups of pathogens of bacterial, viral, protozoan and parasitic origins (**Table 1**) are potentially present in the irrigation wastewater and faecal sludge used in the reuse schemes in Ghana. Due to resource constraints, only *E. coli* and helminths have been directly investigated in irrigation water in previous studies (Obuobie *et al*. 2006; Amoah *et al*. 2005) and in the faecal sludge in this thesis (**Paper III**). Studies have shown that the irrigation water and faecal sludge used in Ghana do not meet the WHO (2006) acceptable benchmark for *E.coli* and *Ascaris*. Amoah *et al*. (2005) found 3-7 log units of faecal coliforms per 100 ml and 3-6 helminth eggs per litre of the irrigation water used by farmers. Besides the irrigation water, farmers also apply chicken manure as soil ameliorant that further elevates health hazards in the fields (Obuobie *et al.* 2006). Thus, Amoah *et al.* (2005) also found high levels of faecal coliforms and helminths eggs in the irrigated soils from the sites where only pipe water was used for irrigation. Compared with irrigation wastewater, the concentration of faecal coliforms and helminth eggs is much higher in collected but not further treated faecal sludge. In Southern Ghana, Heinss *et al.* (1998) recovered 20,000–60,000 helminth eggs per litre from public latrines and ~4000 helminth eggs per litre from septage (septic tank sludge). Also, Gallizi (2003) found 18-242 helminth eggs/gTS from public latrines and septic tanks in the same part of Ghana. In a recent study in Ghana, 9-16 helminth eggs/gTS and 5–118 helminth eggs/gTS were recovered from public latrines and septage respectively (Kone *et al.* 2007). Among the helminths species recovered from the faecal sludge in the country, *Ascaris* *lumbricoides* was the most predominant (Gallizi, 2003; Kone *et al.* 2007); reflecting its high prevalence in the country (Hotez *et al.* 2003).

Table 1: Pathogens potentially present in wastewater and faecal sludge used in agriculture in Ghana

Group	Pathogen	Disease and Symptoms
Bacteria	*Aeromonas sp.*	Enteritis
	Campylobacter jejuni/coli	Campylobacteriosis: diarrhoea, cramping, abdominal pain, fever, nausea, arthritis and Guillain-Barré syndrome
	Escherichia coli	Enteritis
	Salmonella tyhphi/paratyphi	Typhoid/Paratyphoid: fever-headache, fever, malaise, anorexia, bradycardia, splenomegaly, cough
	Salmonella spp.	Salmonellosis: diarrhoea, fever, abdominal cramps
	Shigella spp.	Shigellosis: dysentery (bloody diarrhoea), vomiting, cramps, fever; Reiter's syndrome
	Vibrio cholera	Cholera: watery diarrhoea, lethal if severe and untreated
	Yersinia spp.	Yersiniosis: fever, abdominal pain, diarrhoea, joint pains, rash
Viruses	Enteric adenovirus	Enteritis
	Astrovirus	Enteritis
	Calicivirus (including norovirus)	Enteritis
	Coxsackievirus	Various: respiratory illness, enteritis, viral meningitis
	Echovirus	Aseptic meningitis, encephalitis, often asymptomatic
	Enterovirus types 68-71	Meningitis; encephalitis, paralysis
	Hepatitis A virus	Hepatitis: fever, malaise, anorexia, nausea, abdominal discomfort, jaundice
	Hepatitis E virus	Hepatitis
	Poliovirus	Poliomyelitis: often asymptomatic, fever, nausea, vomiting, headache, paralysis
	Rotavirus	Enteritis
Parasitic Protozoa	*Cryptosporidium parvum/hominis*	Cryptosporidiosis: watery diarrhoea, abdominal cramps and pain
	Cyclospora cayetenensis	Often asymptomatic, diarrhoea, abdominal pain
	Entamoeba histolytica	Amoebiasis: often asymptomatic, dysentery, abdominal discomfort, fever, chills
	Giardia intestinalis	Giardiasis: diarrhoea, abdominal cramps, malaise, weight loss
Helminths	*Ascaris lumbricoides*	Ascariasis: generally no or few symptoms; wheezing, coughing, fever, enteritis, pulmonary eosinophilia
	Taenia solium/saginata	Taeniasis
	Trichuris trichiura (whipworm)	Trichuriasis: unapparent through vague digestive tract distress to emaciation with dry skin and diarrhoea
	Ancyclostoma duodenale / nectar americanus (hookworm)	Itch, rash, cough, anaemia, protein deficiency

Source: Ottoson and Stenström, 2003

1.3.2 Pathogens in Produce from Irrigated Wastewater and Faecal Sludge

As mentioned above, in Ghana faecal sludge is applied mainly to cereals (maize, millet etc) and other crops with edible parts high above the surface and cooked before consumption while wastewater is used for irrigating leafy vegetables, most of which are exotic and eaten uncooked. Due to low risk perception and corresponding unsafe irrigation and agronomic practices (Obuobie *et al.* 2006), all the pathogens of health concern presented in **Table 1** may be found on vegetables irrigated with wastewater in Ghana. Typical ranges of faecal coliforms of 3–6 log units and 2–4 helminths eggs per 100g of lettuce collected from wastewater irrigated fields in the country have been reported (Obuobie *et al.* 2006). In a recent study, *E.coli* O157:H7 implicated for severe gastro-enteric infections was found in wastewater irrigated lettuce in Ghana (Donkor *et al*. 2008). In another study of the microbiological quality of lettuce and tomatoes grown in Accra, unacceptably high levels of faecal coliforms were found on the vegetables (Mensah *et al*. 2001). Organisms such as *Shigella dysenteriae, Shigella flexneri, Shigella boydii, E coli and Salmonella* Group B have also been isolated from tomatoes purchased from farm gates and open markets in Accra (Mensah *et al*. 2001) and *Staphylococcus aureus* in salad prepared from vegetables potentially irrigated with wastewater (Mensah *et al*. 2002). In another study, vegetables (carrots, cabbages, and lettuce) from three markets in Accra were found to have infective stages of parasites. These included *Cryptosporidium parvum, Strongyloides stercolaris* and Hookworms. In a meeting of WHO/FAO experts on microbiological hazards in fruits and vegetables worldwide, *Salmonella* spp., *Shigella* spp., *E. coli*, *Campylobacter*, *Entamoeba coli*, *Cryptosporidium, Ancylostoma* spp. were said to have been isolated from leafy vegetables potentially irrigated with wastewater in Ghana (WHO/FAO, 2008).

1.4 Pathogens Transmission Pathways

Pathogen transmission pathways and exposure in wastewater and faecal sludge reuse depend on several technical and non-technical factors (WHO, 2006). These include, among others, the extent of treatment prior to reuse (e.g., treated vs untreated) (Blumenthal *et al*. 2001); farm practices employed (e.g. labour intensive vs. mechanized farming (Mara *et al.* 2007); perception of health risks (Keraita *et al*. 2010); persons involved (i.e., children vs adults (Schönning *et al*. 2004); and frequency of application (e.g. frequent irrigation vs. seasonal sludge application (Seidu *et al*. 2008). In this thesis, three broad exposure pathways are delineated and assessed. These are direct contact, inhalation of aerosols and consumption of wastewater irrigated produce. These are presented as follows:

Direct Contact: Direct contact with wastewater or sludge may occur during on-farm application. However, the magnitude of contact and subsequent infection depends on a number of factors including the type of technology in use, protective clothing used and perception of health risk. Among the wastewater and faecal sludge farmers, studies have shown that most of them do not wear protective clothes (e.g., gloves, boots etc) (Obuobie *et al*. 2006; Cofie *et al*. 2005); and are therefore directly exposed to pathogens present in the irrigation water or cake faecal sludge (**See Figures 2 and 3**). In addition, animals, especially pets, sent to the farms can also come into contact with contaminated soil and transfer this to the household environment.

In this thesis, exposure pathways related to contact with irrigation water and contaminated soils were assessed in the wastewater irrigation studies (**Paper I**) while direct contact with cake sludge and cake sludge-soil mixture were considered in the sludge application studies (**Paper III**).

Figure 2: Farmers irrigating with polluted water without protective clothes in Ghana

Photo: P. Amoah (IWMI)

Figure 3: Farmers collecting and applying 'cake' sludge without protective clothes in Ghana

Photo: R. Seidu

Inhalation of aerosols: During wastewater irrigation and faecal sludge incorporation, aerosols containing infectious organisms may be generated and inhaled or swallowed not only by farm workers but also residents living close to the farm sites (Teltsch and Katzenelson, 1978; Shuval *et al*. 1989; Carlander, 2006; Brooks *et al*. 2005ab). Microorganisms, especially viruses, can be transported with aerosols and spread by the wind (Höglund, 2001; Carlander, 2006). This exposure pathway is more likely on farms where sprinkler irrigation is used. Risk is less likely where the sprinkler produces large droplets. In Ghana, most of the wastewater farmers use buckets, pipe hose and watering cans, with little aerosol generation during irrigation. Thus, this exposure pathway was not considered in the wastewater irrigation studies. During the incorporation of cake sludge, dust plumes containing infectious organisms may be generated, that can be inhaled by farm workers and community residents living near the fields. Thus, this exposure pathway was considered in assessing the occupational health risk for farm workers applying faecal sludge in **Paper III**.

Consumption: Agronomic practices employed by wastewater farmers in Ghana lead to significant contamination of irrigated vegetables that are eaten raw with pathogens. In this regard, certain vegetables are more prone to contamination than others and therefore present significant health hazard when consumed. For example, lettuce and cabbage have surface properties that safeguard pathogens from exposure to radiation in the field, and equally make the removal of pathogens difficult to wash off. For instance, Shuval *et al*. (1997) found 10.8ml of irrigation water on lettuce compared with 0.36 ml for cucumber. In another study, it was shown that lettuce surfaces retained pathogens (*E. coli* and a bacteriophage (PRD1), from irrigation water while peppers with smooth surfaces did not (Stine *et al*. 2005). Similar findings have been made in Ghana, where wastewater irrigated lettuce were the most contaminated with faecal coliforms and helminth eggs followed by cabbage and carrots (Obuobie *et al*. 2006; Obeng, unpublished data).

Therefore, in **Papers I** & **II**, lettuce was chosen to assess the health risk for consumers of wastewater irrigated vegetables. Furthermore, the default value of 10.8 ml of irrigation water retained by lettuce was adapted with some variations for the risk assessment conducted in **Papers I** & **II**. Following harvest of wastewater irrigated vegetables, poor post-harvest handling practices in markets can lead to further contamination of the vegetables (Illic *et al.* 2010). For instance, a study in Pakistan found significant contamination of wastewater irrigated vegetables in markets relative to low contamination levels on farm (Ensink *et al.* 2007). In Ghana, studies showed the opposite due to high contamination already on farm but also confirmed poor hygiene practices in wholesale and retail markets where the distribution of wastewater irrigated vegetables occur (Amoah *et al*. 2005). In **Paper I**, the assessment of consumer health risk took into account the different marketing channels where contamination of irrigated vegetables may occur.

1.5 Health Risks and Disease Outbreaks Associated with Exposure Pathways

So far, no study has systematically assessed the magnitude of the health risks associated with the foregoing exposure pathways in relation to wastewater and sludge reuse in Ghana. A few studies have distally linked gastro-enteric infections to the consumption of vegetables potentially irrigated with wastewater (Mensah *et al*. 2002; Boadi, 2004). However, more comprehensive epidemiological and quantitative microbial risk studies elsewhere suggest that the exposure pathways can lead to significant infection risk for the following exposed groups given the practices associated with the reuse schemes in Ghana (WHO, 2006):

- Farmers and their families;
- Consumers of wastewater irrigated vegetables; and
- Populations living within or near irrigation/ faecal sludge sites, but not directly involved in wastewater/sludge application.

Farmers and their families: Several epidemiological investigations have found excess parasitic, diarrhoeal and more recently skin infections risks in farmers and their families directly in contact with wastewater (Cifuentes *et al*. 1998; Ensink *et al*. 2006; Blumenthal *et al*. 2001; Trang *et al*. 2007; Rutkowski *et al*. 2007). So far, no study has been undertaken to assess the occupational health risk associated with the application of sludge from on-site sanitation technologies similar to those in Ghana. However, studies from on-site sanitation technologies configured for agricultural reuse such as urine diverting and composting toilets provide some clues. Recent epidemiological and quantitative microbial risk studies indicate a high risk of helminths infection among farmers using poorly treated excreta from composting and dehydration toilets (Schönning *et al*. 2004; Yajima *et al*. 2009). Seasonality of diarrhoea incidence in communities using wastewater has also been reported (Blumenthal *et al.* 2001; Trang *et al*. 2007). These studies, however, largely compared major seasons and did not account for the effect of temperature and rainfall. In **Paper IV**, the effect of rainfall and temperature on diarrhoeal disease incidence in communities applying faecal sludge is investigated.

Consumers: Disease outbreaks have been associated with the consumption of wastewater irrigated vegetables eaten uncooked, including outbreaks of cholera (Shuval *et al.* 1984); typhoid (Shuval, 1993) and shigellosis (Porter *et al.* 1984). Excess diarrhoeal diseases risks have been reported among populations consuming contaminated vegetables (Beuchat, 1998; Harris *et al.* 2003). Several quantitative microbial risk assessments have also associated increased pathogen infection risk with the consumption of wastewater irrigated vegetables (Shuval *et al*. 1997; Hamilton *et al.* 2006; Mara *et al.* 2007). In a recent quantitative risk assessment high *Salmonella* and helminths infection risks above tolerable risk levels were associated with the consumption of carrots and spinach grown in soils amended with dehydrated excreta from urine diversion toilets in South Africa (Jimenez *et al*. 2007).

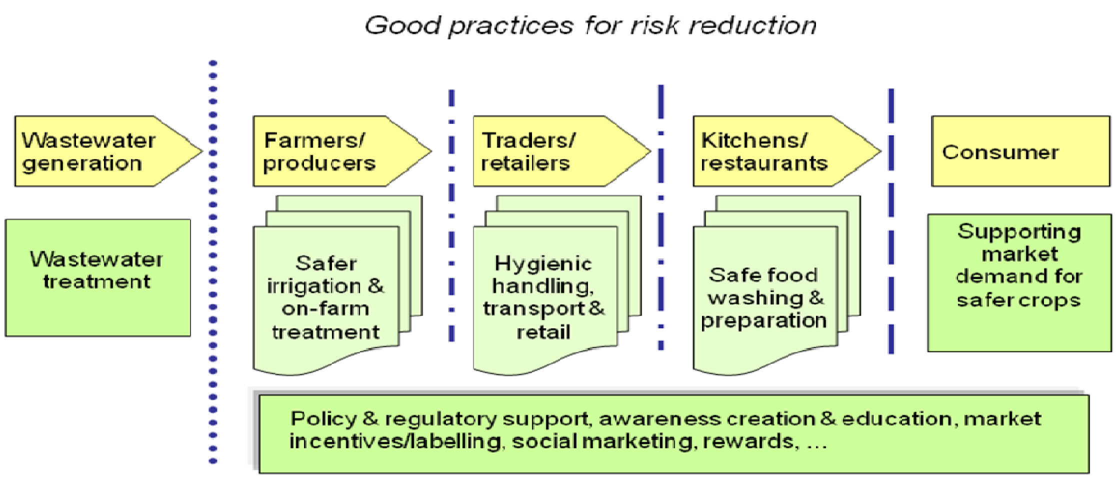
Populations living near wastewater/faecal sludge sites: Populations, particularly children, living within or near wastewater irrigation sites and exposed to aerosols from untreated wastewater may be at risk of bacterial and viral infections (Shuval *et al*. 1989). For instance, children living within 600-1000 m of a sprinkler wastewater irrigated field had a two-fold excess risk of clinical 'enteric' infection, but this was only in the summer months and the average for the year was much lower (WHO, 2006). Melloul *et al.* (2002) also reported high incidence of protozoan and *Salmonella* infections amongst children living in areas with wastewater irrigation compared to control areas. Similar findings were made in a study by Blumenthal *et al.* (2001) where excess helminths infection risk was found in populations living in a wastewater irrigation site compared to control communities. There is also the potential for children living in communities where furrow and flood wastewater irrigation are practiced to have an excess risk of helminths infection but the pathway has not been assessed (WHO, 2006). In the United States, the residential health impact of biological aerosols from land application of biosolids has been studied (Brooks *et al.* 2005a). The study revealed that the highest infection risk occurred during the loading operations of the biosolids, and resulted in a 4×10^{-4} chance of infection from inhalation of coxsackievirus A21. Further validation of this finding using transport models revealed a low infection risk for residences that were 30.5m adjacent downwind to the biosolid application sites (Brooks *et al.* 2005b). In **Paper III**, the health risks associated with inhalation of aerosols generated during tractor incorporation of cake sludge was assessed.

1.6 Health Risk Mitigation Measures in Ghana

In the most recent WHO guidelines, a suite of interventions for mitigating the health risks for the aforementioned risk groups have been made based on a multi-barrier approach (WHO, 2006). The approach is based on a hazard analysis and critical control points (HACCP) framework that progressively reduces health hazards from the farm to fork pathway through the combination of a range of treatment and/or non-treatment interventions. In Ghana, a combination of farm-based and post-harvest non-treatment measures are explored as health risk barrier (**Figure 4**). This include studies on low-cost farm-based measures such as cessation of irrigation, sedimentation ponds and sand filtration (Amoah *et al.* 2005) and post-harvest measures such as improved vegetable washing (Keraita, 2008). These studies demonstrate that significant health risk reduction can be achieved if these practices were in a sustainable and lasting manner adopted by farmers and fast-food vendors selling wastewater irrigated salad. However, these interventions are encumbered by a lot of challenges that make their full adoption by farmers and fast-food sellers a difficult task. Thus, even though the non-treatment interventions appear to be promising in terms of risk reduction, it is increasingly recognized that more efforts on behavior change campaigns are needed to ensure their full actualization (Karg *et al*. 2010).

In **Paper II**, a comparative assessment of the separate and combined effectiveness and cost-effectiveness of the treatment and non-treatment interventions have been made.

Figure 4: The multiple-barrier approach for pathogen reduction



Source: Illic *et al.* (2010)

In terms of sludge application, interventions in Ghana have so far focused on low-cost sludge treatment technologies including sand-drying beds and co-composting of sludge with organic waste (Kone *et al.* 2007). However, these so called low-cost sludge treatment technologies have not been up-scaled and are too technical and/or too expensive for adoption by poor farmers. There are other least explored indigenous sludge treatment technologies including the pit and random-spot spreading method (**See Section 1.2**).

The efficacy of these indigenous sludge dewatering methods in terms of farm workers' health risk reduction have been investigated in Paper **III**. Further assessments of the impacts of the practice at the community and household levels are explored in Papers **IV** and **V**.

2.0 STUDY AIM, RATIONALE AND APPROACHES

2.1 Aim

The overall aim of the thesis was to assess the risk factors, and health risks associated with faecal sludge and wastewater reuse in agriculture. This was undertaken through an integrated quantitative microbial risk assessment and epidemiological modeling framework with emphasis on critical control points for the transmission of infectious microorganisms. The specific research questions addressed by the study were:

i. What is the health risk for farm workers using wastewater for irrigation? (**Paper I**)

ii. Is there any significant difference in consumer health risk associated with the consumption of wastewater irrigated lettuce subjected to different post-harvest handling practices? (**Paper I**)

iii. What is the effectiveness and cost-effectiveness of treatment and non-treatment interventions for mitigating the health risks associated with the consumption of wastewater irrigated lettuce? (**Paper II**)

iv. What is the occupational health risk associated with the handling of sludge treated with traditional on-farm treatment methods? (**Paper III**)

v. Is there any difference in diarrhoeal disease incidence in sludge and non-sludge communities accounted for by the seasonal application of faecal sludge? (**Paper IV**)

vi. How do variations in rainfall and temperature affect the incidence of diarrhoeal disease in sludge and non-sludge communities? (**Paper IV**)

vii. What are the most important risk factors of diarrhoeal disease transmission in sludge applying households? (**Paper V**)

viii. What is the interlinked relationship (mediation proportion) between the different risk factors? (**Paper V**)

2.2 Rationale

Paper I

Studies investigating the occupational health risk associated with wastewater irrigation have largely focused on the quality of irrigation water (Mara *et al.* 2007). However, depending on the agronomic practices employed, significant accumulation of pathogens in wastewater irrigated soils can occur. In this study, the occupational health risk associated with wastewater irrigation is assessed not only in relation to different irrigation water quality, but also accounting for the impact of contaminated soil on health risk. Also, quantitative microbial risk assessments on the health risks associated with the consumption of wastewater irrigated vegetables is often extrapolated based on the initial contamination on farm (Shuval *et al.* 1997; Hamilton *et al.* 2006; Mara *et al.* 2007). However, in poor countries where food hygiene practices are poor, significant contamination of wastewater irrigated vegetables can occur during post-harvest handling (Ensink *et al.* 2007). Thus, the effect of post-harvest handling practices has to be factored into the assessment of consumers' health risk in these countries. In this study, the health risk associated with the consumption of wastewater irrigated lettuce from different post-harvest handling points (i.e., farm, wholesale market and retail market) is assessed.

Paper II

In the most recent WHO guidelines for wastewater irrigation, treatment and non-treatment interventions are proposed for mitigating health risks (WHO, 2006). These interventions are presently fine-tuned and adapted in national studies and promoted and implemented worldwide based on their efficacy against pathogens (Drechsel *et al.* 2008). However, no study has been undertaken to assess their effectiveness and cost-effectiveness in terms of disease burden reduction for their prioritization and allocation of scarce resources.

In this study, the first ever cost-effectiveness analysis of interventions for wastewater irrigation is made for treatment and non-treatment interventions designed for the reduction of diarrhoeal disease burden among consumers of wastewater irrigated lettuce in the case of urban Ghana.

Paper III

Presently, guidelines for mitigating the health risk associated with faecal sludge application are based mainly on low-cost treatment technologies that are rarely adopted by farmers in developing countries due to limited knowledge on their technical functionality and resource constraints. Indigenous technologies developed by farmers that reflect their circumstances are largely ignored by technocrats, and are hardly considered in the formulation of guidelines (Keraita *et al.* 2010). In this study, the efficacy of traditional sludge drying methods developed and practiced by farmers against pathogens is assessed, and the associated occupational health risks quantified. This is to allow for the mainstreaming of these technologies into the development of local guidelines that will be adopted by farmers.

Paper IV

Studies on the seasonality of gastro-intestinal diseases in communities using excreta have largely compared major seasons (wet vs dry) (Blumenthal *et al.* 2001; Trang *et al.* 2007). The potential underlying factors of such differences such as rainfall and temperature in the major seasons have so far not been accounted for in any study. In Northern Ghana, sludge application follows a seasonal pattern with sludge treatment and soil incorporation taking place in the dry season prior to the intensive farming season. In this study, a predictive model was constructed to comparatively assess the seasonality of diarrhoeal disease incidence among individuals in sludge and non-sludge communities, taking into account the effect of rainfall and temperature, as well as the seasonal application of faecal sludge as major risk factors. The study thus, provides a model framework that can be applied not only to assess the seasonal pattern of diarrhoeal disease incidence in relation to sludge application but also provide a predictive diarrhoeal disease incidence model that accounts for temperature and rainfall variations.

Paper V

Risk factors, distal and proximal, act independently and in combination within the public and domestic domains to determine the incidence of gastro-intestinal diseases (Cairncross *et al.* 1996). Studies have shown that within the domestic and public domains, distal factors are mediated by proximal ones in the incidence of gastro-intestinal diseases. Disentangling the effect of different risk factors and identifying their mediation effects is pertinent if effective interventions are to be developed for mitigating gastro-intestinal infections. Unfortunately epidemiological investigations undertaken so far on diarrhoeal risk factors associated with wastewater and excreta reuse have been based on single multivariate models that fail to capture the mediation of different risk factors. This study assesses the effect of proximal and distal risk factors, and their mediation effects on diarrhoea cases within the public and domestic domains of sludge communities. This way, the contribution of risk factors as well as their mediation effects on diarrhoea cases was identified making it possible for the identification of potential interventions for mitigating diarrhoea diseases in the sludge communities.

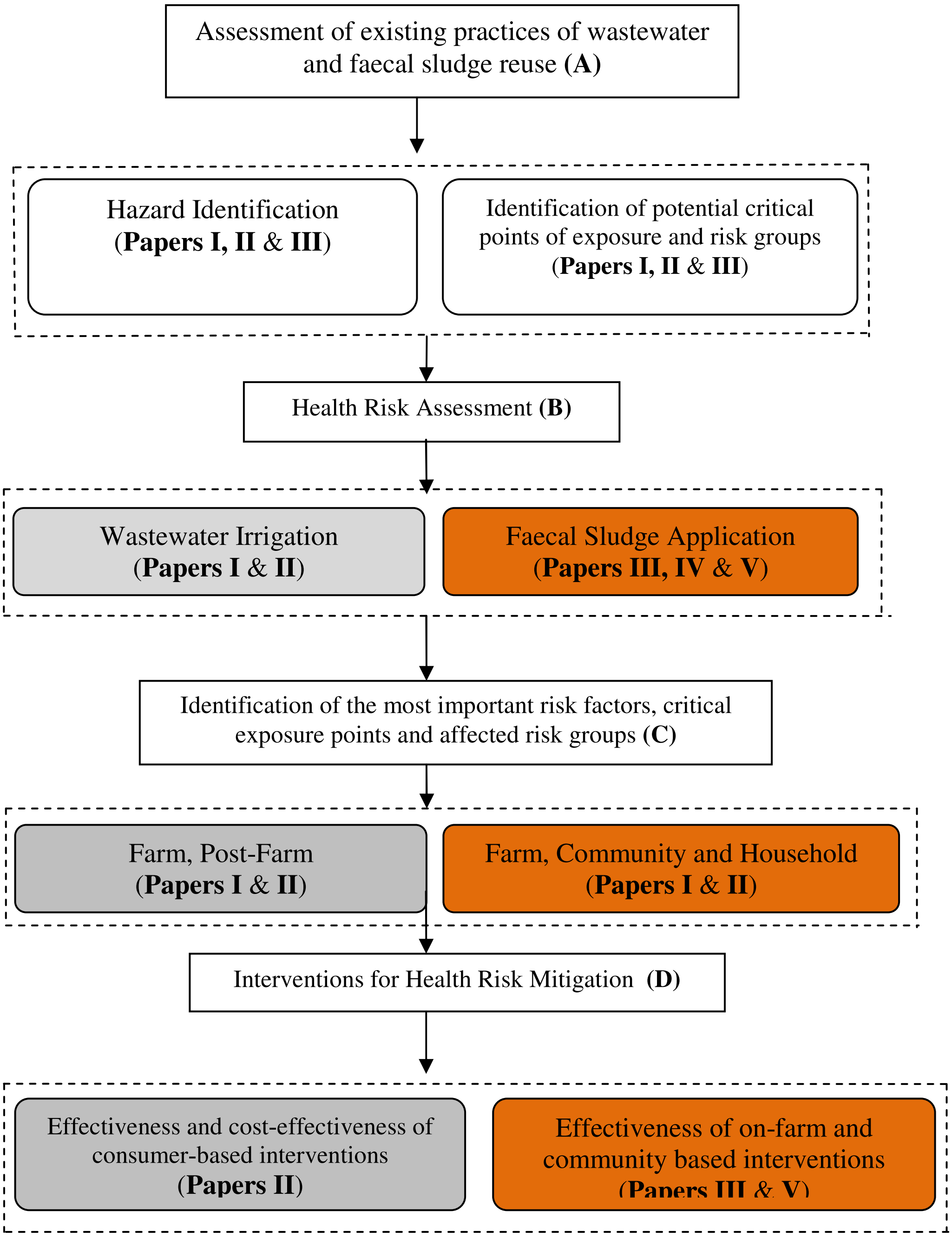
2.3 Conceptual Framework and Approaches

2.3.1 Conceptual Framework

The general conceptual framework underpinning this thesis is the *Stockholm Framework* adapted by the most recent guidelines for wastewater and excreta reuse in agriculture (WHO, 2006). The framework involves the assessment of health risks prior to setting health targets; defining basic control approaches, and evaluating the impact of these combined approaches on public health status. The framework is flexible and allows countries to adjust guidelines to local circumstances and compare the associated health risks with risks that may result from microbial exposures through wastewater and excreta reuse. In this work, the risk assessment and management components of the Framework was the main fulcrum with some variations.

Figure 5 presents the components of the risk assessment and management framework as conceptualized in this thesis. The framework consists of four inter-linked components (**A to D**) in relation to the five papers presented in this thesis. Component **A** involves an assessment of the existing practices of wastewater and faecal sludge reuse in Ghana. Under this component the potential microbial hazards associated with the practices are identified, critical exposure points via which these hazards can be transmitted are mapped out and the different risk groups potentially exposed to the microbial hazards identified. Drawing on the information from **A**, a health risk assessment (**B**) was conducted for wastewater irrigation (**Papers I** & **II**) and faecal sludge application (**Paper III, IV**&**V**). Specifically, QMRA was used in the wastewater irrigation related health risk assessment. In the faecal sludge studies, QMRA and Epidemiology methods were followed to assess the health risks at the farm (**Paper III**) and community/household levels (**Papers IV** & **V**) respectively. Following the health risk assessment, the main risk factors, critical exposure points and affected risk groups (**C**) associated with wastewater irrigation at the farm and post-farm (**Paper I**) and faecal sludge application at farm and community/household (**Papers III, IV** & **V**) were identified. Based on the foregoing, the effectiveness of specific interventions in relation to risk mitigation was identified (**D**) for wastewater irrigation (**Paper II**) and faecal sludge application (**Papers III** & **V**). In **D**, the cost-effectiveness of the interventions for wastewater irrigation was made. A summary of the approaches for the different studies under each of the components are presented in **Section 2.3.2** and further elaborated in **Section 3.0**.

Figure 5: Conceptual framework of the study



2.3.2 Approaches

Paper I

A quantitative microbial risk assessment (QMRA) approach was employed in this study. The rotavirus and *Ascaris* infection risks for farmers' and consumers were assessed in relation to four exposure pathways: (a) accidental ingestion of only wastewater by farmers; (b) accidental ingestion of only contaminated soil by farmers; (c) Accidental ingestion of both wastewater and contaminated soil by farmers; and (d) consumption of the different wastewater irrigated lettuce collected from the farm, wholesale and retail markets by consumers.

Paper II

An integrated QMRA and cost-effectiveness analysis framework was employed. Two main interventions were assessed: treatment and non-treatment. The treatment interventions comprised the planned construction of a new wastewater treatment plant and possible rehabilitation of existing wastewater treatment plants with potential for reuse. The non-treatment intervention were incorporated in a 3-year behaviour campaign targeting farmers using wastewater for irrigation and street fast food sellers of wastewater irrigated lettuce salad. The effectiveness of interventions was quantified in terms of the DALYs averted in comparison with the status quo situation (no intervention). Costing of each of the interventions was made and discounted, and associated cost-effectiveness ratios (CERs) were estimated as the DALYs averted per unit cost. Using information from incremental CERs, an expansion path was constructed for the ranking of the interventions. Further, sensitivity analysis on different adoption rates of the on-farm and post-harvest interventions was undertaken.

Paper III

This study applied three interlinked approaches comprising a qualitative farm survey, microbial analysis and QMRA. The qualitative farm survey was undertaken with semi-structured questionnaires to elicit information on sludge treatment methods, handling practices and potential exposure pathways for disease transmission across 40 farm sites. Samples of cake sludge perceived to pose no health risk by farmers were collected and analyzed for helminths eggs and *E. coli*. By combining information from the farm survey and microbial analysis, a QMRA was undertaken to assess the *Ascaris* and rotavirus infection risks for farm workers on three exposure scenarios : i) accidental ingestion of 'cake' sludge during handling; ii) accidental ingestion of 'cake' sludge-soil mixture and iii) accidental ingestion of aerosols generated during the incorporation of 'cake' sludge.

Paper IV

A prospective bi-weekly cohort of diarrhoeal disease incidence in sludge and non-sludge peri-urban communities covering the period during and after the application of faecal sludge was undertaken. The total study subjects was 2664 comprising 1341 and 1323 from the sludge and non-sludge communities respectively. In addition, climatic data on rainfall and temperature over the period was collected. The central issue in this study was how temperature and rainfall affected the diarrhoeal disease incidence with reference to the period during and after sludge application. Thus, a time series autoregressive Poisson regression model was constructed to assess the effect of sludge application, rainfall and temperature on diarrhoeal disease incidence. The autoregressive model allowed for the effect of temperature and rainfall and their lag effects on diarrhoeal disease incidence to be assessed.

<u>Paper V</u>

To assess the effect of distal and proximal risk factors, and their mediation effect on diarrhoeal disease transmission in the public and domestic domains of the sludge applying households, a hierarchical effect decomposition (HED) model was used. The HED framework comprised three interlinked blocks of risk factors: i) distal socio-economic; ii) proximal public domain and iii) proximal domestic domain. The inter-relationship between the different block of risk factors and the pathways they affect diarrhoea cases was assessed with a sequence of multivariate mixed effect Poisson regression models. From this, multivariate population attribute fraction of the different blocks of risk factors was obtained and compared to identify the most important block of risk factors for diarrhoeal incidence in the sludge communities. Also, the mediation proportions of the different blocks risk factors on the pathway to diarrhoeal disease transmission were assessed.

3.0 RESEARCH METHODOLOGY

3.1 Study Sites

Study I was conducted in Accra, the capital of Ghana. The choice of Accra for this study is because it embodies all aspects of wastewater irrigation in Ghana. The city has several sites in and around it where polluted water from streams and storm drains is used for irrigating vegetables eaten uncooked. **Figure 6** depicts a map of Ghana highlighting some of the wastewater irrigated sites in Accra. For control purposes, there are also sites where pipe water is used for irrigation. The agronomic practices of farmers as well as the irrigation water quality are representative for all sites in the country irrigating with wastewater. In addition, the post-harvest handling practices for wastewater irrigated vegetables in the city (i.e., from farm gate to whole-sale to retail markets) have been well characterized, and present a complete chain of critical post-harvest control points that can impact on consumers' health risk. **Study II** was a national investigation and involved all major cities in Ghana, where wastewater irrigation is practiced. Studies **III, IV** and **V** were undertaken in selected peri-urban farming communities in the Tamale Metropolitan Area (TMA) of the Northern Region of Ghana. The Tamale Metropolitan Area was chosen as there are several farm sites in the surroundings of the Metropolis where faecal sludge is applied. **Figure 7** shows a map of Ghana highlighting faecal sludge sites in the Tamale Metropolitan Area.

Figure 6: Map of Ghana depicting areas of wastewater irrigation in Accra

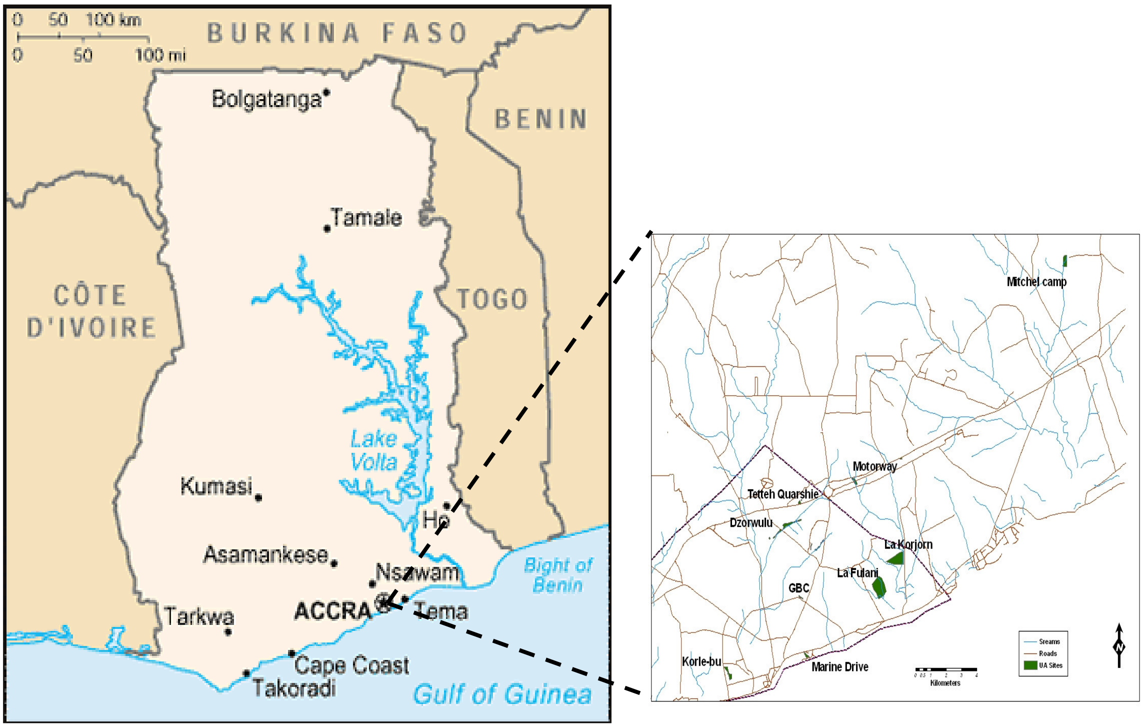
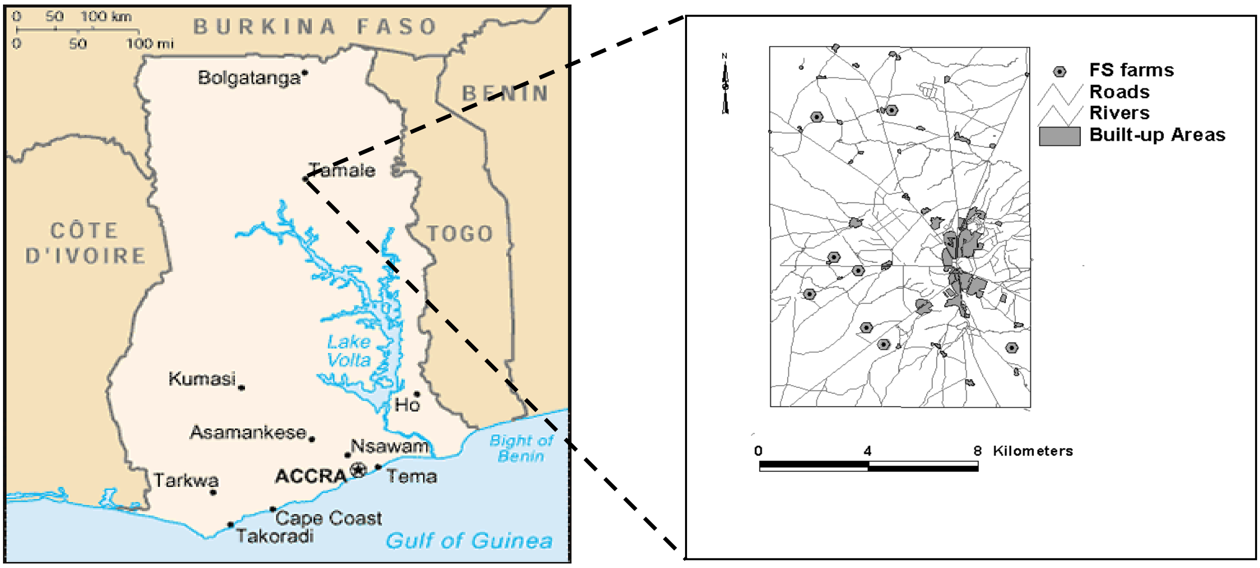


Figure 7: Map of Ghana showing faecal sludge farm sites in the TMA



3.2 Health Risk Assessment

Health risk assessment in this study was undertaken with quantitative microbial risk assessment (QMRA) and epidemiological approaches. QMRA was applied in Papers **I, II** & **III** while Papers **IV** & **V** were mainly based on epidemiology. Following are descriptions of the methods as employed in this thesis:

3.2.1 Quantitative Microbial Risk Assessment

Quantitative microbial risk assessment (QMRA) is an *ex-ante* impact assessment that draws on the concept of chemical risk assessment to estimate the consequences from a planned or actual exposure to infectious microorganisms (Haas *et al.* 1999). Following extensive reviews of the 1989 WHO guidelines for wastewater reuse in agriculture, QMRA has been extensively applied for developing and establishing standards, guidelines and other recommendations regarding wastewater and excreta reuse in agriculture (WHO, 2006). QMRA has been applied to assess the occupational health risk associated with wastewater irrigation and sludge/excreta reuse (Schönning *et al.* 2004; Mara *et al.* 2007; Seidu *et al.* 2008); infection risk associated with the consumption of crops from wastewater and sludge fields (Shuval *et al.* 1997; Hamilton *et al.* 2006; Seidu *et al.* 2008; Mara *et al.* 2007; Navarro *et al.* 2009) and in setting treatment guidelines for wastewater irrigation (WHO, 2006). The approach involves, hazard identification, exposure assessment, dose-response relationship and risk characterization. These are presented *in seriatim* in relation to the QMRA studies in this thesis:

3.2.1.1 Hazard Identification

Hazard identification involves the selection of microbial pathogens for which there is adequate information on their epidemiology and spectrum of diseases in the local context. As indicated in **Section 1.3**, there is a wide range of pathogens that may be present in wastewater and faecal sludge. However, not all these pathogens can be accounted for in QMRA, hence the need for reference or index organisms to be used. The choice of which pathogens to use in the QMRA is important, as it defines to a large extent the magnitude of the health impact. In this thesis, the selection of microbial hazards was based on the following criteria (Westrell, 2004):

i. Persistence of the organism
ii. Evidence of the organism's occurrence in the local population;
iii. Organism has low infectious dose;
iv. The organism and its occurrence are well described in the literature

In this study, the selected reference organisms based on the foregoing criteria were rotavirus and *Ascaris* (**Papers I & III)** and rotavirus as well as *Cryptosporidium* and *Salmonella* in **Paper II**. With the exception of *Ascaris,* the levels of these organisms in the wastewater and faecal sludge were obtained by extrapolation (Table 2). The extrapolation technique widely used for characterizing health hazards, and also applied in this thesis, is the transformation of indicator organisms to pathogens based on predefined ratios (Shuval *et al.* 1997; Brooks *et al.* 2005ab; Hamilton *et al.* 2006; Mara *et al.* 2007). Other extrapolation techniques applied in QMRA have been based on epidemiological indicators such as pathogen incidence and/or prevalence in the population (Ottoson and Stenström, 2003; Westrell, 2004; Heistad *et al.* 2009). The epidemiological approach, although superior over the former method was not used in this study due to the paucity of epidemiological data in Ghana.

Table 2: Extrapolations indices used in QMRA studies

Pathogens	Indicator Organism	Pathogen to Indicator organism Ratio	Reference	Paper
Rotavirus	Faecal coliforms	$1{:}\ 10^5$	Shuval *et al.* (1997)	I
	Faecal coliforms	$1{:}10^5 – 1{:}10^6$	Gerba *et al.* (2008)	II
	E. coli	$1{:}10^5 – 1{:}10^6$	Brooks *et al.* (2005a)	III
Cryptosporidium	Faecal coliforms	$1{:}\ 10^6 – 1{:}10^7$	Mara *et al.* (2007)	II
Salmonella	Faecal coliforms	$1{:}10^4 – 1{:}10^5$	Gerba *et al.* (2008)	II

3.2.1.2 Exposure Assessment

In the exposure assessment, the size and nature of the population exposed as well as the route (single or multiple), frequency, duration and magnitude of pathogens associated with the routes are assessed. In this study, data for the exposure assessment were obtained mainly from primary and secondary sources, with the latter constituting a bulk of the data. Table 3 presents a summary of the exposure inputs used in this study.

In **Papers I & II**, the exposure assessment was based mainly on data collected from surveys conducted by the International Water Management Institute (IWMI). In **Paper I**, the main exposed groups were consumers of wastewater irrigated lettuce, and farmers using wastewater for irrigation. The exposure pathways to pathogens assessed in this paper were the voluntary consumption of lettuce irrigated with wastewater and the involuntary ingestion of different quality of irrigation water and contaminated soils by farmers. For the consumers, the infection risk associated with the consumption of lettuce irrigated with different qualities of irrigation water and collected from various distribution channels was assessed. In **Paper II**, which built on findings in **Paper I**, the main risk group was consumers of wastewater irrigated lettuce. The quantity of lettuce consumed and frequency were obtained from a national survey of wastewater irrigated lettuce consumers. In **Paper III**, the accidental ingestion of cake sludge treated under traditional drying methods and inhalation of aerosols were assessed. The frequency as well as the duration of exposure in this study was based on a participatory farm observation survey while the amount of 'cake' sludge and 'cake' sludge-soil mixture ingested by adults and children was based on literature information.

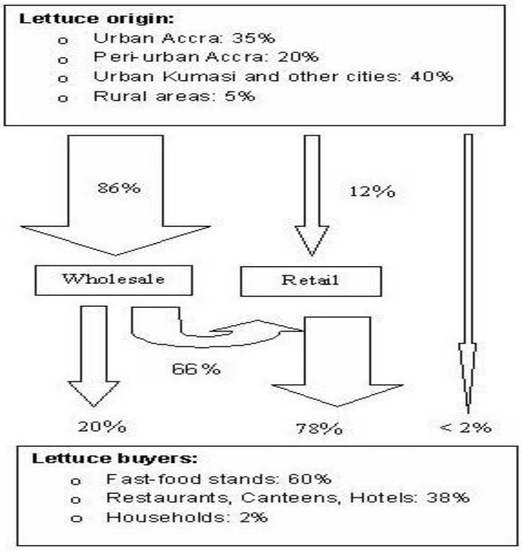
Table 3 : Exposure assessment inputs used in QMRA-based studies

Exposure pathway	Volume ingested	Frequency	Risk group	Number affected	Paper
Consumption of wastewater irrigated lettuce	10-12g[a]	208 days[a]	Consumers	130,000-150,000[a]	I
	13g[b]	208 days[a]	Consumers	700,000	II
Ingestion of irrigation water	1 - 5 ml[c]	75 days[a]	Farmers	-	I
Ingestion of farm soil	10 - 100mg	150 days	Farmers	-	I
Ingestion of cake-sludge	100 – 200 mg[d]	6 – 7 days[e]	Farmers	-	III
Ingestion of cake sludge soil mixture	100 - 200mg[d]	6 – 7 days [e]	Farmers	-	III
Inhalation of aerosols	0.83 m^3[f]	6 hrs per day[e]	Farmers	-	III

a. Obuobie *et al.* (2006);
b. National consumer survey (IWMI, 2009) NA- Not Applicable
c. This range is an extension of the ingestion level reported by Ottoson & Stenström (2003) and it was to account for the predominant use of watering cans for irrigation
d. WHO (2006)
e. Farm observation survey conducted on farm sites.
f. Dowd *et al.* (2000)

Interventions for reducing the health hazards associated with the different exposure pathways were considered where applicable. In Papers **I** & **II**, **Figure 8** formed the basis for the identification of specific intervention points. The figure delineates the potential contamination/exposure points associated with wastewater irrigation from produce generation (farm) through different distribution channels (markets) to the points of produce preparation and consumption (kitchens). In **Paper I**, no reduction in pathogens in both the irrigation water and contaminated soil was assumed prior to ingestion by farmers as most (>90%) do not use any protective gear. In terms of consumer health risk, pathogen reduction due to washing practices observed during salad preparation at fast-food stands or restaurants of major cities were accounted for. In **Paper II**, the effects of improved washing practices at the fast-food stands and restaurants and on-farm based measures on pathogens' reduction were accounted for in assessing consumers' health risk. Also in **Paper II**, the efficacy of the wastewater treatment plants (newly constructed and rehabilitated) were assessed based essentially on the performance of similar wastewater treatment plants in the country. The pathogen reduction efficacy of the different interventions applied in **Papers I** & **II** are presented in **Table 4**. The reduction efficiencies are presented in both point values and probability distribution functions. In Paper **III**, no reduction in pathogens was accounted for in any of the exposure pathways due to the poor farm practices and the limited use of protective gears among farmers observed during the farm observation surveys.

Figure 8: Lettuce distribution pathway from farm to consumers in Accra, Ghana



Source: Obuobie *et al.* (2006)

Table 4: Efficacy of pathogen reducing interventions used in the study

Intervention	Pathogen/ indicator organism	Efficacy ($\log_{10}$ reduction)	Reference	Paper
Washing of lettuce with clean water and lemon	Rotavirus	3	Amoah *et al.* (2007) based on Shuval *et al.* (1997)	I
	Ascaris	Uniform (1, 2)*	WHO (2006)	I
Washing of lettuce with only cold water for 2 mins or washing with water and disinfectant	Faecal coliforms	Uniform (1, 2)*	Drechsel *et al.* (2008)	II
On-farm based measures (cessation of irrigation, overhead irrigation at < 0.5m, drip irrigation)	Faecal coliform	Uniform (2, 3)*	Drechsel *et al.* (2008)	II
Wastewater treatment	Faecal coliforms	Triangular (3; 4 ; 6)¶	WHO (2006)	II

*Uniform probability distribution representing the minimum and maximum values of the distribution
¶Triangular distribution representing the minimum, mode and maximum values of the distribution

3.2.1.3 Dose Response Assessment

The dose-response assessment aims at estimating the probability of infection following exposure to a dose of organisms. Infection has been defined as a situation in which the pathogen, after ingestion and surviving all host barriers, actively grows at its target site (Haas *et al.* 1999). The likelihood of infection depends on two main factors: the probability that the pathogen is ingested and the probability that the ingested organism will survive in the host to initiate an infection. These are, in turn, dependent on other factors including the environment of the host, as well as other physiological characteristics of the host that predisposes to or curtails the likelihood of infection. Dose-response relationships have been obtained *via*: a) human feeding trials b) animal challenge studies and c) outbreak investigations.

Previously, the hypothetical underpinning of dose-response relationship was that *a certain threshold of pathogens was required to cause an infection.* This theory mainly derived from epidemiological investigations. More recent studies have shown that a single organism can initiate an infection. The non-threshold models deriving from this latter understanding and widely used in risk assessment studies are the exponential and beta-dose response models.

The exponential dose-response model (1) assumes that organisms ingested have independent and identical survival and infection probability, *r,* and that those doses of organisms ingested assume a Poisson distribution with a mean of *D* organisms (Haas *et al.* 1999).

$$P_{i\ (d)} = 1 - e^{-(rD_i)} \quad \text{.................. [1]}$$

Where $P_{i\ (d)}$ is the probability of becoming infected by ingesting $\boldsymbol{D_i}$ number of organisms, and $\boldsymbol{r}$ is the probability of one organism initiating an infection.

The beta-Poisson dose-response model (2) modifies the exponential model by assuming that *r* varies according to a beta distribution. The beta-Poisson dose response model is given as:

$$P_{i\ (d)} = 1 - \left[1 + \left(\frac{D_i}{N_{50}}\right)\left(2^{\frac{1}{\alpha}} - 1\right)\right]^{-\alpha} \quad \text{.........[2]}$$

Where $P_{i\ (d)}$ is the probability of becoming infected by ingesting $\boldsymbol{D_i}$ number of organisms, N_{50} is the median infection dose representing the number of organisms that will infect 50% of the exposed population and $\boldsymbol{\alpha}$ is the dimensionless infectivity constant.

The dose-response models used in this study are presented in **Table 5**. In this study, two different dose-response models have been used to assess *Ascaris* infection risk (Westrell, 2004; Navarro *et al.* 2009). In Westrell (2004) it was assumed that the dose-response model for *Ascaris* was exponential, with $r = 1$ under a worst case scenario for the exact single hit model (Teunis and Havelaar 2000). This assumption was used in assessing the *Ascaris* infection risk in **Paper I** as no dose-response relationship was available for *Ascaris*. However, a recent dose-response study in Mexico based on data from an epidemiological investigation found a beta-Poisson dose response model for *Ascaris* (Navarro *et al.* 2009). In **Paper III**, this dose-response model was used to assess the *Ascaris* infection risk. The dose-response model and parameters for the rotavirus infection risk used in **Papers I, II** & **III** was based on human feeding trials (Ward *et al.* 1986) reported in Teunis *et al.* (1996). Similarly, in **Paper II**, the dose-response model for *Salmonella* and *Cryptosporidium* were based on human feeding trials (Haas *et al.* 1999).

Table 5 : Dose response models used in this study

Organism	Dose-response relationship	Parameter	Source	Reference	Paper
Rotavirus	β-Poisson	N_{50} = 6.17 α = 0.253	h.f.t (Ward et. al. 1986)	Teunis *et al.* (1996)	**I , II & III**
Salmonella	β-Poisson	N_{50} = 23600 α = 0.3126	h.f.t McCullough and Eisele (1951a; 1951b; 1951c)	Haas *et al.* (1999)	**II**
Cryptosporidium	Exponential	r = 0.0042	h.f.t Dupont et. al. (1995)	Haas *et al.* (1999)	**II**
Ascaris	Exponential	r = 1	Assumption	Westrell (2004)	**I**
	β-Poisson	N_{50}= 859 α = 0.104	e.i (Navarro *et al.* 2009)	Navarro *et al.* (2009)	**III**

h.f.t = human feeding trials; e.i = epidemiological investigation

3.2.1.4 Risk Characterization

3.2.1.4.1 Single and Annual Infection Risk

Risk characterization integrates all the information in the aforementioned steps to arrive at a level of risk for different exposure scenarios. Here the infection risk can be expressed as single or annual depending on the exposure scenario being modeled. Equations [1] and [2] calculate the probability of infection associated with a single exposure event (e.g the one time consumption of lettuce or ingestion of wastewater). If a series of consecutive exposure events *n* are assumed to be independent, the probability of one or more infections may be estimated under the assumptions of a binomial process. If the probability of infection for a single exposure event is given by $P_{i\,(d)}$ then the probability of not being infected is $\left(1-P_{i\,(d)}\right)$. For *n* exposures, the probability of not being infected is given by $\left(1-P_{i\,(d)}\right)^{n}$. Thus, given *n* exposure events a year, the annual probability of one or more infections is given by (Sakaji and Funamizu, 1998):

$$P_{i\,(A)} = 1-\left(1-P_{i\,(d)}\right)^{n} \text{.........[3]}$$

Where $P_{i\,(A)}$ is the annual probability of infection, and *n* and $P_{i\,(d)}$ are as defined above. In **Papers I, II** & **III**, all infection risk were characterized in annual terms based on the above formulation. The values of *n* in relation to the annual characterization of the exposure scenarios in each of the papers are presented in **Table 3**. Furthermore, in **Paper I**, where farmers ingested both irrigation water and contaminated soil, the combined annual infection risk was determined as (Haas *et al.* 1999):

$$\pi_t = 1-(1-\pi_i)(1-\pi_x) \text{........[4]}$$

Where π_t is the combined annual risk of infection from exposures to wastewater and contaminated soil; π_i is the annual risk of infection resulting from accidental ingestion of irrigation water and π_x is the annual risk of infection resulting from accidental ingestion of contaminated soil.

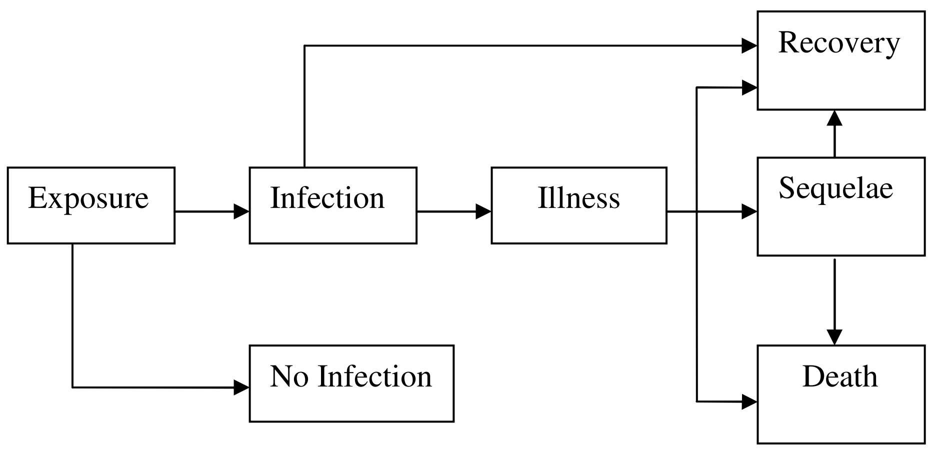
3.2.1.4.2 Tolerable Infection Risk

Tolerable risk is the level of risk from an exposure pathway considered to be acceptable. In the most recent WHO guideline for wastewater and excreta application, an annual tolerable infection risk of 1 in 10,000 per person is proposed (WHO, 2006). This tolerable infection risk level is equivalent to 10^{-6} DALYs per person per year (See **Section 3.2.1.4.4**) and is mainly associated with infection risks related to diarrhoeal diseases. This level of tolerable infection risk has been used by several researchers to assess and compare different exposure pathways in wastewater and excreta reuse (Brooks *et al.* 2005ab; Hamilton *et al.* 2006; Mara *et al.* 2007). In **Papers I** & **II**, this tolerable infection risk was used as a benchmark to assess the annual infection risk estimates for rotavirus, *Salmonella* and *Cryptosporidium*. For infections related to *Ascaris*, a tolerable infection risk level of 10^{-2} per exposed person was used in **Papers I** & **II**.

3.2.1.4.3 Infection to Disease

Infection may or may not result in illness, as asymptomatic infection can be common for some pathogens. In **Paper II**, the disease outcomes resulting from the estimated annual rotavirus, *Cryptosporidium* and *Salmonella* infection risks for the consumer population were determined based on a generic infection to disease transition model depicted in Figure 9.

Figure 9: Infection- disease transition model



For rotavirus, it was assumed that after infection 10-15% are asymptomatic, while 85-90% develop diarrhoea of which in Ghana 12% of the cases are severe, with the rest mild diarrhoea leading to full recovery. From the severe diarrhoea cases it was assumed that 5% will die (Havelaar and Melse, 2003). It was further assumed that the severe diarrhoea cases and deaths would occur mainly in the consumer age groups of 1–14 years (i.e. over and above the widely reported key age group of 0-5 years who from our survey are not frequent consumers of street food served with wastewater-irrigated lettuce) and those over 60 years. The choice of this wide range, including those in the over 60 age group was to account for potential outbreak incidence. We further assumed that the other age groups (15-60 yrs) will develop mild diarrhoea with full recovery. For *Cryptosporidium* infection, it was assumed that 70% of those infected following consumption of lettuce will develop diarrhoea with a mortality rate of 0.1%, to reflect the potentially high mortality rates in developing countries (Havelaar and Melse, 2003). For *Salmonella***,** studies based on the FoodNet database (Kennedy *et al.* 2004; Voetsch *et al.* 2004) were used. From these studies, we estimated that 50.3% and 49.7% of consumers infected with *Salmonella* non-typhoid will develop bloody and non-bloody diarrhoea respectively. From the bloody diarrhoea cases, we assumed that, 20% will be hospitalized as severe cases for an average of 3 days with a 0.6% case fatality rate (Kennedy et al, 2004; Voetsch et al, 2004).

3.2.1.4.4 Disability Adjusted Life Years (DALYs)

In **Paper II**, the mild and severe diarrhoea cases were quantified into disability adjusted life years (DALYs). The approach was first introduced in the *World Development Report* (World Bank 1993); and was revised in 1996 for the Global Burden of Disease studies (Murray and Lopez, 1996). DALYs are a measure of the health of a population or burden of disease due to a specific disease or risk factor. DALYs attempt to measure the time lost due to disability or death from a disease compared with a long life free of disability in the absence of the disease. DALYs are calculated by adding the years of life lost to premature death (YLL) to the years lived with a disability (YLD). Years of life lost are calculated from age specific mortality rates and the standard life expectancies of a given population. YLD are calculated from the number of cases multiplied by the average duration of the disease and a severity factor ranging from 1 (death) to 0 (perfect health) based on the disease (e.g. watery diarrhoea has a severity factor from 0.09 to 0.12 depending on the age group) (Murray and Lopez, 1996; Prüss and Corvalan, 2006). DALYs are an important tool for comparing health outcomes because they account for not only acute health effects but also for delayed and chronic effects, including morbidity and mortality (Murray and Lopez, 1996). Thus, when risk is described in DALYs, different health outcomes (e.g., stomach cancer and giardiasis) can be compared and risk management decisions prioritized.

For each of the pathogenic organism, the DALYs / year were calculated using the equation:

$$\text{DALYs} = \text{YLLs} + \text{YLDs} \quad \ldots\ldots\ldots [5]$$

where YLL is the number of years of life lost due to mortality and YLD is the number of years lived with a disability, weighed with a factor between 0 and 1 for the severity of the disability or disease.

YLLs and YLDs were derived using the equations:

$$YLLs[r,K,\beta] = \frac{KCe^{ra}}{(r+\beta)^2}\{e^{-(r+\beta)(L+a)}[-(r+\beta)(L+a)-1]-e^{-(r+\beta)a}[-(r+\beta)a-1]\}$$

$$+\frac{1-K}{r}(1-e^{-rL}) \quad \ldots\ldots\ldots\ldots\ldots\ldots [6]$$

Where K = age weighting modulation factor; C = constant; r = discount rate; a = age of death; β = parameter from the age weighting function; L = standard expectation of life at age a.

$$YLDs[r,K,\beta] = D\{\frac{KCe^{ra}}{(r+\beta)^2}\{e^{-(r+\beta)(L+a)}[-(r+\beta)(L+a)-1]-e^{-(r+\beta)a}[-(r+\beta)a-1]]$$

$$+\frac{1-K}{r}(1-e^{-rL})\} \quad \ldots\ldots\ldots\ldots\ldots [7]$$

Where K = age weighting modulation factor; C = constant; r = discount rate; a = age of death; β = parameter from the age weighting function; L = standard expectation of life at age a.

3.2.1.4.5 Deterministic vs Stochastic Modelling

The input parameters used in estimating infection risk and disease outcomes can take the form of a *point estimate* (deterministic) or *stochastic* estimate. In deterministic estimates, single values of the input parameters are used in the risk assessment, and extreme single values can be constructed to describe both the best-case and worst case scenarios. Deterministic procedures were largely used in earlier QMRAs to assess the health risk associated with wastewater irrigation (e.g. Asano *et al.* 1992; Shuval *et al.* 1997). Although deterministic models can provide valuable health risk estimates especially where data are lacking or inadequate, they are deficient in addressing the uncertainties of the parameters of the risk estimates. Thus, more recent QMRAs on wastewater and faecal sludge application have employed stochastic modeling techniques to account for uncertainty (Hamilton *et al.* 2006; Mara *et al.* 2007). In stochastic estimates, probability distribution functions are used to describe the input parameters. Techniques such as a Monte-Carlo or Latin Hypercube are applied to arrive at an infection risk distribution. In this study, the stochastic models were mainly used to assess infection risks (**Papers I, II** & **III**).

3.2.1.4.6 Uncertainty and Variability

In risk assessment, there are always elements of *uncertainty* and *variability* of the input values in the hazards, exposure, and aspects of the dose-response relationships. Both variability and uncertainty have to be captured more clearly in the risk characterization (Haas *et al.* 1999). Variability refers to the inherent variations in the data and cannot be reduced while uncertainty is associated with flaws in the data collection. Three main types of variability are identified by the USEPA (1997). These are spatial variability, temporal variability and inter-individual variability. Temporal variability refers to changes with respect to time while inter-individual variability is associated with variability among individuals (e.g. children vs adults). Spatial variability is related to variability in parameter inputs across different geographical levels e.g. local, regional, national etc. Uncertainty is generally delineated into *aleatory* and *epistemic.* Aleatory uncertainty is related to unpredictable natural variation in the inputs of the risk assessment model. The knowledge of experts cannot be expected to reduce aleatory uncertainty although their knowledge may be useful in quantifying the uncertainty. Thus, this type of uncertainty is sometimes referred to as irreducible uncertainty. Epistemic uncertainty is due to a lack of knowledge about input parameters. The epistemic uncertainty can, in principle, be eliminated with sufficient study and, therefore, expert judgments may be useful in its reduction. Other classifications of uncertainty have been made by USEPA (1997) *viz* scenario uncertainty (e.g. incorrect or insufficient information, overlooking an important pathway); parameter uncertainty (e.g. small or unrepresentative samples) and model uncertainty (e.g. excluding relevant variables). To account for uncertainty, traditional stochastic approaches through maximum likelihood estimates have been used to fit distributions to data.

In **Paper I,** lognormal probability distributions were used to describe the uncertainty surrounding the levels of rotavirus and *Ascaris* in irrigation water and on irrigated vegetables. Probability distributions were also constructed to account for the uncertainty in **Papers II** & **III.**

3.2.2 Epidemiological Approach

Papers IV and **V** were based on an epidemiological approach. The study design, data collection, and statistical analysis are presented as follows:

3.2.2.1 Study Design and Population

Papers IV & **V** were based on a cohort survey conducted from February 2008 to March 2009 in the Tamale Metropolitan Area. The survey involved 300 households comprising 165 sludge applying households and 135 non-sludge applying households. A total of 2664 individuals comprising 1341 and 1323 from the sludge and non-sludge households were followed to the end of the cohort or until after their withdrawal. The sludge applying households were identified for inclusion in the study after an initial comprehensive cross-sectional survey of farmers engaged in faecal sludge application in the Tamale Metropolitan Area.

3.2.2.2 Data Collection

3.2.2.2.1 Household Survey

The aim of the household survey was to assess the distribution of different risk factors known to be associated with diarrhoea incidence in the households. The survey was conducted using semi-structured and open-ended questionnaires. Three major data sets describing the households' characteristics were collected, namely, socio-demographic, water and environmental sanitation and general hygiene practices. Specific socio-demographic characteristics of the households including the age and gender of household members, housing characteristics (e.g. type, number of habitable rooms, cemented floors etc), literacy of parents and ownership of specific items (e.g. bicycle, radio, refrigerator etc) were collected. The main data collected on water and sanitation infrastructure were households water source, distance covered to the water source, type of toilet facility used by household members, access to a common refuse disposal point. Data collected on households' hygiene practices related to personal hygiene practices i.e., hand-washing with soap; food practices i.e., eating outside the home, food storage and preservation; water hygiene i.e., water storage practices, household water treatment; general hygiene i.e., presence of animals in the household compound, presence of faeces in the compound among others.

For the sludge households, specific questions related to direct involvement in sludge application, use of protective clothes (eg. gloves, booths, nose-mask etc), frequency of farm visits, and the use of soap on sludge farms were collected. All data in the household survey including subsequent ones were collected by trained field staff.

3.2.2.2.2 Disease Incidence Survey

A diarrhoeal incidence questionnaire was used to collect reported diarrhoea cases on individual household members on a bi-weekly basis over the cohort period. In this study, diarrhoea episode was defined as ≥ 3 loose (or watery) stools within 24 hours, regardless of other gastro-intestinal symptoms (Baqui *et al.* 1991), and without the influence of a purgative (or medication). The diarrhoea episodes for infants and children in the households were reported by their mothers. Additional information on diarrhoeal episodes with respect to their duration and characteristics (e.g. watery or bloody) was collected. An episode of diarrhoea lasting 14 days or more was considered as persistent (WHO, 1988). The total person days followed on each individual household member was recorded. At the end of the cohort, the 1341 and 1323 individuals recruited from the sludge and non-sludge applying households were followed respectively for 489, 465 and 480, 799 days at risk. In **Paper IV**, the total person days at risk during the period of sludge application were 242, 721 and 238, 623 for the sludge and non-sludge groups respectively. In the period after sludge application, 246, 744 and 242,176 person days at risk were recorded for the sludge and non-sludge households respectively.

3.2.2.2.3 Rainfall and Temperature Data

In **Paper IV**, the relationship between climate variables (temperature and rainfall) and diarrhoea cases in the sludge and non-sludge communities was investigated. Data on the daily minimum and maximum temperature and rainfall over the cohort period were collected from the local Meteorological station in the Tamale Metropolitan Area. The bi-weekly means for minimum and maximum temperature and rainfall were calculated from the daily records.

3.2.2.3 Statistical Analysis

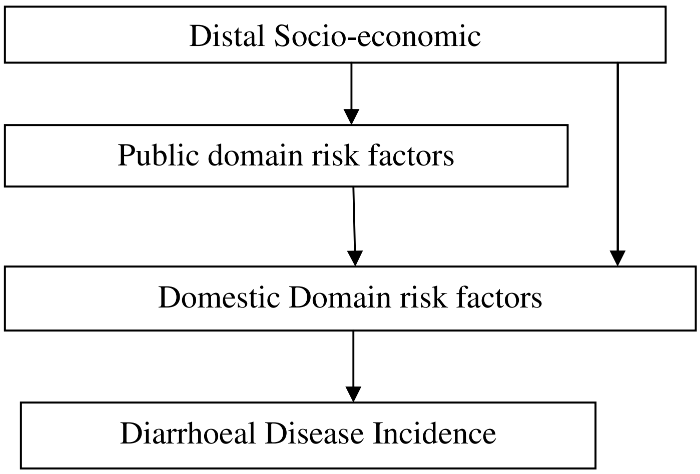
Different statistical approaches were applied for the risk factor analysis in **Paper V** and climate diarrhoea disease relationship for **Paper IV**. In **Paper IV**, a descriptive analysis of the diarrhoea cases were made with time plots to identify any potential peaks and observable trends. Simple stratified analysis was also undertaken to ascertain differences or trends in diarrhoeal disease incidence in the sludge and non-sludge application periods. Following this, integrated time-plots of diarrhoeal incidence in relation to temperature and rainfall were made to identify any first-hand relationship between weather variables and diarrhoeal disease incidence. By assuming that the counts of diarrhoea cases were Poisson distributed, an autoregressive Poisson regression model was constructed to assess the relationship between diarrhoeal incidence, weather variables and the period of sludge application. The general form of the autoregressive Poisson regression model was:

$$In(E[Y_t]) = \beta_0 + \beta_1 Y_{t-n} + \beta_2 Temp_t + \beta_3 Temp_{t-n} + \beta_4 Rain_t + \beta_5 Rain_{t-n} + \beta_6 Sin\left[\frac{2\pi t}{T}\right] + \beta_7 Cos\left[\frac{2\pi t}{T}\right] + \beta_8 X_t$$

where Y_t is the diarrhoea cases for each bi-week; T is the number of time periods described by each sinusoidal function (eg T = 24 bi-weeks); t is the time period (eg. t = 1 for 1st bi-week; t = 2 for second bi-week etc); Y_{t-n} autoregressive terms for diarrhoea cases; $Temp_t$ maximum or minimum temperature; $Temp_{t-n}$ autoregressive terms for maximum or minimum temperature; β_o is the intercept; and X_t (X_t = 1 identifies the period during sludge application; X_t = 0 identifies the period after sludge application).

In **Paper V**, a hierarchical effect decomposition model was applied to assess the relationship between risk factors and diarrhoea cases in the sludge households. This was based on the hypothesis that diarrheal disease incidence in sludge households is the consequence of a number of risk factors of which distal factors are mediated by proximal ones in the pathway to diarrhoeal disease transmission. Distal risk factors are those that do not directly predispose individuals to pathogens while the proximal risk factors are those that directly predispose individuals to pathogens. The risk factors were assigned to three main blocks: i) distal socio-economic (e.g. wealth status, housing type etc) ii) proximal public domain (e.g. water and sanitation infrastructure etc) and iii) proximal domestic domain (e.g. hygiene practices of household members etc). In this study, the public domain was the area outside the households' control where diarrhoeal disease transmission occurs while the domestic domain was limited to the environment of households where diarrhoeal disease transmission occurs (Cairncross *et al.* 1996). The interrelationship between the distal socio-economic factors and proximal public and domestic domain risk factors on the pathway to diarrhoeal disease incidence in the sludge households is presented in **Figure 10**. The arrows in the diagram depict the hypothesized relationship between the different blocks.

Figure 10: Conceptual hierarchical framework for diarrhoeal disease incidence in sludge applying households



Following the hypothetical conceptual framework in **Figure 10**, a hierarchical effect decomposition model was applied to quantify the effect of risk factors on different levels (Ditlevsen *et al.* 2005; Victoria *et al.* 1997). This approach has been applied elsewhere to assess the impact of sanitation interventions on diarrhoeal disease (Barreto *et al.* 2007; Genser *et al.* 2008; Ferrer *et al.* 2008). By this approach we were able to disentangle the direct and indirect mediated effects of the blocks of risk factors using a sequence of mixed effect Poisson regression models (Rabe-Hesketh and Skrondal, 2008). Briefly, the sequence started with model A, accounting for block I variables (distal), followed by model B, accounting for block I and block II variables (public domain) and finally model C accounting for block III (domestic domain) variables in addition to the blocks I and II variables. By comparing the effect estimate before and after adjusting for the next block in the hierarchy of the inter-block analysis an estimate of how much the effect of the block has been mediated by the block on the pathway termed the mediation proportion was obtained (Ditlevsen *et al*. 2005).

3.2.2.4 Ethical Consideration

Prior to the study, a written purpose was read in the local language to all the household heads of the participants and informed consent was obtained from them. The study participants were also free to withdraw from the follow-up at any time during the study. The study instruments and methods were reviewed and approved by the University for Development Studies ethics committee.

3.3 Cost-Effectiveness Analysis

The cost-effectiveness analysis carried out in **Paper II** was based largely on the methodological framework proposed by the WHO project, *Choosing Interventions that are Cost Effective* (WHO, 2003). The interlinked steps applied in this study are presented as follows with further details on each of the steps presented in **Paper II**:

- The estimation of DALYs averted by the independent and combined effect of treatment and non-treatment interventions in relation to the counterfactual (do nothing scenario). The non-treatment intervention was a 3-year campaign based on social marketing, incentives and education that sought to promote improved practices on farm, in markets and in kitchens of the street food sector. The treatment interventions included the rehabilitation of existing wastewater treatment plants located in urban areas where wastewater irrigation was also practiced as well as the construction of a new wastewater treatment plant with the potential for urban vegetable irrigation. DALYs were discounted at a rate of 3% as recommended by the WHO (2003).

- The assessment and discounting of costs associated with the interventions. The costing of the interventions was based on an ingredient approach, where cost was determined based on the cost of inputs (resources). The ingredients approach is useful for many reasons, the most important are that it allows analysts and policy-makers to validate the assumptions used; judge whether the estimates presented can be applied to their settings; and, if necessary, change some of the parameters to replicate the analysis for their settings (Walker, 2001). The costs of the interventions were disaggregated into capital and recurrent costs, and discounted at a rate of 3%.

- The stochastic estimation of cost effectiveness ratios (CERs), which is the US$ per DALY averted from the implementation of the interventions. Stochastic CERs were calculated for the respective interventions by fitting probability distributions to the costs and effects (DALYs averted). Monte Carlo simulations with 10,000 iterations were then run to estimate the mean CERs with 95% confidence intervals.

- An expansion path analysis, based on ICER (Incremental Cost Effectiveness Ratios), was constructed to highlight dominated interventions (i.e. interventions that are both costly and less effective than their comparators) and for the ranking of the interventions.

- Sensitivity Analysis was undertaken. The sensitivity analysis was based on the discount rates used for both the capital and recurrent expenditure as well as on different adoption rates for the non-treatment interventions. Here typical discount rates used were 0% and 6% (WHO, 2003).

4.0 METHODOLOGICAL LIMITATIONS

4.1 Quantitative Microbial Risk Assessment

QMRA is a relatively new approach in health risk assessment for wastewater and excreta reuse in agriculture. The efficacy of the approach depends on the availability of accurate information on health hazards, exposure scenarios and dose-response models. Most of the inputs for these steps are still not well characterized in developing countries including Ghana, and are at best in their embryonic formulation in developed countries. Thus QMRA modeling efforts have been constrained by the availability of adequate data defining the uncertainty and variability of most input parameters on microbial hazards, exposure and dose-response models. For instance, in relation to the health hazards, this study was only able to account for helminths, mainly *Ascaris*, while other pathogens had to be extrapolated due to the lack of data and/or resource constraints. Although extrapolation has been widely used in QMRA and has been adapted in the most recent guidelines for wastewater and excreta reuse (WHO, 2006), the approach can lead to either an overestimation or underestimation of health risks based on the inputs assumptions. Also, the dose-response models used in this study were based on those derived in developed countries. So far, only the work of Navarro *et al.* (2009) in Mexico has derived a dose-response model (for *Ascaris*) based on a developing country situation. More recent studies have sought to address some of these concerns. For instance, norovirus has been identified as a more potent representative hazard for viral infection risk in wastewater irrigation compared to the widely used rotavirus (Teunis *et al.* 2008). Importantly, debate on what is considered an acceptable health risk in wastewater and excreta reuse has deepened and widened to include not only pathogen risk but also the socio-cultural and economic aspects of the practice. For instance, Mara *et al.* (2010) argue that for communities with high levels of diarrhoeal disease, it is probably unrealistic to set the tolerable annual infection risk at $\leq 10^{-6}$ DALY loss pppy (per person per year), and that a more realistic level might be $\leq 10^{-5}$ DALY loss pppy for consumers of wastewater irrigated vegetables eaten uncooked and $\leq 10^{-4}$ DALY for farm workers. On the other hand, Signor and Ashbolt (2009) have demonstrated that the expression of infection risk in annual terms can masquerade the impact of instantaneous exposure events. They argue that the use of single infection risk capturing peak risk events can provide a better incentive for improved water-related disease risk management. This is not accounted for if the annual risk of infection is expressed.

4.2 Epidemiological Approach

Socio-demographic characteristics of the participants were collected at the beginning and at the end of the study. Over the period of the study, most of the fixed infrastructure, housing type, water source, toilet facilities etc. remained largely the same, while more changes were seen in terms of household ownership of items and age-structure. The inability of the survey to capture changes in these variables may affect their relationship with the reported diarrhoeal cases expressed in the regression analysis. Furthermore, the generalization of household level variables to each individual member may not accurately describe the actual exposure status of each individual. For example, even though there may be faeces in the yard of a household, exposure to it by the household members may differ considerably. These inherent variations in exposure at the household level are difficult to adequately capture in the epidemiological approach applied in this study.

Another major source of bias often associated with longitudinal cohort investigations is the tendency for the survey participants to under-report diarrhoea cases due to survey fatigue. To address this problem, household heads (especially mothers) were incentivized through the provision of materials such as sugar and candies for the kids of the households. This strategy also partly contributed to a low loss to follow-up recorded in the study.

Furthermore, the bi-weekly visits employed in our longitudinal study could have resulted in an underestimation of the reported diarrhoeal episodes. A comparative analysis of longitudinal diarrhoeal disease studies revealed that more episodes were likely to be recorded in studies involving more frequent visits than those with less frequent visits (Bern *et al.* 1992).

A major limitation of the epidemiological investigation implemented in this study is the inability to carry out microbial analysis on the reported diarrhoea cases to ascertain causes of the reported diarrhoea cases. However, the risk factor analysis thus gives an indication of the major causes of the diarrhoea cases including the contribution attributed to sludge related risk factors.

The hierarchical effect decomposition model used in this study is also without limitations. In this approach estimates of the direct effects can only be obtained when there is no confounding at the level of the intermediate variable (Robins and Greenland, 1992). For instance, to estimate the effect of the distal socio-economic block on diarrhoeal disease incidence not mediated by the public domain block, it was assumed that there are no unobserved covariates associated with the public domain block. In the conceptual framework efforts were made to consider and group all risk factors into meaningful blocks, thus it was unlikely that other unobserved factors are associated with both an intermediate block and diarrhoeal disease incidence.

In the seasonality analysis, the time aggregation of key weather variables of temperature and rainfall might affect the relationship drawn between them and the incidence of diarrhoea cases (more on this is highlighted in **Paper IV**).

4.3 DALYs and Cost-Effectiveness Approach

The limitations of the cost-effectiveness analytical framework relate essentially to the use of DALYs as a measure of the interventions' effectiveness, narrow considerations in the quantification of the effectiveness of the interventions and the utility of the approach in itself. The issues raised about DALYs relate mainly to limitations associated with its conceptual and technical underpinnings. In-depth reviews of some of these issues have been undertaken by Anand and Hanson (1997) and Robberstad (2005). Among some of the critiques leveled against DALYs are: i) the obscurity with which complex qualitative health parameters are melted into numeric values with mathematical formulation; ii) the discounting of future health gains and losses are inimical to children and future generation; iii) age weighting functions employed in DALYs discriminates against children and the aged (old people); and iv) the age weighting and discounting employed in DALYs tend to measure the societal usefulness of people's life years rather than the individual utility of life.

Furthermore, as cost-effectiveness analysis rather than cost-benefit analysis, this study succinctly omits the economic value associated with wastewater irrigation (including income generated from wastewater irrigation that can be used to defray health costs). Also conspicuously unaccounted for are health benefits such as the nutrients derived from the consumption of the wastewater irrigated produce. More specifically, the wastewater treatment interventions were limited to the health benefits associated with wastewater irrigation derived from such interventions. Wastewater treatment can, in addition to reducing the health risk and disease burden associated with wastewater irrigation, contribute significantly as a barrier against diarrhoea diseases transmitted via other exposure pathways (WHO, 2006; Barreto *et al.* 2007).

5.0 SUMMARY OF RESULTS

5.1 Paper I: Health Risk Associated with Wastewater Irrigation

The effect of exposure to contaminated soil on annual *Ascaris* and rotavirus infection risks for exposed farm workers was high relative to exposure to contaminated irrigation water. The median annual *Ascaris* infection risk was of a magnitude of 10^{-2} per farmer per year accidentally ingesting drain or stream irrigation water; ~10^{0} per farmer per year for the accidental ingestion of farm soil and 10^{0} per farmer per year for the accidental ingestion of any of the irrigation water and contaminated soil. As expected, there was a low (10^{-5}) *Ascaris* infection for farmers using pipe water. The median annual risks of rotavirus infections per farmer for the accidental ingestion of stream and pipe irrigation waters were 3.14 x 10^{-5} and 7.5 x 10^{-7} respectively. The median annual rotavirus infection risk associated with the accidental ingestion of irrigation water and contaminated soil was of a magnitude of 10^{-2} per farmer per year.

In terms of consumer infection risk, the impact of post-harvest handling was insignificant. For drain irrigated lettuce, it increased slightly from 2.3 x 10^{-3} per consumer per year for the farm and wholesale market points to 4.1 x 10^{-3} per consumer per year for the retail market. For stream irrigated lettuce, it increased from 2.2 x 10^{-3} per consumer per year for the farm selling point to 2.6 x 10^{-3} per consumer per year for the wholesale and retail markets. However, the median annual rotavirus infection risks for consumers of pipe irrigated lettuce were the same for all the selling points at 4.1 x 10^{-4} per consumer per year. The median annual rotavirus infection risk associated with the consumption of pipe irrigated lettuce was 10^{-4} per consumer per year with no changes between the post harvest handling points. In terms of *Ascaris* infection, the median annual infection risk was 10^{0} per consumer per year irrespective of the quality of irrigation water and marketing point.

5.2 Paper II: Cost-effectiveness of Interventions for Diarrhoea Disease Reduction

This study revealed that in urban Ghana, annually 12,000 DALYs are lost due to diarrhoeal disease cases associated with the consumption of wastewater irrigated lettuce. A comparative assessment of non-treatment and treatment interventions showed that, non-treatment interventions targeting the farm and post-harvest points are both cost-effective in reducing the diarrhoea disease burden. A campaign targeting improved farm practices could avert up to 92% of the DALYs while up to 74% could be averted through interventions in the street food sector. Also, the rehabilitation of nine selected WWTPs with farmland nearby and well distributed over the country could allow a high DALY reduction of 82% if farmers would agree to move to those sites. Building a new WWTP was very effective in its treatment but could not accommodate all farmers and supply all required vegetables, and thus only averted 44% of the annual DALYs. Combined non-treatment options (farm, off-farm) or non-treatment options and the rehabilitation of the nine WWTPs increased the health benefit by averting 94% of the DALYs, which is not much more than the farm interventions alone if they are broadly adopted.

The cost-effectiveness ratios for the treatment and non-treatment interventions ranged from US$ 31-812/DALY averted (Table 6). All combinations associated with the basic rehabilitation of the treatment plants with either on-farm or post-harvest interventions or both resulted in CERs within the range of US$ 40–57/DALY averted. However, the CERs for the construction of a new wastewater treatment plant either as an independent intervention or in combination with on-farm and post-harvest interventions were unattractive in view of health risk reduction for wastewater irrigation. Although attractive, the sensitivity analysis revealed that the CERs of non-treatment options were dependent on the adoption rates by farmers and food vendors. In this regard, the CER increased by almost five folds when the adoption rate was only 25% by farmers and food vendors; but was attractive as long as adoption rates of either farmers or street food vendors did not fall below 70%.

Table 6: Cost effectiveness ratios of interventions

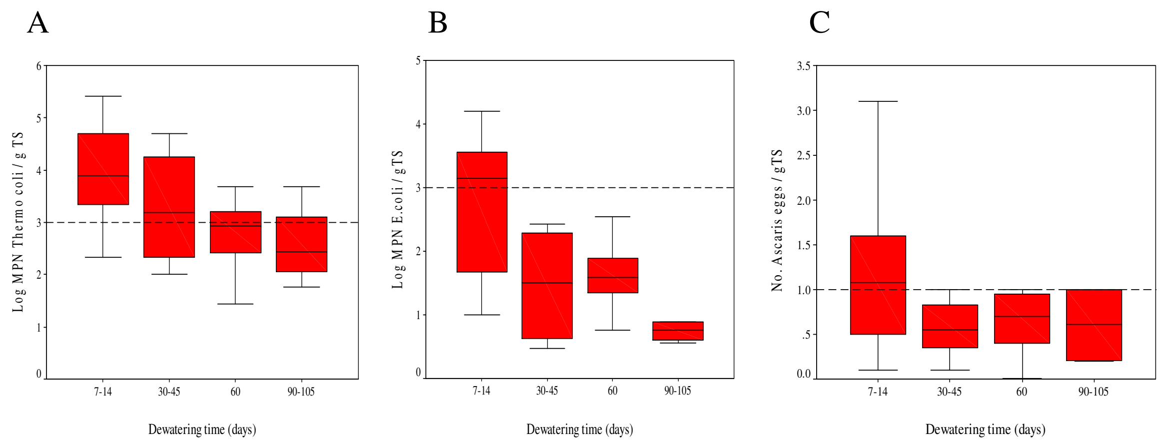
Interventions	**CER (US$ / DALY)**	
	Mean	**CI (5% - 95%)**
Non Treatment Options Campaign		
100% Adoption rate		
On farm	31	27 – 35
Post Harvest	67	58 –76
On farm + post harvest	83	72 - 95
25% or 75% Adoption rate		
25% On farm + 75% Post Harvest	95	82 – 108
75% On farm + 25% Post Harvest	94	81 – 107
25% On farm + 25% Post harvest (worst case)	394	340 – 447
75% On farm + 75% Post Harvest (Best case)	87	75 – 98
Treatment Options		
Rehabilitation of selected urban WWTPs	31	27 – 35
Construction of one new WWTP with household connections	786	678 – 893
Combined Options		
Rehabilitation + on farm	40	34 – 45
Rehabilitation + post harvest	48	41 – 54
Rehabilitation + on farm + post harvest	57	50 – 65
Construction + on farm	771	666 – 877
Construction + post harvest	798	689 – 907
Construction + on farm + post harvest	812	702 – 924

CI: Confidence interval

5.3 Paper III: Occupational Health Risk Associated with the Handling of Sludge

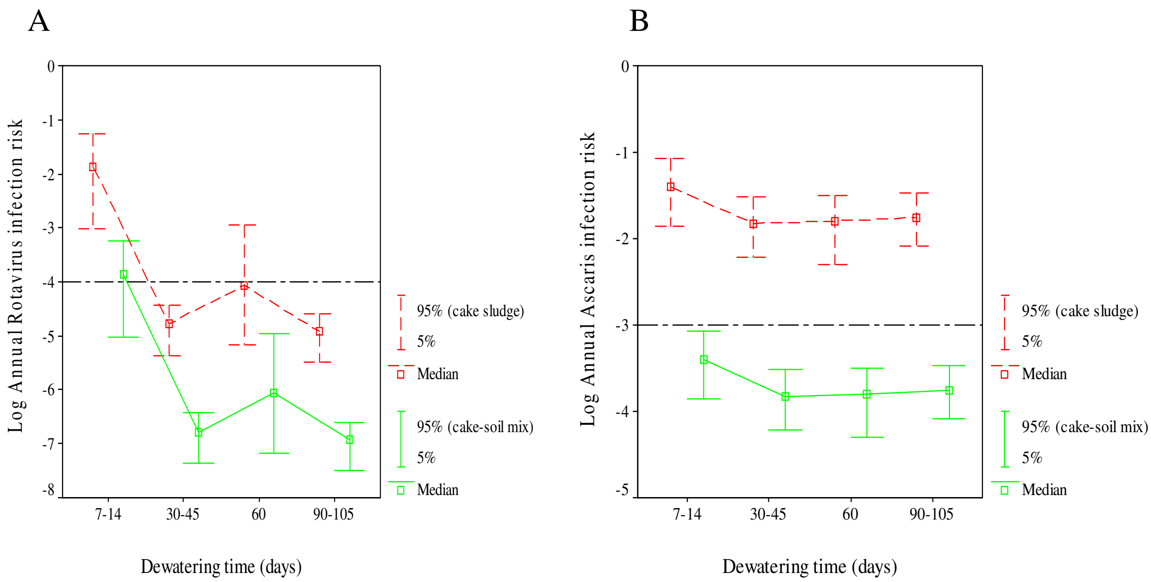
Two on-farm sludge drying methods, random spot spread and pit containment, were practiced by farmers across 40 farm sites in Northern Ghana. Of the two, random spot spread was the most preferred drying method by farmers. Sludge drying times practiced across the 40 farm sites by farmers ranged from 7-60 days for the random spot spreading method and 90-105 days for the pit containment method. The mean concentrations of *Ascaris* eggs (viable and non-viable) and *E. coli* in the dried cake sludge across the sites met the WHO monitoring benchmark ($\leq$ 1 egg/gTS) for sludge application after 30 days or more of drying in the random spot spreading method and 90 days or more of drying in the pit method (**Figure 11**). The *Ascaris* and viral infection risks associated with three exposure pathways: a) accidental ingestion of small amounts of 'cake' sludge; b) accidental ingestion of cake-sludge soil mixture; and c) inhalation of aerosols during cake sludge soil incorporation are presented in **Figures 12** and **Figure 13** respectively.

Figure 11: Distribution of organisms over sludge dewatering days and treatment method



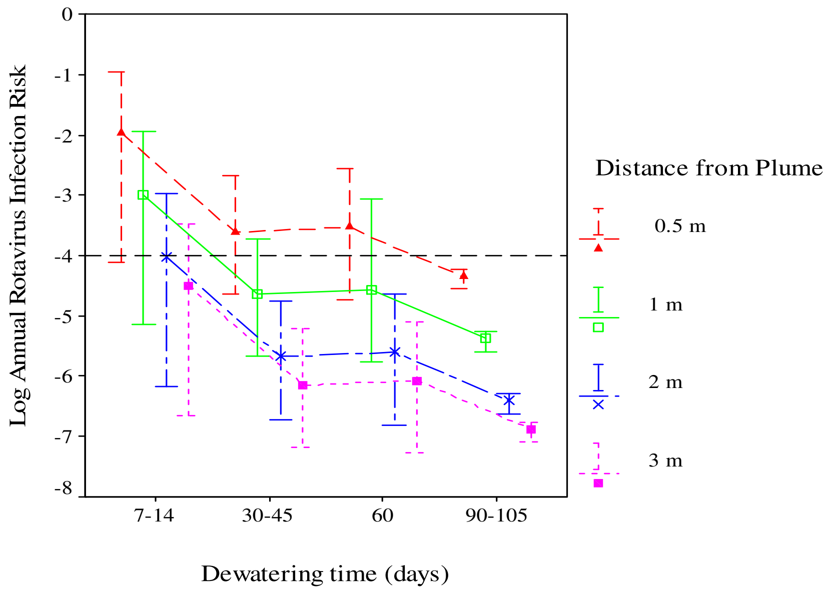
(Random spot spread method: 7-14 days (n = 10); 30-45 days (n = 8); 60 days (18).
Pit method: 90 105 days (n= 4)) (------ WHO monitoring benchmark)

Figure 12 : Rotavirus (A) and *Ascaris* (B) infection risks associated with the accidental ingestion of small amounts of cake sludge and cake-soil mixture



(Random spot spread: 7-14 (n=10), 30-45 (n = 8), 60 (n =18), Pit mehod: 90-105 (n = 4).
--------WHO tolerable infection risk level)

Figure 4: Rotavirus infection risks associated with exposure to aerosols at different distances from sludge plume



(Random spot spread: 7-14, 30-45, 60, Pit mehod: 90-105) (------ WHO tolerable infection risk level)

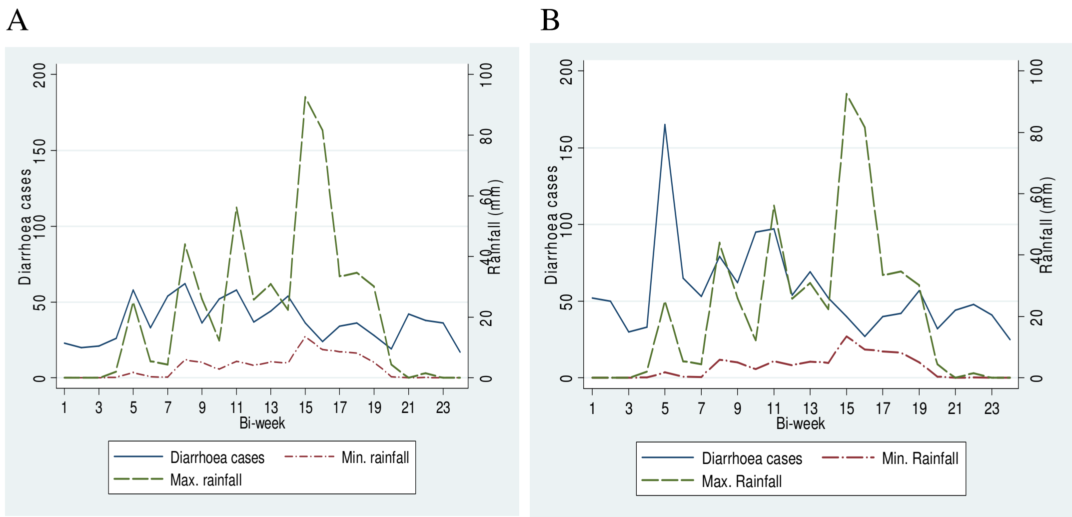
After 30-60 days and 90-105 days of sludge drying with the random spot spread and pit methods respectively, the median annual *Ascaris* infection risk associated with exposure pathway (a) was 10^{-2} per farm worker. This infection risk level reduced to 10^{-4}-10^{-5} per farm worker per year for exposure pathway (b), and met the tolerable *Ascaris* infection risk level of 10^{-3} per farm worker per year. Sludge dried for 30 days or more under the random spot spread method and over 90 days under the pit method were below the WHO tolerable rotavirus infection risk of 10^{-4} per farm worker per year for exposure pathways a) and b). Also, the rotavirus infection risk associated with exposure pathway c) was below the tolerable risk level at an exposure distance of 2 m regardless of the sludge treatment method and dewatering time.

5.4 Paper IV: Effect of Sludge Application and Temperature and Rainfall Variations on Diarrhoeal Disease Incidence

In the faecal sludge communities, the diarrhoeal incidence decreased from 1.04 (95% CI: 0.61-1.45) diarrhoeal episodes per person year in the period of sludge application to 0.99 (95% CI: 0.73-1.24) diarrhoeal episodes per person year in the period after sludge application ($p > 0.05$). Conversely, in the non-sludge communities, the diarrhoeal incidence increased from 0.65 (95% CI: 0.47-0.83) diarrhoeal episodes per person year in the sludge application period to 0.69 (95%CI: 0.55-0.83) diarrhoeal episodes per person year in the non-sludge application period ($p > 0.05$). Both rainfall and temperature were associated with the bi-weekly diarrhoea incidence in the sludge and non-sludge communities. As illustrated in **Figures 14**, in both the sludge and non-sludge communities, peak diarrhoea incidence coincided with the peak bi-weekly rainfall events (except bi-week 16). In the autoregressive

Poisson models, maximum rainfall events in the same bi-week was associated with an increased risk of diarrhoeal incidence in the sludge (RR: 1.034, 95% CI: 1.02–1.05) and non-sludge (RR=1.003, 95%CI: 0.99-1.01) communities. However, this association was not significant in the non-sludge communities ($p > 0.05$). On the other hand, minimum rainfall occurring in the same bi-week decreased the risk of diarrhoea in both communities. Maximum temperature decreased the risk of diarrhoea in the sludge communities (RR: 0.50, 95% CI: 0.38–0.65); but increased it in the non-sludge communities (RR: 1.19, 95% CI: 1.02 – 1.40). Minimum temperature increased diarrhoea disease risk (RR: 3.50, 95% CI: 2.10 – 5.80) in the sludge communities, but decreased the risk (RR: 0.70, 95%CI: 0.54-084.) in the non-sludge communities.

Figure 5: Bi-weekly diarrhoeal incidence and rainfall in A) non sludge and B) sludge communities



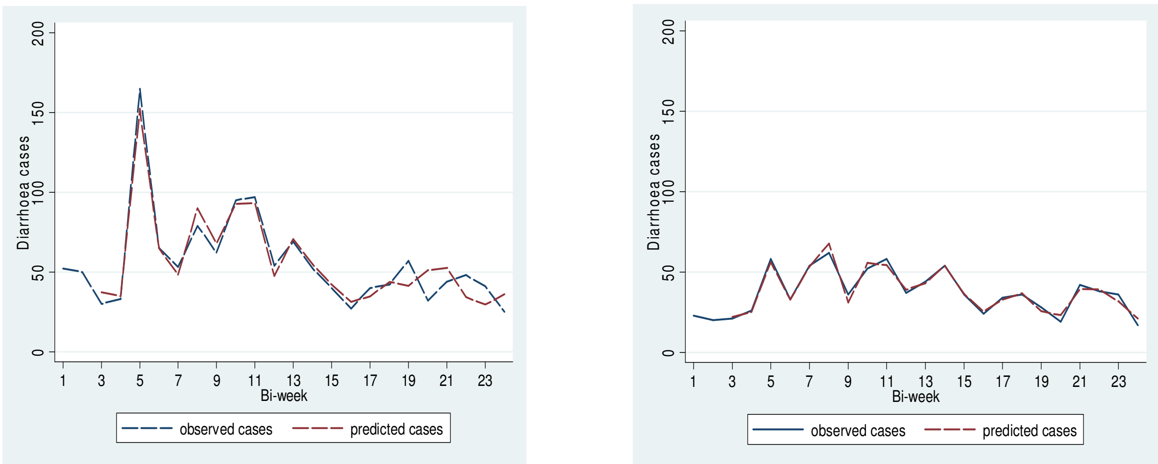
There were also lag effects of rainfall and temperature on the bi-weekly incidence of diarrhoea in both the sludge and non-sludge communities. In the sludge communities, maximum rainfalls in a particular bi-week increased the risk of diarrhoea in the next bi-weeks. Also, in the sludge communities maximum rainfall event in a particular bi-week increased the risk of diarrhoea incidence 3 bi-weeks after. However, in the non-sludge communities, maximum rainfall event in a particular bi-week decreased the risk of diarrhoea in the subsequent bi-week. Unlike the maximum rainfall events, all the minimum bi-weekly rainfall events decreased the risk of diarrhoea cases in both the sludge and non-sludge communities. There was also no observable lag effect of minimum rainfall in the non-sludge communities. However, in the sludge communities, minimum rainfall in a particular bi-week was significantly associated with the risk of diarrhoea cases reported in the subsequent bi-week.

Lag effects of maximum temperature on the bi-weekly incidence of diarrhoea were also observed in both study groups. In this case, maximum temperatures recorded in a particular bi-week increased the risk of diarrhoea incidence in the subsequent bi-week in the sludge communities and in the next two bi-weeks in the non-sludge communities. In terms of minimum temperature, different effects on diarrhoea were observed in the sludge and non-sludge communities. Minimum temperature in a particular bi-week increased diarrhoea risk in the sludge communities but decreased it in the non-sludge communities. Lag effects of minimum temperature on diarrhoea cases were also observed in the sludge and non-sludge communities. In the sludge communities, minimum temperature in a particular bi-week decreased the risk of diarrhoea cases in the subsequent 2 bi-weeks but increased the risk 3 bi-weeks after. In the non-sludge communities, minimum temperature in a particular bi-week decreased the diarrhoea risk in the next bi-week.

After accounting for the effects and lag-effects of the weather variables, the auto-regressive Poisson regression models for the sludge and non-sludge communities fit the bi-weekly incidence of diarrhoea (**Figure 15**).

Figure 6: Observed and predicted diarrhoea cases for (A) faecal sludge and (B) non-faecal sludge communities

A **B**



5.5 Paper V: Risk factors of Diarrhoea Disease Incidence in Faecal Sludge Applying households

The univariate analysis of the blocks of risk factors in the conceptual framework generally confirmed the relationship between specific risk factors and diarrhoeal disease transmission established in previous studies (Trang *et al.* 2007; Barreto *et al.* 2007; Genser *et al.* (2008; Ferrer *et al.* 2008). In line with these studies, poor wealth status, housing conditions and literacy of parents in the distal socio-economic block were all associated with diarrhoeal disease incidence in the sludge households. Public domain risk factors such as drinking water from unprotected dug-out ponds, distance covered to fetch water, lack of access to improved toilet facilities and shorter sludge drying days were all associated with diarrhoeal disease incidence in the sludge households. Also, domestic domain risk factors related to food handling practices, general household environmental hygiene and personal hygiene practices were all associated with diarrhoeal disease transmission.

Table 7 shows the final reduced model from the inter-block mixed effect Poisson regression models on the risk factors associated with diarrhoeal disease incidence in the sludge households. Sludge drying was associated with diarrhoeal disease incidence in the sludge applying households. Individuals living in households drying sludge for ≤ 14 days were more likely to develop diarrhoea compared to those treating sludge for ≥ 90 days. However, of the three blocks of risk factors, the most important in diarrheal disease transmission in terms of population attributable fraction (PAF) was the public domain block. Faecal sludge (also in the public domain) related risk factors had the least impact on diarrhoeal disease transmission in the sludge households. About 24% of the population attributable fraction (PAF) associated with diarrhoea incidence was accounted for by distance to water source (18%) and sludge drying time (6%) in the public domain. This was followed respectively by not washing hands with soap (PAF= 18%) in the domestic domain block; and low wealth status in the distal socio-economic block (15%). Analysis of the interrelationship of the blocks in the pathway to diarrhoeal disease transmission revealed that a substantial proportion of the PAFs of the blocks in the hierarchical framework were mediated. In this regard, 86% of the PAF of the socio-economic block was mediated; 33% by the public domain block and 53% by the domestic domain block. Also, 17% of the PAF of the public domain block was mediated by the domestic domain block. Altogether, the domestic domain block alone mediated 70% of the PAFs attributed to diarrhoeal disease incidence in the sludge households.

Table 7: Population attributable fractions of diarrhoeal disease for blocks of risk factors based on reduced inter-block mixed effect Poisson regression models (N=1431)

BLOCK	(%)	RR (95% CI)[xx]	PAF	PAFT[b]
Model A: Distal Socio-economic				**15**
Wealth status				
Low	18.33	1		
Average	29.56	**1.19 (0.92 – 1.53)**	6	
High	52.11	**1.18 (0.94 – 1.49)**	9	
Model B: Public Domain				**24**
Distance covered to fetch water				
≥ 500 m	47.61	**1.63 (1.43 – 1.85)**	18	
≤ 500 m	52.39	1		
Faecal Sludge Application				
≤14	46.68	1		
21 – 30	21.55	1.04 (0.69 - 2.01)		
60	11.63	1.19 (0.72 – 1.98)	-	
≥ 90	20.13	**1.28 (1.04 - 1.59)**	6	
Model C: Domestic Domain				**18**
Handwashing with soap after toilet				
No	50.71	**1.36 (1.13 – 1.65)**	18	
Yes	49.29	1		

[b]. sum of PAFs of significant variables

[xx] Relative risk in the inter-block Poisson mixed effect models were adjusted for age groups 0 – 4; 5–14; and ≥ 15 and gender

Model A: Distal socio-economic risk factors only

Model B: Distal socio-economic block and Public domain risk factors

Model C: Distal socio-economic, public domain and domestic domain risk factors

6.0 DISCUSSION

6.1 Inputs for Quantitative Microbial Risk Assessment

In the most recent WHO guidelines for wastewater and excreta use in agriculture (WHO, 2006), barriers and practices are recommended to safeguard the health of farmers and consumers based on irrigation water quality. This guideline was mainly based on a comprehensive epidemiological investigations from Mexico (Blumenthal *et al.* 2001) combined with earlier investigations. **Paper I** points out that under the informal irrigation schemes and practices in Ghana, modelling of farmers' health risks based on irrigation water quality can significantly underestimate risk estimates. For instance, the study revealed that exposure to wastewater contaminated soils led to significant rotavirus and *Ascaris* infection risks even where irrigation water quality met the WHO monitoring guideline. Therefore, in settings where informal irrigation is practiced with potential contamination of soils, it is important to account for both irrigation water and soil qualities in modelling farmers' health risk.

Furthermore, in terms of consumers' health risk estimates, **Paper I** indicates that the quantification of microbial hazards based on irrigation water quality (Shuval *et al.* 1997; Mara *et al.* 2007; WHO, 2006) without accounting for actual contamination of vegetables can significantly underestimate consumers' health risk in irrigation schemes where on-farm soil contamination is pervasive and irrigation practices lead to soil splashes. Studies in Ghana have shown that contaminated soils on wastewater irrigated fields are the main cause of vegetable contamination (Amoah *et al.* 2005; Keraita, 2008). More recently, Keraita (2008) demonstrated that on-farm based measures that sought to reduce splashes from contaminated soils on wastewater irrigated farms significantly reduced vegetable contamination. I therefore suggest that where resources allow, the quantification of consumers' health risk should be based on actual contamination of vegetables rather than on extrapolations based on irrigation water quality.

In the context of the multi-barrier framework (**Section 1.7**), **Paper I** revealed that on-farm contamination is critical both for farmers' and consumers' health risks in the wastewater irrigation schemes practiced in Ghana. However, this does not make the other post-harvest critical exposure points (e.g. markets and kitchens) less important given the wide uncertainties associated with the adoption of improved on-farm practices (**Paper II**). For instance, studies in other developing countries have identified markets as the most important control point for vegetables (Ortega *et al.* 1997; Damen *et al.* 2007; Ensink *et al.* 2007; Uga *et al.* 2009). The study of Ensink *et al.* (2007) is more indicative of the need for some level of market interventions. In that study, there was a higher concentration of *E. coli* and helminths eggs in wastewater irrigated vegetable from markets relative to the initial concentration on-farm, which was however much lower than in Ghana. Thus, a combination of on-farm and post-harvest interventions in risk management strategies is still essential depending on local conditions.

The studies conducted in this thesis revealed a relatively high *Ascaris* infection risk compared to viral infection risk for farmers using wastewater and sludge (**Paper I** & **II**) and consumers of wastewater irrigated lettuce (**Paper I**). However, in terms of health impact and disease burden, viral infection may play a more important role at the community level than helminths. Thus, even though this study and others elsewhere identify helminths as significant health hazard, it may not necessarily be the organism of concern in terms of disease burden at the community level. Thus, it is important that beyond infection risks, actual disease burdens are quantified to establish the contribution of health hazards to the total disease burden.

6.2 Complementarity of QMRA and Epidemiology

QMRA is increasingly being applied for the quantification of the health risk associated with wastewater and excreta reuse in agriculture. However, the utility of the approach in developing countries is encumbered by its mechanistic framework that depends on robust data on input parameters that are usually inadequate or non-existent in those countries (**Section 4.1**). The alternative of "informed guesstimates" similarly is based on major insecurity in its assumptions. For instance in **Papers I**, **II** & **III**, input parameters were constructed based mainly on those formulated in developed countries (except for the *Ascaris* dose-response input applied in **Paper III**) with disparate conditions from those prevailing in Ghana. Based on this understanding, my suggestion is that whenever resources permit, an integrated QMRA-epidemiological approach is applied in the study of risk factors and health risks associated with wastewater and excreta reuse. Through such an integrated approach, more information can be obtained on the dynamics of different risk factors and their impact on disease transmission. For instance in the sludge studies, the occupational health risk was assessed via QMRA (**Paper I**), but the impact of sludge application at the community level was only well disentangled through an epidemiological framework. By this approach the contribution of different public and domestic domains risk factors, including sludge application on diarrhoeal disease transmission was assessed (**Paper IV** & **V**). In addition, the distribution of diarrhoeal disease cases among different age-cohorts was ascertained making it possible for the identification of the most vulnerable risk groups in the households that would have been elusive in a QMRA framework. Nwachuku and Gerba (2004) for instance, stress the need for separate risk assessment modelling to be undertaken for adults and children, because of the vulnerability of the latter. However, it should be mentioned that in QMRA, the only distinction made between adults and children is on exposure dose (Seidu *et al.* 2008; Schönning *et al.* 2004). Inherent characteristics of children that affect their response to different dose of pathogens are still not well characterized in present dose-response models used in QMRA. Similar arguments can be made in respect of the lack of dose-response models for other susceptible sub-populations in the community such as the immune-compromised groups.

More importantly, several studies on the application of excreta and wastewater have identified adults (> 15 years) as the most important risk group as they are those also directly engaged in the activity. Hence, there is also the tendency for QMRA to account for only this risk group. While this may lead to the development of on-farm based risk mitigating strategies, the impact of the activity at the household level is completely discounted. As demonstrated in **Paper V**, even though children were not directly involved in sludge application, they were the most affected in terms of sludge application at the household level.

6.3 Disease Burden Associated with Wastewater and Faecal Sludge Reuse

Based on the findings in **Papers I** & **III**, some preliminary comparison of the disease burden associated with faecal sludge and wastewater agricultural reuse in Ghana can be made. Results of the quantitative microbial risk assessment suggest that farmers engaged in wastewater irrigation were at a higher risk of viral and *Ascaris* infection than the farmers applying faecal sludge. The annual rotavirus infection risk for farmers using wastewater for irrigation was higher for farmers engaged in faecal sludge application. Similarly, a higher *Ascaris* occupational infection risk was associated with wastewater irrigation than faecal sludge application. This difference can be attributed to the disparate exposure conditions pertaining in the wastewater and sludge application practices. Whereas wastewater irrigation is an all-year round activity, sludge application is mainly a seasonal activity. This increases the frequency of exposure to pathogens among wastewater farmers than sludge farmers. Also, intensive irrigation of fields with untreated wastewater leads to the accumulation and persistence of pathogenic organisms especially helminths eggs in wastewater irrigated fields (Amoah *et al.* 2005). Conversely, the seasonal application of dried sludge results in a relatively low accumulation of organisms in the sludge applied soils. As demonstrated in **Paper I**, soils in the wastewater irrigated fields posed a significant health hazard in respect of rotavirus infection risk for farmers even on farms where pipe water was used for irrigation. Furthermore, unlike the wastewater farmers, the sludge farmers have some level of treatment of the sludge through the random spot spreading and pit containment prior to exposure.

In terms of disease burden among the different risk groups, farmers irrigating with wastewater were at a higher risk of infection than consumers of the wastewater irrigated produce (**Paper I**). However, the consumer risk group was more likely to contribute significantly to the overall burden of disease in the larger community than farmers. As demonstrated in **Paper II**, the consumer population of wastewater irrigated lettuce in urban Ghana is about 700,000 compared with about 1500 farmers estimated to be engaged in wastewater irrigation in urban Ghana (IWMI, 2009). The diarrhoeal disease incidence among consumers of wastewater irrigated lettuce was 0.68 episodes per consumer per year translating into 0.017 DALYs per consumer per year. This accounted for 10% of the WHO-reported diarrhoeal DALYs occurring in Urban Ghana related to water and sanitation infrastructure (Prüss-Üstün *et al.* 2008).

The diarrhoeal incidence for all age groups in the sludge households (1.09 episodes per person year) (**Papers IV** & **V**), fell within the reported diarrhoeal disease incidence of 0.8 – 1.33 episodes per person per year reported for all age groups in developing countries, but was higher than the global average diarrhoeal disease incidence of 0.7 episodes per person per year (Mathers *et al.* 2002). In line with findings made in wastewater irrigation epidemiological studies (Blumenthal *et al*. 2001; Hein *et al*. 2007), children (≤ 4 years) in the sludge households not directly involved in sludge handling were disproportionately affected by the diarrhoeal disease burden. Children from our sludge households were also more likely to develop diarrhoeal disease than those in the wastewater irrigation studies cited above. Also the diarrhoeal incidence among children of the sludge households' was greater than reported childhood diarrhoeal disease incidence in one study in Northern Ghana (Binka *et al.* 2003). However, as mentioned in **Section 5.5** this diarrhoeal disease burden was most likely due to risk factors other than those related to the faecal sludge application practices of the households.

6.4 Interventions for Health Risk Reduction

In the context of the multi-barrier approach several interventions are recommended for safeguarding the health of farmers and consumers (WHO, 2006). In **Papers I** & **III**, direct accidental ingestion was found to be the main exposure pathway for disease transmission. The infection risks associated with this exposure pathway can be reduced significantly if farmers used protective clothes in their activities (e.g. nose mask, booths, gloves etc) However, studies have shown that farmers rarely used protective gears even where they had been provided (Keraita *et al.* 2010). In **Paper III**, farmers perceived 'cake' sludge to pose no health risk irrespective of the drying time. Thus, some awareness creation and treatment of wastewater and faecal sludge before reuse are necessary to safeguard the health of farmers. Here treatment methods developed by farmers in concert with their local environment and circumstances have to be explored, as they have proven to be more acceptable to farmers than the so called low-cost technologies. For instance, **Paper III** shows that the traditional sludge treatment methods employed by farmers in Northern Ghana, granted that specific drying times are observed, can be as effective as the so called conventional low-cost sludge treatment technologies in safeguarding farmers from infections. In this regard longer sludge drying times of ≥ 60 days in the random spot spread method and ≥90 days in the pit method are suggested (**Paper III**). Besides observing longer sludge drying times in the field, the hierarchical effect decomposition model stresses the need for an integrated multi-barrier risk management strategy in mitigating diarrhoeal disease transmission in the faecal sludge applying households (**Paper V**).This is more so, as children not directly engaged in faecal sludge handling were disproportionately affected by diarrhoeal disease burden (**Section 5.5**).

In terms of consumers' health risk, **Paper II** shows that both treatment and non-treatment interventions can be implemented to safeguard them from infection. In this regard, the non-treatment interventions focusing on farmers and wastewater irrigated salad sellers is of major concern as there are inherent uncertainties in relation to their adoption. For instance, a major incentive for farmers engaged in informal irrigation to adopt particular risk reduction measures is strongly contingent on how it impacts on their livelihood (income). In this regard, risk reduction measures that lead to an increase in farmers' yield and hence incomes are more likely to be adopted than those that reduce their incomes. Cessation of irrigation before harvesting conceived as an effective risk reduction measure, also included in **Paper II**, have been shown to impact negatively on farmers yield and incomes as yields decrease with every day without irrigation (Keraita, 2008). These uncertainties are not only limited to the on-farm based measures, but also to other non-treatment interventions assessed in **Paper II**. In the most recent WHO guidelines different washing methods have been proposed for reducing the health risk associated with the consumption of wastewater irrigated vegetables. Indeed laboratory based studies have proven the efficacy of these washing methods in Ghana (Amoah *et al.* 2007). However, in the kitchens of most developing countries several factors come into play in determining the adoption of specific hygiene practices including among others frequent water supply. Therefore, even though these interventions may be effective in the laboratory environment, the possibility of achieving similar outcomes across kitchens is uncertain.

6.5 Cost-Effectiveness of Interventions

Interventions proposed for reducing the health risk associated with wastewater irrigation can be adequately prioritized for implementation if their efficacy in terms public health impact and cost elements are synchronized. To date, this synchronization has not been done for any of the proposed interventions recommended in the guidelines for wastewater and excreta reuse (WHO, 2006). **Paper II** shows that even though treatment interventions are effective in reducing diarrhoeal disease burden associated with the consumption of wastewater irrigated lettuce, their cost-effectiveness are high compared with the non-treatment interventions. However, as discussed above, a critical issue is how farmers and fast-food vendors can be incentivized and/or motivated to adopt the more attractive non-treatment interventions. This is because the estimated cost-effectiveness ratios for the non-treatment interventions were highly dependent on the extent of the non-treatment interventions adoption by farmers and fast-food vendors. For instance, the paper indicated that an adoption rate below 70 % at both ends (farmers and food vendors) rendered the non-treatment interventions less attractive in terms of DALYs averted per unit cost, while it remained attractive if at least one end, a rate of 70% can be achieved. Thus, even though on-farm and post-harvest non-treatment interventions may be cost-effective, it is recommended that they are not solely implemented in a multi-barrier framework. A combination of treatment and non-treatment interventions would always be ideal to ensure that the health risk of consumers of wastewater irrigated lettuce is adequately safeguarded. Also for reasons brought forth in **Section 4.3**, the cost-effectiveness ratios of the treatment interventions can be attractive if other health benefits associated with wastewater treatment were accounted for. Thus, a more holistic framework assessing all aspects of the benefits (economic, ecological, health, etc) associated with the treatment and non-treatment interventions would give a better indication of the cost-effectiveness ratios of the interventions.

6.6 Guidelines for Health Risk Mitigation

There is ample evidence worldwide to suggest, international guidelines such as those developed by the WHO over the years have only been successfully implemented in settings where reuse schemes are formal (i.e., monitored and controlled by regulatory institutions). In Ghana, as in many developing countries, where wastewater and faecal sludge reuse schemes are informal, ubiquitous, and dependent on the dictates of farmers (with no institutional engagement), the implementation of international guidelines is more challenging. For instance, studies in Ghana have shown that the adoption of the WHO (2006) proposed farm-based risk mitigation measures for microbial risk reduction are encumbered by factors ranging from farmers' economic gains to their perceived health risk. Similarly, none of the so called sludge treatment technologies proposed in the WHO guidelines for meeting tolerable infection risk has been implemented by farmers in Ghana. Indeed, in Ghana, the guidelines for wastewater and excreta reuse thus far, are within the realm of researchers, and without further funding of their dissemination are largely inaccessible to local farmers. Even if they were accessible to them, their complexity in terms of microbial analysis would remain incomprehensible by them. Hence, the need for a paradigm shift from the internationalization of guidelines to their internalization. By internalization, the guidelines must be *responsive,* i.e., meeting farmers health needs without compromising on their ability to sustain their livelihoods*; implementable,* i.e., easily acceptable by farmers and verifiable given local resources and institutional structures; *understandable,* i.e., comprehensible by local technical experts and less complex; and *localized,* i.e., reflect the local environmental conditions and epidemiology. In this regard, international guidelines, although useful, can only serve as reference benchmarks for regions or countries; and *should not be* viewed as the panacea for which all countries should aspire to achieve.

7.0 MAJOR CONCLUSIONS

The major conclusions of the study based on the predefined research questions are:

The informal wastewater irrigation schemes are associated with high rotavirus and *Ascaris* infection risks for farmers and consumers of wastewater irrigated lettuce.

- The rotavirus and *Ascaris* infection risks for farmers exposed to irrigation water and contaminated soil in the irrigated fields were above the WHO tolerable annual infection risk. In this regard, exposure to contaminated soil was the most significant health hazard.

- Consumption of lettuce irrigated with polluted water from storm drains and streams resulted in rotavirus and *Ascaris* infection risks above the WHO tolerable annual infection risk level.

- Post-harvest handling practices did not substantially affect the rotavirus and *Ascaris* infection risks associated with the consumption of wastewater irrigated lettuce.

- To adequately model the infection risk for farmers using wastewater for irrigation, both irrigation water and contaminated soils should be accounted for.

Non-treatment and treatment interventions can be employed independently and in combination in a cost-effective manner to mitigate the diarrhoea disease burden associated with the consumption of wastewater irrigated lettuce.

- The cost-effectiveness ratio (CER) for the non-treatment farm based and fast-food sector interventions were US$ 31/DALY (95% CI: 27-35) and US$ 67/DALY (95% CI: 58-76) respectively, both are attractive based on a benchmark value of US$ 150/DALY averted;

- The cost-effectiveness ratio associated with the rehabilitation and construction of a new wastewater treatment plant were US$ 31/DALY (95% CI: 27- 35) and US$ 786/DALY (95% CI: 678 - 893) respectively, both above the benchmark of US$ 150/DALY;

- A combination of non-treatment (farm based and post-harvest) interventions resulted in a cost-effectiveness ratio of US$ 83 /DALY (95% CI: 72 – 95).

- A combination of non-treatment and treatment interventions resulted in cost-effectiveness ratios in the range of US$ 40 – 812/DALY.

- Adoption rate of the non-treatment options is an important determinant of the cost-effectiveness ratio. Adoption rate either on farm or in kitchens of not less than 70% is required to ensure that all non-treatment interventions remain attractive.

- More efforts with respect to motivating and incentivizing farmers and fast-food kitchens through effective educational campaigns are essential if the non-treatment options are to remain attractive in terms of their cost-effectiveness.

- A combination of treatment and non-treatment interventions is recommended to safeguard the health of consumers of wastewater irrigated produce.

Traditional sludge drying methods practiced in Northern can provide an effective barrier for mitigating the occupational health risks associated with untreated faecal sludge reuse in agriculture

- The mean concentrations of *Ascaris* and *E. coli* in cake sludge dried for ≥ 30 days in a random spot spread method and ≥ 90 days in pits met the WHO microbial benchmark.

- Farmers handling cake sludge and cake sludge-soil mixture were more likely to be infected with *Ascaris* than rotavirus. The infection risk associated with aerosolized viruses was low.

- To safeguard the sludge applying farmers from rotavirus and *Ascaris* infection it is recommended that sludge is dried for ≥ 60 days in the random spot spread method and ≥ 90 days in the pit method. Further risk reduction can be achieved if farmers are incentivized to use protective clothes during sludge handling.

There was no significant difference in the diarrheal disease incidence between the periods of sludge and non-sludge application in both the faecal sludge and non-sludge applying communities. Variations in rainfall and temperature were associated were associated with diarrhoeal disease incidence in the faecal sludge applying and non-faecal sludge applying communities.

- In the sludge applying communities, the diarrhoeal disease incidence was higher during the period of sludge application than the period after sludge application. The vise-versa was the case in the non-sludge communities.

- In both the sludge and non-sludge communities, maximum rainfall events in a particular bi-week increased the risk of diarrhoeal disease incidence. Lag effects of maximum rainfall on diarrhoeal disease incidence were also observed in both the sludge applying and non-sludge applying communities. Also, maximum and minimum temperature conditions were associated with diarrhoeal disease incidence in both sludge and non-sludge communities.

- To adequately model the seasonality of disease incidence in settings where faecal sludge (and or wastewater) is used in agriculture, rainfall and temperature have to be taken into account.

Diarrhoeal disease transmission is accounted for by a complex array of proximal and distal risk factors in settings where sludge is used in agriculture.

- Public domain risk factors (including sludge drying) were the most important determinant of diarrhoeal disease incidence in households applying faecal sludge. However, among all risk factors the sludge drying related risk factors contributed the least to diarrhoeal disease incidence in the sludge households.

- About 70% of the combined effects of the distal socio-economic and public domain blocks of risk factors on diarrhoeal disease incidence in the sludge households were mediated by domestic domain hygiene practices.

- Interventions designed to mitigate diarrhoeal disease risk associated with sludge application should address risk factors at all levels from the public to the domestic domain.

Guidelines for wastewater and sludge application have to be regionalized and at best localized to reflect geographical discrepancies in practices and traditional risk mitigation measures. The present internationalization of guidelines, only lead to research on technologies and interventions that are inaccessible to local farmers using wastewater and faecal sludge in the informal agricultural reuse schemes in developing countries.

8.0 AREAS OF FURTHER RESEARCH

Based on the findings and limitations of this study, the following areas need investigations to further deepen understanding on the risk factors, health risks and cost-effectiveness of interventions associated with informal wastewater irrigation and faecal sludge application:

- Implementation of quantitative microbial risk assessment of wastewater and faecal sludge reuse in Ghana based on actual pathogen concentrations rather than on indicator organisms;

- Development of dose-response models based on subjects in developing countries;

- Holistic assessment of treatment and non-treatment interventions for wastewater irrigation built on social, economic, health and ecological indicators;

- Development of advanced models on the relationship between weather variations and disease incidence associated with faecal sludge and wastewater reuse in agriculture.

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Paper I

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Quantification of the health risk associated with wastewater reuse in Accra, Ghana: a contribution toward local guidelines

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ABSTRACT

Quantitative Microbial Risk Assessment (QMRA) models with 10,000 Monte Carlo simulations were applied to ascertain the risks of rotavirus and *Ascaris* infections for farmers using different irrigation water qualities and consumers of lettuce irrigated with the different water qualities after allowing post-harvest handling. A tolerable risk (TR) of infection of 7.7×10^{-4} and 1×10^{-2} per person per year were used for rotavirus and *Ascaris* respectively. The risk of *Ascaris* infection was within a magnitude of 10^{-2} for farmers accidentally ingesting drain or stream irrigation water; $\sim 10^{0}$ for farmers accidentally ingesting farm soil and 10^{0} for farmers ingesting any of the irrigation waters and contaminated soil. There was a very low risk (10^{-5}) of *Ascaris* infection for farmers using pipe – water. For consumers, the annual risks of *Ascaris* and rotavirus infections were 10^{0} and 10^{-3} for drain and stream irrigated lettuce respectively with slight increases for rotavirus infections along the post-harvest handling chain. Pipe irrigated lettuce recorded a rotavirus infection of 10^{-4} with no changes due to post harvest handling. The assessment identified on-farm soil contamination as the most significant health hazard.

Key words | consumers, farmers, health risk, post-harvest, QMRA, wastewater

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INTRODUCTION

Worldwide, at least 3.5 to 4 million hectares in 50 countries are irrigated with raw, treated/or partially diluted wastewater from domestic and industrial sources (IWMI 2006). In Accra, the capital of Ghana with a population of 2.7 million including its surrounding districts which are growing at 6–9% per annum (Ghana Statistical Service 2002), the use of domestic wastewater for vegetable irrigation has been practiced for more than five decades due to limited access to potable water and freshwater resources (Anyane 1963; Asomani-Boateng 2002; Amoah *et al.* 2006; IWMI 2006; Obuobie *et al.* 2006). The practice provides a livelihood source to a number of poor urban households and contributes to the urban food basket (Keraita & Drechsel 2004; IWMI 2006). However, it is considered highly undesirable by the authorities in Ghana due to the potential health risks associated with it. The question has therefore been how to mitigate the health risks associated with the practice without compromising livelihoods. Abating the health risk associated with the practice demands the development of locally acceptable guidelines for wastewater irrigation based on quantifiable and verifiable health risks (Drechsel *et al.* 2002; WHO 2006).

Over the years, the International Water Management Institute (IWMI) office in Accra with several national and international partners has undertaken a number of studies under its projects CPWF38 and 51, to ascertain and reduce the potential health hazards associated with the practice (Keraita *et al.* 2007; Keraita & Drechsel 2004; Amoah *et al.* 2006, 2007*a*,*b*; Obuobie *et al.* 2006). This work is an extension of the IWMI studies and aims at quantifying the

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health risks associated with the practice using the Quantitative Microbial Risk Assessment (QMRA) approach. It is one of the first times that QMRA is being applied to assess the health risks associated with wastewater irrigation in Sub-Saharan Africa. QMRA has been widely used to establish the health risks associated with wastewater reuse in both developed and developing regions under different scenarios. It has been applied to establish the health risk associated with consuming wastewater-irrigated food crops (Tanaka *et al.* 1998) and vegetables (Shuval *et al.* 1997; Petterson *et al.* 2001; Hamilton *et al.* 2006). Mara *et al.* (2007) have also applied QMRA to assess the health risks for farmers using wastewater under different irrigation and technology regimes. The approach has also been included in the recent WHO guidelines for the safe use of wastewater, excreta and greywater (WHO 2006).

METHODS

The assessment followed the basic methodological framework for QMRA postulated by Haas *et al.* (1999). The microbial data inputs used in the QMRA were largely based on the works from the IWMI CP38 and CP51 projects. Details of the methods used for the microbial enumeration as well as issues regarding quality assurance have been comprehensively presented elsewhere (Amoah *et al.* 2005, 2006, 2007*a*,*b*). In addition a comprehensive literature review of international peer reviewed journals was undertaken to provide inputs for hazard identification, dose-response assessment, exposure assessment and risk characterisation.

Hazard identification

Choice of pathogens and justification

Microbial investigations undertaken so far on wastewater reuse in Accra have focused on the quantification of helminths eggs and faecal coliforms (FC) (Keraita & Drechsel 2004; Obuobie *et al.* 2006; Amoah *et al.* 2006, 2007*a*, *b*). For purposes of our assessment, we chose rotavirus and *Ascaris lumbricoides* as the model organisms. Rotavirus is a major cause of gastroenteritis (Parashar *et al.* 2003; Anderson & Weber 2004; Chandran *et al.* 2006) and has been widely used as a representative organism for enteric viruses in QMRAs of wastewater reuse (Asano & Sakaji 1990; Asano *et al.* 1992; Shuval *et al.* 1997; Hamilton *et al.* 2006). It has also been identified as a major diarrhoeal pathogen in Ghana, accounting for 20% of all diarrhoea cases especially among children (Armah *et al.* 1995). *A. lumbricoides* is the most prevalent parasitic infection worldwide with infection rates ranging from 40–98% in Africa (Freedman 1992). Several studies have established a clear association between *Ascariasis* and wastewater reuse among farmers (Shuval *et al.* 1984; Al Salem & Tarazi 1992; Cifuentes *et al.* 1992; Cifuentes 1998; Peasey 2000; Blumenthal *et al.* 2001) and consumers of wastewater irrigated vegetables (Pound & Crites 1973; Bryan 1997). In Ghana, the prevalence rate of *Ascariasis* is 52% (Hotez *et al.* 2003) with symptoms ranging from abdominal pain, meteorism, nausea, vomiting, diarrhoea and undernourishment (WHO 2006; Jimenez 2007). *Ascaris*, can survive also for months to years under severe environmental conditions (Feachem *et al.* 1983) and has therefore been suggested for QMRAs in developing regions (WHO 2006).

Ascaris and rotavirus levels in irrigation water, contaminated soil and irrigated lettuce

In Accra, irrigation waters used for vegetable farming are sourced mainly from drains, streams and pipes (Gbireh 1999; IWMI 2006; Obuobie *et al.* 2006; Amoah *et al.* 2006, 2007*a*,*b*). We used the *Ascaris* and FC data reported by Amoah *et al.* (2006) and Obuobie *et al.* (2006) for the different irrigation water (drain, stream and pipe) and contaminated soils to assess the health risk for farmers. For the FC concentration in pipe irrigation water, data reported by Gbireh (1999) were used. For consumers' health risk, data on *Ascaris* and FC levels on lettuce irrigated with the different water qualities and sold at the farm, wholesale and retail markets reported by Obuobie *et al.* (2006) and Amoah *et al.* (2007*a*,*b*) were used. The inclusion of the markets was to account for potential effects of post-harvest handling on health risks. For a worse case scenario, we chose lettuce over other vegetables. Lettuce is reported to have a higher *Ascaris* and FC contamination compared with other leafy vegetables irrigated with wastewater in Accra (Obuobie *et al.* 2006) potentially due to its morphology for water retention (Shuval *et al.* 1997).

To account for the rotavirus in our risk assessment models, all reported FC in the above literature sources were converted to rotavirus using a ratio of 1(rotavirus) to 10^5 (FC) applied by Shuval *et al.* (1997). The same approach was followed by Mara *et al.* (2007) but with an assumption of 1 rotavirus to 10^5 *Escherichia coli*. We used the $\log_{10}$normal probability distribution for rotavirus and *Ascaris* in the different irrigation water sources and irrigated lettuce sold at the farm, wholesale and retail markets as shown in Table 1. Applying the same conversion ratio for rotavirus to FC, the FC per 100 g of contaminated soil reported by Amoah *et al.* (2005) was uniformly distributed from 0.039 to 4.1. The *Ascaris* level in the same quantity of soil was also uniformly distributed from 50 to 190 eggs per 100 g of contaminated soil based on Amoah *et al.* (2005). It must be stressed that the FC to rotavirus extrapolation may be an overestimation or underestimation of the rotavirus in both the irrigation water and contaminated soil with a corresponding higher or lower resulting risk of infection. For this, we have accounted for variability in the estimated risk of infection. Field scale investigations are presently underway to establish the most probable level of rotavirus and other pathogenic microorganisms in the above irrigation water and contaminated soil in Ghana.

Exposure assessment

Four exposure scenarios were modelled in the assessment: (a) Accidental ingestion of only *wastewater* by farmers; (b) Accidental ingestion of only *contaminated soil* by farmers; (c) Accidental ingestion of both *wastewater and contaminated* soil by farmers; and (d) Consumption of the different *wastewater irrigated lettuce* collected from the farm, wholesale and retail markets by consumers. The bases for these scenarios are presented below:

Farmers' exposure scenarios

Vegetable farming activities in Accra are labour intensive thus putting farmers who generally do not wear any protective clothes (e.g. boots, mouth covers, gloves etc.) into direct contact with irrigation water and contaminated

Table 1 | Levels of Rotavirus and *Ascaris* in different wastewater sources and irrigated lettuce. The figures in the parenthesis represent the means and standard deviations for the $\log_{10}$normal probability distributions and maximum and minimum for the uniform distribution. Rotavirus data are extrapolated from FC data using the ratio 1(rotavirus) to 10^5 (FC)

Irrigation water source	Irrigation water quality		Quality of wastewater irrigated lettuce collected at various post harvest handling points: Farm		Wholesale market		Retail market	
	Rotavirus ($100\ ml^{-1}$)	*Ascaris** (eggs L^{-1})	Rotavirus§ ($100\ g^{-1}$ wet weight)	*Ascaris** ($100\ g^{-1}$ wet weight)	Rotavirus§ ($100\ g^{-1}$ wet weight)	*Ascaris** (eggs $100\ g^{-1}$ wet weight)	Rotavirus§ ($100\ g^{-1}$ wet weight)	*Ascaris** (eggs $100\ g^{-1}$ wet weight)
Drain	$\log_{10}$normal† (−0.11, −3.87)	$\log_{10}$normal (0.48,0.30)	$\log_{10}$normal (−0.75, −4.26)	$\log_{10}$normal (5.7, 1.1)	$\log_{10}$normal (−0.76, −4.14)	$\log_{10}$normal (5.9, 1.2)	$\log_{10}$normal (−0.52, −4.22)	$\log_{10}$normal (5.2, 1.5)
Stream	$\log_{10}$normal 1† (−0.01, −3.88)	$\log_{10}$normal (0.60,0.60)	$\log_{10}$normal (−0.78, −4.34)	$\log_{10}$normal (3.8, 0.9)	$\log_{10}$normal (−0.71, −4.38)	$\log_{10}$normal (3.1, 0.9)	$\log_{10}$normal (−0.71, −4.38)	$\log_{10}$normal (3.9, 1.2)
Piped Water	Uniform (0, <0.0001)‡	Uniform (0, <0.001)‖	$\log_{10}$normal (−1.56, −4.60)	$\log_{10}$normal (3.2, 0.7)	$\log_{10}$normal (−1.54, −4.57)	$\log_{10}$normal (2.1, 1.2)	$\log_{10}$normal (−1.54, −4.57)	$\log_{10}$normal (3.3, 1.0)

*Based on FC data reported by Obuobie *et al.* (2006); Amoah *et al.* (2006).
†Based on *Ascaris* data reported by Amoah *et al.* (2006); Obuobie *et al.* (2006).
‡Based on FC data reported by Gbireh (1999).
§Based on FC data reported by Obuobie *et al.* (2006); Amoah *et al.* (2007a,b).
‖Based on reported values helminths ova (*Ascaris*) in treated pipe water (Landa *et al.* 1997).

soil. However, the specific doses of irrigation water and contaminated soil accidentally ingested by farmers have not been reported in the literature in Ghana. Therefore, data from other studies with some adjustments were used. The amount of irrigation water ingested was assumed to be uniformly distributed from 1–5 mL per day for a total of 75 days of active irrigation per year. This range is an extension of the 1 ml ingestion level reported by Ottoson & Stenstrom (2003) and it was to account for the predominant use of watering cans for irrigation. A uniformly distributed accidental ingestion of 10 – 100 mg of soil per daily exposure for a total of 150 days per year was also used for the farmers (Haas *et al.* 1999; WHO 2001; Mara *et al.* 2007). For a worse case scenario, we assumed there was no reduction for both rotavirus and *Ascaris* before the ingestion of irrigation water and contaminated soil.

Consumers' exposure scenario

The majority of harvested lettuce in Accra is distributed on farm via wholesale markets to retail markets. Of the total lettuce sold at the wholesale and retail markets, 60% is purchased by some 5000 fast food sellers who daily serve between 130,000 and 150,000 people in Accra with lettuce salads as part of other dishes (Obuobie *et al.* 2006). An additional 38% is sold to canteens and restaurants. Only about 2% is purchased by households (Obuobie *et al.* 2006). Therefore, it was assumed that lettuce salad consumed in Accra is predominantly served by the fast food sellers. To ascertain the combined effect of irrigation water quality and post harvest handling on consumers' health risks, it was assumed that the fast food sellers could buy lettuce irrigated with any of the irrigation waters from either the farm, wholesale or retail distributions points. The amount of lettuce salad consumed was uniformly distributed from 10 to 12 g per single meal (Obuobie *et al.* 2006). This is far lower than the 100 g of lettuce per meal used in other studies (Shuval *et al.* 1997; Mara *et al.* 2007) and reflects the low consumption of lettuce salad in Ghana. The frequency of consumption was taken to be 4 times per week (IWMI 2006; Obuobie *et al.* 2006) giving 208 days of exposure per consumer of lettuce salad per year. For the amount of pathogens ingested by consumers during exposure, we assumed there will be no reductions in rotavirus and *Ascaris* in the fields given that farmers do not cease irrigation for some period before harvesting as they want their lettuce to look fresh at the point of harvest. About 99% of the fast food sellers are reported to wash lettuce with tap water and use disinfectants such as lemon, household bleach and vinegar sparingly during the preparation of lettuce salad (Amoah *et al.* 2007*a*). Reductions due to these practices were therefore considered. According to the WHO (2006) a 1 $\log_{10}$ reduction of pathogens (rotavirus) on lettuce can be achieved through washing with only water. An additional 2 $\log_{10}$ reduction of pathogens is also achievable when a mild disinfectant is used. It was therefore assumed that the combined effect of washing and disinfection during salad preparation would lead to a 3 $\log_{10}$ reduction of rotavirus before ingestion as used by Shuval *et al.* (1997). Amoah *et al.* (2007*b*) have also shown that a 1–2 $\log_{10}$ reduction of *Ascaris* on lettuce can be achieved with the above practice. For this, a uniform distribution of 1–2 $\log_{10}$ reduction was assumed for *Ascaris* on lettuce before ingestion.

Dose response assessment

The ß-poison dose response model was used to estimate the risk of rotavirus infection (Haas *et al.* 1999) while the exponential model was used for *Ascaris* infection (Westrell 2004). In the case of a single exposure, the ß-poison and exponential dose response models are expressed respectively as:

$$P_1(d) = 1 - [1 - (d/N_{50})(2^{1/a} - 1)]^{-a} \quad \text{and}$$

$$P_1(d) = 1 - \exp(-rd)$$

Where P_I (d) is the probability of becoming infected by ingesting d number of organisms, N_{50} is the median infection dose representing the number of organisms that will infect 50% of the exposed population; and a and r are the dimensionless infectivity constants. For rotavirus, N_{50} and a are 6.17 and 0.253 respectively (Haas *et al.* 1999). The exact value of r for *Ascaris* is not yet established in dose-response studies. Therefore, a conservative value of r based on a worse case evaluation was used. For a worse case evaluation, the exact single-hit model ($r = 1$), which represents the maximum risk curve (Teunis & Havelaar 2000) can be used. The same value has been used by

Westrell (2004) to model the health risk associated with *Ascaris* infection.

Risk characterisation

Given the infection per single exposure above, the annual risk of infection for multiple exposures per person $P_{I(A)}$ was calculated as (Sakaji & Funamizu 1998):

$$P_1(A) = 1 - [1 - P_1(d)^n]$$

Where P_I (d) is as before, the risk of infection from a single exposure to a dose d of organisms; and n being the number of days in a year when a person is exposed to this single dose d. For the scenario of farmers' ingesting both irrigation water and contaminated soil, the combined annual risk of infection was determined by using the relation (Haas *et al.* 1999):

$$\pi_t = 1 - (1 - \pi_i)(1 - \pi_x)$$

Where π_t is the combined annual risk of infection from exposures to wastewater and contaminated soil; π_i is the annual risk of infection resulting from accidental ingestion of irrigation water and π_x is the annual risk of infection resulting from accidental ingestion of contaminated soil.

Monte Carlo Simulations were run using @Risk version 4.5.2 professional edition (Palisade Corporation) added on to Microsoft Excel. Random variables were sampled from the probability distribution functions for the dose of wastewater and contaminated soil (in the case of farmers) and lettuce (in the case of consumers) using the Latin hypercube sampling at 10,000 iterations. The median annual risks of infections were reported for the different scenarios. The 5th and 95th percentiles were also presented to account for variability in the estimated risks. Diarrhoea was used as a proxy for infections related to rotavirus. For comparative analyses, we used the WHO (2006) benchmark for annual tolerable risk (TR) for diarrhoea per person of 7.7×10^{-4} for rotavirus in developing countries. This is extremely conservative given that the incidence of diarrhoeal diseases in developing countries is in the range of 0.8 − 1.3 per person per year (Mathers *et al.* 2002). For *Ascaris* infection, a tolerable risk of 1×10^{-2} (Mara *et al.* 2007) was used to account for its high prevalence in developing countries and in wastewater reuse (Hotez *et al.* 2003; WHO 2006).

RESULTS

Farmers health risk

The median annual risk of rotavirus and *Ascaris* infections (including the 5th and 95th percentile range) associated with the accidental ingestion of the different irrigation water and contaminated soil is presented in Figure 1. For rotavirus infections among farmers, there was a descending order of magnitude of risk from drain to stream to pipe irrigation waters with drain water resulting in rotavirus infections above the WHO–TR of 7.7×10^{-4} per farmer per year. The median annual risks of rotavirus infections per farmer for the accidental ingestion of stream and pipe irrigation waters were 3.14×10^{-5} and 7.5×10^{-7} respectively. For *Ascaris*, the median annual risks due to the accidental ingestion of drain and stream irrigation water were of the same order of magnitude at 8.2×10^{-2} and 8.4×10^{-2} respectively and slightly above the TR. For pipe water it was some 3 orders lower than the TR at 9.5×10^{-5} per farmer.

Compared with irrigation water, the accidental ingestion of contaminated farm soils posed the greatest health risk to farmers. Both the median annual risks of *Ascaris* and rotavirus infections for such incidents were above the TRs

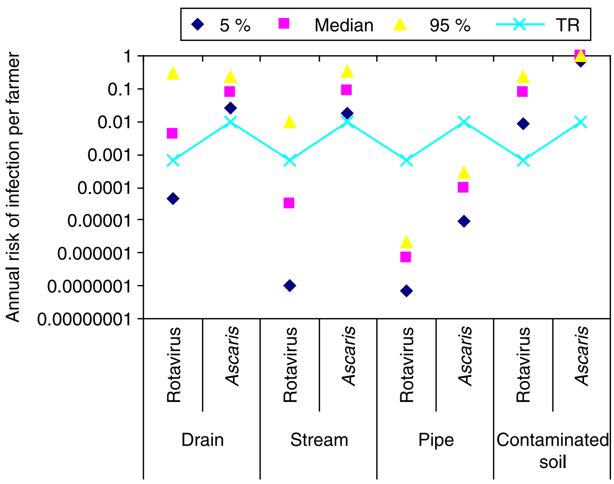

Figure 1 | Farmers' annual risk of rotavirus and *Ascaris* infections associated with the accidental ingestion of different irrigation water and contaminated soil.

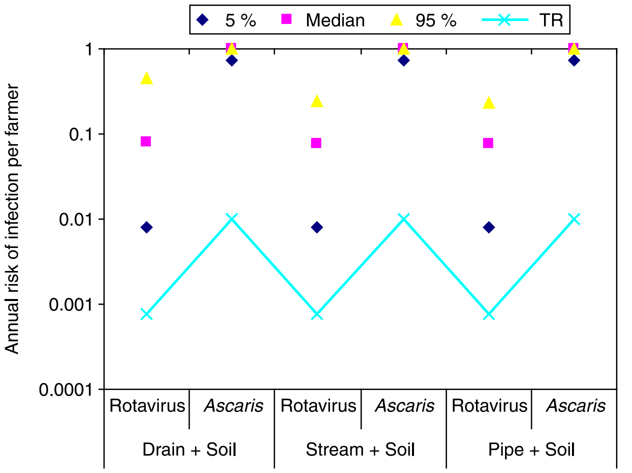

Figure 2 | Farmers' annual health risk associated with the combined accidental ingestion of both wastewater and contaminated soil.

with the highest risks accounted for by *Ascaris* infection as depicted in Figure 1. For this, the median annual risks of *Ascariasis* and rotavirus infections for the farmers were 0.99 and 7.6×10^{-2} respectively. Mara *et al.* (2007) also reported a median annual risk of rotavirus infection of 9.9×10^{-2} for farmers accidentally ingesting 10–100 mg of soil containing 105–106 *Escherichia coli*/100 g for 150 days.

As mentioned under the exposure assessment, farmers are likely to ingest both irrigation water and contaminated soil. The outcome of such incidents represents the most probable health risks for farmers. For this, the median annual risks of rotavirus and *Ascaris* infections exceeded the annual TR per farmer regardless of the irrigation water quality as depicted in Figure 2. The median annual risk of rotavirus infection was 8.0×10^{-2} for farmers ingesting drain irrigation water and contaminated soil and 7.7×10^{-2} for those ingesting contaminated soil in addition to stream or pipe irrigation water.

For *Ascariasis*, the median annual risk of infection was $\sim 10^{0}$ (i.e. 0.99) for all the irrigation water types given the same dose of contaminated soil as depicted in Figure 2. This shows that even when irrigation water quality meets the standards set for irrigation in the WHO guidelines, as was the case with pipe water (0 – < 10FC/100 mL) in our assessment, tolerable health risk outcomes can still be elusive if farm practices that contaminate soils are still pervasive (Drechsel *et al.* 2000).

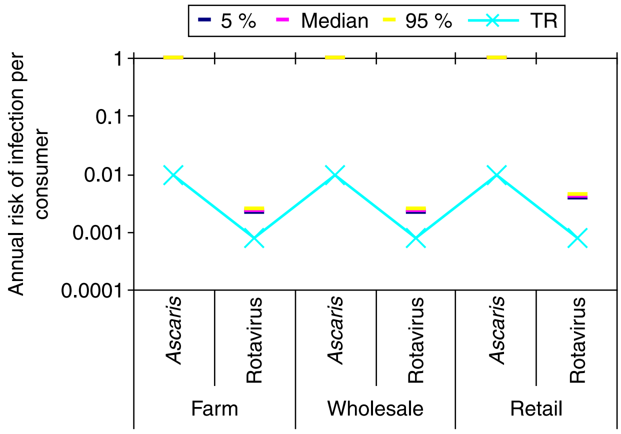

Figure 3 | Annual Rotavirus and *Ascaris* infections associated with the consumption of pipe irrigated lettuce collected from different marketing points.

Consumers' health risk

Figures 3–5 present the median annual risks of rotavirus and *Ascaris* infections from the consumption of lettuce irrigated with the different irrigation water collected from the farm, wholesale and retail markets. The results indicate that the background irrigation water quality and on farm contamination are the most potential risk factors for consumers of the irrigated lettuce. The effect of post harvest handling through contamination in the markets on health risk was low. As depicted in Figures 3 and 4, the median annual risks of rotavirus infection for consumers of drain

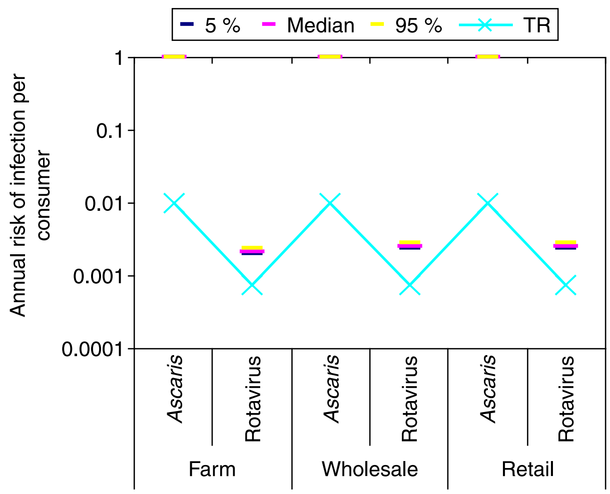

Figure 4 | Annual rotavirus and *Ascaris* infection associated with the consumption of stream irrigated lettuce collected from different marketing points.

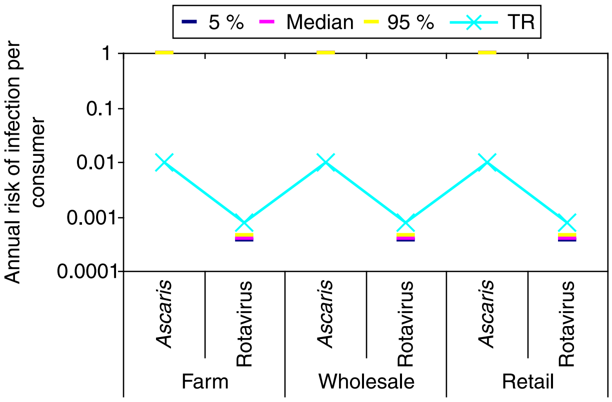

Figure 5 | Annual rotavirus and *Ascaris* infections associated with the consumption of pipe irrigated lettuce collected from different marketing points.

and stream irrigated lettuce were of the same magnitude and increased slightly during post harvest handling. During post harvest handling, the estimated annual risk of rotavirus infection for consumers of drain irrigated lettuce increased slightly from 2.3×10^{-3} per consumer from the farm and wholesale market points to 4.1×10^{-3} for the retail market. For stream irrigated lettuce, it increased from 2.2×10^{-3} for the farm selling point to 2.6×10^{-3} for the wholesale and retail markets. However, the median annual risk of rotavirus infection for consumers of pipe irrigated lettuce was the same for all the selling points at 4.1×10^{-4} as shown in Figure 5. In terms of *Ascaris* infection, the median annual risk of infection was 10° for consumers irrespective of the quality of irrigation water and marketing point as depicted in Figures 3 – 5. These risk estimates, are in contrast with the findings made by Ensink *et al.* (2007) where post harvest market handling was identified as a major risk factor for consumers of wastewater irrigated vegetables.

DISCUSSION

A major observation was the increased levels of *Ascaris* and rotavirus infection for farmers due to the accidental ingestion of *contaminated soil* compared to the ingestion of the different *irrigation water*. The elevated hazard posed by soils on-farm could be attributed to the persistence of *Ascaris* and FC in the soils due to several reasons. In contrast to arid and semi-arid regions where the de-activation of *Ascaris* occurs in soils rapidly (Hotez *et al.* 2003), the average annual temperature (27.1°C), relative humidity (81%) and solar radiation (18.6MJ/m^2/day) prevailing in Accra (Agodzo *et al.* 2003) can lead to the persistence of *Ascaris* in the soil. *Ascaris* can embyronate given the above humid and warm conditions and become infectious (Maier *et al.* 2000). Also, farm practices including fertilization of soils with poorly treated manure (Drechsel *et al.* 2000) and cow faeces by farmers in Accra (Amoah *et al.* 2007*b*) explains the high levels of FC in the soil. The FC concentrations in fresh poultry and cow faeces are 1.3×10^6/gram and 2.3×10^5/gram respectively (Geldreich 1978) and when mixed into the soil without proper treatment can persist over a long time given the climatic conditions prevailing in Accra (Byappanahalli & Fujioka 1998). According to Zaleski *et al.* (2005) faecal coliforms and other pathogens have the potential to re-grow and re-colonize in soils amended with poorly treated manure/bio-solids especially during the rainy season. A study by Amoah *et al.* (2006) found the same magnitude of FC and *Ascaris* contamination for soils irrigated with pipe, stream and drain irrigation water indicating the application of untreated manure rather than wastewater was the main cause of soil contamination.

From the foregoing it can be concluded that irrigation water quality alone may not be an appropriate input into the assessment of the health risks for farmers using wastewater for irrigation as was the case in the QMRA of Mara *et al.* (2007) where soil and wastewater were assumed to have the same level of *E. coli* contamination. This also questions the helminths guideline by the WHO, which makes provision for only irrigation water quality of 0.1–1eggs/litre (WHO 2006). As our results indicate, the consumption of contaminated soil may pose a significant health risk above TR levels even when the irrigation water quality meets the WHO guidelines. A combination of irrigation water and soil quality into risk models will thus give a better picture of the health risks for farmers.

Also the initially high contamination of lettuce on farms resulting from the irrigation water and already contaminated soils may explain the risk of rotavirus and *Ascaris* infections among consumers. It is reported that irrigation water is sprayed directly overhead on lettuce by farmers (Amoah *et al.* 2006) using uncapped watering cans and buckets (Amoah *et al.* 2007*a*,*b*). This irrigation practice leads to splashes from the already contaminated soil further contaminating the lettuce on farm. Therefore, a reduction of the splash intensity from the already contaminated soil through proper irrigation practices can significantly reduce health risks on farm. Keraita *et al.* (2007) showed that using watering cans with caps on their spouts reduced the intensity of splashes from already contaminated soil resulting in a correspondingly higher reduction in lettuce contamination compared to uncapped watering cans. The study revealed that by irrigating from a low height of < 0.5 m with capped watering cans the thermotolerant coliforms reduced by 2.5 log units and helminthes by 2.3 eggs per 100 g of lettuce compared to irrigating with uncapped watering cans at a height of > 1 m. Drip irrigation can also substantially reduce soil splashes and contamination of lettuce with wastewater with a correspondingly significant reduction in health risks. According to Keraita *et al.* (2007), lettuce irrigated with drip kits have, on average, 4 $\log_{10}$ units per 100 g, fewer thermotolerant coliforms than those irrigated with watering cans. These simple but effective on farm risk reduction measures have been adopted by the WHO in its most recent guidelines for wastewater reuse in agriculture. The efficacy and adoptability of these methods as well as other simple on farm, post-harvest handling and household level health risk reduction measures are presently being explored through field scale investigations in Ghana.

The slight increases in the annual risk of rotavirus infection for consumers of drain and stream irrigated lettuce along the distribution chain (farm to wholesale to retail markets) gives an indication of potential contamination from post-harvest handling. Studies have highlighted unhygienic conditions and practices prevailing in these markets as a possible cause of contamination for wastewater irrigated vegetables. In a comparative survey of the contamination of wastewater irrigated lettuce on agricultural fields and in markets, Ensink *et al.* (2007) found a higher level of *E. coli* and helminths contamination in markets compared to on farm. The survey found relatively low concentrations of *E. coli* (1.9 *E. coli* per gram), but relatively high concentrations of helminths (0.7 eggs per gram) on vegetables collected from agricultural fields. Higher concentration of both *E. coli* (14.3 *E. coli* per gram) and helminths (2.1 eggs per gram) were recovered from the vegetables collected from the market. Amoah *et al.* (2007*a*) however found a very low FC contamination of lettuce in the markets in Accra as reflected in our risk estimates. Potential contamination of lettuce in these markets include the use of contaminated water for lettuce re-freshening (Ensink *et al.* 2007) and the display of lettuce under unhygienic conditions (Nyanteng 1998; Drechsel *et al.* 2002). In Accra, for example, sellers display wastewater irrigated lettuce on the bare floor of the market and on tables unprotected from flies and dust. Therefore for a holistic assessment of health risks associated with the consumption of wastewater irrigated vegetables it is pertinent that post harvest handling is factored into models in addition to the irrigation water quality and on farm contamination. This is especially critical in developing countries where poor packing and storage facilities as well as unhygienic conditions might characterize post harvest handling.

The estimated risks of *Ascaris* and rotavirus infections recorded in this assessment have to be interpreted with some caution. For *Ascaris*, our assessment only reports the probability of infection and does not reflect the worm load of the infected farmers and consumers. Therefore, the probability of infection eventhough the same for consumers and farmers, is not tantamount to both groups having the same level of worm load. All things being equal, the level of worm load will be higher for farmers than consumers due to their annual dose of *Ascaris* ingestion. The worm load within the farming as well as the consumer populations will also differ due to the characteristic over-dispersed distribution of *Ascaris* load burden by age among infected populations (Bundy *et al.* 2004). This over dispersed distribution will reflect in children engaged in wastewater irrigation and eating wastewater irrigated lettuce harbouring a disproportionately higher *Ascaris* burden than adults (Bundy 1988). Also, the rotavirus health risks presented here should not be misconstrued as a representative for all the possible enteric virus infections because of the diverse symptoms of enteric virus infections (Westrell 2004). Presently, a WHO funded project in Ghana is investigating the prevalence, distribution and load of *Ascaris* worms and diarrhoea incidence among farmers and children using different wastewater qualities for irrigation and consumers of the irrigated vegetables. The outcome of this study will complement the risk estimates arrived at in this assessment.

The QMRA presented here provides the building block for a quantitatively oriented local guideline for wastewater irrigation in Ghana. The model can be extended to encapsulate the effects of different interventions and their efficacy in reducing the health risks reported here to tolerable levels. However, this will require that more investigations are carried out into the occurrence and concentration of etiological agents of bacteria, viral, parasitic and protozoan origins which are of health significance in Ghana.

CONCLUSION

The assessment has revealed a high risk of *Ascaris* and rotavirus infections above TR for farmers using different irrigation water quality and the consumers of irrigated lettuce. Soils on-farm posed the greatest hazard to farmers for both *Ascaris* and rotavirus infections. For consumers, the already contaminated lettuce collected from the farms had the greatest effect on their levels of *Ascaris* and rotavirus infections. There were minor increases in consumer health risks associated with post-harvest handling at the markets, these increases were however very low.

To abate the health risks for farmers and consumers, conscious efforts have to be made to develop local guidelines based on interventions that are implementable from the short-medium-long term. These local guidelines should reflect different quantifiable tolerable risk levels associated with the reuse of different irrigation water qualities for farmers and consumers. The development of such quantitatively verifiable health risk guidelines could serve as the basis for a fruitful engagement among the different stakeholders concerned with public health issues in Ghana.

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Paper II

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Cost-Effectiveness Analysis of Interventions for Diarrhoeal Disease Reduction among Consumers of Wastewater-Irrigated Lettuce in Ghana

Razak Seidu and Pay Drechsel

Abstract

Interventions proposed and implemented for the mitigation of diarrhoeal diseases associated with wastewater reuse in agriculture have received little, if any, comparative assessment of their cost-effectiveness. This chapter assesses the costs, outcomes and cost-effectiveness of the so-called 'treatment' and 'non- or post-treatment' interventions as well as a combination of these for wastewater irrigation in urban Ghana using an approach that integrates quantitative microbial risk assessment (QMRA), disability-adjusted life years (DALYs) and cost-effectiveness analysis (CEA). The cost-effectiveness ratios (CERs) for the treatment and non-treatment interventions assessed ranged from US$31/DALY to US$812/DALY averted. Risk-reduction measures targeting farming practices and the basic rehabilitation of local wastewater treatment plants were the most attractive interventions with a CER well below the threshold of US$150/DALY, sometimes considered as the upper limit for a health intervention to be cost-effective in developing countries. All combinations associated with the basic rehabilitation of the treatment plants, with either on-farm or post-harvest interventions or both, resulted in CERs within the range of US$40/DALY to US$57/DALY. However, the CERs for the construction

of a new wastewater treatment plant either as an independent intervention or in combination with on-farm and post-harvest interventions were unattractive in view of health-risk reduction for wastewater irrigation. Although attractive, the CERs of non-treatment options are largely dependent on compliance (adoption) by farmers and food vendors. In this regard, the CER increased by almost fivefold when the adoption rate was only 25 per cent by farmers and food vendors; but was attractive as long as adoption rates did not fall below 70 per cent. On the other hand, the success of the treatment option depends on the functionality of the treatment plants which is not without challenges in a country like Ghana. Thus, this chapter stresses the need for a balanced risk-management approach through a combination of treatment and non-treatment interventions to hedge against failures that may affect CERs at any end. While this chapter provides a contribution to the debate on interventions for health-risk mitigation in wastewater irrigation, more case studies would be useful to verify the data presented here.

Introduction

Irrigation with raw, diluted and treated wastewater for vegetable production is increasingly becoming a central component of the urban food matrix in many countries due to depleting freshwater resources, increased demand for fresh vegetables and the need to reuse water based on a deeper understanding of sustainability issues. The benefits of the practice are many and encapsulate social, economic and environmental returns that dovetail neatly into food security, freshwater conservation and sustainable wastewater management. At the same time, wastewater irrigation can serve as a conduit for severe and sometimes fatal health consequences with a cost to society greater than its benefits if not undertaken in a safe manner. Many of the infectious pathogenic organisms of viral, bacterial, protozoan and parasitic origins implicated in gastroenteric diseases are present in wastewater and may be transmitted via the consumption of wastewater-irrigated vegetables. A review of several wastewater-irrigation studies worldwide showed clear evidence of direct correlations between the consumption of wastewater-irrigated vegetables and the occurrence of gastroenteric diseases including diarrhoea (Blumenthal and Peasey, 2002).

To reduce the health risk associated with wastewater irrigation while optimizing its benefits, a multi-pronged approach that progressively reduces microbial health hazards has been proposed by the most recent World Health Organization (WHO) Guidelines for wastewater irrigation (WHO, 2006). This approach to health-risk management appreciates the diverse and disparate socio-cultural, technical and institutional dynamics of wastewater irrigation and thus postulates a wide range of flexible and locally specific health-risk barriers. This is of particular importance where the main conventional risk barrier, i.e. wastewater treatment, does not sufficiently work, as in most developing countries. Here, so-called ‘post-treatment’ or 'non-treatment' options gain significance (see Chapter 2). These comprise measures for risk reduction along the farm to fork pathway, such as drip-kit irrigation or vegetable-washing.

Several of these health-risk barriers have been explored in different geographical areas in terms of their efficacy in view of risk reduction and, in some cases, their feasibility of implementation, acceptability and potential sustainability. One of these cases is Ghana. In urban Ghana, where wastewater irrigation is common and poses a significant health risk (Seidu et al., 2008), non-treatment interventions at the farm and post-harvest points have been explored in different cities, on farms, in markets and in street-food restaurants (see references in Drechsel et al., 2008). These studies, together with others elsewhere (WHO, 2006), have shown that a significant risk reduction is also possible where public health cannot yet rely on conventional wastewater treatment, especially if different options are combined. However, decisions as to which intervention to implement have largely accounted for only the efficacy of the interventions in terms of reduced bacterial counts or helminth eggs, without rigorous analysis of the health gains and cost-effectiveness.

An approach that has been used to address this gap is cost-effectiveness analysis (CEA). The approach provides a framework for the assessment of interventions in terms of their costs per standardized health benefit measured in DALYs averted (WHO, 2003). This approach, although widely used to assess water and sanitation interventions, is yet to be applied to wastewater irrigation to rigorously assess the different interventions proposed in the 2006 WHO Guidelines. This chapter presents the first attempt at applying a holistic CEA framework that integrates the health gains in terms of diarrhoeal disease reduction and cost of treatment and non-treatment interventions associated with wastewater irrigation in urban Ghana.

Description of interventions

Both intervention types, treatment and non-treatment, were considered in comparison with the common (baseline) practices of wastewater irrigation, independently and in combination. For the non-treatment option a variety of improved practices were tested at different critical control points, i.e. on the farm, in markets and in kitchens of the street-food sector, in terms of their ability to reduce faecal coliforms and helminth eggs on vegetables mostly eaten raw (Drechsel et al., 2008). Chapters 10 and 12 in this book provide more details on this. For the promotion of these practices the International Water Management Institute (IWMI) and national partners suggested a 36-month campaign.

The campaign targeted farmers using wastewater for irrigation and street-food kitchens selling wastewater-irrigated salads as part of common urban fast-food dishes. For the CEA, the on-farm and off-farm components of the campaign were assessed separately and in combination. The campaign was largely based on social marketing, incentives and education (see also Chapter 16), and included improved irrigation practices such as cessation of irrigation, drip irrigation and improved overhead irrigation at the farm level, as well as more effective vegetable-washing practices at the post-harvest level.

A set of possible interventions was compiled at the farm and fast-food restaurant level, taking into account different possibilities and constraints at different locations. As some practices will have a higher applicability and adoption potential at one site than another their average risk reduction was used in the analysis presented here. Thus, in the assessment, the specific improved practices were categorized into two groups, on farm and post-harvest respectively, with no further distinctions between the different interventions. Aside from those 'non-treatment' options, the IWMI project carried out an inventory of all 70 (largely dysfunctional) wastewater treatment plants (WWTP) in Ghana to analyse, among things, their costs of rehabilitation. Nine smaller wastewater treatment plants with minor technical problems were selected for rehabilitation across five major cities in Ghana where wastewater irrigation is practised, each meeting the following criteria:

- The treatment plant had farmland available for irrigation purposes.
- Wastewater irrigation is undertaken in the town/city where the treatment plant is located.
- The readiness and willingness of local regulatory authorities and managers of the plant to use wastewater for irrigation.
- The cumulative area would be large enough to absorb the large majority of farmers currently using untreated wastewater.

In addition to the rehabilitation option, the ongoing construction of a smaller new wastewater treatment plant in Legon, Accra[1] (with a theoretically possible large-scale irrigation component) was assessed, using official cost estimates. Finally, all possible combinations of treatment and non-treatment options were assessed.

METHODS

An integrated approach combining QMRA, DALYs and CEA was applied to estimate quantitatively the health effects and cost-effectiveness of the interventions. For this, the QMRA framework presented by Haas et al. (1999) was followed while DALY estimations were based on Murray (1994). The cost-effectiveness of the interventions was constructed following the WHO guide to cost-effectiveness analysis (WHO, 2003). A detailed description of the methodology is presented as follows.

Health-risk assessment

Hazard identification

All diarrhoea-causing pathogenic organisms of viral, bacterial, protozoan and parasitic origins are present in wastewater and can be transmitted via the consumption of wastewater-irrigated vegetables. In Ghana, studies on the microbial hazards in wastewater have so far been limited to faecal coliforms and helminths (Amoah et al., 2007; Obuobie et al., 2006). However, epidemiological investigations of diarrhoea prevalence have consistently detected a wide range of pathogenic organisms including rotavirus (Reither et al., 2007), (non-typhi) *Salmonella* and *Cryptosporidium* (Adjei et al., 2004) suggesting that these organisms can potentially be found in the wastewater used for vegetable irrigation. Therefore, for this assessment, we chose rotavirus, *Cryptosporidium* and *Salmonella* respectively as representative organisms for the viral, protozoan and bacterial infections and diarrhoea cases.

Rotavirus has been used as a representative organism in health-risk assessments associated with wastewater irrigation in Ghana (Seidu et al., 2008) and elsewhere (Hamilton et al., 2006; Mara et al., 2007; Shuval et al., 1997). (Non-typhi) *Salmonella* has been found in street-salad vegetables potentially irrigated with wastewater (Mensah et al., 2002). It is also a major cause of foodborne diseases worldwide and has been used as a representative organism for bacterial infections in a risk-assessment study (Gerba et al., 2008). *Cryptosporidium* has also been used as a representative organism in quantitative microbial risk studies (Mara et al., 2007) and is widely associated with diarrhoeal diseases worldwide.

As indicated above, none of these organisms has been directly investigated and detected in wastewater in Ghana. Therefore, their concentrations in irrigation wastewater were determined by extrapolation using ratios (pathogenic bacteria/virus/protozoan to indicator bacteria) ranging from a conservative $1{:}10^5$ to the least conservative $1{:}10^6$ and $1{:}10^4$ to $1{:}10^5$ were used to predict the concentration of rotavirus and *Salmonella* in wastewater respectively (Gerba et al., 2008). For *Cryptosporidium,* a range of $1{:}10^6$ to $1{:}10^7$ (Mara et al., 2007) was used. For the wastewater treatment options, the faecal coliform concentrations reported for domestic wastewater in Ghana (Awuah et al., 1996) were used. For the non-treatment interventions (farm and post-harvest improved practices), the reported concentration of faecal coliforms in stormwater drains in Ghana (Keraita and Drechsel, 2004; Obuobie et al., 2006) and on crops (Amoah et al., 2007) were used. To account for uncertainty, the reported faecal coliform concentrations in the wastewater were assumed to follow a lognormal probability distribution (Table 13.1).

Exposure assessment, dose-response and risk of infection

Exposure to the pathogenic organisms for each of the interventions was modelled for wastewater-irrigated lettuce by accounting for the reductions in faecal coliforms

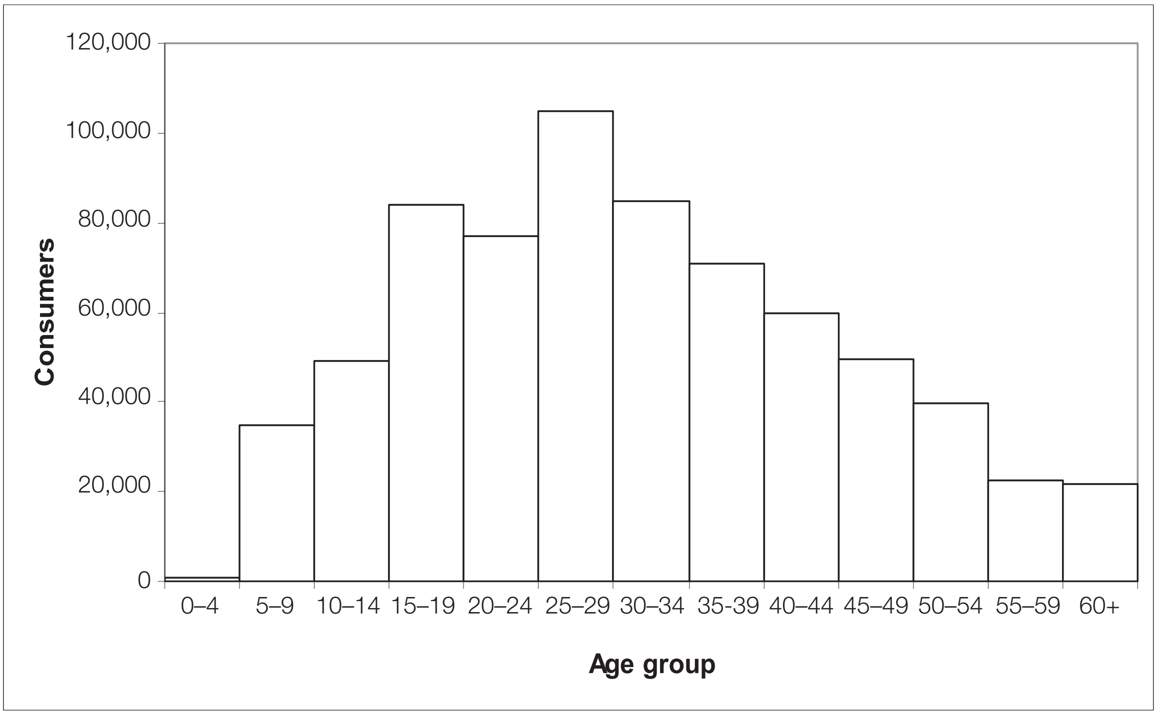

Figure 13.1 *Projected distribution of wastewater-irrigated lettuce consumer population in urban Ghana*

attributable to each of the interventions using the probability distributions in Table 13.1. The exposed consumer population was estimated from surveys of restaurants and food vendors serving wastewater-irrigated lettuce salad by following the distribution-consumption path described by Amoah et al. (2007) and was approximately 700,000 per day in Ghana's five largest cities where urban fast food is common (IWMI, 2009). From this survey and an earlier study (Obuobie et al., 2006), it was found that consumers in the streets of Accra and Kumasi, on average, ate about 13g of lettuce salad three times per week, resulting in an annual consumption of 1.87kg per person (IWMI, 2009). Since response to various pathogenic organisms is age-dependent, this was accounted for by stratifying consumers of lettuce at restaurants and fast-food vendors. Figure 13.1 shows a standardized age-cohort distribution of the exposed consumer population.

The dose of organisms D_i ingested by consuming irrigated lettuce was determined as:

$$D_i = Q_i \,.\, V_i \,.\, V_c \,.\, 10^{-n} \qquad 13.1$$

Q_i is the mass of lettuce consumed per meal (g); V_i is the volume of irrigation water left on lettuce after harvest (ml g^{-1}); V_c is the concentration of pathogens per volume of wastewater (number of pathogens g^{-1}); and n log unit reduction in pathogens associated with the interventions. V_i was assumed to be between 10.8ml

Table 13.1 *Efficacy of treatment and non-treatment interventions*

Concentration of faecal coliforms in irrigation water source	Interventions	Log_{10} reduction	References	Probability distribution used for reduction in faecal coliforms
Treatment options: Domestic wastewater	Wastewater treatment plant	3–6	WHO (2006)	Triangular (3, 4, 6)
Lognormal (10^8, 10^8)[a]		2–3	Hodgson (2000); Awuah et al. (1996)	
Non-treatment options:	On farm: Cessation of irrigation	0.65–0.66 per day	Drechsel et al. (2008)	Uniform (2, 3)[c]
Stormwater drain wastewater	On farm: Overhead irrigation at <0.5m	2–2.5	Drechsel et al. (2008)	
Lognormal (10^6,	On farm: Drip irrigation	3–4	Drechsel et al. (2008)	
10^8)[b]	Post-harvest: Washing of vegetables with only clean water (cold water for 2 min)	1–1.4	Drechsel et al. (2008)	Uniform (1, 2)
	Post-harvest: Washing of lettuce with clean water and disinfectant	2.1–2.2	Drechsel et al. (2008)	

[a]Awuah et al. (1996).
[b]Obuobie et al. (2006) and Keraita and Drechsel et al. (2004).
[c]A maximum of 3 log unit reduction instead of 4 log was taken to account for problems of clogging associated with the use of drip kits by farmers in Ghana.

and 15ml (Mara et al., 2007; Seidu et al., 2008), a range based on the 10.8ml reported by Shuval et al. (1997).

For the dose-response relationships, the beta-Poisson dose-response model (which assumes the pathogen-host survival probability to vary according to a beta distribution) was used for rotavirus and *Salmonella* (non-typhi), as it best describes the dose-response relationships for both organisms (Haas et al., 1999) in human feeding trials involving rotavirus (Ward et al., 1986) and *Salmonella* of several strains (McCullough and Eisele, 1951a; 1951b; 1951c). For *Cryptosporidium* the single hit exponential dose-response model (which assumes constancy of the pathogen-host survival probability) best describes its dose-response relationship obtained from human feeding trials (DuPont et al., 1995; Haas et al., 1999). In the case of a single exposure, the beta-Poisson and exponential dose-response models are respectively expressed as:

$$P_{i\,(d)} = 1 - \left[1 + \left(\frac{D_i}{N_{50}}\right)\left(2^{\frac{1}{\alpha}} - 1\right)\right]^{-\alpha} \qquad 13.2$$

$$P_{i\,(d)} = 1 - e^{-(rD_i)} \qquad 13.3$$

$P_{i\,(d)}$ is the probability of becoming infected by ingesting D_i number of organisms, N_{50} is the median infection dose representing the number of organisms that will infect 50 per cent of the exposed population; and α and r are the dimensionless infectivity constants. For rotavirus, N_{50} and α are 6.17 and 0.253 respectively; for *Salmonella*, N_{50} is 23,600 and α is 0.3126; and for *Cryptosporidium* r is 0.0042 (Haas et al., 1999). We estimated the annual risk of infection for the organisms by accounting for the dose and frequency of consumption presented above using the formula:

$$P_A = 1 - (1 - P_{i(d)})^{156} \qquad 13.4$$

P_A is the annual risk of infection and $P_{i\,(d)}$ is as described above. All the models were constructed in Microsoft Excel and calculated with Monte Carlo simulation at 10,000 iterations using the @ Risk 4.5 (Palisade Corporation) software add-on to Excel.

Diarrhoea morbidity, mortality and Disability-Adjusted Life Years

Epidemiological data on the transition from infection with the selected pathogenic organisms to disease (mild or severe) or death are lacking for Ghana. Therefore, studies undertaken in other regions were relied on. For rotavirus, it was assumed that after infection 10–15 per cent are asymptomatic, while 85–90 per cent develop diarrhoea of which in Ghana 12 per cent of the cases are severe, with the rest suffering mild diarrhoea leading to full recovery. From the severe diarrhoea cases it was assumed that 5 per cent die (Havelaar and Melse, 2003).

Rotavirus diarrhoea-related disease is common among children. However, some studies have also reported the incidence of diarrhoea among adults infected with rotavirus. A rotavirus outbreak study among college students has reported that of the 83 cases of rotavirus infection, 93 per cent had diarrhoea with a full recovery (Fletcher et al., 2000). In another study of children with rotavirus in 28 families, 18 of 54 adult family members exposed to rotavirus developed evidence of infection, and all but four had diarrhoea (Grimwood et al., 1988).

Based on this, it was assumed that the severe diarrhoea cases and deaths can occur mainly in the consumer age groups of 1–14 years (i.e. over and above the widely reported key age group of 0–5 years who, from our survey, are not frequent consumers of street food served with wastewater-irrigated lettuce) and those over 60 years. The choice of this wide range, including those in the over 60 age group, was to account for potential outbreak incidence. It was further assumed that the other age groups (15–60 years) will develop mild diarrhoea with full recovery.

For *Cryptosporidium* infection, it is known that in developed countries, 71 per cent of infected immunocompetent persons develop gastroenteritis, while population-based outbreak studies and volunteer experiments report relapses of diarrhoea in 40–70 per cent of patients (Havelaar and Melse, 2003). The only well-documented *Cryptosporidium*-related mortality is the waterborne disease outbreak in Milwaukee where four deaths were reported out of 400,000 diarrhoea cases (Mackenzie et al., 1994). For the purposes of this study, it was assumed that 70 per cent of those infected with *Cryptosporidium* following consumption of lettuce will develop diarrhoea with a mortality rate of 0.1 per cent, to reflect the potentially high mortality rates in developing countries (Havelaar and Melse, 2003).

For *Salmonella*, studies based on the FoodNet database (Kennedy et al., 2004; Voetsch et al., 2004) were used. From these studies, it was estimated that 50.3 per cent and 49.7 per cent of consumers infected with *Salmonella* non-typhoid will develop bloody and non-bloody diarrhoea respectively. From the bloody diarrhoea cases, it was assumed that 20 per cent will be hospitalized as severe cases for an average of three days with a 0.6 per cent fatality rate (Kennedy et al., 2004; Voetsch et al., 2004).

To ascertain the efficacy of the interventions in comparison with the status quo, the burden of morbidity and mortality of the diarrhoeal disease cases resulting from the infections under each of the interventions was estimated using the DALY approach. DALY combines years of life lost by premature mortality with years lived with a disability, standardized using severity or disability weights (Murray, 1994). The approach was first introduced in the *World Development Report* (World Bank 1993) and was revised in 1996 for the *Global Burden of Disease* studies (Murray and Lopez, 1996). For each of the pathogenic organisms, the DALYs/year were calculated using the equation:

$$\text{DALYs} = \text{YLLs} + \text{YLDs} \qquad 13.5$$

YLL is the number of years of life lost due to mortality and YLD is the number of years lived with a disability, weighed with a factor between 0 and 1 for the severity of the disability or disease.

YLLs and YLDs were derived using the equations:

$$YLLs[r, K, \beta] = \frac{KCe^{ra}}{(r+\beta)^2}\{e^{-(r+\beta)(L+a)}[-(r+\beta)(L+a)-1]-e^{-(r+\beta)a}[-(r+\beta)a-1]\} + \frac{1-K}{r}(1-e^{-rl}) \qquad 13.6$$

$$YLDs[r, K, \beta] = D \{\frac{KCe^{ra}}{(r+\beta)^2} \{e^{-(r+\beta)(L+a)}[-(r+\beta)(L+a)-1]-e^{-(r+\beta)a}[-(r+\beta)a-1]\} + \frac{1-K}{r}(1-e^{-rl})\} \qquad 13.7$$

K = age weighting modulation factor; C = constant; r = discount rate; a = age of death; β = parameter from the age weighting function; L = standard expectation of life at age a.

For rotavirus the severity indexes of mild diarrhoea and severe diarrhoea were taken as 0.1 and 0.23. For *Cryptosporidium* and *Salmonella,* 0.067 was used as the severity index for watery diarrhoea cases. Bloody *Salmonella*-related diarrhoea was accounted for with a severity index of 0.39 (Havelaar and Melse, 2003). All mild and severe diarrhoea cases lasted seven days while the very severe cases with blood lasted 5.6 days based on bloody diarrhoea associated with *E. coli* O157 (Havelaar and Melse, 2003). Deaths resulting from all the diarrhoea cases irrespective of the organism involved had a severity index of 1. A standard life expectancy of 60 years (GSS, 2002) across all the age groups with a standard age-weighting modulation factor ranging from 0 to 1 was used, and the parameters β and C were set at 0.04 and 0.1658 respectively (Murray, 1996). The DALY model for the interventions was constructed and simulated in Excel and discounted at 3 per cent annually (WHO, 2003).

Costing interventions

The ingredient approach, which totals all the inputs as the products of their respective quantities and values, was used to estimate the cost of the interventions. For the suggested three-year campaign (IWMI, 2009) targeting farmers and fast-food vendors/restaurants, all relevant stakeholders including the Ghana Social Marketing Foundation, Ministry of Food and Agriculture (MOFA) and the Food and Drugs Board (FDB) were interviewed to get a feasible cost-assessment for the campaign.

For the nine treatment plants selected for rehabilitation, a facility assessment survey was carried out by local sanitation consultants to elicit information on the inputs/materials required for a basic (low-cost) upgrading towards effective operation (IWMI, 2009). In the case of the new wastewater treatment plant all costs were obtained from the appraisal reports of the African Development Bank-funded Accra Sewerage Improvement Project (ASIP) (IWMI, 2009). All cost streams obtained for the different interventions were separated as capital or recurrent. All cost items for the various interventions including their components are summarized in 2008 US dollars (Tables 13.2–13.3). Capital costs were annualized and recurrent costs discounted over three years for the non-treatment campaign and ten years for the treatment interventions. For comparability across regions, capital and recurrent costs for the interventions were annualized and

Table 13.2 *Summary of costs for non-treatment options (national campaign)*

Intervention	Component	Cost (US$) (36 months)	Total Cost (US$)
Campaign reaching all vegetable *farmers* in five major cities	Programme Management & Administration	300,000	1,100,000
	Training and Materials	440,000	
	Enforcement/Follow-Up	260,000	
	Marketing Study	100,000	
Campaign reaching all vegetable *street-food vendors/restaurants* in five major cities	Programme Management & Administration	310,000	1,820,000
	Training/Social Marketing	1,050,000	
	Enforcement/Follow-Up	240,000	
	Marketing Study	220,000	
Total			2,920,000

Source: IWMI (2009)

Table 13.3 *Summary of costs of two 'treatment' options*

	Selected Plants	Cost (US$)
1) WWTP Rehabilitation Restricted rehabilitation of core functions of selected plants with agricultural lands	Roman Ridge, Accra	5,500
	PRESEC, Accra	48,500
	KNUST, Kumasi	50,000
	Asafo, Kumasi	7,000
	Pantang, Accra	20,000
	Kamina Barracks, Tamale	20,000
	UCEW, Winneba	25,000
	Ankaful WWTP	25,000
	Volta Star WWTP, Juapong	17,000
	Total	**218,000**
	Total annual O&M incl. staff labour for all 9 plants	+333,000
2) Construction New construction of a small treatment plant with sewer rehabilitation and extension (part of the already funded and ongoing ASIP project)	University of Ghana, Accra:	
	Sewer (re)connection	16,500,000
	Ponds and pumping station	6,700,000
	Total	**23,200,000**

Source: IWMI (2009)

discounted at 3 per cent as the base case and at rates of 0 per cent and 6 per cent for sensitivity analysis (WHO, 2003). To account for uncertainty around the cost estimates, the triangular probability distribution was fitted to all the capital and recurrent costs by taking the minimum and maximum likely values at +/– 20 per cent, respectively.

Cost-effectiveness

Cost-effectiveness of the interventions was modelled with the TreeAge ProHealth Suit Software (www.treeage.com) (Robberstad et al., 2007). The average cost-effectiveness ratios (CER) were calculated in US$ per DALY (i.e. the cost incurred for each DALY averted by the intervention) as well as the incremental cost-effectiveness ratios (ICER) (i.e. the additional cost needed for each additional unit of DALY averted resulting from investment in the intervention rather than its comparator) after accounting for the DALYs averted for each of the interventions in relation to the status quo (no intervention scenario). An expansion path analysis, based on the ICER, was also made to highlight dominated interventions (i.e. interventions that are both costly and less effective than their comparators) and for the ranking of the interventions. All costs and DALYs averted were discounted at 3 per cent as baseline with further sensitivity analysis at 0 per cent and 6 per cent, as suggested by the WHO. The cost-effectiveness ratios were compared with a cut-off value of US$150/DALY averted, which was used for many years as a rough economic evaluation criterion by which a health intervention in a developing country is considered cost-effective (World Bank, 1993). All interventions with cost-effectiveness ratios of < US$150/DALY were considered cost-effective while those > US$150/DALY were classified as unattractive.[2]

Sensitivity and uncertainty analysis

A one-way sensitivity analysis was also made to ascertain the effects of variations in the discount and campaign adoption rates as well as costs on the CER and ICER. The CER and ICER were calculated for each of the interventions by varying the discount rate for costs and benefits (DALYs) from 0 per cent to 6 per cent. As the calculations were based on a successful campaign with 100 per cent adoption, the sensitivity analysis was used to address lower adoption rates. Adoption rates of 25 per cent and 75 per cent representing pessimistic and optimistic scenarios respectively were assessed for the on-farm and post-harvest interventions. For the costs, as stated above, triangular distributions were applied for both the capital and recurrent costs with minimum and maximum values at 20 per cent below and above the most likely value, calculated from the ingredient approach (Robberstad et al., 2007). From the triangular distributions, 10,000 Monte Carlo simulations were made and CERs calculated. From these iterations mean CERs with 95 per cent confidence intervals were derived for each of the interventions.

Results

Infection risks, diarrhoea cases and DALYs

The annual infection risk associated with the consumption of lettuce salad irrigated under the current wastewater-irrigation and post-harvest practices across the country showed a high viral infection risk. The median viral infection risk was of a magnitude of 10^{-1} per person per year (pppy) while those of bacterial and protozoan were 10^{-5} pppy indicating that the risks of bacterial and protozoan infection given the current wastewater irrigation practices met the WHO tolerable infection risk of 10^{-4} pppy. These infection risks resulted in 477,258 self-limiting (mild) diarrhoea cases, representing 0.68 episodes per consumer per year. This falls outside the range of diarrhoea incidence of 0.8–1.3 pppy for all ages in developing countries, but approximates the global average diarrhoea incidence of 0.7 pppy (Mathers et al., 2002). Of the 0.68 diarrhoea episodes, about 14 per cent and 0.1 per cent were severe and fatal respectively and translated into 12,016 DALYs annually, representing 0.017 DALYs pppy. This figure represents nearly 10 per cent of the WHO-reported DALYs occurring in urban Ghana due to various types of water- and sanitation-related diarrhoea (Prüss-Ustün et al., 2008).

Effectiveness of interventions

The assessment shows that 41–92 per cent of the total DALYs (related to the consumption of wastewater-irrigated salads) can be averted through the different on-farm and post-harvest interventions (Figure 13.2). A campaign targeting improved farm practices could avert up to 92 per cent of the DALYs while up to 74 per cent could be averted through interventions in the street-food sector. Also, the rehabilitation of the nine selected WWTPs with farmland nearby and well distributed over the country could allow a high DALY reduction of 82 per cent if farmers would agree to move to those sites. Building a new WWTP (independently of its level of sophistication and cost) would certainly be very effective in its treatment but could not accommodate all farmers (even in Accra, with the greatest amount of irrigated urban farming) and supply all required vegetables. Thus, it would only avert in the best case 44 per cent of the annual DALYs. Combined non-treatment options (on farm, off farm) or non-treatment options and the rehabilitation of the nine WWTPs would in all cases increase the health benefit by averting 94 per cent of the DALYs, which is not much more than the farm interventions alone if they are broadly adopted.

Cost-effectiveness of interventions

As presented in Table 13.4, the CERs ranged from US$31/DALY to US$812/DALY on average. Based on the rough CER benchmark of US$150/DALY, the

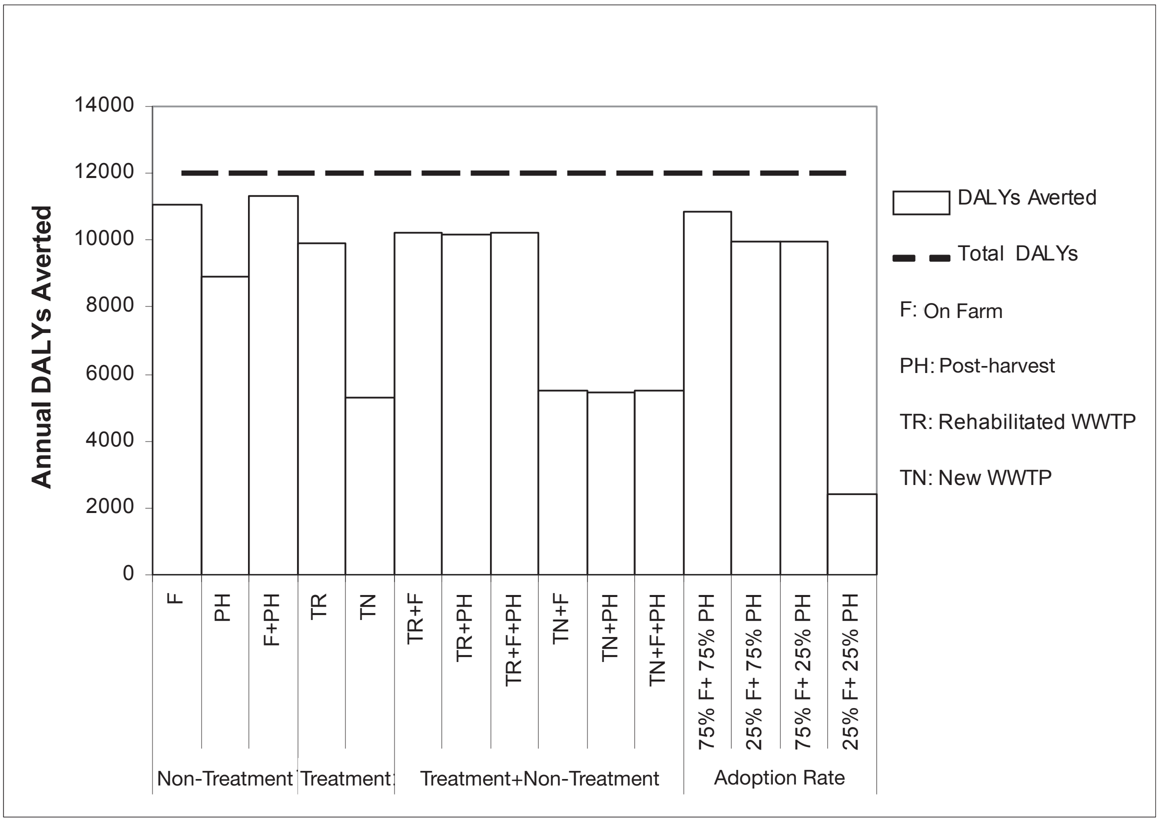

Figure 13.2 *DALYs averted by interventions*

most cost-effective interventions are those targeting health-risk reduction at the farm level (CER of US$31/DALY). Also, the low-cost rehabilitation of a larger number of existing but underperforming WWTPs well distributed over urban Ghana can be very cost-effective. These two options demand that farmers either adopt safer irrigation practices or move to sites with safer (treated) water. Also combining both options to offer farmers more choices is still very cost-effective (US$40/DALY) and so is the multiple-barrier approach combining low-cost rehabilitations, on-farm interventions and post-harvest (street-food) interventions. This is important as it offers more options and security for risk reduction while only marginally increasing the costs per DALY averted.

Only the construction of new WWTPs could not be considered as cost-effective in view of health-risk reduction related to wastewater-irrigated salads. The reason is not only the low coverage but the high costs, even of simple pond systems, if sewer connections are planned. Thus, increasing the number of new plants to cover all land needed for satisfying the current demand for salad greens would even decrease the CER despite averting all DALYs. This also applies to any non-treatment intervention combined with construction of a new WWTP.

The high cost-competitiveness of the WWTP rehabilitation is due to the limited investments needed to get the selected systems working again; the costs

Table 13.4 *Cost-effectiveness ratios of interventions*

Interventions	CER (US$/DALY)	
	Mean	CI (5–95%)
Non-Treatment Options Campaign		
100% adoption rate (AR) on farm	31	27–35
100% AR post-harvest	67	58–76
100% AR on farm + post-harvest	83	72–95
25% AR on farm + 75% AR post-harvest	95	82–108
75% AR on farm + 25% AR post-harvest	94	81–107
25% AR on farm + 25% AR post-harvest (pessimistic scenario case)	394	340–447
75% AR on-farm + 75% AR post-harvest (optimistic scenario case)	87	75–98
Treatment Options		
Rehabilitation of selected urban WWTPs	31	27–35
Construction of one new WWTP with household connections	786	678–893
Combined Options		
Rehabilitation + on farm	40	34–45
Rehabilitation + post-harvest	48	41–54
Rehabilitation + on farm + post-harvest	57	50–65
Construction + on farm	771	666–877
Construction + post-harvest	798	689–907
Construction + on farm + post-harvest	812	702–924

are even lower than the funds required for a national campaign on non-treatment options. However, as mentioned before, this option assumes no further costs on sewer to household connections and that the farmers move to those sites with treated wastewater. Where this would increase their transport costs, incentives will be needed to ensure that farmers do not maintain their current high-risk plots.

Even though the CERs provide significant information regarding the efficacy of interventions, they cannot be used to rank the interventions without considering resource constraints. Therefore, an expansion path, based on the incremental cost-effectiveness of the interventions, was undertaken by first ranking all the interventions in terms of their effectiveness. Figure 13.3 shows the expansion path for the interventions given that there is no resource constraint. The associated incremental cost-effectiveness analysis shows that the most cost-effective path for the implementation of possible interventions is from the rehabilitation of the WWTPs to on-farm interventions to a combination of on-farm and post-harvest interventions. All other interventions were completely dominated, i.e. resulted in negative incremental effects against a comparator.

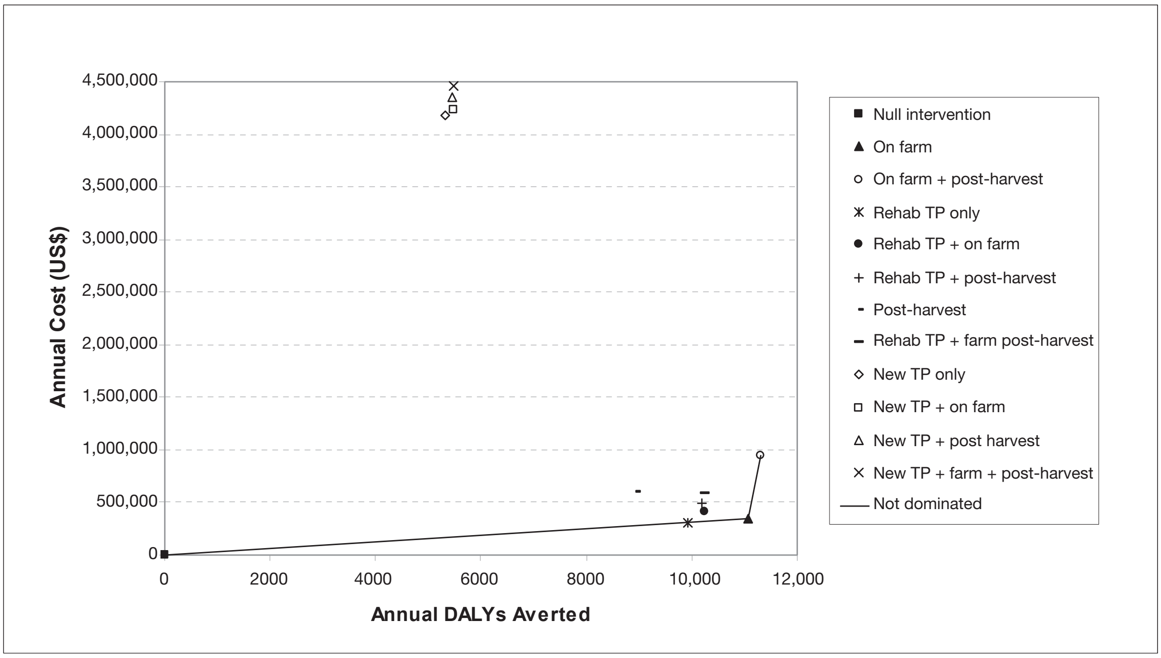

Figure 13.3 *Expansion path showing dominated interventions*

Sensitivity and uncertainty analysis

Discounting the cost and health benefits at 0 per cent and 6 per cent significantly affected the average CER, but this did not affect the ranking of the interventions in terms of incremental cost-effectiveness ratios (results not shown). Also, there was a remarkable effect of the campaign adoption at the farm and post-harvest sectors on the overall effectiveness and, hence, the cost-effectiveness of the interventions (Figure 13.2 and Table 13.4).

Generally, the relationship describing this phenomenon was exponential. Given the pessimistic scenario where only 25 per cent of farmers and food vendors adopted the improved practices of the campaign, only 20 per cent of the DALYs lost were averted, resulting in a CER of US$394/DALY, which is more than twice the benchmark CER and thus making the campaign unattractive. The optimistic scenario representing 75 per cent adoption of improved practices across the farm and post-harvest sectors averted about 90 per cent of the DALYs, leading to a CER of US$87/DALY. This shows that significant health gains can still be made cost-effectively at marginal non-compliance rates of up to 25 per cent for the optimistic scenario in this study across the farm and post-harvest sectors. Further calculations based on the exponential relation show that a maximum non-compliance (non-adoption) rate of about 30 per cent across the farm and post-harvest sectors could still make the campaign attractive in view of the US$150 benchmark.

DISCUSSION

The assessment has shown that the consumption of wastewater-irrigated lettuce is likely to significantly contribute to cases of diarrhoea and DALYs with a disproportionate impact on children. The results were compared with the EU-funded SWITCH project which used QMRA to assess the disease burden associated with contaminated piped drinking water, flooding, playing in open storm water drains, swimming at urban beaches and occupational contact with faecal matter in Accra (Lunani et al., 2009). It was found that for the same urban area and population the consumption of wastewater-irrigated vegetables appears to be the second highest in risk after children exposed to an open stormwater drain (IWMI, 2009).

Mensah et al. (2002) found a wide range of pathogenic organisms including *Staphylococcus aureus* in street-food salad in Accra and concluded that the lettuce and cabbage used in the preparation of the salad were potentially irrigated with wastewater and/or fertilized with poorly composted manure. In the same study, poor hygiene practices by street-food vendors serving salad were also implicated in the microbial contamination of the salad served. This study, together with others (Amoah et al., 2007; Obuobie et al., 2006; Seidu et al., 2008), stressed the importance of on-farm and post-harvest practices as control points for the reduction of the health hazards associated with wastewater irrigation.

As the results indicate, health-reduction measures at these points have the potential to avert a high number of DALYs and are cost-effective as well. Nevertheless, the sensitivity analysis showed the importance of strategies that support the adoption of non-treatment options as non-compliance of more than 30 per cent rendered the campaign increasingly unattractive in terms of costs and health gains.

Thus, strategies that ensure a consistent increase in the adoption of improved practices are vital. In this regard, constraints including the additional labour requirements (e.g. farm ponds) or investment needs (e.g. drip kits) of some of the improved practices, or risk of lower yields due to cessation of irrigation or furrow irrigation (see Chapter 12) have to be taken into account in the design of incentive systems and effective campaign programmes. A framework combining incentive systems, education, social marketing and regulations to achieve a high adoption rate as well as practical examples from participatory on-farm research are discussed in Chapters 16 and 17.

It should be stressed that the assessment here generally reflected an endemic situation, accounting for variations in the pathogenic organisms in the stormwater-drain irrigation water with probability distribution functions. These distributions did not account for an epidemic or outbreak situation. In an outbreak or epidemic situation, where the concentration of pathogenic organisms in the irrigation water is significantly elevated, even an adoption of 70–75 per cent may not reduce the total DALYs significantly as an elevated incidence of diarrhoea and DALYs could occur in a cluster of consumer population not affected by the intervention.

Given the sensitivity of the CERs of the non-treatment interventions to farmers' and vendors' adoption rates, it would not make sense to select a single critical control point. It is thus proposed that both treatment (rehabilitation of wastewater treatment plants for wastewater treatment) and non-treatment interventions (on-farm improved irrigation practices and post-harvest washing practices by fast-food vendors) be combined to increase the probability of DALY reduction while only marginally decreasing the CER. In this regard, a combination involving the basic rehabilitation of the nine Ghanaian wastewater treatment plants together with both or either of the non-treatment options will not only reflect best the 'multi-barrier' approach promoted by the WHO (2006) but also provide some safety against potential failures in the suggested campaigns.

It is, for example, uncertain whether the probability of behaviour-change will be higher among farmers than vendors or vice versa. To increase the probability of success, it is thus recommended to address both groups.

In the CEA of interventions to reduce health risks related to wastewater-irrigated vegetables, those involving the construction of a new wastewater treatment plant were less attractive. Despite the small size of the plant, a major cost factor in the Accra case was the rehabilitation and construction of household connections which dominated the actual pond construction by a factor of three to one.

However, WWTPs might be cost-effective in terms of other reduced health risks (e.g. if underground sewers replace open drains), household support and/or environmental protection, which are not considered here. There is also no question about the effectiveness of WWTPs for pathogen and diarrhoeal disease reduction (Barreto et al., 2007; Kolahi et al., 2009; WHO, 2006). It is therefore recommended to be, on the one hand, location- and case-specific, but on the other, to carry out a more encompassing cost-effectiveness assessment that includes all locally relevant diarrhoeal-related risk factors that may be impacted by the construction of a WWTP and other benefits of WWTPs.

The estimated CERs for the interventions presented here are comparable with those of other water, sanitation and hygiene interventions worldwide, which range from US$3.35–$20/DALY for hygiene behaviour-change to up to US$6,396/DALY for improved urban water supply and sanitation systems (Table 13.5). The comparison shows that the non-treatment options as well as low-cost rehabilitation of existing treatment plants can be as cost-effective as the promotion of hand-washing or water chlorination. Also, the estimated CER for the non-treatment (on-farm and post-harvest practices) and basic rehabilitation of treatment plants for vegetable irrigation compares favourably with an estimated cost-effectiveness ratio of US$516/DALY for the reduction of diarrhoea associated with the coverage of stormwater drains in Accra (IWMI, 2009). However, due to the fact that these CERs have been arrived at via different methodologies, such comparisons should be used with caution. On the other hand, we may be relatively confident that

Table 13.5 *CER of interventions for diarrhoeal disease reduction*

Intervention	CER (US$/DALY)	
	Mean	Range
Hygiene behaviour-change campaign	–	3–20
Chlorination at household level	–	46–266
Solar disinfection	54	40–74
Ceramic filtration	125	83–59
Basic sanitation (pit latrine) construction and promotion	≤ 270	–
Basic sanitation (promotion only)	11	–
Water supply via hand pumps/stand posts	94	–
Water supply via house connection	223	–
Oral rehydration therapy	1062	132–2570
Rotavirus immunization	2478	1402–8357
Cholera immunization	2945	1658–8274
Improved rural water supply and sanitation	1974	–
Improved urban water supply and sanitation	6396	–
A campaign leading to 75% adoption of safer irrigation and vegetable-washing practices[a]	87	75–98

Source: Cairncross and Valdmanis (2006); Clasen and Haller (2008); Hutton and Haller (2004); Keusch et al. (2006); Lvovsky (2001); [a]this study

an intervention with a CER of US$45/DALY is better than another one with US$450/DALY (Clasen and Haller, 2008).

The assessment applied QMRA to estimate health risks from extrapolated microbial hazards. The extrapolation of the empirically analysed thermotolerant coliform bacteria to the different pathogenic organisms remains, however, only an estimate based on the best available transfer functions; this may result in an underestimation or overestimation of the health risks with the accompanied DALYs and hence the CERs. The study of Donkor et al. (2008), for example, shows that in view of *E. coli* O157:H7, our assessment might be on the safe side. Such uncertainty surrounding the estimates has been accounted for by providing the 95 per cent confidence interval (CI) around the mean CER, to provide policy-makers with an opportunity to better assess intervention options on a continuum. However, a more rigorous study based on epidemiological investigations of the interventions and their associated impact on diarrhoea is needed to further validate the QMRA results and CERs arrived at in this assessment.

CONCLUSIONS

The health risk associated with wastewater irrigation in terms of diarrhoea cases and the associated DALYs can be significant. This study has demonstrated that by implementing on-farm and post-harvest interventions, both independently and in combination, the DALYs could be significantly reduced in a very cost-effective way. Although these interventions are attractive, their implementation and subsequent cost-effectiveness relies significantly on the adoption rates by farmers and vendors in the fast-food sectors. It is thus suggested that these interventions be well promoted, taking advantage of tangible or intangible incentives and combined with the rehabilitation of wastewater treatment plants where this is possible at low cost, to ensure, by an only marginally decreased CER, the best allocation of scarce resources. The study also suggests that the construction of new wastewater treatment ponds and related sewer systems is much less cost-effective in terms of public-health-risk reduction from the (limited) perspective of wastewater irrigation. Further studies looking at other 'non-treatment options', as well as the larger impact of treatment plants, are recommended.

Notes

1 Based on a set of anaerobic, facultative and maturation ponds with a planned intake of 6424m^3/day.
2 In more recent literature, other criteria are used, for example based on the GDP of a country. The Commission on Macroeconomics and Health classifies interventions that have a cost-effectiveness ratio of less than three times GDP per head as cost-effective (CMH, 2001).

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Paper III

Razak Seidu and Thor Axel Stenström (2010) Occupational Health Risk of Cake Sludge Application in Northern Ghana. *Journal of Water Research (Submitted).*

Occupational Health Risk of Cake Sludge Application in Northern Ghana

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ABSTRACT

In this study, the efficacy and occupational health risks of two on-farm sludge drying methods, random spot spread and pit containment, practiced by farmers across 40 farm sites in Northern Ghana were assessed. Varying sludge drying times ranging from 7-60 days and 90-105 days for the random spot spread and pit methods respectively were practiced by farmers. The mean level of *Ascaris* eggs (viable and non-viable) in the cake sludge across the sites met the WHO monitoring guideline for sludge application after 30 days or more and 90 days or more of sludge treatment using the random and pit methods respectively. Over the same sludge dewatering time for the two methods, *E. coli* was effectively reduced to levels below the WHO monitoring guideline. The *Ascaris* and viral infection risks associated with three exposure pathways were assessed: a) accidental ingestion of small amounts of 'cake' sludge; b) accidental ingestion of cake-sludge soil mixture; and c) inhalation of aerosols during cake sludge soil incorporation. After 30-60 days and 90-105 days of sludge dewatering by farmers under the random spot and pit methods respectively, the median annual *Ascaris* infection risk associated with exposure pathway (a) was 10^{-2} per farm worker. This infection risk level reduced to 10^{-4}-10^{-5} per farm worker for exposure pathway (b), and met the tolerable *Ascaris* infection risk level of 10^{-3} per farm worker per year. Sludge dewatered for 30 days or more under the random spot spread method and over 90 days under the pit method were below the WHO tolerable rotavirus infection risk of 10^{-4} per farm worker per year for exposure pathways a) and b). The rotavirus infection risk associated with exposure pathway c) was below the tolerable risk level at an exposure distance of 2 m regardless of the sludge treatment method and dewatering time. Combined with personal protective measures, the traditional sludge dewatering methods, as practiced by farmers, can provide an alternative option to conventional treatment technologies for on-farm health risk reduction. The study proposes a tolerable annual *Ascaris* infection risk of 10^{-2}. It is also recommended that sludge is dewatered for 60 days or more and 90 days or more under the random spot spread and pit methods respectively.

Key Words: *Ascaris,* cake sludge, rotavirus**,** infection risk, sludge treatment, QMRA

1. INTRODUCTION

Faecal sludge application in agriculture is increasingly considered as a component of sustainable sanitation to assure that vital plant nutrients are returned to the soil, reduce aquatic contamination and provide a cheap source of fertilizer to poor farmers. Nevertheless, the reuse practices can also lead to negative health consequences, particularly in regions where technologies and measures for the treatment, handling and application of excreta are either inadequate, operating sub-optimally or are non-existent. Some epidemiological studies have associated gastro-enteric infections with the application of human excreta in agriculture (Blumenthal and Peasey, 2002). Thus, a major challenge is how to minimize the health risks associated with the practice without compromising its benefits. To address this, the World Health Organization (WHO), has developed microbial guidelines for the safe application of human excreta including a multi-barrier (MB) approach that progressively reduces health hazard from 'farm' to 'fork' (WHO, 2006). These guidelines recognize the need for health risk mitigating interventions that encapsulates local socio-cultural, institutional and economic dynamics. However, in most cases, guidelines are developed without eliciting farmers' local treatment practices.

In the semi-arid Northern part of Ghana, farmers over decades have used sludge from on-site sanitation technologies as an alternative to expensive chemical fertilizers to improve soil quality. Studies have shown that levels of indicator organisms in faecal sludge from on-site sanitation technologies in Ghana are above the WHO monitoring guideline (1 helminth egg/g TS and <1000 *E. coli* / g TS) for agricultural application. In Southern Ghana, Heinss et al. (1998) recovered between 20,000-60,000 helminth eggs per litre from public toilets and ~4000 helminth eggs per litre from septage (septic tank sludge). Also, Gallizi (2003) found 18-242 helminth eggs / g TS from public latrines and septic tanks in the same part of Ghana. In a recent study, 9 - 16 eggs /g TS and 5 – 118 eggs /g TS were recovered from public toilet and septic tank sludge respectively (Kone et al., 2007). Among the helminths species recovered from the faecal sludge in the country, *Ascaris lumbricoides* was the most predominant (Gallizi, 2003; Kone et al., 2007); reflecting its high prevalence in the country (Hotez et al., 2003). *Ascaris* has long been recognized as the organism of concern in the land application of sludge. Its eggs can remain viable and infective for several years in sludge-amended fields under ideal environmental conditions (Faechem et al., 1983). They have also been shown to persist for longer times in the vaults of latrines designed for the hygienization and reuse of excreta; and in some low-cost sludge treatment technologies (Carlander and Westrell, 1999; Schonning et al., 2004; Kegne et al., 2009). Besides the helminths, viruses may be present in large numbers in faecal sludge, and can lead to high infection risk during the land application of faecal sludge due to their low infectivity dose (Faechem et al., 1983). In the MB framework, several low-cost sludge technologies have been proposed for sludge treatment. Although, considered as low cost, these technologies remain largely inaccessible to the vast majority of poor farmers applying faecal sludge in poor countries including Ghana.

In Northern Ghana, farmers applying sludge to agricultural lands employ two traditional sludge treatment methods, *random spot spreading* and *pit containment*, to process raw sludge into 'cakes' for health risk mitigation, easy handling and application. These methods are comprehensively described elsewhere (Cofie et al., 2005). Dewatering of the sludge is undertaken in the dry-season months of November to April when temperatures across the Northern Zone of the country can reach 39^0 C. Although the treatment methods are perceived to be safe by farmers, and provide an alternative option to conventional sludge treatment technologies, they are considered illegal by public health authorities. However, no alternative health risk reduction measures have been made available to the farmers, and farmers continue to apply sludge using the traditional methods.

This study was part of a comprehensive WHO risk assessment study, aimed at predictive assessment of the occupational and community health risks associated with the current practices of cake sludge application. Specifically, the study investigated the efficacy of the local sludge treatment methods employed by farmers in relation to the reduction of indicator organisms. In addition, potential on-farm exposure pathways for the transmission of diseases associated with sludge application practices were identified, and the associated viral and *Ascaris* infection risks quantified.

2. MATERIALS AND METHODS

2.1 Conceptual Framework

This study comprised 3 main parts. (1) A qualitative farm observation survey combined with questionnaires and interviews that identified and partly quantified the frequency and magnitude of the potential exposure pathways for disease transmission on farms. The interviews included questions related to the source of sludge and implements used in sludge collection and incorporation. (2) Microbial analysis of sludge after drying, which was considered by farmers to pose no health risk. These formed input data for (3) a predictive quantitative microbial risk assessment (QMRA). This was based on exposure scenarios and integrated information from the farm observation survey, the microbial analysis and information from literature on aspects of exposure pathway (supplemented by the farm observation survey).

2.2 Site Selection and Farm Observation Survey

The site selection was preceded by a pre-selection phase with interviews of 90 farmers applying faecal sludge in the Tamale Metropolis of Northern Ghana. Semi-structured questionnaires were used. Information collected included: a) sources of sludge, b) sludge dewatering method and duration, c) sludge incorporation methods, d) type of implements used for collection, spreading and incorporating cake sludge, and e) the type of protective clothes used during sludge application related activities. Based on this a subset of 40 farm sites were selected and these farmers were asked to inform investigators when they were to receive sludge. Investigators then visited these sites during the period the sludge was received and documented a) the source of the raw sludge, b) date of treatment c) treatment method used, and d) location of the treatment sites. This constituted the initial farm observation survey. The farmers were then asked to inform investigators when the dewatered (cake) sludge were ready for collection, with subsequent spreading and soil incorporation. At the time the sites were re-visited when the cake sludge were being collected for spreading and soil incorporation. In this last phase of the farm observation survey, the following information were collected for each site for the exposure scenarios: i) days of sludge dewatering, ii) persons involved in the ‘cake’ sludge activities, ii) number of days or hours spent on the ‘cake’ sludge activities iii) types of implements used and iv) types of protective clothing used.

2.3 Cake Sludge Sampling and Microbial Analysis

Microbial monitoring was performed during the last phase of the farm observation survey. Composite samples of the dewatered 'cake' sludge were collected from each site with sterilized spoons. They were put in sterile bags, placed on ice and transported to the laboratory for microbial analysis. 10 g from each composite sample were dried in a convection oven at 104^0C during 24h to obtain the dry mass values. The microbial analysis comprised thermotolerant coliforms, *E. coli* and helminths and was assessed from 100 g of each composite cake sludge sample. Prior to the coliform analysis, the samples were homogenized by placing 10 g into 90 ml 0.1% peptone water. The mixture was shaken vigorously for some minutes, and a ten-fold serial dilution was prepared. A set of triplicate tubes of Bouillon MacConkey broth (BioMerieux, France) was inoculated with sub-samples from each of the dilution and incubated for 24 or 48 hrs at 44^0C for the determination of number of thermotolerant coliforms (APHA-AWWA-WEF, 1998). For *E. coli,* loop full from all the positive tubes from the thermotolerant coliform test were streaked out on Membrane Lactose Glucuronide Agar (MLGA) and incubated for 24 hr at 44 ^{0}C. Helminth eggs were enumerated using the US-EPA modified concentration method (Schwartzbrod, 2001) and *Ascaris* identified using the WHO bench aid (WHO, 1994). The helminth analysis refers to the total quantities of undamaged eggs but did not account for the viability of these eggs. All the microbial data were reported in terms of dry mass.

2.4 Health Risk Assessment

The occupational health risks were assessed by the four step Quantitative Microbial Risk Assessment (QMRA) approach (Haas *et al*. 1999).

Hazard identification: The selected index organisms for the risk assessment included rotavirus as a representative organism for viral infection and *Ascaris* for the helminth infection. Viruses in the cake sludge could not be analyzed in Ghana. We therefore followed the approach of Brooks et al. (2005 a b). For this, ratios ranging from conservative 1:100 000 to least conservative 1:1000 000 (pathogenic *E. coli/*virus to indicator *E. coli/* virus) were used as an index for rotavirus in the cake sludge (Brooks et al., 2005 a b). These ratios represent a range of expected concentrations for both organisms present in Class B biosolids (Gerba et al., 2002). Such extrapolations although employed in several risk assessment studies (Shuval et al., 1997; Hamilton et al., 2006; Seidu et al., 2008ab; Tanner et al., 2008) and adapted by the most recent WHO guideline for wastewater and excreta reuse (WHO, 2006) can result in the under or over estimation of infection risks. This limitation is partly addressed here with the use of stochastic instead of deterministic approaches in the quantification of the health hazards.

Exposure Assessment: Data for the exposure assessment was based on the farm observation survey including potential exposure pathways, the risk groups involved, and the duration and frequency of exposure. Dose of organisms ingested through the different exposure pathways are assumptions and were largely obtained from literature review. The following exposure pathways were assessed in relation to the pit and the spread treatment methods and dewatering time: a) accidental ingestion of 'cake' sludge b) accidental ingestion of cake sludge incorporated into the soil and c) inhalation of aerosols containing viruses transported.

Dose Response Assessment: For *Ascaris,* we used the β-Poisson dose response model derived in Mexico (Navarro et al., 2009). For rotavirus, the β - Poisson dose response model was used (Haas et al., 1999). Generally, the β-Poisson dose-response model is given as:

$$P_i = 1 - \left[1 + \left(\frac{d}{N_{50}}\right)\left(2^{1/\alpha} - 1\right)\right]^{-\alpha}$$

where P_i is the probability of becoming infected by ingesting an exposure dose of d infectious organisms. For rotavirus, N_{50} = 6.17 and α = 0.253 (Haas et al., 1999). For *Ascaris,* N_{50} = 859 and α = 0.104 respectively (Navarro et al., 2009). The viability of the *Ascaris* eggs was accounted for by assuming a uniform distribution ranging from 20% - 50% based on Kone et al. (2007).

For exposure pathways a) and b), *d* was determined using the equation:

$$d = w \times \mu$$

where *w* is the number of organisms per *mg* of cake sludge, and μ is the quantity of 'cake' ingested (*mg*) accidentally per day of exposure.

For exposure pathway c), the volume and thus the dose of viruses ingested by exposure to aerosols was calculated using the Gaussian plume spread model developed by Pasquill (1961), which is given as:

$$X(x,y,z,H) = \frac{Q}{2\pi\sigma_y\sigma_z\mu} \times exp\frac{-y^2}{2\sigma_y^2} \times \left[exp - \frac{(z-H)^2}{2\sigma_z^2}\right] + exp - \left[\frac{(z+H)^2}{2\sigma_z^2}\right]$$

Where *X* is the particle rotavirus concentration in the aerosol at a particular downwind location (x, y, z) from the source (particles/m^3), *H* is the height of the source (m), Q is the rate of release from the source (particles/sec), σ_y and σ_z refer to the diffusion coefficient in the y and z directions measured in (m). *H=0* assuming that the sludge was spread across the field before tractor discing, y = 0 m; $\sigma_y = ax^b$ (a = 0.36 , b = 0.86); $\sigma_z = cx^d$ (c = 0.22; d= 0.86); μ, the wind speed at the time was assumed to be uniformly distributed from 5m/s -10m/s; and z = 1.5m. We modeled exposure to rotavirus particles in aerosols at distances ranging from 0.5m – 4m from the plume; *Q,* was assumed to be 0.5 of the background rotavirus concentration in the spread cake sludge. In order to calculate the dose for the aerosol exposure pathway, the average human breathing rate of 0.83 m^3 per hour (Dowd et al., 2000) and exposure duration of 6 hours based on our farm observation survey, were used. Thus the dose was calculated as:

$$D = C_d \times 0.83$$

Annual Infection Risk and Tolerable Risk: For the three exposure scenarios, the annual rotavirus and *Ascaris* infection risks were calculated as $P_A = 1 - (1 - Pi)^d$ where *P*i is the one-time infection risk as above and *d* is the annual exposure frequency days associated with each exposure obtained through the farm observation survey. Exposure to rotavirus resulting in an infection risk of 10^{-4} per person per year was considered tolerable (WHO, 2006). For *Ascaris*, the estimated health risks were compared with a tolerable infection risk of 10^{-3} per person per year (Mara and Sleigh, 2009). This tolerable infection risk is based on a DALY loss per case of *Ascariasis* of 8.25 x 10^{-3}, and as a worst case scenario an *Ascaris* disease / infection ratio of 1 (Mara and Sleigh, 2010).

2.5 Statistical and Health Risk Analyses

All statistical analyses were undertaken using STATA 10 and SPSS 11. The health risk models were constructed in Microsoft Excel 2007 and simulated with the @ Risk 4.5 software (Palisade Corporation).

3 RESULTS

3.1 Sludge Dewatering and Perceived Risk

Sludge dewatering at the forty sites was mainly by random spot spreading, except for four sites that used the pit method. Sludge dewatering time ranged from 7 to 105 days averaging 48.5 days. The dewatering time was dependent on both the type of treatment (pit or spot spreading) and the perceived health risk associated with the treated sludge. Farmers using the pit method dewatered sludge for 90 days or more. In the random spot spreading, the sludge was rapidly dewatered and was not perceived to pose a health risk if it was completely dry and had no bad odour irrespective of the dewatering time. The dewatering time here ranged from 7 to 60 days. Farmers did associate high risk cake sludge with diseases such as diarrhoea, vomiting, foot rot and skin infection.

3.2 Occurrence of Indicator Organisms in Cake Sludge

The level of thermotolerant coliform bacteria in the cake sludge after each stated dewatering time across the forty sites ranged from 3 x 10^{1} MPN /g TS - 2.5 x 10^{5} MPN /g TS with a mean level of 1.4 x 10^{4} MPN/g TS. The corresponding *E. coli* levels was 2.4 MPN /g TS – 1.6 x 10^{4} MPN /g TS with a mean of 1 x 10^{3} MPN / g TS. *Ascaris* in the cake sludge ranged from 0.01 eggs / g TS – 3.1 eggs / g TS averaging 0.79 eggs / g TS. Figures 1 A, B and C show the levels of indicator organisms in the cake sludge collected from the two treatment methods. The pit method had lower levels of all the indicator organisms as compared to the spot spread method. However, this difference was only statistically significant ($p < 0.05$) for *E. coli*. In both treatment methods, the mean levels of *Ascaris* and *E. coli* across the 40 investigated sites met the WHO monitoring guideline. The mean levels of thermotolerant coliforms, *E. coli* and *Ascaris* in the cake sludge from the random spot spread method were 1.5 x 10^{4} MPN / g TS, 1.1 x 10^{3} MPN / g TS and 0.8 eggs/ g TS respectively. The corresponding mean levels for thermotolerant coliforms, *E. coli* and *Ascaris* for the pits were 1.4 x 10^{3} MPN / g TS, 6 MPN / g TS and 0.6 eggs/ g TS respectively.

Relationship between Indicator Organisms and Dewatering Time

In Figures 2 A, B and C the levels of the indicator organisms have been subdivided into 4 sub- groups representing different ranges of dewatering days employed by farmers. When the sludge was dewatered for 30 days or more, all random spot spreading sites had mean *E. coli* values that met the WHO guideline (WHO, 2006). The same was the case for *Ascaris*, if the monitoring guideline value of 1 egg / g TS, applicable for adults, is used. The mean levels of *E. coli* and *Ascaris* in cake sludge dewatered with the pit method for 90-105 days, also achieved the WHO monitoring guideline. In Figures 3A, B and C, the relationships between the persistent remaining fraction of thermotolerant coliform (A), *E. coli* (B) and *Ascaris* (C) and dewatering days for the random spot spread treatment sites is presented. Similar relationships could not be derived for the pit method due to insufficient data. There was a direct significant relationship ($p < 0.05$) between the number of dewatering days and the decay of thermotolerant coliform, *E. coli,* and *Ascaris*. *Ascaris,* was as expected, the most persistent.

3.3 Occupational Handling Practices and Health Risk

Occupational health risk is here defined as risk of infection resulting from exposure to pathogenic organisms during occupational related activities in the farm sites. The following activities related to the handling of the cake sludge provided the basis for our exposure assessment:

3.3.1 Handling Practices

Cake sludge collection and spreading: This was undertaken by farmers with traditional farm implements including hoes, shovels, broken pots, pans and bowls. On the 4 pit treatment sites, shovels were used to collect the sludge 'cakes' into sacks and thereafter transported to the farm for spreading. On the random spot spread sites, the sludge 'cakes' were scraped off the ground into heaps, before collection and spreading. Spreading was carried out with broken pots or bowls. Adults were the main risk groups engaged in the collection and spreading but at four sites children (<15years) were also actively involved. These constituted 0.1 % of the persons involved. The activities ranged from 6 to 7 days per site during 2 and 6 hours and were mainly carried out in the early morning and late afternoon.

Cake Sludge Incorporation: This was carried out with hoes or tractors, accounting for 5.6% and 55.6% of the observed farm workers respectively. About 37.8% combined both hoeing and tractor discing while the remaining sites used shovels. In the risk assessment it was assumed that hoe and tractor incorporation resulted in 'cake' sludge to soil mixture ratio of 1: 100 and 1: 1000 respectively. Cake sludge incorporation with tractors resulted in dust plumes, for which workers (farmers) were likely to be exposed to. For this, we accounted for four exposure distance scenarios (0.5m (worst case), 1m, 2m and 3m) from the dust plume without any further microbial die-off.

Use of Protective Clothes: In all the above activities, the use of protective cloth was scarce. The farm observation survey revealed that 87% of the farmers did not wear any protective clothes like boots, gloves and nose mask. Among the additional, 7% wore only boots and 5% wore only gloves. Just 1% wore both gloves and boots. Farmers wearing gloves occasionally freed one of their hands and when asked why indicated that the gloves constrained their work. There was no objection in handling the sludge cakes with bare hands. Further interviews revealed that the protective clothes were provided through a WHO research intervention and was not commonly used by farmers. Thus we assumed a conservative scenario, where none of the farmers used any of the aforementioned protective gears. Hence for exposure pathways a) and b), adults and children were assumed to most likely ingest between 100 mg and 200 mg of the material respectively through accidental touching of their face and mouth (WHO, 2006). Thus, a uniform distribution ranging from 100 – 200 mg was used to describe the exposure dose of organisms potentially ingested by the workers.

3.3.2 Infection Risks

Exposure Scenario 1: *Accidental Ingestion of 'Cake' Sludge*
Figures 4 A and 4B show the annual rotavirus (A) and *Ascaris* (B) infection risks associated with this exposure scenario for cake sludge dewatered over time under the random spot spread and pit methods. The median annual *Ascaris* infection risks were above the WHO tolerable infection risk level of 10^{-3} per worker irrespective of the sludge dewatering time and method used (Figure 4 B). In terms of viral infection, the median annual rotavirus infection risk on the random spot sites ranged from 10^{-2} - 10^{-5} per farm worker per year (Figure 4A). Exposure to sludge dewatered for 30 days or more on these sites resulted in rotavirus infection risks below the WHO tolerable risk level of 10^{-4} per worker per year. Accidental ingestion of cake sludge from the pit method also resulted in a median annual rotavirus infection risk below the WHO tolerable infection risk level (WHO, 2006).

Exposure Scenario 2: *Accidental Ingestion of Cake Soil Mixture*
Figures 4A and 4B also show the rotavirus and *Ascaris* infection risks associated with the accidental ingestion of cake-soil mixture after hoe incorporation. In this exposure scenario, the median annual *Ascaris* infection risks associated with the different sludge dewatering time and methods as practiced by farmers were all below the WHO tolerable infection risk (Figure 4B). Similar median annual rotavirus infection risks were associated with exposure to the cake-soil mixture on the random spot spread sites treating sludge for 30 days or more (Figure 4A).

Exposure Scenario 3: Unprotected Exposure to aerosols
Figure 5 shows that exposure to aerosols at a distance of 0.5m (worst-case) on the random spot spread sites resulted in an annual rotavirus infection risk above the WHO tolerable infection risk. On the pit sites (treating sludge for 90 days or more), exposure to aerosols resulted in acceptable median rotavirus infection risk even at a distance of 0.5m. To achieve the WHO median tolerable rotavirus infection risk for all the random spot spread sites (including the 7-14 days dewatered sludge), exposure to aerosols had to occur at a distance of 2 m or more from the plume.

4. DISCUSSION

This study has demonstrated that under the semi-arid conditions in Northern Ghana, indicator organisms can be effectively removed with the sludge dewatering methods developed locally by farmers. Assuming a background mean concentration of viable *Ascaris* eggs in raw sludge of 5-242 eggs/ g TS in Ghana (Kone et al., 2007), the dewatering methods applied by farmers, on average achieved 0.8 – 2.5 log reduction in *Ascaris* eggs. For this, the mean level of the total *Ascaris* eggs (viable and non-viable) in the cake sludge across the 40 sites met the WHO monitoring guideline of 1 viable helminth egg / g TS after 30 days or more and 90 days or more of sludge dewatering under the random spot and pit methods respectively even though our measurements may be conservative, since the total number of undamaged eggs were measured. Also, indicator organisms such as *E. coli* were effectively reduced to levels below the WHO monitoring guideline of < 1000 *E. coli* /g TS following 30 days or more of sludge dewatering across the investigated sites (WHO, 2006). These treatment performances are comparable with those of the conventional low-cost sludge treatment technologies investigated with respect to *Ascaris* removal in Ghana and other developing countries. Depending on the design configuration and operational conditions, planted or unplanted dewatering beds are reported to reduce helminth eggs by ≤ 0.5-3.14 logs (Heinz et al., 1998; Koottatep et al., 2005; Kegne et al., 2009). Thermophilic co-composting of faecal sludge with organic waste can also reduce helminth eggs by 1.40 – 1.9 log after 60 days of treatment (Kone et al., 2007). However, compared with the aforementioned low cost technologies, that are usually operated under controlled and supervised conditions, the sludge treatment methods reported here are largely indiscriminate and unplanned as exemplified in the dewatering time variations across the 40 sites. From our study, a large proportion of the sites investigated dewatered sludge for 60 days mainly using the random spot spread method. Those applying the pit method dewatered for 90 days or more. Under these methods and dewatering times, both the WHO *Ascaris* and *E.coli* monitoring guidelines were achieved. Hence we recommend 60 days or more of sludge dewatering under the random spot spread method and 90 days or more under the pit method. A major challenge here would be how to incentivize farmers, particularly those dewatering sludge below these proposed limits to adopt the new set guidelines.

To our knowledge, this study presents the first attempt at quantifying the occupational health risk associated with the application of 'cake' faecal sludge from on-site sanitation technologies in developing countries. By assessing the different farm practices through exploratory observational survey, specific exposure pathways were identified and their associated health risks quantified. Thus the risk estimates arrived at in this study inherently captured the perceived health risk of farmers while providing possibilities of what is potentially feasible for implementation. By this approach, the study revealed that the main exposure pathway for the transmission of viral and *Ascaris* infection was the handling of 'cake' sludge without any protective gear. In this regard, *Ascaris* was of major concern, irrespective of the sludge dewatering time and method. However, an overestimation of the *Ascaris* infection risks in this study is most certain as the dose-response model used was derived through a study involving children (<15 years). Thus, the estimates made here may be too prohibitive for the adult risk groups who constituted > 99% of the exposed population. Further work on *Ascaris* dose-response models that distinguishes children from adults is warranted to improve future *Ascaris* infection risk estimates. For instance, the tolerable infection risk is too prohibitive given that most of the infections associated with *Ascaris* are asymptomatic; and with the transition from infection to disease dependent on a wide array of risk factors including malnutrition and socio-economic status (Hotez et al., 2003). In most settings where faecal sludge is applied, as in Northern Ghana, the non-sludge related risk factors are pervasive and account for a significant proportion of *Ascaris* disease burden. Therefore, an infection risk of 10^{-2} for which our proposed sludge dewatering time and methods above adequately meet can be considered safe. For instance, given 10^{-2} *Ascaris* infection risk per farm worker and assuming an infection to disease ratio of 1 for a worst case scenario (Mara and Sleigh, 2009), 1 in 100 farm workers would develop *Ascariasis* compared to the reported 5 in 10 *Ascariasis* in the general population in Ghana (Hotez et al. 2003). By this simple comparison, a crude estimate of 0.5 % of the *Ascarisis* cases can be attributed to exposure to the cake sludge with the remaining proportion accounted for by other risk factors. Whether this is acceptable or not to the general society in terms of cost is a question of local decisions and priorities. A non-treatment strategy that effectively reduced *Ascaris* infection risk was the incorporation of cake-sludge into the soil prior to exposure. Cake sludge incorporation reduced the *Ascaris* infection risk by 2-3 orders depending on the implement used. In this case, exposure to sludge dewatered for 30 days or more, and incorporated into the soil with a hoe, resulted in median annual *Ascaris* infection risks below the tolerable infection risk level of 10^{-3}. Cake sludge incorporated into the soil with a tractor resulted in acceptable median annual viral and *Ascaris* infection risks, even if the sludge had been dewatered for 7-14 days.

Compared with the *Ascaris* infection risks, the viral infection risks expressed in terms of rotavirus infections were generally low. In this regard, the median rotavirus infection risk associated with the handling of the cake sludge and cake-soil mixture were all below the tolerable viral infection risk for sludge dewatered for 30 days or more. The low viral infection risk compared to *Ascaris* infection found here is consistent with one QMRA study that assessed the viral and *Ascaris* infection risks associated with similar exposure pathways during the land application of dehydrated faeces from urine diverting toilets (Schönning et al., 2004). In the Schönning et al. (2004) study, the *Ascaris* infection risk was much higher than the viral infection risk, and storage of faeces for more than 12 months in the UD vaults was required to achieve tolerable *Ascaris* infection risk.

Exposure to aerosolized rotavirus during tractor discing of cake-soil mixture resulted in limited infection risk below tolerable levels at a distance of 2 m or more irrespective of the sludge dewatering method and time employed by farmers. One other study also found a low viral infection risk during exposure to aerosolized Class B biosolid during loading operations (Tanner et al., 2008). In the Tanner et al. (2008) study, the coxsackievirus A-21 infection risk associated with the loading of biosolid was estimated and found to range from 0.78 to 2.1% per worker.

5. CONCLUSION

In this study, two sludge treatment methods, *random spot spreading* and *pit containment,* used by farmers in Northern Ghana were assessed with respect to their barrier efficacy against indicator organisms. In addition, on farm practices predisposing farmers to microbial hazards were identified and the associated viral and *Ascaris* infection risk quantified. Following are the main findings of the study:

1. Both WHO monitoring guidelines for *E. coli* and *Ascaris* were achievable provided that farmer treated sludge for 60 days or more in the random spot spread method and 90-105 days in the pit method.

2. The above dewatering times, assured a tolerable rotavirus infection risk, but not for the tolerable *Ascaris* infection risk. However, on-farm practices such as cake-sludge incorporation with either a hoe or tractor reduced the *Ascaris* and rotavirus infection risk to tolerable levels.

3. The rotavirus infection risk associated with bioaerosols was below the tolerable rotavirus infection risk level at an exposure distance of 2m regardless of the sludge treatment method and dewatering time.

4. For *Ascaris* infection, it is recommended that the tolerable infection risk is set at 10^{-2} per person per year particularly where a large proportion of the risk group are adults.

5. It is recommended that sludge is dewatered for 60 days or more in the random spot spread method and 90 days or more in the pit method.

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Figure 1: Distribution of Thermotolerant coliform (A) *E. coli* (B) and *Ascaris* (C), in cake sludge under the random spot spread and pit treatment methods (------ WHO monitoring benchmark)

Figure 1 A

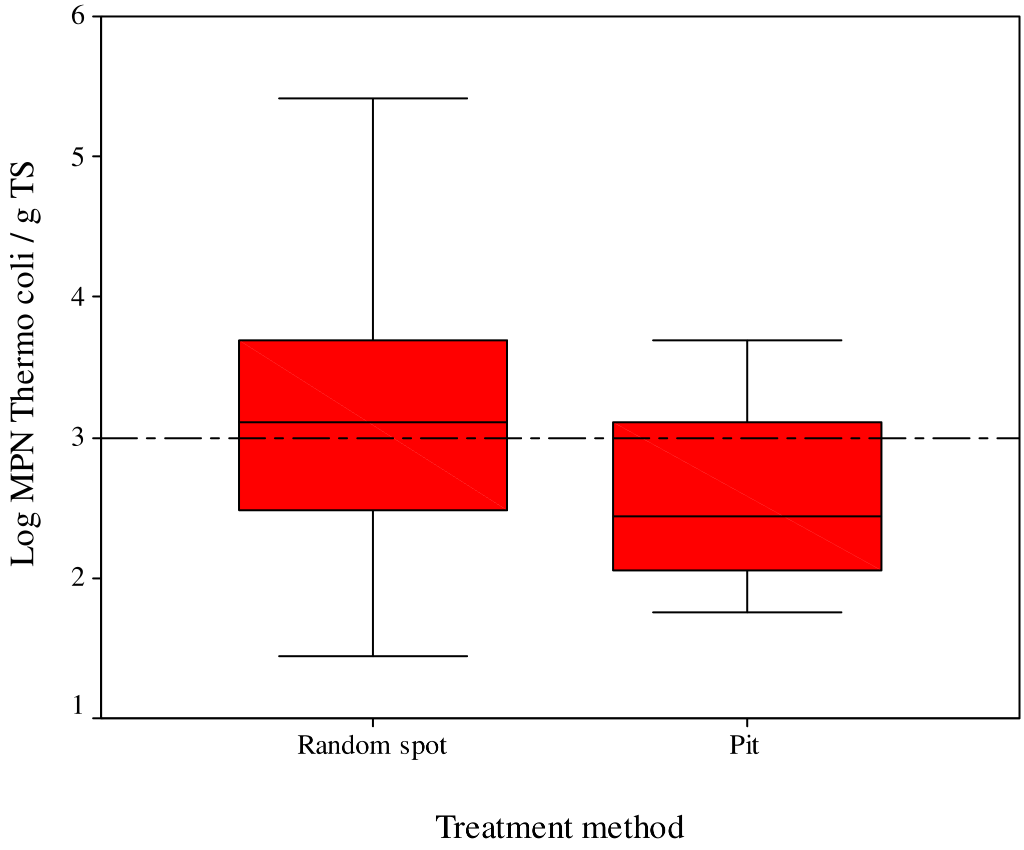


Figure 1 B

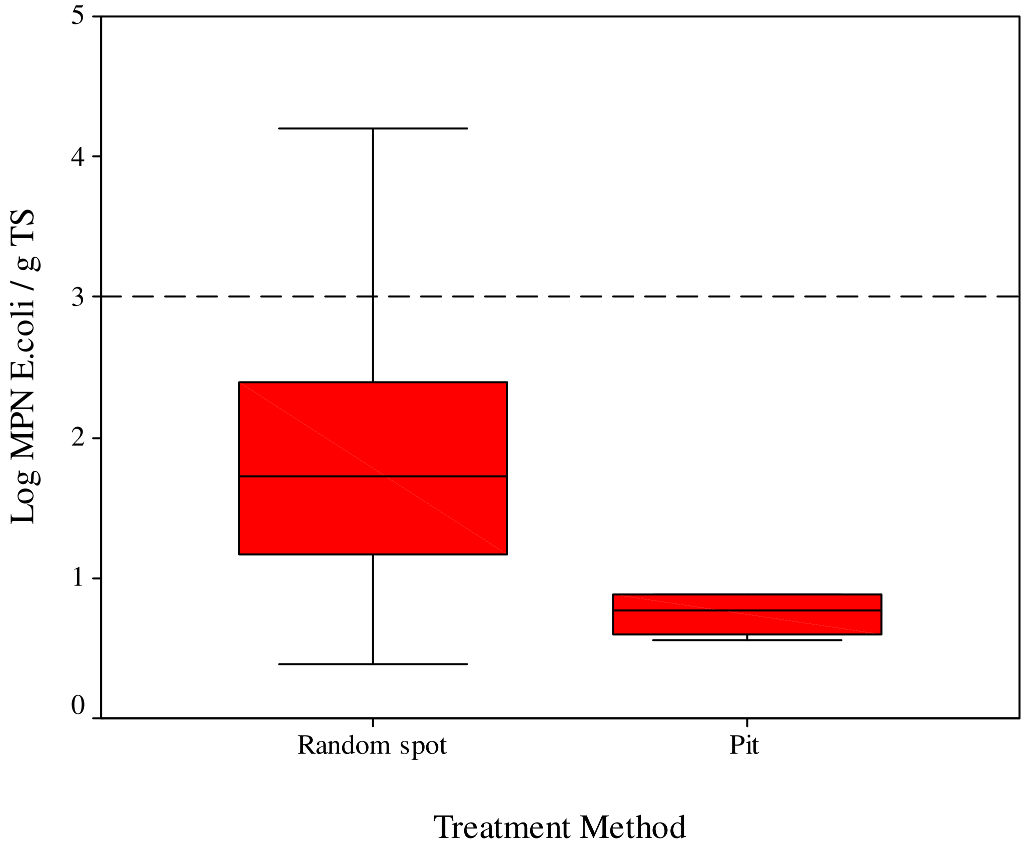


Figure 1 C

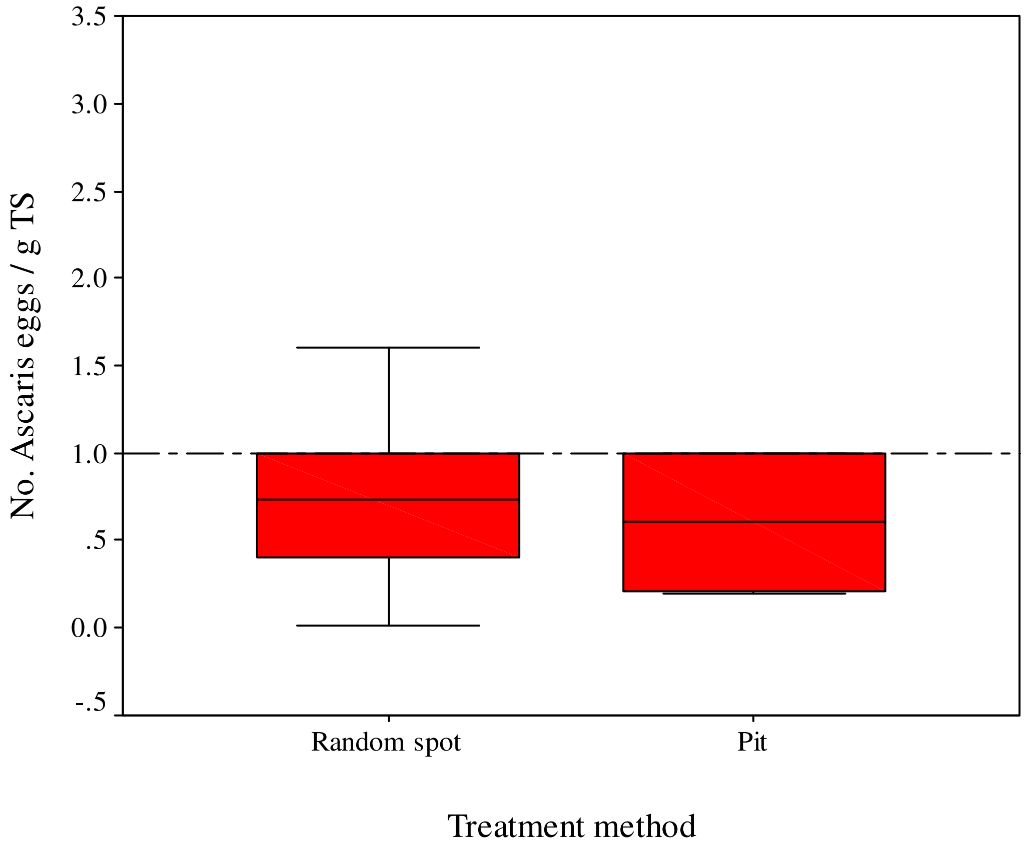

No. Ascaris eggs / g TS
3.5
3.0
2.5
2.0
1.5
1.0
.5
0.0
-.5
Random spot
Pit
Treatment method

Figure 2: Distribution of Thermotolerant coliform (A) *E. coli* (B) and *Ascaris* (C) over sludge dewatering days and treatment method. (Random spot spread method: 7-14 days (n = 10); 30-45 days (n = 8); 60 days (18). Pit method: 90-105 days (n= 4)) (------ WHO monitoring benchmark)

Figure 2 A

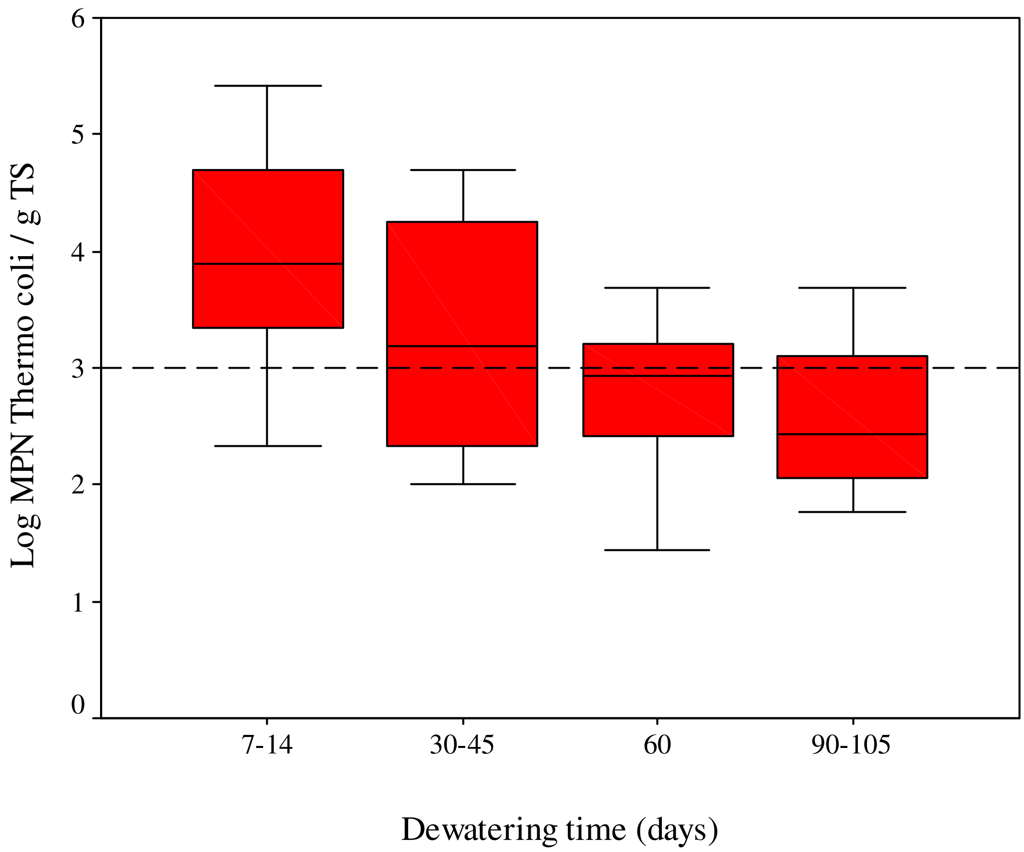
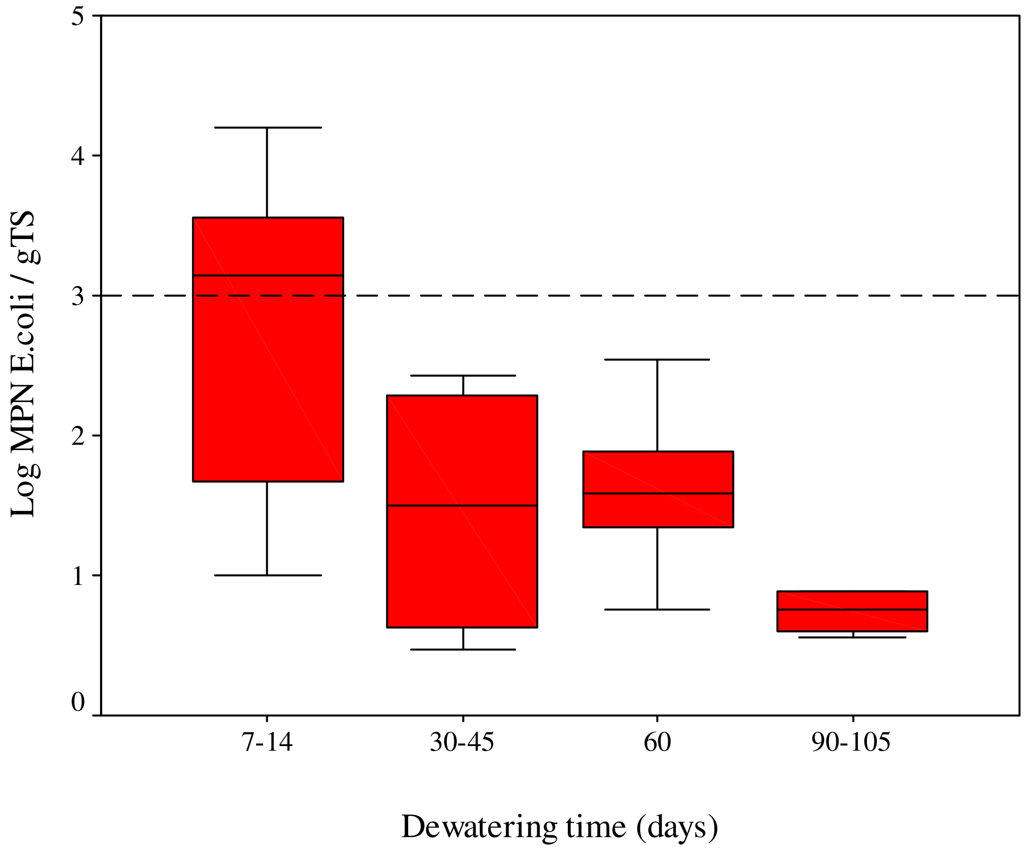


Figure 2 B



5
4
3
2
1
0
Log MPN E.coli / gTS
7-14
30-45
60
90-105
Dewatering time (days)

Figure 2 C

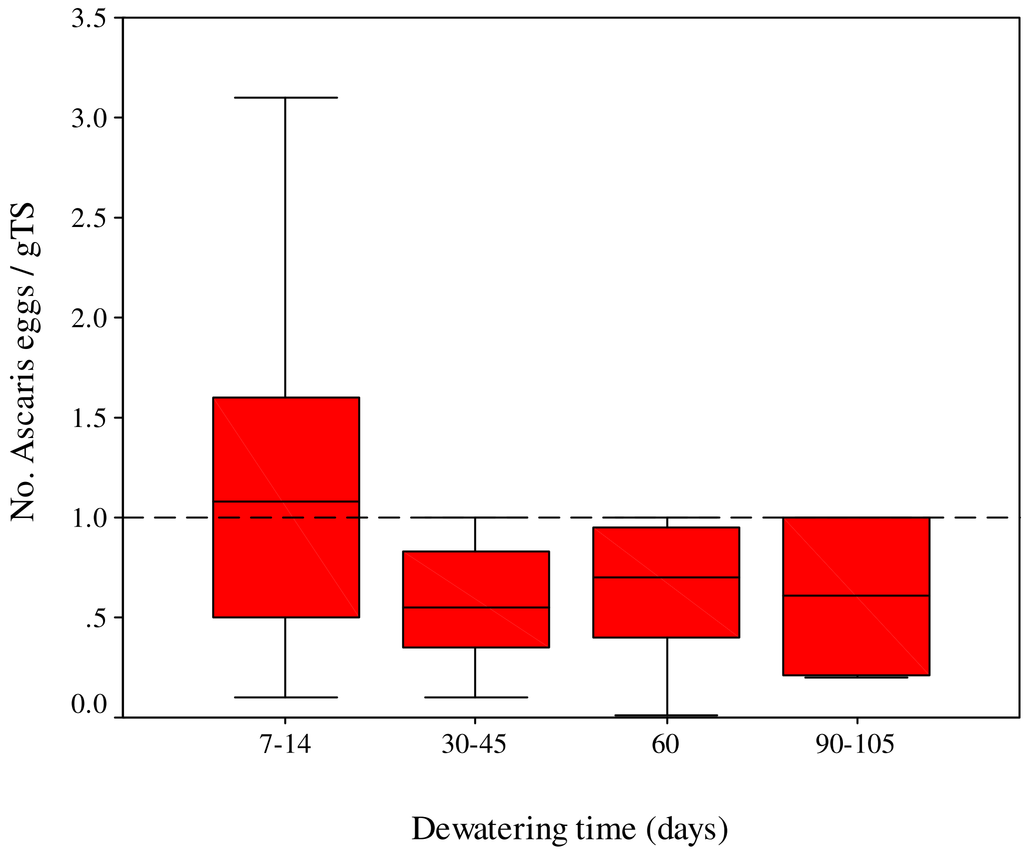

No. Ascaris eggs / gTS
3.5
3.0
2.5
2.0
1.5
1.0
.5
0.0
7-14
30-45
60
90-105
Dewatering time (days)

Figure 3: Decay of thermotolerant coliform (A), *E. coli* (B) and *Ascaris* (C) over dewatering days using the random spot spread dewatering method.

Figure 3 A

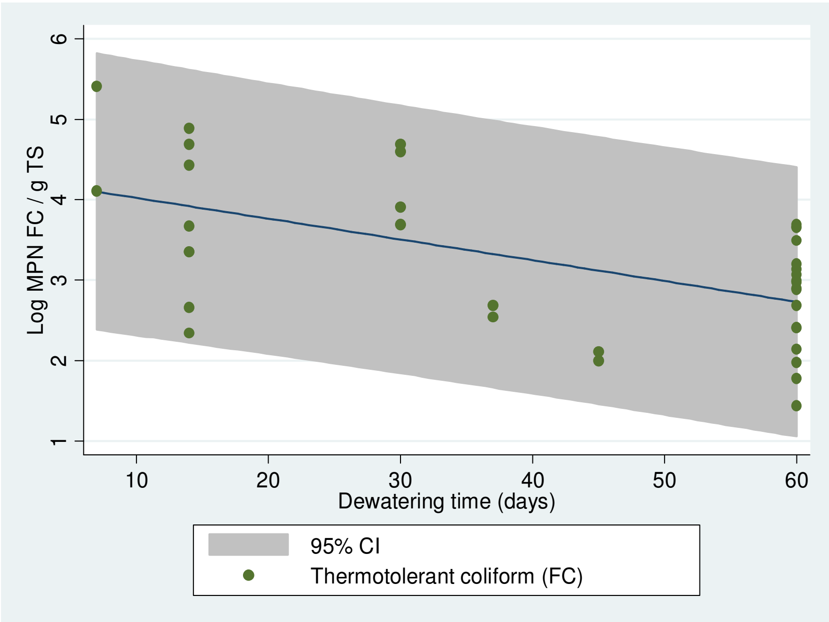


Figure 3 B

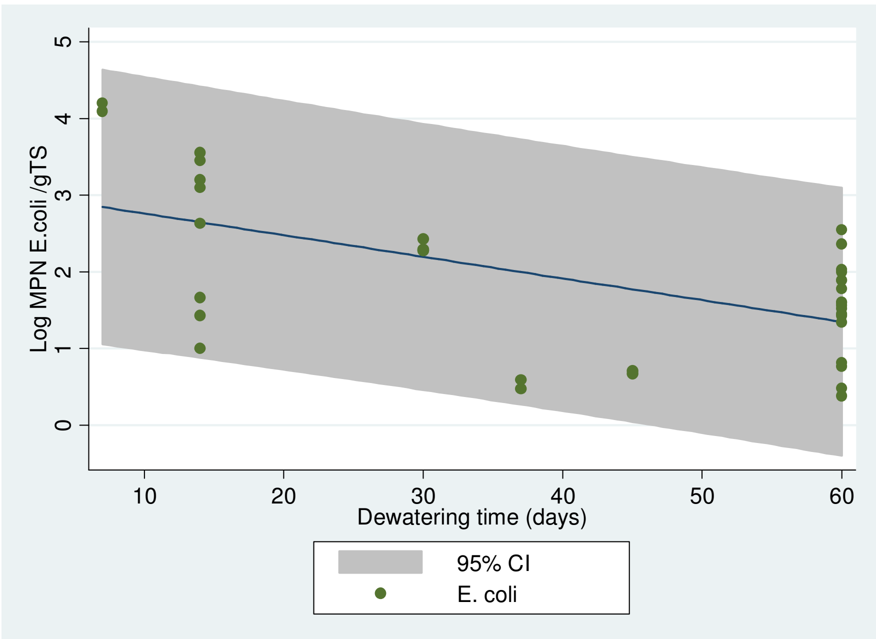
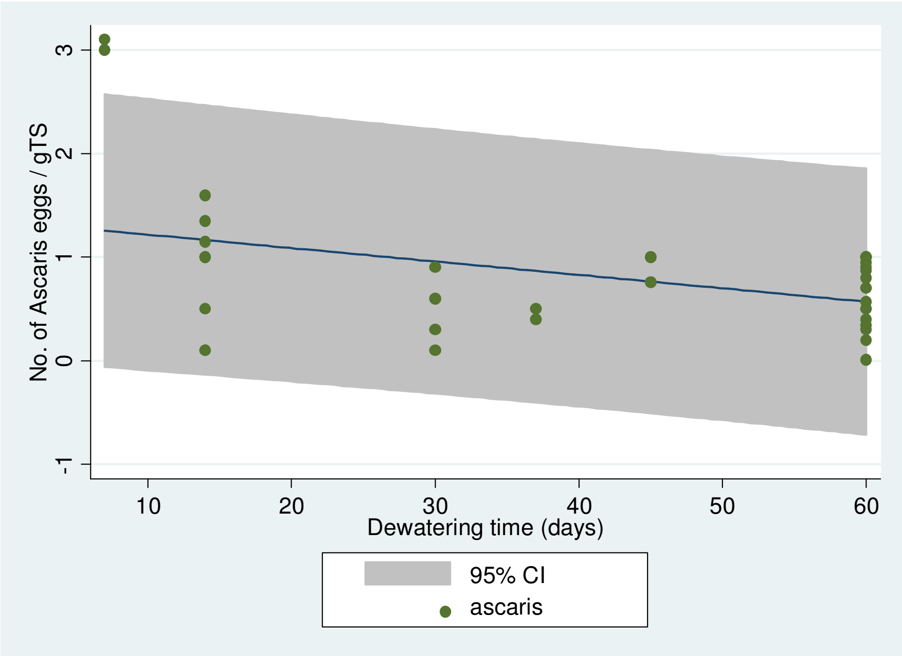


Figure 3 C



No. of Ascaris eggs / gTS
-1
0
1
2
3
10
20
30
40
50
60
Dewatering time (days)
95% CI
ascaris

Figure 4: Rotavirus (A) and *Ascaris* (B) infection risks associated with the accidental ingestion of small amounts of cake sludge and cake-soil mixture treated over time with the random spot spread and pit methods (Random spot spread: 7-14 (n=10), 30-45 (n = 8), 60 (n =18), Pit mehod: 90-105 (n = 4). --------WHO tolerable infection risk level)

Figure 4 A

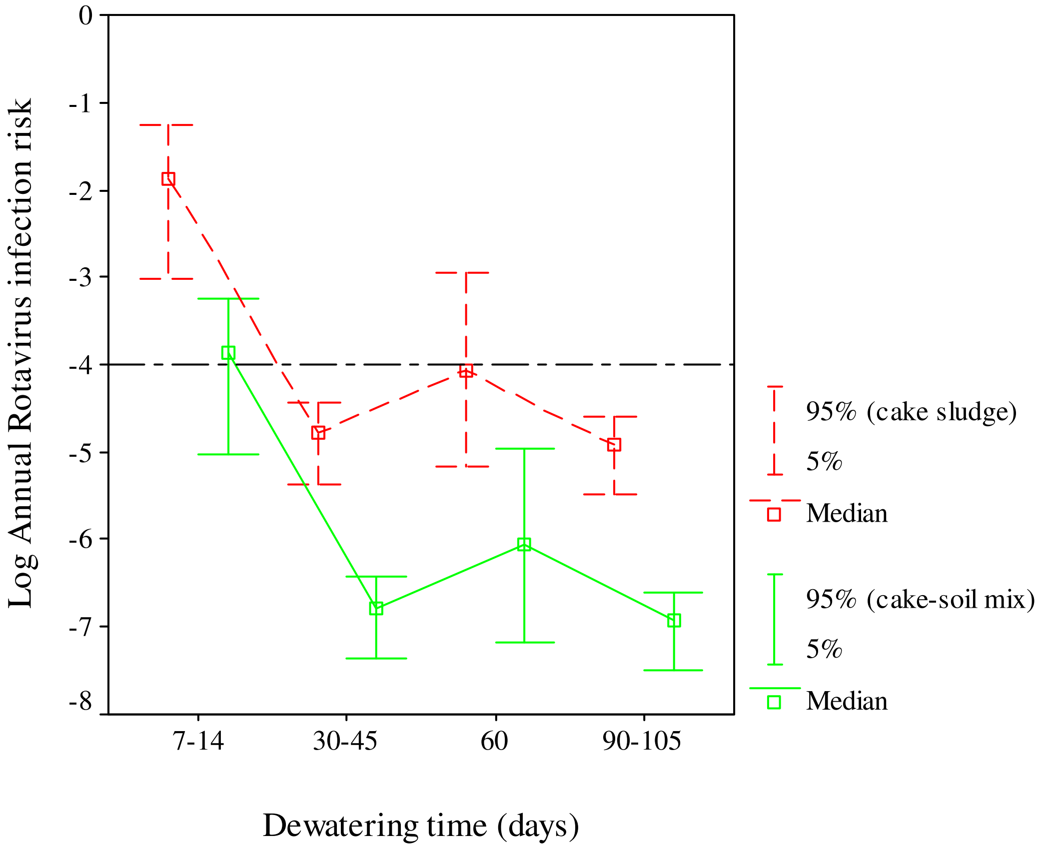


Figure 4 B

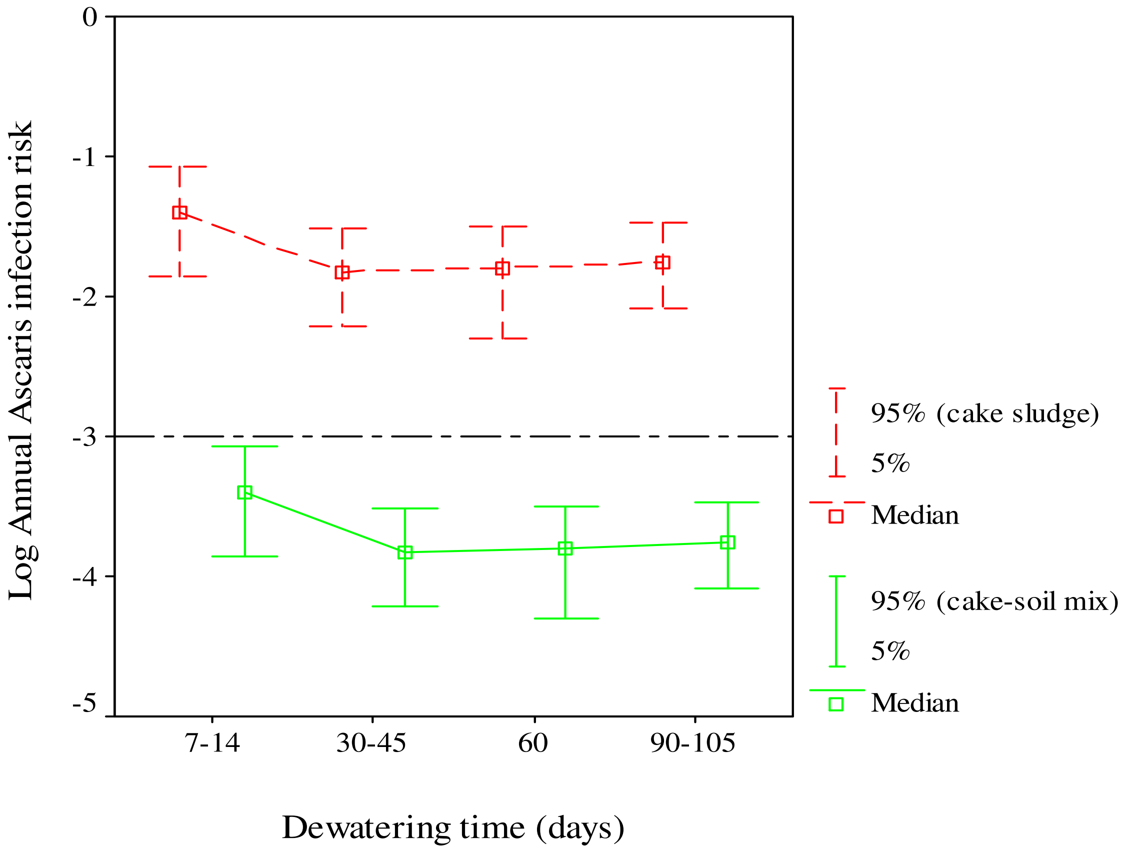
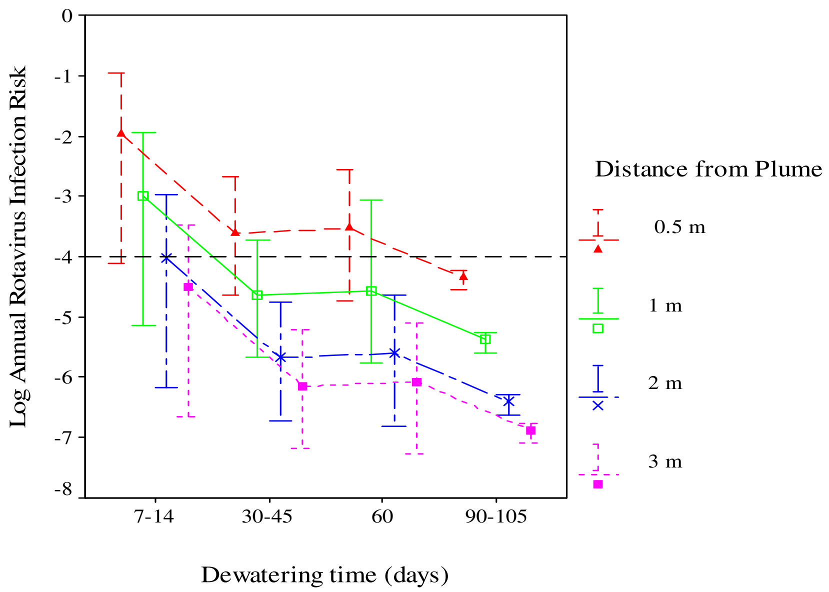

0
-1
-2
-3
-4
-5
Log Annual Ascaris infection risk
7-14
30-45
60
90-105
Dewatering time (days)
95% (cake sludge)
5%
Median
95% (cake-soil mix)
5%
Median

Figure 5: Rotavirus infection risks associated with exposure to aerosols at different distances from sludge plume



(Random spot spread: 7-14, 30-45, 60, Pit mehod: 90-105) (------ WHO tolerable infection risk level)

Paper IV

Razak Seidu, Thor Axel Stenström and Owe Löfman (2010) A Comparative Cohort Study of the Effect of Rainfall and Temperature on Diarrhoea Disease in Faecal Sludge Communities, Northern Ghana. *Journal of Water and Climate (Submitted)*

A Comparative Cohort Study of the Effect of Rainfall and Temperature on Diarrhoea Disease in Faecal Sludge Communities, Northern Ghana

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ABSTRACT

This study assesses the effect of seasonal sludge application, temperature and rainfall on diarrhoeal incidence in faecal sludge and non-faecal sludge applying communities in Northern Ghana. Data on diarrhoea episodes were obtained from a cohort survey involving 1341 and 1323 from the sludge and non-faecal sludge communities. The effects of the temperature and rainfall on diarrhoeal disease incidence were analysed using autoregressive Poisson regression models. In the sludge applying communities, the diarrhoeal disease incidence was higher during the period of sludge application than the period after sludge application ($p > 0.05$). The vise-versa was the case in the non-sludge communities ($p > 0.05$). Maximum rainfall events in the same bi-week increased the risk of diarrhoea in the sludge (RR: 1.034, 95%CI: 1.02-1.05) and non-sludge (RR: 1.003, 95%CI: 0.99-1.01) communities. However, this was not significant in the non-sludge communities ($p>0.05$). Minimum rainfall occurring in the same bi-week decreased the risk of diarrhoea in both communities. Maximum temperature decreased the risk of diarrhoea in the sludge communities (RR: 0.50, 95%CI: 0.38-0.65); but increased it in the non-sludge communities (RR: 1.19, 95%CI: 1.02-1.40). Minimum temperature increased diarrhoea disease risk (RR: 3.50, 95% CI: 2.10-5.80) in the sludge communities, but decreased the risk (RR: 0.70, 95% CI: 0.54-084) in the non-sludge communities. The model can be used to predict diarrhoea incidence in relation to untreated faecal sludge application given local climatic data.

Key words: diarrhoea, rainfall, risk factors, seasonality, sludge application, temperature

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INTRODUCTION

Diarrhoea remains a major cause of morbidity worldwide accounting for the death of some 1.8 million people annually (WHO, 2009). Diarrhoeal disease incidence exhibits seasonal pattern (Faechem *et al*. 1983) dictated by a myriad of complex factors within the public and domestic domains (Cairncross *et al.* 1996), of which the impact of public domain factors such as the application of faecal sludge in agriculture is significant (WHO, 2006). The risk of diarrhoeal diseases associated with faecal sludge application, depends on the occurrence of pathogens in farm soils and their decay rates - all of which are, to some extent, influenced by seasonal variations in temperature and precipitation (Gerba and Britton, 1984). The ultraviolet light from the sun inactivates viruses and bacteria (Gerba and Britton, 1984; Feachem *et al.* 1983). For instance, viruses and *Salmonella* occurring in faecal sludge can just survive for < 70days (usually <20) and < 100days (usually <20) respectively in farm soils at temperatures of 20-30^{0}C (WHO, 2006). However, under constantly low temperatures, the survival of viruses and *Salmonella* can increase to 1 year, to cause infections in exposed farmers (Feachem *et al.* 1983). Increased precipitation is associated with the transport of pathogens on sludge amended farms. The movement of *Cryptosporidium,* through tilled and untilled soils under different rainfall intensity has been demonstrated in a recent study (Ramirez *et al.* 2009). Depending on the precipitation intensity and hydro geological conditions this may lead to the contamination of surface and underground water resources. Hoorman and Shipitalo (2006) recently reported results from a survey they conducted that investigated 98 incidents, over a 4-yr period (2000–2003), where agricultural wastes in subsurface drainage waters contaminated streams in Ohio. The foregoing suggests that variations in these key weather variables can mediate in the transmission of diarrhoeal disease incidence especially in settings where the land application of untreated faecal sludge is practiced.

To our knowledge, no study has assessed the relationship between weather variables and diarrhoea incidence in communities applying faecal sludge or wastewater in agriculture. However, ample evidence exist on the impact of seasonal variations in temperature and rainfall on the occurrence of pathogens in the environment and of the incidence of diarrhoea diseases (Hu *et al.* 2007; Checkley *et al.* 2000; Rose *et al.* 2001; Hashizume *et al.* 2007). For instance, diarrhoea (particularly that caused by the bacteria and protozoan pathogens which predominate in developing regions) is highly sensitive to variations in both temperature and precipitation over daily, seasonal, and inter annual time periods (Checkley *et al.* 2000; Curriero *et al.* 2001). In settings where untreated faecal sludge application is common, clarifying the potential role of weather variables in the transmission of diarrhoeal disease is important. From an applied perspective, interventions can be developed not only within the matrix of curtailing exposure to pathogens as presently prescribed by the WHO guidelines (WHO, 2006), but also, related to temperature and rainfall variations.

In this study, a comparative assessment of the effects of seasonal sludge application, rainfall and temperature on the diarrhoeal disease incidence in faecal sludge and non-faecal sludge applying communities in Northern Ghana is made. The study addressed two main questions: i) Is there any difference in diarrhoeal disease incidence in sludge and non-sludge communities accounted for by seasonal application of faecal sludge?; and ii) How do variations in rainfall and temperature affect the incidence of diarrhoeal disease in sludge and non-sludge communities?

This study, differs in scope and methodology compared to other studies assessing the effect of temperature and rainfall on diarrhoea cases. It employs a prospective cohort framework in combination with the observation of weather variables from a local station. Thus, specific local heterogeneities are implicitly captured, to allow a better assessment of the effect of temperature and rainfall, at a very local scale that compares communities in relation to the application of faecal sludge.

METHODS

The Study Population and Data Collection

The study was performed in the Tamale Metropolitan Area (9^0 18'-9^0 26'N, 1^0 15'E-1^0 23'W) of the Northern Region of Ghana. It is situated in the Guinea Savanna Agro-Ecological Zone and characterized by one distinct wet (rainy) and one dry season. The uni-modal rainfall pattern gives a precipitation of about 1000 mm per annum and the mean annual temperature is 29^0C (Tamale Metropolitan Assembly, 2000). Tamale is an urban centre, but has fringe areas where people practice traditional subsistence agriculture. In these communities, the land application of faecal sludge follows a seasonal pattern. Sludge collected from pit latrines and septic tanks by trucks is mainly dried in the field adjacent to agricultural land in the dry season (November-April) when temperatures reach about 39°C and is subsequently incorporated into the soil, by tilling with hoes or tractor before the start of the rainy season that last from May to October.

A prospective cohort-study was conducted from February 2008 to March 2009. Participants of the study were drawn from peri-urban farming communities in the Tamale Metropolitan Area. A total of 300 households were involved in the prospective cohort study including 165 households from two communities applying untreated faecal sludge in the fields and 135 from two non-faecal sludge communities. The total subjects from the 300 households was 2664 individuals comprising 1341 and 1323 individuals from the sludge and non-sludge applying communities respectively. The subjects were followed to the end of the cohort or after their withdrawal. Prior to the study, a written purpose was read in the local language to all the household heads of the participants and informed consent was obtained from them. The study instruments and methods were reviewed and approved by the University for Development Studies ethics committee. Standard pre-coded disease incidence questionnaires were developed and revised after conducting a pilot survey in two communities with similar socio-demographic characteristics as our study areas. All questionnaires were administered by trained fieldworkers and supervised by the lead investigator. The disease incidence questionnaires were used to collect information of diarrhoea on the individual level in the selected households at bi-weekly intervals over a full year- cycle. In this study, an episode of diarrhoea was defined as three or more loose (or watery) stools within 24 hours, regardless of other gastro-intestinal symptoms (Baqui *et al.* 1991), and without the influence of a purgative (or medication). The diarrhoea episodes for infants and children in their households were collected from the mothers. In addition to the disease incidence survey, a comprehensive farm observation survey was conducted to document the timing of faecal sludge application in the sludge communities and related practices. The rainfall and temperature variables over the study period for both community groups were collected from the Ghana Meteorological local station in Tamale. It was assumed to be the same for all peri-urban communities of the Tamale Metropolitan area. We obtained the daily rainfall and maximum and minimum temperature. The bi-weekly means for minimum and maximum temperature and rainfall were calculated from the daily records.

Statistical Analysis

All statistical analyses were carried out using STATA 10 (Stata Corporation, College Station, TX, USA). The calculations were based on the bi-weekly incidence of diarrhoea cases, aggregated from the reported episodes for the individuals in each of the study community. A descriptive analysis of the diarrhoea cases was made with time plots to identify any potential peaks and observable trends. A simple stratified analysis was also undertaken to identify whether there was any difference in diarrhoeal incidence, in the period during and after the application of sludge. Following this, integrated time-plots of diarrhoeal cases in relation to temperature and rainfall were made to identify any first-hand relationship between weather variables and the incidence of diarrhoea cases. By assuming that the counts of diarrhoea cases were Poisson distributed, an autoregressive Poisson regression model was constructed to assess the relationship between diarrhoea cases, weather variables and the period of sludge application. The period of sludge application was introduced into the model as a dummy, with 1 and 0 representing the periods during and after the application of faecal sludge respectively. The seasonal component of the model was accounted for by introducing sinusoidal trigonometric terms into the auto-regressive model. In our model specifications for the faecal sludge and non-faecal sludge communities, all variables were entered and eliminated manually from the model in a stepwise manner, with the criterion for elimination being a P-value > 0.05. Autocorrelation function (ACF) and partial autocorrelation function (PACF) were used to detect autocorrelation of diarrhoea cases and weather variables. The Akaike's Information Criterion (AIC) was used to examine the best model fit. The model with the smallest AIC fits the data better. AIC = -2 In (L) + *2k,* where L is the likelihood function and *k* is the number of free parameters. Further goodness of fit test was undertaken by graphically examining the ACF and PACF plots of the residuals that minimized the residuals autocorrelation.

The final model adjusted for autocorrelation and seasonality took the general form:

$$In(E\,[Y_t\,]) = \beta_0 + \beta_1 Y_{t-n} + \beta_2 Temp_t + \beta_3 Temp_{t-n} + \beta_4 Rain_t + \beta_5 Rain_{t-n} + \beta_6 Sin\left[\frac{2\pi t}{T}\right] + \beta_7 Cos\left[\frac{2\pi t}{T}\right] + \beta_8 X_t$$

where Y_t is the diarrhoea cases for each bi-week; T is the number of time periods described by each sinusoidal function (eg T = 24 bi-weeks); t is the time period (eg. t = 1 for 1st bi-week; t = 2 for second bi-week etc); Y_{t-n} autoregressive terms for diarrhoea cases; $Temp_t$ maximum or minimum temperature; $Temp_{t-n}$ autoregressive terms for maximum or minimum temperature; β_o is the intercept; and X_t (X_t = 1 identifies the period during sludge application; X_t = 0 identifies the period after sludge application).

RESULTS AND DISCUSSION

Results

Temperature and Rainfall Variables

Descriptive statistics of the rainfall and temperature data used in the study are presented in Table 1. The mean bi-weekly maximum and minimum temperatures for the sludge and non-sludge application periods were 31.6 ^{0}C and 23.2 ^{0}C respectively and the corresponding bi-weekly rainfall were 26.4 mm and 3.4 mm respectively. For both periods, there was a significant difference ($p < 0.05$) in maximum temperature and maximum and minimum rainfall. However, no significant difference in minimum temperature ($p > 0.05$) was observed.

Table 1: Descriptive Statistics of Aggregated bi-weekly Rainfall and Temperature in the Tamale Metropolis

Climatic variables	Period after Sludge application (May to October)			Sludge Application Period (November-April)		
	Range	Mean	S.D	Range	Mean	SD
Temperature						
Maximum (^{O}C)	29.7 – 35.3	31.5	1.7	36.3 – 39.0	36.8	1.5
Minimum (^{O}C)	22.5 – 25.4	23.2	0.7	18.6 – 27.2	23.1	3.1
Rainfall						
Maximum (mm)	4.4 – 92.6	37.5	26.4	0 – 44	6.8	13.6
Minimum (mm)	0.4 – 13.6	6.1	3.4	0 – 6	0.7	1.7

SD= standard deviation

Diarrhoea Incidence and Sludge Application

At the end of the cohort the 1341 and 1323 individuals recruited from the sludge and non-sludge applying communities were followed for 489,465 and 480,799 days at risk. The total person days at risk during the period of sludge application was 242,721 for the sludge communities and 238, 623 for the non-sludge communities. In the period after sludge application, 246,744 and 242,176 person days at risk were recorded for the sludge and non-sludge communities respectively.

In the faecal sludge communities, the diarrhoeal disease incidence decreased from 1.04 (95% CI: 0.61-1.45) diarrhoea episodes per person year in the period of sludge application to 0.99 (95% CI: 0.73–1.24) diarrhoea episodes per person year in the period after sludge application. Conversely, in the non-sludge communities, diarrhoea incidence rate increased from 0.65 (95% CI: 0.47- 0.83) diarrhoea episodes per person year in the sludge application period to 0.69 (95% CI: 0.55-0.83) diarrhoea episodes per person in the non-sludge application period. In both the sludge and non-sludge communities, there was no significant difference ($p > 0.05$) in diarrhoea incidence for the periods of sludge and non-sludge application. Also, the effect of the sludge and non-sludge application periods as risk factors, was not significant ($p >0.05$) in both the sludge and non-sludge communities' autoregressive Poisson models, and thus was not included in the final models.

Figure 1 shows the predicted bi-weekly cases of diarrhoea against the observed cases in the sludge and non-sludge communities as derived from the Poisson autoregressive model after controlling for autocorrelation, seasonality and the effects of rainfall and temperature. The accompanying ACF and PACF plots of the models' residuals are shown in Figures 2 and 3 respectively. Examining the functions indicates random distribution and no significant spike in the PACF; thus the final model was properly adjusted. Further scatter plot of the predicted and observed diarrhoea cases of the models revealed a goodness of fit with a correlation coefficient of 0.99 ($p < 0.001$).

Figure 1: Observed and Predicted diarrhoea cases for (A) Faecal Sludge and (B) Non-Faecal Sludge Communities

A B

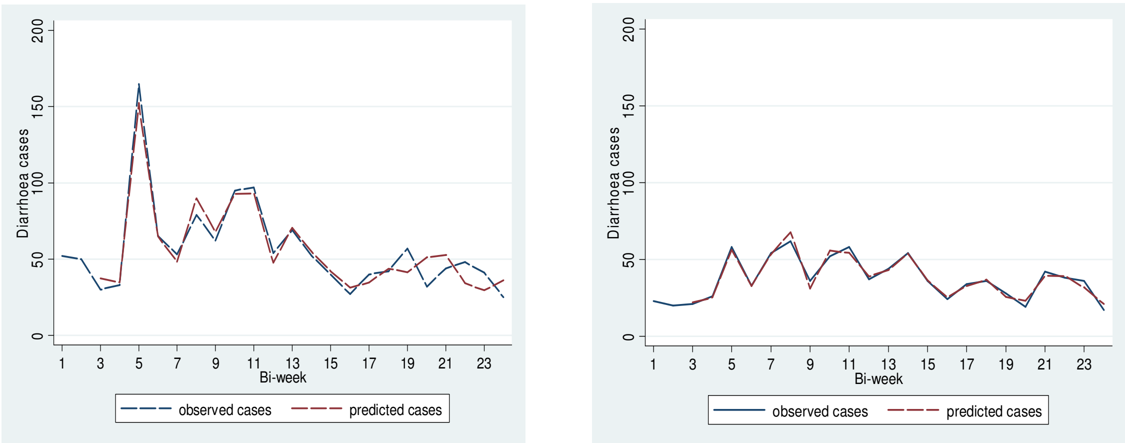


Figure 2: PACF Plots of Residuals for Faecal Sludge (A) and Non-Faecal Sludge (B) Communities

A B

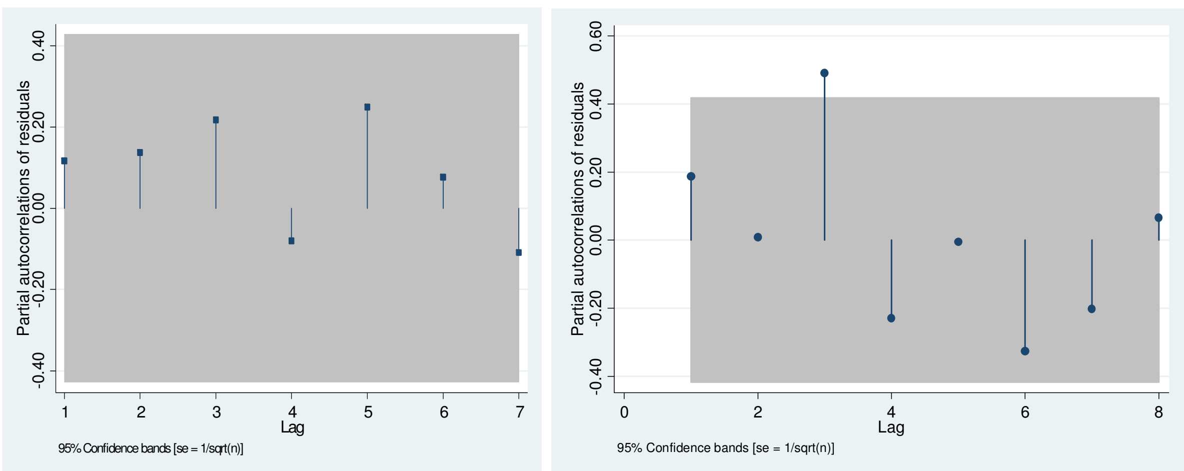
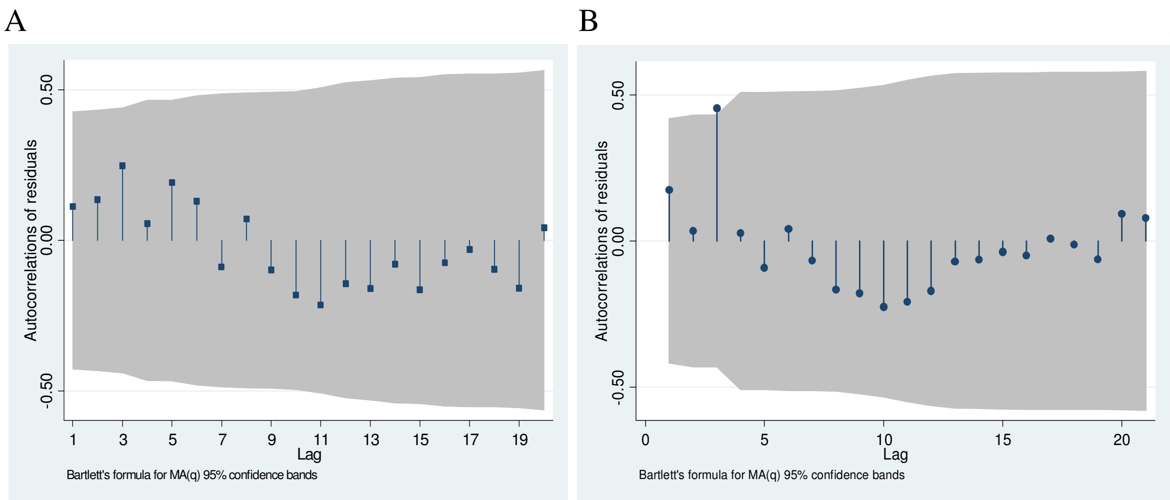


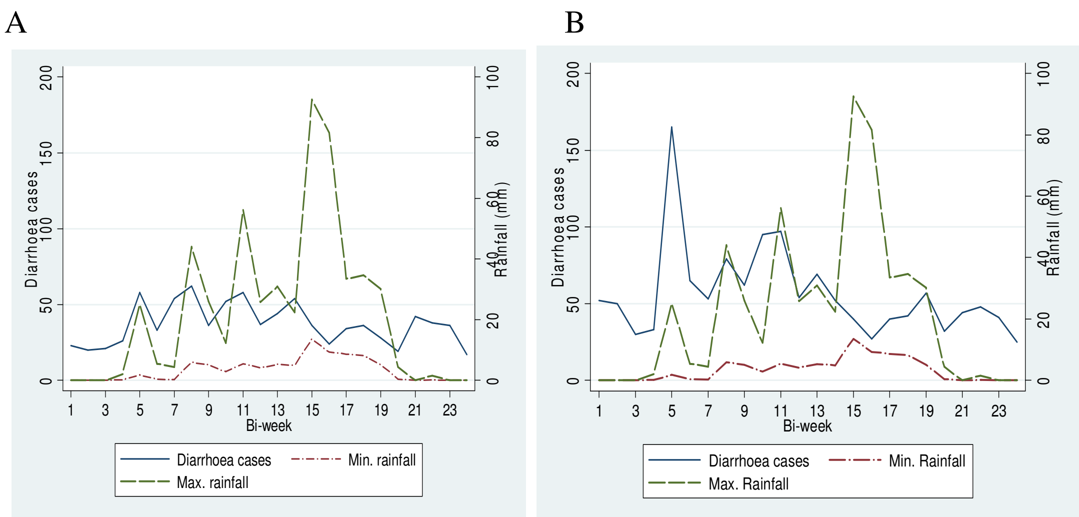
Figure 3: ACF Plots of Residuals for Faecal Sludge (A) and Non-Faecal Sludge (B) Communities



Effect of Rainfall on Diarrhoea Incidence

Figure 4 shows the bi-weekly incidence of rainfall in relation to the bi-weekly incidence diarrhoea in the non-sludge and sludge communities respectively. In the sludge and non-sludge communities an increase in diarrhoea cases was seen with rainfall in bi-weeks 5, 8 and 11. For the sludge communities, the largest bi-weekly diarrhoea incidence coincided with the on-set of the first rainfall in April (bi-week 5) following a long dry period. The same occurred in the non-faecal sludge communities, but with a lower peak of diarrhoea incidence. Subsequent maximum rainfall in bi-week 13 was associated with increased diarrhoea cases in both communities. There was no increase in diarrhea cases associated with the highest rainfall of the entire study period recorded in bi-week 16 which occurred towards the end of the rainy season. From Figure 4, no clear associations could be drawn between minimum rainfall and the bi-weekly incidence of diarrhoea cases.

Figure 4: Bi-weekly diarrhoea cases and rainfall in A) Non sludge and B) sludge communities



The effect of maximum and minimum rainfall on the bi-weekly incidence of diarrhoea as predicted by the adjusted Poisson autoregressive models for the sludge and non-sludge communities are presented in Tables 2 and 3 respectively. The model parameters indicate that maximum rainfall increased the risk of diarrhea cases in both the sludge and non-sludge communities. The model also shows positive and negative lag effects of maximum rainfall events on the reported bi-weekly diarrhoea cases in both the sludge and non-sludge communities. In the sludge communities, maximum rainfalls in a particular bi-week increased the risk of diarrhoea in the next bi-weeks. Also, in the sludge communities maximum rainfall event in a particular bi-week increased the risk of diarrhoea incidence 3 bi-weeks after. However, in the non-sludge communities, maximum rainfall event in a particular bi-week decreased the risk of diarrhoea in the subsequent bi-week. Unlike the maximum rainfall events, all the minimum bi-weekly rainfall events decreased the risk of diarrhoea cases in both the sludge and non-sludge communities. There was also no observable lag effect of minimum rainfall in the non-sludge communities. However, in the sludge communities, minimum rainfall in a particular bi-week was significantly associated with the risk of diarrhoea cases reported in the subsequent bi-week.

Effect of Temperature on Diarrhoea Incidence

The relationship between maximum and minimum temperatures and the bi-weekly incidence of diarrhoea cases in the sludge and non-sludge communities as estimated by the models are shown in Tables 2 and 3. The models show that maximum temperature occurring in a given bi-week decreased the risk of diarrhoea incidence in that bi-week in the sludge communities, but increased it in the non-sludge communities. Lag effects of maximum temperature on the bi-weekly incidence of diarrhoea were also observed in both study groups. In this case, maximum temperatures recorded in a particular bi-week increased the risk of diarrhoea incidence in the subsequent bi-week in the sludge communities and in the next two bi-weeks in the non-sludge communities. In terms of minimum temperature, different effects on diarrhoea were observed in the sludge and non-sludge communities. Minimum temperature in a particular bi-week increased diarrhoea risk in the sludge communities but decreased it in the non-sludge communities. Lag effects of minimum temperature on diarrhoea cases were also observed in the sludge and non-sludge communities. In the sludge communities, minimum temperature in a particular bi-week decreased the risk of diarrhoea cases in the subsequent 2 bi-weeks but increased the risk 3 bi-weeks after. In the non-sludge communities, minimum temperature in a particular bi-week decreased the diarrhoea risk in the next bi-week.

Discussion

To our knowledge, this is the first study reporting the effect of temperature and rainfall on diarrhoea incidence in faecal sludge communities. In both the sludge and non-sludge communities, maximum rainfall events occurring in the same bi-week increased the risk of diarrhoeal disease incidence. This is consistent with findings made in other studies elsewhere. In Fiji, high rainfall was associated with significant increases in diarrhoea incidence among infants after adjusting for the effect of long term trends and seasonal pattern (Singh *et al.* 2001). In our study, the impact of maximum rainfall on diarrhoea incidence was higher in the sludge communities compared to the non-sludge communities suggesting a greater mediation of rainfall in the exposure to pathogens in the sludge communities. In this study, during the sludge application period, two maximum rainfall peak events occurred, and were both associated with peak diarrhoea cases. Blumenthal *et al.* (2001) associated high diarrhoea prevalence in the wet season with increased rainfall in communities using untreated wastewater for irrigation. However, that study did not quantify the effect of rainfall as an explanatory or risk factor of diarrhea. In this study, initial maximum rainfall peaks coincided with increased diarrhoea incidence in both the sludge and non-sludge communities. However, prolonged peaks up to the 16^{th} bi-week led to a significant reduction in diarrhoea disease incidence in both communities. A similar finding was made in a study in Fiji where a reduction in diarrhoea cases was observed in months with prolonged high rainfall events (Singh *et al.* 2001). A possible explanation for this is that, initial rainfall flush faecal contaminants from fields and dwellings into environmental routes for disease transmission, but continued rainfall peaks lead to a subsequent improvement in the levels of contaminants along these routes. This study together with one study in Dhaka, Bangladesh (Hashizume *et al.* 2007), showed a decreased risk of diarrhoea disease incidence under minimum rainfall events. In contrast, a study in Fiji associated increased diarrhoea cases occurring in the same month and subsequent months with low rainfall (Singh *et al.* 2001).

A major observation was the disparate effect of maximum temperature on diarrhoea disease incidence in the sludge and non-sludge communities. A positive relationship was found between maximum temperature and diarrhoea incidence occurring in the same bi-week in the non-sludge communities. In Lima, increased diarrhoea cases were associated with maximum temperature following El-Nino events (Checkley *et al.* 2000). Also, in Bangladesh a positive linear relationship was found between non-cholera diarrhoea and temperature (Hashizume *et al.* 2007). In a Vietnamese study involving farmers using wastewater and excreta on crops, a higher incidence of diarrhea was observed in the hottest months compared to the coldest months (Trang *et al.* 2007). However, this was not statistically significant, and it was not clear whether increased temperature had any direct role in the diarrhea occurrence. Generally, temperature is known to influence the transmission of diseases in several ways. For instance, in the sludge communities, the negative relationship found between maximum temperature and diarrhoea disease incidence occurring in the same bi-week may be attributed to the potential die-off of pathogens in the sludge amended fields. Seidu *et al.* (2010a) found low counts of *E. coli* /g TS in dewatered cake sludge handled by farmers in the sludge communities during the period of maximum temperatures.

This study has some limitations that need to be stressed. Time-aggregation of the data may produce biased estimates as it reduces sample size and introduces measurement errors that are negatively correlated with the duration (Peterson and Koput, 1992). Therefore, our bi-weekly aggregation may be too coarse to fully establish the predictability of our autoregressive models. However, it is the best measure we could use in this study and the fact that our model so closely predicts reported incidence data is an indication that our approach in minimizing the model error has been successful. Also recall and reporting bias, may affect the overall incidence of diarrhoea cases reported here given the cohort design employed in the study. Furthermore the aetiological agents of the diarrhea cases were not assessed. Most aetiological agents implicated for the occurrence of diarrhea exhibit a seasonal pattern. For instance, studies have shown that rotavirus related diarrhea among children in Northern Ghana exhibit a seasonal pattern with higher cases in the dry season compared to the wet season (Binka *et al.* 2003). Other studies elsewhere have reported seasonal variations in diarrhoea cases implicating *Salmonella* (Zhang *et al.* 2008), *Cryptosporidium* (Hu *et al.* 2007) and vibrio cholera (Fernandez *et al.* 2009). Further research on the seasonal variations of diarrhea aetiology in the faecal sludge communities is thus warranted. Furthermore this study, did not account for other population vulnerability factors such as access to water and sanitation facilities as well as the socio-demographic variables of the communities. It has been shown that the relative importance pathogens, which thrive at lower temperatures appears to be greater in populations of regions with higher standards, specifically access to clean water and sanitation (for which there is no clear and consistent evidence for peaks in all-cause diarrhoea in warmer months), compared to less well-off populations (where diarrhoea is usually more common in warmer, wetter months). For instance, Hashizume *et al.* (2007) found a relatively high effect of temperature on non-cholera diarrhea for people with lower educational attainment and with poor socio-economic indicators. In a study in South Africa, clear summer peaks of diarrhoea in black, but not white infants was observed in Johannesburg (Robins-Browne, 1984). Building on the findings made in this study, a more comprehensive hierarchical effect decomposition assessment of risk factors associated with diarrhoeal disease incidence in the sludge communities was undertaken (Seidu *et al.* 2010b).

CONCLUSION

A major finding made here is that key weather variables may have a significant mediating role in the incidence of diarrhea cases in communities applying faecal sludge and by extension those using wastewater for irrigation. Thus, it is important that these factors are included in modeling the relationship between disease outcome and risk factors associated with sludge/wastewater reuse. This is more so, as significant changes in key weather variables are anticipated in the future.

The modelling approach used here can be applied to predict diarrhoea disease incidence in relation to untreated faecal sludge application given local climatic data. This could be extended to include other socio-demographic risk factors. Looking ahead, we recommend that subsequent WHO guidelines on wastewater and faecal sludge reuse clearly enunciate risk models that adequately capture the effect of key weather variables.

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Table 2: Parameters estimated by autoregressive adjusted Poisson regression for the Faecal Sludge communities

Parameters	RR	P	95% CI
Lag1 cases[a]	0.950	0.000	(0.929 0.969)
Lag2 cases	0.988	0.000	(0.983 0.992)
Lag3 cases	0.989	0.000	(0.984 0.994)
Minimum rainfall	0.695	0.000	(0.595 0.810)
Rainmin lag1	0.533	0.000	(0.397 0.713)
Maximum rainfall	1.034	0.000	(1.018 1.050)
Rainmax lag1	1.048	0.001	(1.020 1.075)
Rainmax lag3	1.038	0.000	(1.020 1.057)
Maximum temp	0.504	0.000	(0.388 0.654)
Tempmax lag2	2.337	0.001	(1.444 3.783)
Minimum temp	3.479	0.000	(2.090 5.791)
Tempmin lag2	0.629	0.005	(0.456 0.866)
Tempmin lag3	1.633	0.000	(1.297 2.056)
Cos 24	1.163	0.711	(0.523 2.581)
Sin 24	0.082	0.004	(0.014 0.457)
Cos12	1.490	0.006	(1.122 1.987)
Sin 12	1.822	0.004	(1.206 2.754)
Constant		0.001	

a. Cases: Diarrhoea cases.

Rainmin: average bi-weekly minimum rainfall; Rainmax: average bi-weekly maximum rainfall; Tempmax: average bi-weekly maximum temperature; Tempmin: average bi-weekly minimum temperature

Lag: Lag effects of parameters on bi-weekly diarrhoea incidence (eg. tempmax lag1 indicate the effect of maximum temperature in a particular bi-week on the incidence of diarrhoea in the next bi-week)

Table 3: Parameters estimated by autoregressive adjusted Poisson regression for the Non-Sludge Communities

Parameters	RR	P	95% CI
Minimum Rainfall	0.880	0.004	(0.807 0.960)
Maximum rainfall	1.003	0.440	(0.994 1.012)
Rainmaxlag1	0.988	0.000	(0.983 0.993)
Maximum temp	1.186	0.024	(1.022 1.376)
Tempmax lag1	1.331	0.001	(1.128 1.571)
Tempmax lag2	0.959	0.480	(0.854 1.076)
Minimum temp	0.678	0.001	(0.544 0.844)
Tempmin lag1	0.692	0.000	(0.584 0.819)
Cos 24	0.067	0.000	(0.025 0.179)
Sin 24	0.545	0.217	(0.208 1.427)
Cos12	0.373	0.000	(0.245 0.568)
Sin 12	1.139	0.187	(0.938 1.382)
Constant		0.124	

Rainmin: average bi-weekly minimum rainfall; Rainmax: average bi-weekly maximum rainfall; Tempmax: average bi-weekly maximum temperature; Tempmin: average bi-weekly minimum temperature

Lag: Lag effects of parameters on bi-weekly diarrhoea incidence (eg. tempmax lag2 indicate the effect of maximum temperature in a particular bi-week on the incidence of diarrhoea in the 2 bi-weeks after)

Paper V

Razak Seidu, Owe Löfman, Pay Drechsel, Arve Heistad and Thor Axel Stenström (2010) Risk Factor Analysis of Diarrhoea disease in Faecal Sludge Applying Households using a Hierarchical Effect Decomposition Model. (*Manuscript*)

Risk Factor Analysis of Diarrhoea disease Incidence in Faecal Sludge Applying Households using a Hierarchical Effect Decomposition Model

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ABSTRACT

This study applies a hierarchical effect decomposition model to assess the effect of risk factors and their inter-related mediation on diarrhoeal disease transmission in households applying faecal sludge in agricultural fields in the Tamale Metropolitan Area of Northern Ghana. The risk factors were assigned to three inter-related blocks: distal socio-economic, proximal public domain, and proximal domestic domain. The study involved a cohort of 1431 individuals drawn from 165 households applying faecal sludge followed for 489465 person days at risk. A total of 1356 diarrhoeal episodes were reported during the follow up resulting in 1.09 (95% CI: 0.78-1.23) diarrhoeal episodes per person year at risk. The distribution of the diarrhoeal disease episodes among the different age-groups revealed that children were disproportionately affected. The diarrhoeal disease incidence among children aged ≤ 4 years was 2.9 (95% CI: 2.25-3.66) episodes per person year at risk compared with 1.22 (95% CI: 0.92-1.52) episodes per person year at risk for the 5-14 age group and 0.59 (95%CI: 0.36-0.82) episodes for the ≥ 15 age group respectively.

Of the three blocks of risk factors, the most important in diarrhoeal disease transmission was the public domain block (PAF= 24%) followed by the domestic domain (PAF=18%) and distal socio-economic (PAF=15%) blocks. Among the specific risk factors, those related sludge application had the least impact on diarrhoeal disease transmission in the sludge households. On the pathway to diarrhoeal disease transmission, 53% of the effect of the distal socio-economic block and 17% of the effect of the public domain block were mediated by the domestic domain block. The study recommends an integrated multi-barrier risk management strategy for mitigating diarrhoeal disease incidence in the faecal sludge applying households.

Key Words: Diarrhoeal incidence, Distal factors, Domestic domain, Faecal Sludge Application, Hierarchical Effect Decomposition Model, Public domain, Tamale Metropolitan Area

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INTRODUCTION

Human excreta[2] reuse in agriculture has been practiced for centuries in several countries, particularly in Far East countries like China (WHO, 2006). Although the practice has many benefits, it is associated with significant health risks that tend to erode its benefits if not undertaken in a safe manner (WHO, 2006). Health risks often associated with human excreta application in agriculture are helminthiasis and other gastro-enteric infections (Blumenthal and Peasey, 2002). In settings where the agricultural application of excreta is practiced, disease transmission is mainly the consequence of several risk factors including those related to direct contact with excreta (Blumenthal and Peasey, 2002; WHO, 2006). These risk factors can be categorized into distal and proximal risk factors, of which the *distal* factors are mediated through causal pathways involving more *proximal* ones (Cairncross *et al.* 1996).

Distal factors are those that indirectly mediate exposure to pathogens via proximal pathways. These factors may act independently or in tandem within complex settings of domestic and/or public domain(s) in the transmission of gastro-enteric infections (Cairncross *et al.* 1996). Understanding the effects of these factors and their interactions is critical for the development of effective interventions. In the context of excreta reuse, *distal factors* such as the socio-economic status of households can be mediated by *proximal* public and domestic domain factors such as access to water and sanitation facilities and hygiene practices in the pathway to diarrhoeal disease transmission. So far, risk factor analysis of diseases associated with the application of excreta have accounted for the relative importance of different public and domestic domain risk factors using single multivariate models. However, single multivariate models are not able to capture the mediation proportions of the *distal* and *proximal* risk factors in the pathway to disease transmission (Victoria *et al.* 1997). To address this shortcoming, a conceptual framework specifying how different distal and proximal risk factors of disease transmission are inter-related in settings applying excreta can be developed. Based on the conceptual framework, the specific effects of different risk factors as well as their associated mediated proportions can then be assessed using hierarchical effect decomposition models (Victoria *et al.* 1997; Ditlevsen *et al.* 2005).

In this study, a hierarchical effect decomposition model was applied to assess the risk factors of diarrhoeal disease transmission in households applying faecal sludge in the Tamale Metropolitan Area of Northern Ghana. The aims of the study are two-fold: i) to identify the most important risk factors of diarrhoeal disease transmission in the sludge applying households; and ii) assess the interlinked relationship (mediation proportion) between the different risk factors.

[2] Excreta is used as a generic term and refers to faecal sludge, biosolid, night soil and septage

MATERIALS AND METHODS

Study Area

This study was conducted in the Tamale Metropolitan Area (TMA) (9^0 18'- 9^0 26'N, 1^0 15'E - 1^0 23'W) of Northern Ghana. TMA has a population of 293 900 with a growth rate of 2.5%. For several decades, some farmers in the Metropolis have used faecal sludge as an alternative soil ameliorant for crop production. Crops cultivated in the sludge fields include cereals, legumes and vegetables (excluding all kinds of leafy vegetables eaten uncooked). A description of the sludge application practices is presented elsewhere (Seidu *et al.* 2010a).

Study Design and Data Collection

The study was a closed cohort involving 165 faecal sludge applying agricultural households in the Tamale Metropolitan Area. The households were drawn from two peri-urban areas of the Metropolis where faecal sludge application has been practiced for several decades. A total of 1431 individuals lived in these households. General characteristics of the households were obtained using semi-structured questionnaires. These characteristics included personal information of the individual members of the households such as age, sex, literacy level and occupation. Also, information related to households' ownership of certain items, room occupancy, access to water and sanitation facilities, and sludge treatment practices were collected. In addition to the general household characteristics, an observational survey was conducted in each household using open-ended questionnaire. In this survey, information on food preparation and storage, water collection and storage, presence of pets and animals in the household compound, garbage and/or faeces in the household compound, soap for handwashing, characteristics of the floors of sleeping rooms, among others, were observed and documented. The characteristics of a particular household were assigned to individuals in that household.

In addition to the household characteristics, pre-coded diarrhoeal incidence questionnaire was used to record diarrhoeal episodes on individuals in the households on a bi-weekly basis from February 2008 to March 2009 until after their withdrawal. Additional information on diarrhoeal episodes with respect to duration and characteristics (e.g. watery or bloody) was collected. In this study, an episode of diarrhoea was defined as three or more loose (or watery) stools within 24 hours, regardless of other gastro-intestinal symptoms (Baqui *et al.* 1991), and without the influence of a purgative (or medication). Two independent episodes were separated by at least 3 diarrhoeal-free days (Baqui *et al.* 1991). An episode of diarrhoea lasting 14 days or more was classified as persistent (WHO, 1988). The diarrhoeal episodes for infants and children were collected from their mothers.

All data were collected by trained fieldworkers. Prior to the data collection, a written purpose of the study was read in the local language to all the household heads and informed consent was obtained from them. The study instruments and methods were also reviewed and approved by the University for Development Studies Ethics Committee.

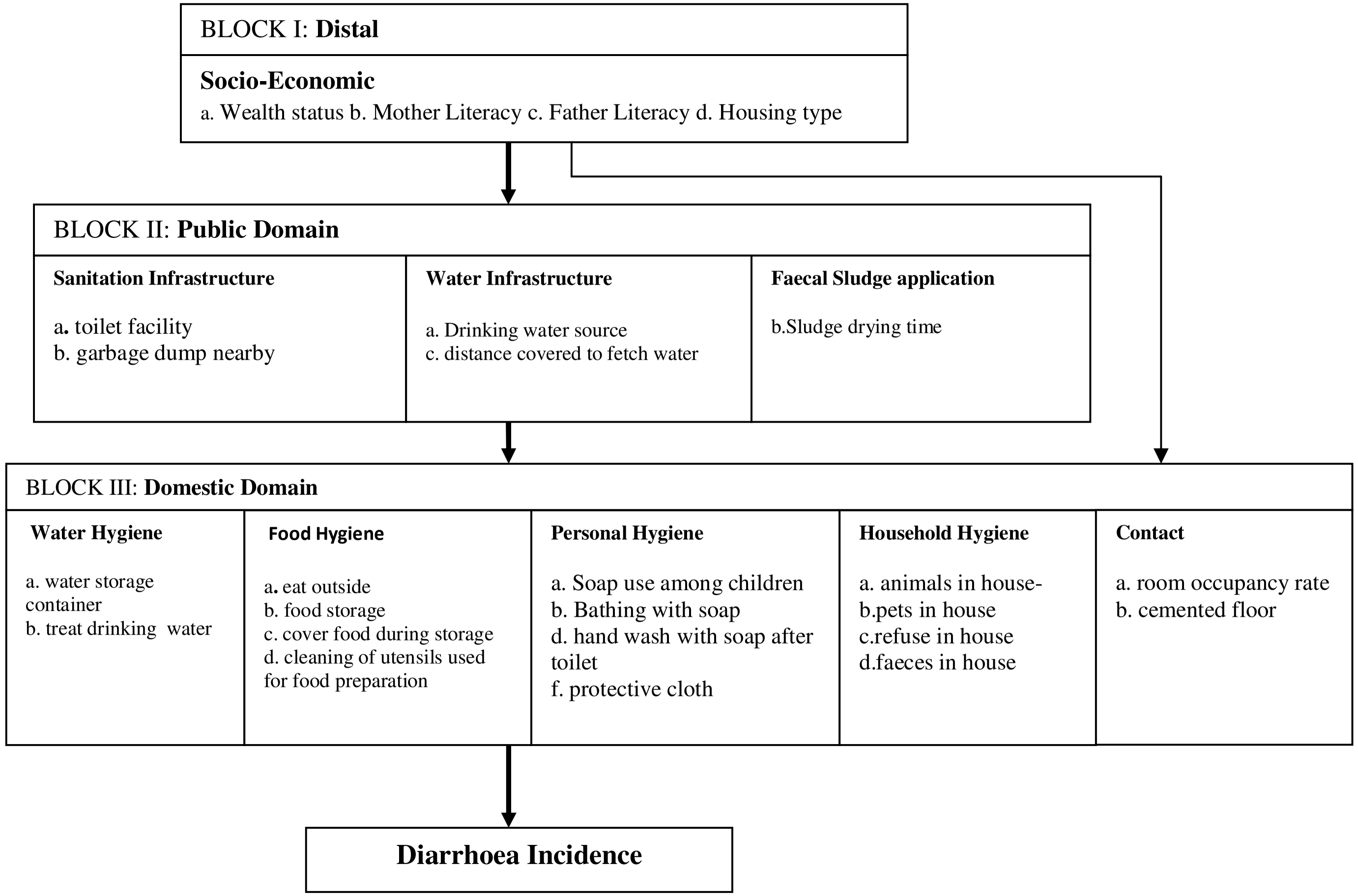
Conceptual Framework and Statistical Analysis

Statistical analysis was undertaken based on the conceptual framework presented in Figure 1. The framework specifies the general hypothesis underpinning how diarrhoeal risk factors in sludge households are grouped into blocks, the inter-relationships existing between these blocks and the pathway these variables affect diarrhoeal disease incidence. This framework is similar to others applied in Brazil to assess risk factors of childhood diarrhoeal disease incidence (Barreto *et al.* 2007; Genser *et al.* 2008 and Ferrer *et al.* 2008). In this study, diarrhoeal disease risk factors in the sludge households were broadly grouped into distal and proximal. The proximal risk factors were further grouped into public and domestic domain blocks. This resulted in three inter-linked blocks of risk factors: i) distal socio-economic ii) proximal public domain; and iii) proximal domestic domain. The inter-relationship between the three blocks was informed by an extensive literature search while variable inclusion in each block was based on information gathered from the household survey.

Following the conceptual framework, a hierarchical effect decomposition approach was applied to quantify the effect of risk factors on different levels (Ditlevsen *et al.* 2005; Victoria *et al.* 2007). By this approach, we were able to disentangle the direct and indirect mediated effects of the blocks. Descriptive statistics was made to examine the distribution of the variables in each of the block. Following this, a univariate analysis was conducted on the variables to identify which ones were significantly associated with the outcome (diarrhoeal disease incidence). Significant variables from the univariate analysis ($p \leq 0.1$) were entered into an intra-block multivariate analysis and analyzed using mixed effect Poisson regression models. Diarrhoeal disease clustering in households and individuals was accounted for by random coefficients in the mixed effect Poisson models with a gamma distribution (Rabe-Hesketh and Skrondal, 2008). Variable selection in the intra- block was done using a backward stepwise selection procedure ($p \leq 0.1$). From the intra-block analysis, multivariate relative risks were obtained. All significant ($p \leq 0.1$) variables retained in the intra-block multivariate models were included in an inter-block multivariate analysis. The inter-block multivariate analysis involved a sequence of mixed effects Poisson regression models. The sequence started with model A, accounting for block I variables (distal), followed by model B, accounting for block I and block II variables (public domain) and finally model C accounting for block III (domestic domain) variables in addition to the blocks I and II variables. Further we calculated the multivariate adjusted inter-block estimates of population attributable fraction (PAF) from the relative risks (RR) of both exposed subjects and the entire study population. The PAF was estimated using the formulae: P_e (RR-1) / 1+ P_e (RR-1) where P_e is the proportion of exposed group and RR is the relative risk associated with the risk factor (Rothman and Greenland, 1998). All models were adjusted for confounding by age (0-4; 10-14; ≥15) and gender.

By comparing the effect estimate before and after adjusting for the next block in the hierarchy of the inter-block analysis an estimate of how much the effect of the block has been mediated by the block on the pathway termed the mediation proportion was obtained (Ditlevsen *et al.* 2005; Victoria *et al.* 2007). The mediation proportions (MP) were obtained from the adjusted and unadjusted multivariate population attributable fraction according to the formula: MP= (unadjusted PAF – adjusted PAF) /PAF unadjusted x 100 (Genser *et al.* 2008). All statistical analyses were conducted using STATA (version 10, STATA Corporation, College Station, TX, USA).

Figure 1: Conceptual framework of how different blocks of risk factors affect Diarrhoeal disease incidence in sludge applying households



RESULTS

Diarrhoea Incidence and Characteristics

A total of 1356 diarrhoeal episodes were recorded over 489,465 person days at risk resulting in 1.09 (95% CI: 0.78–1.23) diarrhoeal episodes per person year at risk. The distribution of the diarrhoeal disease episodes among the different age-groups revealed that children were disproportionately affected. Children aged ≤ 4 years had 2.9 (95% CI: 2.25-3.66) diarrhoeal episodes per person year at risk compared with 1.22 (95% CI: 0.92-1.52) episodes per person year for the 5-14 year age group and 0.59 (95% CI: 0.36-0.82) episodes per person year for the ≥15 age groups respectively. The mean duration of a diarrhoea episode was 3.2 days (range: 1-8 days). Ten diarrhoeal episodes were persistent and occurred mainly (60 % (n = 8)) in household members aged ≤ 14 years. Of the total diarrhoeal episodes recorded, 88 were bloody translating to 0.06 severe diarrhoeal episodes per person year at risk. About 30 % of these bloody diarrhoea episodes occurred among children in the age group of ≤ 4 years.

Diarrhoeal Disease Risk Factors

The univariate and intra-block multivariate analyses of risk factors associated with diarrhoeal disease incidence are presented in Tables 1 and 2 respectively. The univariate analysis revealed that distal factors such as wealth status, literacy of mothers and fathers and housing type were associated with diarrhoeal disease risk. Individuals from households with low wealth status were more likely (RR=1.18, 95% CI: 0.94-1.49) to develop diarrhoeal disease than those from households of high wealth status. Also individuals living in traditional housing units were slightly more likely (RR=1.10, 95% CI: 0.32-3.81) to report diarrhoeal disease than those living in modern housing units. An increased diarrhoeal disease risk was also associated with households where either the mother or father was an illiterate. In the intra-block multivariate analysis, the independent predictors of diarrhoeal disease transmission in the distal socio-economic block were wealth status and housing type.

In the public domain univariate analysis, access to community stand pipe, distance covered to collect water and access to communal toilet facility were all significantly associated with diarrhoeal disease incidence ($p \leq 0.1$). Individuals from households whose source of drinking water was unprotected dug-out ponds were more likely to develop diarrhoeal disease (RR=1.66, 95% CI: 1.39-1.98) than those drinking from a community stand pipe. Members of households covering ≥ 500m to collect water were more likely (RR=1.63, 95% CI: 1.43-1.85) to develop diarrhoeal disease than those covering a lesser distance to collect water. Individuals from sludge applying households with no access to a communal KVIP latrine and practiced open defaecation were also more likely to report diarrhoeal disease. Also different sludge drying times practiced in the fields were associated with diarrhoeal disease incidence. In the intra-block multivariate analysis of the public domain risk factors, the only factors that remained significantly associated with diarrhoeal disease risk ($p \leq 0.1$) were distance covered to collect water, faecal sludge drying times and access to communal stand pipe.

In the domestic domain block of risk factors, drinking untreated water was significantly associated with diarrhoeal disease risk. Also, not washing hands with soap after toilet was strongly associated with diarrhoeal disease risk. The diarrhoeal disease risks were also high for individuals who ate food prepared outside the home environment and those who did not cover left-over food. Keeping pets and animals in the household compound also increased diarrhoeal disease risk. Also, the presence of faeces and garbage in a household compound was strongly associated with diarrhoeal disease risk. Individuals from households where members engaged in sludge application and had no protective clothes (e.g. gloves, nose-masks, boots etc) had slightly increased risk of diarrhoea (RR=1.05, 95% CI: 0.83-1.34). Sleeping on un-cemented floors was also associated with increased diarrhoeal disease risk (RR=1.14, 95% CI: 0.85-1.51) and so was living in a crowded room. In the intra-block multivariate analysis, the independent predictors of diarrhoeal disease outcome of the domestic domain were drinking untreated water, keeping pets and not washing hands with soap after defaecation.

Important Risk Factors and Mediation Proportions

Based on the population attributable fractions (PAFs) derived in the inter-block mixed effect Poisson models, the public domain block (including sludge drying times) was the most important determinant of diarrhoeal disease transmission in the sludge households (Table 3). This was followed by the domestic domain and distal socio-economic blocks respectively. The combined population attributable fractions (PAFs) of the public domain block was 24% accounted for by distance covered to water sources (18%) and sludge drying times (6%). Not washing hands with soap after toilet (PAF=18%) was the main risk factor in the domestic domain. In the distal socio-economic domain, the main risk factor was the wealth status of the households (PAF=15%). The foregoing PAFs on specific risk factor indicate that the sludge application related risk factor was the least important in the transmission of diarrhoeal disease in the sludge households. Analysis of the inter-relationships of the different blocks showed that 86% of the PAF of the socio-economic block was mediated; 33% by the public domain block and 53% by the domestic domain block. Also, 17% of the PAF of the public domain block was mediated by the domestic domain block. Altogether, the domestic domain block alone mediated 70% of the PAFs attributed to diarrhoeal disease incidence in the sludge households.

DISCUSSION

To our knowledge this is the first study assessing diarrhoeal disease incidence in households applying faecal sludge. Thus, the findings made here have been compared with those reported in wastewater irrigation studies. Generally, children from our sludge households were more likely to develop diarrhoeal disease than those from households using untreated wastewater for irrigation in Vietnam (Hein *et al.* 2007). Also, adults from our sludge households had an increased diarrhoeal disease risk than those engaged in untreated wastewater irrigation in Vietnam and Mexico (Trang *et al.* 2007; Blumenthal *et al.* 2001). However, as shown in this study, the diarrhoeal disease incidence in the sludge households was mainly accounted for by non-sludge related risk factors. Based on the estimated PAFs, sludge application related risk factors contributed only 6% of the diarrhoeal disease incidence in the sludge applying households. This is low, compared with the PAFs of diarrhoeal disease incidence associated with exposure to untreated wastewater in Mexico (PAF=17-35%) and Vietnam (PAF=35%) (Blumenthal *et al.* 2001; Trang *et al.* 2007).

Consistent with findings from wastewater irrigation studies, children in the sludge households not directly engaged in sludge handling were more likely to develop diarrhoeal disease than the adult members of the households. It can therefore be hypothesized that the effect of sludge application in the transmission of diarrhoeal disease within the sludge households was more indirect than direct. From a farm observation survey, farmers engaged in sludge handling rarely used protective clothes (Seidu *et al.* 2010a); and thus were more likely to transfer pathogens from the farm domain (public) to the domestic domain. Even where protective clothes such as gloves were in use, the likelihood of pathogens transfer from the farm to the home environment remained high. In a cross-over experiment among 20 farmers from the sludge applying households, significant contamination of the fingers of farmers using gloves during sludge handling was found (Seidu *et al.* 2010b). In many instances, the *E. coli* levels recovered from the fingers of farmers using gloves was of the same magnitude as those not using gloves. From the same study, it was found that farmers had no water and soap for washing contaminated clothes after sludge handling. Instead, the contaminated clothes were sent to the home where mothers and girls taking care of babies were responsible for washing them. These mothers and girls were thus more likely to transfer pathogens to children of the households.

A major strength of this study is the application of a hierarchical effect decomposition model to disentangle the effects and mediation proportions of risk factors associated with diarrhoeal disease transmission in sludge applying households. By developing a conceptual framework to describe the inter-relationship of different risk factors, we were able to disentangle the effect of the different blocks of risk factors as well as their mediation proportions on the pathway to diarrhoeal disease transmission. Thus, even though the public domain block of risk factors appeared to be the most important in terms of PAFs, about 17 % of its effect in diarrheal disease transmission was mediated by domestic domain factors. Similarly, 53% of the distal socio-economic factors were mediated by the domestic domain block. By applying a single multivariate model, these mediation proportions would not have been identified, and thus could have led to a distorted prioritization of interventions for diarrhoeal disease mitigation in the sludge households.

The importance of the domestic domain block as exemplified here by its mediation effect is in line with findings made in several studies (Curtis *et al.* 2000; Genser *et al.* 2008). In this study, poor domestic domain hygiene practice that predisposed individuals to diarrhoeal disease was not washing hands with soap after toilet. Studies have shown that hygiene interventions are effective in reducing diarrhoeal incidence, particularly if they are centered on hand washing (Khan, 1982; Han and Hliang, 1989; Wilson *et al.* 1991; Curtis and Cairncross, 2003). A meta-analysis of several epidemiological studies revealed that focused hand-washing interventions may be more effective than hygiene education measures (Fewtrell *et al.* 2005). Indeed, diarrhoeal disease reduction efficacies ranging from 30% to 89% have been attributed to hand washing with soap (Khan, 1982; Han and Hliang, 1989; Wilson *et al.* 1991).

From the foregoing, it can be concluded that no single intervention would be sufficient in mitigating diarrhoeal disease transmission in sludge applying households. A multi-barrier risk management framework targeting public and domestic domain risk factors is thus recommended. This is more so, as children found mainly in the domestic domain environment and not directly engaged in sludge application are disproportionately affected by the diarrhoeal disease burden in the households. For example, in the public domain, longer sludge drying times prior to sludge handling can significantly reduce the transfer of pathogens to the domestic domain. In the domestic domain, personal hygiene practices such as hand washing with soap can also serve as an effective barrier against diarrhoeal disease transmission. However, effective handwashing can only be achieved if it is supported by adequate water provision within a reasonable distance. This is because hygiene practices such as hand washing is grossly affected where households have to cover longer distances to collect water. In one study, handwashing among mothers was substantially reduced in households that had to cover more than 1km to collect water (Cairncross *et al.* 1997). This also partly supports the finding made in this study where individuals living in households that covered more than 500 m to collect water were more likely to report diarrhoeal disease.

This study has some limitations that need to be stressed. To start with, the study did not account for some important risk factors implicated for diarrhoeal disease transmission. For instance, the study did not account for malnutrition, which is an important risk factor of diarrhoeal disease incidence among children in developing countries (Trang *et al.* 2007; Genser *et al.* 2008). Furthermore, no microbial analysis was carried out on the potential agents of the diarrhoeal diseases reported in this study. Studies in Northern Ghana have identified viral infections especially rotavirus as the main cause of diarrhoea among children (Armah *et al.* 2001; Armah *et al.* 2003; Binka *et al.* 2003; Reither *et al.* 2007). In a Vietnam study, rotavirus was also identified as the main cause of diarrhoea among pre-school children from households using untreated wastewater in agriculture and aquaculture (Hein *et al.* 2007). However, among adults engaged in wastewater fed agriculture and aquaculture in Vietnam, pathogenic gastro-enteric bacteria (mainly diarrhoeagenic *E.coli*) were the most common cause of diarrhoea (Trang *et al.* 2007). Furthermore, the bi-weekly visits employed in our longitudinal study could have resulted in an underestimation of the reported diarrhoeal episodes. A comparative analysis of longitudinal diarrhoeal disease studies revealed that more episodes were likely to be recorded in studies involving more frequent visits than those with less frequent visits (Bern *et al.* 1992). The hierarchical effect decomposition model used in this study is also without limitations. In this approach estimates of the direct effects can only be obtained when there is no confounding at the level of the intermediate variable (Robins and Greenland, 1992). In our conceptual framework efforts were made to consider and group all risk factors into meaningful blocks. Thus, it was unlikely that other unobserved factors are associated with both an intermediate block and diarrhoeal disease incidence.

CONCLUSIONS

In this study, a hierarchical effect decomposition model was implemented to disentangle and assess the effect of risk factors associated with diarrhoeal disease incidence in households applying faecal sludge in the Tamale Metropolis of Northern Ghana. The risk factors were assigned to three inter-related blocks: distal socio-economic, proximal public domain and proximal domestic domain. Following are the main conclusions of the study:

i. Children living in sludge households not directly engaged in sludge application accounted for the greatest burden of diarrhoeal disease in frequency and severity.

ii. The most important determinant of diarrhoeal disease transmission was the proximal public domain block followed respectively by the domestic and distal socio-economic blocks. Faecal sludge related risk factors contributed the least to diarrhoeal disease transmission in the sludge households;

iii. A substantial proportion (70%) of the combined effect of the public domain and distal blocks were mediated by the domestic domain block;

iv. An integrated multi-barrier risk management strategy is recommended for mitigating diarrhoeal disease transmission in the faecal sludge applying households.

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Table 1: Univariate analyses of Potential Risk Factors Associated with Diarrhoeal Disease in Sludge Households in the Tamale Metropolitan Area, Ghana (N=1341)

	N(%)	RR (95% CI)[xx]	P
BLOCK I: DISTAL FACTORS			
Literate mother			
No	99	1.10 (0.32 – 3.81)	0.069
Yes	1	1	
Literate father			
Yes	8	0.87(0.64 – 1.19)	0.386
No	92		
Housing Type[a]			
Traditional	44	1.10 (0.89 – 1.25)	0.487
Modern	56	1	
Wealth status			
Low	18	1	
Average	30	1.19 (0.92 – 1.53)	0.175
High	52	1.18 (0.94 – 1.49)	0.144
BLOCK II: PUBLIC DOMAIN			
Community standpipe pipe			
No	67	1.66 (1.39 – 1.98)	0.000
Yes	33	1	
Distance covered to fetch water			
≥ 500 m	48	1.63 (1.43 – 1.85)	0.000
≤ 500 m	52	1	
Communal ventilated improved pit latrine			
No	67	1.67 (1.39 – 2.00)	0.000
Yes	33	1	
Faecal Sludge Application			
≤14	47	1	
21 – 30	21	1.14 (1.10 - 2.01)	0.727
60	12	1.21 (1.12 – 1.98)	0.523
≥ 90	20	1.31 (1.05 – 1.62)	0.014

[a] Traditional houses are built with mud and have thatch roofs. Modern houses are those built with cement blocks and with corrugated iron roofing sheets.

[xx] Relative risk in the univariate Poisson mixed effect models were adjusted for age groups 0 – 4; 5 – 14; and ≥ 15 and gender

Table 1 cont: Univariate analyses of Potential Risk Factors Associated with Diarrhoeal Disease in Sludge Households in the Tamale Metropolitan Area, Ghana (N=1341)

	N (%)	RR (95% CI)[xx]	P
BLOCK IV: DOMESTIC DOMAIN			
Treat Drinking Water			
No	32	1.29 (1.09 – 1.52)	0.002
Yes	68	1	
Handwashing with soap			
No	51	1.27(1.08 – 1.50)	0.004
Yes	49	1	
Eat food prepared outside the home			
Yes	96	1.65 (1.04 – 2.61)	0.032
No	4	1	
Leftover food covered			
Yes	85	1.25 (1.00 – 1.57)	0.048
No	15	1	
Clean utensils after eating			
Next morning	34	0.94 (0.78 – 1.11)	0.464
Immediately after eating	66	1	
Household has pet			
Yes	63	1.27 (1.07 – 1.51)	0.006
No	37	1	
Household keep animals in compound			
Yes	73	1.24 (1.03 – 1.50)	0.023
No	27	1	
Garbage in household compound			
Yes	47	1.27 (1.07 – 1.52)	0.008
No,,	53	1	
Faeces in household compound			
Yes	56	1.20 (1.02 – 1.42)	0.030
No	44	1	
Ownership of at least one protective clothing			
No	84	1.05 (0.83 – 1.34)	0.671
Yes	16	1	
Cemented Floor			
No	9	1.14 (0.85 – 1.51)	0.361
Yes	91	1	
Room occupancy[§]			
1-2	76	0.85 (0.70 – 1.04)	0.129
3-4	24	1	

[xx] Relative risk adjusted for age groups 0 – 4; 5 – 14; and ≥ 15 and gender

[§] Room occupancy rate is based on floor area of rooms

Table 2: Multivariate Intra-block analyses of Potential Risk Factors Associated with Diarrhoeal Disease in Sludge Households in the Tamale Metropolitan Area, Ghana (N=1341)

	N (%)	RR (95% CI)[xx]
BLOCK I: DISTAL FACTORS		
Wealth status		
Low	18	1
Average	30	**1.19 (0.93 – 1.54)**
High	52	**1.20 (0.94 – 1.53)**
Housing Type [a]		
Traditional	44	1.08 (0.92 – 1.29)
Modern	56	1
BLOCK II: PUBLIC DOMAIN		
Community standpipe pipe		
No	67	**1.69 (0.62 – 4.64)**
Yes	33	1
Distance covered to fetch water		
≥ 500 m	48	**1.54 (1.32 – 1.80)**
≤ 500 m	52	**1**
Faecal Sludge Application		
≤14	47	1
21 – 30	21	1.04 (0.69 - 2.01)
60	12	1.19 (0.72 – 1.98)
≥ 90	20	**1.28 (1.04 – 1.59)**
BLOCK III: DOMESTIC DOMAIN		
Treat water		
No	32	**1.20 (1.02 – 1.42)**
Yes	68	1
Pets in the house		
Yes	63	**1.15 (0.97 – 1.38)**
No	37	1
Handwashing with soap after toilet		
No	51	**1.22 (1.03 – 1.44)**
Yes	49	1

Significant factors are in bold.

[a] Traditional houses are built with mud and have thatch roofs. Modern houses are those built with cement blocks and with corrugated iron roofing sheets.

[xx] Relative risk in the univariate Poisson mixed effect models were adjusted for age groups 0 – 4; 5 – 14; and ≥ 15 and gender

Table 3: Population Attributable Fractions of Diarrhoeal Disease for blocks of Risk Factors based on reduced Inter-block Mixed Effect Poisson Regression Models (N=1431)

	N (%)	RR (95% CI)[xx]	PAF	PAFT[b]
BLOCK I: DISTAL FACTORS				15
Wealth status				
Low	18	1		
Average	30	**1.19 (0.92 – 1.53)**	**6**	
High	52	**1.18 (0.94 – 1.49)**	**9**	
BLOCK II: PUBLIC DOMAIN				
Distance covered to fetch water				**24**
≥ 500 m	48	**1.63 (1.43 – 1.85)**	**18**	
≤ 500 m	52	**1**		
Faecal Sludge Application				
≤14	47	1		
21 – 30	21	1.04 (0.69 - 2.01)		
60	12	1.19 (0.72 – 1.98)	-	
≥ 90	20	**1.28 (1.04 – 1.59)**	**6**	
BLOCK III: DOMESTIC DOMAIN				**18**
Handwashing with soap after toilet				
No	51	**1.36 (1.13 – 1.65)**	**18**	
Yes	49	1		

[b] sum of PAFs of significant variables

[xx] Relative risk in the univariate Poisson mixed effect models were adjusted for age groups

0 – 4; 5 – 14; and ≥ 15 and gender

Model A: Distal socio-economic factors only

Model B: Distal socio-economic block and public domain block

Model C: Distal socio-economic block, public domain block and domestic domain block