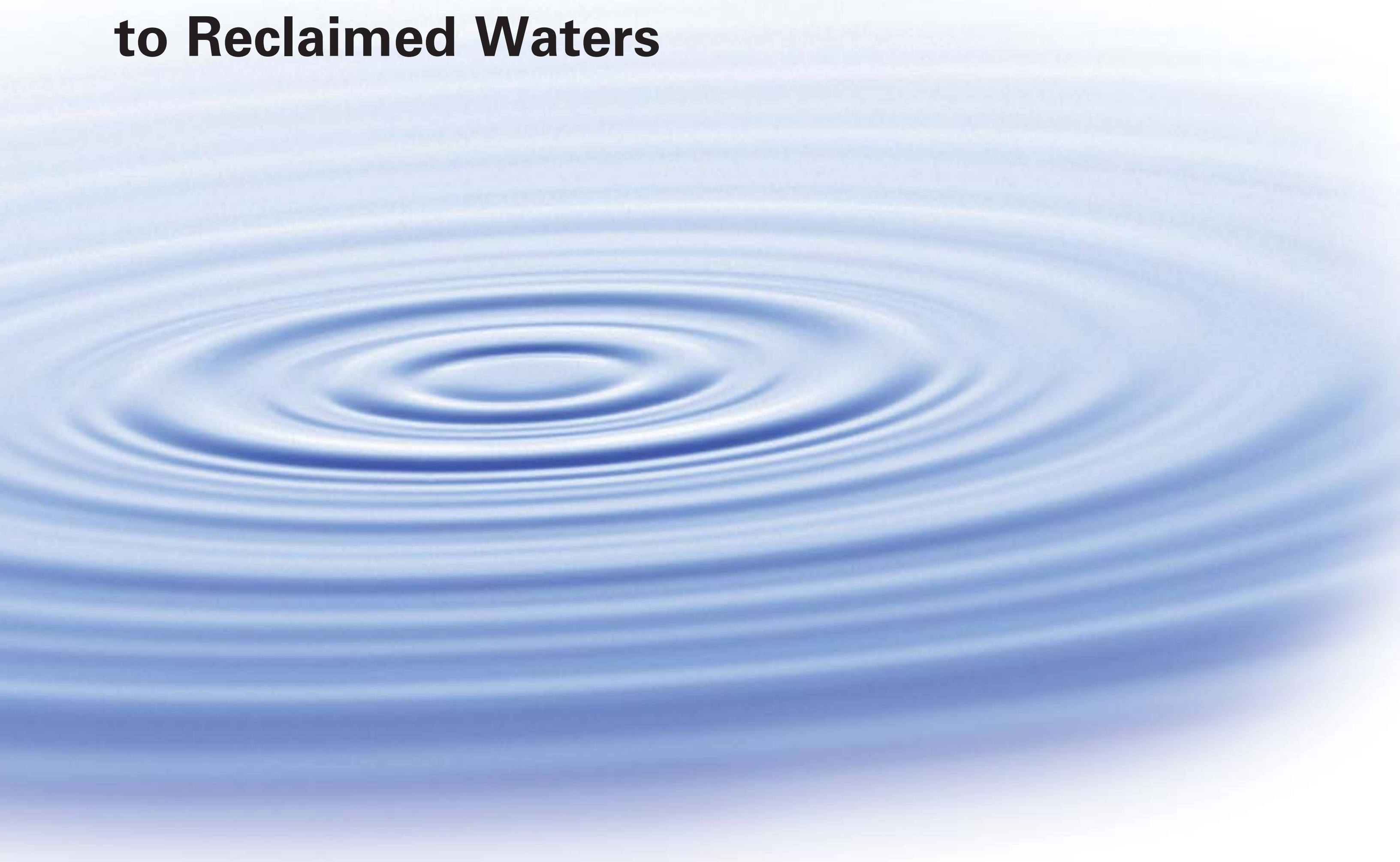
WATEREUSE
FOUNDATION

Application of Microbial Risk Assessment Techniques to Estimate Risk Due to Exposure to Reclaimed Waters



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About the WateReuse Foundation

The mission of the WateReuse Foundation is to conduct and promote applied research on the reclamation, recycling, reuse, and desalination of water. The Foundation's research advances the science of water reuse and supports communities across the United States and abroad in their efforts to create new sources of high quality water through reclamation, recycling, reuse, and desalination while protecting public health and the environment.

The Foundation sponsors research on all aspects of water reuse, including emerging chemical contaminants, microbiological agents, treatment technologies, salinity management and desalination, public perception and acceptance, economics, and marketing. The Foundation's research informs the public of the safety of reclaimed water and provides water professionals with the tools and knowledge to meet their commitment of increasing reliability and quality.

The Foundation's funding partners include the U.S. Bureau of Reclamation, the California State Water Resources Control Board, the Southwest Florida Water Management District, and the California Department of Water Resources. Funding is also provided by the Foundation's Subscribers, water and wastewater agencies, and other interested organizations. The Foundation also conducts research in cooperation with the Global Water Research Coalition.

Application of Microbial Risk Assessment Techniques to Estimate Risk Due to Exposure to Reclaimed Waters

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ACRONYMS

CT	contact time (chlorine)
gpm	gallons per minute
MGD	million gallons per day
MMWD	Marin Municipal Water District
MPN	most probable number
MRA	microbial risk assessment
MRAIT	Microbial Risk Assessment Interface Tool
NTU	nephelometric turbidity units
SBWR	South Bay Water Recycling (CA)
TSS	total suspended solids
WERF	Water Environment Research Foundation
WPCP	water pollution control plant
WRF	water reclamation facility
WWTP	wastewater treatment plant

FOREWORD

The WateReuse Foundation, a nonprofit corporation, sponsors research that advances the science of water reclamation, recycling, reuse, and desalination. The Foundation funds projects that meet the water reuse and desalination research needs of water and wastewater agencies and the public. The goal of the Foundation's research is to ensure that water reuse and desalination projects provide high-quality water, protect public health, and improve the environment.

A Research Plan guides the Foundation's research program. Under the plan, a research agenda of high-priority topics is maintained. The agenda is developed in cooperation with the water reuse and desalination communities, including water professionals, academics, and Foundation Subscribers. The Foundation's research focuses on a broad range of water reuse research topics including the following:

- Evaluating methods for managing salinity and desalination;
- Public perceptions of the benefits and risks of water reuse;
- Economics and marketing of water reuse;
- Groundwater recharge and aquifer storage and recovery;
- Defining and addressing emerging contaminants; and
- Management practices related to indirect potable reuse.

The Research Plan outlines the role of the Foundation's Research Advisory Committee (RAC), Project Advisory Committees (PACs), and Foundation staff. The RAC sets priorities, recommends projects for funding, and provides advice and recommendations on the Foundation's research agenda and other related efforts. PACs are convened for each project and provide technical review and oversight. The Foundation's RAC and PACs consists of experts in their fields and provide the Foundation with an independent review, which ensures the credibility of the Foundation's research results. The Foundation's Project Managers facilitate the efforts of the RAC and PACs and provide overall management of projects.

The Foundation's funding partners are the U.S. Bureau of Reclamation, the California State Water Resources Control Board, the Southwest Florida Water Management District, the California Department of Water Resources, Foundation Subscribers, water and wastewater agencies, and other interested organizations. The Foundation leverages its financial and intellectual capital through these partnerships and funding relationships. The Foundation is also a member of the Global Water Research Coalition.

This publication is the result of a study sponsored by the Foundation and is intended to communicate the results of this research project. The objective of this project was to use existing microbial risk assessment approaches to assess nonpotable water reuse applications and develop a matrix of relative microbial risks associated with the use of reclaimed water under a range of different conditions.

This report provides water and wastewater utility managers important supporting information to make informed risk-based management decisions about reclaimed water treatment, end uses, and management options. The information developed will aid regulatory agencies in evaluating public health risks associated with existing or proposed water reuse regulations. Improved science and reduced uncertainty also may lead to increased public acceptance of reclaimed water.

Ronald E. Young	G. Wade Miller
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The research team would like to thank the WateReuse Foundation for funding this applied research project, as well as the following organizations for their in-kind contributions: City of St. Petersburg (FL), Marin Municipal Water District (CA), East Bay Municipal Utility District (CA), City of Sunnyvale Water Pollution Control Plant (CA), and South Bay Water Recycling (CA).

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EXECUTIVE SUMMARY

ES.1 OBJECTIVES

The objective of this project was to use existing microbial risk assessment approaches to assess nonpotable water reuse applications and develop a matrix of relative microbial risks associated with the use of reclaimed water under a range of different conditions. The risk matrix and insights generated as a product of this work provide perspective on water reuse applications that water and wastewater utility managers can use as decision-making tools. The range of conditions that were considered included the following:

- Occurrence of various infectious agents in reclaimed water (obtained from available occurrence data)
- Treatment processes used to produce the reclaimed water
- End uses and use-specific exposure pathways
- Disease end points
- Exposed population characteristics, from healthy to sensitive subgroups

ES.2 METHODS

The basic approach for this project was to utilize existing data and microbial risk assessment methods to derive a matrix of relative risks based on combinations of specific pathogens that are representative of the pathogens most likely to be of public health concern, treatment processes that are representative of those currently used to produce reclaimed water, and relevant exposure routes based on nonpotable reclaimed water applications currently used in the United States.

Data were obtained from the literature to characterize the concentrations of the pathogens at various points in the wastewater treatment process and the expected levels of reductions of those pathogens through wastewater treatment for the combination of treatment processes investigated. The reclaimed water treatment processes evaluated, secondary treatment with chlorine disinfection and tertiary treatment (secondary treatment plus chemical addition and filtration) with chlorine disinfection, were intended to be representative of the wastewater treatment processes that are in operation at reclamation facilities in Arizona, California, and Florida. Data from the published literature were also used to estimate the volume of water ingested for each of the routes of exposure, as well as the relation between the number of organisms ingested (dose) and the probability of infection and/or illness (depending on the pathogen of interest). Numerical simulation was used to address variability and uncertainty in the computed estimates of risk. The microbial risk assessment simulations were conducted using the recently developed Microbial Risk Assessment Interface Tool (MRAIT) (Soller et al., 2007). Static (individual-level) microbial risk assessment simulations were used as the base model to compute risks for the matrix. In addition, dynamic (population-level) microbial risk assessment simulations were run for selected scenarios for comparative purposes.

Finally, four public agencies in California that have water reclamation programs (City of Sunnyvale, South Bay Water Recycling, East Bay Municipal Utility District, and Marin Municipal Water District) and one in Florida (City of St. Petersburg) were used as case study examples to illustrate how water and wastewater utility managers might use the results of the risk matrix to provide insight about relative risks from microbial contaminants in reclaimed water and nonpotable uses of that water.

ES.3 RESULTS

A summary microbial risk assessment simulation results is presented in Table ES.1. Each set of simulations consisted of 5000 individual estimates of risk (the probability of infection or illness) associated with exposures to reclaimed water for specific combinations of pathogens, routes of exposure, and classes of wastewater treatment.

Review of the results presented in Table ES.1 indicates the following:

- Of the three routes of exposure investigated, the risks associated with full body contact recreation in undiluted effluent are estimated to be greater than those associated with landscape irrigation by approximately 5× and greater than those associated with crop irrigation by approximately 1 order of magnitude (10×).
- Under equivalent assumptions regarding exposure to reclaimed water and wastewater treatment level, the estimated attributable risks associated with human viruses, *Cryptosporidium parvum*, and *Giardia lamblia* are of similar magnitude.
- For reclaimed water exposures, the risks associated with exposure to human viruses, *Cryptosporidium*, and *Giardia* are higher than those associated with other pathogens.
- The risks associated with disinfected tertiary effluent are lower than those associated with disinfected secondary effluent by approximately a 0.5 order of magnitude.
- The variability and uncertainty associated with the estimated levels of risk associated with exposure to pathogens present in reclaimed water are substantial. The 90% confidence bounds of the risk estimates span approximately 3 orders of magnitude.

For the scenarios investigated, the static and dynamic model results are in relatively good agreement. However, it appears that accounting for person-to-person transmission of infection and immunity slightly increases the magnitude of the estimated risks for all the scenarios investigated. This observation is consistent with previously reported results (Soller et al., 2004).

Table ES.1. Summary of Individual-Level Microbial Risk Assessment Simulation Results

			Health	Estimated Risk per Event[3]		
Pathogen	**Treatment**	**Exposure**	**Outcome[2]**	**10%-ile**	**Median**	**90%-ile**
Human viruses[1]	Disinfected secondary	Recreation[4]	Infection	9.2E-06	2.2E-04	5.1E-03
Human viruses[1]	Disinfected secondary	Landscape irrigation	Infection	3.8E-06	6.2E-05	9.5E-04
Human viruses[1]	Disinfected secondary	Crop irrigation	Infection	2.7E-07	1.7E-05	1.1E-03
Human viruses[1]	Disinfected tertiary	Recreation	Infection	1.5E-06	5.1E-05	1.6E-03
Human viruses[1]	Disinfected tertiary	Landscape irrigation	Infection	5.3E-07	1.4E-05	3.0E-04
Human viruses[1]	Disinfected tertiary	Crop irrigation	Infection	4.5E-08	3.9E-06	3.5E-04
Cryptosporidium	Disinfected secondary	Recreation	Infection	3.2E-05	5.4E-04	8.4E-03
Cryptosporidium	Disinfected secondary	Landscape irrigation	Infection	1.3E-05	1.4E-04	1.3E-03
Cryptosporidium	Disinfected secondary	Crop irrigation	Infection	6.8E-07	3.9E-05	1.6E-03
Cryptosporidium	Disinfected tertiary	Recreation	Infection	4.1E-06	1.5E-04	5.1E-03
Cryptosporidium	Disinfected tertiary	Landscape irrigation	Infection	1.4E-06	4.0E-05	9.2E-04
Cryptosporidium	Disinfected tertiary	Crop irrigation	Infection	1.1E-07	1.0E-05	9.0E-04
Giardia	Disinfected secondary	Recreation	Infection	1.9E-05	4.0E-04	9.1E-03
Giardia	Disinfected secondary	Landscape irrigation	Infection	6.2E-06	1.1E-04	1.7E-03
Giardia	Disinfected secondary	Crop irrigation	Infection	4.6E-07	3.1E-05	2.0E-03
Giardia	Disinfected tertiary	Recreation	Infection	1.6E-06	6.7E-05	2.4E-03
Giardia	Disinfected tertiary	Landscape irrigation	Infection	5.4E-07	1.6E-05	4.9E-04
Giardia	Disinfected tertiary	Crop irrigation	Infection	4.6E-08	4.5E-06	5.1E-04
Salmonella spp.	Disinfected secondary	Recreation	Illness	<1E-9	<1E-9	<1E-9
Salmonella spp.	Disinfected secondary	Landscape irrigation	Illness	<1E-9	<1E-9	<1E-9
Salmonella spp.	Disinfected secondary	Crop irrigation	Illness	<1E-9	<1E-9	<1E-9
Salmonella spp.	Disinfected tertiary	Recreation	Illness	<1E-9	<1E-9	<1E-9
Salmonella spp.	Disinfected tertiary	Landscape irrigation	Illness	<1E-9	<1E-9	<1E-9
Salmonella spp.	Disinfected tertiary	Crop irrigation	Illness	<1E-9	<1E-9	<1E-9
E. coli O157:H7	Disinfected tertiary	Recreation	Infection	1.5E-08	4.6E-07	1.4E-05
E. coli O157:H7	Disinfected tertiary	Landscape irrigation	Infection	5.1E-09	1.1E-07	2.3E-06
E. coli O157:H7	Disinfected tertiary	Crop irrigation	Infection	<1E-9	3.1E-08	2.4E-06

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1. Simulations are intended to be representative of risks to humans from enteric viruses and are based on enterovirus occurrence and rotavirus infectivity (dose response).
2. Health outcomes shown are consistent with human feeding studies for the various pathogens. Outcomes are the probability of illness for *Salmonella* and the probability of infection for other pathogens. The probability that an infection results in illness varies among pathogens.
3. Values shown are per exposure event.
4. Assumes full body contact and ingestion of water consistent with that observed during epidemiological studies.

ES. 4 COMPARISON WITH PREVIOUSLY REPORTED RESULTS

Tanaka et al. (1998) examined the safety of wastewater reclamation and reuse and developed tables of estimated annual risks of infection from enteric viruses for chlorinated secondary effluents and tertiary chlorinated effluents used for golf course irrigation, food crop irrigation, recreational impoundments, and groundwater recharge. A more detailed discussion is contained in section 4.1. Tanaka et. al. employed a number of different assumptions from those used in this investigation, including basic assumptions about treatment efficacy and exposure; nevertheless, a comparison of the results is illustrative.

Comparison of the average daily risk of infection from enteric viruses related to recreational exposure to treated effluent reported by Tanaka et al. (1998) with the estimates presented in Table ES.1 indicates the following:

- The computed mean daily risks for recreation in disinfected (chlorinated) secondary effluent reported by Tanaka et al. (1998) range from 3×10^{-6} to 2×10^{-4}, with upper 95% confidence limits ranging from 7×10^{-6} to 3×10^{-4}.

- In our investigation, the estimated median risk from human viruses per event for recreation in disinfected secondary effluent is 2×10^{-4} with a reported 90th percentile of 5×10^{-3} (Table ES.1).

- The computed mean daily risks for recreation in disinfected (chlorinated) tertiary effluent reported by Tanaka et al. (1998) range from 1×10^{-7} to 8×10^{-6}, with upper 95% confidence limits ranging from 3×10^{-7} to 2×10^{-5}.

- In our investigation, the estimated median risk from human viruses per event for recreation in disinfected tertiary effluent is 5×10^{-5} with a reported 90th percentile of 2×10^{-3} (Table ES.1).

It is important to note that a number of different assumptions were employed by Tanaka et al. in their analysis, compared to the analysis conducted as part of this investigation. However, based on the comparison, it appears that the estimated microbial risk results for recreational exposure presented in this report are slightly higher (i.e., by approximately 1 order of magnitude) than those reported by Tanaka et al. (1998).

ES.5 CASE STUDY RESULTS

Five public agencies that have water reclamation programs—four in California (City of Sunnyvale, City of San Jose, East Bay Municipal Utility District, and Marin Municipal Water District) and one in Florida (City of St. Petersburg)—provided data and information to conduct case studies and interpret the microbial risk assessment output matrix.

Section 3.3 contains the estimated microbial risk results for each facility. The case studies include descriptions of the facilities and the reclaimed water that is produced, summaries of the reclaimed water uses, summaries of data provided by the agencies, and an explanation of how to interpret the risk matrix results presented previously within the context of each agency.

In four of the five case studies, pathogen data were not available to conduct risk assessment calculations. For these case studies without pathogen data, it was not possible to directly compute the risks to human health associated with exposure to effluent. However, by assuming that the effluent quality from different facilities that use similar treatment processes is similar when the facilities are operated under designed operating conditions, it is possible to draw insights from the risk simulations presented in Table ES.1. A summary of the results for one use is contained in Table ES.2.

Table ES.2 Summary of Individual-Level Relative Microbial Risk Assessments for Case Study Examples

Facility Name	Treatment Type	Reuse Type(s) Evaluated	Est. Microbial Risk (Median) of Infection per Exposure[1]	Basis of Est. Microbial Risk[2]
City of Sunnyvale, CA	Disinfected tertiary	Landscape (includes golf courses and parks)	4×10^{-5}	Table ES.1
City of San Jose, CA	Disinfected tertiary	Landscape (includes golf courses and parks), industrial	4×10^{-5}	Table ES.1
East Bay Municipal Utility District, CA	Disinfected tertiary	Landscape	1×10^{-4}	Table ES.1
Marin Municipal Water District, CA	Disinfected tertiary	Landscape	4×10^{-5}	Table ES.1
		Car washing	2×10^{-4}	
City of St. Petersburg, FL	Disinfected tertiary	Landscape (includes golf courses and parks)	4×10^{-5}	Table ES.1
			6×10^{-6}	*Giardia* data
			6×10^{-5}	*Cryptosporidium* data

1. Estimates are reported as the highest of the median risks of infection for enteric viruses, *Cryptosporidium*, and *Giardia.*
2. Estimates based on simulation results shown in Table ES.1 or for limited pathogen data, as noted.

Because of the uncertainty in the underlying assumptions associated with the simulation results, the inferences drawn from the case studies without pathogen data should be interpreted cautiously. Nevertheless, the case studies provide valuable perspectives on the relative risks associated with the selected reuse exposure to reclaimed water for a series of pathogens of potential public health concern.

ES.6 LIMITATIONS AND DATA GAPS

Several important simplifying assumptions were needed to conduct the analyses, and several important gaps in knowledge became apparent during the conduct of this investigation. A summary of the most important assumptions and data gaps is provided below.

Microbial Risk Assessment Model Form: With respect to the selected models for disease transmission, it is well known that a variety of model forms can be employed to characterize infectious disease transmission and to evaluate the potential for effective interventions. In our analysis, the salient assumption was that the epidemiological status of the population could be approximated reasonably well with the relatively simple structure of individual- and population-level microbial risk assessment models. It is possible that other model structures could yield additional and/or alternative insights.

Health Outcomes: The health outcomes considered in this investigation were illness (for *Salmonella* spp.) and infection (for all other pathogens). The most common adverse health outcome from the pathogens investigated is gastroenteritis. However, there are a number of other more serious but less likely disease outcomes that also are associated with these and other enteric pathogens. Characterization of end points more serious than gastroenteritis (such as long-term sequelae) was beyond the scope of this investigation. Nevertheless, the relative insights provided by the assessments presented here would likely also be valid for other end points.

Model Parameterization: The reported results are applicable only to the extent that the parameter values used for the microbial risk assessment models are reasonable and appropriate. Although a substantial effort was made to characterize the parameter values in a health-protective manner, it is possible that parameter values could be refined or changed based on future research.

Sensitive Subgroups within a Population: In this investigation, an attempt was made to quantitatively characterize risks to highly susceptible or vulnerable subgroups within a population for exposures to microbial contaminants in water. However, sufficient quantitative data were not available to enable the characterization of risk for those subpopulation groups separately from the population at large. Similar findings have been reported previously (Parkin et al., 2003).

Noroviruses: Noroviruses are estimated to cause approximately 23,000,000 cases of illness in the United States annually (Mead et al., 1999) and are believed to be associated with up to 90% of the epidemic nonbacterial gastroenteritis worldwide (Lindesmith et al., 2003). At the current time, rigorous modeling of norovirus transmission is extremely difficult due to lack of data on the relation between dose and response, cross-strain immunity, the magnitude of person-to-person transmission, and immunity. Hence, it was not feasible to include noroviruses in this investigation.

Treatment Effectiveness for Wastewater Treatment Processes: In this investigation, the efficacies of two reclaimed water treatment process configurations were evaluated. The reclaimed water treatment processes evaluated, secondary treatment with chlorine disinfection and tertiary treatment (secondary treatment plus chemical addition and filtration) with chlorine disinfection, were intended to be representative of the wastewater treatment processes that are in operation at reclamation facilities in Arizona, California, and Florida. A more comprehensive understanding of the treatment efficacy associated with wastewater unit processes, including alternative types of treatment, would add additional insight to the information presented in this report.

ES.7 POLICY CONTEXT

Several states have developed water reuse standards for nonpotable uses that include treatment process requirements and microbial and other water quality limits. However, no states have regulations that are fundamentally risk based. It is, therefore, not surprising that the actual and/or perceived stringency of the resultant criteria varies widely among the existing state criteria. Thus, one possible extension of this research would be as a starting point to consider the scientific basis of water reuse regulations and, hence, the public health protection afforded by existing and potential future regulations.

If states were to consider risk-based reclaimed water regulations, one of the most important issues that would need to be addressed is that of acceptable or tolerable risk. That is, evaluating the adequacy of a particular treatment train requires a benchmark level (or set of criteria) that can be used for comparison. Selection of a benchmark level of risk can be a complicated process that involves technical, political, and social factors. For example, the existing Ambient Water Quality Criteria for bacteria in recreational waters are set to limit the rate of highly credible gastrointestinal illness in swimmers to a median value of 8 per 1000 (8×10^{-3}) in freshwater and a median of 19 per 1000 (1.9×10^{-2}) in marine waters (U.S. EPA, 1986). It is not suggested that the above value is appropriate for reclaimed waters. Rather, it is suggested that consideration of the processes used to determine acceptable risk levels for other water-related exposures may be useful in determining how to arrive at an acceptable or tolerable level of risk which could be used for future regulation of reclaimed water.

Several other important issues would also need to be considered if states were to consider risk-based reclaimed water regulations. For example, states would need to determine which pathogens to regulate, if there are appropriate surrogates or indicators for those pathogens, and how to ensure regulations protect the public against exposure to pathogens that are extremely difficult or expensive to enumerate. Nevertheless, the research presented here is sufficiently robust to initiate such discussions if regulators, water quality managers, and the public are ready to consider moving to risk-based reclaimed water regulations.

ES.8 CONCLUSIONS AND RESEARCH RECOMMENDATIONS

In this investigation, microbial risk assessment numerical simulations were conducted to provide insight toward understanding the relative risks to human health associated with nonpotable water reuse applications. To this end, a risk matrix was developed to facilitate understanding of the relative microbial risks associated with the use of reclaimed water for nonpotable reuse applications under a range of different conditions. The conditions evaluated included the occurrence of five infectious agents of public health concern in reclaimed water, the efficacy in reducing pathogen concentrations of two reclaimed water treatment process trains, and the predicted volume of water ingested via three end-use-specific exposure pathways.

The information presented in this report will be useful to water and wastewater utility managers, regulators, and water quality scientists and engineers, because it is based on scientifically defensible data that can be used to compare the potential relative risks associated with nonpotable water reuse applications under a wide range of relevant conditions. The estimated risks reported in this investigation are consistent with, although slightly higher than, those reported by others in the published literature.

A prioritized list of recommendations that emanate from this work is as follows:

- Develop a more comprehensive understanding of the treatment efficacies associated with various wastewater unit processes, including alternative types of treatment

- Evaluate the scientific basis of water reuse regulations and, hence, the public health protection afforded by existing and potential future regulations

- Continue to consider addressing if and how sensitive subgroups within the population and/or life stages are subject to risks that are different from those for the general population

CHAPTER 1

INTRODUCTION

1.1 OBJECTIVE

The main objective of this investigation was to use existing microbial risk assessment (MRA) approaches to assess the relative risks associated with nonpotable water reuse applications and provide water and wastewater utility managers with decision-making tools for water reuse applications. The objective was to be realized by developing a matrix of relative microbial risks associated with the use of reclaimed water for nonpotable reuse applications under a range of different conditions, including the following:

- Occurrence of various infectious agents in reclaimed water
- Treatment processes used to produce the reclaimed water
- End uses and use-specific exposure pathways
- Disease end points
- Exposed population characteristics, from healthy to sensitive subgroups

To accomplish the project's objective, it was necessary to conduct a critical review of existing MRA tools. The WateReuse Foundation request for proposals for this project also requested documentation of data gaps encountered during the course of the project and a list of research needs based on the results of the study.

1.2 BACKGROUND

While potable reuse has been receiving increasing attention in recent years, most reclaimed water is used for nonpotable applications. In general, considerably lower levels of wastewater treatment are required for nonpotable applications than for potable reuse applications.

The potential transmission of infectious diseases by pathogenic agents is the most common concern associated with nonpotable reuse of treated municipal wastewater. Sanitary engineering and preventive medical practices have combined to reach a point where waterborne disease outbreaks of epidemic proportions have, to a great extent, been controlled. However, the potential for disease transmission through the water route has not been completely eliminated. With a few exceptions, the disease organisms of epidemics in history are still present in today's sewage, and their status is more one of minimizing transmission rather than a total eradication of the disease agent. Thus, the potential spread of infectious diseases through water reuse remains a public health concern.

The occurrence and concentration of pathogenic microorganisms in raw municipal wastewater depend on a number of factors, and it is not possible to predict with any degree of assurance what the general characteristics of a particular wastewater will be with respect to infectious agents. The infectious agents that may be present in untreated municipal wastewater can be classified into three broad groups: bacteria, parasites (protozoa and helminths), and viruses.

Currently, either total or fecal coliform organisms are the preferred indicator organisms for reclaimed water in the United States. Regulatory decisions regarding both the selection of which coliform group to use and the appropriate limit are somewhat subjective. Other indicator organisms, e.g., enterococci and *Escherichia coli*, have been proposed but for various reasons are not recommended or required in any existing reuse regulations or guidelines in the United States, with the one exception that *E. coli* is used as the indicator in Colorado reclaimed water regulations. Indicator organisms by themselves are not adequate to predict the presence or absence of pathogens. Factors that may influence the likelihood of the presence of pathogens include but are not limited to treatment processes, type of disinfection, and specific characteristics of the water being treated.

While several states have developed water reuse standards for nonpotable uses that include treatment process requirements and microbial and other water quality limits, no existing state regulations are based on risk assessment methodology. This has resulted in widely varying criteria among the states that have developed regulations and has raised issues and concerns (both real and perceived) by regulatory agencies, operating agencies, reclaimed water users, and the public in general related to the scientific basis of water reuse regulations and, hence, the public health protection afforded by existing regulations. While routine monitoring for all pathogenic microorganisms potentially present in reclaimed water clearly is impractical and prohibitively expensive, MRA techniques can be used to better define relative health risks associated with exposure to reclaimed water. Through analysis of differing reclaimed water management scenarios and reuse applications, relative health risks may be compared. Relative health risks, using predictive models, can be compared to inform decisions about water reuse projects.

This research project addresses the need to better understand the risks from microbial contaminants associated with nonpotable water reuse. By combining existing data on pathogen occurrence and wastewater treatment efficacy, exposure scenarios representative of realistic indirect potable reuse applications, and sensitivity analysis, this project advances the science of MRA within the context of water reuse by reducing the uncertainty associated with predicting potential health effects. MRA models used under a range of conditions to produce a matrix of relative risks under those conditions provide water and wastewater utility managers important supporting information to make informed risk-based management decisions about reclaimed water treatment, end uses, and management options. The information developed will aid regulatory agencies in evaluating public health risks associated with existing or proposed water reuse regulations. Improved science and reduced uncertainty also may lead to increased public acceptance of reclaimed water reuse, which has been problematic for several reclaimed water projects in the past.

1.3 TECHNICAL APPROACH

The general approach for this project included the following tasks:

- Assemble and synthesize available information on MRA of reclaimed water models and pathogen data
- Select an appropriate MRA model(s) and conduct MRAs for a range of conditions

- Provide recommendations for water reuse management options
- Assess research needs

In addition to the technical approach, case studies were utilized to provide a context in characterizing, to the extent feasible, the potential adverse human health effects that may be associated with exposure to pathogenic microorganisms through nonpotable reuse applications of reclaimed water. Five public agencies that have water reclamation programs —four in California (City of Sunnyvale, City of San Jose, East Bay Municipal Utility District, and Marin Municipal Water District) and one in Florida (City of St. Petersburg)— provided data and information to conduct case studies and interpret the MRA output matrix. More specific information on the project tasks is provided below.

1.3.1 Assemble and Synthesize Available Information

A comprehensive literature search was performed. Sources of information included peer-reviewed journal articles, published conference proceedings, regulatory monitoring and survey reports, and publicly available research documents. The literature search focused on updating available information specifically related to current models for MRAs of reclaimed water and pathogen data. Based on the literature review related to pathogens of health concern, their exposure routes, and data collected from several utilities, the waterborne pathogens of public health concern analyzed in this investigation included the following:

- Human enteric viruses, as estimated by enterovirus concentrations and rotavirus dose response (representative of human viruses)
- *Cryptosporidium parvum* and *Giardia lamblia* (representative of protozoa)
- *Salmonella* spp. and *E. coli* O157:H7 (representative of bacteria)

The literature review indicated that the selected pathogens of public health concern are responsible for a large majority of waterborne infections in the United States (Mead et al., 1999). Therefore, it was assumed for this investigation that the potential public health risk associated with exposure to these pathogens would provide a conservative (health-protective) representation of the overall human health risk through contact with reclaimed water. The literature further suggests that ingestion is the predominant route of pathogen acquisition; thus, the MRAs used in this study were based on ingestion as the exposure route. Exposure to pathogens via inhalation of reclaimed water transported via aerosolized droplets was also considered. However, the literature suggests that aerosolized droplets are likely ingested rather than inhaled; thus, it is reasonable to assume the route of ingestion is also relevant to exposures to reclaimed water that is transported via aerosolized droplets.

1.3.2 Select Appropriate MRA Model and Conduct Assessments

MRA is a process that evaluates the likelihood of adverse human health effects that can occur following exposure to pathogenic microorganisms or to a medium in which pathogens are present (ILSI, 1996, 2000). MRA model options were selected from existing MRA approaches including but not limited to the static (individual-level) and dynamic (population-level) approaches discussed in a previously published Water Environment Research

Foundation (WERF) report (Soller et al., 2004). Descriptions of these MRA models are provided in Chapter 2.

Based on the available but limited information on the total number of diseased individuals, host immunity, and other requisite information by which to compare conditions under which different MRA models would predict similar or divergent estimations of risk, a static risk assessment approach was primarily used for this investigation. The use of the static model in a screening-level risk characterization is consistent with literature in the field (Rose et al., 1991; Gerba et al., 1996; Crabtree et al., 1997; Mena et al., 2003) and was compared to a dynamic model in specific situations for which sufficient data were available (Eisenberg et al., 1996, 1998; Soller et al., 2003, 2006). For comparison, dynamic model assessments were conducted for a limited number of appropriate cases based on the results contained in the WERF MRA project report (Soller et al., 2004).

The methods employed for these MRAs are described in Chapter 2. Modeling and risk characterization took into account combinations of pathogen concentrations, reclaimed water treatment classes, exposure scenarios, and adverse outcome end points encompassing the following:

- Five pathogens: human viruses, as estimated by enterovirus concentrations and rotavirus dose response; *Cryptosporidium*; *Giardia*; *Salmonella*; and *E. coli* O157:H7[1]
- Two reclaimed water treatment process configurations: (1) secondary treatment and disinfection via chlorination and (2) secondary treatment, chemical coagulation, filtration, and disinfection via chlorination (referred to as tertiary treatment)
- Three nonpotable reclaimed applications: golf course and public park irrigation, crop irrigation, and body contact recreation in undiluted effluent
- Two adverse health end points: infection and illness

Based on the scenarios involving the representative pathogens of concern, the end uses of reclaimed water for nonpotable reuse applications, the treatment processes employed, and health end points introduced above, a series of MRAs were conducted using numerical simulation. The simulations were conducted using the Microbial Risk Assessment Interface Tool (MRAIT) recently developed by the same investigators under contract to the WERF (Soller et al., 2007). A printout of the MRAIT for an example assessment is provided in Appendix A.

These simulations represent the estimated risks to human health from pathogens in reclaimed water under normal operating conditions at the types of treatment facilities that are most commonly used to produce reclaimed water. The simulations were not intended to address the potential increased probability of higher pathogen concentrations due to excursions outside

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[1] Bacterial indicator organisms, such as enterococci, *E. coli*, and coliforms, were useful as indicators of treatment performance within the context of the case studies, whereas pathogens were used as the basis for risk characterization and the development of the relative risk matrix.

the range of normal operating conditions or the subsequent risks associated with exposure to effluent produced under such conditions. Rather, this investigation assumes that treatment plant operations are controllable and water produced under conditions outside of the normal range would be diverted or otherwise handled appropriately prior to distribution.

The results of the MRA simulations are summarized in tables and graphs in Chapter 3. The results illustrate the estimated relative risks that are associated with the combinations of pathogens, treatment, and end uses summarized above. To provide perspective on the reported ranges of estimated relative risks, case study examples are provided to illustrate how the matrix of relative risks can be used to provide insight for specific agencies.

1.3.3 Develop Conclusions and Recommendations

Conclusions and recommendations for water and wastewater utilities were developed based on the findings of the MRAs and are presented in Chapter 4.

1.3.4 Assess Research Needs

Based on the results of the study, a discussion of important data gaps and a list of potential research needs prioritized based on the anticipated level of effort relative to the expected benefits also are presented in Chapter 4.

CHAPTER 2

METHODS

2.1 OVERVIEW

The general approach for this project was to utilize existing data and MRA methods to derive a matrix of relative risks based on the following: (1) combinations of specific pathogens that are representative of the pathogens most likely to be of public health concern, (2) treatment processes that are representative of those currently used to produce reclaimed water, and (3) relevant exposure routes based on nonpotable reclaimed water applications currently used in the United States.

Data were obtained from the literature to characterize the concentrations of the pathogens at various points in the wastewater treatment process and the expected levels of reductions of those pathogens through wastewater treatment for the treatment classes investigated. Literature data were also used to estimate the volume of water ingested for each of the routes of exposure, as well as the relation between the number of organisms ingested (dose) and the probability of infection and/or illness (depending on the pathogen of interest). Numerical simulation was used to address variability and uncertainty in the computed estimates of risk. The MRA simulations were conducted using the recently developed MRAIT (Soller et al., 2007). Static (individual-level) MRA simulations were used as the base model to compute risks for the matrix. In addition, dynamic (population-level) MRA simulations were run for selected scenarios for comparative purposes.

Finally, four public agencies in California that have water reclamation programs (City of Sunnyvale Water Pollution Control Plant [WPCP], San Jose/Santa Clara WPCP, East Bay Municipal Utility District, and Marin Municipal Water District) and one in Florida (City of St. Petersburg) were used as case study examples to illustrate how water and wastewater utility managers might use the results of the risk matrix for decision making.

2.2 MICROBIAL RISK ASSESSMENT BASE (STATIC) MODEL

MRA is a process that evaluates the likelihood of adverse human health effects that can occur following exposure to pathogenic microorganisms or to a medium in which pathogens are present (ILSI, 1996, 2000). Quantitative methods to characterize human health risks associated with exposure to pathogenic microorganisms began to appear in the published literature in the 1970s (Fuhs, 1975; Dudley et al., 1976; Haas, 1983a, 1983b; Cooper et al., 1986; Olivieri et al., 1986). Since that time, many MRAs have been conducted based on the assumption that risk is manifest at an individual level and that the number of individuals susceptible to infection is not varying with time (i.e., is static) (Eisenberg et al., 2002). Examples of these types of assessments for both waterborne pathogens (Haas, 1983a; Regli et al., 1991; Rose et al., 1991; Gerba et al., 1996; Crabtree et al., 1997; Teunis et al., 1997; Mena et al., 2003) and foodborne pathogens (Farber et al., 1996; Buchanan et al., 1998, 2000) are prevalent in the scientific literature.

Assessments using a static model for evaluating microbial risk typically focus on estimating the probability of infection or disease for an individual as a result of a single exposure event. These assessments generally assume that multiple or recurring exposures constitute independent events with identical distributions of contamination (Regli et al., 1991). Secondary transmission and immunity are assumed to be negligible or to effectively cancel out each other. Inclusion of secondary transmission may increase or decrease the level of infection attributable to a specific exposure to pathogens, while inclusion of immunity will decrease the level of infection in a community attributable to a specific exposure to pathogens (Eisenberg et al., 2004; Soller et al., 2004).

Conceptually, individual-based models employ two or three epidemiological states: a susceptible state, an infected state, and/or a diseased state (Fig. 2.1). Although pathogens may derive from a number of potential environmental sources, in this investigation it is assumed that susceptible individuals are exposed to pathogens from reclaimed water. Susceptible individuals, when exposed to pathogens from a specific environmental source, move into an infected state with a probability that is governed by the dose of pathogen to which they are exposed and the infectivity of the pathogen. The probability of infection is often multiplied by a morbidity factor (ρsym in Fig. 2.1) to estimate the probability of illness (disease) and/or the number of exposed individuals to estimate the expected number of infected or diseased individuals for the exposure scenario under consideration.

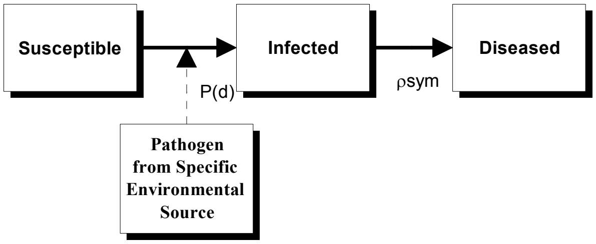

Figure 2.1. Individual-based microbial risk assessment conceptual model.

A dose is defined as a quantitative measure for the intensity of exposure of the host to the pathogen of interest. The units of dose are usually given as the number of organisms ingested, and dose is typically calculated by estimating two quantities: the concentration of pathogens at the exposure site and the volume of water ingested.

By studying the effects of various doses, it is possible to determine a dose–response relationship between the dose and the frequency of infection within the exposed population of hosts. Researchers have studied and published quantitative descriptions of dose–response relationships for many organisms to provide insight into the risk of becoming infected after the ingestion of a certain dose of organisms (Haas et al., 1999; McBride et al., 2002) (where infection may be defined as the invasion, colonization, and multiplication of a pathogenic microorganism [Teunis et al., 1996]).

The critical health effects information required for the static model, therefore, is summarized in the function that represents the probability of infection, *P*(d), known as a pathogen-specific dose–response function. Mechanistically, the probability of infection following exposure to a virulent pathogen depends on several host and pathogen-specific factors which can be viewed as a series of conditional events, in which each event must occur in order to result in infection. The infection status depends on a number of factors, such as (1) the number of organisms that enter the host, (2) the host's ability to inactivate these organisms, (3) the number of organisms that can withstand the host's local immune defenses, adhere to mucosal surfaces, and multiply in order to infect the host, and (4) variation in pathogen virulence and host susceptibility (Colford et al. 2003; Eisenberg et al. 1996, 2003).

Figure 2.2 illustrates the overall process by which risks were estimated for this investigation. For each pathogen–treatment process–route of exposure combination of interest, the following process was used. First, data were obtained to characterize the pathogen concentration in either raw wastewater or undisinfected secondary effluent (1)[2]. The next step was to fit these data to a lognormal distribution (2) via the method of maximum likelihood (Ott, 1995; Olivieri et al., 1999). Statistical distributions were used rather than the raw data so that the effects of variability and uncertainty could be efficiently encapsulated in the resultant risk estimate. Reductions in the concentrations of the pathogen of interest that are expected to occur through wastewater treatment were estimated and applied (4) to estimate effluent concentrations (5). Based on the exposure route of interest, ingestion rates were estimated (6). By combining the ingestion rate (7) with the effluent concentration, the dose of pathogen ingested per exposure event was estimated (8). A dose–response relationship, derived from the literature (9), was then used to estimate the risk associated with the dose for the trial (10), and the process was repeated 5000 times to generate a distribution of estimated risk. Two possible risk end points (infection and illness) were considered, depending on the data available in the literature to characterize those end points for each pathogen.

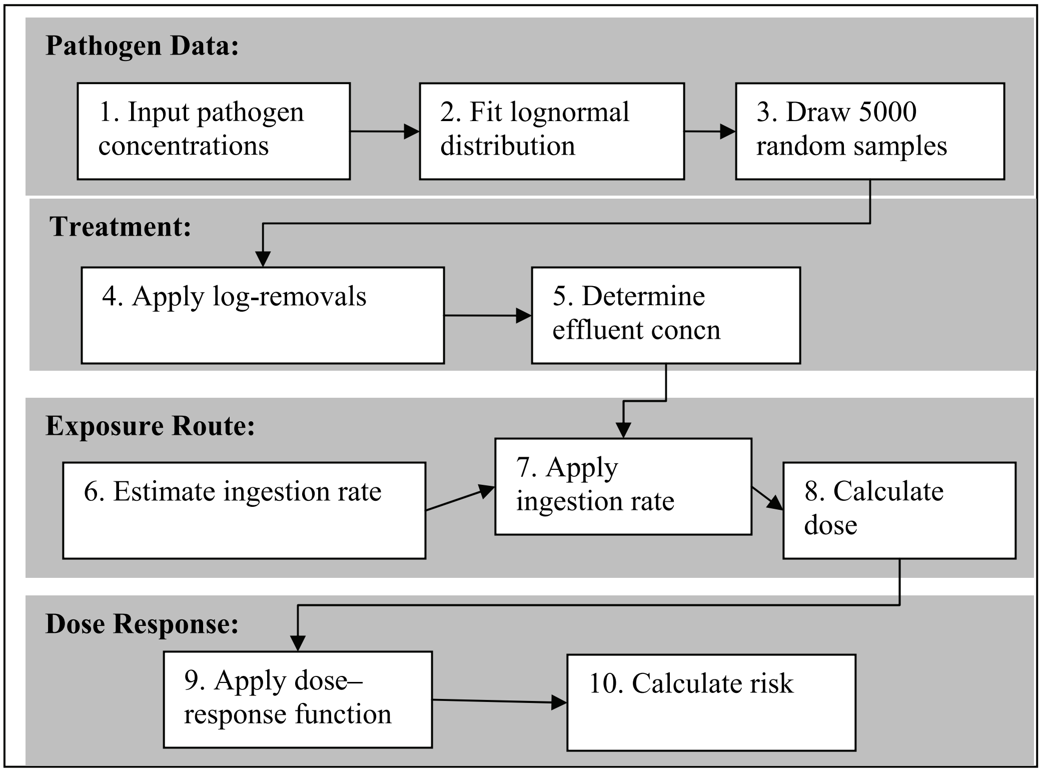

Figure 2.2. Flow diagram for conducting microbial risk assessments.

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[2] Raw wastewater data were used as the input to estimate the risks associated with disinfected tertiary effluent, and undisinfected secondary effluent data were used as the input to estimate the risks associated with disinfected secondary effluent. In both cases, appropriate treatment reductions were applied, as shown in Figure 2.2, step 4.

2.3 PATHOGEN CONCENTRATIONS IN RAW WASTEWATER AND UNDISINFECTED SECONDARY EFFLUENT

As introduced in Section 1.3.2, the waterborne pathogens of public health concern analyzed in this investigation were the following:

- Human enteric viruses, as estimated by enterovirus occurrence in reclaimed water and rotavirus dose response (representative of human viruses)
- *Cryptosporidium parvum* and *Giardia lamblia* (representative of protozoa)
- *Salmonella* spp. and *E. coli* O157:H7 (representative of bacteria)

Data representing the concentrations of each of the above pathogens in raw wastewater and secondary effluent were sought and obtained from the literature. A brief description of the sources of the data used as input for the simulations is presented below. A summary of the relevant pathogen occurrence data from the literature review along with raw data employed as input for the MRA simulations are provided in Appendix B.

Based on the results of a comprehensive literature review, a previously published WERF report (Rose et al., 2004) was the primary source of data used as input in this investigation to characterize the risks associated with exposure to human viruses, *Cryptosporidium*, and *Giardia*. In that investigation, six full-scale wastewater treatment and reclamation facilities in Arizona, California, and Florida were each monitored over a 1-year period for a variety of pathogens and indicator organisms. For the purposes of this investigation, it is assumed that the six wastewater treatment facilities evaluated in the WERF investigation are representative of the types of reclamation facilities that are currently being employed in the United States and that the operating conditions of those facilities at the time that they were monitored are representative and/or conservative relative to other facilities in the United States with respect to normal operating conditions.

Based on the results of the literature review (refer to Appendix B), the results reported by Lemarchand and Lebaron (2003), Elliott and Ellis (1977), Argent et al. (1977), and Hench et al. (2003) were used together as input in this investigation to characterize the risk associated with exposure to *Salmonella*.

The amount of data available to characterize *E. coli* O157:H7 in raw wastewater and secondary effluent was extremely limited. Quantitative data for *E. coli* O157:H7 in raw wastewater were reported by three research teams (Garcia-Aljaro et al., 2005; Heijnen and Medema, 2006; Muniesa et al., 2006). A summary of those data is provided in Appendix B. The results reported by Garcia-Aljaro et al. (2005) were used as the basis for input to this investigation, and 250 concentration values were drawn randomly from a lognormal distribution based on their reported results.

The data shown in Appendix B characterizing the concentrations of enteroviruses, *Cryptosporidium*, *Giardia,* and *Salmonella* in both raw wastewater and secondary effluent were used as input to the MRAIT (Soller et al., 2007). The data shown in Appendix B characterizing the concentration of *E. coli* O157:H7 in raw wastewater were also used as input to the MRAIT. Data were not available in the literature to characterize the concentration of *E. coli* O157:H7 in secondary effluent.

To rigorously account for the variability observed in pathogen concentrations in raw wastewater and secondary effluent, the pathogen concentration data summarized above were fit to lognormal probability distributions using a maximum likelihood estimation (Ott, 1995), as shown in Figure 2.2. The lognormal distribution is a commonly used distributional form for environmental data fitting, in particular for concentrations of microorganisms in water (U.S. EPA, 1991), because values from this distribution are nonnegative numbers that are right (positive) skewed. Five thousand random samples from the lognormal maximum likelihood estimation were generated and used in subsequent calculations.

2.4 PATHOGEN REDUCTIONS ACROSS WASTEWATER TREATMENT

The study conducted by Rose et al. (2004) for WERF was the primary basis used in this investigation for estimating pathogen inactivation and/or removal through wastewater treatment. That investigation was conducted to compare the effectiveness of full-scale biological treatment, filtration, and disinfection for removal and/or inactivation of bacterial and viral indicators, enteric viruses, and protozoan pathogens. Thus, the data generated in that study were particularly relevant for this investigation.

Raw data from the Rose et al. (2004) study were reanalyzed by Soller et al. (2007) to generate estimates of pathogen reductions across the various treatment unit processes. For each facility, treatment process monitoring location, and pathogen included in the Rose et al. investigation, reductions across treatment processes were computed based on the reported data (Soller et al., 2007). Enterovirus data were used to estimate human virus reductions, enterococci data were used to estimate *Salmonella* reductions, and fecal coliform data were used to estimate *E. coli* O157:H7 reductions (data justifying this approach are available in Soller et al., 2007) (Appendix A). A summary of the reductions used in the MRAIT for rotavirus (human viruses), *Cryptosporidium*, *Giardia*, *Salmonella*, and *E. coli* O157:H7 is provided in Table 2.1 (Soller et al., 2007).

Table 2.1. Summary of Pathogen Reductions through Wastewater Treatment Used in the Simulations

	Giardia		*Cryptosporidium*		Rotavirus		*Salmonella* spp.		*E coli* O157:H7	
Treatment	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Raw through disinfected filtered secondary effluent	3.2	0.7	2.3	0.7	3.6	0.7	5.8	1.0	6.53	0.93
Secondary treatment through disinfected filtered secondary effluent	1.0	0.6	0.8*	0.5	1.3	0.6	3.4	1.1	4.2	1.3
Filtered secondary treatment through disinfected filtered secondary effluent	0.2	0.2	0.2	0.3	0.6	0.5	1.9	1.0	2.0	1.4

Note: The values shown in are the expected log reductions due to the corresponding wastewater treatment processes. Shown are the means and standard deviations of a normal distribution. A reduction of 1 log corresponds to 90% reduction, a reduction of 2 logs corresponds to 99% reduction, etc. Normal distributions were truncated, and so negative values were not sampled.

Two slightly different methods for estimating effluent concentrations via treatment were employed in this investigation. To estimate the concentrations of pathogens in disinfected secondary effluent, the estimated distributions of pathogen reductions across the disinfection unit process (as computed by Soller et al., 2007) were used in conjunction with the secondary effluent pathogen concentration distributions. To estimate the concentrations of pathogens in disinfected tertiary effluent, the estimated distributions of pathogen reductions from raw wastewater through filtered (tertiary) disinfected water (as computed by Soller et al., 2007) were used in conjunction with raw wastewater concentration distributions.

For each set of simulations, 5000 pathogen concentrations were sampled from the maximum likelihood estimate lognormal distribution and the reduction distributions and subsequently multiplied. The products from these multiplications resulted in 5000 estimated effluent concentrations (number per liter).

2.5 ROUTES OF EXPOSURE

Ingestion rates (in units of mL per event) as estimated in the WERF MRAIT (Soller et al., 2007) for three exposure routes were utilized: recreation, crop irrigation, and landscape and golf course irrigation. Each exposure route involved a different estimation method, as summarized below. In each simulation, a sample from the posttreatment effluent concentration data (as described above) was multiplied by a random sample from the ingestion distributions. The product resulted in an estimated dose (number of pathogens per event) of pathogens for an exposure event.

The three exposure routes were selected to be representative of the types of exposures that are expected to be typical for reclaimed water applications. Exposure to pathogens via inhalation of reclaimed water transported via aerosolized droplets (such as aerosolized droplets from car washes) was also considered. However, the literature suggests that aerosolized droplets are likely ingested rather than inhaled. Thus, it is reasonable to assume the ingestion routes of exposure considered herein are (1) relevant to exposures to reclaimed water that is transported via aerosolized droplets and (2) bound the risks associated with reclaimed water exposures, such as ingestion of reclaimed water transported via aerosolized droplets. Finally, pathogen die-off, which is known to occur in the environment, is not included in the calculations presented here. Thus, in this regard, it is reasonable to assume that the results presented herein are conservative.

2.5.1 Recreation

For the recreation route of exposure, it is assumed that individuals are exposed to pathogens via ingestion of reclaimed water through recreational activities in undiluted effluent. The key data used to characterize the volume of water ingested during recreational activities for this investigation were reported by Dufour et al. (2006). Raw data from that investigation were supplied by the investigators and were subsequently fit to statistical distributions via the method of maximum likelihood (Soller et al., 2007) (Fig. 2.3). The resultant distribution has a median consumption value of approximately 19 mL.

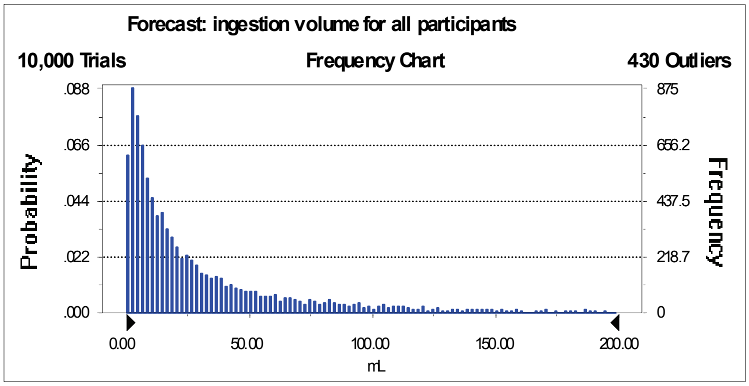

Figure 2.3. Ingestion volumes during recreational activities (based on results from Dufour et al., 2006).

2.5.2 Crop Irrigation

For the crop irrigation route of exposure, it is assumed that individuals are exposed to pathogens via ingestion of crops that are irrigated with reclaimed water. The method used to characterize exposure via this route (Soller et al., 2007) is based on that described by Hamilton et al. (2006) and is consistent with earlier work conducted by other researchers in the field (van Ginneken and Oron, 2000; Petterson et al., 2001).

This approach is based on the assumption that the ingestion of reclaimed water is the product of three distributions: the rate of consumption of crops irrigated with reclaimed water (g/kg-day), body mass (kg), and volume uptake (mL/g). Lettuce consumption was used as the model crop for consumption because the consumption value is health protective relative to other vegetables (U.S. EPA, 2003). The consumption value for lettuce is a point estimate of 0.205 g/kg-day (U.S. EPA, 2003). Body mass is estimated by a lognormal distribution with a mean of 61.429 and a standard deviation of 13.362 kg (U.S. EPA, 1997). Volume uptake is estimated as a normal distribution with a mean of 0.108 and standard deviation of 0.02 mL/g (Hamilton et al., 2006).

The resultant distribution of ingestion volumes (Fig. 2.4) has a median value of approximately 1.5 mL.

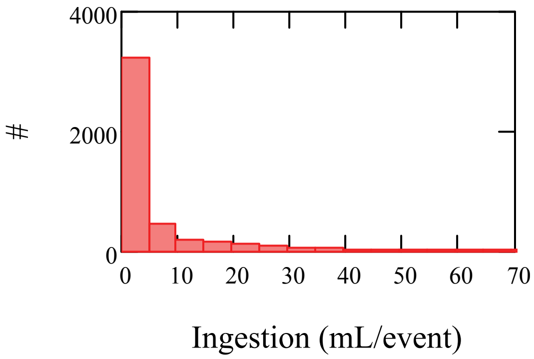

Figure 2.4. Distribution of ingestion volumes for the crop irrigation route of exposure.

2.5.3 Landscape and Golf Course Irrigation

For the landscape and golf course irrigation route of exposure, it is assumed that individuals are exposed to pathogens via incidental or accidental ingestion of reclaimed water applied on a golf course, park, or a landscape site with similar access and exposure. Little quantitative data were available to rigorously characterize this route of exposure. The method employed assumes that the volume ingested is the product of the total amount of water ingested (daily) and the proportion of total water ingested daily due to reclaimed water from irrigation (Soller et al., 2007). The total amount of water ingested daily by the U.S. population is based on data from the U.S. EPA and is a point estimate of 1.232 L/day (U.S. EPA, 2000). The proportion of daily drinking water intake due to park irrigation is informed by data reported by various researchers (Cooper and Olivieri, 1998; Sakaji and Funamizu, 1998; Ottoson and Stenstrom, 2003) and is represented by a uniform distribution with bounds of 0.0001 and 0.01 (representing 0.01 to 1%). The resultant distribution of ingestion volumes for the landscape irrigation exposure pathway has a median value of approximately 6 mL.

2.6 DOSE–RESPONSE RELATIONS

Pathogen-specific dose–response relationships were used to estimate the probability of illness (for *Salmonella*) or infection (for all other pathogens) associated with the computed doses. For each of the pathogens investigated, a summary of the functional forms, distributions used to describe the dose–response parameters, and the dose–response parameters along with corresponding references to support those data (Soller et al., 2007) is presented in Table 2.2. The dose–response relations for rotavirus, *Cryptosporidium*, and *Giardia* are relatively straightforward and commonly used in the field of MRA. The relations utilized for *E. coli* O157:H7 and *Salmonella* are explained in more detail below.

The dose–response relation for *E. coli* O157:H7 is based on a reported outbreak that occurred in Japan in 1996 (Teunis et al., 2004). The outbreak occurred in an elementary school, and school lunches were implicated as the source of contamination. An extraordinary amount of information was available for this outbreak because of the following: (1) in Japan, it is common for catering services to store refrigerated samples of prepared meals, and thus the suspected foods were available for estimating the concentration of bacteria they contained; (2) all of the exposed subjects (pupils and teachers) were examined for the occurrence of symptoms and illness (fecal specimens were taken) and, thus, health authorities were able to record the occurrence of illness and infection; and (3) the average numbers of bacteria consumed could be estimated relatively accurately (Teunis et al., 2004). Based on the available data, different dose–response relationships for teachers and pupils were derived using a Bayesian approach. The relation that was derived by Teunis et al. for students was used in this investigation.

Table 2.2. Summary of Pathogen Dose–Response Relations

Pathogen	Dose–Response Form (End Point)	Parameter Distribution	Value(s)	Value(s)	Reference(s)
Rotavirus	Hypergeometric (infection)	Point estimates	$\alpha = 0.167$	$\beta = 0.191$	Teunis and Havelaar, 2000
Cryptosporidium	Exponential (infection)	Uniform	$r_{lower} = 0.04$	$r_{upper} = 0.16$	U.S. EPA, 2006
Giardia	Exponential (infection)	Point estimate	$r = 0.0199$		Rose et al., 1991; Teunis et al., 1996
E. coli O157:H7	Hypergeometric (infection)	Point estimates	$\alpha = 0.08$	$\beta = 1.44$	Teunis et al., 2004
Salmonella spp.	Gompertz log (illness)	Uniform	$\alpha_{lower} = 29$	$\alpha_{upper} = 50$	Coleman and Marks, 1998, 2000; Coleman et al., 2004; Oscar, 2004
		Point estimate	$\beta = 2.148$		

Salmonella dose–response experiments were conducted in the 1940s and reported by McCullough and Eisele (1951a; 1951b). The data set is comprised of observations for healthy adult males who were administered 13 different strains of *Salmonella*, most of which did not result in illness. The results from the *Salmonella* dosing experiment showed substantial strain variability (Fig. 2.5).

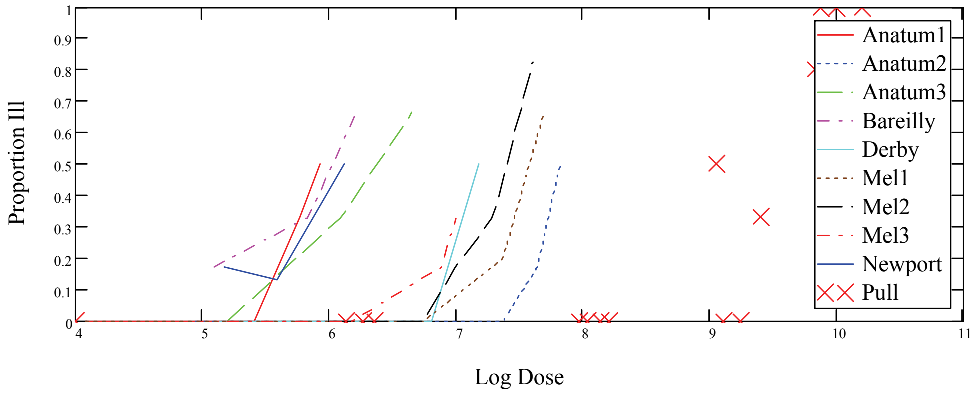

Figure 2.5. Strain variability associated with *Salmonella* infectivity.

Much previous work has been conducted to characterize the *Salmonella* dose–response relation (Coleman and Marks, 1998, 2000; Latimer et al., 2001; Coleman et al., 2004; Oscar, 2004), the simplest of which is to ignore strain variability (as reported by Haas et al., 1999). Coleman and Marks (1998) reported that pooling all the data (that is, ignoring strain variability) results in a model which is rejected due to lack of fit. Their results also indicated that the best fit to the data is provided by a model that fully accounts for strain effects.

For this project, all the available *Salmonella* dose–response information in the literature was reviewed in detail. Based on that review, it was concluded the approach suggested by Coleman and Marks (1998; 2000) and further described by Coleman et al. (2004) is an appropriate approach. Unfortunately, the explicit dose–response values were never published; rather, the recommended approach was described, and "average" results were graphed (refer to Coleman and Marks, 1998, Figure 6).

Using the approach recommended in the literature (Coleman and Marks, 1998, 2000), gompertz log dose–response functions were fit during this investigation to the strains of *Salmonella* employed in the feeding study. This approach yielded appropriate gompertz log dose–response parameter values for each strain (Soller et al., 2007). Based on the optimal values for each strain, a simplified range of parameter values for all strains based on the median value for the gompertz log dose–response parameter *b* (median = 2.148) was derived. It is believed that this simplified range [log(a) varies uniformly from 29–50] is appropriate for waterborne exposures. The range of dose–response relations used in this investigation are summarized in Figure 2.6.

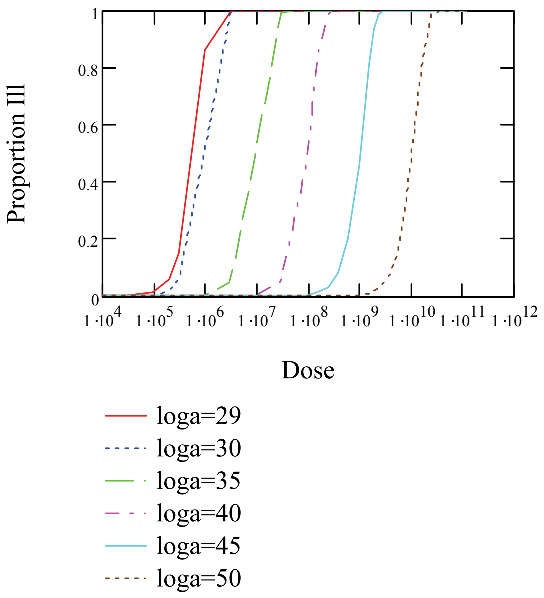

Figure 2.6. Range of feasible *Salmonella* dose–response relations accounting for strain variability.

2.7 DYNAMIC MICROBIAL RISK ASSESSMENT METHODS

For selected pathogen–treatment process–exposure combinations, the results of risk assessment modeling via the static model were compared with those from a dynamic model to illustrate how accounting for person-to-person transmission of infection and/or immunity could impact the risk assessment results for exposures to pathogens in reclaimed water from a population-level perspective.

In a dynamic risk assessment model, the population is assumed to be comprised of several epidemiological states. These models are termed dynamic, because the number of people in each epidemiological state changes over time. In the model, individuals move from state to state based on epidemiologically relevant data (duration of infection, duration of immunity, and so on). Only a portion of the population is in a susceptible state at any point in time, and only those in the susceptible state can become infected or diseased through exposure to microorganisms. The probability that a susceptible person moves into an exposed state is governed by the dose of pathogen to which he or she has been exposed, the infectivity of that pathogen, and the number of infected or diseased individuals with whom he or she may come into contact (Hethcote, 1976, 2000; Anderson and May, 1991).

For both dynamic and static representations of the disease process, infectivity as a function of dose (estimated using a dose–response function) is an important factor in estimating risk. Just as the dose–response function is a critical component of a static MRA model, it is also used in a dynamic MRA model; however, other factors, such as person-to-person transmission, immunity, asymptomatic infection, and/or incubation period, may also be important. Accounting for these additional factors when estimating risks associated with exposure to pathogenic microorganisms requires a more sophisticated mathematical model than the static model shown in Figure 2.1. When a dynamic disease transmission model is used, one can account for attributes specific to the transmission of infectious diseases. Depending on the infectious disease processes that are important for specific exposures, the dynamic model may include more or less components.

The dynamic MRA model implemented in this investigation accounts for person-to-person transmission, immunity, incubation, and asymptomatic infection (Fig. 2.7). Similar to the static model, the solid lines in Figure 2.7 represent the movement of individuals from one epidemiological state to another, and dotted lines represent the movement of pathogens. Rate parameters specifying the movement between epidemiological states and the probability of response are shown as symbols. A more detailed description and explanation of the dynamic risk assessment model is provided elsewhere (Soller et al., 2004).

The approach to dynamic risk modeling is based on a series of steps involving parameter estimation, model calibration, and the estimation of the attributable risk from reclaimed water exposures (Soller et al., 2006). For a detailed description of the procedures used to conduct the dynamic model simulations, interested readers are referred to Soller et al. (2007).

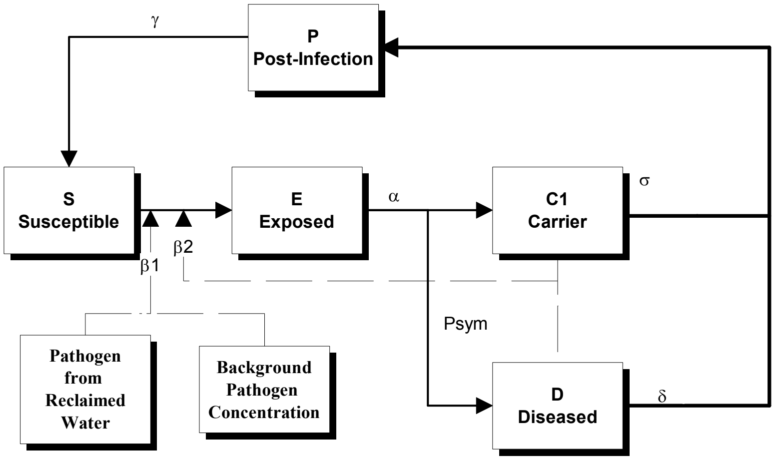

Figure 2.7. Dynamic risk assessment conceptual model.

Briefly, parameter estimation was carried out via a literature review of current laboratory and epidemiological studies that define the various aspects of the transmission process, such as incubation, proportion of infected individuals developing symptoms, etc. Where possible, the variability expressed in the studies is accounted for by specifying statistical distributions for each parameter. As indicated above, the dose–response calculation was also used for the dynamic model. Hence, all of the steps leading to computation of a pathogen- and exposure-specific probability of infection or illness in the static modeling (Fig. 2.2) were also used in defining the distribution of the transmission rate due to ingestion of reclaimed water (β), shown in Figure 2.7.

A model calibration procedure was employed to estimate the endemic (background) transmission rate due to food- or waterborne transmission within the population and the person-to-person transmission rate within the population. The calibration consists of fitting the two parameters such that the model produces results that are consistent with estimates of the background incidence rate of disease within the United States (Mead et al., 1999) and estimates of the proportion of cases that are the result of secondary transmission based on data from the literature (Soller et al., 2007).

With all the models' parameters either estimated from the literature or via the calibration procedure, simulations were run to determine the attributable risk associated with a specific pathogen, reclaimed water treatment level, and exposure. The attributable risk calculation accounted for the additional cases above background that would occur from exposure to reclaimed water (i.e., the "background level" cases were subtracted). Numerical details have been provided by Soller et al. (2007). As with the static model, 5000 Monte Carlo simulations were run whereby the model was run each time with different sampled parameter values from the statistical distributions. This process resulted in risk estimates that could roughly be compared against those from the static model.

CHAPTER 3

RESULTS

3.1 OVERVIEW

An overview of the MRA simulations that were run for this investigation is provided in Table 3.1. Representative output from one set of simulations that were run for exposure to *Cryptosporidium* in disinfected tertiary effluent from recreational activities is presented in Appendix A. Similar output was also generated for each of the sets of simulations itemized in Table 3.1.

Table 3.1. Overview of Microbial Risk Assessment Simulations

Pathogen	Treatment	Exposure	Model	Risk Metric
Rotavirus	Disinfected secondary	Recreation	Static	Individual level
Rotavirus	Disinfected secondary	Landscape irrigation	Static	Individual level
Rotavirus	Disinfected secondary	Crop irrigation	Static	Individual level
Rotavirus	Disinfected tertiary	Recreation	Static	Individual level
Rotavirus	Disinfected tertiary	Landscape irrigation	Static	Individual level
Rotavirus	Disinfected tertiary	Crop irrigation	Static	Individual level
Cryptosporidium	Disinfected secondary	Recreation	Static	Individual level
Cryptosporidium	Disinfected secondary	Landscape irrigation	Static	Individual level
Cryptosporidium	Disinfected secondary	Crop irrigation	Static	Individual level
Cryptosporidium	Disinfected tertiary	Recreation	Static	Individual level
Cryptosporidium	Disinfected tertiary	Landscape irrigation	Static	Individual level
Cryptosporidium	Disinfected tertiary	Crop irrigation	Static	Individual level
Giardia	Disinfected secondary	Recreation	Static	Individual level
Giardia	Disinfected secondary	Landscape irrigation	Static	Individual level
Giardia	Disinfected secondary	Crop irrigation	Static	Individual level
Giardia	Disinfected tertiary	Recreation	Static	Individual level
Giardia	Disinfected tertiary	Landscape irrigation	Static	Individual level
Giardia	Disinfected tertiary	Crop irrigation	Static	Individual level
Salmonella	Disinfected secondary	Recreation	Static	Individual level
Salmonella	Disinfected secondary	Landscape irrigation	Static	Individual level
Salmonella	Disinfected secondary	Crop irrigation	Static	Individual level
Salmonella	Disinfected tertiary	Recreation	Static	Individual level
Salmonella	Disinfected tertiary	Landscape irrigation	Static	Individual level
Salmonella	Disinfected tertiary	Crop irrigation	Static	Individual level
E. coli O157:H7	Disinfected tertiary	Recreation	Static	Individual level
E. coli O157:H7	Disinfected tertiary	Landscape irrigation	Static	Individual level
E. coli O157:H7	Disinfected tertiary	Crop irrigation	Static	Individual level
Rotavirus	Disinfected tertiary	Recreation	Dynamic	Individual level
Rotavirus	Disinfected tertiary	Recreation	Static	Individual level
Cryptosporidium	Disinfected secondary	Recreation	Dynamic	Individual level
Cryptosporidium	Disinfected secondary	Recreation	Static	Individual level
Giardia	Disinfected tertiary	Landscape irrigation	Dynamic	Individual level
Giardia	Disinfected tertiary	Landscape irrigation	Static	Individual level
E. coli O157:H7	Disinfected tertiary	Crop irrigation	Dynamic	Individual level
E. coli O157:H7	Disinfected tertiary	Crop irrigation	Static	Individual level

Note: Simulations were not conducted for *E. coli* O157:H7 in disinfected secondary.
effluent because data were not available for undisinfected effluent as input

3.2 MICROBIAL RISK ASSESSMENT SIMULATION RESULTS

3.2.1 Static MRA Model Results

The results of each of the simulation sets presented in Table 3.1 (i.e., each row in Table 3.1) consist of 5000 individual estimates of risk (probability of infection or illness) associated with exposures to reclaimed water for specific combinations of pathogens, routes of exposure, and classes of wastewater treatment. A summary of the results for the static model simulations is presented in matrix format in Table 3.2 and depicted graphically in Figures 3.1, 3.2, and 3.3 for the recreation, landscape irrigation, and crop irrigation routes of exposure, respectively.

Table 3.2. Summary of Individual-Level Microbial Risk Assessment Simulation Results

				Estimated Risk per Event[2,3]		
Pathogen	**Treatment**	**Exposure**	**Model**	**10%-ile**	**Median**	**90%-ile**
Human viruses[1]	Disinfected secondary	Recreation[4]	Static	9.2E-06	2.2E-04	5.1E-03
Human viruses[1]	Disinfected secondary	Landscape irrigation	Static	3.8E-06	6.2E-05	9.5E-04
Human viruses[1]	Disinfected secondary	Crop irrigation	Static	2.7E-07	1.7E-05	1.1E-03
Human viruses[1]	Disinfected tertiary	Recreation	Static	1.5E-06	5.1E-05	1.6E-03
Human viruses[1]	Disinfected tertiary	Landscape irrigation	Static	5.3E-07	1.4E-05	3.0E-04
Human viruses[1]	Disinfected tertiary	Crop irrigation	Static	4.5E-08	3.9E-06	3.5E-04
Cryptosporidium	Disinfected secondary	Recreation	Static	3.2E-05	5.4E-04	8.4E-03
Cryptosporidium	Disinfected secondary	Landscape irrigation	Static	1.3E-05	1.4E-04	1.3E-03
Cryptosporidium	Disinfected secondary	Crop irrigation	Static	6.8E-07	3.9E-05	1.6E-03
Cryptosporidium	Disinfected tertiary	Recreation	Static	4.1E-06	1.5E-04	5.1E-03
Cryptosporidium	Disinfected tertiary	Landscape irrigation	Static	1.4E-06	4.0E-05	9.2E-04
Cryptosporidium	Disinfected tertiary	Crop irrigation	Static	1.1E-07	1.0E-05	9.0E-04
Giardia	Disinfected secondary	Recreation	Static	1.9E-05	4.0E-04	9.1E-03
Giardia	Disinfected secondary	Landscape irrigation	Static	6.2E-06	1.1E-04	1.7E-03
Giardia	Disinfected secondary	Crop irrigation	Static	4.6E-07	3.1E-05	2.0E-03
Giardia	Disinfected tertiary	Recreation	Static	1.6E-06	6.7E-05	2.4E-03
Giardia	Disinfected tertiary	Landscape irrigation	Static	5.4E-07	1.6E-05	4.9E-04
Giardia	Disinfected tertiary	Crop irrigation	Static	4.6E-08	4.5E-06	5.1E-04
Salmonella spp.	Disinfected secondary	Recreation	Static	<1E-9	<1E-9	<1E-9
Salmonella spp.	Disinfected secondary	Landscape irrigation	Static	<1E-9	<1E-9	<1E-9
Salmonella spp.	Disinfected secondary	Crop irrigation	Static	<1E-9	<1E-9	<1E-9
Salmonella spp.	Disinfected tertiary	Recreation	Static	<1E-9	<1E-9	<1E-9
Salmonella spp.	Disinfected tertiary	Landscape irrigation	Static	<1E-9	<1E-9	<1E-9
Salmonella spp.	Disinfected tertiary	Crop irrigation	Static	<1E-9	<1E-9	<1E-9
E. coli O157:H7	Disinfected tertiary	Recreation	Static	1.5E-08	4.6E-07	1.4E-05
E. coli O157:H7	Disinfected tertiary	Landscape irrigation	Static	5.1E-09	1.1E-07	2.3E-06
E. coli O157:H7	Disinfected tertiary	Crop irrigation	Static	<1E-9	3.1E-08	2.4E-06

1. Simulations are intended to be representative of risks from human enteric viruses and are based on enterovirus occurrence and rotavirus infectivity (dose response).
2. Health outcomes shown are consistent with human feeding studies for the various pathogens. Outcomes are the probability of illness from *Salmonella* and probability of infection for other pathogens. The probability that an infection results in illness varies among pathogens.
3. Values shown are per exposure event.
4. Assumes full body contact and ingestion of water consistent with that observed during epidemiological studies.

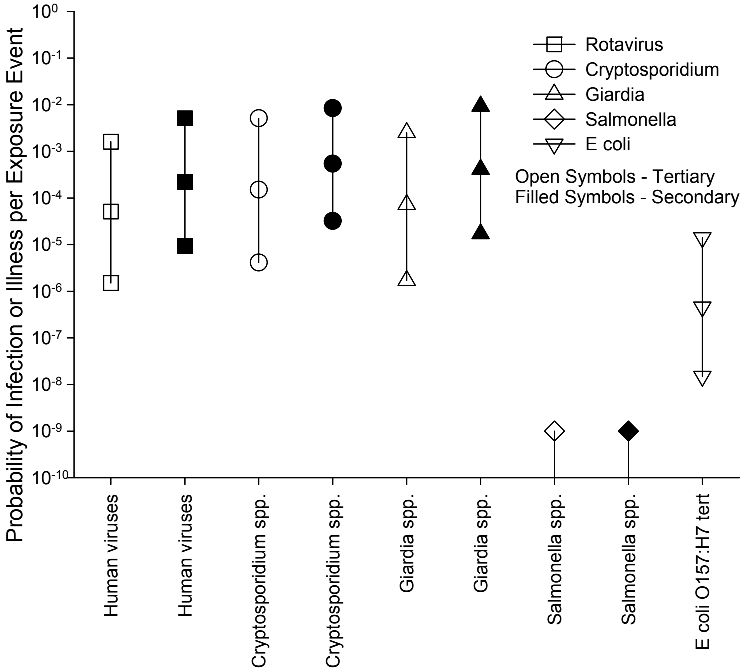

Figure 3.1. Individual-level microbial risk assessment results for recreational exposure. Note: Values shown are the 10th, 50th, and 90th percentiles of the computer results.

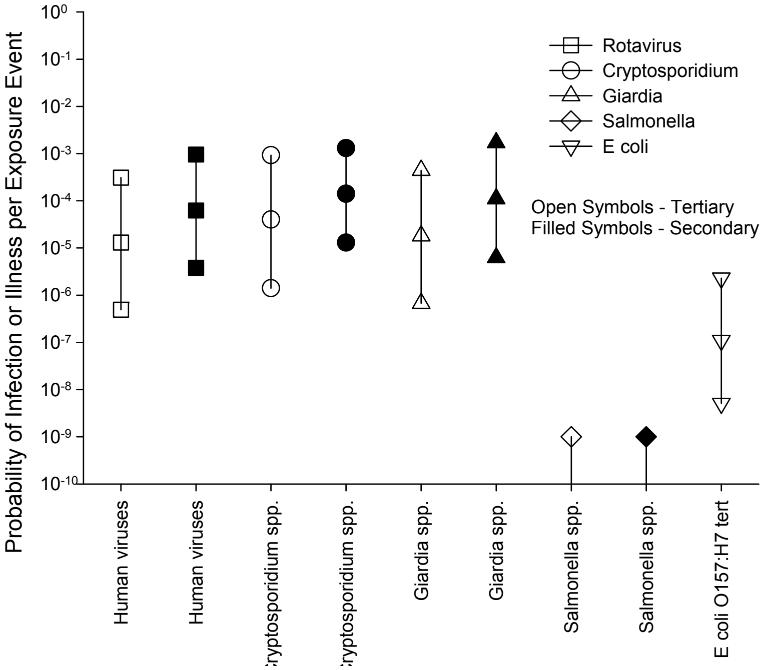

Figure 3.2. Individual-level microbial risk assessment results for landscape irrigation exposure. Note: Values shown are the 10th, 50th, and 90th percentiles of the computer results.

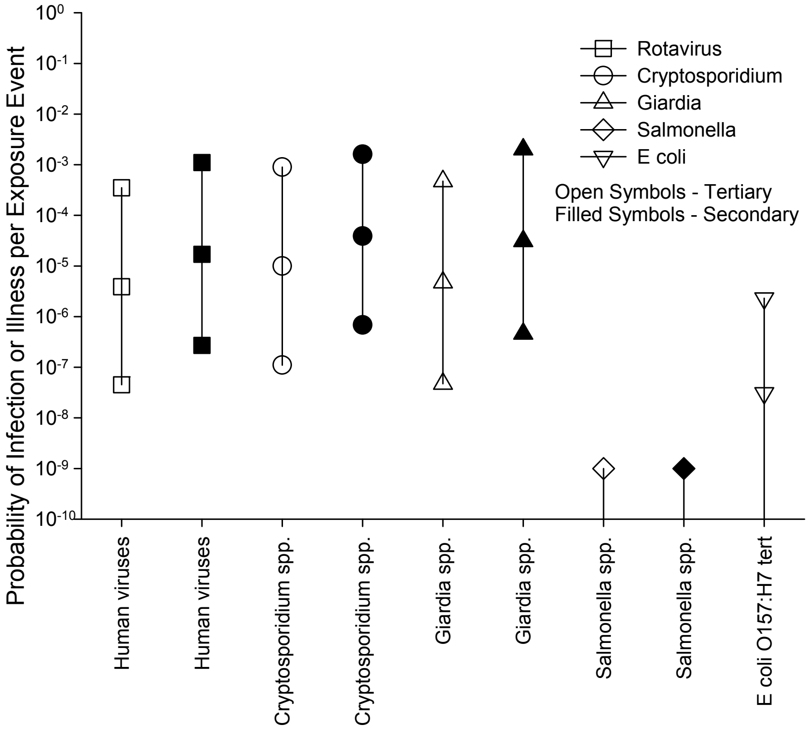

Figure 3.3. Individual-level microbial risk assessment results for crop irrigation exposure. Note: Values shown are the 10th, 50th, and 90th percentiles of the computer results.

Review of the results presented in the preceding table and figures indicates the following:

- Of the three routes of exposure investigated, the risks associated with recreation in undiluted effluent (Fig. 3.1) are estimated to be greater than those associated with landscape irrigation (Fig. 3.2) by approximately 5× and greater than those associated with crop irrigation (Fig. 3.3) by approximately 1 order of magnitude (10×).

- Under equivalent assumptions regarding exposure to reclaimed water and wastewater treatment level, the estimated attributable risks associated with human viruses, *Cryptosporidium*, and *Giardia* are of similar magnitude.

- For reclaimed water exposures, the risks associated with *Salmonella* illness and *E. coli* O157:H7 infection are well below the risks associated with human viruses, *Cryptosporidium*, and *Giardia.*

- The estimated risks associated with disinfected tertiary effluent are lower than those associated with disinfected secondary effluent by approximately a 0.5 order of magnitude.

- The variability and uncertainty associated with the estimated levels of risk associated with exposure to pathogens present in reclaimed water are substantial. The 90% confidence bounds of the risk estimates span approximately 3 orders of magnitude.

3.2.2 Comparison of Dynamic and Static MRA Model Results

A total of eight sets of population-level MRA simulations were conducted (Table 3.1). The purpose of running these simulations was to evaluate how accounting for person-to-person transmission of infection and immunity could impact the risk assessment results for exposures to pathogens in reclaimed water from a population-level perspective. These simulations encompassed four different pathogens (human viruses, *Cryptosporidium*, *Giardia*, and *E. coli* O157:H7), three routes of exposure (recreation, landscape irrigation, and crop irrigation), and two levels of wastewater treatment (disinfected secondary and disinfected tertiary).

In addition to the assumptions that were necessary to run the static model simulations, a number of additional assumptions were necessary to run the dynamic model simulations. As noted previously, the dynamic model parameterization was conducted via literature review and calibration. Model parameter values for the pathogens evaluated were developed and have been documented elsewhere (Soller et al., 2007). In these simulations, it was assumed that 5% of a population of 100,000 individuals was exposed to reclaimed water at a frequency of once per month on average.

A summary of the results from the population-level assessments comparing the static and dynamic model simulations is presented in matrix format in Table 3.3. The results are summarized graphically in Figure 3.4.

Review of the information presented in Table 3.3 and Figure 3.4 indicates that, in general for the scenarios investigated, the static and dynamic model results are in relatively good agreement. However, it appears that accounting for person-to-person transmission of infection and immunity slightly increases the magnitude of the distribution of the expected number of infections for all the scenarios investigated. This observation is consistent with previously reported results (Soller et al., 2004).

Table 3.3. Summary of Population-Level Microbial Risk Assessment Simulation Results

				Estimated Risk[2]		
Pathogen	**Treatment**	**Exposure**	**Model**	**10%-ile**	**Median**	**90%-ile**
Human viruses[1]	Disinfected tertiary	Recreation	Dynamic	3.80E-04	1.20E-02	4.20E-01
Human viruses[1]	Disinfected tertiary	Recreation	Static	2.80E-04	8.90E-03	2.80E-01
Cryptosporidium	Disinfected secondary	Recreation	Dynamic	2.80E-02	5.00E-01	7.20E+00
Cryptosporidium	Disinfected secondary	Recreation	Static	5.30E-03	8.50E-02	1.30E+00
Giardia	Disinfected tertiary	Landscape irrigation	Dynamic	5.80E-04	1.80E-02	5.50E-01
Giardia	Disinfected tertiary	Landscape irrigation	Static	8.90E-05	2.60E-03	7.10E-02
E. coli O157:H7	Disinfected tertiary	Crop irrigation	Dynamic	2.40E-07	2.10E-05	1.60E-03
E. coli O157:H7	Disinfected tertiary	Crop irrigation	Static	5.80E-08	4.50E-06	4.00E-04

Notes:

1. Simulations were based on enterovirus occurrence and rotavirus infectivity (dose response).
2. Results shown are the expected number of infected individuals out of a population size of 100,000 for the scenario investigated.

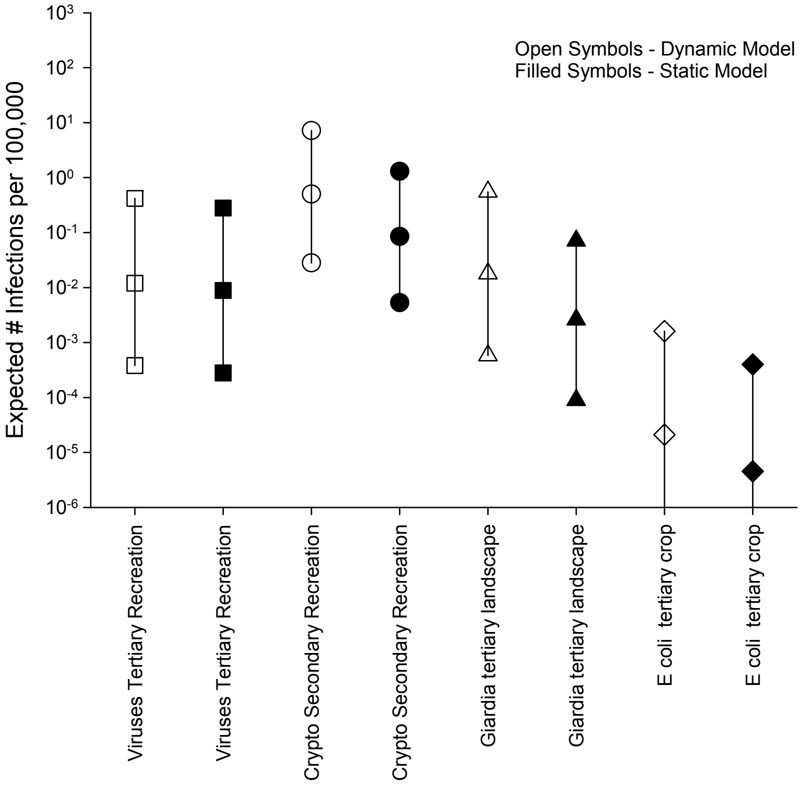

Figure 3.4. Population-level microbial risk assessment results. Note: Values shown are the 10th, 50th, and 90th percentiles of the computer results.

3.3 CASE STUDY RESULTS

Five public agencies that have water reclamation programs—four in California (City of Sunnyvale, City of San Jose, East Bay Municipal Utility District, and Marin Municipal Water District) and one in Florida (City of St. Petersburg)—provided data and information to conduct case studies and interpret the MRA output matrix.

Following are summary case studies for each facility. The case studies include descriptions of the facilities and the reclaimed water that is produced, summaries of the reclaimed water uses, summaries of data provided by the agencies, and an explanation of how to interpret the risk matrix results presented previously within the context of each agency.

In four of the five case studies, pathogen data were not available to conduct risk assessment calculations. For these case studies without pathogen data, it was not possible to directly compute the risks to human health associated with exposure to effluent. However, by assuming that the effluent quality is similar from different facilities that use similar treatment processes when operating within designed operating conditions, it is possible to draw insights from the risk simulations presented in Table 3.2.

Because of the uncertainty in the underlying assumptions associated with the simulation results, the inferences drawn from the case studies without pathogen data should be interpreted cautiously. Nevertheless, the case studies provide valuable perspectives on the relative level of public health concern associated with the selected reuse exposure to reclaimed water for a series of pathogens of potential public health concern. Also, provided that the results are interpreted in a relative manner, it is possible to consider the potential incremental benefits of, for example, additional treatment, reduced exposure, and/or pathogen monitoring.

3.3.1 Case Study 1: City of Sunnyvale, CA

The City of Sunnyvale WPCP is located in Sunnyvale, CA. The plant provides advanced secondary treatment of wastewater from domestic, commercial, and industrial sources within the City of Sunnyvale, Rancho Rinconada, and Moffett Field. The service area has a population of approximately 127,000. The plant has an average dry weather flow design capacity of 29.5 million gallons/day (MGD) and a peak flow capacity of 40 MGD.

Disinfected tertiary reclaimed water is produced intermittently to meet user demand and to fill a 2-million gallon storage tank, which then serves as a supply source. The reclaimed water is distributed throughout the northern portion of the City of Sunnyvale, where it is used mainly for irrigation purposes.

The wastewater treatment process consists of influent grinding, preaeration and grit removal, primary sedimentation, secondary biological treatment (oxidation ponds), fixed film reactor nitrification, dissolved air flotation with coagulation, dual media filtration, chlorination, and dechlorination. During periods of reclaimed water production, plant operating conditions are adjusted to meet the State of California's Water Recycling Criteria for disinfected tertiary reclaimed water: average turbidity of less than 2 nephelometric turbidity units (NTU) prior to chlorination, chlorine contact time (CT) of >450 mg-min/L, as estimated by residual chlorine concentration times the CT, with 90 min minimum modal chlorine CT, and median total coliforms of <2.2 most probable number (MPN). These conditions are achieved through changes in dissolved air flotation polymer dose, chlorine dose, and flow rates through the contact basins used for reclaimed water. Filtered water turbidity, final chlorine residual, and CT are monitored continuously by the control system. If turbidity or CT exceeds the regulatory limits, the control system will automatically divert water from the reclaimed water pump station to the NPDES "normal" discharge. CT values are normally much higher than the minimum requirement.

The reclaimed water flow from the contact tanks to the reclaimed water pump station is partially dechlorinated with sodium bisulfite to maintain a chlorine residual of approximately 2–3 mg/L. The calculated CT does not include any additional contribution from the chlorine residual in the distribution system.

During the peak reclaimed water production season (April–October), the plant effluent is highly nitrified. Between May and July, ammonia levels prior to chlorination are typically below 0.5 mg/L, indicating that chlorine is most likely initially present in the free residual form during this period. During the late summer, fall, and winter, some or all of the chlorine is likely present in the form of a combined residual.

In 2005, 265 million gallons of reclaimed water were distributed to customers throughout the northern portion of the City of Sunnyvale. In 2004 the total reclaimed water distributed was 306 million gallons. A summary of reclaimed water usage by reuse application category for 2005 is provided in Table 3.4. Review of the table clearly indicates that landscape and park irrigation accounts for the vast majority of reclaimed water use.

3.3.1.1 *Available Data*

Data for flow, filtered water turbidity, chlorine residual, and CT are recorded continuously by the plant's Supervisory Control and Data Acquisition system. Grab samples collected during each reclaimed water production run are analyzed for total coliform and dissolved oxygen as required by the City's permit (Water Reuse Order). During the summer of 2006, 19 samples were also analyzed for enterococcus. Those results varied from <1–3/100 mL (MPN). Additional water quality monitoring is conducted to track long-term trends and to provide information to interested reclaimed water customers. The parameters analyzed include chloride, bicarbonate, sulfate, nitrate, phosphate, calcium, magnesium, sodium, total dissolved solids, conductivity, hardness, alkalinity, salinity, boron, ammonia, and pH.

Table 3.4. Summary of 2005 Reclaimed Water Usage for City of Sunnyvale WPCP

Reuse Application[1]	No. of Sites	Area Applied (acres)	Volume Delivered[2] (MG)	% of Total Reuse Flow
Landscape Irrigation				
Parks[3]	3	65	36.8	13.9
Golf Courses	1	100	78.8	29.8
Green Belts[4]	12	10	5.8	2.2
Other[5]	68	150	134.6	50.8
Industrial[6]	2	—	8.4	3.2
Dual Plumbing[7]	1	—	0.30	0.11
TOTAL	88	325	265	100

Notes:

1. Two sites are listed under two categories because of multiple uses.
2. Based on totals recorded at each site's meter (water billing records), reduced by 16% to account for the average system-wide potable water fraction.
3. The Parks category includes a County park, a large sports complex, and baseball fields.
4. Consists of freeway interchange and street median sites.
5. Primarily comprised of landscaping at commercial and industrial office buildings; some use in fountains.
6. Industrial processes receiving reclaimed water include cooling, construction applications, soil compaction and dust control, etc. (Reclaimed water is supplied to one cooling tower site as a backup supply, but no water is actually used.)
7. As defined in Title 22.

3.3.1.2 *Reclaimed Water Use Management Concerns*

In the early days of the program, concerns regarding the safety of reclaimed water used in golf course water features were raised by golf course maintenance staff. Similar concerns are typically raised when use of reclaimed water at parks and playgrounds is proposed. The Parks Department staff has also raised concerns about potential exposure to reclaimed water that may be on picnic tables as a result of irrigation overspray or drift.

3.3.1.3 *Interpretation of Risk Matrix with Case Study Context*

The City of Sunnyvale produces a disinfected tertiary reclaimed water that is consistent with and meets California's water reuse regulations. Data provided by the City indicate that the most common end use of the reclaimed water is for landscape irrigation and reported concerns regarding the safety of reclaimed water are also related to that use.

No pathogen data were available for this treatment facility; therefore, it was not possible to directly compute the risks to human health associated with exposure to effluent from this facility. Assuming that the effluent from this facility is similar to other water reclamation facilities that produce disinfected tertiary effluents, it is possible to draw insights from the risk simulations presented previously. Based on this assumption and the results of the MRA simulations presented in Table 3.2 and shown in Figure 3.2, it is expected that the relative risks of infection from human enteric viruses, *Cryptosporidium*, and *Giardia* would each be similar, with median risks on the order of 10^{-5} per exposure with 90% confidence intervals ranging from 10^{-6}–10^{-3} per exposure, provided that the WPCP is operating in a manner consistent with planned operations.

3.3.2 Case Study 2: City of San Jose, CA

The San Jose/Santa Clara WPCP is located in San Jose, CA. The plant provides tertiary treatment of wastewater from domestic, commercial, and industrial sources from the cities of San Jose, Santa Clara, and Milpitas; County Sanitary Districts 2 and 3; the West Valley Sanitation District, including Campbell, Los Gatos, Monte Sereno, and Saratoga; and the Cupertino, Burbank, and Sunol Sanitary Districts. The service area has a population of approximately 1,300,000.

The wastewater treatment process consists of screening and grit removal, primary sedimentation, secondary (biological nutrient removal) treatment, secondary clarification, filtration, disinfection with chlorine, and dechlorination. The WPCP has an average dry weather flow design capacity of 167 MGD and a peak hourly flow capacity of 271 MGD. The secondary treatment process is a biological nutrient removal process that consists of anoxic, aerobic, anoxic, and aerobic zones in sequence. The mean cell residence time in summer is 6–10 days and in winter is 8–12 days. The multimedia gravity filters with 22 in. of anthracite, 12 in. of sand, and 12 in. of gravel are divided into filters which produce plant effluent discharged to the receiving water (at hydraulic loading rates between 5.3 and 7.2 gallons per minute [gpm]/ft^2) and filters which produce reclaimed water (at hydraulic loading rates between 4.3 and 4.8 gpm/ft^2). Chlorine is used for intermittent prefilter chlorination. The filters are backwashed every 24 to 25 h on average using 0.28 MG of filtered plant effluent per backwash. Aluminum sulfate is used for backwash water treatment.

Reclaimed water from the plant is delivered to customers in the service area by the South Bay Water Recycling Program (SBWR). Treated water from the San Jose/Santa Clara WPCP is redirected from the South San Francisco Bay discharge to an effluent diversion structure and pipe, where it receives an additional chlorine dose to achieve a CT of 450 mg-min/L (5 mg/L after 90 min CT), and then flows into the reclaimed water distribution system via a transmission pump station. The reclaimed water production quality is monitored continuously via an on-line system for turbidity and chlorine residual.

In 2005 the total reclaimed water production was over 2.6 billion gallons, and the WPCP discharged 100 MGD to the receiving water. In the average peak summer months, reclaimed water production is 12 MGD, and the annual average monthly supply is 8–10 MGD. A summary of reclaimed water usage by reuse application category for 2005 is provided in Table 3.5. There are currently 541 customers served through SBWR's four retailers, the San

Jose Municipal Water System, San Jose Water Company in the City of San Jose, the City of Milpitas, and the City of Santa Clara.

3.3.2.1 *Available Data*

Daily data from 2005 are available for flow, total coliform, dissolved oxygen, pH, chlorine residual, plant effluent enterococcus, filter effluent turbidity, and total CT. Median total coliform sample results were 1.0 MPN/100 mL for 2005. The chlorine residual ranged from 3.5–9.0 mg/L with an average value of 5.8 mg/L and a standard deviation of 0.95 mg/L. The total CT ranged from 938–7607 mg-min/L with an average value of 2472 mg-min/L and a standard deviation of 1233 mg-min/L. The filter effluent turbidity ranged from 0.02–2.2 NTU with an average value of 0.6 NTU and a standard deviation of 0.25 NTU.

Table 3.5. Summary of 2005 Reclaimed Water Usage for SBWR

Reuse Application	No. of Sites[1]	Volume Delivered[2] (MG)	% of Total Reuse Flow
Landscape Irrigation[3]	501	1687	67
Agriculture	3	0.9	0
Industrial[4]	8	823.5	33
Dual Plumbing[5]	5	3.7	0
TOTAL	517	2515.1	100

Notes:

1. Customers that used reclaimed water for beneficial use during 2005.
2. Amount distributed represents the amount of reclaimed water used by customers
3. Landscape irrigation includes parks, golf courses, green belts, and schools.
4. Industrial processes receiving reclaimed water include cooling, construction applications, soil compaction and dust control, etc.
5. Commercial buildings.

3.3.2.2 *Reclaimed Water Use Management Concerns*

Concerned citizens have occasionally contacted the SBWR Program regarding public contact with reclaimed water from irrigation sprinklers, wet grass in parks and/or golf courses, condenser drift from cooling towers, overspray from decorative fountains, and other incidental means of public contact. In most cases, they have been satisfied to learn that reclaimed water provided by the SBWR program meets the full body contact requirements contained in the California Water Recycling Criteria (State of California, 2000).

3.3.2.3 *Interpretation of Risk Matrix within Case Study Context*

The City of San Jose produces a disinfected tertiary reclaimed water that is consistent with California’s water reuse regulations. Data provided by the City indicate that the most common end use of the reclaimed water is for landscape irrigation, and reported concerns from citizens regarding the safety of reclaimed water are most often related to that use.

No pathogen data were available for this treatment facility; therefore, it was not possible to directly compute the risks to human health associated with exposure to effluent from this facility. Assuming that the effluent from this facility is similar to other water reclamation facilities that produce disinfected tertiary effluents, it is possible to draw insights from the risk simulations presented previously. Based on this assumption and the results of the MRA simulations presented in Table 3.2 and shown in Figure 3.2, it is expected that the relative risks of infection from human enteric viruses, *Cryptosporidium*, and *Giardia* would each be similar, with median risks on the order of 10^{-5} per exposure with 90% confidence intervals ranging from 10^{-6}–10^{-3} per exposure, provided that the WPCP is operating in a manner consistent with planned operations.

3.3.3 Case Study 3: East Bay Municipal Utility District, CA

3.3.3.1 Main Wastewater Treatment Plant

East Bay Municipal Utility District's (EBMUD's) main wastewater treatment plant (WWTP) is located in Oakland, CA. The main WWTP provides secondary treatment of wastewater from residential, commercial, and industrial sources within the cities of Alameda, Albany, Berkeley, Emeryville, Oakland, and Piedmont and for the Stege Sanitary District, which includes El Cerrito, Kensington, and parts of Richmond. EBMUD's wastewater service area of 83 sq mi serves a population of about 645,000. EBMUD also provides potable water to a service area that covers 325 sq mi in portions of Alameda and Contra Costa Counties and serves a population of approximately 1.3 million.

The wastewater treatment process consists of prechlorination (for odor control), screening, grit removal, primary sedimentation, secondary treatment using high-purity oxygen-activated sludge, final clarification, disinfection (with sodium hypochorite), and dechlorination (with sodium bisulfite). There is no filtration at the plant. The plant provides secondary treatment for a maximum flow of 168 MGD. The average annual daily flow is approximately 80 MGD.

The main WWTP currently produces approximately 5.9 MGD of disinfected secondary treated reclaimed water for various industrial processes at the main WWTP and for landscape irrigation. The landscape irrigation reclaimed water is used only on-site at the main WWTP facility.

The March–December 2005 effluent total suspended solids (TSS) ranged from 0.05–770 mg/L with an average value of 61 mg/L. Fecal coliform concentrations in 2005 ranged from 2–5000 MPN/100 mL with a geometric mean of 3.5 MPN/100 mL. Additional indicator and pathogen data are presented in Table 3.6.

Table 3.6. Fecal Indicator and Pathogen Data from EBMUD Main WWTP: 2005–2006[1]

	E. COLI,	**ENTEROCOCCUS,**	***GIARDIA,***	**MS PHAGE (ADAMS),**
Date	**MPN/100 mL**	CFU/100 mL	cysts/L	PFU/mL
09/21/05	23	14	5	66
			1	
01/14/06	4	60		
02/27/06	2	8		
03/06/06	2	56		
03/25/06	11	3		
03/29/06		5		

Notes: Methods used: *E. coli*, EPA 40 CFR, detection limit of 2; enterococcus, SM(18)2930C, detection limit of 1–5; *Giardia*, WERF 98-HHE-1 modified for P1 staining; MS phage, Adams double-layer agar method 1959.

3.3.3.2 North Richmond Water Reclamation Plant

EBMUD has partnered with the West County Wastewater District to deliver reclaimed water to the Chevron refinery in Richmond for cooling tower use. Secondary effluent from West County Wastewater District is further treated at EBMUD's North Richmond Water Reclamation Plant to produce tertiary treated reclaimed water with specific water quality requirements for cooling towers. Chevron's historic reclaimed water demand has been approximately 3 MGD.

The North Richmond Water Reclamation Plant includes four deep bed continuous backwash sand filters with a total filter surface area of 800 ft^2. Each of the four filters is comprised of four modules. Flow to each filter (four modules) is controlled by one influent weir gate. Each module (16 total) has separate backwash components. Filter influent flows down the filter cell feed well from the influent channel to the bottom of the filter cell. Filter influent then flows up through the filter sand medium and spills into the filter effluent trough. The four filter effluent trough flows collect in the filter effluent channel and flow by gravity to the chlorine contact basin. The filtration rate is normally 5.0 gpm/ft^2; however, with one filter out of service, the rate increases to 6.8 gpm/ft^2. The filtration system is designed to operate effectively with one filter out of service for maintenance or repairs. A constant flow of filtered effluent is produced, because the filters are continuously backwashed. At a maximum backwash flow rate of 0.4 MGD reclaimed back to the reactor clarifiers and a filter influent flow of 5.8 MGD, a maximum of 5.4 MGD of filtered effluent is available. This meets Chevron's demand for cooling tower make-up water.

Sodium hypochlorite is added to the filter effluent channel and blended by a mechanical mixer prior to gravity flow to the chlorine contact basin. To meet the disinfection criteria, the finished water must maintain a chlorine residual of 5 mg/L of chlorine after 90 min of CT, and facilities must be provided to dose chlorine at a residual of up to 10 mg/L as chlorine. At the minimum basin operating depth of 14.5 ft., 4.5 ft. above the chlorine contact basin floor, the dual serpentine basin configuration provides 45 min of CT at design flow. An additional 45 min of detention time is provided in the delivery line from the water reclamation plant to the Chevron refinery, meeting the 90 min of CT required by California's water reuse criteria.

Daily total coliform results in 2005 were all 2 MPN/100 mL except for one result of 4 MPN/100mL. Daily TSS results in 2005 ranged from 0.6–5.4 mg/L, with an average value of 1.4 mg/L.

3.3.3.3 West County Wastewater District

The West County Wastewater District has a dry weather design flow of 12 MGD. Wastewater treatment consists of bar screens, aerated grit chambers, primary clarifiers, roughing filter, aeration basins, secondary sedimentation basins, sodium hypochlorite disinfection, and dechlorination. The Richmond Country Club uses 0.18 MGD of disinfected secondary treated reclaimed water from the West County Wastewater District for irrigation.

In July 2006 the monthly average effluent flow was 7.9 MGD and the average TSS was 6.2 mg/L. The plant used 1043 lb of chlorine for disinfection and had an average chlorine residual of 3.5 mg/L. The 12 total coliform results for the month ranged from <2–350 MPN/100 mL with a median value of 3.5 MPN/100 mL.

3.3.3.4 Interpretation of Risk Matrix within Case Study Context

EBMUD produces disinfected tertiary reclaimed water that is used for industrial cooling towers and disinfected secondary effluent that is used, among other applications, for landscape irrigation.

No pathogen data were available for this treatment facility; therefore, it was not possible to directly compute the risks to human health associated with exposure to effluent from this facility. Assuming that the effluent from this facility is similar to other water reclamation facilities that produce disinfected tertiary effluents, it is possible to draw insights from the risk simulations presented previously. Based on this assumption and the results of the MRA simulations presented in Table 3.2 and shown in Figure 3.2, it is expected that the relative risks from human enteric viruses, *Cryptosporidium*, and *Giardia* would have median values on the order of 10^{-4} per exposure to reclaimed water from the landscape irrigation applications, with 90% confidence intervals ranging from 10^{-6}–10^{-3} per exposure, provided that the main WWTP or West County Wastewater District is operating in a manner consistent with planned operations. The fact that these predicted risks are slightly higher than those predicted in the previous two case studies is consistent with the indicator bacteria results reported. In Case Study 1, enterococcus results varied from <1–3/100 mL (MPN), and in Case Study 2 the median total coliform sample results were 1.0 MPN/100 mL. Those results can be compared to the results shown in Table 3.6, which show enterococcus results varying from 3–60 *CFU*/100 mL and *E. coli* counts varying from 2–23 MPN/100 mL. It is understood that this comparison is crude, given the potential differences due to analytical methods and other issues; nevertheless, these observations appear to support the risk-based simulation results from a comparative perspective.

Because data were not available to characterize human exposures to reclaimed water from the Chevron cooling towers, it was not possible to provide insight relative to the potential risks associated with the effluent from the North Richmond Water Reclamation Plant that are used for industrial activities.

3.3.4 Case Study 4: Marin Municipal Water District, CA

The Marin Municipal Water District (MMWD) operates the Las Gallinas Reclaimed Water Plant, which is located in San Rafael, CA. The recycling plant receives secondary treated wastewater from the Las Gallinas Valley Sanitary District WWTP. The recycling plant provides tertiary treatment and distributes reclaimed water primarily for landscape irrigation, along with other nonpotable applications. The plant has a design flow rate of 2.0 MGD. Although reclaimed water is used year round, usage drops significantly in the rainy season and the plant is generally shut down and supplemented with potable water from November through March.

The reclaimed water treatment process consists of full conventional treatment (clarification, sedimentation, filtration, and disinfection). The first step uses a Densadeg high-density solids-contact clarification unit, which incorporates rapid mixing, coagulation and flocculation, liquid–solids separation, reclaimed sludge, and removal of excess sludge in one unit. Aluminum sulfate and polymers are used as coagulants. Filtration is performed in eight filter cells with 36 in. of anthracite coal. Most of the solids are removed in the clarifier. The turbidity measured at the clarifier effluent is typically below 1 NTU, and the filters remove only several tenths of an NTU. After the filters, caustic and zinc orthophosphate are added for pH and corrosion control. Reclaimed water is then sent to the storage facility, which consists of three 225,000-gal polyethylene-lined concrete storage vaults. Storage allows for differences between production and demand and also provides additional chlorine contact time for disinfection.

From the storage facility the reclaimed water enters the distribution system. The reclaimed water distribution system takes water from the vault storage to terminal storage at the Terra Linda tanks (two 500,000-gal tanks) and to the reclaimed water customers.

The recycling plant has seven points of chlorine (Cl_2) injection available, three with residual control. Chlorine residual is monitored at the influent, prior to storage, and prior to entering the distribution system. This on-line monitoring of chlorine residual, turbidity, flow, and other operational parameters is performed using a programmable logic controller linked to desktop personal computers and utilizing ladder logic control and the INTELLUTION DMACS operator interface software program.

In 2005, 180 million gallons of reclaimed water were distributed to customers throughout the City of San Rafael. A summary of reclaimed water usage for 2005 is provided in Table 3.7. Review of the data in the table indicates that irrigation accounts for over 95% of the reclaimed water use.

3.3.4.1 Available Data

In 2005 (April–November 2005), all total coliform samples collected were below detectable limits. The average chlorine residual was 3.31 mg/L with a range of 0.55–6.2 mg/L. The average turbidity measured at the start of the distribution system from July 2003 to June 2004 was 0.46 NTU, pH was 7.5, chlorine residual was 3.5 mg/L, and dissolved oxygen was 8.2 mg/L.

Table 3.7. Summary of 2005 Reclaimed Water Usage for MMWD

Reuse Application	No. of Sites	Water Entitlement (acre-ft)
Landscape Irrigation		912
Parks[1]	16	
Commercial	118	
Multifamily Residential	52	
Single-Family Residential	28	2.2
Green Belts[2]	28	
Schools	11	
Other		
Industrial		
Cooling	2	11.0
Commercial Laundry	1	5.0
Car Washes	3	11.4
Toilet and Urinal Flushing	16	16.2
Total Water Entitlements	275	958
Total Amount Distributed		180 MG

Notes:

1. Parks includes municipal parks, playgrounds, a golf course, and a skate park.
2. Consists of freeway interchange and street median sites

3.3.4.2 Reclaimed Water Use Management Concerns

MMWD staff did not express any management concerns for exposure to reclaimed water. The highest level of exposure likely comes from car wash staff using a spray wand to rinse cars with reclaimed water before they enter the car wash (Fig. 3.5).

Figure 3.5. Exposure to reclaimed water via commercial car washing.

3.3.4.3 Interpretation of Risk Matrix within Case Study Context

MMWD produces disinfected tertiary reclaimed water that is consistent with California's Water Recycling Criteria. Data provided by the District indicate that the most common end use of the reclaimed water is for landscape irrigation. MMWD staff indicated that reclaimed water used at car washes exhibits the highest potential for human exposure.

No pathogen data were available for this treatment facility; therefore, it was not possible to directly compute the risks to human health associated with exposure to effluent from this facility. Assuming that the effluent from this facility is similar to other water reclamation facilities that produce disinfected tertiary effluents, it is possible to draw insights from the risk simulations presented previously. Based on this assumption and the results of the MRA simulations presented in Table 3.2 and shown in Figure 3.2, it is expected that the relative risks of infection from human enteric viruses, *Cryptosporidium*, and *Giardia* would each be similar, with median risks on the order of 10^{-5} per exposure with 90% confidence intervals ranging from 10^{-6}–10^{-3} per landscape irrigation exposure, provided that the facility is operating in a manner consistent with planned operations.

With the assumption that the exposures to reclaimed water from car washes are no greater than those that would be experienced during recreational activities, it is expected that the median risks of infection from human enteric viruses, *Cryptosporidium*, and *Giardia* would each be on the order of 10^{-4} per exposure with 90% confidence intervals ranging from 10^{-6}–10^{-2} per exposure, provided that the WPCP is operating in a manner consistent with planned operations.

3.3.5 Case Study 5: City of St. Petersburg, FL

The City of St. Petersburg is a densely populated urban area in the state of Florida. The population is approximately 250,000 and is growing. The City of St. Petersburg Water Resources Department manages four water reclamation facilities: Albert Whitted Water Reclamation Facility (WRF), St. Petersburg Northeast WRF, St. Petersburg Northwest WRF, and St. Petersburg Southwest WRF. The facilities provide tertiary treatment (via media filtration) and disinfection. Excess reclaimed water is disposed of through deep well injection.

St. Petersburg is a center for sports and leisure activities. Beaches, state parks, marinas, and golf courses play a vital role in this environment. The St. Petersburg City Council voted in 1972 to eliminate wastewater discharges to Tampa Bay and Boca Ciega Bay. A major component of the program was the construction of an innovative and precedent-setting reclaimed water distribution system. The first stages of the reclaimed water system went into operation in 1977. By 1987 the City of St. Petersburg was the first major utility in the United States to achieve zero discharge of effluent to surface waters.

The reclaimed water system was developed from a plan which originated in the early 1970s. The demand for irrigation water grew with the droughts of the 1980s and 1990s and restricted use of potable water. The system quickly became popular as a source for inexpensive irrigation and commercial process water. The reclaimed water system consists of large storage tanks totaling 25 million gallons and more than 300 mi of pipeline in a “looped” system connecting the four water reclamation facilities. More than 95% of the connections are for residential irrigation. In St. Petersburg, the typical residential lawn can require up to 30,000 gal of irrigation water/month during the growing season, but the average sewer customer only discharges 6000 gal/month to the system. Therefore, it takes five sewer customers to produce enough reclaimed water to supply one home with irrigation water. As a result, it is not presently possible to supply all the homes in St. Petersburg with reclaimed water. Treated effluent is considered more valuable than potable water for growing plants due to the nutrients contained in the effluent.

The treatment plants are all complete mix activated sludge domestic wastewater treatment plants. Treatment at each of the four plants consists of preliminary treatment (bar screen and grit removal), aerated secondary treatment, clarification, filtration (deep bed or shallow beds with sand or sand and crushed anthracite), and high-level disinfection with chlorine. The City maintains a minimum standard of 4.0 mg/L chlorine residual. The annual average daily flow at the four plants and other operating criteria for the four water reclamation facilities are summarized in Table 3.8.

Table 3.8. City of St. Petersburg WRF Operating Data

	Whitted WRF	Northeast WRF	Northwest WRF	Southwest WRF
Design Flow (MGD)	12.4	16.0	20.0	20.0
Avg Flow (MGD)	8.3	10.3	11.89	12.75
Avg Reclaim Flow (MGD)	3.7	3.49	6.89	2.5
Filter Media Depth (in.)	4 @ 24 in., 2 @ 16 in.	8 @ 48 in. sand and 24 in. anthracite	5 @ 12 in. sand, 1 @ 24 in. sand	8 @ 48 in. sand and 24 in. anthracite
Filter Chemical Use	0	1228 lb alum/day	0	0
Filter Avg Hydraulic Loading Rate (gpm/ft^2)	0.86	1.27	0.78	1.57
Filter Backwashing Frequency (h)	30	30	5 @ 3.3 h, 1 @ 12 h	30
Filter Volume per Backwash (gal/filter)	4 @ 24,300, 2 @ 42,240	8 @ 480,000	5 @ 453,600, 1 @ 16,896	8 @ 294,000
Avg Chlorine CT (min)	53.6	81	42	54
Effluent Avg TSS (mg/L)	1.62	1.27	1.77	1.67
Effluent Avg Total Residual Chlorine (mg/L)	2.6	3.53	3.25	2.0
Effluent Avg pH	7.2	7.1	6.93	7.08
Effluent Avg Fecal Coliform (/100 mL)	0	0	97% nondetect	0
Effluent Avg Ammonia (mg/L)	11.86			
Effluent Max Fecal Coliform (/100 mL)	100	20	12	200
Effluent Max Turbidity (NTU)	2.7	2.4	2.7	1.8

The wastewater treatment plants use in-line analyzers for pH, turbidity, and chlorine residual. These operational parameters, along with analysis of samples collected for suspended solids and chlorides, are used to determine if the facilities are operating within normal parameters. Turbidity and suspended solids are monitored after the filters, and chlorine residual and chlorides are monitored after chlorination.

The reclaimed water system serves golf courses, schools, parks, cooling towers, and residential irrigation. A summary of reclaimed water usage by reuse application for 2005 is provided in Table 3.9. Residential irrigation comprises more than 95% of the reclaimed water connections. There are 10,238 single-family residences, 66 schools, 128 parks, playgrounds, and medians, 318 commercial properties, and 111 multifamily residences with reclaimed water service.

Table 3.9. Summary of Reclaimed Water Usage for the City of St. Petersburg

Reuse Application	Capacity, MGD	Flow, MGD	Area, acres
Public Access Areas and Landscape Irrigation			
Golf Course Irrigation	8.7	2.50	1086
Residential Irrigation	24.0	8.22	3744
Other Public Access Areas	31.2	9.00	2938
Industrial			
At Treatment Plant	4.0	1.15	—
Cooling Towers	0.5	0.14	—
Total Reuse	**68.4**	**19.72**	**7768**

Source: *2005 Annual Reuse Report*.

3.3.5.1 Available Data

In addition to the operational data presented above, the City has also conducted limited *Giardia* and *Cryptosporidium* effluent monitoring from 2000 to 2006. The results of these sampling events are summarized in Table 3.10.

3.3.5.2 Reclaimed Water Use Management Concerns

The City's concerns requiring possible investigation include the potential health risks associated with exposure to reclaimed water irrigation aerosols, the potential for dermal absorption from human or animal contact with reclaimed water, and the possibility of carrying *Cryptosporidium* and *Giardia* through a reclaimed water system to a public irrigation site.

Table 3.10. Summary of Pathogen Monitoring Conducted by the City of St. Petersburg

Albert Whitted WRF

Date Sampled	Volume Examined Liters	Giardia Total Detected	With internal features	Equivalent Giardia cysts/100 L	DAPI positive cysts/100 L	Cryptosporidium Total Detected	With internal features	Equivalent Crptosporidium oocysts/100 L	MPN Infectious oocysts/100 L [1]	DAPI positive oocysts/100 L
11/27/00	378.5	1	1	0.26	NR	7	0	1.85	NR	NR
08/05/02	51.09	11	11	21	NR	83	83	162	4.66	NR
04/19/04	50.7	6	4	11.8	NR	0	0	<2	<2.0	NR
04/17/06	50.25	6	NR	12	8	18	NR	36	NR	36
06/19/06	50.5	8	NR	16	6	26	NR	51	NR	40

Northeast WRF

Date Sampled	Volume Examined Liters	Giardia Total Detected	With internal features	Equivalent Giardia cysts/100 L	DAPI positive cysts/100 L	Cryptosporidium Total Detected	With internal features	Equivalent Crptosporidium oocysts/100 L	MPN Infectious oocysts/100 L [1]	DAPI positive oocysts/100 L
03/22/01	423.92	13	2	3.06	NR	5	0	1.18	NR	NR
08/05/02	47.31	4	4	8	NR	151	151	319	2.26	NR
04/21/04	54.3	11	8	20.3	NR	0	0	<1.8	<1.8	NR
04/03/06	50.29	15	NR	30	6	136	NR	270	NR	270
6/2/2006	50.58	4	NR	8	6	86	NR	170	NR	164

Northwest WRF

Date Sampled	Volume Examined Liters	Giardia Total Detected	With internal features	Equivalent Giardia cysts/100 L	DAPI positive cysts/100 L	Cryptosporidium Total Detected	With internal features	Equivalent Crptosporidium oocysts/100 L	MPN Infectious oocysts/100 L [1]	DAPI positive oocysts/100 L
02/07/01	181.49	20	10	11.01	NR	3	3	1.65	NR	NR
08/05/02	47.31	14	14	30	NR	26	26	55	<2	NR
04/21/04	52.6	11	7	20.9	NR	0	0	<1.9	10.1	NR
04/17/06	50	60	NR	120	68	5	NR	10	NR	8
6/19/2006	51.0	127	NR	249	186	68	NR	133	NR	106

Southwest WRF

Date Sampled	Volume Examined Liters	Giardia Total Detected	With internal features	Equivalent Giardia cysts/100 L	DAPI positive cysts/100 L	Cryptosporidium Total Detected	With internal features	Equivalent Crptosporidium oocysts/100 L	MPN Infectious oocysts/100 L [1]	DAPI positive oocysts/100 L
10/23/99	113.8	0	0	<0.87	NR	6	0	5.27	NR	NR
12/08/99	386.07	0	0	<0.26	NR	16	3	4.14	NR	NR
02/07/00	283.87	6	0	2.11	NR	4	0	1.40	NR	NR
04/13/00	170.3	1	0	0.59	NR	4	0	2.34	NR	NR
06/15/00	122.06	0	0	<0.82	NR	0	0	<0.82	NR	NR
08/21/00	143.64	13	3	9.05	NR	1	1	0.69	NR	NR
03/22/01	380.39	5	2	1.31	NR	5	2	1.31	NR	NR
04/25/02	48.44	41	34	84.6	NR	4	4	8.26	<2	NR
05/08/02	51.1	34	19	66	NR	107	63	209	8	NR
08/05/02	47.31	1	0	2 [2]	NR	5	1	11 [2]	<2	NR
04/30/03	48.1	2	0	4.2	NR	7	5	14.6	16.9	NR
04/19/04	41.05	0	0	<2.4	NR	0	0	<2.4	5.1	NR
10/26/05 [3]	48.41	5	NR	10	NR	6	NR	12	NR	NR
11/04/05 [3]	50.3	0	NR	<2	NR	166	NR	330	NR	NR
11/18/05 [4]	50.21	0	NR	<2	NR	0	NR	<2	NR	NR
11/21/05 [3]	52.33	1	NR	2	NR	84	NR	161	NR	NR
12/06/05 [4]	50.56	0	NR	<2	NR	7	NR	14	NR	NR
12/16/05 [3]	50	0	NR	<2	NR	4	NR	8	NR	NR
12/19/05 [3]	50	2	NR	4	NR	15	NR	30	NR	NR
12/30/05 [3]	50.25	4	NR	8	NR	11	NR	22	NR	NR
01/03/06 [3]	51.5	2	NR	4	NR	31	NR	60	NR	NR
02/13/06 [4]	50.03	4	NR	8	NR	4	NR	8	NR	NR
02/24/06 [4]	50	0	NR	<2	NR	0	NR	<2	NR	NR
04/03/06	50.65	4	NR	8	6	331	NR	654	NR	654
06/02/06	51.15	12	NR	23	16	32	NR	63	NR	59

All analyses prior to 2005 performed by USF Department of Marine Science Water Quality Laboratory.
Analyses during and subsequent to 2005 performed by City of Tampa Water Quality Laboratory.
NR - not reported
[1] MPN infectious oocyts determined by cell culture.
[2] Analyst reported matrix interference which may have affected recovery.
[3] Sampled at ASR during injection
[4] Sampled at ASR during withdrawal

3.3.5.3 Interpretation of Risk Matrix within Case Study Context

The City of St. Petersburg produces disinfected tertiary treated reclaimed water that is used for landscape irrigation and other nonpotable uses. Based on the results of the MRA simulations presented in Table 3.2 and shown in Figure 3.2 for disinfected tertiary effluent, it is expected that the median risks of infection from human enteric viruses, *Cryptosporidium*, and *Giardia* would each be on the order of 10^{-5} per exposure to reclaimed water from the landscape irrigation applications, with 90% confidence intervals ranging from 10^{-6}–10^{-3} per exposure, provided that the water reclamation facilities are operating in a manner consistent with planned operations.

To evaluate how the results presented in Table 3.2 compare to the site-specific risks for the City of St. Petersburg, the data presented in Table 3.10 were used as input to the MRAIT based on several simplifying assumptions. Namely, all reported *Giardia* and *Cryptosporidium* organisms detected were assumed to be infectious, data from all facilities were grouped[3] and assumed to be representative of risks for exposures to reclaimed water from all WRFs in the City, all observations reported below detectable levels were assumed to contain pathogens at the detection limit, and landscape irrigation was assumed to be the exposure route of interest. The results of these MRA simulations are presented in Table 3.11.

Table 3.11. Comparison of Individual-Level MRA Simulation Results with Results from Case Study 5

				Estimated Risk of Infection[2]		
Pathogen	**Source**	**Exposure**	**Model**	**10%-ile**	**Median**	**90%-ile**
Cryptosporidium	Disinfected secondary[1]	Landscape irrigation	Static	1.3E-05	1.4E-04	1.3E-03
	Disinfected tertiary[1]	Landscape irrigation	Static	1.4E-06	4.0E-05	9.2E-04
	St. Petersburg pathogen data[3]	Landscape irrigation	Static	3.5E-06	5.9E-05	9.4E-04
Giardia	Disinfected secondary[1]	Landscape irrigation	Static	6.2E-06	1.1E-04	1.7E-03
	Disinfected tertiary[1]	Landscape irrigation	Static	5.4E-07	1.6E-05	4.9E-04
	St. Petersburg pathogen data[3]	Landscape irrigation	Static	5.9E-07	6.1E-06	5.5E-05

Notes:
1. Results previously shown in Table 3.2.
2. Results shown are the probability of infection per exposure event.
3. Based on data presented in Table 3.10.

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[3] Monitoring results that were sampled at the ASR withdrawal point were not included in this analysis because it was felt that they may not be representative of the plant effluent.

Inspection of Table 3.11 indicates that the predicted risks of infection for *Giardia* and *Cryptosporidium* associated with exposure to reclaimed water produced by the City of St. Petersburg WRFs are very similar to the risks predicted for disinfected tertiary effluent (as shown in Table 3.2). The possible exception to this statement is that the predicted risks from exposure to *Giardia* in St. Petersburg are slightly lower than those predicted in Table 3.2. Caution is needed in interpreting this result, however, because data from St. Petersburg were used as one component of the data used to generate Table 3.2. Thus, these results should not be considered independent validation. The actual risks associated with exposure to effluent from the City of St. Petersburg may be lower than those presented in Table 3.10, because recent research conducted on reclaimed waters in Florida indicates that the concentration of infectious cysts and oocysts in reclaimed water may be substantially lower than the total number of cysts and oocysts reported (Gennaccaro et al., 2003; Huffman et al., 2006).

CHAPTER 4

DISCUSSION

To understand and fully appreciate the results presented previously, it is important to understand the context within which the results may apply. The following sections are intended to clarify this context.

4.1 COMPARISON WITH PREVIOUSLY REPORTED RESULTS

Tanaka et al. (1998) examined the safety of wastewater reclamation and reuse and developed tables of estimated annual risks of infection from enteric viruses for chlorinated secondary effluents and tertiary chlorinated effluents used for golf course irrigation, food crop irrigation, recreational impoundments, and groundwater recharge. For the chlorinated secondary effluents, virus occurrence data were collected from the unchlorinated effluents of four treatment facilities, and 3.9 logs of virus inactivation were assumed to occur during the disinfection process (chlorination). For the tertiary chlorinated effluents, 5.2 logs of virus inactivation were assumed to occur between unchlorinated secondary effluents and the final effluent. A rotavirus dose–response model was employed to characterize infectivity. Although Tanaka et al. employed a number of different assumptions than those used in this investigation, including basic assumptions about treatment efficacy and exposure, a comparison of the results is illustrative.

For the recreational exposure scenario, Tanaka et al. (1998) assumed that 100 mL of water was ingested per swimming event and that the exposure occurred 40 days per year. For the golf course irrigation exposure scenario, 1 mL of water was assumed to be ingested at an exposure frequency of twice per week, and for the crop irrigation exposure scenario, 10 mL of water was assumed to be ingested at an exposure frequency of every day. Because the analysis associated with recreational exposure conducted in our investigation was shown to exhibit the highest estimated microbial risk for the various scenarios investigated, it is used for illustrative purposes to compare against the results reported by Tanaka et al. (1998). Direct comparison with the golf course and crop irrigation exposure scenarios is somewhat more complicated, because Tanaka et al. accounted for the reduction of pathogens in the environment due to the assumed time between irrigation and exposure, whereas no such reduction was assumed in this investigation. Further, to facilitate the comparison it was necessary to derive average daily risks based on the annual risks reported by Tanaka et al. (Table 4.1).

Comparison of the average daily risk of infection from enteric viruses related to recreational exposure to treated effluent reported by Tanaka et al. (1998) with the estimates presented in Table 3.2 indicates the following:

- The computed mean daily risks for recreation in disinfected (chlorinated) secondary effluent reported by Tanaka et al. (1998) range from 3×10^{-6}–2×10^{-4}, with upper 95% confidence limits ranging from 7×10^{-6}–3×10^{-4}.

- In this investigation, the estimated median risk per event from human viruses for recreation in disinfected secondary effluent is 2×10^{-4} with a reported 90th percentile of 5×10^{-3} (Table 3.2).

- The computed mean daily risks for recreation in disinfected (chlorinated) tertiary effluent reported by Tanaka et al. (1998) range from 1×10^{-7}–8×10^{-6}, with upper 95% confidence limits ranging from 3×10^{-7}–2×10^{-5}.

- In this investigation, the estimated median risk per event from human viruses for recreation in disinfected tertiary effluent is 5×10^{-5} with a reported 90th percentile of 2×10^{-3} (Table 3.2).

Table 4.1. Risk Estimates for Exposure to Chlorinated Secondary and Tertiary Effluents via Recreation, as Reported by Tanaka et al. (1998)

		Mean Risk		Upper 95% Confidence Limit	
Treatment	Facility	Annual (1)	Daily (2)	Annual Risk (1)	Daily Risk (2)
Chlorinated Secondary Effluent	OCSD TF	1.7E-03	4.3E-05	2.6E-03	6.5E-05
	OCSD AS	1.2E-04	3.0E-06	2.6E-04	6.5E-06
	Pomona	4.3E-04	1.1E-05	2.1E-03	5.3E-05
	MRWPCA AS	6.6E-03	1.7E-04	1.3E-02	3.3E-04
Tertiary Chlorinated Effluent	OCSD TF	8.6E-05	2.2E-06	1.3E-04	3.3E-06
	OCSD AS	5.9E-06	1.5E-07	1.3E-05	3.3E-07
	Pomona	2.2E-05	5.5E-07	1.0E-04	2.5E-06
	MRWPCA AS	3.3E-04	8.3E-06	6.8E-04	1.7E-05

Notes: 1 - Tanaka et al estimates, 2 - Conversion to daily risk assessments

It is important to note that a number of different assumptions were employed by Tanaka et al. in their analysis compared to the analysis conducted as part of this investigation. It was not the intent to conduct a detailed comparison of all assumptions but rather to generally identify if the estimated microbial public health risks are similar. The most notable differences are the assumed volumes ingested during recreational activities and the reductions of viruses due to the disinfection unit process. In both cases, the data employed in our investigation are more recent and are believed to be the most current and reliable data at this time (Rose et al., 2004; Dufour et al., 2006). Further, it should be noted that the comparison above is based on comparing mean values to median values, which is likely to exacerbate the noted differences between the studies. Based on the comparison, it appears that the estimated microbial risk results for recreational exposure presented in this report are slightly higher (i.e., by approximately an order of magnitude) than those reported by Tanaka et al. (1998).

4.2 LIMITATIONS

Several important simplifying assumptions were needed to conduct the analysis. These assumptions relate to the form of the MRA models employed, the health outcomes investigated, and treatment of the variability and uncertainty in the data used to inform the model.

With respect to the selected disease transmission model, it is well known that a variety of model forms can be employed to characterize infectious disease transmission and to evaluate the potential for effective interventions. Particular characteristics of each model form capture different aspects of the disease transmission system (Soller, 2006). In this analysis, the salient assumption was that the epidemiological status of the population could be approximated reasonably well with the relatively simple structure of the individual- and population-level MRA models. It is possible that other model structures could yield additional and/or alternative insights.

The health outcomes considered in this investigation were illness (for *Salmonella* spp.) and infection (for all other pathogens) based on available dose–response information. The most common adverse health outcome from the pathogens investigated is gastroenteritis. However, there are a number of other more serious but less likely disease outcomes that also are associated with enteric pathogens. However, characterizing end points more serious than gastroenteritis or long-term sequelae was beyond the scope of this investigation. Nevertheless, the relative insights provided by the assessments presented here would likely also be valid for other end points.

With respect to the variability and uncertainty in the data used to inform the model, it should be understood that the reported results are applicable only to the extent that the parameter values used for the MRA models are reasonable and appropriate. Although a substantial effort was made to characterize the parameter values in a scientifically defensible and health-protective manner, it is possible that parameter values could be refined or changed based on future research. For example, the 90% confidence bounds of many of the risk estimates presented in Chapter 3 span three or more orders of magnitude. One of the important factors in the uncertainty associated with those results is the reported wide range of pathogen concentrations in both raw wastewater and treated effluent. Reducing uncertainty could thus be realized either by better characterizing raw wastewater pathogen concentrations and treatment efficacy or by better characterizing treated effluent pathogen concentrations.

Finally, the analyses presented here represent normal operating conditions for wastewater treatment facilities. Treatment plant upsets, large-scale outbreaks or epidemics, and other out-of-the-ordinary conditions are most likely not represented by the work described here. If additional data were to become available related to these issues, the work presented here could be augmented to provide additional insight relative to the incremental risks associated with these types of conditions. In the mean time, risk managers are urged to exercise caution under such conditions.

4.3 DATA GAPS

In conducting this investigation, several important gaps in knowledge became apparent. Some of the most important areas where sufficient data are lacking for quantitative MRA include the following: (1) data to characterize the risk to highly sensitive or susceptible individuals separately from the general population; (2) data to estimate the risks associated with exposure to noroviruses; and (3) robust data sets to characterize concentrations of pathogens of public health concern across different wastewater treatment processes.

4.3.1 Sensitive Subgroups within a Population

The 1996 Amendments to the Safe Drinking Water Act specify that the U.S. EPA must consider susceptible subpopulations in its health risk assessments. With respect to microbial exposures, little progress has been made in determining the degree to which individuals may differ in the completeness of protection offered by their immune system (Balbus et al., 2000).

In this investigation, an attempt was made to quantitatively characterize risk to highly susceptible or vulnerable subgroups within a population for exposures to microbial contaminants in water. However, sufficient quantitative data were not available to enable the characterization of risk for those subpopulation groups separately from the population at large, which is consistent with previously reported findings (Parkin et al., 2003).

In the future, the extent to which risk assessors will be able to address if and how sensitive subpopulations may be subject to risks that are different from the general population will vary depending on the breadth of the conceptual risk assessment model employed. For example, in an individual-based assessment, it would be reasonable to assume sensitive subpopulations could be modeled differently from the general population in the following ways:

- Different dose–response relation (that is, for a given dose the probability of infection could vary between the general population and subgroups)
- Different morbidity ratio for infected individuals
- Different disease severities among diseased individuals

Similarly, in a population-based assessment, sensitive subpopulations could be modeled differently from the general population in the following ways, in addition to those presented above for the individual-level model:

- Different duration of infection
- Different duration of illness
- Different duration of immunity
- Different background level of infection prevalence
- Different incubation period
- Different intensity of pathogen shedding during infection and/or illness

The relative importance of the factors listed above with respect to risk to human health is, for the most part, not well quantified. However, several examples from the published literature indicate that at least some of these factors can be quantified and, thus, could be incorporated into quantitative MRAs in the future to address risks to sensitive subpopulations (Riley et al., 2003; Teunis et al., 2004; McBride and French, 2006).

4.3.2 Noroviruses

Noroviruses are estimated to cause approximately 23,000,000 cases of illness in the United States annually (Mead et al., 1999) and are associated with up to 90% of epidemic nonbacterial gastroenteritis worldwide (Lindesmith et al., 2003). Rigorous modeling of norovirus transmission is extremely difficult at the present time for a number of reasons:

- The dose–response relation has yet to be published. Until a dose relation is published, it will be extremely difficult to quantitatively characterize the risk to human health from these pathogens.

- Little is known about the potential for cross-strain immunity. Approximately 300 norovirus outbreaks were documented in the United States between 1993 and 1999, and the genetic diversity of the noroviruses responsible for those outbreaks encompassed approximately 68 strains (Ando et al., 2000). It is not known whether or not infection to one strain confers immunity to other strains.

- The person-to-person transmission potential appears to be substantial based on outbreak data. Further, although noroviruses are highly infectious, volunteer studies have shown that some subjects remain uninfected even after challenges with high doses (Johnson et al., 1990; Matsui and Greenberg, 2000). Recent research indicates that a substantial portion of the population (approximately 20%) may not be susceptible to infection at any point in time (Lindesmith et al., 2003). For the population that could be susceptible at some point in time, it was found that a portion of the population (35%) was resistant to infection, suggesting that a memory immune response or some other unidentified factor also affords protection from norovirus infection (Lindesmith et al., 2003).

4.3.3 Treatment Effectiveness for Wastewater Treatment Processes

In this investigation, the efficacies of two reclaimed water treatment process configurations were evaluated. The reclaimed water treatment processes evaluated, secondary treatment with chlorine disinfection and tertiary treatment with chlorine disinfection, were intended to be representative of the wastewater treatment processes that are in operation at reclamation facilities in Arizona, California, and Florida.

The wastewater treatment processes used for reclamation can, however, vary substantially. In practical terms, it would appear that the level of treatment required for unrestricted irrigation reuse under California's Water Recycling Criteria represents the high and relatively stringent end of the range of accepted treatment technology that has been shown by many years of application to be adequately protective of human health. The lower end of the generally accepted treatment range appears to be represented by direct filtration of secondary effluent followed by chlorine with a CT as low as 15 mg-min/L, which is the minimum CT allowed for unrestricted irrigation reuse under State of Florida water reuse regulations [subject to also meeting specified fecal coliform standards and other design requirements; Florida Administrative Code Chapter 62-600, Section 440(5)(b)].

Further, a number of different unit processes or combinations of unit processes could also be considered to produce water for reclamation, and it is reasonable to ask how the risk associated with alternative treatment processes would compare to the risks presented herein. For example, UV disinfection is the other generally accepted disinfection process for these uses. Although removal of pathogens in a reclamation facility employing UV disinfection could be measured and characterized, data were not available for use in this investigation.

Clearly, a more comprehensive understanding of the treatment efficacy associated with various wastewater unit processes, including alternative types of treatment, would add additional insight to the information presented in this report. At the individual treatment facility level, barring collection of pathogen data, information on the management practices that are in place to reduce risk may be worthy of consideration.

4.4 POLICY CONTEXT

Several states have developed water reuse standards for nonpotable uses that include treatment process requirements and microbial and other water quality limits. However, no states have regulations that are fundamentally risk based. It is therefore, not surprising that the actual and/or perceived stringency of the resultant criteria varies widely among the existing state criteria. MRA is one tool that could be useful to help harmonize water reuse standards nationally, by providing a common metric that could be used to better define the relative health risks associated with exposure to reclaimed water produced by various types and combinations of wastewater treatment processes. Thus, one possible extension of this research would be as a starting point to consider and discuss the scientific basis of water reuse regulations and, hence, the public health protection afforded by existing and potential future regulations.

If states were to consider risk-based reclaimed water regulations, one of the most important issues that would need to be addressed is that of acceptable or tolerable risk. That is, evaluation of the adequacy of a particular treatment train requires a benchmark level (or set of criteria) that can be used for comparison. Selection of a benchmark level of risk can be a complicated process that involves technical, political, and social factors. For example, in the Surface Water Treatment Rule (which was developed as one component of the Safe Drinking Water Act) a risk of one infection per 10,000 people per year was taken as an acceptable health goal for *Giardia* (Macler and Regli, 1993). As drinking water regulations evolved, so did the process that is used to evaluated the adequacy of treatment. One of the more recent drinking water regulations, the Long-Term 2 Enhanced Surface Water Treatment (LT2) rule, requires public water systems to augment their water treatment processes if the mean source water *Cryptosporidium* levels correspond to an estimated annual infection level of 2/1000 or greater (U.S. EPA, 2006). The process that was used to arrive at the levels described in the Final LT2 Rule involved review by a scientific advisory committee, public comment, and numerous technical considerations, including monitoring feasibility. As another example, the existing Ambient Water Quality Criteria for bacteria in recreational waters are set to limit the rate of highly credible gastrointestinal illness in swimmers to 8/1000 in fresh water and 19/1000 in marine waters (U.S. EPA, 1986). It is not suggested that any of the above values are appropriate for reclaimed waters. Rather, it is suggested that consideration of the processes used to determine acceptable risk levels for other water-related exposures may be useful in determining how to arrive at an acceptable or tolerable level of risk which could be used for future regulation of reclaimed water.

Several other important issues would also need to be considered if states were to consider risk-based reclaimed water regulations, for example, which pathogens should be regulated, whether there are surrogates or indicators that can be used for those indicators, and how regulations protect the public from exposure to pathogens that are extremely difficult or expensive to enumerate. Nevertheless, the research presented here is sufficiently robust to initiate those discussions if regulators, water quality managers, and the public are ready to consider moving to risk-based reclaimed water regulations.

CHAPTER 5

CONCLUSIONS

In this investigation, MRA numerical simulations were conducted to provide insight toward understanding the relative risks to human health associated with nonpotable water reuse applications. To this end, a risk matrix was developed to facilitate understanding of the relative microbial risks associated with the use of reclaimed water for nonpotable reuse applications under a range of different conditions. The conditions evaluated included the occurrence of five infectious agents of public health concern in reclaimed water, the efficacy in reducing pathogen concentrations of two reclaimed water treatment process trains (i.e., disinfected secondary and disinfected tertiary treatment), and the predicted volume of water ingested via three end-use-specific exposure pathways.

The matrix of estimated public health risks presented in this report will be useful to water and wastewater utility managers, regulators, and water quality scientists and engineers, because it is based on a scientifically defensible, consistent metric that can be used to compare the potential relative risks associated with nonpotable water reuse applications under a wide range of relevant conditions. The estimated risks reported in this investigation are consistent with, although slightly higher than, those reported elsewhere in the literature.

Based on the results of this work, several recommendations can be made for future investigation. A prioritized list of recommendations is as follows:

- Develop a more comprehensive understanding of the treatment efficacy associated with various wastewater unit processes, including alternative types of treatment

- Use this research as a starting point to consider and discuss the scientific basis of water reuse regulations and, hence, the public health protection afforded by existing and potential future regulations

- Continue to consider whether it is possible to address if and how sensitive subgroups within a population are subject to risks that are different from the general population.

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APPENDIX A

EXAMPLE OUTPUT FROM THE MICROBIAL RISK ASSESSMENT INTERFACE TOOL

This appendix presents sample output from the MRA Interface Tool (MRAIT) (Soller et al., 2007) to illustrate how the MRA simulations described herein were conducted. This output presents a case study example that assumes that *Cryptosporidium* data are available for raw wastewater which will be treated by a conventional tertiary wastewater treatment plant employing primary treatment, activated sludge secondary treatment, clarification, coagulation, and chlorine disinfection. This type of wastewater treatment for reclamation purposes is consistent with agencies in California, Arizona, and Florida, for example.

It is further assumed that that the exposure of interest to the reclaimed water is recreation in undiluted effluent. Based on these inputs, the MRAIT was used to conduct an assessment to estimate the risks to an individual for a single exposure event. Default values for pathogen reduction across wastewater treatment, dose response, and exposure are used in the case study example.

Following are printouts of the MRAIT worksheet for the assessment described above. The *Cryptosporidium* concentrations in raw wastewater represent total oocysts and are from the results of WERF investigation 00-PUM-2T (Rose et al., 2004). The results are consistent with those presented in the main body of the report and should be interpreted within that context.

Microbial Risk Assessment Interface Tool

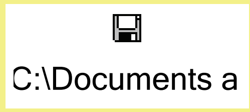
Developed by EOA, Inc. through
WERF projects 00-PUM-3 and 04-HHE-3

Introduction

The Microbial Risk Assessment Interface Tool esimates the population risk of microbial infection or illness associated with ingestion of reclaimed water from various exposure scenarios.

To run the model, below you will be asked to provide pathogen concentration data, and to specify a set of parameters that define the model. For an example case study and guidance in specifying the parameters, please refer to the user documentation that accompanies this tool.

A. Input data. Specify an input file with concentration data.
The file must be a text file with no header, and contain one column of concentrations (units of pathogens per liter).

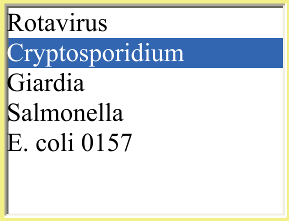


C:\Documents a

(right-click on disk icon, and select properties to change the path and filename)

▶ Pathogen Details

B. Specify pathogen. The input data specified above are for the following pathogen (units in #/L):



Rotavirus
Cryptosporidium
Giardia
Salmonella
E. coli 0157

C. Wastewater treatment. Specify what treatment processes will be applied. If the input data correspond to final effluent concentrations (i.e., no additional wastewater treatment applied), select "None" below:

- Secondary treatment, filtration, and disinfection
- Filtration and disinfection
- Disinfection
- None - Effluent concentrations provided as input

The default inactivation and/or removal distribution for this treatment - pathogen combination is as follows in units of log reduction:

Distribution	normal
mean:	2.3
standard	0.7

Check below if you wish to override the defaults to the left:

☐ override defaults

Distribution:

- Normal
- Uniform
- Triangular
- Point Estimate
- Log Normal
- Gamma
- Negative Binomial

log removal:

D. Fit concentration data to a statistical distribution. Specify the form of the statistical distributional that will be used to fit the input concentration data specified above in Section A (default is Lognormal):

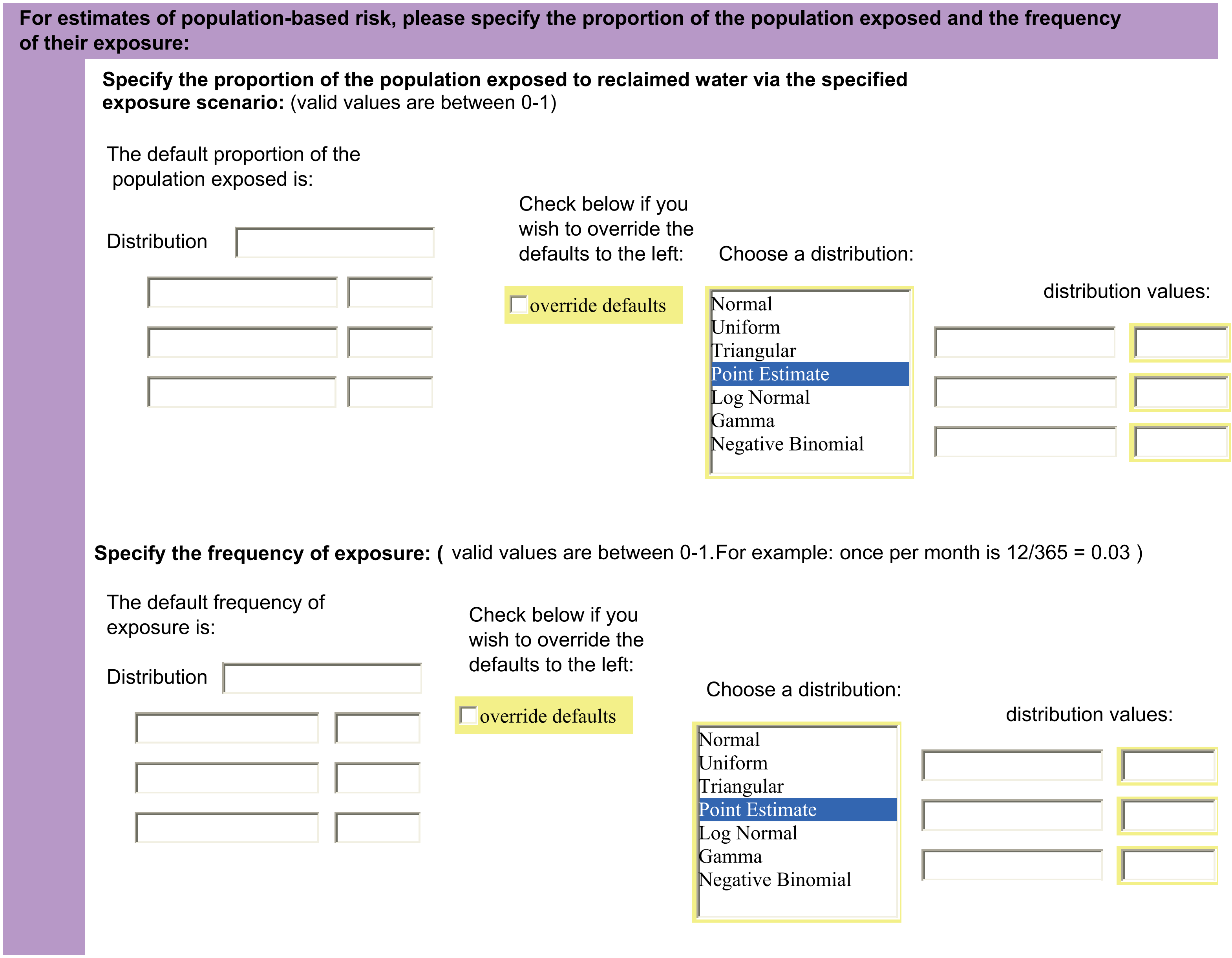
- Lognormal
- Weibul

▶ Exposure Details

E. Specify an exposure scenario: There are three alternative exposure scenarios built into this interface:

1. Crop irrigation assumes that exposure to pathogens occurs via ingestion of crops irrigated via reclaimed water.
2. Recreation assumes that exposure to pathogens occurs via ingestion of reclaimed water through recreational activities in an unrestricted impoundment.
3. Golf Course/Landscape Irrigation assumes that exposure to pathogens occurs via incidental or accidental ingestion of reclaimed water from a golf course or park.

For the specified exposure scenario, do you wish to estimate individual or population-based risk?



For estimates of population-based risk, please specify the proportion of the population exposed and the frequency of their exposure:

Specify the proportion of the population exposed to reclaimed water via the specified exposure scenario: (valid values are between 0-1)

The default proportion of the population exposed is:

Distribution

Check below if you wish to override the defaults to the left:

☐ override defaults

Choose a distribution:

distribution values:

Specify the frequency of exposure: (valid values are between 0-1.For example: once per month is 12/365 = 0.03)

The default frequency of exposure is:

Distribution

Check below if you wish to override the defaults to the left:

☐ override defaults

Choose a distribution:

distribution values:

Parameters for Recreation:

Recreation Exposure Pathway: (Note if recreation is not selected above as the exposure route of interest the following section is inactive and cannot be changed)

Specify the volume that is ingested per exposure event: (units of ml)

The default ingestion volume for an exposure event associated with recreational exposure:

Distribution lognormal

log 2.92

log 1.43

Check below if you wish to override the defaults to the left:

☐ override defaults

Choose a distribution:

- Normal
- Uniform
- Triangular
- Point Estimate
- Log Normal
- Gamma
- Negative Binomial

distribution values in units of ml:
(or ln(ml) if log normal distribution)

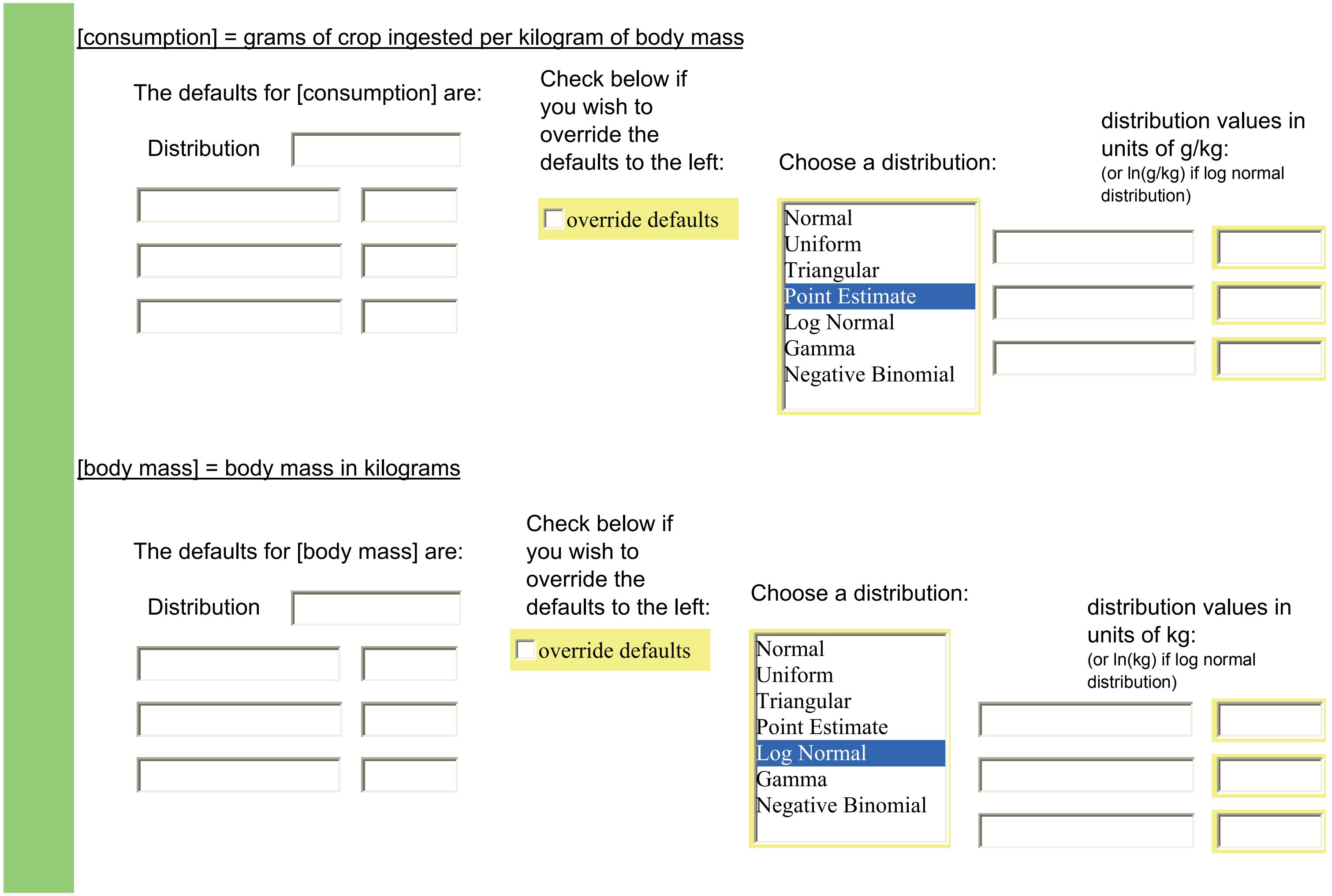
Parameters for Crop Irrigation:

Crop Consumption Exposure Pathway: (Note if crop consumption is not selected above as the exposure route of interest the following section is inactive and cannot be changed)

Crop consumption distributions:

Exposure via crop irrigation depends upon consumption rates, body mass, and the volume of water ingested per mass of crop:

$$\text{exposure} = \underset{(g/kg)}{[\text{consumption}]} \times \underset{(kg)}{[\text{body mass}]} \times \underset{(ml/g)}{[\text{volume fraction}]}$$



[consumption] = grams of crop ingested per kilogram of body mass

The defaults for [consumption] are:

Distribution

Check below if you wish to override the defaults to the left:

☐ override defaults

Choose a distribution:

- Normal
- Uniform
- Triangular
- Point Estimate
- Log Normal
- Gamma
- Negative Binomial

distribution values in units of g/kg:
(or ln(g/kg) if log normal distribution)

[body mass] = body mass in kilograms

The defaults for [body mass] are:

Distribution

Check below if you wish to override the defaults to the left:

☐ override defaults

Choose a distribution:

- Normal
- Uniform
- Triangular
- Point Estimate
- Log Normal
- Gamma
- Negative Binomial

distribution values in units of kg:
(or ln(kg) if log normal distribution)

[volume fraction] = milliliters volume of water ingested per gram of crop ingested

The defaults for [volume] are:

Distribution

Check below if you wish to override the defaults to the left:

☐ override defaults

Choose a distribution:

- Normal
- Uniform
- Triangular
- Point Estimate
- Log Normal
- Gamma
- Negative Binomial

distribution values in units of ml/g:
(or ln(ml/g) if log normal distribution)

Parameters for Golf Course/Landscape Irrigation:

Golf Course/Landscape Irrigation Exposure Pathway: (Note if golf course/landscape irrigation is not selected above as the exposure route of interest the following section is inactive and cannot be changed)

Golf Course/Landscape Irrigation consumption distributions:

Exposure via golf course/landscape irrigation depends upon the total volume of water ingested per day and the proportion of that volume due to reclaimed water from golf course/landscape irrigation:

exposure = [total volume ingested] x [proportion due to golf course/landscape irrigation]
(ml)

Specify the total volume of water ingested per day from all sources including non-golf course/landscape irrigation and non-reclaimed water: (units of ml)

The default ingestion volume per day:

Distribution

Check below if you wish to override the defaults to the left:

☐ override defaults

Choose a distribution:

- Normal
- Uniform
- Triangular
- [✓ Point Estimate]
- Log Normal
- Gamma
- Negative Binomial

distribution values in units of ml:
(or ln(ml) if log normal distribution)

Specify the proportion of the total water ingested that is reclaimed water from golf course/irrigated landscape:

The default proportion of ingested volume attributable to reclaimed water from golf course/landscape irrigation:

Distribution

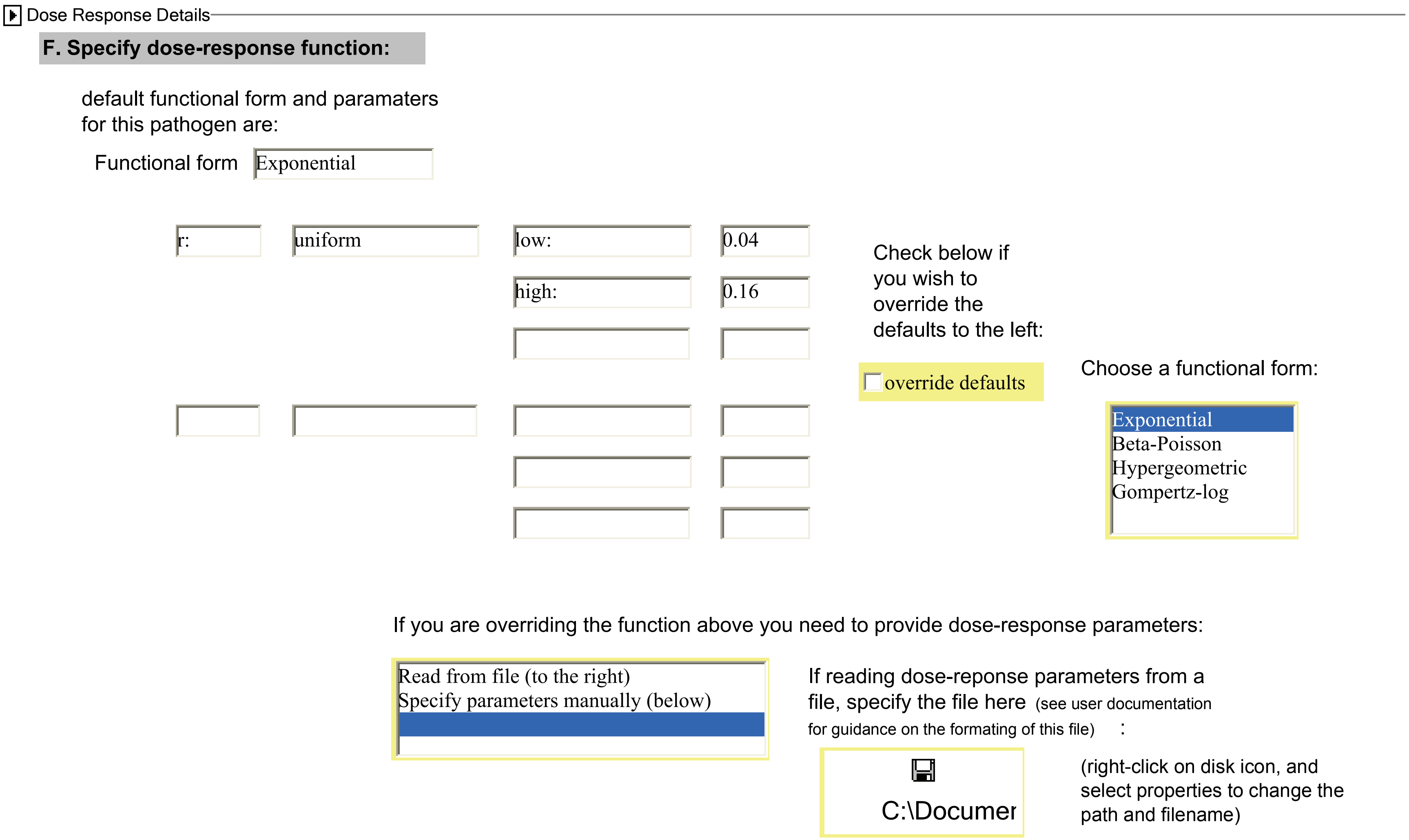
Check below if you wish to override the defaults to the left:

☐ override defaults

Choose a distribution:

- Normal
- [✓ Uniform]
- Triangular
- Point Estimate
- Log Normal
- Gamma
- Negative Binomial

distribution values for the proportion:



▶ Dose Response Details

F. Specify dose-response function:

default functional form and paramaters for this pathogen are:

Functional form: Exponential

r:	uniform	low:	0.04
		high:	0.16

Check below if you wish to override the defaults to the left:

☐ override defaults

Choose a functional form:

- Exponential
- Beta-Poisson
- Hypergeometric
- Gompertz-log

If you are overriding the function above you need to provide dose-response parameters:

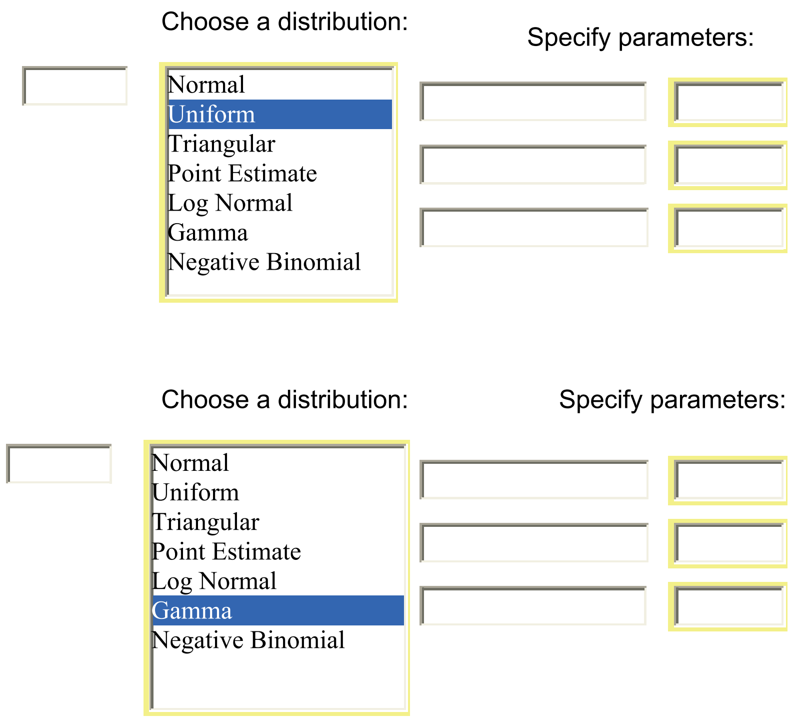
- Read from file (to the right)
- Specify parameters manually (below)

If reading dose-reponse parameters from a file, specify the file here (see user documentation for guidance on the formating of this file) :

C:\Documer

(right-click on disk icon, and select properties to change the path and filename)

If specifying dose-response parameters manually, set them here:



Choose a distribution:

Normal
[✓ Uniform]
Triangular
Point Estimate
Log Normal
Gamma
Negative Binomial

Specify parameters:

Choose a distribution:

Normal
Uniform
Triangular
Point Estimate
Log Normal
[✓ Gamma]
Negative Binomial

Specify parameters:

G. Model selection suggestion: Based on values for specified exposure, dose, the dose-response function, and the following tolerance for error, the program will suggest either the static or dynamic model.

Specify your tolerance for error: Difference in predicted incidence between static and dynamic models

[✓ <10/100,000]
<1/100,000
<0.01/100,000

per year

Specify the number of simulations you wish to run:

100
500
1000
[✓ 5000]

Example runtimes

Static	**Dynamic**
5 secs	1 min
5 secs	5 mins
5 secs	10 mins
5 secs	1 hour

Model Selection Details

Based on following values:

	min	max
Exposure intensity:	0.0e+0	0.0e+0
Dose:	2.4e-7	1.1e+2
Dose-response (Beta-Poisson fit, β):	1.7e+2	1.7e+2

If individual-based risk is selected above for the exposure scenario, you will only be allowed to run the static model.

Based on your settings, the following model type is recommended:

Static

Check below if you wish to override the default to the left:

☐ override defaults

Specify which model will be run:

[✓ Static]
Dynamic

▶ Dynamic Parameter Details

H. Dynamic model parameters If Dynamic Model is selected above, transmission parameters must be specified below:

Duration of incubation in days

default for this pathogen is:

Distribution

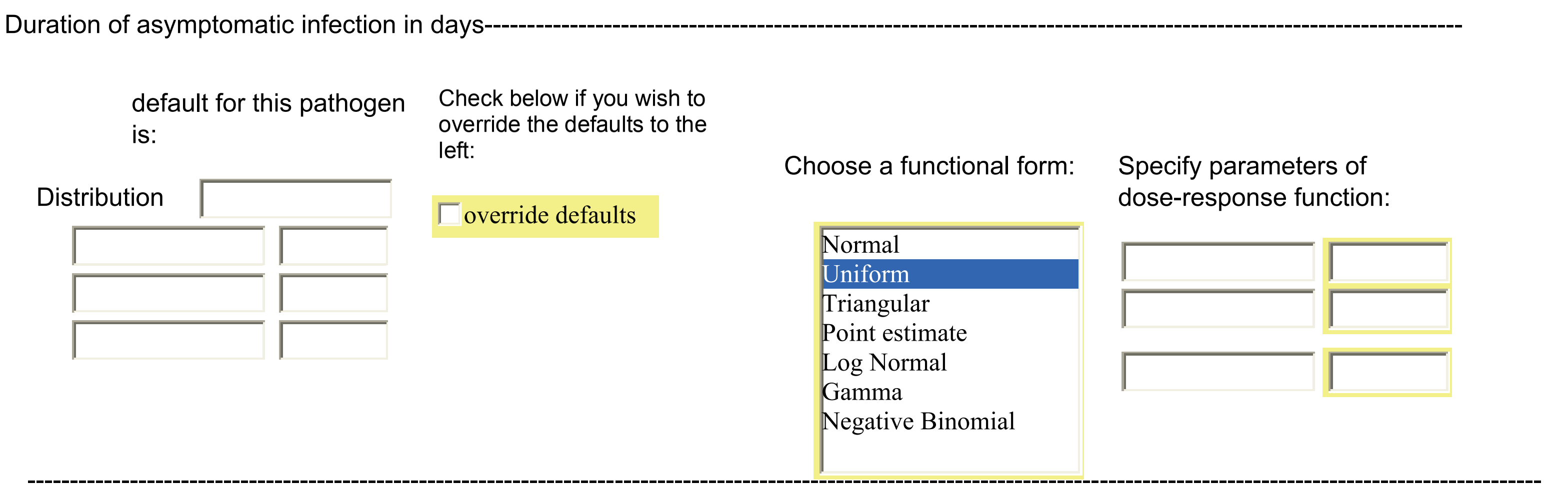
Check below if you wish to override the defaults to the left:

☐ override defaults

Choose a functional form:

Normal
[✓ Uniform]
Triangular
Point estimate
Log Normal
Gamma
Negative Binomial

Specify parameters of dose-response function:


Duration of asymptomatic infection in days

default for this pathogen is:

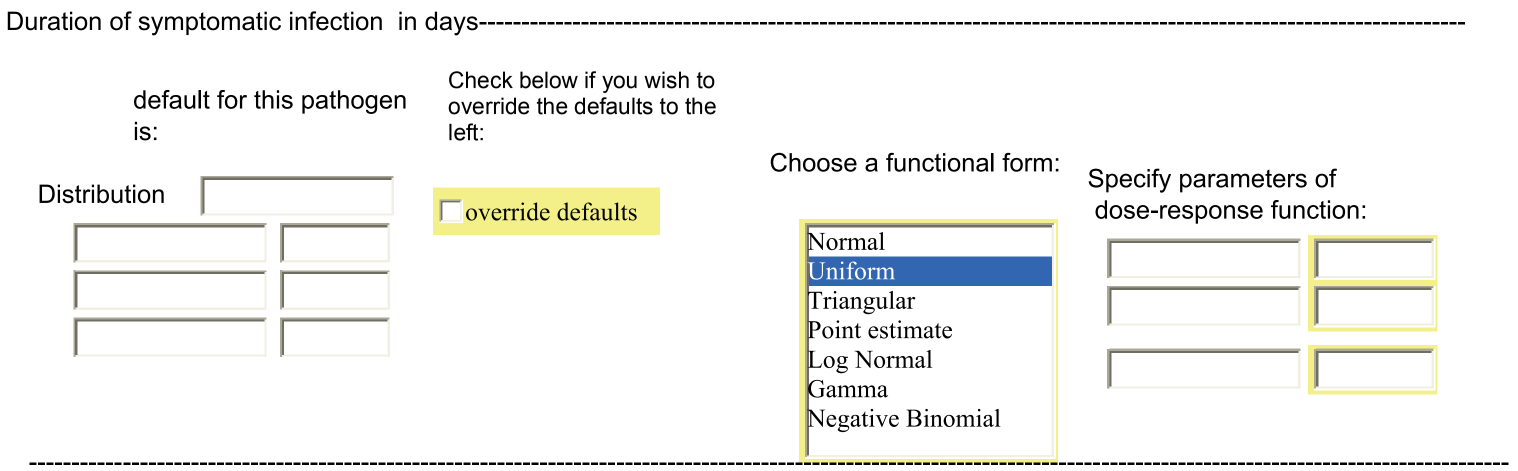
Distribution

Check below if you wish to override the defaults to the left:

☐ override defaults

Choose a functional form:

Specify parameters of dose-response function:


Duration of symptomatic infection in days

default for this pathogen is:

Distribution

Check below if you wish to override the defaults to the left:

☐ override defaults

Choose a functional form:

Specify parameters of dose-response function:

Duration of asymptomatic infection in days---

default for this pathogen is:

Distribution

Check below if you wish to override the defaults to the left:

☐ override defaults

Choose a functional form:

Normal
Uniform
Triangular
Point estimate
Log Normal
Gamma
Negative Binomial

Specify parameters of dose-response function:

Duration of symptomatic infection in days---

default for this pathogen is:

Distribution

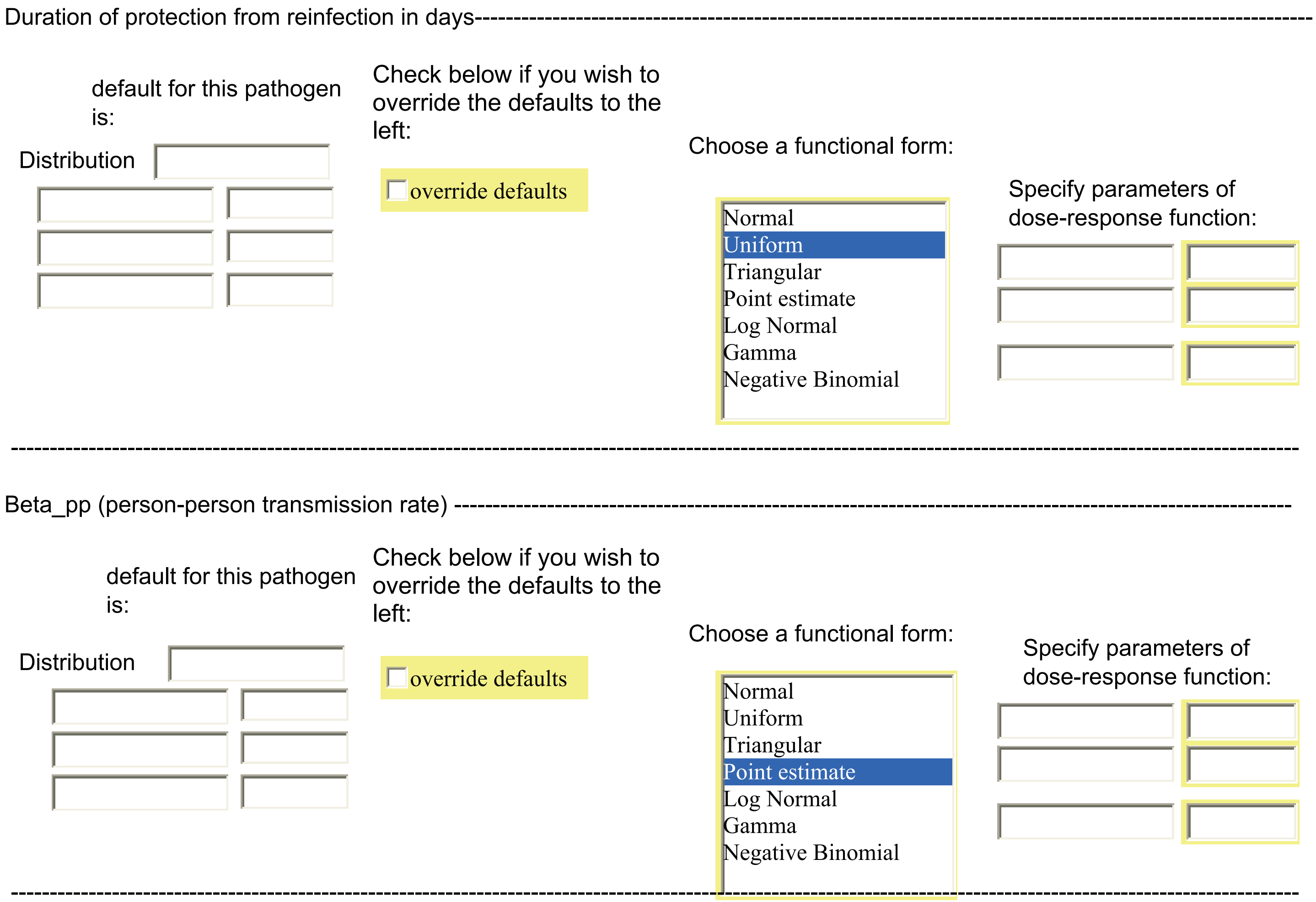
Check below if you wish to override the defaults to the left:

☐ override defaults

Choose a functional form:

Normal
Uniform
Triangular
Point estimate
Log Normal
Gamma
Negative Binomial

Specify parameters of dose-response function:



Duration of protection from reinfection in days--

default for this pathogen is:

Distribution

Check below if you wish to override the defaults to the left:

☐ override defaults

Choose a functional form:

Normal
[✓ Uniform]
Triangular
Point estimate
Log Normal
Gamma
Negative Binomial

Specify parameters of dose-response function:

Beta_pp (person-person transmission rate) --

default for this pathogen is:

Distribution

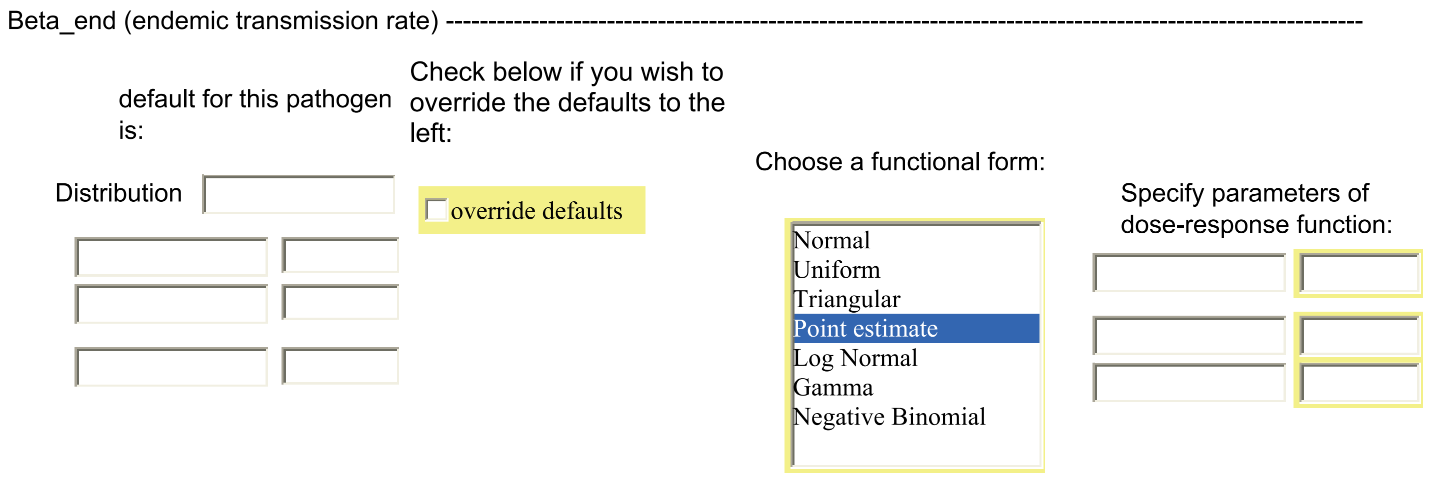
Check below if you wish to override the defaults to the left:

☐ override defaults

Choose a functional form:

Normal
Uniform
Triangular
[✓ Point estimate]
Log Normal
Gamma
Negative Binomial

Specify parameters of dose-response function:



Beta_end (endemic transmission rate)

default for this pathogen is:

Distribution

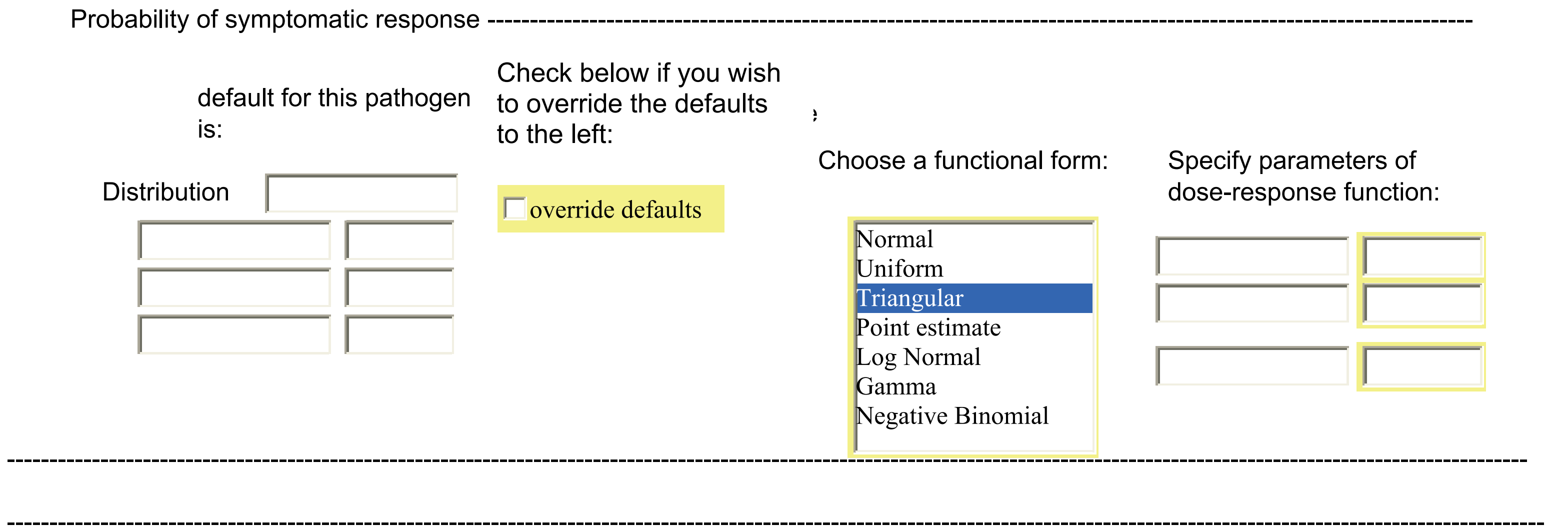
Check below if you wish to override the defaults to the left:

☐ override defaults

Choose a functional form:

- Normal
- Uniform
- Triangular
- [✓ Point estimate]
- Log Normal
- Gamma
- Negative Binomial

Specify parameters of dose-response function:



Probability of symptomatic response

default for this pathogen is:

Distribution

Check below if you wish to override the defaults to the left:

☐ override defaults

Choose a functional form:

- Normal
- Uniform
- [✓ Triangular]
- Point estimate
- Log Normal
- Gamma
- Negative Binomial

Specify parameters of dose-response function:

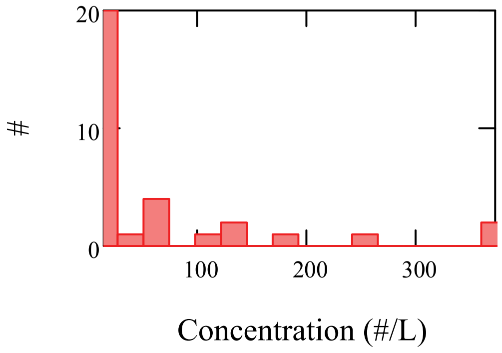
Press here to calculate the results: Calculate

▶ Calculation Details

▶ Dynamic Calcs

I. Results

Histogram of input concentrations for: Cryptosporidium



Number of input points: conc_n = 32

Summary stats:

mean(conc) = 62.714

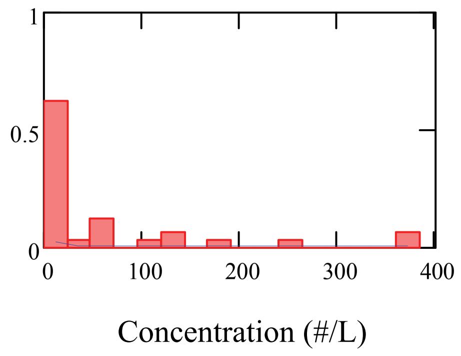
Stdev(conc) = 103.124

skew(conc) = 2.252

min(conc) = 0.528

median(conc) = 12.8

max(conc) = 384


Distribution fit to input concentrations

lognormal, alpha=2.8e+0 beta=1.7e+0

$$\mathrm{Lognormal\_dist}(x,\alpha,\beta) := \frac{1}{\sqrt{2\cdot\pi}\cdot\beta\cdot x}\cdot\exp\left[-\frac{1}{2\cdot\beta^2}\cdot(\ln(x)-\alpha)^2\right]$$

$$\mathrm{Weibul\_dist}(x,\alpha,\beta) := \alpha\cdot\beta\cdot x^{\beta-1}\cdot\exp\left(-\alpha\cdot x^{\beta}\right)$$

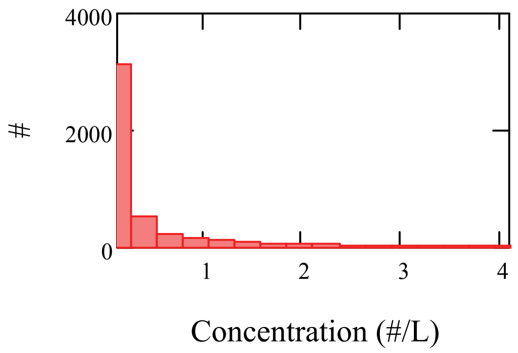
Number of samples: $\mathrm{rows}(\mathrm{conc\_fit}) = 5\times 10^3$

Summary stats:
$\mathrm{mean}(\mathrm{conc\_fit}) = 80.728$
$\mathrm{Stdev}(\mathrm{conc\_fit}) = 340.526$
$\mathrm{skew}(\mathrm{conc\_fit}) = 24.559$
$\min(\mathrm{conc\_fit}) = 0.032$
$\mathrm{median}(\mathrm{conc\_fit}) = 17.094$
$\max(\mathrm{conc\_fit}) = 1.574\times 10^4$

Histogram of concentrations after treatment:

Secondary treatment, filtration, and disinfection

parameters:

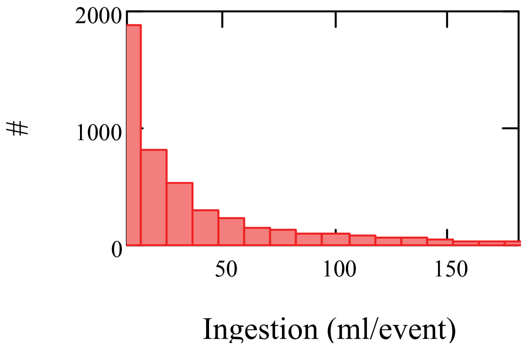


Histogram of exposure:

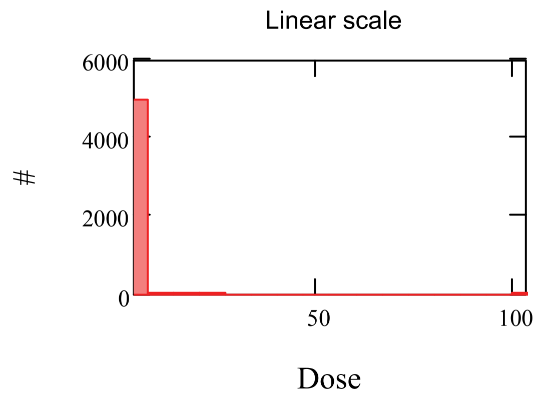
Recreation

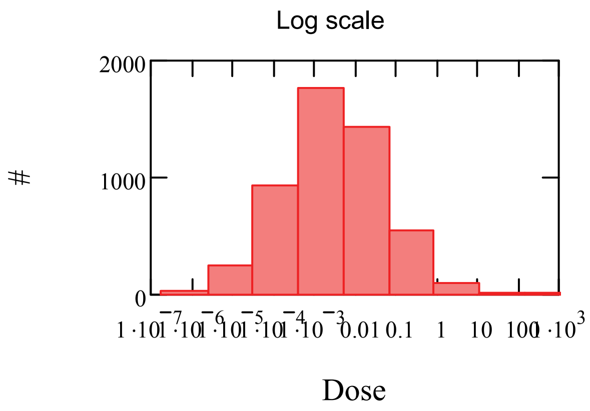
ingestion: lognormal 2.92 1.43

Individual-based

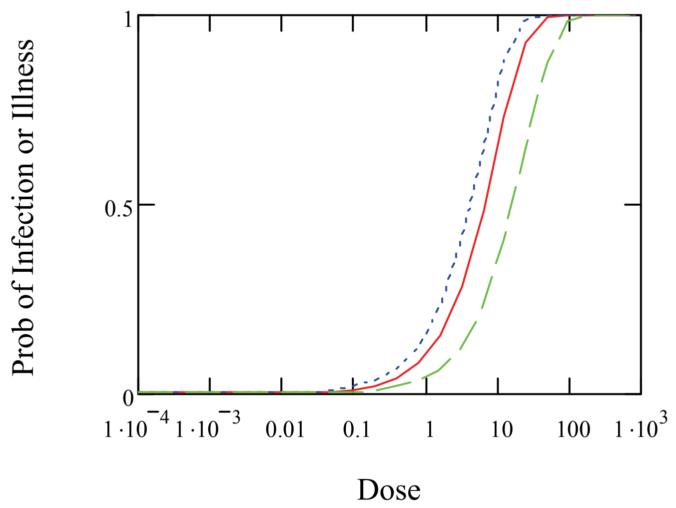


Histogram of dose:





Dose-response curve:



exponential
uniform

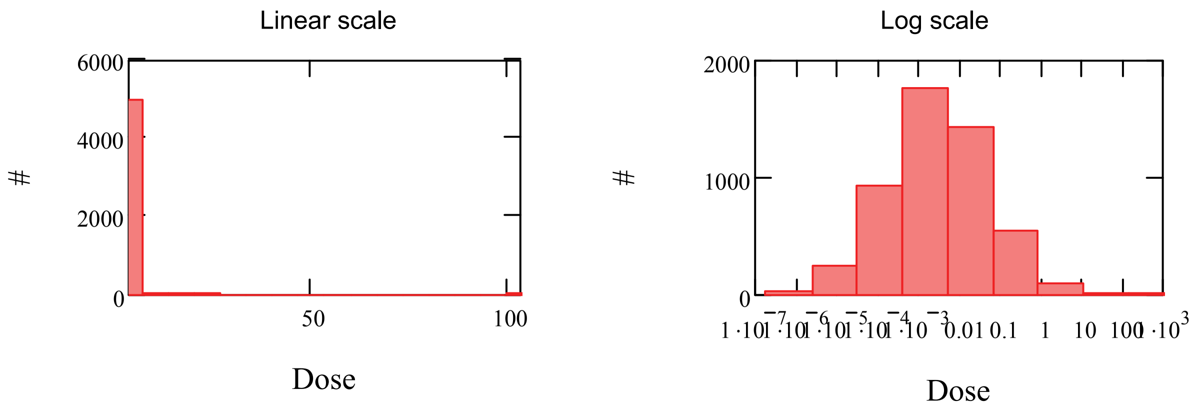
$$\text{exponential\_DR}(d, r) := 1 - \exp(-r \cdot d)$$

$$\text{betapoisson\_DR}(d, \alpha, \beta) := 1 - \left(1 + \frac{d}{\beta}\right)^{-\alpha}$$

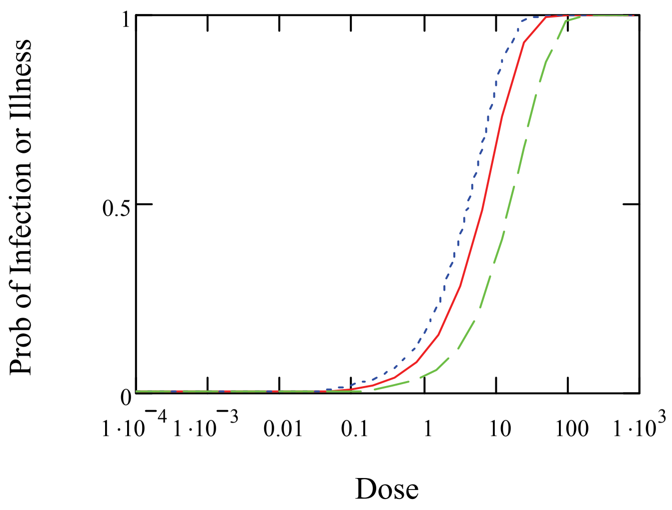
$$\text{hypergeom\_DR}(d, \alpha, \beta) := 1 - \text{mhyper}(\alpha, \alpha + \beta, -d)$$

$$\text{gompertz\_log\_DR}(d, x, y) := 1 - \exp(-\exp(-x + y \cdot \ln(d)))$$

Histogram of dose:



Dose-response curve:



exponential
uniform

$$\text{exponential\_DR}(d, r) := 1 - \exp(-r \cdot d)$$

$$\text{betapoisson\_DR}(d, \alpha, \beta) := 1 - \left(1 + \frac{d}{\beta}\right)^{-\alpha}$$

$$\text{hypergeom\_DR}(d, \alpha, \beta) := 1 - \text{mhyper}(\alpha, \alpha + \beta, -d)$$

$$\text{gompertz\_log\_DR}(d, x, y) := 1 - \exp(-\exp(-x + y \cdot \ln(d)))$$

Risk result:

Based on the Static model the distribution of probability of infection per exposure event is:

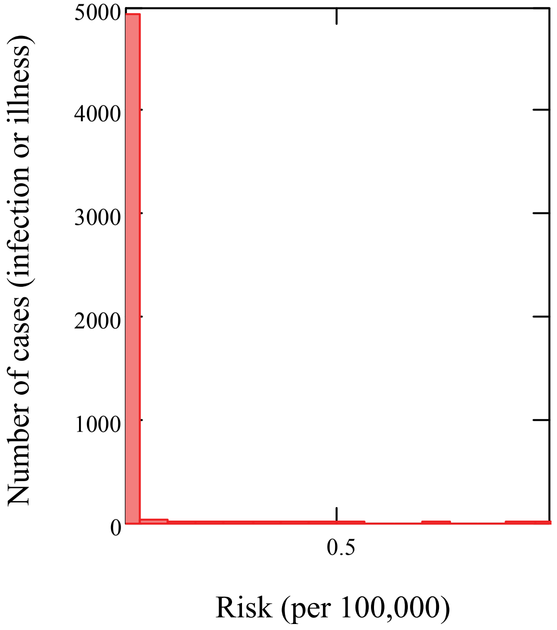
number

10th %ile: 4.0e-6

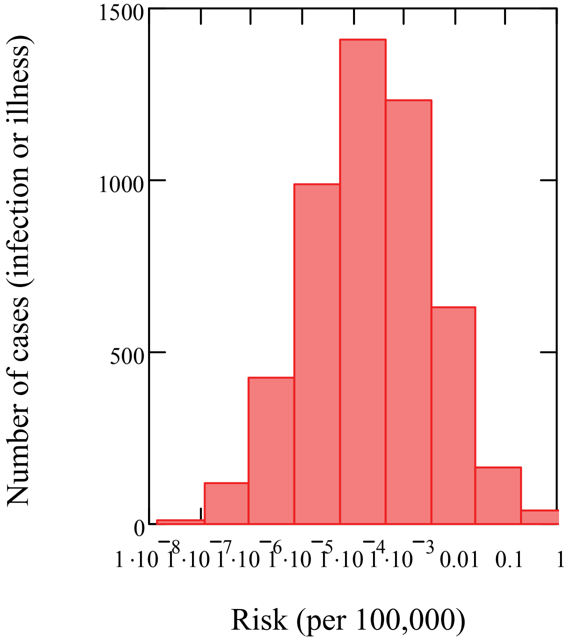
Median: 1.5e-4

90th %ile: 5.0e-3

Linear scale



Log scale



APPENDIX B

SUPPORTING DATA: PATHOGEN CONCENTRATIONS IN RAW WASTEWATER AND SECONDARY EFFLUENT

Table B1. Summary of Enterovirus Concentrations Used as Input to MRA Simulations

Sample No.	Inflow, MPN/100 L	Secondary, MPN/100 L
A-1	2.22E+02	1.70E+00
A-2	4.45E+02	2.00E+00
A-3	8.01E+02	5.85E+00
A-4	8.30E+02	8.90E+00
A-5	1.70E+03	3.86E+01
B-1	7.20E+02	5.80E+00
B-2	2.70E+03	1.10E+01
B-3	4.10E+03	4.70E+01
B-4	1.10E+04	6.20E+01
B-5	5.30E+04	8.00E+01
B-6		
B-7		
C-1	4.00E+03	3.50E+01
C-2	6.30E+03	9.60E+01
C-3	2.20E+04	2.00E+02
C-4	2.30E+04	2.30E+02
C-5	6.30E+04	2.70E+02
C-6		
C-7		
D-1	2.84E+02	2.50E+00
D-2	7.37E+02	2.90E+00
D-3	9.21E+02	3.00E+00
D-4	1.39E+03	4.00E+00
D-5	3.97E+03	8.80E+00
D-6	5.06E+03	8.90E+00
D-7		
E-1	1.84E+02	5.00E-01
E-2	2.27E+02	5.00E-01
E-3	3.01E+02	5.20E+00
E-4	6.59E+02	8.70E+00
F-1	1.10E+03	2.20E+00
F-2	3.40E+03	5.90E+00
F-3	4.50E+03	1.10E+01
F-4	3.20E+04	2.00E+01
F-5	3.50E+04	2.60E+01
F-6		
F-7		

Note: Data are from Rose et al. (2004).

Table B2. Summary of Literature Review for Enterovirus Concentrations in Wastewater Treatment Processes

Source(s)	Total Oocysts/100 L			
	Influent	**Secondary**	**Filtered**	**Disinfected**
Rose et al., 2004	9E+03	4E+01	6E+00	1E+00
Rose et al., 1996	1E+03	2E+01	3E+00	3E-01
Cooper et al., 1997	2E+03			3E-01
Buras, 1976	1E+07			
Funderburg and Sorber, 1983	6E+03	5E+02		
Grabow et al., 1980	1E+04	2E+03	5E+02	ND
Irving and Smith, 1981	1E+05	1E+04		
Leong et al., 1983		1E+02		
Leong et al., 1989		4E+00	1E-01	
Lewis et al., 1986	2E+04			
Morris, 1984	1E+06			
Schwartabrod et al., 1985	4E+03	6E+02		
Rose and Gerba, 1991a		1E+02	1E-01	1E+00
Rolland et al., 1983a, 1983b	1E+03	2E+02		
Rao et al., 1987	1E+04			1E+02
Rao et al., 1981	1E+05			
Payment et al., 1986	1E+04	1E+02		
Sedmak et al., 2005	1E+05			5E+02

Note: ND, not determined.

Table B3. Summary of *Cryptosporidium* Concentrations Used as Input to MRA Simulations

Sample No.	Inflow, Oocysts/100 L	Secondary, Oocysts/100 L
A-1	6.60E+01	1.00E+01
A-2	7.57E+02	3.17E+01
A-3	1.06E+03	2.22E+02
A-4	2.89E+03	2.28E+02
A-5	3.84E+04	2.59E+02
B-1	4.76E+02	1.39E+01
B-2	1.70E+03	1.76E+01
B-3	2.00E+03	3.10E+01
B-4	6.70E+03	6.12E+01
B-5	7.09E+03	1.03E+02
B-6	3.80E+04	1.79E+02
B-7		
C-1	4.35E+02	1.00E+01
C-2	4.40E+02	1.28E+01
C-3	8.16E+02	1.37E+01
C-4	5.60E+03	1.83E+01
C-5	1.10E+04	6.15E+02
C-6		6.79E+02
C-7		
D-1	3.03E+02	1.06E+01
D-2	3.11E+02	1.06E+01
D-3	3.31E+02	2.12E+01
D-4	3.84E+02	2.12E+01
D-5	1.75E+04	2.70E+01
D-6	2.63E+04	3.45E+02
D-7		
E-1	1.50E+03	1.80E+01
E-2	2.10E+03	2.10E+01
E-3	1.23E+04	4.20E+01
E-4	1.33E+04	8.40E+01
F-1	5.28E+01	2.67E+01
F-2	4.78E+02	3.57E+01
F-3	7.14E+02	3.92E+01
F-4	7.69E+02	9.35E+01
F-5	9.52E+02	9.90E+01
F-6	5.96E+03	3.33E+03

Note: Data are from Rose et al. (2004).

Table B4. Summary of Literature Review for *Cryptosporidium* Concentrations in Wastewater Treatment Processes

Source	Total Oocysts/100 L			
	Influent	Secondary	Filtered	Disinfected
Rose et al., 2004	6E+03	1E+02	7E+01	3E+01
McCuin and Clancy, 2006	6E+02	3E+02		
Rose et al., 1996	1E+03	1E+02	4	2
Cooper et al., 1997	2E+02		4E-01	
Rose and Gerba, 1991b			5	
Huffman et al., 2006	3E+03			2E+01

Table B5. Summary of *Giardia* Concentrations Used as Input to MRA Simulations

Sample No.	Inflow, Cysts/100 L	Secondary,Cysts/100 L
A-1	7.57E+02	1.90E+01
A-2	2.37E+03	2.11E+02
A-3	1.30E+04	2.00E+03
A-4	4.21E+05	2.20E+03
A-5	1.25E+06	1.40E+04
B-1	4.70E+03	1.39E+01
B-2	1.30E+04	3.10E+01
B-3	2.00E+04	7.14E+01
B-4	4.80E+04	1.23E+02
B-5	1.80E+05	1.43E+02
B-6	2.50E+05	6.21E+02
B-7		
C-1	2.00E+04	1.00E+01
C-2	2.20E+04	1.90E+01
C-3	3.57E+04	9.17E+01
C-4	3.40E+05	1.37E+02
C-5	5.90E+05	1.01E+03
C-6		9.35E+03
C-7		
D-1	9.10E+03	1.06E+01
D-2	1.13E+04	2.12E+01
D-3	1.54E+04	6.50E+01
D-4	2.10E+04	7.30E+01
D-5	1.34E+05	9.52E+01
D-6	2.01E+05	8.45E+03
D-7		
E-1	1.81E+04	4.10E+01
E-2	3.89E+04	5.50E+01
E-3	8.00E+04	1.06E+02
E-4	1.48E+05	2.41E+02
F-1	6.60E+02	3.57E+01
F-2	2.87E+03	1.95E+02
F-3	3.56E+03	3.74E+02
F-4	4.29E+03	5.28E+02
F-5	1.14E+04	9.22E+02
F-6	1.60E+05	9.35E+02
F-7		

Note: Data are from Rose et al. (2004).

Table B6. Summary of Literature Review for *Giardia* Concentrations in Wastewater Treatment Processes

	Total Cysts/100 L			
Source	**Influent**	**Secondary**	**Filtered**	**Disinfected**
Rose et al., 2004	1E+05	1E+03	9E+01	8E+01
Rose et al., 1996	7.E+03	4.E+02	4.E+00	1.E+00
Cooper et al., 1992	2.E+04			
Cooper et al., 1997	3.E+04		1.E+00	
Sykora et al., 1991	1.E+05	2.E+03		
Roach et al., 1993	1.E+05			
Enriquez et al., 1995		2.E+01		
Rose and Gerba, 1991b			8.E+01	
Huffman et al., 2006	~1E+05			5E+02

Table B7. Summary of *Salmonella* Concentrations Used as Input to MRA Simulations

Concentrations are Salmonella per liter

Source	Influent	Secondary
Lemarchand and Lebaron, 2003	1100	125
	289	40
	1100	240
	3	3
	6	3
	403	570
	3	3
	30	3
	18	3
Elliott and Ellis, 1977	5500	
Argent et al., 1977	1000	
Hench et al., 2003	1.47E+06	
	1.25E+06	
	1.44E+06	
	1.03E+06	
	6.23E+05	
	2.06E+06	
	1.84E+06	
	2.93E+06	
	9.07E+06	
	3.49E+06	
	3.94E+06	
	3.62E+06	
	3.76E+06	
	3.18E+06	
	9.70E+05	
	2.09E+06	
	1.18E+06	
	3.23E+06	
	1.76E+06	
	1.28E+06	
	1.21E+06	
	1.40E+06	
	2.93E+06	
	1.69E+06	

Note: The concentration value shown for Argent et al (1977) is based on primary treated sludge not raw wastewater.

Table B8. Summary of *E. coli* O157:H7 Concentrations Used as Input to MRA Simulations (Units are #/L).

Lit review comparisons of average reported values
Concentrations are O157 per Liter

Source	Influent	Notes
Heijnen and Medema, 2006	0-5000/L	2 samples below detection, 1 at 400 and 1 at 5000
Muniesa et al., 2006	100-1000/L	
Garcia-Alero et al., 2006	2E+03	Based on 8 samples, log CFU/ml, 0.2 with SD 0.2

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