A CONCEPTUAL MODEL OF PATHOGEN-SPECIFIC HAZARDS IN PIT LATRINES OVER TIME

Lisa L. Fleming

A thesis submitted to the faculty of the University of North Carolina at Chapel Hill in partial fulfillment of the requirements for the degree of Master of Science in the Department of Environmental Science and Engineering in the Gillings School of Global Public Health.

Chapel Hill
2017

Approved by:

Peter Kolsky

Jill Stewart

Barbara Evans

ABSTRACT

Lisa L. Fleming: A Conceptual Model of Pathogen-Specific Hazards in Pit Latrines Over Time

(Under the direction of Peter J. Kolsky)

A conceptual model of pathogen-specific hazards in pit latrines over time is presented. The development, limitations, and results of an illustrative application of the model are reviewed. Literature reviews were conducted to determine the required model inputs of each reference pathogen included in the illustrative application. Findings of the reviews are included. Results of the illustrative model application indicate hazard reaches a steady-state equilibrium and the majority of cumulative hazard for a two-year latrine use period is contributed in the most recent month. As a result of these behavioral trends, we found manipulating pit emptying frequency (or pit fill rates) and utilizing double pit technology could have large impacts on the relative hazard posed by a community's pit latrine waste stream. Our model also provides evidence that unless sewerage with wastewater treatment is of relatively high quality, it may be no more effective than properly managed pit latrines at reducing pathogens.

ACKNOWLEDGEMENTS

First and foremost I want to thank my advisor, Pete Kolsky. It has been an honor to be one of his M.S students. His deep love and enthusiasm for the field of sanitation was contagious and motivational for me, particularly during the tough times in my M.S pursuit. I sincerely appreciate all of his contributions of time, ideas, patience and thought-provoking questions that made my graduate school experience stimulating and deeply fulfilling.

My fellow Water Institute colleagues have contributed immensely to my personal and professional time at the University of North Carolina. The group has been a source friendship as well as invaluable advice. I am especially grateful for Allison Fechter, David Holcomb, and Lauren Joca who offered to read over multiple drafts of this thesis and share ideas over coffee.

I would like to thank my defense committee, Jill Stewart (UNC) and Barbara Evans (Univ. Leeds), for their time, interest, and insightful questions. I would also like to thank Jaime Bartram for sharing his professional insight and encouraging me to think about the bigger picture. Their comments challenged me to think deeper about my thesis.

I gratefully acknowledge the funding source, the Bill & Melinda Gates Foundation, that made my Masters work possible.

Lastly, I would like to thank my family for all their love and encouragement. In particular, I would like to thank my mom for raising me with a love of science and supporting me in all my pursuits.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF EQUATIONS

LIST OF ABBREVIATIONS

DALYs	Disability-adjusted life years
EPA	Environmental Protection Agency (USA)
GBD	Global Burden of Disease
ID50	Infectious Dose (Median)
IQR	Interquartile Range
JMP	Joint Monitoring Programme
NOx	Nitrogen Oxide
OD	Open Defecation
PM2.5	Fine particulate matter (2.5 microns)
QMRA	Quantitative Microbial Risk Assessment
RP	Reference Pathogen
SFD	Shit Flow Diagram
SPP	Several Species
UNICEF	United Nations Children's Fund
WaSH	Water, Sanitation, and Hygiene
WHO	World Health Organization
WW	Wastewater

CHAPTER 1: INTRODUCTION

Sanitation remains a major public health concern with an estimated 2.3 billion people still lacking access to basic sanitation services, and among them nearly 900 million people still practicing open defecation [UNICEF & WHO, 2013]. The failure to effectively contain and manage human excreta is associated with a wide range of health problems and a large disease burden [Bartram et al., 2010; Pruss-Ustun et al., 2008; Boschi-Pinto et al., 2009]. Recent systematic reviews have suggested that improvements in sanitation can be effective in reducing a range of important health outcomes, including diarrheal disease [Waddington et al., 2009; Carincross et al., 2010; Clasen et al., 2010; Fewtrell et al., 2005] and soil-transmitted helminth infections [Ziegelbauer et al., 2012].

While sanitation planners and engineers have promoted improved sanitation for public health benefit, they do not currently have a clear method for assessing the relative threat of different sanitation problems arising from various interventions [Kolsky et al., 2015]. This is largely because of the vast diversity among disease-causing agents (pathogens), environmental conditions, human exposure routes, and a limited understanding of the relative public health hazard posed by different sanitation technologies [Feachem et al., 1983].

Pit latrines are the main form of sanitation for many low and middle income countries [UNICEF & WHO 2013; Graham et al., 2013], and the primary focus of many sanitation interventions [Waddington et al., 2009; Fewtrell et al., 2005]. Numerous studies suggest they will reduce morbidity from fecally-related diseases [Clasen et al., 2010; Carincross et al., 2010], but the behavior (e.g. accumulation and subsequent decay) of fecal pathogens in pit latrines is still not well understood [Williams et al., 2015; Schonning et al., 2004; Feachem et al., 1983]. The public health impact of pit latrines will vary significantly depending upon the natural history of the pathogens present in excreta. Because of natural die-off of pathogens, wastes stored in isolation for two years in a pit latrine pose less threat to public health than fresh waste deposited by open defecation or untreated sewerage [Feachem et al., 1983].

Unless planners understand and account for these variations in pathogen hazards, the public health impact of sanitation interventions cannot be maximized.

Recent efforts have resulted in the Shit Flow Diagram (SFD), a powerful tool to help engineers, planners, and policy makers assess which sanitation services are "safe" and "unsafely" managed [Fernandez-Martines et al., 2016; Blackett et al., 2016; SFD Promotion Initiative, 2015]. However, currently the SFD does not weight unsafe waste flows by the relative threats each poses to human health; some contain many more viable pathogens (hazards) than others (see 'A Note About Hazard' below for more information) [JMP 2015; SFD Promotion Initiative, 2015]. As a result, all on-site sanitation waste, once removed from containment is considered "unsafe" unless it undergoes additional treatment [Fernandez-Martines et al., 2016; Joint Monitoring Program et al., 2015]. A method to account for the reduction of disease-causing organisms in pit latrines during storage is needed to aid in prioritizing sanitation interventions that will maximize public health benefits.

This paper presents the development (Section 2), limitations (Section 5), and results of an illustrative application (Section 6) of a conceptual model of pathogen-specific hazards in pit latrines over time. The model explicitly represents the accumulation and subsequent decay of pathogens in pit latrines under daily use conditions. We model the pit latrine waste stream for a community, where pathogens are added via daily excreta loading events and are lost through pathogen die-off; this preliminary version of the model does not account for leakage from or overflow of the pit. To illustrate the kinds of results the model can produce we apply it to a case study of a 5,000 person population infected with five reference pathogens[1] (Rotavirus, *Shigella* spp., *Cryptosporidium* spp., Ascaris, and *E. coli* spp.). A comprehensive literature review (Section 4) determined best estimates of the specific model parameters such as the pathogen-specific decay rates in the absence of treatment. Because of their critical importance in the model, a sensitivity analysis (Section 6) of decay rates was performed. Our model provides a method to estimate the viable pathogens in pit latrines and quantify the potential disease burden they pose to a

[1] A select number of pathogens are included in the model; each is referred to as a reference pathogen (RP) (see Section 2).

given community. This technically simple conceptual model provides a tool to aid planners in understanding and accounting for variations in hazards in pit latrines under different operating conditions, and provides the foundations of a framework to allow for comparison of pit latrines to other sanitation technologies from a public health perspective.

A Note About Hazard & Hazard Assessments

Hazard in this paper refers to pathogens present in human excreta which can harm human health and it is quantified in potential disability-adjusted life years (defined here as "Meta-DALYs", derived from DALY estimates of *actual* burden of disease, measured in DALYs.[2]). "Hazard" and "risk" are two terms that are often used interchangeably in everyday language [Young et al., 1990], but in public health literature they have two distinct definitions [Mitchell et al., 2016; Barlow et al., 2015]. Hazard is broadly defined as anything that can cause harm (e.g. a chemical, electricity, ladders, etc.) and risk is the probability someone will be harmed by a specified hazard [Ropeik et al., 2002]. In particular, fecal contamination risk results from a combination of pathogen hazards and an exposure pathway [WHO, 2016]. It is important to note that the model introduced in this paper does not examine exposure and therefore does not quantify risk. Our model quantifies the potential public health threat posed by pathogens in pit latrine sludge. The details of our method for quantifying the hazard is the basis of the model presented in this paper.

Hazard identification is cited as one of the first steps required for a quantitative microbial risk assessment (QMRA) [WHO 2016a] to define the scope. However, hazard identification is largely a qualitative process in QMRAs to identify microorganisms of concern [WHO 2016a]. The authors have not seen a quantitative pathogen hazard assessment of on-site sanitation described in water, sanitation, and hygiene literature. While risk assessments are valuable tools, they are typically very involved and in particular for sanitation the exposure routes may be too numerous [WHO 2016a; EPA, 2010]. The quantitative pit latrine hazard model we introduce here is a part of a larger quantitative sanitation hazard

[2] Based on GBD 2015 estimations of Disability-adjusted life years (DALYs).

assessment model being developed. Assessing the hazard provides an opportunity for planners to identify which sanitation problems are the worst sources of pathogen "pollution", and act accordingly. But it does not allow estimation of the probability of infection attributed to each source based on different associated routes of exposure (i.e. risk). This is similar to identifying which sources emit the greatest quantities of air pollutants (e.g. NOx, PM2.5), a public health hazard [Arden Pope et al., 2006; WHO 2016b] in order to reduce total pollution emissions. As opposed to trying to estimate the risk of a range of pulmonary diseases through different exposure routes in a population [WHO 2016b]; while helpful, determining risk is a decidedly more difficult task [WHO 2016b]. Hazard assessments may provide a helpful method for conducting a large-scale assessment to identify and compare which sanitation problems are the greatest emitters of pathogen "pollution

CHAPTER 2: MODELING OBJECTIVES & APPROACH

No model solves all problems. And most models, like many experts, provide only imperfect answers. The conceptual pit latrine hazard model we introduce here is intended to help with the following activities in the context of a low or middle income country:

- Estimate the number of viable pathogens in a given community's[3] pit latrine waste stream;
- Quantify the potential disease burden the viable pathogens might inflict on the given community;
- Demonstrate how pathogen hazard may behave over time in pit latrines under daily use conditions;
- From the pathogen behavior, determine if any pit latrine management options can effectively reduce pit latrine hazard;
- Identify which fecal pathogens pose the greatest public health threat, for a given community
- Derive an estimate of pit latrine hazard that may be used in sanitation hazard assessments, for a given community.

Our pit latrine hazard model provides a rational application of pathogen decay in simple onsite sanitation. It demonstrates the potential feasibility of assessing the public health significance of pit latrines by tracking pathogens and the potential feasibility of performing comparative hazard assessments with different sanitation technologies and management options. Finally, our model demonstrates the potential of natural die-off and storage in pit latrines to maximize public health benefits from sanitation.

To the author's knowledge, our model is the first to explicitly represent pathogen hazards and their relative accumulation and decay in pit latrines over time. The general approach (see Figure 1 for summary of model) is to determine the viable pathogen count in a community's pit latrine waste stream,

[3] We apply our model to an illustrative case study to further demonstrate these objectives.

using a constant pathogen loading rate and a constant species-specific rate of exponential pathogen decay. Given the viable pathogen count, we determined the total potential number cases (i.e. infectious doses) and finally the resulting potential disease burden of a given community's pit latrine waste stream. Our estimate of potential disease burden (Meta-DALYs) is meant to provide an estimate of cumulative public health hazard, and will hopefully be used as a comparable metric to help determine which sanitation problems are the worst "polluters" in future hazard assessments. Note that we do not propose Meta-DALYs as a predictive tool of disease prevalence, but rather as a better indicator pf the public health threat of a waste stream than any other currently used waste stream parameter.

Our model is comprised of six components (summarized in Figure 1 and described in detail below). The first five components represent a five-step sequence that needs to be repeated for each reference pathogen species being modeled. The final component is the summation of the potential disease burdens attributable to each reference pathogen species. Microsoft Office Excel © software was used to manage the model data and perform the hazard analysis described in this paper.

2.1 List of Assumptions and Model Parameters

- *Reference pathogens*: A select number of pathogens are included in the model; each is referred to as a reference pathogen (RP). While our model is able to handle a large number of pathogen species, it is not likely a sanitation planner or engineer will have relevant information on all fecal-related disease causing agents, nor that they are all of major public health significance.
- *Viable pathogens introduced daily*: To simulate pit latrines in use, a fixed number of RPs are introduced daily[4, 5].
- *Steady-state inputs*: The daily loading rate for each reference pathogen is constant.

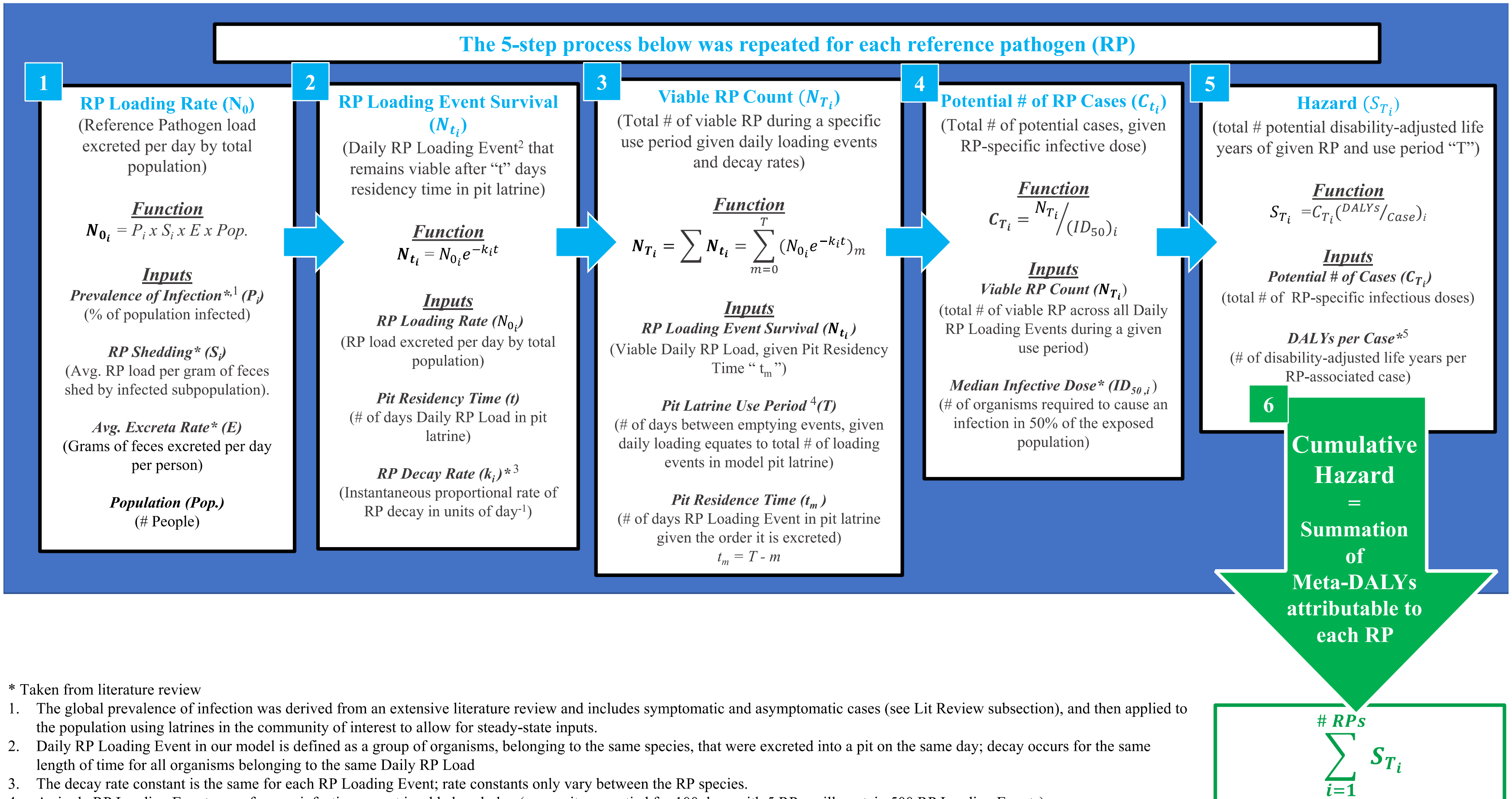
[4] Pathogen load= the daily load (number) of pathogens introduced each day in normal use.

[5] Reference pathogen loading event is defined as a group of organisms, belonging to the same species, that were excreted into a pit on the same day. A single loading event per reference pathogen is introduced each day.

- *Hazard was assessed on a community-scale*: Each RP loading rate was quantified for total number of people using pit latrines in the community of interest, thus allowing us to average endemic infections, and assume a steady-state of inputs (e.g. constant daily loading rate) more reasonable[6].
- *No leakage or overflow of pit latrine occurs*: No pathogens lost through another route; pathogens only removed from pit latrine through pathogen die-off.
- *Pathogen die-off is modeled by exponential first-order decay functions* $(\mathrm{N}_{t_i} = \mathrm{N}_{0_i}\mathrm{e}^{-\mathrm{k}_i \mathrm{t}})$
- *No interaction between reference pathogens*
- *Determinants of Die*-off[7]: Decay rate "k_i", pit residency time or time passed since the RP loading event was excreted "t", and the initial concentration of pathogens, which is equivalent to the daily RP loading rate (N_{0_i}).
- *Decay rates "k_i" constant across all cohorts comprised of same pathogen species*: Decay rates only vary between different pathogen species.

[6] For a single pit latrine, the users will recover from an infection relatively quickly and pathogen shedding will stop. However, if we consider an entire community, once one individual recovers from an infection another individual may develop the same infection and the pathogen load remains constant over time.

Figure 1. Flow diagram of the pit latrine hazard model.



* Taken from literature review

1. The global prevalence of infection was derived from an extensive literature review and includes symptomatic and asymptomatic cases (see Lit Review subsection), and then applied to the population using latrines in the community of interest to allow for steady-state inputs.
2. Daily RP Loading Event in our model is defined as a group of organisms, belonging to the same species, that were excreted into a pit on the same day; decay occurs for the same length of time for all organisms belonging to the same Daily RP Load
3. The decay rate constant is the same for each RP Loading Event; rate constants only vary between the RP species.
4. A single RP Loading Event per reference infectious agent is added each day (e.g. a pit unemptied for 100 days with 5 RPs, will contain 500 RP Loading Events)
5. A DALY is defined in the literature as a year of healthy life lost due to ill-health, disability, or death; DALYs per Case were determined from the 2015 Global Burden of Disease study

2.2 Reference Pathogen Loading Rate

$$[N_0]_i = P_i \times S_i \times E \times Pop. \quad \text{Eq. 1}$$

Equation 1 describes the first component of our model, and represents the reference pathogen loading rate for a given reference pathogen species. In Eq. 1, P_i = the prevalence of infection in the population for a given reference pathogen, or the proportion of the population that is infected at a given time; S_i = the reference pathogen shedding rate, or the number of organisms shed per gram of feces by an infected individual per day; *E* = the average fecal excretion rate, or the average grams of feces excreted per person per day; *Pop*. = the total number of people using pit latrines in the community of interest; i = specifies that this component was calculated individually for each reference pathogen. The loading rate is a per day rate; the group of organisms for a given reference pathogen excreted per day is hereafter referred to as a loading event. The reference pathogen loading rate describes inflow of pathogens into the pit for our model, it is assumed constant over time, and is the model's primary input.

The loading rate is determined for a community, rather than for a single household, to take advantage of the law of large numbers [Renze et al., 2017]. At this scale, assuming a constant daily loading rate, or steady-state inputs, is more reasonable. For example, for a single pit latrine, the users will recover from an infection relatively quickly and pathogen shedding will stop. However, if we consider an entire community, once one individual recovers from an infection another individual may develop the same infection and the pathogen loading rate remains constant over time. Finally, analyzing hazard at a community-scale, will likely be more helpful for public health officials and engineers as sanitation planning typically occurs at the district level and interventions involve multiple households.

2.3 Reference Pathogen Loading Event Survival "N_{t_i}"

$$[\boldsymbol{N_t}]_{\boldsymbol{i}} = N_{0_i} e^{-k_i t} \quad \text{Eq. 2}$$

Equation 2 describes the second component of our model, and represents the number of surviving viable pathogens from a single daily loading event $[N_t]_i$, given the length of time since the loading event was excreted into the pit "t". A loading event is defined as a group of reference pathogens, belonging to the same species, excreted into the model pit latrine on the same day. In Eq. 2, N_{0_i} = the RP loading rate, or the total number of viable organisms excreted into the model pit latrine per day by total population, it is the primary outcome variable from component 1; e = is the mathematical constant that is the base of the natural logarithm [Marsden, 1985]; k_i = the RP-specific decay rate[8] reported in days^{-1}, which is assumed constant over time and for all RP loading events; t = pit residency time, or the number of days since the loading event was excreted into the model pit; i = specifies that this component was calculated individually for each reference pathogen.

Our reference pathogen loading event survival analysis used the first order exponential decay equation to describe inactivation kinetics [Rogers et al., 2011]. While it may oversimplify the death kinetics, the first order exponential decay equation is widely used in microbiology [Petrucci, 2007]. The only determinants of die-off (or survival) is k_i the RP-specific decay rates, the initial concentration of RP (equivalent to N_{0_i} the RP loading rate), and t the pit residence time. The authors are fully aware that environmental conditions (e.g. temperature, pH, moisture content, etc.) affect the rate of pathogen die-off. In our model the variation in these abiotic factors is captured in the decay rates k_i.

A new loading event for a given reference pathogen species is added each day. Our model is based on the principle theory that pathogen decay begins upon the moment of excretion from a human host [Feachem et al., 1983]; a loading event excreted 200 days ago is likely to have far fewer viable pathogens present compared to a loading event excreted 1 day ago. To account for the temporal nature of pathogen excretions in pit latrines and the resulting effect on pathogen survival, we analyzed the survival of each loading event individually.

We assumed no leakage or overflow occurs between emptying events. In our model pathogens are only removed from the model pit between loading events by death or pathogen inactivation,

[8] Comprehensive literature reviews (section 4) were used to determine the RP-specific decay rates for the illustrative case study.

described by Eq. 2. Additionally, we assumed no interaction occurs between reference pathogens, so no predation or replication occurs in the model pit latrine.

2.4 Viable Reference Pathogen Count " N_{T_i} "

$$[\boldsymbol{N_T}]_{\boldsymbol{i}} = [\textstyle\sum_{m=0}^{T}(N_t)_m]_i \qquad \text{Eq. 3.1}$$

$$N_{T_i} = [\textstyle\sum_{m=0}^{T}(N_t)_m]_i = \left[\sum_{m=0}^{T}\left(N_{0_i}e^{-k_i t}\right)_m\right]_i = N_{0_i}\left(\frac{1-e^{-k_i(T+1)}}{1-e^{-k_i}}\right) \qquad \text{Eq. 3.2}$$

$$t_s = T - s \qquad \text{Eq. 3.3}$$

Equation 3.1 describes the third component of our model, and represents the viable reference pathogen count $[N_{T_i}]$, given a specified pit latrine use period "*T*" (number of days between pit emptying events). The total viable pathogen count is the summation of surviving pathogens across each loading event (Eq. 3.1); "*m*" is the identifying index number for a given loading event.

When the summation of Eq. 3.1 is expanded out, it simplifies to Eq. 3.2 (see Annex for full derivation). In Eq. 3.2, N_{t_i}= the number of surviving viable pathogens from a single daily loading event; N_{0_i}= the RP loading rate, or the total number of viable organisms excreted into the model pit latrine per day by total population; *e* = is the mathematical constant that is the base of the natural logarithm [Marsden, 1985]; k_i = the RP-specific decay rate; *t* = pit residency time, or the number of days since loading event was excreted into the model pit; *T* = pit latrine use period, or the time between emptying events, given daily loading events it is also equivalent to the total number of loading events in the model pit latrine for a given RP; *i* = specifies that the third component was calculated individually for each reference pathogen.

Given that we analyzed the survival of each loading event separately (Eq. 2) and the distinguishing variable of each loading event is its pit residence time, we developed an equation for pit residence time that was dependent upon the order in which the loading event was excreted into the model pit latrine (Eq. 3.3). In Eq. 3.3, t_m = the pit residency time for a given loading event; m = is the identifying index number for each loading event and correlates with the order in which the loading event was introduced into the model pit latrine (e.g. m = 0 is the first loading event excreted into the pit latrine and m = 1 was excreted a day later and is the second loading event added); T = the pit latrine use period.

It should be noted that while T = the pit latrine use period, or number of days between pit emptying events, it can also be thought as a measure of the pit emptying frequency. And given daily loading events it is also equivalent to the total number of loading events in the model pit latrine for each reference pathogen species. For example, if T = 100, then the pit is emptied every 100 days. Additionally, if T = 100 and there are 3 reference pathogen species being modeled, there are a total of 300 loading events (100 for each reference pathogens species).

Components 1 – 3 characterize the pathogen behavior in the model pit latrine. The inflow, or pathogen flow rate, is described by component 1, and the subsequent outflow through pathogen die-off or inactivation is described by component 2. Component 3 describes the resulting total viable pathogen count for a given pit latrine use period. Components 4 – 6 are simply translations of component 3, the viable reference pathogen count.

2.5 Potential Number of Reference Pathogen Cases "C_{t_i}"

$$\boldsymbol{C_{T_i}} = \frac{[\sum N_T]_i}{[ID_{50}]_i} \qquad \text{Eq. 4}$$

Equation 4 describes the fourth component of our model, and represents the total number of potential cases, or infectious doses, present in the pit latrine sludge given a specified pit latrine use period "T". Potential cases are derived individually for each pathogen species being modeled (reference pathogen). In Eq. 4, C_i = number of potential cases, the primary outcome variable for component 4; $[\sum N_t]_i$= the viable reference pathogen count at a given specified use period, it was the primary outcome variable derived in component 3; $[ID_{50}]_i$ = the median infective dose for a given RP; *i* = specifies that this component was calculated individually for each reference pathogen. The total potential number of RP cases is simply a weighting of the viable RP count by infectivity (e.g. a translation of the viable count).

Our estimation of potential cases does not provide an estimate for actual cases that will occur as a result of the pathogens present in the pit latrine sludge. The number of pathogens required to cause an infection will not be doled out in perfect doses to a unique susceptible individual. Some people will ingest more organisms than is needed to cause an infection, others will not ingest enough, and others who ingest the organisms have already developed an immunity. Our results are meant to estimate the *total potential* cases to provide a measure of hazard, or potential public health threat.

2.6 Reference Pathogen Hazard "S_{T_i}"

$$S_{T_i} = C_{T_i} \times ({}^{DALYs}/_{Case})_i \quad \text{Eq. 5}$$

Equation 5 describes the fifth component of our model, and represents the total potential DALYs[9] (Meta-DALYs) attributed to a given reference pathogen present in the pit sludge, given a specified pit latrine use period "T". In Eq. 5 $(S_T)_i$ = the Meta-DALYs attributable to each RP for a given use period, the primary outcome variable for component 5; C_{T_i} = the total potential RP cases, the primary outcome variable from component 4; $({}^{DALYs}/_{Case})_i$ = is the DALYs per prevalent case unique to each RP. DALYs per prevalent case was based off the 2015 global DALY estimates [GBD 2015] and the global prevalent cases [GBD 2015; Fletcher et al., 2011; Walker et al., 2010; Abba et al., 2009; Huilan et al., 1991] attributable to a given RP. DALYs are a measure of disease burden and therefore reflect disease severity. The RP Meta-DALYs is simply a translation of total potential cases to account for disease severity, and thus is a weighting of the viable RP count (component 3) by infectivity and disease severity.

[9] GBD, 2015.

We introduce Meta-DALYs, a new metric in our hazard assessment model. It is a measure of potential disease burden rather than the widely used measure of observed disease burden, DALYs (GBD 2015). The Meta-DALY is the primary measure of hazard in our model.

Components 1 - 5 represent a five-step sequence which is repeated for each reference pathogen species being modeled.

2.7 Cumulative Hazard

$$Cumulative\ Hazard_T = \sum_{i=1}^{5} S_{T_i} \qquad \text{Eq. 6}$$

The final component of our model is the summation of Meta-DALYs attributable to each reference pathogen S_{T_i}, and is described by Eq. 6. The summation of RP Meta-DALYs estimates the cumulative hazard present in the population's pit sludge, given a specified pit latrine use period "T". It is the primary outcome variable for our pit latrine hazard model introduced in this paper.

Our model is the first to explicitly represent pathogen hazards and their relative accumulation and decay in pit latrines over time. While admittedly conceptual, our pit latrine hazard model can provide practical insights. By providing a full look at the "natural history" of a given waste stream, it allows planners to account for variations in hazards. It is intended to provide information that is currently unavailable or difficult to obtain through field studies [Clasen et al., 2010]. We hope that our simple formulation can be adapted and extended to solve a wide-variety of problems.

CHAPTER 3: DESCRIPTION OF SIMULATED CASE STUDY

3.1 Description of Simulated Pit Latrine Case Study Parameters

To provide an illustrative example of the model, we applied it to a simulated case study of a 5,000 person population infected with five reference pathogens. The authors chose a common fecal indicator organism and the organisms attributed with the greatest global disability-adjusted life years (DALYs) from each of the four pathogen classes [GBD 2015] - *E. coli* spp., Rotavirus, *Shigella* spp., *Cryptosporidium* spp., and Ascaris. Reference pathogen-specific decay rates in the absence of treatment and the other required model inputs were determined through comprehensive literature reviews. The methods and results of the literature reviews are described in the following section (see Section 4).

3.2 Description of Comparative Analysis of Different Waste Streams

To gain a preliminary understanding of the public health significance of pit latrines relative to other sanitation waste we included three other identical[10] populations (total of four populations), each using a different form of sanitation – 1) pit latrines; 2) open defecation; 3) sewerage with wastewater treatment that consistently removes 1-Log_{10} of all reference pathogens daily; and 4) sewerage with wastewater treatment that consistently remove 2-Log_{10} of all reference pathogens daily[11]. We estimate and compare the cumulative hazard attributable to each population's waste streams.

[10] "identical" population refers to a 5,000 person population infected with the same five reference pathogens. As a result, the reference pathogen-specific loading rates and DALYs/prevalent case is the same for each population in our case study.

[11] These removal efficiencies cover the range of secondary wastewater treatments, except high quality membranes and chemical disinfection. Additionally, these removal efficiencies do not necessarily cover primary treatment paired with chemical disinfection [Jimenez et al., 2010; Ottson et al., 2006; Williams et al., 2015].

Open defecation (OD) refers to the practice whereby people defecate in open spaces (e.g. fields, open water bodies, etc.) rather than using a toilet [UNICEF and WHO, 2013]. With open defecation, pathogen hazards are immediately released into the environment; no die-off occurs in containment prior to release. For the purposes of this analysis, we equated OD with daily emptying in our model. Due to the differences in times scales of hazard discharge between pit latrines and OD (e.g. annual vs. daily), we converted cumulative hazard to average daily hazard discharged for pit latrines, given an average use period (e.g. number of days between pit emptying events) [Eq. 7].

$$(Avg.\,Daily\ Hazard\ Discharged)_T = \frac{Cumulative\ Hazard_T}{T} \qquad \text{Eq. 7}$$

With growing public health concerns and advances in technology, recent studies have examined pathogen removal efficiencies during different types of wastewater treatment. Primary treatment reportedly removes 0 – 1Log_{10} and most secondary treatment[12] remove 0 – 2Log_{10} of the pathogen species investigated [WHO, 2006; Jimenez et al., 2010]. For the purposes of our analysis, we equated WW-treatment with 1-Log and 2-Log removal[13] efficiencies [Eq. 8; Eq. 9]. Similar to OD, there is a difference in time scales between WW-treatment and pit latrines, therefore we also used average daily hazard discharged for pit latrines, given an average use period [Eq. 8] to allow for comparison of these two hazard estimations.

$$\frac{OD\ S}{10^1} = WW\ 1Log_{10} \qquad \text{Eq. 8}$$

$$\frac{OD\ S}{10^2} = WW\ 2Log_{10} \qquad \text{Eq. 9}$$

3.3 Sensitivity Analysis

The only determinants of pathogen survival in our model are the initial concentration of pathogens (the magnitude is equivalent to the daily loading rate N_{0_i}), the pit residency time "t", and the

---

[12] These removal efficiencies cover the range of secondary wastewater treatment technologies, except high quality membranes and chemical disinfection. Additionally, these removal efficiencies do not necessarily cover primary treatment paired with chemical disinfection [Jimenez et al., 2010; Ottson et al., 2006; Williams et al., 2015].

[13] For our analysis, we assumed consistent daily 1Log_{10} and 2Log_{10} removal of all pathogens for our sewerage and wastewater treatment hazard estimations.

decay rate "k_i". The effect of variation in environmental conditions (e.g. temperature, pH, and moisture content) are well-documented to impact the rate of decay [Alum et al., 2014; Robertson et al., 1992; Atherholt et al., 1998; Jamieson et al., 2002]. To understand how the results of our simulated case study were impacted by differences in these environmental conditions we performed a sensitivity analysis using the pathogen-specific decay rates found in the systematic literature review described in the following section (Section 4). Median decay rates were used in the main analysis of the simulated case study. The interquartile range of pathogen-specific decay rates were used in the sensitivity analysis. Results of the extreme max and min decay rates are included in the Annex.

CHAPTER 4: SUMMARY OF LITERATURE REVIEWS

4.1 Pathogen Decay Rates – Systematic Literature Review

A systematic literature review was conducted to determine the rate of pathogen decay in excreta in the absence of treatment for the five reference pathogens (Rotavirus, *Shigella* spp., *Cryptosporidium* spp., Ascaris, and *E. coli* spp.) included in our model. We searched PubMed, SCOPUS, and Web of Science databases for studies that reported decay rates for at least one of the five reference pathogens in human excreta, feces, sludge, or animal manure. We included studies from peer-reviewed journals, textbooks, and grey literature published in English from any year. Many studies reported both treatment and non-treatment (control) trials; data from any non-treatment trials were included in the review and all data corresponding to treatment was excluded. Studies that examined decay in soil, on plants, in water, urine[14], or from a clarified form of the pathogen were excluded (see full list of exclusion and inclusion criteria in Table 1 below; see Figure 2 for literature review flow diagram below).

[14] The authors are aware excreta is defined as a mixture of feces and urine. Studies that examined clarified urine or urine diverted from feces was excluded, but studies that examined excreta were included.

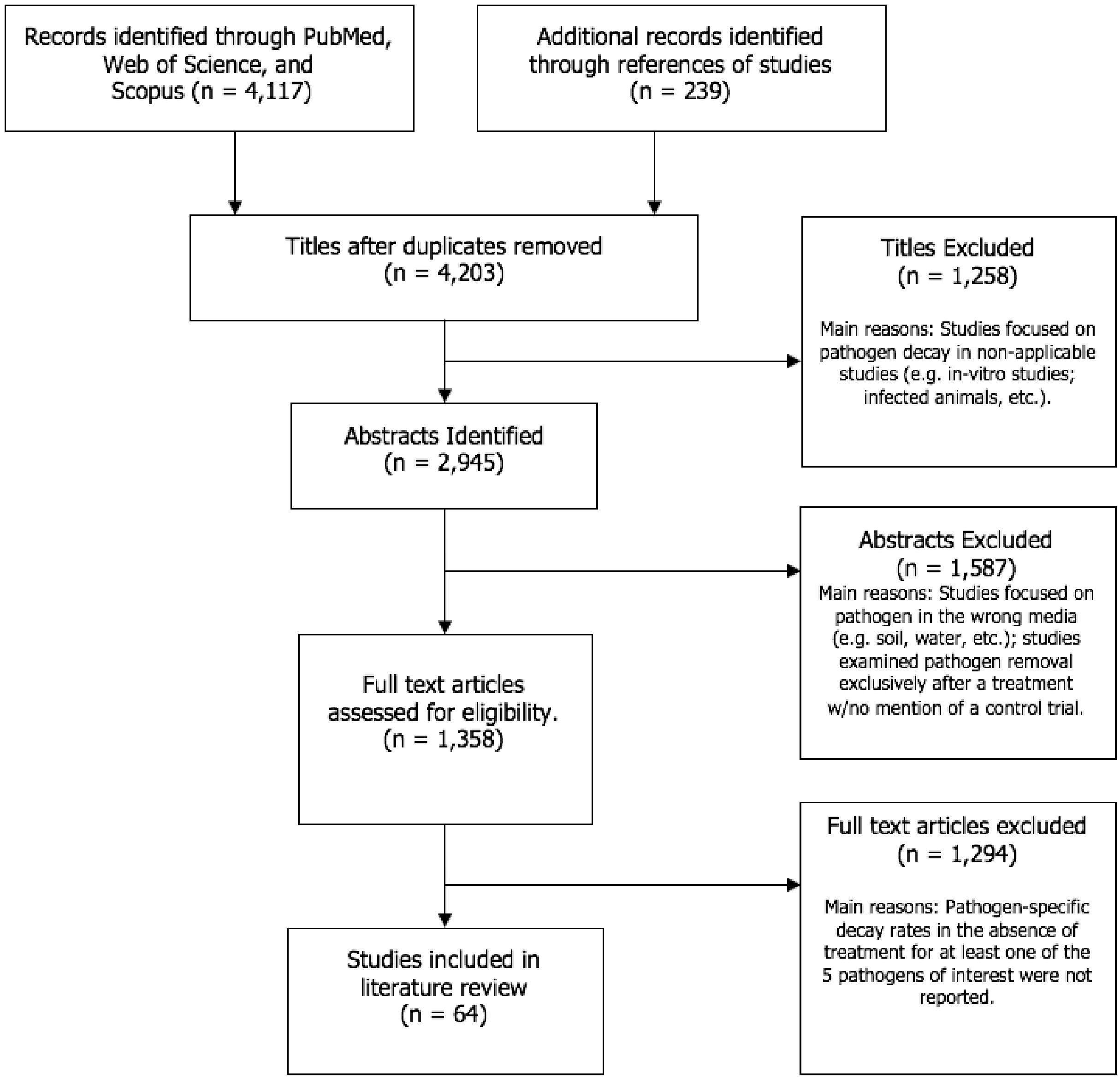


Figure 2. Flow diagram of systematic literature review of pathogen decay study screening process.

Table 1. Inclusion and exclusion criteria for systematic literature review

Inclusion Criteria	Exclusion Criteria
• Study examined at least one of the five reference pathogens • Decay of pathogens recorded in human excreta, feces, sludge, and/or animal manure • Static pile composting included • Urine diverted pit latrine studies included • Control trials in treatment studies included • Studies that examine the effect of storage • All years • Types of Literature: Peer-reviewed journals, textbooks, grey literature, graduate student theses • All trials that met the inclusion and exclusion criteria from the same study	• Chemical treatments • Pit additives excluded except in the case of urine • Aerated and turned composting excluded • Waste stabilization pond studies excluded • Wastewater treatment studies excluded • Anaerobic and aerobic sludge digestion • Any trials that just examined decay in urine • Studies that did not report decay rates and/or exact time with an attributed quantity of removal • Studies report decay rates in water, soil, seawater, or any other media that is not included in our inclusion criteria

We identified 4,356 papers for title and abstract screening. Sixty-four studies met our inclusion and exclusion criteria and were included in the final analysis. From the included studies, we extracted rate constants and the variables of each trial (e.g. temperature, pH, moisture content, pathogen detection method, and the excreta media) where available. The median rate constants were used in the main analysis presented in this paper. For the sensitivity analysis, interquartile range of decay rates for each reference pathogen was used. We present a summary of decay rates in Table 2 below for use in our simulated case study.

Table 2. Summary of Reference Pathogen Decay Rates "K" in fecal material in the absence of treatment.1 (All k values provided below are reported in days-1)

Reference Pathogen	***Decay Rate "k" (IQR)***	***Decay Rate K_{max}***	***Decay Rate K_{min}***	***K_{max}/K_{min}***
Rotavirus	0.13 (0.033 – 0.17)	3.3	0.012	2.8×10^2
Shigella spp.	1.2 (0.34 – 21)	38	0.077	4.9×10^2
Cryptosporidium spp.	0.047 (0.01 – 0.16)	6.9	0.0007	9.9×10^3
Ascaris	0.034 (0.012 – 0.072)	0.37	0.0002	1.8×10^3
E. coli spp.	0.86 (0.12 – 1.4)	4.6	0.066	6.9×10^1

1 Barnard, 1946; Berendes et al., 2015; Bychkovskaia, 1955; Caballero-Hernandez et al., 2004; Chien et al., 2002; Cote et al., 2006; Crane et al., 1986; Dumontet et al., 2001; Endale et al., 2012; Feachem et al., 1983 Fidjeland et al., 2015; Fidjeland et al.,

2013; Fischer et al., 2002; Fremaux et al., 2008; Fujioka et al., 2002; Ghigiletti et al., 1995; Ghigilletti et al., 1997; Gibbs et al., 1995; Gibson et al., 2014; Guan et al., 2003; Inoue et al., 2006; Jenkins et al., 1998; Jensen et al., 2008; Jensen et al., 2009; Jimenez et al., 2007; Katakam et al., 2013; King et al., 2007; Kuczynska et al., 1999; Lemos et al., 2005; Lepeuple et al., 2004; Magri et al., 2015; Magri et al., 2013; Martens et al., 2009; McKinley et al., 2012; Mehl et al., 2008; Mehl et al., 2011; Moe et al., 1982; Nakamura et al., 1965; Nasser et al., 2016; Nordin et al., 2009; Ogunyoku et al., 2016; Orstavik et al., 1974; Pandey et al., 2015; Paula et al., 2000; Paulsrud et al., 2004; Pecson et al., 2007; Pell et al., 1997; Peng et al., 2008; Pesaro et al., 1995; Polprasert et al., 1981; Pompeo et al., 2016; Robertson et al., 1992; Romero et al., 2014; Rose et al., 1997; Rze et al., 2004; Schmitz et al., 2016; Schonning et al., 2005; Stenstrom et al., 2002; Strauch, 1991; Trimmer et al., 2016; Turner et al., 1997; Vinneras, 2013; Wang et al., 1966; Williams et al., 2015; Ziemer et al., 2010

4.2 Pathogen Hazard Inputs – Review of Major Studies & Literature Reviews

Four literature reviews were conducted to determine the following inputs for each of our five references pathogens (Rotavirus, *Shigella* spp., *Cryptosporidium* spp., Ascaris, and *E. coli* spp.), included in our pit latrine hazard model:

- Global disability-adjusted life years (DALYs) attributed to each reference pathogen;
- Global prevalence of infection, including symptomatic and asymptomatic cases for all ages;
- Median infective dose; and
- Pathogen shedding rate for infected individuals

Targeted Boolean searches were conducted in PubMed, Scopus, and Web of Science databases. Included literature for our review was limited to other literature reviews and major studies published in English. For studies concerning median infective dose and shedding rate all publication years were included. However, for studies concerning DALYs and prevalence of infection, papers published before 2010 were excluded in our review. Median figures for each of the five reference pathogens were determined from our literature review and included in our hazard model.

We identified 876 papers for title and abstract screening. For global DALYs we identified only 1 study [GBD, 2015], that provided an estimate of global DALYs for the identified reference pathogens. Eight studies were included in the final analysis for global prevalence of infection; sixteen studies met the inclusion and exclusion criteria for median infective dose; and five studies met our inclusion and exclusion criteria for pathogen shedding rates. From the included studies, we determined average values for each of the four inputs to use in our simulated case study.

We present a summary of the average values for each input in Table 3 below for use in our simulated case study.

Table 3. Average value of each input

Reference Pathogen	% of Diarrheal Disease [1,2] Prevalence	Global Prevalence [3]	Shedding Rate per day per gram [4]	Median Infective Dose, ID_{50} [5]	Global DALYs [6]
Rotavirus	9.03%	0.046%	1×10^6	6.2	1.58×10^7
Shigella spp.	2.72%	0.014%	1×10^6	1.48×10^3	8.14×10^6
Cryptosporidium spp.	0.55%	0.003%	1×10^5	1.21×10^1	5.53×10^6
Ascaris	N/A	10.8%	1×10^4	5	1.08×10^6
E. coli spp.	7.36%	0.0038%	1×10^8	2.11×10^6	4.54×10^6

1 Prevalence of diarrheal-related pathogens were reported as a percentage of global diarrheal disease prevalence in studies. Prevalence of Ascaris was not reported as a part of diarrheal-disease prevalence.

2. Fletcher et al., 2015; Platts-Mills et al., 2015; Fischer-Walker et al., 2010; Kotloff et al., 2013; Abba et al., 2010

3. GBD 2015; Brooker et al., 2010; Pullan et al., 2014

4. Feachem et al., 1983; Czumbel et al., 2016; Juilan et al., 2016; Fewtrell et al., 2015; WHO, 2005

5. Juilan et al., 2016; WHO, 2016; Feachem et al., 1983; DuPont et al., 1971; DuPont et al., 1972; Messner et al., 2001; Ward et al., 1986; Chapell et al., 2006; Strachan et al., 2005; Teunis et al., 2004; Haas et al., 2000; Powell et al., 2000; Niyogi, 2005; Levine et al., 1973; Crocket et al., 1996; Kotloff et al., 1995;

6. GBD 2015

CHAPTER 5: LIMITATIONS

The major limitations of our pit latrine hazard model arise from five main sources:

1. Not considering exposure (quantifying hazard vs. risk);
2. Simplicity of the model inputs do not account for infectious disease dynamics;
3. Use of first-order exponential decay models to describe pathogen die-off (and survival);
4. Quality of data used in the simulated case study;
5. Method for defining the hazard attributed to other sanitation waste streams.

(1) Not Considering Exposure – Hazard vs. Risk. As a result of modeling hazard and not risk, exposure is not considered [WHO, 2016]. For microbial hazards, exposure is characterized by estimating the amount and the period of exposure to the pathogens [WHO, 2003]. Therefore, our model cannot provide an estimate of how likely the discharged excreta from different sanitation technologies will harm a population. Our model estimates what is being discharged to the environment at the technological source (i.e. pit latrine), but does not account for varying levels of exposure after the excreta is discharged. In particular, our model does not account for the point of discharge into the environment. For example, if sewerage discharges to the ocean and pit latrines are emptied directly into the streets, the latter exposes a much larger population to infectious pathogens [WHO, 2016].

Exposure is an important variable to consider when trying to define what is "safe" and "unsafe" [WHO, 2016; SFD Promotion Initiative, 2015]. However, the exposure routes for fecal pollution are numerous making risk assessments difficult to conduct [WHO, 2016]. Our method is simplistic and as a result easier to quantify. Estimating hazard at the origin, provides a basis for comparison of different sanitation waste streams and provides the foundation for estimating the hazard attributed to "leaks" along the sanitation service chain. However, since exposure and risk are not accounted for, caution should be taken when trying to apply terms like "safe" and "unsafe" based on the results of our model.

(2) Simplicity of Model and its Inputs. Our choice of constant pathogen loading rates, constant decay rates, and not explicitly accounting for the influence of environmental conditions on pathogen decay imposes several restrictions on the model's ability to represent infectious disease dynamics and as a result the system accurately [Heesterbeck et al., 2015]. While, our model estimates hazard for the pit latrine waste stream of a community rather than an individual household allowing for some averaging, in the field there will be temporal fluctuations in the loading rate due to a number of factors that impact disease dynamics (e.g. developing immunities, seasonality of infections, outbreaks, etc.) [Heesterbeck et al., 2015]. By using constant decay rates and not explicitly accounting for environmental conditions, the seasonal trends in decay rates are also not captured. However, the simplicity of model inputs allows for a more detailed temporal representation of a community's pit latrine waste stream than would be possible with other available methods.

(3) First-Order Exponential Decay Models. First-order exponential decay models may not be the best representation of die-off for all fecal-related pathogen species. From the limited microbiological studies, which have modeled pathogen decay in fecal material in the absence of treatment, it was found that certain organisms do not necessarily adhere to this decay structure [Berendes et al., 2015]. This may be particularly true for helminths [Berendes et al., 2015]. While first-order exponential decay models may oversimplify the death kinetics of some pathogen species, they are widely used in microbiology [Rogers et al., 2011]; the majority of decay rates found in the literature were determined for first-order exponential decay models [Rogers et al., 2011]. With advances in microbiological data, the incorporation of more sophisticated decay functions is possible in future iterations of our pit latrine hazard model.

(4) Quality of Data Applied in Illustrative Case Study. Comprehensive literature reviews were conducted to determine global averages for each input used in our illustrative case study. While we believe the numbers we used are a good reflection of the current body of literature, within the literature there are gaps and as a result our model may not accurately depict what is occurring in the field. In particular, the decay rates in fecal material in the absence of treatment for many pathogen species is not

well documented [Berendes et al., 2015; Schonning et al., 2005]. Additionally, there is only one source that reports the global disability-adjusted life years [GBD 2015].

Moreover, by the nature of literature reviews this collection of data, arises from various studies conducted at different times, under varying experimental conditions, for different purposes and was not necessarily developed to be integrated as we have done in our model. In particular, we derived an estimate for DALYs per prevalent case. While, DALYs reported by the GBD 2015 are based on reported prevalence, this figure was not available for any of the diarrheal disease pathogens [GBD 2015]. We determined a global prevalence from recent literature reviews and meta-analyses conducted [Fletcher et al., 2015; Platts-Mills et al., 2015; Fischer-Walker et al., 2010; Kotloff et al., 2013; Abba et al., 2010; GBD 2015; Brooker et al., 2010; Pullan et al., 2014] and applied this to the reported DALYs to determine the DALYs per prevalent case we used in our model.

(5) Defining Hazard for Other Waste Streams. No clear guidance exists on how to compare the relative hazards between the different sanitation waste streams. Very little literature exists concerning the relative pathogen content and hazard posed by open defecation or how it changes over time. The guidelines associated with wastewater treatment are meant to control environmental pollution (e.g. biochemical oxygen demand, nitrogen, etc.) therefore the pathogen removal efficiency is highly variable and is just recently being extensively studied [WHO, 2006; Jimenez et al., 2010]. Additionally, the proportion of liquid (i.e. urine) and solid (i.e. feces) waste varies extensively between these different waste streams. The relative proportion of pathogens found in the solid versus liquid stream is also not well understood [Schonning et al., 2005; Hoglund et al., 2002]. The method we propose is relatively conceptual and the comparison is imperfect, but we believe it can still yield practical insights on relative hazards between the different sanitation technologies.

Problems with inputs and data will always exist for a conceptual model. The approach taken to model hazard in pit latrines is a technologically simple once, but we believe it will aid planners in better understanding the flow of pathogens through a pit latrine waste stream and allow for helpful assessments of the public health significance of pit latrine waste under different management conditions.

CHAPTER 6: RESULTS & DISCUSSION OF ILLUSTRATIVE CASE STUDY

To the author's knowledge, our model is the first to explicitly represent pathogen hazards and their relative accumulation and decay in pit latrines over time. A variety of informative results are available from our model. Direct and indirect outputs include: estimates of viable pathogen count, estimates of number of potential cases, estimates of cumulative pit latrine hazard measured in Meta-DALYs, estimates of hazard attributed to each reference pathogen, proportion of hazard contributed by recent loading events, and proportion of hazard reduced based on different management practices (e.g. pit emptying frequency). These results yield practical insights into pit latrine behavior as a treatment technology, and can lead to conclusions about management decisions.

To illustrate the kinds of results the model can produce we apply it to a case study of a 5,000 person population infected with five reference pathogens (RP) - Rotavirus, *Shigella* spp., *Cryptosporidium* spp., Ascaris, and *E. coli* spp (see Table 4 below for a summary of case study characteristics). The main body of analysis is conducted with median pathogen decay rates; the analysis is repeated considering the interquartile range of pathogen decay rates to determine how sensitive our results are to difference in rates of pathogen inactivity. While the model inputs used (prevalence of infection, shedding rates, median infective dose, and DALYs per prevalent case) reflect global averages, determined through comprehensive literature reviews, the authors do not intend the absolute numbers we present here to describe the magnitude of hazard posed by pit latrine waste globally. Rather we find the illustrative case study assists with understanding the temporal trends and general behavior of pathogen hazards in pit latrines under daily use conditions.

In particular, we found while hazard increases in the beginning it does not increase indefinitely with time; cumulative hazard tends a steady-state equilibrium when the daily input of pathogens balances the exponential die-off of those already in the pit. With the parameter values of the model we used, the majority of cumulative hazard is contributed in the most recent month. As a result of these discoveries we found manipulating pit emptying frequency (or pit fill fates) and utilizing double pit technology could have large impacts on the relative hazard posed by a community's pit latrine waste stream. Additionally, our model provided evidence that pit latrines operated with good management practices discharge markedly less pathogen "pollution" relative to open defecation, can outperform sewerage with wastewater treatment achieving 1-Log_{10} daily pathogen removal, and can perform comparably to sewerage with wastewater treatment achieving 2-Log_{10} daily pathogen removal.

Table 4. Summary characteristics of illustrative case study.

Pathogen	**Rotavirus**	***Shigella* spp.**	***Cryptosporidium* spp.**	**Ascaris**	***E. coli* spp.**
Prevalence (%)	0.046	0.014	0.003	10.8	0.038
#Pathogens Shed by Infected Individual per day per gram of feces	1×10^6	1×10^6	1×10^5	1×10^4	1×10^8
Decay Rate "k" in days^{-1} (IQR)	0.13 (0.033 – 0.17)	1.2 (0.34 - 21)	0.047 (0.01 – 0.16)	0.034 (0.012 – 0.072)	0.86 (0.12 – 1.4)
Median Infective Dose	6.2	1.5×10^3	1.2×10^1	5	2.1×10^6
DALYs/Prev. Case	4.9	8.4	28	0.001	2.4
Total Population			5,000		
Feces Excreted Per Day Per Person (grams)			100		

6.1 Characterizing Hazard Behavior and Management Implications

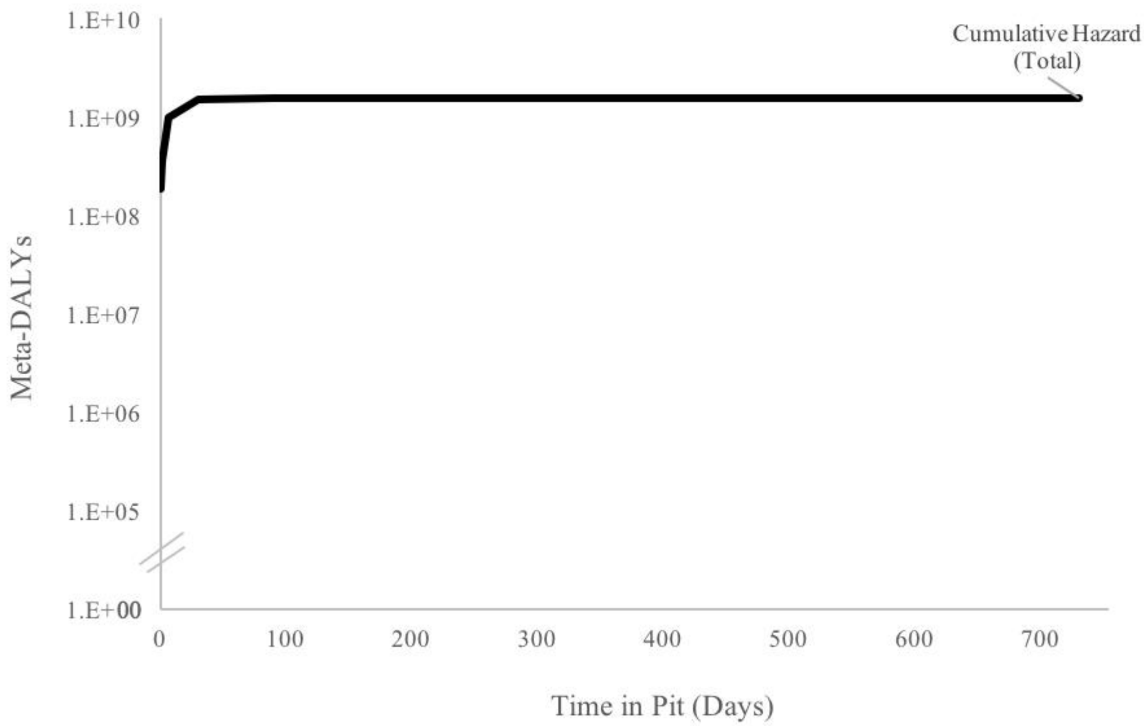


Figure 3. Cumulative hazard (Meta-DALYs) determined for the model pit latrine; summation of Meta-DALYs attributable to each reference pathogen.

Figure 3 presents the cumulative hazard (Meta-DALYs) determined. Cumulative hazard is summation of potential disease burden attributed to each of the five reference pathogens. We estimated cumulative hazard posed by the 5,000 person pit latrine waste stream on day 1 to be 1.86×10^{8} Meta-DALYs and it increases to 1.54×10^{9} Meta-DALYs by day 730.

Additionally, if we consider each reference pathogen individually (see Figure 4) we estimated the hazard attributed to Rotavirus increases from 1.82×10^{8} Meta-DALYs (day 1) to 1.46×10^{9} Meta-DALYs (day 730), for *Shigella* spp. the hazard increases from 3.92×10^{5} Meta-DALYs (day 1) to 5.73×10^{5} Meta-DALYs (day 730), for *Cryptosporidium* spp. we estimated the hazard increases from 3.26×10^{6} Meta-DALYs (day 1) to 7.03×10^{7} Meta-DALYs (day 730), for Ascaris we estimated the hazard increases from 1.08×10^{5} Meta-DALYs (day 1) to 3.09×10^{6} Meta-DALYs (day 730), and finally we estimated the hazard attributed to *E. coli* spp. increases from 2.10 x 10^4 Meta-DALYs (day 1) to 3.64 x 10^4 Meta-DALYs (day 730).

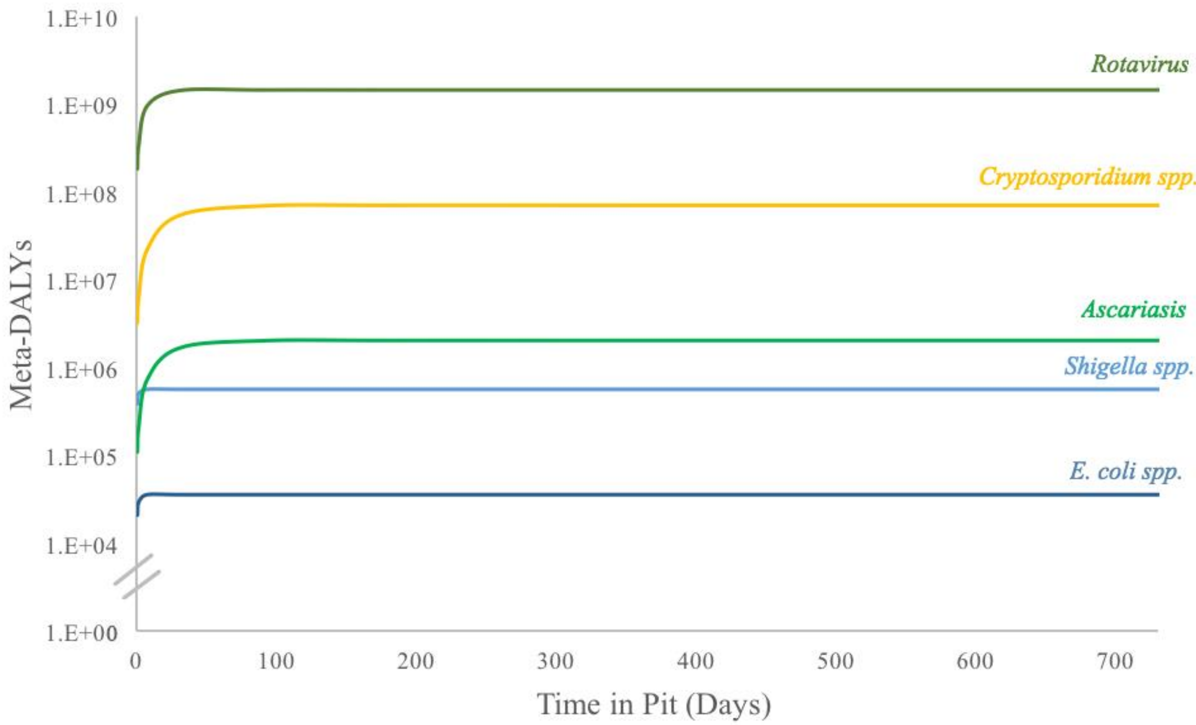


Figure 4. Meta-DALYs attributable to each reference pathogen in model pit latrine over two-year period.

6.1.1 Checking model numbers

Comparing model output with figures reported in the literature is a first check on whether the model and its results may be reasonable. Since there has been no direct measurement of latrine hazard, we must work indirectly with other data.

The model also predicts a viable reference pathogen (RP) count, and we check our results with studies that reported pathogen concentrations found in pit sludge. Our model reported fluctuations between 4-Log (day 1) to 2-Log (day 730) viable RPs/gram. Studies reported bacterial concentrations were 8-Log to 2-Log MPN/grams dry weight and 4-Log to 2-Log Ascaris eggs/mL, given roughly less than one gram of pit sludge was in each ml sample [Ogynyoku et al., 2016; Berendes et al., 2015; Jimenez et al., 2007; Chien et al., 2002; Stenstrom et al., 2002]. The pathogen concentrations found in our model are within the range seen in the literature[15].

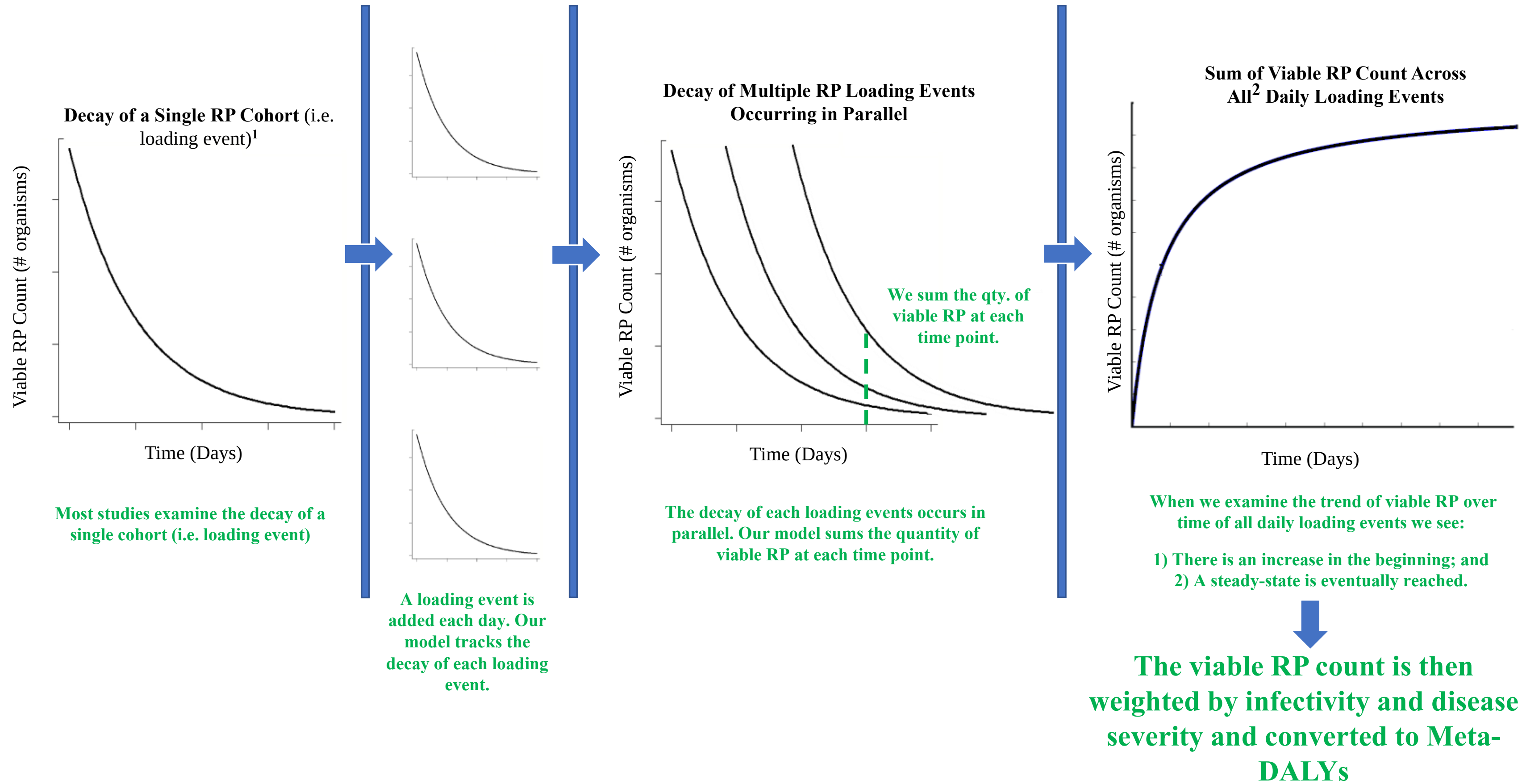
Our reported cumulative Meta-DALYs (1.54×10^9) for a population of 5000 are large; the Meta-DALYs we report are greater than the annual global diarrheal disease DALYs (7.1×10^8 DALYs)! [GBD, 2015; Fletcher et al., 2011; Walker et al., 2010; Abba et al., 2009; Huilan et al., 1991]. However, The DALYs reported in the GBD study were calculated from *recorded infections* [GBD, 2015], whereas our study reports *potential* DALYs, and do not reflect actual infections.

6.1.2 Why do we see an increase in hazard?

We observed an increase in the viable RP count for all five included RPs and as a result an increase in cumulative hazard, by approximately an order of magnitude with no subsequent decrease (see Figure 4). The majority of microbiological studies in the WaSH field examine the behavior of a single pathogen cohort (e.g. a closed system) under varying experimental conditions. Our model studies a pit latrine system in use (e.g. an open system) and therefore includes a continuous daily inflow of viable pathogens (see Figure 1 for flow diagram of methods). Given that the RP loading rate for our model is constant, we can expect the cumulative hazard to increase with time.

[15] Our pathogen concentrations were calculated under the assumption of conservation of mass. The authors are keenly aware that due to biodegradation and exfiltration of liquids mass is not conserved in pit latrines [Foxon et al., 2011]. When mass is lost, the concentration would increase. In particular, the concentration on day 730 would increase relative to that on day 1 but it would likely still be within the range reported in the literature. Concentrations are only used (a) day zero of each cohort, to get a total number, and (b) here, in this exercise, to compare with published results. Computations of cumulative viable organisms and hazard are NOT dependent upon either concentrations, or conservation of mass.

Figure 5. Visual representation of how multi-loading event model structure used in this paper differs from the conventional single loading event study structure.



[1]***Loading Event*** is defined as a group of organisms belonging to a single RP species (e.g. *Rotavirus or E.coli*) that were excreted at the same time; decay starts and occurs for the same length of time for all organisms in a single loading event. The rate of decay does not vary between loading events of the same RP species.
[2] Sum of viable RP count was calculated across all daily loading events for a single RP species; the process was repeated for each of the 5 RP included in our illustrative case study.

6.1.3 Steady-state behavior

In addition to an increase in cumulative hazard with time, we observed cumulative hazard reached a constant level and therefore obtained a steady state equilibrium (see Figure 3). To the author's knowledge, steady-state pathogen behavior has not been reported in other WaSH studies [Ogynyoku et al., 2016; Berendes et al., 2015; Jimenez et al., 2007; Chien et al., 2002; Stenstrom et al., 2002]. However, steady state behavior has been widely documented in microbial ecology, where open-systems are more commonly considered [Hsu et al., 1991; Dung et al., 1997; Hanemaajier et al., 2015]. This finding provides evidence that even under use conditions, the public health hazard from on-site sanitation does not increase indefinitely with time.

The time required to reach steady state[16] is dependent upon the RP-specific decay rate (Eq. 10). Rapidly decaying microorganisms, such as *Shigella* spp. and *E. coli* spp. achieved a steady state within 20 days. In contrast, Ascaris required 271 days to achieve an absolute constant equilibrium (NOTE: By day 100, all five RP reached ≥99% of their absolute steady-state equilibrium level). Despite the varying persistence of RP species in our model, we find all organisms reach a steady state equilibrium within one year, under daily use conditions (see Table 5).

$$\lim_{t \to \infty} N_t = \frac{N_0}{(1-e^{-k})} \qquad \text{Eq. 10}$$

Table 5. Description of hazard (Meta-DALYs) at steady-state equilibrium.

Reference Pathogen	Qty. of Hazard at Steady-State Equilibrium (Meta-DALYs)	Time to Reach 99% of Steady-State Equilibrium (Days $T_{99\%}$)	Time to Reach Steady-State Equilibrium (Days T)
Rotavirus	1.46×10^9	34	146
Shigella spp.	5.73×10^5	<1	8
Cryptosporidium spp.	7.10×10^7	97	300

[16] By Eq. 11 a steady-state, or constant value, will not be reached but it will be approached asymptomatically. When we refer to a "steady-state" this refers to unchanging value at 99.99% level.

Ascaris	3.19×10^6	99	271
E. coli spp.	3.64×10^4	4	11
Cumulative (TOTAL)	1.54×10^9	99	353

Finding a steady state long-run level of hazard in latrines is a mathematical result of utilizing first-order log-linear decay models with constant inputs and constant decay rates (see Methods Section 2.2 – 2.3) [Wade et al., 2015; Hsu et al., 1983]. Altering this component of our model, could result in changes to our steady-state findings. For instance, if the dynamic nature of environmental factors such as seasonal fluctuations in temperature or competition among pathogens for resources, was accounted for, variations in inputs and decay rates would arise [Mehl et al., 2011; Feachem et al., 1983]. In theory, steady state levels would exist but they would fluctuate with the fluctuations in inputs and decay rates.

Additionally, while first-order log-linear decay models are the most used to describe pathogen inactivation in the literature [see Sys. Lit Review Section 4.1], recent studies report that survival curves for some pathogen species are often nonlinear and may exhibit a "recalcitrant" long tail [Bevilacqua et al., 2015; Marks et al., 2007]. Moving away from first-order inactivation kinetics towards non-linear decay models, has two major implications on our findings. As mentioned above, it is possible that our steady state equilibrium finding, even theoretical, may no longer be valid. Also, according to the literature, a long tail signifies the existence of a more resistant subpopulation [Marks et al., 2007; Li et al., 2007]. If we accept this theory, then our results found using first-order log-linear decay models are likely underestimating the viable pathogen count over time, leading to negative public health implications and may face the challenge of practicality for real-world application in sanitation planning. However, due to limited evidence of non-linear decay kinetics for the five pathogens used in our simulated case study (see Sys. Lit Review Section 4.1), the authors believe the findings we present here can still offer helpful insight on long-run hazard behavior in pit latrines.

6.1.4. Implications of steady-state behavior: pit emptying frequency

Our findings suggest that long periods between emptying (provided they do not lead to overflows!) are better from a public health perspective. If we consider each pit emptying event as a discharge of pathogens (e.g. hazard) into the environment, our model suggests the longer a pit remains unemptied the less total cumulative hazard is discharged into the environment over time, assuming no leakage or overflow. This may not immediately be intuitive from Figure 3. From the graph of cumulative hazard over time, we can determine the quantity of hazard that would be discharged upon pit emptying at any given point in time (see Figure 6). For example, if the pit latrine was emptied at 100 days the cumulative hazard discharged would be approximately 1.54×10^9 Meta-DALYs, and if the pit latrine was emptied at 200 days the cumulative hazard discharged would also be approximately 1.54×10^9 Meta-DALYs. However, these are point values; they do not provide a total cumulative hazard discharged to the environment over the same time frame. In Figure 6, we demonstrate that given approximately equivalent point values due to the steady-state nature of our model, a pit emptied every 100 days essentially discharges 2x the total cumulative hazard to the environment compared to a pit emptied every 200 days.

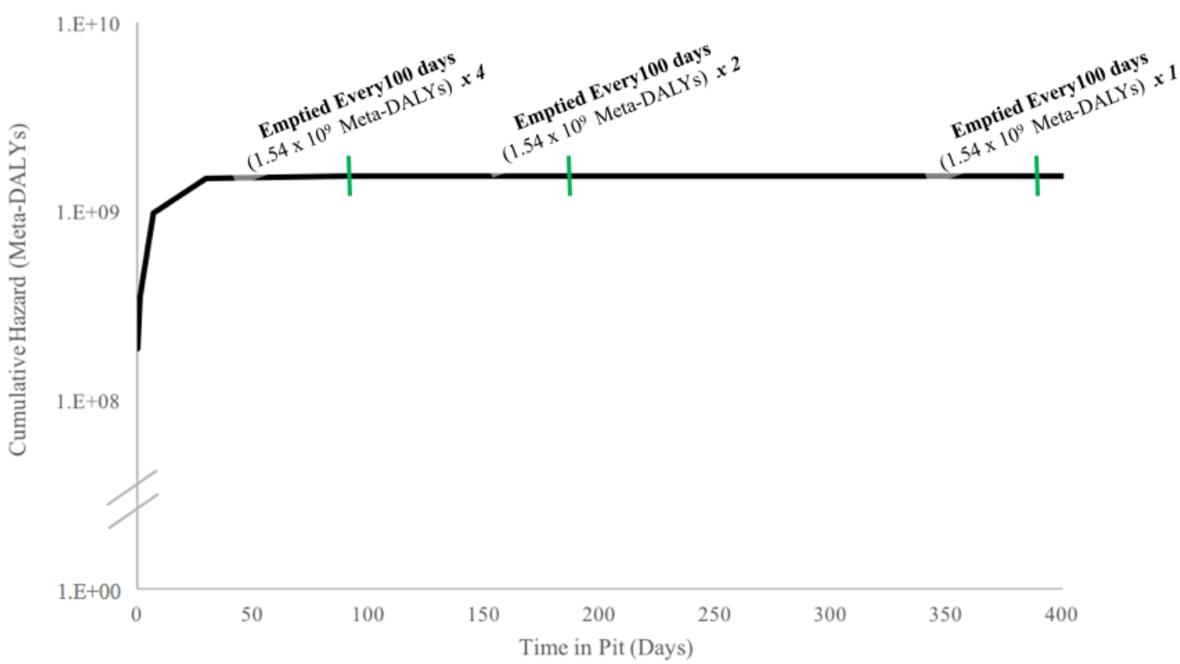


Figure 6. Estimation of hazard (Meta-DALYs) discharged into the environment based on emptying frequency.

Total cumulative hazard discharged to the environment is reduced by the pathogen die-off that occurs in a pit latrine prior to emptying. From our model, we can estimate the total cumulative hazard averted with different emptying frequencies (see Figure 7). For example, if we consider the extreme case of daily emptying as our base, a switch to emptying every two-years reduces total cumulative hazard discharged to the environment by approximately 99%. Adjusting pit emptying frequency takes advantage of the naturally occurring pathogen die-off in pit latrines, and can reduce the public health hazard posed by on-site sanitation.

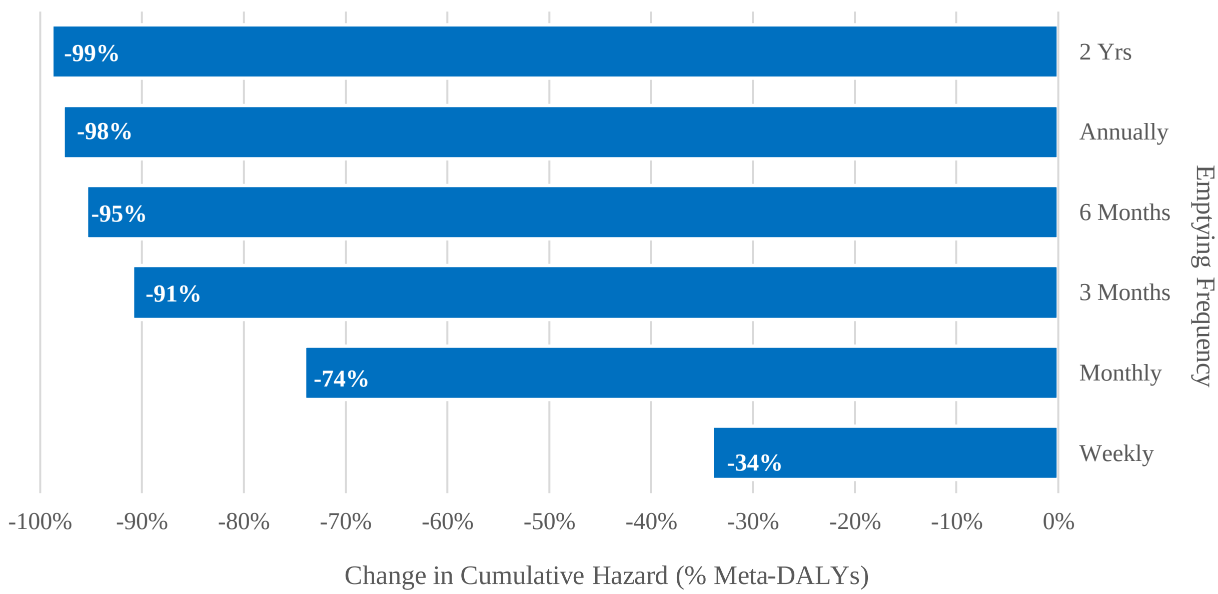


Figure 7. Percentage change in cumulative hazard (Meta-DALYs) discharged into the environment with different pit latrine emptying frequencies (base = daily emptying).

Currently the primary focus of safe fecal sludge management (FSM) for on-site sanitation is examining hygienic pit latrine emptying services and excreta disposal [Foxon et al., 2011; Jenkins et al., 2015; Thye et al., 2012; Jenkins et al., 2012; Opel et al., 2013]. While these are two important FSM considerations, our model provides evidence that encouraging management practices that reduce pit emptying frequency can also have a strong public health impact. Emptying frequency is largely dictated by sludge accumulation rates [Jenkins et al., 2015; Zwia et al., 2016a; Zwia et al., 2016b; Still et al., 2012]. Zzwia et al. (2016a) found pit latrines in Kampala filled up faster than expected due to "inappropriate" use, in particular using pits for disposal of solid waste. They report that public pit latrines actually had slower accumulation rates compared to private latrines partly due to the restriction of solid waste disposal. Jenkins et al. (2015) found pit latrines previously emptied required more frequent emptying into the future due to a failure of available pit emptying methods to remove all of the contents of full pits. While the rate of sludge accumulation is largely dictated by biological and environmental factors that are not easily influenced by pit latrine users [Foxon et al., 2011], there is evidence that certain behaviors such as proper solid waste disposal and complete pit emptying may have a positive public health impact by reducing pit emptying frequency.

6.1.5 Recent loading events are the most hazardous, but by how much?

The conventional belief that the most recent excreta loading events are the most hazardous [Feachem et al., 1983] is supported by our model. Given a two-year use period, we estimated approximately 12.5% of total cumulative hazard is contributed by the most recent day's load and nearly 97% is contributed by the most recent month's load (see Figure 8).

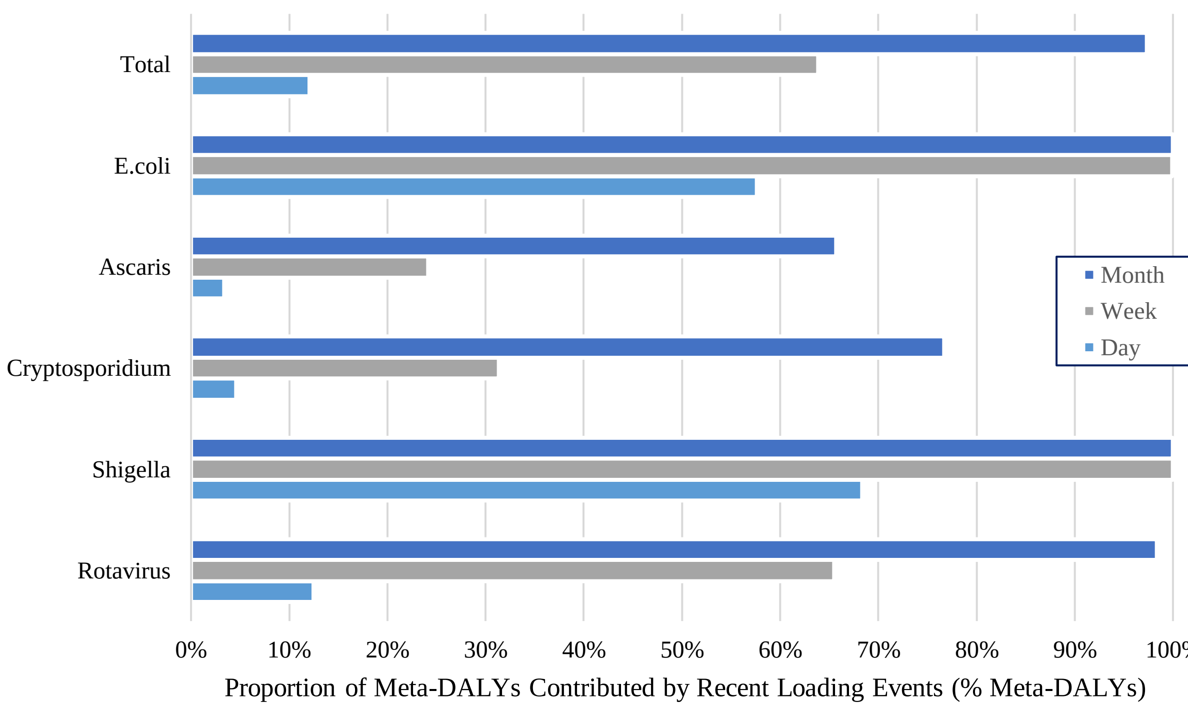


Figure 8. Proportion of Meta-DALYs contributed from recent loading events (day, week, and month) given a two-year use period.

While the majority of hazard for all five RP is contributed by the most recent loading events, the relative contribution correlates with RP-specific decay rates. For the rapidly-decay RP, namely *E. coli* spp. and *Shigella* spp., nearly 100% of the total Meta-DALYs from a two-year use period are contributed in the most recent month. Whereas for the most persistent RP, Ascaris, approximately 66% of the Meta-DALYs were contributed in the most recent month.

Our findings suggest that loading events contributed over a year ago may no longer pose a public health hazard. For the purposes of this paper we define a "non-hazardous" loading event as posing $\leq$ 1 Meta-DALY to our 5,000-person population. Given this definition, loading events[17] contributed more than 353 days ago, or roughly a year ago, in our model would be considered non-hazardous. This is best illustrated by examining the decay of hazard from a single loading event (see Figure 9) as opposed to looking at the cumulative hazard over all the loading events in the pit latrine (see Figure 3). This finding should not be conflated with the results discussed above. For example, given a two-year use period, roughly half of the daily loading events (47%) would be considered hazardous and approximately 97% of the cumulative hazard is contributed in the most recent month (see Figure 8).

[17] The authors are aware that due to biodegradation of solids, mass is not conserved in pit latrines over time. Hazard contribution estimates are given on a per "loading event" unit and by volume of excreta.

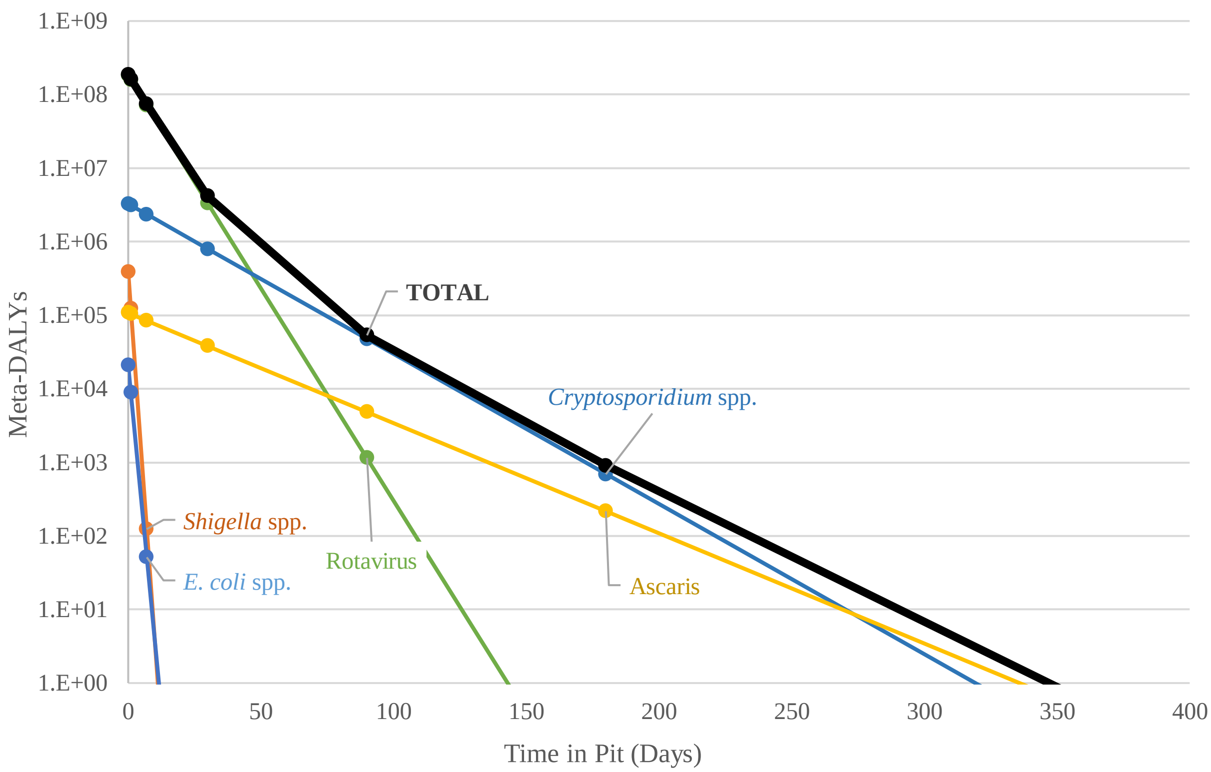


Figure 9. Change in Meta-DALYs of a single loading event over time.

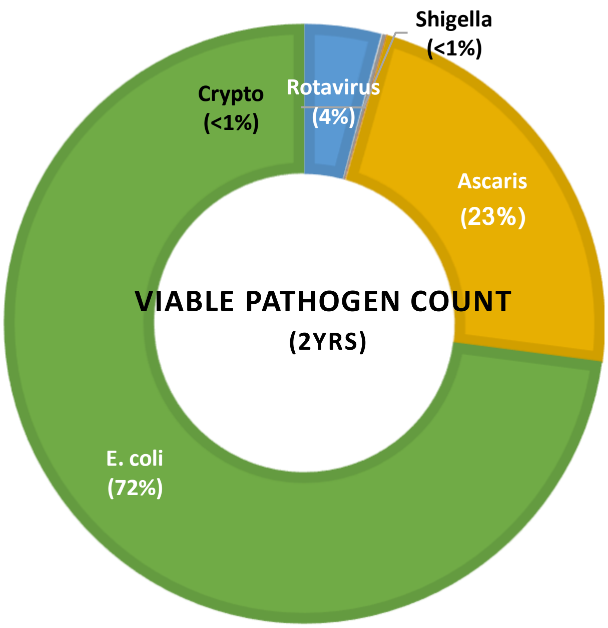
6.1.6 Implications of hazardous recent loading events: double pit technology

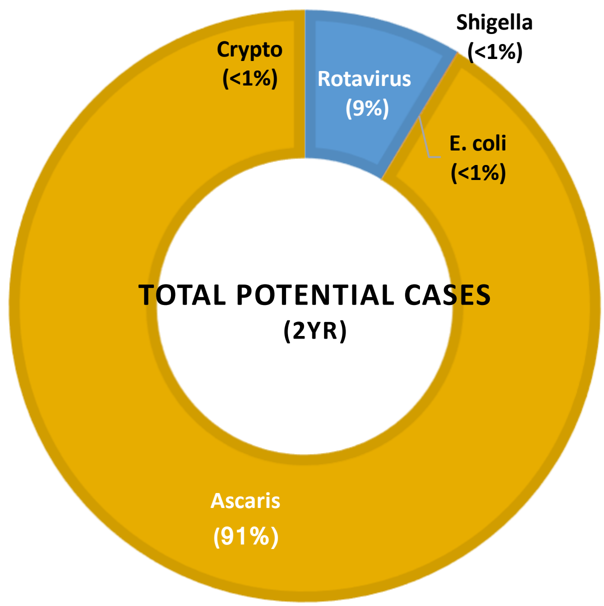
Given our findings that the majority of cumulative hazard is contributed in the most recent month and loading events contributed over a year ago may effectively be ignored, our results support studies that find double vault pit latrines could significantly reduce the public health hazard posed by on-site sanitation [Hussain et al., 2017; Jensen et al., 2009; Mara et al., 1984; Tilley et al., 2014]. Jensen et al. (2009) report double vault composting pit latrines used in Vietnam reduced Ascaris eggs by 99% during a three-month storage period, regardless of the pit additives (i.e. lime) and starting pH. Hussain et al. (2017) report several benefits of using double pit technology including, generation of fertilizer, reduction of environmental contamination, a longer life span compared to single pit latrines, and the ability of users to empty the pit themselves. Despite the potential management and public health benefits, the majority of global pit latrines use single pit technology, which may point to a barrier in uptake (e.g. cost or space requirements). However, if double pit technology could be effectively used, our model suggests a substantial proportion of the public health hazard posed by pit latrines could be averted.

6.2 Identifying and Prioritizing Pathogens of Concern

A wide range of pathogens found in human excreta can cause diseases [Feachem et al., 1983]. When different measures are used to assess pathogen hazards (see Figure 10, 11, 12), it may affect how one identifies and prioritizes sanitation public health threats/these hazards. Figure 10, 11, 12 characterize the same pit latrine contents in our model after a two-year use period. The addition and/or removal of pathogens is summarized by the viable RP count, phase three of our model (see Figure 1). The subsequent phases – estimating potential number of cases (see Figure 11) and estimating cumulative Meta-DALYs (see Figure 12) – are translational measures of the viable RP count. Each subsequent phase incorporates an additional biologic and/or epidemiologic factor important for identifying and comparing pathogen hazards [WHO, 2016a]. For example, when we examine pure counts prevalence and persistence are accounted for, and as a result we see *E. coli* spp. (64%) and Ascaris (32%) are the primary pathogens of concern. Once infectivity is included, *E. coli* spp. becomes a negligible hazard and Ascaris (89%) with Rotavirus (9%) collectively constitute the majority of potential cases. Finally, when disease severity is accounted for, we find Rotavirus contributes approximately 94% of the cumulative hazard. *Cryptosporidium* spp., which constitutes >1% of the viable count and potential cases, contributes 5% of the cumulative hazard, and Ascaris contributes > 1% of the cumulative hazard.

We were surprised to find Rotavirus constitutes the vast majority of cumulative hazard after a two-year use period (see Figure 12). Sanitation guidelines have historically reported viruses do not pose a public health hazard in pit latrine sludge because of their relatively quick decay rates, relative to other pathogen classes including bacteria and helminths [Feachem et al., 1983; WHO, 2004; Lewis et al., 1980]. Our results appear to conflict with much of the microbiology literature and sanitation guidelines [Feachem et al., 1983]. However, we find our results do reflect the findings in epidemiology literature [GBD, 2015; Lanata et al., 2013; Platts-Mills et al., 2015; Kotloff et al., 2013]. Rotavirus is often cited as the most common cause of severe diarrheal disease in young children around the world [GBD, 2015; Lanata et al., 2013]. Our confounding results may be an outcome of using different measures to assess pathogen hazards (i.e. pure counts vs. DALYs) and former studies not considering pit latrines under use conditions (i.e. accounting for recent loading events).





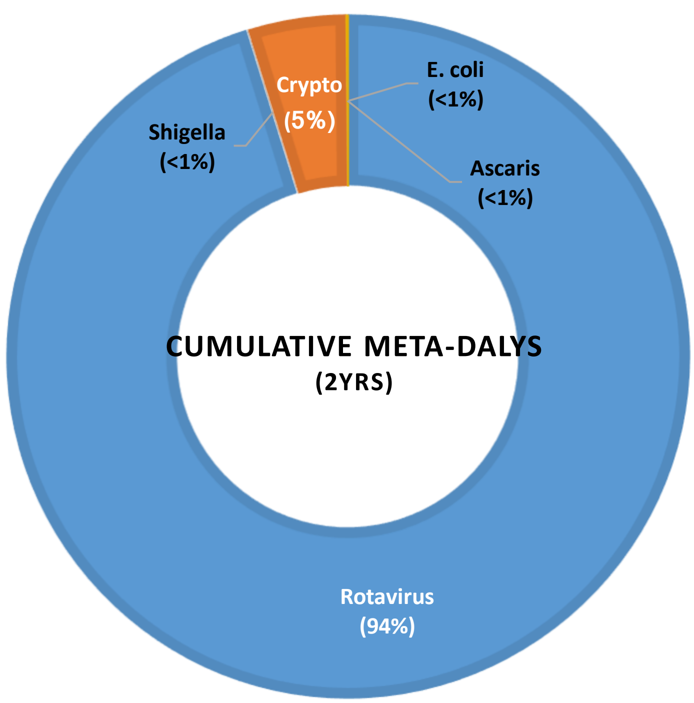


Figure 10. (upper left). Proportion of total viable pathogen count attributed to each reference pathogen, given a two-year use pit latrine use period.

Figure 11. (upper right). Proportion of total potential cases attributed to each reference pathogen, given a two-year pit latrine use period.

Figure 12. (center). Proportion of cumulative hazard (Meta-DALYs) attributed to each reference pathogen, given a two-year pit latrine use period.

Table 6. Proportion of total viable pathogen count, total potential cases, and cumulative hazard given a two-year pit latrine use period. Infectious doses and DALYs per prevalent case also provided for reference.

Pathogen	**Infectious Dose[18]**	**DALYs/Prevalent Case[18]**	**Proportion Given a Two-Year Latrine Use Period**		
			Viable Pathogen Count	**Potential Cases**	**Cum. Hazard Meta-DALYs**
Rotavirus	6.2	4.9	4%	9%	94%
Shigella spp.	1.5×10^3	8.4	<1%	<1%	<1%
Cryptosporidium spp.	1.2×10^1	28	<1%	<1%	5%
Ascaris	5	0.001	23%	91%	<1%
E.coli spp.	2.1×10^6	2.4	72%	<1%	<1%

6.3 Comparison to Other Sanitation Waste Streams

6.3.1 Open defecation

To understand the effect on pathogen hazard reduction when people practicing open defecation adopt pit latrines, we used the results of our model to conduct a comparative analysis. Open defecation (OD) refers to the practice whereby people defecate in open spaces (e.g. fields, open water bodies, etc.) rather than using a toilet [UNICEF & WHO, 2013]. With open defecation, pathogen hazards are immediately released into the environment; no die-off occurs in containment prior to release. For the purposes of this analysis, we equated OD with daily emptying in our model. Due to the differences in

[18] Determined through literature reviews (see Section 4).

times scales of hazard discharge between pit latrines and OD (e.g. annual vs. daily), we converted cumulative hazard to average daily hazard[19] discharged for pit latrines, given an average use period (e.g. time between pit emptying). As expected, we found pit latrines discharged markedly less pathogen hazards into the environment compared to open defecation, with infrequent pit emptying/longer use periods (see Figure 13). Given a two-year use period, pit latrines reduce the average daily Meta-DALYs discharged by nearly 2-Logs; in absolute terms, we found 1.84×10^8 Meta-DALYs[20] were averted per day. Supported by our model findings presented in section 6.1.3, we see that less frequent pit emptying averts more hazard, and as a result is more effective relative to open defecation. Our findings indicate that if a community practicing open defecation adopted and consistently used pit latrines with infrequent pit emptying, the magnitude of pathogen hazards discharged into the environment would be substantially reduced.

[19] Average daily hazard discharged is a particularly useful metric for our model which estimated pit latrine hazard at the community-level. For example, in a given community if the average pit latrine use period is one year, while each household will empty their pit latrine annually they will not all empty on the exact same day. Rather it is more likely on any given day at least one household will be emptying their pit.

[20] 1.86×10^8 (OD) – 2.10×10^6 (2-year) = 1.84×10^8 (Meta-DALY difference)

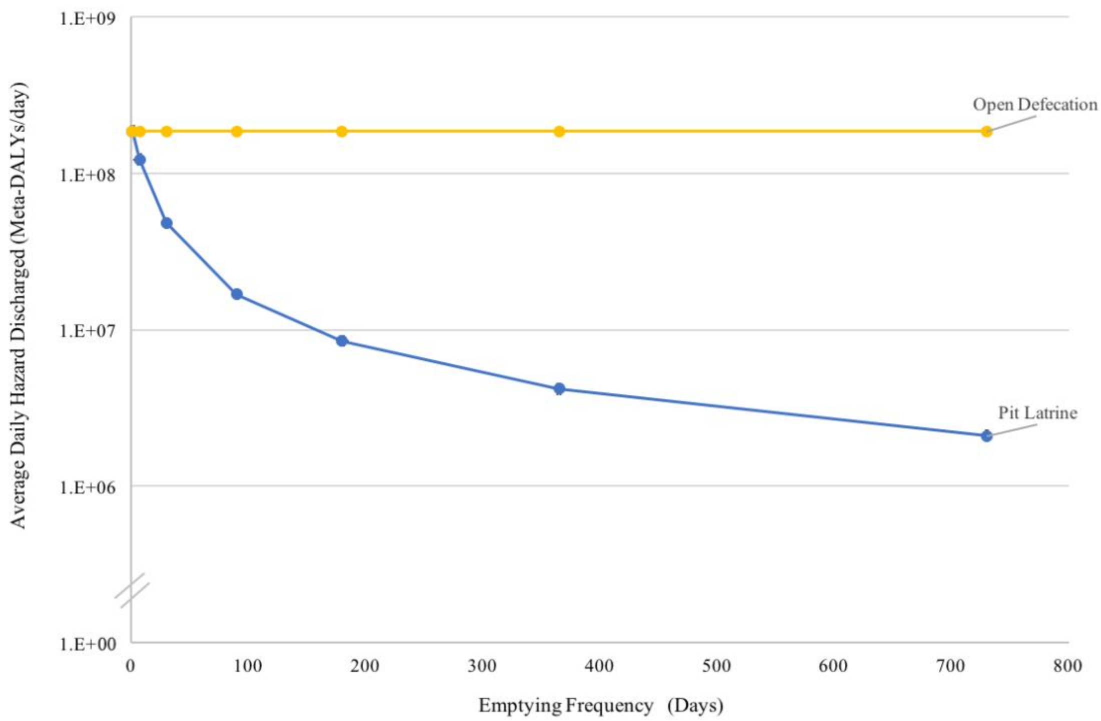


Figure 13. Daily average hazard discharged to the environment (Meta-DALYs per day) by open defecation vs. daily average hazard released to the environment by pit latrines with different emptying frequencies.

Shifting from open defecation to using a simple pit latrine is one of the primary steps on the sanitation ladder (UNICEF & WHO, 2013; Karvanstrom et al., 2011) and a major target of the Sustainable Development Goals [JMP, 2015]. It is believed this transition will have a positive public health impact [Spears et al., 2013], however the magnitude of the public health impact is not well understood or well documented [Patil et al., 2014; Clasen et al., 2010; Brocklehurst et al., 2014]. Recent systematic reviews that examined the public health effect of water, sanitation, and hygiene (WaSH) interventions, found using pit latrines reduced fecal-related diseases relative to practicing open defecation [Waddington et al., 2009; Cairncross et al., 2010; Clasen et al., 2010; Fewtrell et al., 2005; Ziegelbauer et al., 2012]. However, they consistently reported the evidence in this area was the weakest in the WaSH field [Carincross et al., 2010; Waddington et al., 2009; Fewtrell et al., 2005]. Each review found only 2 - 4 studies in this area that met their inclusion criteria. A multitude of limitations were reported that were believed to affect the quality of the majority of sanitation/OD studies, including the small sample size due to the high cost of hardware interventions and the relative difficulty of blinding interventions that involve provision of hardware and/or behavior change. The recent Total Sanitation Campaign (TSC) in India allowed for a large randomized controlled trial that would overcome many of the reported study limitations of past sanitation interventions. Yet Clasen et al. [2012] reported that evaluating the true health impact of sanitation (i.e. when sustained behavior change and consistent latrine use has been achieved) may be beyond the scope of their study design. While our analysis is conceptual, it provides helpful insight into the potential long-term public health significance of shifting from open defecating to consistently using a pit latrine, an issue that is not easily observed during field studies [Clasen et al., 2012; Barnard et al., 2013; Spears et al., 2013].

6.3.2 Conventional sewerage with wastewater treatment

To understand the potential public health significance once a community switches from pit latrines to conventional sewerage with wastewater treatment, we conducted a comparative analysis. Primary wastewater treatment reportedly achieves 0-1Log_{10} and most secondary wastewater treatment achieves 0-2Log_{10} pathogen removal [WHO, 2006; Jimenez et al., 2010; Blumenthal et al., 2001; Ottson et al., 2006; Hui-Wen et al., 2012; Williams et al., 2015]. We were surprised to find pit latrines outperform sewerage with 1Log_{10} wastewater treatment and is nearly as effective as 2Log_{10} wastewater treatment, given infrequent pit emptying (see Figure 14). Our results provide evidence that pit latrines may actually discharge less cumulative pathogen hazard into the environment compared to most primary and secondary wastewater treatment. As a result, pit latrines may pose less public health hazard compared to sewerage unless relatively high wastewater treatment levels are available.

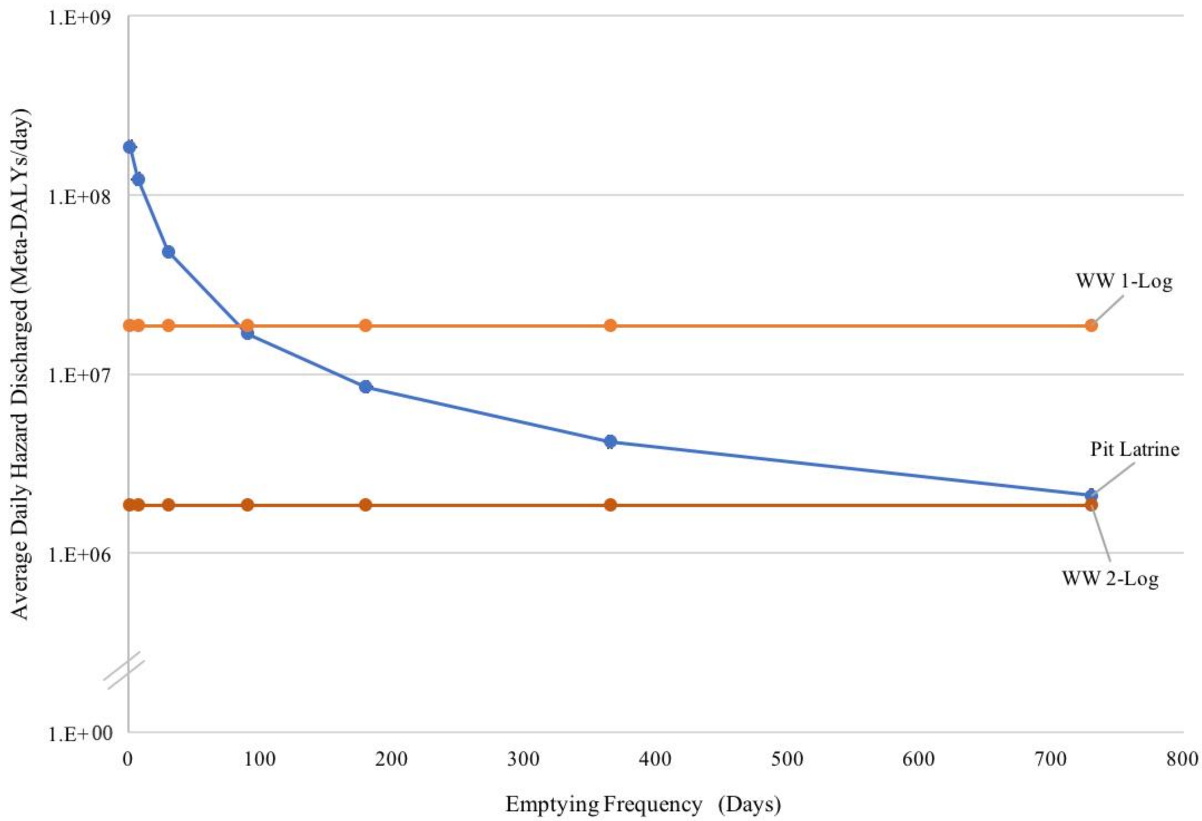


Figure 14. Daily average hazard discharged (Meta-DALYs per day) to the environment by pit latrines with different emptying frequencies vs. daily average hazard discharged to the environment by conventional sewerage treated $1Log_{10}$ and $2Log_{10}$.

Our findings conflict with the commonly held belief that sewerage is superior to pit latrines from a public health perspective [Hall et al., 2008; Holden et al., 2008]. A recent systematic review which conducted a meta-analysis found sewerage systems reduced diarrhea incidence by roughly 30% (RR 0.7, 95% CI 0.61 – 0.79) [Norman et al., 2010]. However, the majority of comparison groups in each study were flush toilets discharging to open drains, a considerable public health threat [Moraes et al., 2003]. Additionally, the level (or lack of) wastewater treatment and whether the communities populating the point of final sewerage discharge were included in the studies is not reported. While the review reported a protective effect from sewerage, the authors urged "cautious" interpretation of these findings particularly when comparing the health benefits of sewerage to pit latrines. Depending on where the sewerage is discharged, it may have protective effect for the individual household that is sewered, but not necessarily for the population at large [Hall et al., 2008; Norman et al., 2010]. Our results suggest that sewerage with wastewater treatment may be no more effective than properly managed pit latrines at reducing pathogen hazards.

Our model provides a method to help identify and target hazardous sources of fecal pathogens. Our technically simple model does not account for variations in exposure levels and as a result does not provide insight into risk. While this limit of our model has been discussed in previous sections, because of its important implications on our findings it necessitates another mention here.

Not accounting for exposure has its tradeoffs. While our model provides a method to help identify which sanitation sources may be the greatest sources of "pollution", which if tackled could reduce overall levels of fecal pollution in the environment, it does not prioritize sources of fecal pathogens based on discharge locations relative to human populations. For example, while a community's wastewater treatment plant may be less effective than their pit latrines at reducing pathogens, if the sewage is dumped far away while the majority of the pit latrine waste is dumped within the community, focusing on wastewater could potentially misallocate resources. Additionally, our model provides the foundation for estimating the hazard attributed to "leaks" along the sanitation service chain. However, if we examine leaks from the same sanitation technology, the hazard estimates will be similar but when exposure is considered the risk estimates could vary significantly.

While considering exposure and risk are decidedly important and worthwhile factors to consider, obtaining the necessary information to the numerous exposure pathways that exist and examine multiple sanitation technologies is a time and resource intensive feat. In particular, at a larger scale in communities which have diverse sanitation technologies and emptying practices, it will be difficult to disentangle and connect original sources of fecal pollution with their corresponding exposure pathways and assign appropriate risk estimates. The method of hazard quantification we propose here is technically simpler and potentially provides a clearer method for identifying and targeting the most hazardous sources of fecal pathogens in a community's sanitation network.

6.4. Sensitivity Analysis

Environmental factors influence the survival of pathogen species [Alum et al., 2014; Robertson et al., 1992; Atherholt et al., 1998; Jamieson et al., 2002], and as a result impact the effectiveness of sanitation interventions. Among environmental conditions, temperature, moisture levels, and pH are often cited as having significant effects on the survival of microorganisms [Alum et al., 2014; Atherholt et al., 1998]. To understand how sensitive our findings are to variations in these abiotic factors, we conducted a sensitivity analysis with the range of decay rates found in our systematic literature review. The decay rates we included only reflect changes in environmental conditions and do not reflect chemical treatments. All decay rates were determined for reference pathogens in fecal material; studies that examined decay in water, soil, surfaces, or waste stabilization ponds were excluded.

In the following sensitivity analysis, we reanalyzed the various results we presented above using the interquartile range (25^{th} percentile "K_{25}" to 75^{th} percentile "K_{75}") of pathogen decay rates we determined through our literature review. A graph of the interquartile decay rates is provided below for reference (see Figure 15). In particular, it should be noted that for all five reference pathogens there was a positive skew towards quicker decay rates.

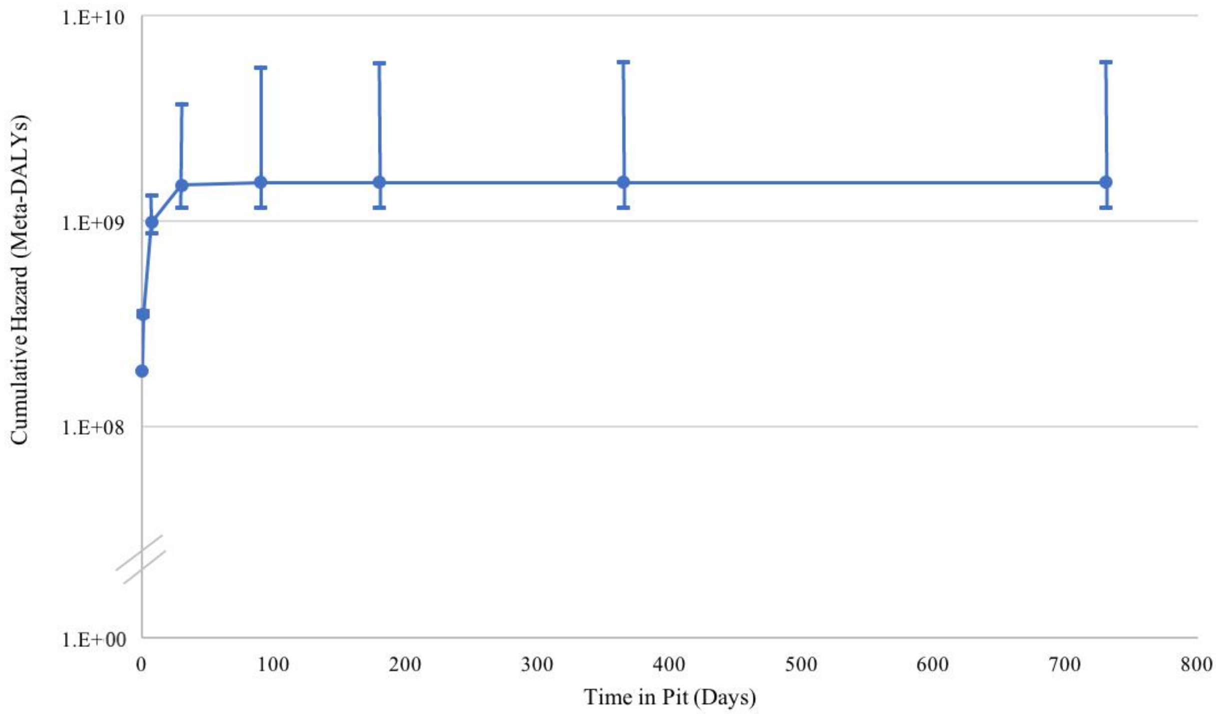


Figure 15. Cumulative hazard (Meta-DALYs) determined for the model pit latrine; summation of Meta-DALYs attributable to each reference pathogen with interquartile (IQR) range of decay rates displayed.

Under the range of decay rates, we found the temporal trends remained the same. Hazard increased and reached a constant level, or steady-state equilibrium (see Figure 15). While the general trends were the same, we found that comparison of the results between the first quartile(slower), the median, and the third quartile (faster) decay rates ($K_{2,}$ K_{50}, K_{75}) affected the magnitude of cumulative hazard and the time it took pit latrines to reach steady-state equilibrium. To our surprise, cumulative hazard at steady-state equilibrium varied by less than a factor of two [5.95×10^9 (K_{25}) to 1.16×10^9 (K_{75}) Meta DALYs]. However, the time it took to reach an steady-state equilibrium[21] was markedly increased at slower decay rates (1074 days) compared to the median decay rates (353 days). To reach 99% of the absolute steady state equilibrium level at K_{25} required 446 days, over 4x the number of days for median decay rates. Additionally, since the decay rates exhibited a positive skew we found there was not a

[21] By Eq. 11 a steady-state, or constant value, will not be reached but it will be approached asymptomatically. When we refer to a "steady-state" this refers to unchanging value at 99.99% level.

marked difference in the time it took K_{75} rates (257 days) to reach absolute steady state equilibrium levels compared to median decay rates.

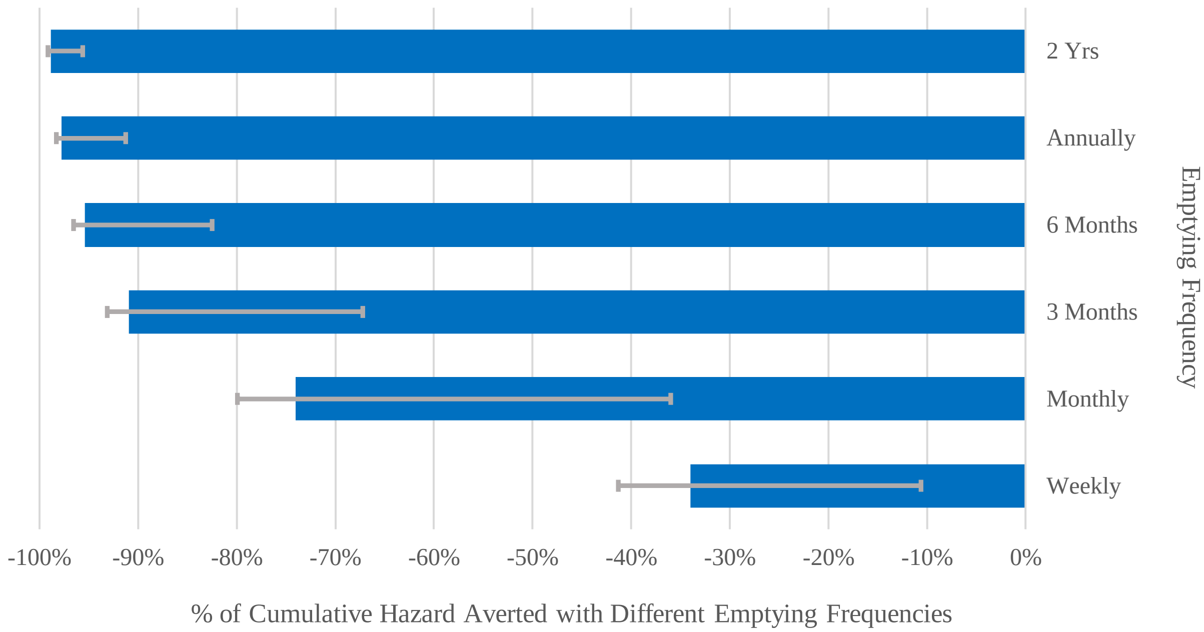


Figure 16. Percentage change in cumulative hazard (Meta-DALYs) discharged into the environment with different pit latrine emptying frequencies (base = daily emptying) and different IQR range of reference pathogen decay rates.

Decay rates affected the proportion of hazard averted based on different emptying frequencies (see Figure 16). However, with more infrequent emptying we found the impact from decay rates was reduced, despite the magnitude of the comparison group remaining the same (base = daily emptying aka OD) (see Figure 16). For example, the proportion of hazard averted by monthly emptying ranged from 79% to 46% whereas the proportion of hazard averted by annual emptying ranged from 97% to 92%. This presents further evidence that reducing pit emptying frequency, even in areas with unfavorable environmental conditions, can have a substantial influence on the quantity of hazard discharged by pit latrines.

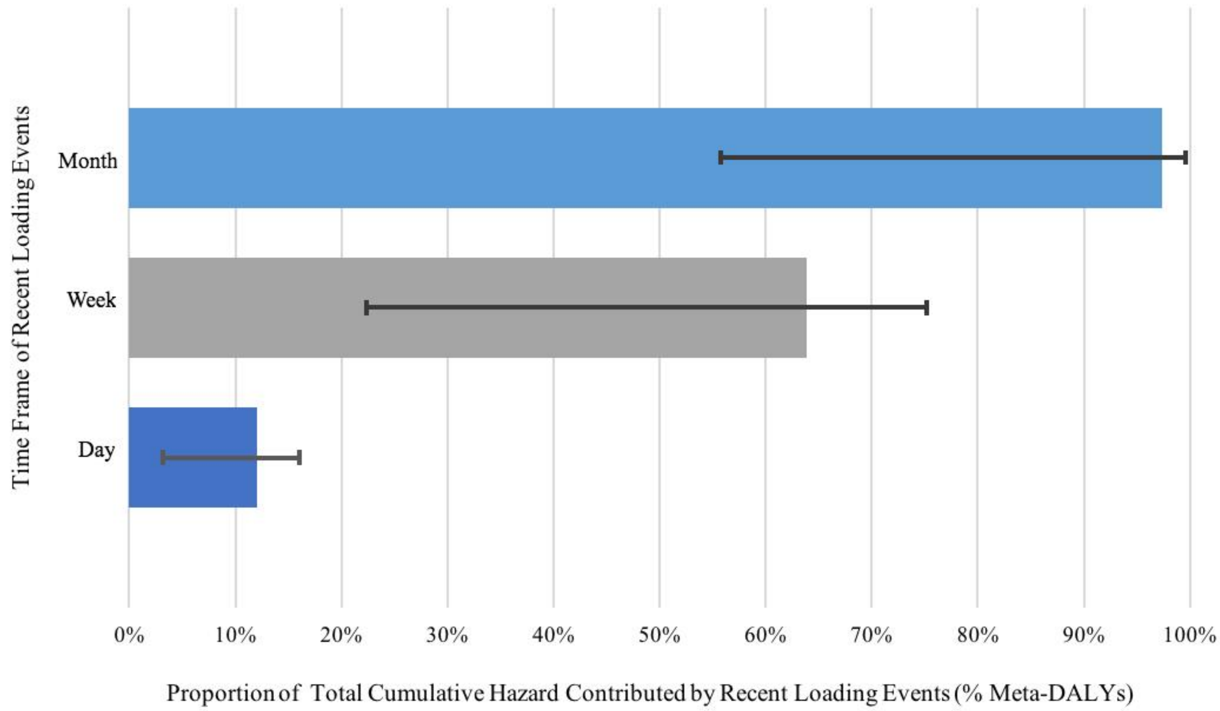


Figure 17. Proportion of Meta-DALYs contributed from recent loading events (day, week, and month) given a two-year use period with IQR range of pathogen decay rates displayed.

Variation in decay rates has a marked impact on the proportion of hazard that can be attributed to the most recent loading events (see Figure 17). Under median decay rates we estimated nearly 97% of the cumulative hazard was contributed in the most recent month whereas in poor environmental conditions we might find approximately 56% of the hazard is contributed in the same time frame, given a two-year use period. Despite a considerable decrease, this is still a substantial portion of the hazard, and provides further evidence that effective use of double pit technology can reduce total hazard discharged into the environment.

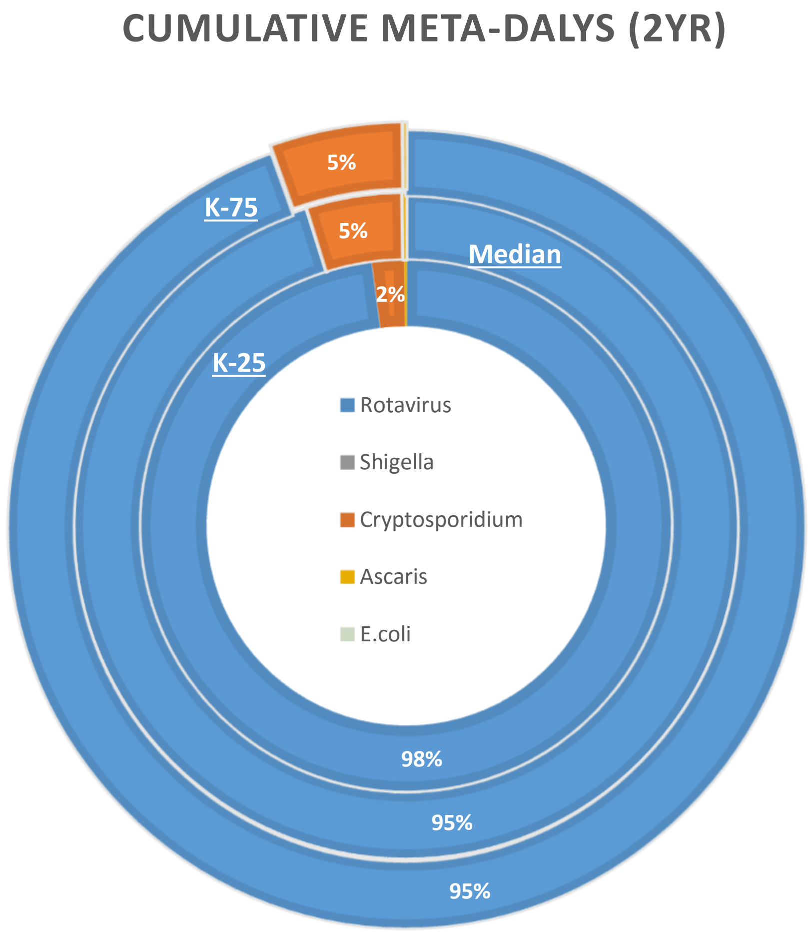


Figure 18. Proportion of cumulative hazard (Meta-DALYs) attributed to each reference pathogen, given a two-year pit latrine use period. The outer ring displays the proportional breakdown under K75 decay rates; the middle ring displays the proportional breakdown under median decay rates; and the inner ring displays the proportional breakdown under K_{25} decay rates. NOTE: The pathogens not displayed explicitly (i.e. *Shigella* spp., Ascaris, and *E. coli* sp.) comprise <1% of the cumulative hazard.

To our surprise, with the variation in decay rates, Rotavirus and *Cryptosporidium* spp. still comprised over 99% of the cumulative hazard (see Figure 18). There was no noticeable difference between the median decay rates and K_{75} decay rates. Under K_{25} rates, we found Rotavirus composed an even greater proportion of the cumulative hazard despite the fact that *Cryptosporidium* spp. is the more persistent microorganism.

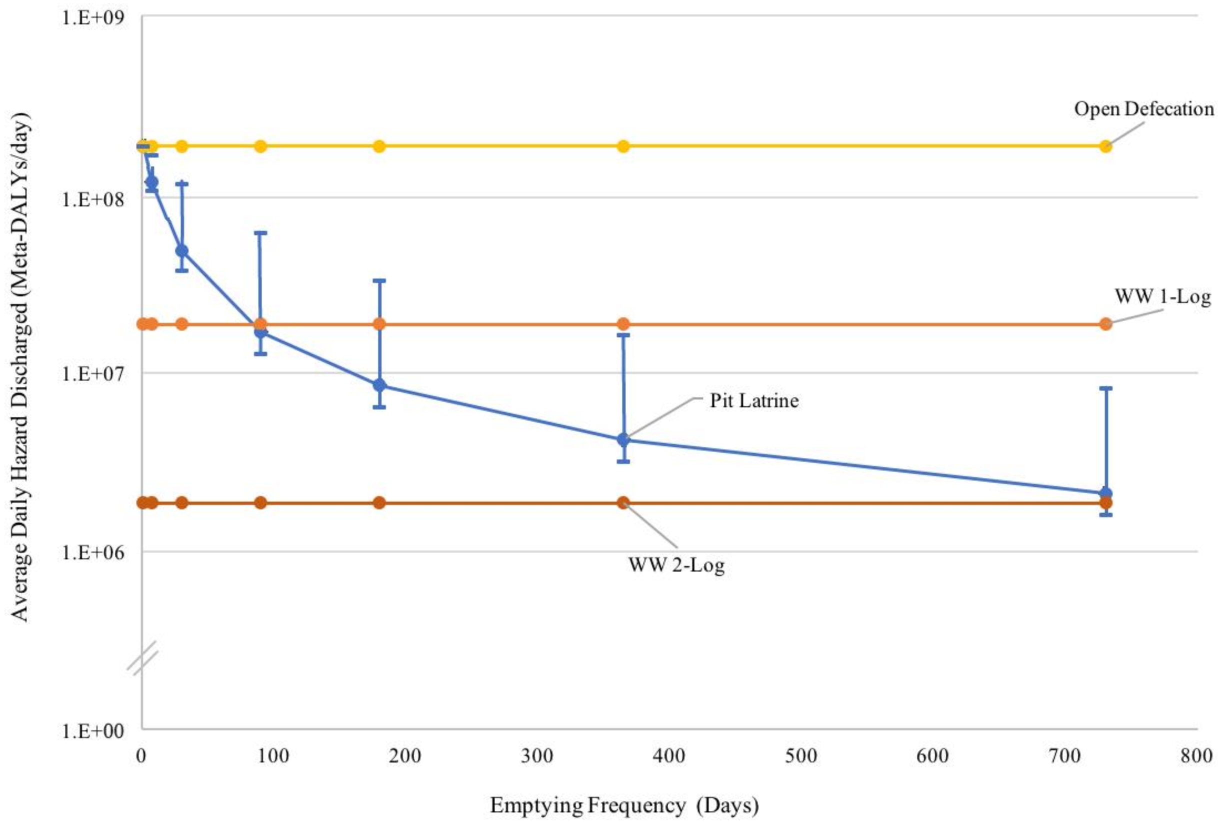


Figure 19. Daily average hazard discharged (Meta-DALYs per day) to the environment by pit latrines with different emptying frequencies vs. daily average hazard discharged to the environment by (1) open defecation, and conventional sewerage treated (2) $1Log_{10}$ and (3) $2Log_{10}$

Given a two-year emptying frequency (e.g. pit latrine use period), we found average daily hazard discharged ranged from 8.14×10^6 to 1.59×10^6 Meta-DALYs per day (see Figure 19) depending upon the assumed decay rates of pathogens. Given the range in average daily hazard discharged, we found pit latrines can reduce the average daily Meta-DALYs discharged by open defecation by 1.3 to 2-Log_{10}. Additionally, we were surprised to find that pit latrines, even in unfavorable environmental conditions can outperform 1-Log_{10} wastewater treatment, given an emptying frequency greater than 1 year. Furthermore, we found that under favorable environmental conditions pit latrines can actually outperform 2-Log_{10} wastewater treatment with a 2-year emptying frequency. The results of our sensitivity analysis, while relatively simple, provide evidence that pit latrines may pose less public health hazard compared to sewerage with wastewater treatment, even in unfavorable environmental conditions.

CHAPTER 7: CONCLUSIONS

The pit latrine hazard model we presented in this paper is the first to explicitly represent pathogen hazards and their relative accumulation and decay in pit latrines over time. While admittedly conceptual, our pit latrine hazard model can provide practical insights. By providing a full look at the "natural history" of a given waste stream, it allows planners to account for variations in pathogen hazards in a given community's pit latrine waste. It is intended to provide information that is currently unavailable or difficult to obtain through field studies. The major conclusions of this work are:

1. The hazard in pit latrines does not increase indefinitely with time, even for pit latrines in daily use. Given large enough pits, we found that the hazard will effectively reach a steady state equilibrium level of hazard in a relatively short period of time.
2. Less frequent pit emptying is better from a public health perspective; encouraging management practices (for example larger pits, effective solid waste management) that slow pit latrine fill rates could have a significant positive public health impact.
3. The most recent deposits contribute the vast majority of cumulative hazard in pit latrines and using systems like double pit technology can substantially reduce the hazard posed by pit latrines.
4. If people practicing open defecation were to adopt and consistently use pit latrines, a substantial fraction of pathogen hazard could be averted.
5. Unless wastewater treatment accompanying sewerage is of relatively high quality, it may be no more effective than properly managed pit latrines at reducing pathogen discharge to the environment.

Our model may help demonstrate that natural die-off and storage in pit latrines could effectively reduce the total hazard discharged into the environment and the feasibility of estimating the public health significance of pit latrines by tracking pathogens. Our technically simple conceptual model may help planners account for variations in pit latrine hazards. We believe that our simple formulation can be adapted and extended to assess different sanitation technologies, interventions, and a wide-range of sanitation problems.

ANNEX

Derivation of viable pathogen count:

$$N_t = \sum_{t=0}^{n} N_0 e^{-kt} = N_0 e^{-k(0)} + N_0 e^{-k(1)} + N_0 e^{-k(2)} + \cdots + N_0 e^{-kt}$$

$$N_t = N_0 + N_0 e^{-k(1)} + N_0 e^{-k(2)} + \cdots + N_0 e^{-k(t)}$$

$$N_t = N_0 (1 + e^{-k(1)} + e^{-k(2)} + \cdots + e^{-k(t)})$$

The "funny" section involved an arithmetic trick to simplify the equation

$$\left(\mathbf{1} - \boldsymbol{e^{-k}}\right) \times N_t = [N_0(1 + e^{-k(1)} + e^{-k(2)} + \cdots + e^{-k(t)})] \times (\mathbf{1} - \boldsymbol{e^{-k}})$$

NOTE:

1) $(1 - e^{-k}) \times N_t = N_t - N_t e^{-k}$

2) $e^{-k} \times (-e^{-k}) = -e^{-k-k} = -e^{-k(2)}$

3) $e^{-k} \times \left(-e^{-k(t)}\right) = -e^{-k-k(t)} = -e^{-k(1+t)}$

$$(N_t - N_t e^{-k}) = N_0[\left(1 + e^{-k} + e^{-k(2)} + \cdots + e^{-k(t)}\right) + (-e^{-k} - e^{-k(2)} - \cdots - e^{-k(t)} - e^{-k(1+t)})]$$

after cancelling out terms

$$N_t - N_t e^{-k} = N_0[1 - e^{-k(t+1)}]$$

$$N_t(1 - e^{-k}) = N_0[1 - e^{-k(t+1)}]$$

$$N_t = N_0 \frac{(1 - e^{-k(t+1)})}{(1 - e^{-k})}$$

REFERENCES

Alum, A., Absar, I. M., Asaad, H., Rubino, J. R., & Ijaz, M. K. (2014). Impact of environmental conditions on the survival of cryptosporidium and giardia on environmental surfaces. *Interdisciplinary Perspectives on Infectious Diseases*. http://doi.org/10.1155/2014/210385

Ambesh, P., & Ambesh, S. P. (2016). Open Defecation in India: A Major Health Hazard and Hurdle in Infection Control. *Journal of Clinical and Diagnostic Research : JCDR*, *10*(7), IL01-IL02. http://doi.org/10.7860/JCDR/2016/20723.8098

Anand, C. K., & Apul, D. S. (2014). Composting toilets as a sustainable alternative to urban sanitation – A review. *Waste Management*, *34*(2), 329–343. http://doi.org/10.1016/j.wasman.2013.10.006

Arnold, B. F., Hogan, D. R., Colford, J. M., & Hubbard, A. E. (2011). Simulation methods to estimate design power: an overview for applied research. *BMC Medical Research Methodology*, *11*(1), 94. http://doi.org/10.1186/1471-2288-11-94

Arthurson, V. (2008). Proper sanitization of sewage sludge: a critical issue for a sustainable society. *Applied and Environmental Microbiology*, *74*(17), 5267–5275. http://doi.org/10.1128/AEM.00438-08

Atherholt, T. B., LeChevallier, M. W., Norton, W. D., & Rosen, J. S. (1998). Effect of rainfall on Giardia and crypto. *Journal / American Water Works Association*, *90*(9), 66–80.

Baqui, A. H., Blackf, R. E., Md, Y., Hoque, R. A. A., Chowdhurv, H. R., & Sackf, R. B. (1991). Methodological Issues in Diarrhoeal Diseases Epidemiology: Definition of Diarrhoeal Episodes. *International Journal of Epidemiology*, *20*(20), 1057–1063.

Barlow, S. M., Boobis, A. R., Bridges, J., Cockburn, A., Dekant, W., Hepburn, P., … Bánáti, D. (2015). The role of hazard- and risk-based approaches in ensuring food safety. *Trends in Food Science & Technology*, *46*(2), 176–188. http://doi.org/10.1016/j.tifs.2015.10.007

Barnard, H. F. (1946). The effect of temperature on the survival of Shigella sonnei and Shigella flexneri in faeces. *Monthly Bulletin of the Ministry of Health and the Public Health Laboratory Service*, *5*, 261–264. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-84956549044&partnerID=40&md5=1d97f6a5329fcdace80ce659ffe16ac9

Barnard, S., Routray, P., Majorin, F., Peletz, R., Boisson, S., Sinha, A., & Clasen, T. (2013). Impact of Indian Total Sanitation Campaign on Latrine Coverage and Use: A Cross-Sectional Study in Orissa Three Years following Programme Implementation. *PLoS ONE*, *8*(8). http://doi.org/10.1371/journal.pone.0071438

Bartram, J., Cairncross, S., Kay, D., Enanoria, W., Haller, L., Cairncross, S., & Barreto, M. (2010). Hygiene, Sanitation, and Water: Forgotten Foundations of Health. *PLoS Medicine*, *7*(11). http://doi.org/10.1371/journal.pmed.1000367

Baum, R., Luh, J., & Bartram, J. (2013). Sanitation: A global estimate of sewerage connections without treatment and the resulting impact on MDG progress. *Environmental Science and Technology*, *47*(4), 1994–2000. http://doi.org/10.1021/es304284f

Bell, A., Layton, A. C., McKay, L., Williams, D., Gentry, R., & Sayler, G. S. (2009). Factors Influencing the Persistence of Fecal in Stream Water. *Journal of Environment Quality*, *38*(3), 12–24. http://doi.org/10.2134/jeq2008.0258

Berendes, D. M., Sumner, T. A., & Brown, J. M. (2017). Safely managed sanitation for all means fecal sludge management for at least 1.8 billion of the world's poorest people. *Envrionmental Science & Technology*, *51*(5), 3074–3083. http://doi.org/10.1021/acs.est.6b06019

Berendes, D., Levy, K., Knee, J., Handzel, T., Hill, V. R., & Labare, M. (2015). Ascaris and Escherichia coli Inactivation in an Ecological Sanitation System in Port-au-Prince, Haiti. *PloS One*, *10*. http://doi.org/10.1371/journal.pone.0125336

Biglan, A., Ary, D., Wagenaar, A. C., Cumming, O., Jenkins, M., Ensink, J. H. J., … Schmidt, W.-P. (2000). The effect of improved rural sanitation on diarrhoea and helminth infection: design of a cluster-randomized trial in Orissa, India. *Prevention Science*, *1*(1), 31–49. http://doi.org/10.1023/A:1010024016308

Boschi-Pinto, C. (2008). Estimating child mortality due to diarrhoea in developing countries. *Bulletin of the World Health Organization*, *86*(9), 710–717. http://doi.org/10.2471/BLT.07.050054

Boschi-Pinto, C., Lanata, C. F., & Black, R. E. (2009). The Global Burden of Childhood Diarrhea. In *Maternal and Child Health* (pp. 225–243). Boston, MA: Springer US. http://doi.org/10.1007/b106524_13

Brocklehurst, C. (2014). Scaling up Rural Sanitation in India. *PLoS Medicine*, *11*(8). http://doi.org/10.1371/journal.pmed.1001710

Brouckaert, C., Foxon, K., & Wood, K. (2013). Modelling the filling rate of pit latrines. *Water SA*, *39*(4). http://doi.org/10.4314/wsa.v39i4.15

Bychkovskaia, O. (1955). Duration of survival of dysenterial bacilli in dried feces. *Zhurnal Microbiology Epidemiology*, *3*, 19–22. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-77049220646&partnerID=40&md5=67712b85545b0ccb1aa8b48eecbcfd1b

Caballero-Hernandez, A., Castrejon-Pineda, F., Martinez-Gamba, R., Angeles-Campos, S., Perez-Rojas, M., & Buntinx, S. (2004). Survival and viability of Ascaris suum and Oesophagostomum dentatum in ensiled swine faeces. *Bioresource Technology*, *94*(2), 137–142. http://doi.org/10.1016/j.biortech.2003.12.008

Cairncross, S., & Petach, H. (2013). The risk of unimproved water and sanitation and the global burden of disease. *Journal of Water Sanitation and Hygiene for Development*, *3*(4), 479–480. http://doi.org/10.2166/washdev.2013.054

Cairncross, S., Bartram, J., Cumming, O., & Brocklehurst, C. (2010). Hygiene, Sanitation, and Water: What Needs to Be Done? *PLoS Medicine*, *7*(11). http://doi.org/10.1371/journal.pmed.1000365

Cairncross, S., Hunt, C., Boisson, S., Bostoen, K., Curtis, V., Fung, I. C. H., & Schmidt, W. P. (2010). Water, sanitation and hygiene for the prevention of diarrhoea. *International Journal of Epidemiology*, *39*, 193–205. http://doi.org/10.1093/ije/dyq035

Carlucci, A. F., & Pramer, D. (1959). Microbiological Process Report: Factors Affecting the Survival of Bacteria in Sea Water. *Applied Microbiology*, *7*, 388–392. Retrieved from http://aem.asm.org/content/7/6/388.full.pdf

Cheng, H.-W. A., Lucy, F. E., Broaders, M. A., Mastitsky, S. E., Chen, C.-H., & Murray, A. (2012). Municipal wastewater treatment plants as pathogen removal systems and as a contamination source of noroviruses and Enteroccus faecalis. *Journal of Water and Health*, *10*, 380–389. http://doi.org/10.2166/wh.2012.138

Chien, B. T., Chung, B. C., Nam, N. V., Nga, N. H., Noi, H., Stenstrom, T. A., … Winblad, U. (2002). Biological study on retention time of microoganisms in feacal material in urine- diverting eco-san latrines in vietnam. In *First International Conference on Ecological Sanitation* (pp. 1–5). Nanning, China.

Chunga, R. M., Ensink, J. H. J., Jenkins, M. W., & Brown, J. (2016). Adopt or Adapt: Sanitation Technology Choices in Urbanizing Malawi. *PLoS ONE*, *11*(8). http://doi.org/10.1371/journal.pone.0161262

Clasen, T. F., Bostoen, K., Schmidt, W.-P., Boisson, S., Fung, I. C.-H., Jenkins, M. W., … Cairncross, S. (2010). Interventions to improve disposal of human excreta for preventing diarrhoea. *Cochrane Database of Systematic Reviews*, *6*, 1–30. http://doi.org/10.1002/14651858.CD007180.pub2

Clasen, T., Fabini, D., Boisson, S., Taneja, J., Song, J., Aichinger, E., … Nelson, K. L. (2012). Making Sanitation Count: Developing and Testing a Device for Assessing Latrine Use in Low-Income Settings. *Environmental Science & Technology*, *46*(6), 3295–3303. http://doi.org/10.1021/es2036702

Clasen, T., Pruss-Ustun, A., Mathers, C. D., Cumming, O., Cairncross, S., & Colford, J. M. J. (2014). Estimating the impact of unsafe water, sanitation and hygiene on the global burden of disease: evolving and alternative methods. *Tropical Medicine and International Health*, *19*(8), 884–893. http://doi.org/10.1111/tmi.12330

Côté, C., Villeneuve, A. ., Lessard, L. ., & Quessy, S. . (2006). Fate of pathogenic and nonpathogenic microorganisms during storage of liquid hog manure in Québec. *Livestock Science*, *102*(3), 204–210. http://doi.org/10.1016/j.livsci.2006.03.018

Crane, S. R., & Moore, J. A. (1986). Modeling enteric bacterial die-off: A review. *Water, Air, & Soil Pollution*, *27*(3–4), 411–439. http://doi.org/10.1007/BF00649422

Diallo, M. O., Hopkins, D. R., Kane, M. S., Niandou, S., Amadou, A., Kadri, B., … Zingeser, J. A. (2007). Household latrine use, maintenance and acceptability in rural Zinder, Niger. *International Journal of Environmental Health Research*, *17*(6), 443–52. http://doi.org/10.1080/09603120701633529

Dumontet, S., Scopa, A., Kerje, S., & Krovacek, K. (2001). The Importance of Pathogenic Organisms in Sewage and Sewage Sludge. *Journal of the Air & Waste Management Association*, (51), 1096–2247. http://doi.org/10.1080/10473289.2001.10464313

Dung, L., & Smith, H. L. (1999). Steady States of Models of Microbial Growth and Competition with Chemotaxis. *Journal of Mathematical Analysis and Applications*, *229*(1), 295–318. http://doi.org/10.1006/jmaa.1998.6167

Eawag, & Sandec. (2006). Urban Excreta Management -Situation, Challenges, and Promising Solutions Sandec Water and Sanitation in Developing Countries. In *1st International Faecal Sludge Management Policy Symposium and Workshop* (pp. 1–12). Dakar, Senegal. Retrieved from www.sandec.ch

Endale, Y. T, Yirsaw, B. D., & Asfaw, S. L. (2012). Pathogen reduction efficiency of on-site treatment processes in eco-sanitation system. *Waste Management and Research*, *30*(7), 750–754. http://doi.org/10.1177/0734242X11432190

Esrey, S. A., Potash, J. B., Roberts, L., & Shiff, C. (1991). Effects of improved water supply and sanitation on ascariasis, diarrhoea, dracunculiasis, hookworm infection, schistosomiasis, and trachoma. *Bulletin of the World Health Organization*, *69*(5), 609–21. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/1835675

Evans, B. (2007). Understanding the Urban Poor's Vulnerabilities in Sanitation and Water Supply. In *Innovations for an Urban World, the Rockefeller Foundation's Urban Summit*. Bellagio, Italy: Center for Sustainable Urban Development. Retrieved from http://csud.ei.columbia.edu/files/2012/04/Week1_-Sanitation-and-Water-Supply_Finance_Evans.pdf

Feachem, R. G., Bradley, D. J., Garelick, H., & Mara, D. D. (1981). Health Aspects of Excreta and Sullage Management: A State-of-the-Art Review. In World Bank (Ed.), *Appropriate Technology for Water Supply and Sanitation* (pp. 1–328). Retrieved from http://www.ircwash.org/sites/default/files/303-81HE-18994.pdf

Feachem, R. G., Bradley, D. J., Garelick, H., & Mara, D. D. (1983). *Sanitation and Disease : Health Aspects of Excreta and Wastewater Management*. (World Bank, Ed.). Published for the World Bank by Wiley. Retrieved from http://documents.worldbank.org/curated/en/704041468740420118/Sanitation-and-disease-health-aspects-of-excreta-and-wastewater-management

Fernández Martínez, L. (2016). *Using the Shit/Excreta Flow Diagrams – SFDs-for modelling future scenarios in Kumasi, Ghana*. Loughborough University.

Fewtrell, L., Kaufmann, R. B., Kay, D., Enanoria, W., Haller, L., & Colford, J. M. (2005). Water, sanitation, and hygiene interventions to reduce diarrhoea in less developed countries: a systematic review and meta-analysis. *The Lancet Infectious Diseases*, *5*(1), 42–52. http://doi.org/10.1016/S1473-3099(04)01253-8

Fidjeland, J., Magri, M. E., Jönsson, H., Albihn, A., & Vinnerås, B. (2013). The potential for self-sanitisation of faecal sludge by intrinsic ammonia. *Water Research*, *47*(16), 6014–6023. http://doi.org/10.1016/j.watres.2013.07.024

Fidjeland, J., Nordin, A., Pecson, B. M., Nelson, K. L., & Vinnerås, B. (2015). Modeling the inactivation of ascaris eggs as a function of ammonia concentration and temperature. *Water Research*, *83*, 153–160. http://doi.org/10.1016/j.watres.2015.06.030

Fischer Walker, C. L., Sack, D., & Black, R. E. (2010). Etiology of diarrhea in older children, adolescents and adults: a systematic review. *PLoS Neglected Tropical Diseases*, *4*(8). http://doi.org/10.1371/journal.pntd.0000768

Fischer, T., Steinsland, H., & Valentiner-Branth, P. (2002). Rotavirus particles can survive storage in ambient tropical temperatures for more than 2 months. *Journal of Clinical Microbiology*, *40*(12), 4763–4764. http://doi.org/10.1128/JCM.40.12.4763-4764.2002

Fletcher, S. M., Stark, D., & Ellis, J. (2011). Prevalence of gastrointestinal pathogens in developed and developing countries: systematic review and meta-analysis. *Journal of Public Health Research*, *2*(2), e30. http://doi.org/10.4081/jphia.2011.e30

Foxon, K., Buckley, C., Brouckaert, C., & Bakare, B. (2011). What Happens When the Pit is Full ? - Developments in on-site Faecal Sludge Management (FSM). In Water Information Network South Africa (Ed.), *FSM Seminar 14-15 March 2011* (p. 48). Durban, South Africa.

Franceys, R., Pickford, J., & Reed, R. (1992). *A Guide to the Development of On-Site Sanitation*. World Health Organization. http://doi.org/10.1002/ppul.1950120122

Fremaux, B., Prigent-Combaret, C., & Vernozy-Rozand, C. (2008). Long-term survival of Shiga toxin-producing Escherichia coli in cattle effluents and environment: An updated review. *Veterinary Microbiology*, *132*(1–2), 1–18. http://doi.org/10.1016/j.vetmic.2008.05.015

Fujioka, R., & Yoneyama, B. (2002). Sunlight inactivation of human enteric viruses and fecal bacteria. *Water Science and Technology*, *46*(11–12), 291–295. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-0036951466&partnerID=40&md5=f97c9d348fc3d12c1869ebb7879fec89

GBD 2015, Kassebaum, N. J., Arora, M., Barber, R. M., Bhutta, Z. A., Brown, J., … Murray, C. J. L. (2016). Global, regional, and national disability-adjusted life-years (DALYs) for 315 diseases and injuries and healthy life expectancy (HALE), 1990–2015: a systematic analysis for the Global Burden of Disease Study 2015. *The Lancet*, *388*(10053), 1603–1658. http://doi.org/10.1016/S0140-6736(16)31460-X

GEMI. (2016). *Step-By-Step Monitoring Methodology for Indicator 6.2.1 : Integrated Monitoring of Water and Sanitation Related SDG Targets*.

Ghiglietti, R., Genchi, C., Matteo, L. Di, Calcaterra, E., & Colombi, A. (1997). Survival of Ascaris suum eggs in ammonia-treated wastewater sludges. *Bioresource Technology*, *96*, 195–198. http://doi.org/10.1016/S0960-8524(96)00147-2

Ghiglietti, R., Rossi, P., Ramsan, M., & Colombi, A. (1995). Viability of Ascaris suum, Ascaris lumbricoides and Trichuris muris eggs to alkaline pH and different temperatures. *Parassitologia*, *37*(2–3), 229–232. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-0029440087&partnerID=40&md5=7173081cc8c0f0cc2cddb5acf319c0b0

Gibbs, R., Hu, C., Ho, G., Phillips, P., & Unkovich, L. (1995). Pathogen die-off in stored wastewater sludge. *Water Science and Technology*, *31*, 91–95. http://doi.org/http://dx.doi.org/10.1016/0273-1223(95)00247-K

Gibson, D., Mihelcic, J., Izurieta, R., & Qiong, Z. (2014). *Inactivation of Ascaris in Double-Vault Urine-Diverting Composting Latrines in Panama: Methods and Environmental Health Engineering Field Applications*. University of South Florida.

Graham, J. P., & Polizzotto, M. L. (2013). Pit Latrines and Their Impacts on Groundwater Quality: A Systematic Review. *Environmental Health Perspectives*, *121*(5), 521–530. http://doi.org/10.1289/ehp.1206028

Guan, T. Y., & Holley, R. A. (2003). Pathogen Survival in Swine Manure Environments and Transmission of Human Enteric Illness—A Review. *Journal of Environment Quality*, *32*(2), 383. http://doi.org/10.2134/jeq2003.3830

Hall, D., & Lobina, E. (2008). *Sewerage Works - Public Investment in Sewers Saves Lives*. London. Retrieved from http://gala.gre.ac.uk/2426/1/HalldLobinae2008011.pdf

Hanemaaijer, M., Roling, W. F. M., Olivier, B. G., Khandelwal, R. A., Teusink, B., & Bruggeman, F. J. (2015). Systems modeling approaches for microbial community studies: from metagenomics to inference of the community structure. *Frontiers in Microbiology*, *6*, 213. http://doi.org/10.3389/fmicb.2015.00213

Hawkins, P. (1982). Emptying On-Site Excreta Disposal Systems in Countries: An Evaluation of the Problems. *WHO International Reference Centre for Wastes Disposal*, *17*, 16. Retrieved from http://www.eawag.ch/fileadmin/Domain1/Abteilungen/sandec/publikationen/ircwd/IRCWD_news_17.pdf

Hawkins, P., Blackett, I., Heymans, C., Evans, B., & Peal, A. (2014). The missing link in sanitation service delivery : a review of fecal sludge management in 12 cities. *Water and Sanitation Program: Research Brief*, (April), 1–8. Retrieved from http://documents.worldbank.org/curated/en/2014/04/19549016/targeting-urban-poor-improving-services-small-towns-missing-link-sanitation-service-delivery-review-fecal-sludge-management-12-cities

Hawkins, P., Blackett, I., Heymans, C., Perez, E., Moulik, S. G., Gambrill, M., … Ravikumar, J. (2013). Poor-Inclusive Urban Sanitation: An Overview Targeting the Urban Poor and Improving Services in Small Towns. *Water and Sanitation Program: Study*, 24. Retrieved from https://www.wsp.org/sites/wsp.org/files/publications/WSP-Poor-Inclusive-Urban-Sanitation-Overview.pdf

Hsu, S.-B. (1983). Steady States of a System of Partial Differential Equations Modeling Microbial Ecology. *SIAM Journal on Mathematical Analysis*, *14*(6), 1130–1138. http://doi.org/10.1137/0514087

Hussain, F., Clasen, T., Akter, S., Bawel, V., Luby, S. P., Leontsini, E., … Winch, P. J. (2017). Advantages and limitations for users of double pit pour-flush latrines: a qualitative study in rural Bangladesh. *BMC Public Health*, *17*(1), 515. http://doi.org/10.1186/s12889-017-4412-7

Hutton, G., & Varughese, M. (2016). *The Costs of Meeting the 2030 Sustainable Development Goal Targets on Drinking Water, Sanitation, and Hygiene*. Retrieved from http://documents.worldbank.org/curated/en/415441467988938343/pdf/103171-PUB-Box394556B-PUBLIC-EPI-K8543-ADD-SERIES.pdf

Inoue, M., Uga, S., Oda, T., Rai, S., Vesey, G., & Hotta, H. (2006). Changes of physical and biochemical properties of Cryptosporidium oocysts with various storage conditions. *Water Research*, *40*(5), 881–886. http://doi.org/10.1016/j.watres.2005.11.047

Jenkins, M. B., Bowman, D., & Ghiorse, W. C. (1998). Inactivation of Cryptosporidium parvum Oocysts by Ammonia. *Applied and Environmental Microbiology*, *64*(2), 784–788. Retrieved from http://aem.asm.org.libproxy.lib.unc.edu/content/64/2/784.full.pdf

Jenkins, M. W., Cumming, O., & Cairncross, S. (2015). Pit latrine emptying behavior and demand for sanitation services in Dar Es Salaam, Tanzania. *International Journal of Environmental Research and Public Health*, *12*. http://doi.org/10.3390/ijerph120302588

Jenkins, M. W., Cumming, O., Scott, B., & Cairncross, S. (2014). Beyond "improved" towards "safe and sustainable" urban sanitation: Assessing the design, management, and functionality of sanitation in poor communities of Dar es Salaam, Tanzania. *Journal of Water, Sanitation and Hygiene for Development*, *4*(1), 131–141.

Jenkins, M., Bowman, D., & Ghiorse, W. (1998). Inactivation of Cryptosporidium parvum Oocysts by Ammonia. *Applied and Environmental Microbiology*, *64*(2), 784–788. Retrieved from http://aem.asm.org.libproxy.lib.unc.edu/content/64/2/784.full.pdf

Jensen, M., Phuc, P., Knudsen, L., Dalsgaard, A., & Konradsen, F. (2008). Hygiene versus fertiliser: The use of human excreta in agriculture - A Vietnamese example. *International Journal of Hygiene and Environmental Health*, *211*(3–4), 432–439. http://doi.org/10.1016/j.ijheh.2007.08.011

Jensen, P., Phuc, P., Flemming, K., Klank, L., & Dalsgaard, A. (2009). Survival of Ascaris eggs and hygienic quality of human excreta in Vietnamese composting latrines. *Environmental Health: A Global Access Science Source*, *8*(1). http://doi.org/10.1186/1476-069X-8-57

Jiménez, B., Mara, D., Carr, R., & Brissaud, F. (2010). Wastewater Treatment for Pathogen Removal and Nutrient Conservation: Suitable Systems for Use in Developing Countries. In *Wastewater Irrigation and Health: Assessing and Mitigating Risk in Low-income Countries* (p. 21). Earthscan/James &James. Retrieved from http://publications.iwmi.org/pdf/H042608.pdf

Jiménez, B., Maya, C., & Galván, M. (2007). Helminth ova control in wastewater and sludge for advanced and conventional sanitation. *Water Science and Technology*, *56*(5), 43–51. http://doi.org/10.2166/wst.2007.555

Joint Monitoring Programme. (2015). *JMP Green Paper: Global monitoring of water, sanitation and hygiene post-2015*.

Katakam, K. K., Roepstorff, A., Popovic, O., Kyvsgaard, N. C., Thamsborg, S. M., & Dalsgaard, A. (2013). Viability of Ascaris suum eggs in stored raw and separated liquid slurry. *Parasitology*, *140*(3), 378–84. http://doi.org/10.1017/S0031182012001722

King, B. J., & Monis, P. T. (2007). Critical processes affecting Cryptosporidium oocyst survival in the environment. *Parasitology*, *134*, 309–323. http://doi.org/10.1017/S0031182006001491

Jensen, P., Phuc, P., Konradsen, F., Klank, L., Dalsgaard, A.. (2009). Survival of Ascaris eggs and hygienic quality of human excreta in Vietnamese composting latrines. *Environmental Health: A Global Access Science Source*, *8*(1). http://doi.org/10.1186/1476-069X-8-57

Kotloff, K. L., Nataro, J. P., Blackwelder, W. C., Nasrin, D., Farag, T. H., Panchalingam, S., … Levine, M. M. (2013). Burden and aetiology of diarrhoeal disease in infants and young children in developing countries (the Global Enteric Multicenter Study, GEMS): A prospective, case-control study. *The Lancet*, *382*(9888), 209–222. http://doi.org/10.1016/S0140-6736(13)60844-2

Kuczynska, E., & Shelton, D. (1999). Method for detection and enumeration of Cryptosporidium parvum oocysts in feces, manures, and soils. *Applied and Environmental Microbiology*, *65*(7), 2820–2826. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-0033019980&partnerID=40&md5=5ea62b3b13fae111d502381aae344856

Kvarnström, E., McConville, J., Bracken, P., Johansson, M., & Fogde, M. (2011). The sanitation ladder – a need for a revamp? *Journal of Water Sanitation and Hygiene for Development*, *1*(1). Retrieved from http://washdev.iwaponline.com/content/1/1/3

Lanata, C. F., Fischer-Walker, C. L., Olascoaga, A. C., Torres, C. X., Aryee, M. J., & Black, R. E. (2013). Global Causes of Diarrheal Disease Mortality in Children <5 Years of Age: A Systematic Review. *PLoS ONE*, *8*(9). http://doi.org/10.1371/journal.pone.0072788

Lemos, V., Graczyk, T. K., Alves, M., Lobo, M. L., Sousa, M. C., Antunes, F., & Matos, O. (2005). Identification and determination of the viability of Giardia lamblia cysts and Cryptosporidium parvum and Cryptosporidium hominis oocysts in human fecal and water supply samples by fluorescent in situ hybridization (FISH) and monoclonal antibodies. *Parasitology Research*, *98*(1), 48–53. http://doi.org/10.1007/s00436-005-0018-6

Lepeuple, A., Gaval, G., Jovic, M., & De Roubin, M. (2004). *Literature review on levels of pathogens and their abatement in sludges, soil and treated biowaste Horizontal project Literature review on levels of pathogens and abatements of them in the field of sludge, soil and treated biowaste*. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.531.6070&rep=rep1&type=pdf

Lewis, W. J., Foster, S. S. D., & Drasar, B. S. (1980). *THE RISK OF GROUNDWATER POLLUTION BY ON-SITE SANITATION IN DEVELOPING COUNTRIES A Literature Review*. Duebendorf, Switzerland. Retrieved from https://www.ircwash.org/sites/default/files/244-82RI-15490.pdf

Mackie Jensen, P. K., Phuc, P. D., Knudsen, L. G., Dalsgaard, A., & Konradsen, F. (2008). Hygiene versus fertiliser: The use of human excreta in agriculture - A Vietnamese example. *International Journal of Hygiene and Environmental Health*, *211*(3–4), 432–439. http://doi.org/10.1016/j.ijheh.2007.08.011

Magri, M. E., Philippi, L. S., & Vinnerås, B. (2013). Inactivation of pathogens in feces by desiccation and urea treatment for application in urine-diverting dry toilets. *Applied and Environmental Microbiology*, *79*, 2156–2163. http://doi.org/10.1128/AEM.03920-12

Magri, M., Fidjeland, J., Jönsson, H., Albihn, A., & Vinnerås, B. (2015). Inactivation of adenovirus, reovirus and bacteriophages in fecal sludge by pH and ammonia. *Science of the Total Environment*, *520*, 213–221. http://doi.org/10.1016/j.scitotenv.2015.03.035

Malik, O. A., Hsu, A., Johnson, L. A., & de Sherbinin, A. (2015). A global indicator of wastewater treatment to inform the Sustainable Development Goals (SDGs). *Environmental Science and Policy*, *48*, 172–185. http://doi.org/10.1016/j.envsci.2015.01.005

Mara, D. (1984). *The Design of Ventilated Improved Pit Latrines*. Washington, DC, USA. Retrieved from http://documents.worldbank.org/curated/en/618101468749362028/pdf/multi0page.pdf

Mara, D., Lane, J., Scott, B., & Trouba, D. (2010). Sanitation and Health. *PLoS Medicine*, *7*(11). http://doi.org/10.1371/journal.pmed.1000363

Martens, W., & Böhm, R. (2009). Overview of the ability of different treatment methods for liquid and solid manure to inactivate pathogens. *Bioresource Technology*, *100*, 5374–5378. http://doi.org/10.1016/j.biortech.2009.01.014

McKinley, J. W., Parzen, R. E., & Guzmán, Á. M. (2012). Ammonia inactivation of Ascaris ova in ecological compost by using urine and ash. *Applied and Environmental Microbiology*, *78*(15), 5133–5137. http://doi.org/10.1128/AEM.00631-12

Mehl, J. A. (2008). *Pathogen Destruction and Aerobic Decomposition in Composting Latrines: A Study from Rural Panama*. Michigan Technological University.

Mehl, J., Kaiser, J., Hurtado, D., Gibson, D. A., Izurieta, R., & Mihelcic, J. R. (2011). Pathogen destruction and solids decomposition in composting iatrines: study of fundamental mechanisms and user operation in rural Panama. *Journal of Water and Health*, *9*(1). http://doi.org/10.2166/wh.2010.138

Mitchell, C., Abeysuriya, K., & Ross, K. (2016). Making pathogen hazards visible : a new heuristic to improve sanitation investment efficacy. *Waterlines*, *35*(2), 163–181. http://doi.org/http://dx.doi.org/10.3362/1756-3488.2016.014

Moe, K., & Shirley, J. (1982). The effects of relative humidity and temperature on the survival of human rotavirus in faeces. *Archives of Virology*, *72*(3), 179–186. http://doi.org/10.1007/BF01348963

Moraes, L. R. S., Cancio, J. A., Cairncross, S., & Huttly, S. (2003). Impact of drainage and sewerage on diarrhoea in poor urban areas in Salvador, Brazil. *Transactions of the Royal Society of Tropical Medicine and Hygiene*, *97*(2), 153–158. http://doi.org/10.1016/S0035-9203(03)90104-0

Naidoo, S., & Olaniran, A. O. (2013). Treated wastewater effluent as a source of microbial pollution of surface water resources. *International Journal of Environmental Research and Public Health*, *11*(1), 249–70. http://doi.org/10.3390/ijerph110100249

Nakamura, M., & Taylor, B. (1965). Survival of Shigella in biological materials. *Health Laboratory Science*, *2*(4), 220–226. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-0013806205&partnerID=40&md5=e48eef1e05564f89771b29b3589ea82b

Nasser, A. (2016). Removal of Cryptosporidium by wastewater treatment processes: A review. *Journal of Water and Health*, *14*(1), 1–13. http://doi.org/10.2166/wh.2015.131

Nordin, A., Nyberg, K, & Vinnerås, B. (2009). Inactivation of ascaris eggs in source-separated urine and feces by ammonia at ambient temperatures. *Applied and Environmental Microbiology*, *75*(3), 662–667. http://doi.org/10.1128/AEM.01250-08

Norman, G., Pedley, S., & Takkouche, B. (2010). Effects of sewerage on diarrhoea and enteric infections: a systematic review and meta-analysis. *The Lancet Infectious Diseases*, *10*, 536–544. http://doi.org/10.1016/S1473-3099(10)70123-7

Ogunyoku, T. A., Habebo, F., & Nelson, K. L. (2016). In-toilet disinfection of fresh fecal sludge with ammonia naturally present in excreta. *Journal of Water Sanitation and Hygiene for Development*, *6*(1), 104–114. http://doi.org/10.2166/washdev.2015.233

Opel, A., & Bashar, M. K. (2013). Inefficient technology or misperceived demand: the failure of Vacutug-based pit-emptying services in Bangladesh. *Waterlines*, *32*(3), 213–220. http://doi.org/10.3362/1756-3488.2013.022

ORSTAVIK, I., FIGENSCH.KJ, & ULSTRUP, J. C. (1974). ROTAVIRUS IN STORED SPECIMENS OF FECAL EXTRACTS. *LANCET*, *2*(7888), 1083.

Ottoson, J., Hansen, A., Björlenius, B., Norder, H., & Stenström, T. A. (2006). Removal of viruses, parasitic protozoa and microbial indicators in conventional and membrane processes in a wastewater pilot plant. *Water Research*, *40*(7), 1449–1457. http://doi.org/10.1016/j.watres.2006.01.039

Pandey, P. K., Biswas, S., Vaddella, V. K., & Soupir, M. L. (2015). Escherichia coli persistence kinetics in dairy manure at moderate, mesophilic, and thermophilic temperatures under aerobic and anaerobic environments. *Bioprocess Biosystem Engineering*, *38*, 457–467. http://doi.org/10.1007/s00449-014-1285-3

Patil, S. R., Arnold, B. F., Salvatore, A. L., Briceno, B., Ganguly, S., Colford, J. M., & Gertler, P. J. (2014). The Effect of India's Total Sanitation Campaign on Defecation Behaviors and Child Health in Rural Madhya Pradesh: A Cluster Randomized Controlled Trial. *PLoS Medicine*, *11*(8). http://doi.org/10.1371/journal.pmed.1001709

Paula, A., Ramos, D., Stefanelli, C. C., Elisa, R., Linhares, C., Guimara, B., … Nozawa, C. (2000). The stability of porcine rotavirus in feces. *Veterinary Microbiology*, *71*, 1–8. Retrieved from http://ac.els-cdn.com/S0378113599001406/1-s2.0-S0378113599001406-main.pdf?_tid=d670c0a4-22cf-11e7-80e9-00000aacb362&acdnat=1492366351_ab4b542483ea07a5d3940fc68979418d

Paulsrud, B., Gjerde, B., & Lundar, A. (2004). Full scale validation of helminth ova (Ascaris suum) inactivation by different sludge treatment processes. *Water Science and Technology*, *49*(10), 139–146. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-3242759175&partnerID=40&md5=13d8d6ff0ecc3eada0454dfd1a7bdd4a

Peal, A., Evans, B., Blackett, I., Hawkins, P., & Heymans, C. (2015). *A Review of Fecal Sludge Management in 12 Cities*. *Water and Sanitation Program*. Retrieved from http://www.susana.org/en/resources/library/details/2212

Pecson, B. M., Barrios, J. A., Jiménez, B. E., & Nelson, K. L. (2007). The effects of temperature, pH, and ammonia concentration on the inactivation of Ascaris eggs in sewage sludge. *Water Research*, *41*(13), 2893–2902. http://doi.org/10.1016/j.watres.2007.03.040

Pell, A. N. (1997). Manure and microbes: Public and animal health problem? *JOURNAL OF DAIRY SCIENCE*, *80*(10), 2673–2681. Retrieved from http://citeseerx.ist.psu.edu.libproxy.lib.unc.edu/viewdoc/download?doi=10.1.1.473.2285&rep=rep1&type=pdf

Peng, X., Murphy, T., & Holden, N. (2008). Evaluation of the effect of temperature on the die-off rate for Cryptosporidium parvum oocysts in water, soils, and feces. *Applied and Environmental Microbiology*, *74*(23), 7101–7107. http://doi.org/10.1128/AEM.01442-08

Pesaro, F., Sorg, I., & Metzler, A. (1995). In situ inactivation of animal viruses and a coliphage in nonaerated liquid and semiliquid animal wastes. *Applied and Environmental Microbiology*, *61*(1), 92–

97. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-0028888023&partnerID=40&md5=0cf9e5460ec8e48eddb5f7c00309fb5c

Platts-Mills, J. A., Babji, S., Bodhidatta, L., Gratz, J., Haque, R., Havt, A., … MAL-ED Network Investigators. (2015). Pathogen-specific burdens of community diarrhoea in developing countries: a multisite birth cohort study (MAL-ED). *The Lancet. Global Health*, *3*(9), e564-75. http://doi.org/10.1016/S2214-109X(15)00151-5

Polprasert, C., & Valencia, L. (1981). The inactivation of faecal coliforms and Ascaris ova in faeces by lime. *Water Research*, *15*(1), 31–36. http://doi.org/10.1016/0043-1354(81)90179-2

Pompeo, R., Andreoli, C., De Castro, E., & Aisse, M. (2016). Influence of Long-Term Storage Operating Conditions on the Reduction of Viable Ascaris Eggs in Sewage Sludge for Agricultural Reuse. *Water, Air, and Soil Pollution*, *227*(5), 144. http://doi.org/10.1007/s11270-016-2816-0

Pope, C. A., & Dockery, D. W. (2006). Health Effects of Fine Particulate Air Pollution: Lines that Connect. *Journal of the Air & Waste Management Association*, *566*, 1096–2247. http://doi.org/10.1080/10473289.2006.10464485

Prüss-Ustün, A., Bartram, J., Clasen, T., Colford, J. M. J., Cumming, O., Curtis, V., … Cairncross, S. (2014). Burden of disease from inadequate water, sanitation and hygiene in low- and middle-income settings: a retrospective analysis of data from 145 countries. *Tropical Medicine & International Health : TM & IH*, *19*(8), 894–905. http://doi.org/10.1111/tmi.12329

Prüss-Üstün, A., Bos, R., Gore, F., & Bartram, J. (2008). *Safe water, better health: costs, benefits and sustainability of interventions to protect and promote health*. Geneva: World Health Organization. Retrieved from http://apps.who.int/iris/bitstream/10665/43840/1/9789241596435_eng.pdf

Prüss-Üstün, A., Kay, D., Fewtrell, L., Bartram, J., Pruss, A., Kay, D., … Bartram, J. (2002). Estimating the burden of disease from water, sanitation, and hygiene at a global level. *Environmental Health Perspectives*, *110*(5), 537–542. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/12003760

Reed, R. (1994). Why pit latrines fail: some environmental factors. *Waterlines*, *13*(2), 5–7. http://doi.org/10.3362/0262-8104.1994.036

Robertson, L., Campbell, A., & Smith, A. (1992). Survival of Cryptosporidium parvum Oocysts under Various Environmental Pressures. *Applied and Envrionmental Microbiology*, *58*(11), 3494–3500.

Romero-Maraccini, O. C. (2014). *Inactivation kinetics and mechanisms of rotavirus: The roles of sunlight, temperature, and sensitizers*. *ProQuest Dissertations and Theses*. University of Illinois at Urbana-Champaign, Ann Arbor. Retrieved from http://libproxy.lib.unc.edu/login?url=http://search.proquest.com/docview/1652503793?accountid=14244

Ropeik, D., & Gray, G. (2002). *Risk : a practical guide for deciding what's really safe and what's dangerous in the world around you*. Boston: Houghton Mifflin. Retrieved from http://search.lib.unc.edu/search?R=UNCb4222756

Rose, J. B. (1997). Environmental ecology of Cryptosporidium and public health implications. *Annual Review of Public Health*, *18*, 135–161. http://doi.org/10.1146/annurev.publhealth.18.1.135

Rze, A., & Cook, N. (2004). Survival of human enteric viruses in the environment and food. *FEMS Microbiology Reviews*, *28*, 441–453. http://doi.org/10.1016/j.femsre.2004.02.001

Schmidt, W. P., Cairncross, S., Barreto, M. L., Clasen, T., & Genser, B. (2009). Recent diarrhoeal illness and risk of lower respiratory infections in children under the age of 5 years. *International Journal of Epidemiology*, *38*(3), 766–772. http://doi.org/10.1093/ije/dyp159

Schmitz, B. W. (2016). *Reduction of Enteric Pathogens and Indicator Microorganisms in the Environment and Treatment Processes.* The University of Arizona. Retrieved from http://search.proquest.com.libproxy.lib.unc.edu/docview/1777617018?pq-origsite=summon

Schönning, C., Stenström, T. A., & Programme, E. (2005). Guidelines for the safe use of urine and faeces in ecological sanitation systems. *Journal of Indian Water Works Association*, *37*(4), 291–292. Retrieved from www.sei.se

Schüle, S. A., Clowes, P., Kroidl, I., Kowuor, D. O., Nsojo, A., Mangu, C., … Saathoff, E. (2014). Ascaris lumbricoides infection and its relation to environmental factors in the Mbeya region of Tanzania, a cross-sectional, population-based study. *PloS One*, *9*(3). http://doi.org/10.1371/journal.pone.0092032

SFD Promotion Initiative. (2017). *SFD Manual Volume 1 and 2*. Retrieved from http://www.susana.org/_resources/documents/default/3-2357-7-1501150297.pdf

Spears, D., Ghosh, A., Cumming, O., Ramachandran, P., & Sankar, M. (2013). Open Defecation and Childhood Stunting in India: An Ecological Analysis of New Data from 112 Districts. *PLoS ONE*, *8*(9). http://doi.org/10.1371/journal.pone.0073784

Stenstrom, T. A. (2002). Reduction Efficiency of Index Pathogens in Dry Sanitation Compared With Traditional and Alternative Wastewater Treatment. *Environmental Microbiology*, 1–5.

Still, D., & Foxon, K. (2012). *Tackling the Challenges of Full Pit Latrines Volume 1: Understanding sludge accumulation in VIPs and strategies for emptying full pits*. Durban, South Africa. Retrieved from http://www.wrc.org.za/Knowledge Hub Documents/Research Reports/1745 Volume 1.pdf

Strauch, D. (1991). Survival of pathogenic micro-organisms and parasites in excreta, manure and sewage sludge. *Rev. Sci. Tech. Off. Int. Epiz*, *10*(3), 813–846. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/1782431

Thye, Y. P., Templeton, M. R., & Ali, M. (2009). Pit Latrine Emptying: Technologies, Challenges and Solutions. In *EWB-UK-Research Conference* (p. 10). London: Imperial College London and Practical Action, UK.

Tilley, E., Lüthi, C., Morel, A., Zurbrügg, C., & Schertenleib, R. (2014). *Compendium of Sanitation Systems and Technologies* (2nd Revise). EAWAG Aquatic Research. http://doi.org/SAN-12

Tremolet, S., Prat, M.-A., & Monsour, G. (2014). *Un-sewered Sanitation Improvements for the Urban-Poor Overview of the African Water Facility project portfolio*. Retrieved from https://www.africanwaterfacility.org/fileadmin/uploads/awf/Publications/Urban_Sanitation_Portfolio_Review.pdf

Trimmer, J., Nakyanjo, N., Ssekubugu, R., Sklar, M., Mihelcic, J., & Ergas, S. (2016). Estimation of Ascaris lumbricoides egg inactivation by free ammonia treatment of ash-amended UDDT vault products using stored urine in Uganda. *Journal of Water Sanitation and Hygiene for Development*, *6*(2), 259–268. http://doi.org/10.2166/washdev.2016.111

Trondel, B. (2010). Sanitation Ventures Literature Review : on-site sanitation waste characteristics. *London School of Hygiene and Tropical Medicine*, *4*(1), 1–30.

Turner, C., & Burton, C. H. (1997). The inactivation of viruses in pig slurries: A review. *Bioresource Technology*, *61*, 9–20. http://doi.org/10.1016/S0960-8524(97)84693-7

U.S. Environmental Protection Agency - Office of Water. (2010). *Quantitative Microbial Risk Assessment to Estimate Illness in Freshwater Impacted by Agricultural Animal Sources of Fecal Contamination*. Retrieved from https://www.epa.gov/sites/production/files/2015-11/documents/quantitiave-microbial-risk-fecal.pdf

UNICEF, & WHO. (2015). *Progress on Sanitation and Drinking Water - 2015 Update and MDG Assessment*. Geneva. Retrieved from http://www.who.int/about/licensing/copyright_form/en/index.html

Verbyla, M. E. (2015). *Pathogen Removal in Natural Wastewater Treatment and Resource Recovery Systems: Solutions for Small Cities in an Urbanizing World*. *ProQuest Dissertations and Theses*. University of South Florida, Ann Arbor. Retrieved from http://libproxy.lib.unc.edu/login?url=http://search.proquest.com/docview/1747438579?accountid=14244

Vinneras, B. (2013). Sanitation and Hygiene in Manure Management. In L. Sommer, SG and Christensen, ML and Schmidt, T and Jensen (Ed.), *Animal Manure Recycling: Treatment and Management* (pp. 91–104).

Waddington, H., Snilstveit, B., White, H., & Fewtrell, L. (2009). *Water, sanitation and hygiene interventions to combat childhood diarrhoea in developing countries*.

Walker, C. L. F., Aryee, M. J., Boschi-Pinto, C., & Black, R. E. (2012). Estimating diarrhea mortality among young children in low and middle income countries. *PloS One*, *7*(1). http://doi.org/10.1371/journal.pone.0029151

Wang, W. L., Dunlop, S. G., & Munson, P. S. (1966). Factors influencing the survival of Shigella in wastewater and irrigation water. *Journal of the Water Pollution Control Federation*, *38*(11), 1775–1781. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-0013967976&partnerID=40&md5=ebcc90128a2576fbcaff233bb39ef7d1

Whitmore, T., & Robertson, L. (1995). The effect of sewage sludge treatment processes on oocysts of Cryptosporidium parvum. *Journal of Applied Bacteriology*, *78*(1), 34–38. http://doi.org/10.1111/j.1365-2672.1995.tb01670.x

Williams, A. R., & Overbo, A. (2015). *Unsafe return of human excreta to the environment: a literature review*. Chapel Hill.

Wolf, J., Prüss-Ustün, A., Cumming, O., Bartram, J., Bonjour, S., Cairncross, S., … Higgins, J. P. T. (2014). Assessing the impact of drinking water and sanitation on diarrhoeal disease in low- and middle-income settings: systematic review and meta-regression. *Tropical Medicine & International Health : TM & IH*, *19*(8), 928–942. http://doi.org/10.1111/tmi.12331

Wood, K. (2013). *Transformation of faecal sludge in VIPS: modelling fill rate with an unsteady-state mass balance*. University of KwaZulu-Natal.

World Health Organization. (2006). *Excreta and Greywater in Agriculture*. *Guidelines for the Safe Use of Wastewater, Excreta, and Greywater* (Vol. IV). Geneva. http://doi.org/10.1007/s13398-014-0173-7.2

World Health Organization. (2016). *Quantitative Microbial Risk Assessment: Application for Water Safety Management*. Geneva. Retrieved from http://www.who.int/about/licensing/

Young, S. L., Brelsford, J. W., & Wogalter, M. S. (1990). Judgments of Hazard, Risk, and Danger: Do They Differ? *Proceedings of the Human Factors Society Annual Meeting*, *34*(5), 503–507. http://doi.org/10.1177/154193129003400515

Ziegelbauer, K., Speich, B., Mausezahl, D., Bos, R., Keiser, J., & Utzinger, J. (2012). Effect of sanitation on soil-transmitted helminth infection: systematic review and meta-analysis. *PLoS Medicine*, *9*(1). http://doi.org/10.1371/journal.pmed.1001162

Ziemer, C., Bonner, J., Cole, D., Vinjé, J., Constantini, V., Goyal, S., … Saif, L. (2010). Fate and transport of zoonotic, bacterial, viral, and parasitic pathogens during swine manure treatment, storage, and land application. *Journal of Animal Science*, *88*, 84–94. http://doi.org/10.2527/jas.2009-2331

Zziwa, A., Lugali, Y., Wanyama, J., Banadda, N., Kabenge, I., Kambugu, R., … Tumutegyereize, P. (2016). Contextual investigation of factors affecting sludge accumulation rates in lined pit latrines within Kampala slum areas, Uganda. *Water SA*, *42*(3). http://doi.org/10.4314/wsa.v42i3.15

Zziwa, A., Nabulime, M. N., Kiggundu, N., Kambugu, R., Katimbo, A., & Komakech, A. J. (2016). A critical analysis of physiochemical properties influencing pit latrine emptying and feacal sludge disposal in Kampala Slums, Uganda. African Journal of Environmental Science and Technology, 10, 316–328. http://doi.org/10.5897/AJEST2016.21