QMRA manual for the Indian context (D4.4)

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CONTENTS

TERMINOLOGY AND ABBREVIATIONS

AC	Activated Carbon
BIS	Bureau of Indian Standards (refers to Drinking Water Specification)
CFU	Colony Forming Units (measure for number of bacteria)
DALY	Disability Adjusted Life years
FIB	Faecal Indicator Bacteria
HWT	Household Water Treatment
MPN	Most Probable Number (estimate of number of bacteria)
NTU	Normalised Turbidity Units
PDF	Probability Density Function
PFU	Plaque Forming Units (measure for number of viruses)
POE	Point Of Entry system
POU	Point Of Use system
QMRA	Quantitative Microbial Risk Assessment
RO	Reverse Osmosis (membrane filtration)
TSS	Total Suspended Solids
UF	Ultra Filtration (membrane filtration)
USEPA	United States Environmental Protection Agency
UV	Ultra Violet
WHO	World Health Organisation
WSP	Water Safety Plan

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1 PUBLISHABLE EXECUTIVE SUMMARY

Introduction
Drinking water supply in rural India is challenged by many factors both qualitative and quantitative. The central drinking water supply may still pose microbial risks since drinking water sources are polluted and treatment systems may not be sufficient to remove pathogens to an acceptable level. Central water supply is generally provided intermittently for a few hours per day or days. The lack of constant pressure means distributions system hydraulic integrity isn't maintained and microbial contamination can occur. Most households need to collect and store water in their homes, also leading to potential contamination. When central water supply is insufficient or not preferred, people turn to other sources such as private open wells, bore wells, springs, rainwater harvesting or local surface waters. When consumers think there is a risk they may treat the water in various ways such as boiling, filtering with sieve, cloth, biosand filter or commercial home filters. People generally use different sources during different periods of the year based on tradition, observations and perceptions. The European Water4India project strives to provide technologies to improve drinking water supply in rural India and reduce health risks. Understanding of the behaviour and perception of people is essential to identify or develop adequate treatment that addresses the main health risk. The first step is to assess which drinking water sources and behaviours introduce the highest risk.

Objective
The objective of this study was to translate the behaviour of people in rural India with respect to drinking water sources and use into a multi-route quantitative microbial risk assessment (QMRA). The goal of the QMRA was to identify the most relevant risk sources and the knowledge gaps due to lack of data. This report is a starting point to discuss the risk based approach with Indian stakeholders and identify potential applications for QMRA in India. One foreseen application is to assess how introduction of treatment technologies could reduce risk.

Methods
We visited two regions in rural Karnataka, India: Gulbarga and Shimoga. There we spoke to general people, village leaders, local and regional authorities, water suppliers, NGO's and medical doctors and observed their behaviour with respect to drinking water. From this we developed a multi-route QMRA model that allowed for variations in water sources and treatment over the year. Since no pathogen data is available for Indian water sources and indicator data are unreliable, we estimated pathogen densities in various sources from literature and performed a sensitivity analysis for these assumptions. A similar approach was used for contamination of drinking water during distribution and storage and for water treatment interventions. The QMRA model estimates the exposure to various pathogens and combines that with dose-response models to estimate the risk of infection. The contribution of each route to the total risk is then evaluated.

Results
The field visit provided insight in the behaviour of the rural Indian communities with respect to drinking water. The choice and treatment of drinking water sources varies per region due to climate differences. But also within a community there are great differences between individuals caused by economic and social status, religious motivation, level of education and perception of vulnerability. This means that there is no single exposure scenario that applies to the general population. A general trend is the introduction of multiple village schemes where villages are supplied with treated surface water from a surface water source. The condition and operation of these treatments as observed however seems inadequate to provide safe water to consumers. In addition, the lack of hydraulic integrity of distribution systems and the need for secondary transport and home storage hinder significant improvement by improved treatment. The lack of reliable microbial water quality data in India, especially on pathogens, is a main cause of uncertainty in the risk assessment.

Conclusions

The water supply situation in rural India is complex and vulnerable. Only introducing centralised drinking water supply through multi-village schemes won't significantly improve health in many cases due to the variation of sources people use. The multi-route QMRA provides more quantitative insight in the most relevant health risk. It also highlights the need for better data, especially on pathogen concentrations in contamination sources, to assess risk and support effective and efficient risk management.

2 INTRODUCTION

2.1 Purpose of this document

Goal of the Water4India project is to provide solutions to improve drinking water supply in rural India. Improvements should lead to sufficient water of sufficient quality. This document focuses on how to assess microbial health risks through drinking water. Drinking water quality is generally evaluated against water quality guideline values. For microbial contamination the absence of faecal indicator bacteria in 100 ml is the target when monitoring the water quality. However the indicator concept has several shortcomings: absence of indicator organisms does not guarantee absence of pathogenic microorganisms and analysis takes over 24 hours. Several countries have adopted quantitative microbial risk assessment (QMRA) to overcome these shortcomings. QMRA has been used within the framework of water safety planning to improve risk management of pathogens through drinking water. The purpose of this document is to introduce QMRA and to adapt the existing QMRA methodology to the water supply situation in rural India.

2.2 Structure of the deliverable

In Chapter 3 the QMRA concept and methodology is introduced. In Chapter 4 an adapted QMRA approach for the rural Indian situation is presented. This describes the QMRA calculation tool that was also developed in this task. Chapters 5 to 7 provides supporting information for each of the QMRA steps in the Indian situation. Sources of information are provided, and examples how to use this information in QMRA are given. The approach is demonstrated in a case study in Chapter 8. Conclusions are summarised in Chapter 9.

2.3 Relationship to the project objectives

The objective of the Water4India project is to provide solutions to improve drinking water quality and to support decisions on technology selection with a decision support system (DSS). An understanding of the relation between water quality and health impact is crucial to select solutions that result in highest improvement of health (or reduction of health risks). This document provides advanced insights in microbial health risks through drinking water.. Contribution to specific project objectives as numbered in the DoW:

Objective 1: *Identify the main vulnerable areas suffering from water scarcity taking into account different factors such as current and future water availability, supply from centralised or decentralised sources, and qualitative and quantitative requirements of communities in the light of available sources and their quality.* **Contribution**: The QMRA method allows quantitative comparison of risks from various sources and through various supply routes. Thus the routes with highest risks can be prioritized for risk mitigation. It also provides an estimate of the reduction of health burden by implementing Water4India solutions.

Objective 4: *Assess and quantify existing technologies for water quality monitoring to evaluate the quality of raw and treated water, and also the composition of waste water. Special attention will be given to pathogens, studying the quality of water by state-of-the-art methods such as Quantitative Microbial Risk Assessment within the framework of Water Cycle Safety Plans based on good house*

keeping. **Contribution**: The QMRA methodology provides a method to translate results of water quality monitoring to actual health risk.

Objective 5: *Develop a Decision Support System which integrates Multi-criteria Evaluation of technological alternatives for obtaining drinking water of the appropriate quality in each socio-economic situation, together with its management and sustainability assessment. This DSS will allow stakeholders and authorities to compare and select the best components to meet environment, economic and social aspects.* **Contribution**: The presented QMRA methodology will be used to set treatment targets for feasible water supply solutions in the context of the source water used.

Objective 6: *Propose best practice guidelines for the end-users, especially for the cases when small scale technologies are chosen. Best practice guidelines will also allow policy makers to develop new regulations which make water access easier for all the Indian people.* **Contribution**: The presented QMRA methodology will be made available to Indian end users and policy makers, and training in QMRA will be provided. This will allow Indian policy makers to develop new drinking water regulations that focus on health based targets in line with risk-based approached adopted by WHO and in other countries.

2.4 Relationship to other deliverables and tasks

This document is closely related to the other deliverables in work package 4. Water4India deliverable 4.2 provided an overview of the available water quality data in India that will be used in this document to perform QMRA. The other way around this document provided requirements for water quality monitoring that were then included in Water4India deliverable 4.2. The QMRA approach in this document will be used to evaluate the effect of the treatment solutions in WP3 in various contexts of water supply in rural India. The same approach will also be used to set boundary conditions for feasible water supply systems in the DSS in WP6. The information gaps identified in this study form a basis for the research to be performed in the technical deployment in WP7 where additional information will be collected to (partly) fill these gaps.

3 QMRA FOR DRINKING WATER MANAGEMENT

3.1 Role of QMRA in risk management

Sufficient water of adequate quality is essential for the development of a society. The millennium development goals (MDG) for drinking water aimed to increase the access to improved water source over the past decade. Although the MDG were reached in terms of quantity, the quality of the supplied water is still a point of discussion. Bartram et al. (2013) concluded that "Improved water sources does not mean they are safe". Therefore the safety of drinking water sources and supplies is still a focus point of the world health organization (WHO). Together with the international water association (IWA) WHO launched the Water Safety Plan concept in 2002. The WSP concept is now also part of the WHO drinking water guidelines (WHO 2011). The WSP concept provides a risk-based approach to assess and manage risks of drinking water supplies. This risk assessment is uses qualitative or semi quantitative risk assessment methods such as sanitary inspections (WSP manual 2011). However adequate assessment of the microbial risks is often compromised by the fact that risks cannot be observed easily, and even small levels of contamination, even below detection limits of water analysis methods, can cause significant health effects. Quantitative microbial risk assessment (QMRA) methods have been developed to address this issue (Haas 1999). Using the best available knowledge, QMRA can provide a quantitative estimate of the health risk of a water supply, and also the uncertainty about that risk. The WHO guidelines for drinking water quality provide an introduction of QMRA and its use to set health based targets for water quality. Smeets et al. (2010) showed how QMRA can be used within the WSP approach to improve risk assessments and support decisions on risk management. QMRA has been used to develop drinking water legislation such as the long term second enhanced surface water treatment rule (LT2ESWTR, USEPA 2006). In the Netherlands, QMRA of drinking water supply that uses surface water sources has become mandatory since 2001 (Anonymous 2001). This lead to a uniform protocol for QMRA of surface water supplies (VROM-inspectorate 2005). Experiences showed the added value of QMRA to make appropriate and efficient adaptations to drinking water supply systems (Smeets et al. 2013). The methodology of QMRA will be discussed in more detail in Chapter 4.

3.1.1 Current practices of QMRA

In the US, QMRA has been used in the 1990 to set water treatment requirements to reach the health based target of 1 infection per 10.000 people per year (10^{-4} risk target). Initial studies such as Gerba et al. (1988) evolved into elaborate guidelines of the *Long term second enhanced surface water treatment rule* (LT2ESWTR, USEPA 2006). Since 2001 water companies in the Netherlands are required to perform QMRA for their surface water treatment system and show that they comply with the 10^{-4} risk target (Anonymous 2001). Over the past decade they have used QMRA to support decisions on source water selection (river or bank filtration), treatment expansion (UV disinfection) treatment optimization (Ozonation) and operating conditions (UV fluence, ozone dose) (Smeets et al. 2009). More recently the water companies are expanding the QMRA approach to contamination risks during distribution (Blokker et al. 2014). In Australia QMRA has been used to develop regulations for water reuse in the *Water reuse guidelines* (NRMMC 2008). They apply a 10^{-6} DALY risk target rather than the risk of infection.
The world health organization incorporated both WSP and QMRA in the 2011 revision of the Guidleines for drinking water quality (WHO, 2011). In 2012 the USEPA implemented the *Recreational Water Quality Criteria* (USEPA 2012) where QMRA is used to set different targets for FIB in bathing water to distinguish between human and animal sources of contamination.

3.2 QMRA in rural Indian context

The Indian government is currently investing in improvement of water supply through the NRDWP program (MoDWS, 2013). The primary focus is on providing sufficient water from improved water sources to the rural population. The water supply is characterized by a great diversity of water sources, ranging from private open wells to centralized supplies of treated surface water in multiple village schemes. The water supply situation and developments are discussed in detail in report D2.2 (Gross et al 2014).

At the same time water quality monitoring of the various water sources is performed to assess if the supplied water is safe to drink (Uniform Drinking Water Quality Monitoring Protocol, Government of India 2013). Microbial water quality is assessed by monitoring for fecal indicator bacteria (FIB) such as thermotolerant coliforms or *E. coli* . Detection of FIB in 100 ml provides an indication of recent fecal contamination and therefore the possible presence of pathogenic micro-organisms and thus an increased health risk. However the absence of FIB in 100 ml is not a guarantee that pathogens are also absent because some pathogens (*Cryptosporidium* , *Giardia* , Ascaris, enteroviruses) are more persistent in the environment than FIB. Secondly, monitoring programs have shown that microbial contamination is highly variable, and the current monitoring program is limited with respect to the number of samples that can be taken. QMRA provides a methodology to improve interpretation of microbial water quality data such as FIB to assess the health risk. It also allows to test plausible scenarios of drinking water contamination events to assess the potential health risk from these events. Thus QMRA can be used to identify the most relevant risk sources. Then the expected effect of risk mitigation measures, for example improved water treatment, can be evaluated. Thus effective and efficient risk management can be achieved that goes beyond compliance of water quality analysis.

At this moment, data to support QMRA in India is expected to be scarce, leading to uncertainties in the risk estimates. The current study will therefore also be used to identify the most relevant data and knowledge gaps in the risk assessment. This can form a basis for risk based monitoring programs and research to improve health risk assessments and consequently risk management. The ongoing development of new methods for microbial water quality analysis, such as molecular methods, are expected to lead to cheaper, simpler and more reliable methods over the coming years. Identifying monitoring needs now will prepare the Indian water sector to adopt these new methods where they provide the most added value in health risk management. India will need to make decisions that require reliable quantitative basis for many years to come.

3.3 Previous QMRA studies in India and developing countries

Over the last two decades, QMRA has been develop and applied mostly in developed countries (Haas et al 1999, Medema et al. 2006, Schijven et al. 2011). More recently QMRA has also been applied in developing context.

Howard et al (2006) explored the use of QMRA in a developing world context through a case study in Kampala, Uganda. They concluded that “QMRA…to be a useful tool in supporting investment planning and decision-making for promoting safer water supply” and “QMRA is a valuable tool for a water supplier in understanding the potential public health risks associated with their supplies”. In this study pathogen concentrations were based on indicator organism data. Pathogenic *E. coli* concentrations were assumed to be a proportion of monitored thermotolerant coliforms, whereas sulphite-reducing

clostridia concentrations were used as a model for *Cryptosporidium* and somatic coliphages for rotavirus. The authors identified the need for better data to refine the risk estimates.

Two authors have used QMRA to compare risks from Arsenic and Fluoride to microbial health risks in India (Mondal et al. 2014) and Bangladesh (Howard et al. 2007). Due to lack of data on pathogens, the authors used the relative occurrence of FIB and pathogens in sewage to estimate pathogen concentrations, partly based on personal communication. Despite the scarcity of data and the need for assumptions, the authors showed that quantitative health risk assessment was possible and provided basis for better decision making.

Hunter et al. (2009) used QMRA to assess the reliability of interventions in drinking water supply in developing countries. They found that "poor reliability of drinking water interventions in developing countries can be undermining much of the hoped for improvements in public health". The effect of interventions on de mid- and long term was compromised by failure of the technology or inconsistent use of the technology. They showed that a single event of drinking water from a contaminated source completely compromised the positive effect of the intervention.

In general these studies showed the added value of QMRA gain insight in health risks from water supplies and as a tool to support (investment) decisions for risk management. All studies identified the need for better data to support the risk assessment. All studies estimated pathogen concentrations based on fecal indicator organisms, mostly thermotolerant coliforms. In several cases these assumptions were estimates without data to support them.

3.4 Use of drinking water sources in India

The general water supply situation in India is described in report D2.2 (Gross et al, 2014). For the current QMRA study we wanted to obtain more detailed insights in the drinking water situation in rural India. Therefore we visited two regions in rural Karnataka, India: Gulbarga and Shimoga. There we spoke to general inhabitants, village leaders, local and regional authorities, water suppliers, NGO's and medical doctors and observed their behaviour with respect to drinking water. This was followed up by two long term visits to the same regions where a researcher stayed with a family for a social assessment. Also during this period the actual practice with respect to water was observed and interviews were conducted. Findings of these visits were reported in work package 5. Here only the relevant information that was used to a multi-route QMRA model are discussed. As a consequence the case studies strongly influenced by these observations of only a very small part of India. However the QMRA framework was designed to accommodate also other situations that may occur in India.

We observed a large diversity in the way people obtained and treated their drinking water between the two regions, but also between individuals in the same village. People generally have various options for their water sources. Their choice based on the availability, which varies with seasons, and their preferences. Relevant considerations include:

- Availability (season)
- Tradition, habit
- Ease of collection, use
- Perceived quality, attractiveness, trust
- Reliability
- Affordability

- Status
- Religion

In Western countries the majority of the population is connected to the drinking water supply and receives 24/7 reliable drinking water from multiple taps in the home. Obtaining and using water is much more laborious in rural India. Some people in a village may have a tap in the house, but water is only provided discontinuously, typically one hour per day or less. People with private groundwater supplies may have a rooftop tank that they can fill with an electric pump (when electrical power is available) and therefore have a more reliable water source from a tap in the house. Most people however have to collect the water by hand from private or public open wells, hand pumps, standpipes, water vendors or surface water. Thus the rural Indian population is very conscious about water use and wastage. Figure 3.1 provides an impression of the various water sources used. It isn't possible to define one situation for the whole of rural India, since water use varies between individuals. Two case studies were defined in section 4.4 that represent observed water uses. The case studies provide basic insights in the water use and associated risk, and can be adapted to assess the impact of a different situation or mitigation measures.

Figure 3.1 Illustration of the various drinking water sources and potential contaminations identified in rural India

4 MULTI ROUTE QMRA CONCEPT

4.1 Concept of multi route QMRA

QMRA has generally been applied for centralized water supply, with one clear path from source to treated water (Schijven et al. 2014). We set up the multi-route QMRA framework to allow a more flexible way to model the diverse and variable drinking water situation in rural India. Most importantly the possibility of recontamination taking place between source and consumption was added to the conventional QMRA approach. The QMRA framework uses 'building blocks' to model the exposure and risk for a specific group of people that have organized their water supply in that way (see section 4.2). Each block is filled in with as much local and quantitative information as possible. This report provides available information to demonstrate how such information can be obtained. However this information is not extensive and we recommend to look for more information when performing a QMRA. Thus each route of exposure is characterized for each pathogen. The health risk resulting from each route is thus calculated as a risk per day. This provides insight in the relative risk from each route of exposure. By defining the number of days per year that each route is used, the annual risk can be calculated. The effect of interventions e.g. excluding routes, adding treatment, improving storage or handling, can be modelled in the QMRA framework to assess how they affect the risk from that route and the annual risk estimate.

4.2 QMRA building blocks

The QMRA building blocks address the common elements of drinking water supply in rural India. Not all block may be relevant for each route. In those cases the parameters of these block are chosen such that they don't affect the risk assessment (e.g. zero contamination or no effect of a treatment step). Each block can contain multiple input values. For contamination this is likelihood or contamination occurring and resulting pathogen concentration when contamination occurs. For each block a point estimate, representing what can occur (a realistic estimate), and a range representing the uncertainty about this estimate can entered.

Input

- Source (surface water, groundwater, harvested rainwater)
- Treatment (three possible steps)
- Storage (recontamination likelihood and magnitude)
- Distribution (recontamination likelihood and magnitude)
- Secondary distribution (recontamination and magnitude)
- Household treatment (single steps)
- Household storage (recontamination likelihood and magnitude)
- Days used (total route)
- Consumed drinking water (per route)
- Dose-response relationship

Calculated results (per route and combined routes)

- Pathogens in drinking water
- Pathogens consumed
- Infection risk per day
- Infection risk per year

4.3 Point estimate versus stochastic approach including variability and uncertainty

4.3.1 Point estimate

Each block is represented by a discrete value representing the realistic value (of concentration or treatment efficacy) or expected value (of recontamination) resulting in a high estimate of risk (poor removal or high recontamination). Although this is a strong simplification, it is easier to understand, there is less chance of errors. Using a point estimate helps thinking about the model, increases insight and provides a 'check' for stochastic calculations. The point estimate is used to assess what can happen in case of contamination and failure. Apart from the point estimate, a stochastic risk assessment is performed to estimate the actual current risk and the uncertainty about that risk estimate. The following paragraphs discuss how variability and uncertainty are addressed in the model.

4.3.2 Stochastic approach for variability

Variability is the actual difference in concentrations between water volumes. Observed concentrations in samples provide insight in this variability and the more samples are taken, the better the variability is known, however the number of samples does not affect the actual variability of concentrations in the water. Available data show that pathogen concentrations in source waters can vary over several orders of magnitude through the year. This can follow a seasonal pattern but can also be a spatial heterogeneity resulting in variations from day to day. Data is generally limited and stochastic approaches can be used to extrapolate data and predict concentrations that would be expected if more samples were taken. In QMRA variability is described with a probability density function (PDF), often a Lognormal or Gamma distribution is used. The parameters of the PDF are generally estimated from the data using a maximum likelihood method (MLM). The observed sampling results are 'most likely' for these parameters, however they could also be the result of (slightly) different parameters. There is always some level of UNCERTAINTY when estimating these parameters.

4.3.3 Stochastic approach for uncertainty

Uncertainty describes how well we know the actual concentrations, removals and contamination likelihoods in the QMRA. By taking more samples or collecting more data this uncertainty can be reduced. Uncertainty can be applied to different aspects of the data. When we want to describe the variability of the data, we need to address the uncertainty about the parameters of the PDF. The Lognormal and Gamma distributions are two-parameter distributions, therefore the uncertainty about the parameter pairs would need to be addressed.

Alternatively one can only be interested in the uncertainty about the annual average concentration, since that is the main driver for the level of annual infection risk. This can be regarded as the uncertainty about the point estimate of the concentration to be used in QMRA. Currently this aspect of uncertainty is rarely addressed in drinking water QMRA studies or mixed up with the variability. Petterson et al. (2015) used a Markov Chain Monte Carlo to estimate the uncertainty of PDF parameters.

Including both variability and uncertainty in QMRA results in very complex calculation methods. For the Indian context microbial water quality data is scarce, resulting in high levels of uncertainty which are

expected to have more impact on the risk estimations than variability (in Monte Carlo simulation variability will not affect the annual mean population risk due to the high number of simulations). The uncertainty will be modelled in the stochastic Monte Carlo simulations by assuming normal distributions of log concentrations or log removal. Based on data the values for the 95% likelihood interval (2.5 en 97.5 percentiles) will be chosen. The resulting mean of the distribution does not equal the point estimate discussed in section 4.3.1, since the point estimate represents an unfavourable estimation of the parameter value (high pathogen concentration or low removal).

4.4 Example cases for Water4India project

The methodology will be applied for two situations that were observed during the field visit in November 2014 of the Shimoga and Gulbarga districts in Karnataka state. Site specific data will be combined with scientific knowledge from other regions in the world to provide the best available knowledge base for QMRA. Similar site specific data can be obtained for other regions of India and combined in the same way with the scientific knowledge allowing interested parties to perform QMRA for other regions. The general cases are described here and will be elaborated in the following chapters.

The cases will focus on de risk from a single pathogen, *Giardia* , to demonstrate the principle of the QMRA framework and the data collection. The same approach can be followed for other pathogens.

4.4.1 Shimoga case

The centralized drinking water supply in Thithahalli is one of the pilot test sites in Water4India. Surface water is treated and distributed in the region. The treatment plant runs almost continuously to fill the overhead tanks with drinking water. Distribution valves are opened at specified times to supply the different areas with drinking water for a short period of time, until the overhead tank is empty and needs to be filled up again. Private and public open wells are common sources of groundwater for the rural population. When available these are often preferred as for drinking water for various reasons (see social assessment in work package 5). During the dry period wells may run dry while during monsoon the water can become turbid or smelly. During those periods harvested rainwater or centralized water supply is used for drinking, or the well water is treated in the home. Annual rainfall in Shimoga is approximately 1800 mm, so relatively high. Some homes have implemented rainwater harvesting, although this source is not preferred for drinking. For the QMRA case study the following combination of routes for drinking water supply of a household are evaluated.

- Centralised surface water supply
    - Tunga river
    - conventional treatment (aeration, coagulation, sedimentation, filtration, chlorine dosing)
    - Storage tank (overhead tank)
    - Distribution 1 hour per 2 days
    - Public tap <100 from the house (standpipe)
    - Collection and secondary distribution in open vessels (codas)
    - In house storage in vessel with lid
    - No household water treatment
    - 14 days per year
    - 2 litre per day
- Private open well
    - Shallow groundwater (5-10 m deep, >25 m from latrine, walled 1 m)
    - Collection by bucket or submergible pump into open vessel (codas)

  - In house storage in vessel with lid
  - No household water treatment
  - 300 days per year
  - 2 litre per day
- Harvested rainwater
  - Rainwater harvested from house rooftop
  - Storage in closed plastic rooftop tank
  - Collection at in-house tap
  - Water is boiled before drinking
  - 50 days per year
  - 2 litre per day

4.4.2 Gulbarga case

The Gulbarga area is much drier with an annual rainfall of approximately 770 mm per year. Groundwater supply is less reliable and Fluoride levels in some cases exceed the guideline values. Centralised supply consists of deep bore wells that directly fill the overhead reservoirs without any treatment. Distribution valves are opened at specified times to supply the different areas with drinking water for a short period of time, until the overhead tank is empty and needs to be filled up again. Public shallow bore wells with hand pumps are common. None of the observed wells was fenced to keep animals away, and concrete slabs were often showing cracks, or were missing completely. The sanitary conditions are not always optimal indicating risk of contamination. Some villages have implemented desalination (RO membrane filtration) of well water to remove Fluoride and UV disinfection as an additional barrier against microbes. This water is sold in 25 litre vessels closed with a lid, or people collect in their own containers. For the QMRA case study the following combination of routes for drinking water supply of a household are evaluated.

- Centralised ground water supply
  - Deep borewell
  - No treatment
  - Storage tank (overhead tank)
  - Distribution 1 hour per 2 days
  - Public tap <100 from the house (standpipe)
  - Collection and secondary distribution in open vessels (codas)
  - In house storage in vessel with lid
  - No household water treatment
  - 50 days per year
  - 2 litre per day
- Public shallow well with hand pump
  - Shallow groundwater (5-10 m deep, >25 m from latrine)
  - Collection by hand pump into open vessel (codas)
  - In house storage in vessel with lid
  - No household water treatment, boiling when turbid or odour (monsoon)
  - 15 days per year
  - 2 litre per day
- Village RO-UV treated water
  - Groundwater from Fluoride and/or microbial shallow borewell

- Treatment by RO membrane filtration and UV disinfection
- Collection from treatment tap in closed storage vessel
- Storage vessel installed in drinking water dispenser in the home
- No household water treatment
- 300 days per year
- 2 liter per day

5 SOURCE WATER QUALITY

5.1 River water quality

The concentration of pathogens in drinking water sources is the starting point of QMRA. Fecal contamination of river waters can occur in various ways. Untreated sewage contains high levels of fecal pathogens, but levels in treated sewage are only slightly lower because primary and secondary wastewater treatment is not designed to remove pathogens. Disinfection of wastewater is not practiced in India. Other sources of pathogens can be runoff during rainfall, wildlife, bathing of humans and animals, slaughterhouse waste etc. Since both the river flow and the fecal input vary in time and space (mixing), measured pathogen concentrations in rivers vary considerably (Hoogenboezem 2001, MicroRisk 2007). We conducted a literature study and consulted databases to find pathogen data for Indian rivers, but no such data was found. Monitoring pathogens in water requires advanced and expensive techniques, which explains the lack of such data. However data of fecal indicator bacteria (FIB, for example fecal coliforms or *E. coli*) is available for the major rivers in India. This data was used to estimate pathogen levels by comparing them to datasets from other countries.

5.1.1 Fecal indicator bacteria and pathogens in water

Other QMRA studies have used a ratio of FIB versus pathogens to calculate pathogen levels from FIB data (Lieverloo et al. 2007, Howard et al. 2007, Mondal et al. 2015). However, supporting data for these assumptions is often lacking. For example Howard et al. (2007) used ratio's based on 'personal communication'. The ratios were often based on sewage or wastewater data, however Lieverloo et al. (2007) showed that ratios in surface water are generally higher because many pathogens are more persistent in the environment than FIB. For Water4India we assessed a collection of data from various regions and projects (Hoogenboezem 2001, Lieverloo et al. 2007, Smeets et al. 2007, Dechesne 2007). To assess the ratio between FIB and various pathogens, reported concentrations of FIB and pathogens from the same sampling point on the same day were plotted on the X- and Y-axis respectively. Figure 5.1 shows an example for thermotolerant coliforms versus *Giardia* in eight river monitoring locations. THCOL concentrations range from 40 to 66,000 per litre, whereas *Giardia* concentrations vary from 0.03 to 41 per liter. On average the log ratio is 3.4 (2500:1), varying between 1.2 and 5.4 log. Howard et al. 2007 used a ratio of 6 logs based on wastewater, which would lead to an underestimation of pathogens in river water, according to Figure 5.1. Applied to the FIB data in Figure 5.1 this would result in a 2.6 log underestimation of pathogen concentrations. Therefore we chose to use river water data from literature to base the ratios on in the current study.

Since the range of individual ratios is 4.2 log, estimating pathogen concentrations based on FIB in individual samples would result in very uncertain estimates of pathogen concentrations. The uncertainty in the ratio could potentially overwhelm the quantitative information that is obtained from the FIB data. For QMRA we are not interested in predicting individual sample concentrations. Goal is to estimate the level of pathogens over a long period of time. Therefore a different approach was tried based on total FIB and pathogen datasets.

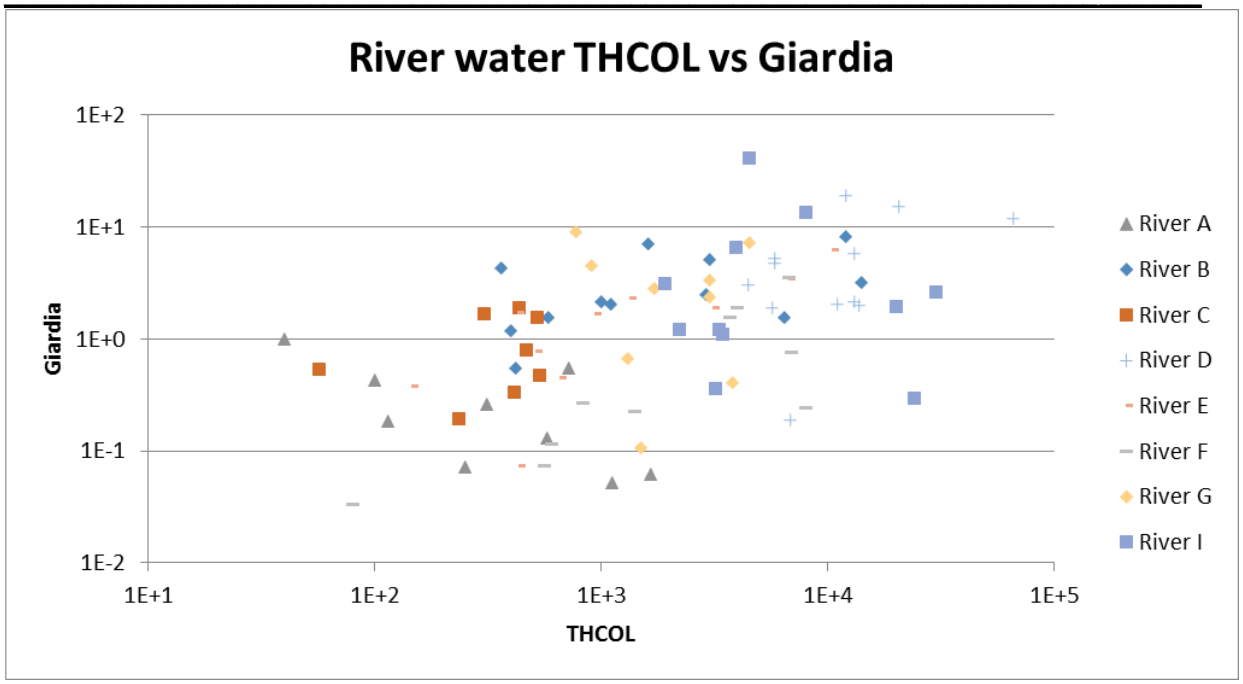

Figure 5.1 Monitored Thermotolerant coliforms versus Giardia in eight rivers paired by date.

The level of contamination of a river can be represented by the mean of the monitored concentrations of that river (Smeets 2008). (Note: When MLE is used to estimate PDF parameters, the mean of the PDF always equals the mean of the data. So commonly applied stochastic approaches to address annual variability in QMRA will not affect the estimated mean concentration). This has the additional advantage that negative samples also contribute to the characterization of the contamination level (individual ratios cannot be determined for negative samples). Also data no longer need to be paired by date, allowing more datasets to be used. Figure 5.2 Shows the average concentrations per sampling point for all available datasets of surface water, treated and untreated wastewater. The result is much more consistent, rivers with higher FIB levels also contain more pathogens. The average ratio is 3.6 log, ranging between 2.1 and 5.4. Figure 5.2 clearly shows that the ratio is related to the level of contamination. The FIB concentration is high in sewage and wastewater samples (top right data) compared to the *Giardia* concentration but lower in the various surface water (bottom left data). *Giardia* is more persistent in the environment than FIB and therefore the ratio increases as the fecal contamination is less recent. For the QMRA a variable ratio that is THCOL concentration dependent will be used:

$$\text{Log ratio} = 1.8 + 0.4 \times {}^{10}\log(\text{THCOL}/l)$$

This relation between FIB and pathogens will used in the QMRA to estimate pathogen levels based on reported FIB monitoring data in Indian rivers. The range of the ratios will be interpreted as uncertainty about the mean annual pathogen concentration, not the variation of concentration over the year.

This approach implicitly assumes that the ratios in India are similar to those in Western countries. Since the number of people with gastroenteritis in India is higher, it can be expected that feces contain more pathogens while the number of FIB is similar. On the other hand the Indian diet may also affect the FIB level in feces, resulting in higher or lower FIB levels. Currently there is no data available to assess if

there is a difference. The impact of the assumption will be included in the sensitivity analysis of the QMRA.

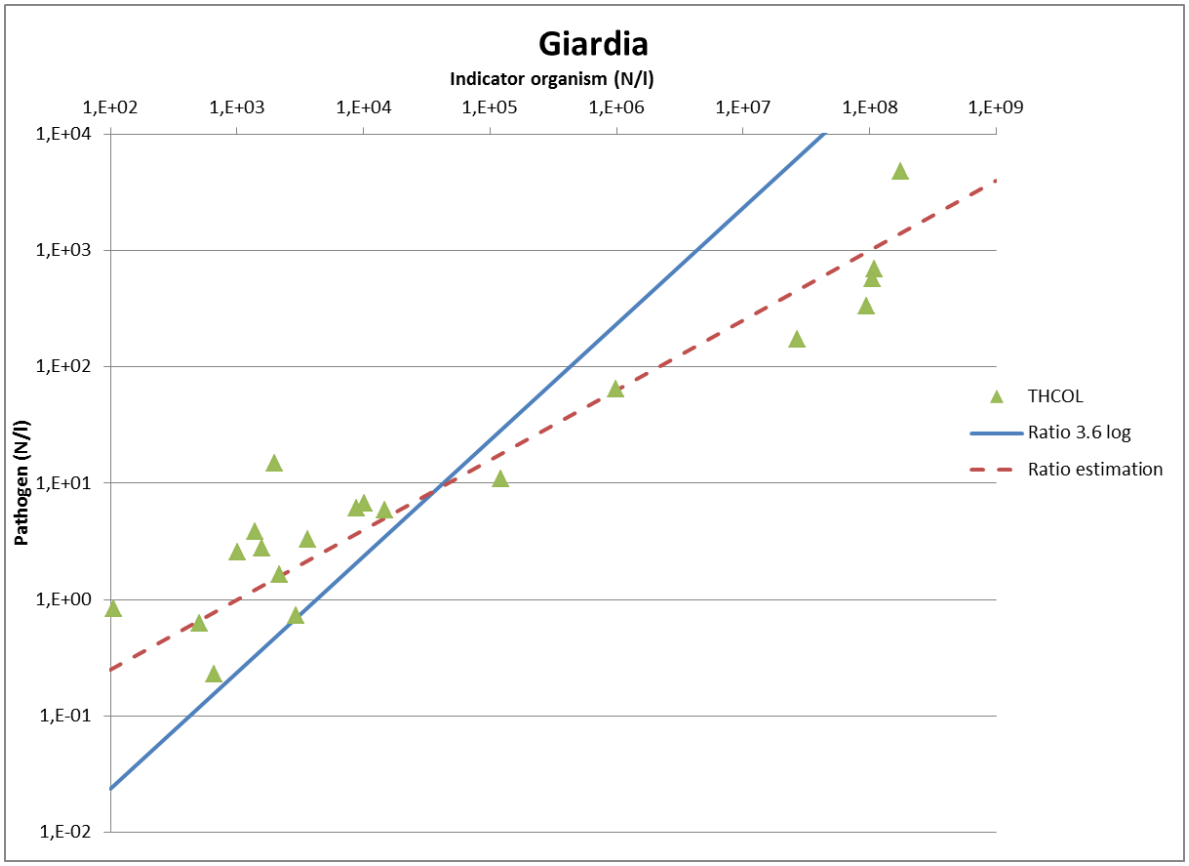

Figure 5.2 Monitored thermotolerant coliforms versus Giardia concentrations averaged per river water sampling point.

5.1.2 Fecal indicator bacteria in Indian rivers

The river water quality is monitored by the CPCB and the resulting data is available from their online database (CPCB 2015). This data was discussed in report D2.2 (Smeets et al. 2015) and is only summarized here. Specific data for the Shimoga case study will also be discussed. Values of mean fecal coliform concentrations per sampling point ranged from 10 to 10^9 MPN/l for the whole of India (note that 100 ml samples were reported in D2.2, but for QMRA concentrations are always reported per litre to avoid errors of conversion). The literature data in Figure 5.2 covers the same range of concentrations for thermotolerant coliforms. Fecal coliforms and thermotolerant coliforms are actually the same parameter (Saxena et al. 2015) so the data in Figure 5.2 can be used to estimate pathogen concentrations from the Indian monitoring data. THCOL concentrations in wastewater exceeded 10^7 CFU/l, and this level was exceeded in 1.1% of the river monitoring points (9 locations).

5.1.3 Estimated pathogen concentrations based on monitored fecal indicator bacteria

The FIB to pathogen ratios determined in section 5.1.1 were applied to the FIB monitoring data in Indian rivers. Because the ratio between FIB and pathogen is larger at higher FIB concentrations, the pathogen concentration in river waters is estimated to be less diverse than the indicator concentration.

At 95% of the monitoring location it is estimated that the average *Giardia* concentration is below 100 oocysts/l and 70% to be below 10 oocysts/l. This seems to be similar to the observed *Giardia* concentrations in Western countries, except for the 5% highest contaminated rivers in India.

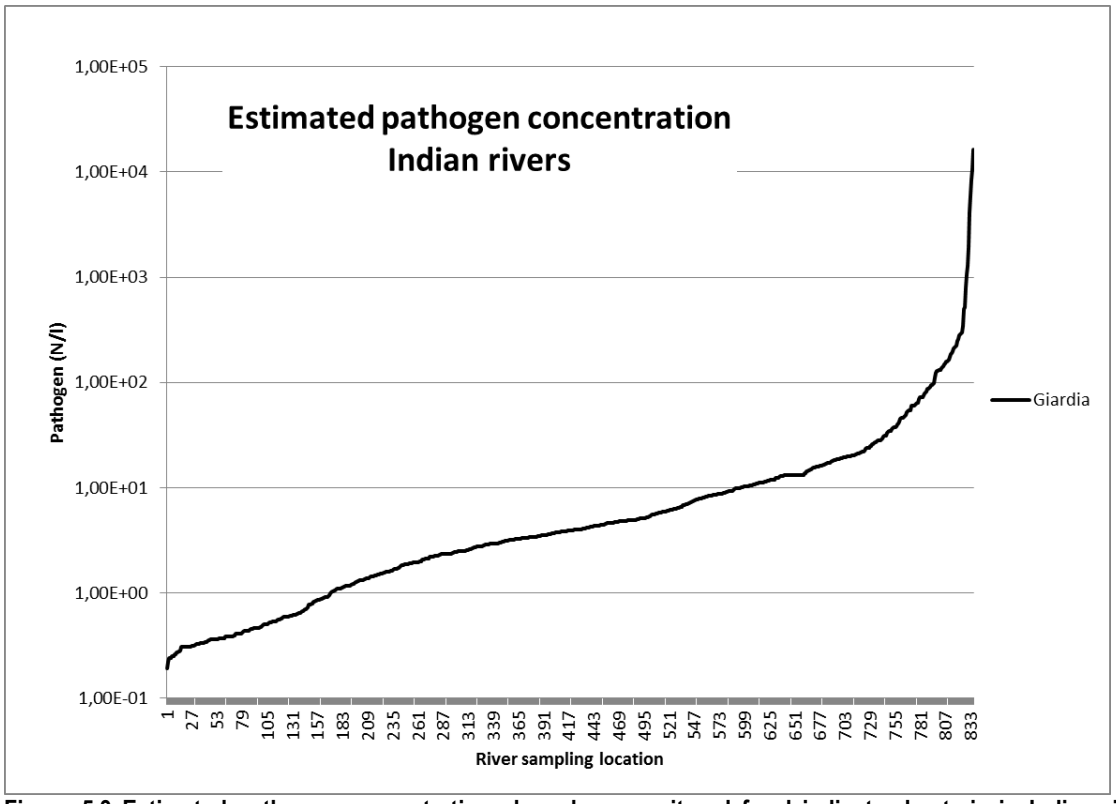

Figure 5.3 Estimated pathogen concentrations based on monitored fecal indicator bacteria in Indian rivers and scientific knowledge about indicator to pathogen ratios

For the Shimoga case study, the FIB concentration of the Tunga river (station code 1168) is relevant. The reported mean fecal coliform concentration in 2011 is 600 MPN/l (minimum 500, maximum 1400). Comparing these values to Figure 5.2 makes clear that the Tunga river is relatively clean with respect to fecal pollution. Based on the ratio, the estimated mean *Giardia* concentration is 0.7 oocysts/l. Based on Table 5.1 the uncertainty about the ratio, and thus the *Giardia* concentration, is less than + or - 0.5 log. A Gamma PDF with 5% of 0.2 and 95% of 1.2 log will be used to assess the impact of this uncertainty on the assessed risk.

5.2 Groundwater quality

A well designed, built, protected and used groundwater source will not be fecally contaminated. Contamination can occur either through the well itself or the groundwater can be contaminated by latrines or other sources. Various reference material on sanitary inspections and water safety plans discuss these issues in detail (WHO 1998, WSP manual, EU small supply…). The level of contamination is therefore very site specific and can vary in time, for example under the influence of rain events. Since groundwater wells are numerous in rural India, their water quality is not monitored intensively. The available data on groundwater monitoring was discussed in report D4.2. The reported *E. coli* concentrations varied from absent in 100 ml, to a most probable number of 1000 in 100 ml, corresponding to 10.000 MPN/l. The sources of fecal contamination can be diverse, sewage, latrine,

personal hygiene or animals. Therefore the ratio of FIB to pathogens can also be diverse, especially since contamination may be from one specific individual instead of a large mixture of a population as in sewage. Table 5.1 summarizes literature on the occurrence of pathogens in various fecal contamination sources. Feces from an infected human (either ill or asymptomatic) can contain up to one thousand times more pathogens than indicator bacteria (Westrell 2004). This would mean a FIB-pathogen ratio of -3 log. It also means that a negative FIB sample doesn't mean that pathogens are absent.

When feces is of animal origin, it is unlikely to contain human pathogenic waterborne viruses and levels of other human pathogens are often lower. For example chicken feces (Bird in Table 5.1) does not contain high levels of *Cryptosporidium* , but *Campylobacter* levels can be similar to human feces. Cows (Rumanant in Table 5.1) and especially calves are known to shed very high levels of *Cryptosporidium* , while other pathogens can also occur. Both cows and chickens roam free in rural (and urban) areas and are commonly observed around groundwater wells which are not fenced off. When the well construction is inadequate or damaged, contamination of the well is likely to occur.

Table 5.1 Pathogens and indicator organisms in various sources of fecal contamination in [10]log of concentration n/l. (- = not expected, + = expected, empty = no data)

Organism	Sewage [1,2,4]	Surface Waterter[7]	Human Faeces[8]	Rumi-nant[2,3,4,6]	Dog [2,3]	Sheep [2,3]	Bird [2,3]	Deer[2,3]
	Log n/l	Log n/l		Log n/g or Log DNA/g				
Indicator organisms								
E. coli	7,5-8,6	4,1	6	5,3	8,1		5,0-6,7	
Enterococcus	6,4-7,5	4,3	5,5	-	4,4		2,0-5,1	
C. perfringens	5-6,3							
Somatic coliphage	3-6,4	2,9						
F-specific RNA phage	5,7-7	3,7						
Pathogens[3]								
Enterovirus	0,5-3,1	-0,3	+	-	-	-	-	-
Campylobacter	2,5-6	1,9	6-9	2,0-5,7 [6]2,0-8,7		3,1 8,0	1.2-7,3	2,1 7,2
Cryptosporidium	1,6-4,5	1,8	7-8	1,7-3,6 [6]0-8,3		<8,3	2,3-3,9	<0-2,9
Giardia	0,8-5,8	1,9	5-8	<0,0-6,8 [6]1,3-8,3			0,0-4,9	

1 Koenraad 1994
2 BTO 2015.023 Eigenschappen van DNA merkers
3 Soller et al. 2010 minimum en maximum
4 Hoogenboezem et al. Riwa 2001
5 BTO 2013.014 Ontwikkeling en toepassing van kwantitatieve PCR methoden voor het identificeren van de bron van fecale besmettingen
6 KWR 2009.023 Pathogenen in de mest van grazers
7 Dechesne et al. 2007
8 Westrell 2006

The approach to translate monitored FIB concentrations in surface water to pathogen concentrations cannot be applied groundwater because of the high uncertainty about the FIB to pathogen ratios. In addition a negative sample doesn't proof that a well is not contaminated and wells are rarely sampled, so a temporary contamination is likely to be missed. Even if a sanitary inspection could identify likely origins of fecal contamination, the corresponding pathogen level would still be highly uncertain. The goal of the current QMRA is to assess the relative impact of various routes of exposure for drinking water and to identify knowledge gaps for this assessment. For this purpose basic assumptions are made about input variables and the impact of those assumptions is tested in a sensitivity analysis.

Indian monitoring data is used to estimate the likelihood of a well to be contaminated. Comparing the regular monitoring program to specific studies of fecal contamination provides an estimate of the level of underreporting due to the limited sampling frequency. In Karnataka state 4.5% of the NRDPW samples were positive, whereas Mukhopadhyay et al. (2012) found that 27.5% of the Karnataka sources were contaminated with *E. coli* . This indicates underreporting by a factor of 6.

The potential pathogen level when a well is contaminated is estimated from the literature cited in Table 5.1. Comparing sewage to the various feces in Table 5.1 makes clear that the FIB to pathogen ratio in feces is potentially smaller than in sewage or even negative (more pathogens than FIB). In order to assess how high the risk CAN be, it is assumed that a FIB positive (>1 per 100 ml) result is caused by an infected fecal source. Assuming a ratio of -2 log (for *Campylobacter*, *Cryptosporidium* and *Giardia*) 1 FIB/100 ml corresponds to 100 pathogens per 100 ml. Analogous to the observed relation between FIB level and ratio in sewage and surface water, it is assumed that the ratio is larger when higher FIB concentrations are detected (so less pathogens per FIB). As a simplified approach the estimated pathogen concentration is set to 1000 pathogens/l to assess the potential risk of a contaminated well. To identify the knowledge gap, the uncertainty about the pathogen concentration in a contaminated well (uncertainty about the ratio) the pathogen concentration will be modelled as a lognormal distribution with a 95 interval of 10^{-4} to 10^{4} pathogens per liter, based on a detection limit of 1 FIB per 100 ml and the range of possible ratios (5 to -3 log).

5.3 Rainwater harvesting

Rainwater is considered as an alternative water source when other sources are not available. Harvested rainwater will mainly be contaminated by the rooftop surfaces that are used to collect it. The 'first flush' of rainwater generally contains a higher level of contamination and is therefore generally diverted away from the rainwater storage. Data from literature was used to assess the potential health risk. Pathogens have rarely been quantified in rainwater harvesting studies, and findings show a broad range of concentrations. Quantification of fecal indicator organisms in harvested rainwater has been performed to a larger extend. Results indicate a broad range of fecal contamination level across systems. The ratio between fecal indicators and pathogens depends on the fecal source (human, type of animal), the prevalence of illness in communities and the presence of other sources of fecal indicators (Table 5.1). Studies indicate that a large proportion of harvested rainwater is faecally contaminated, but the levels of pathogens are very uncertain.

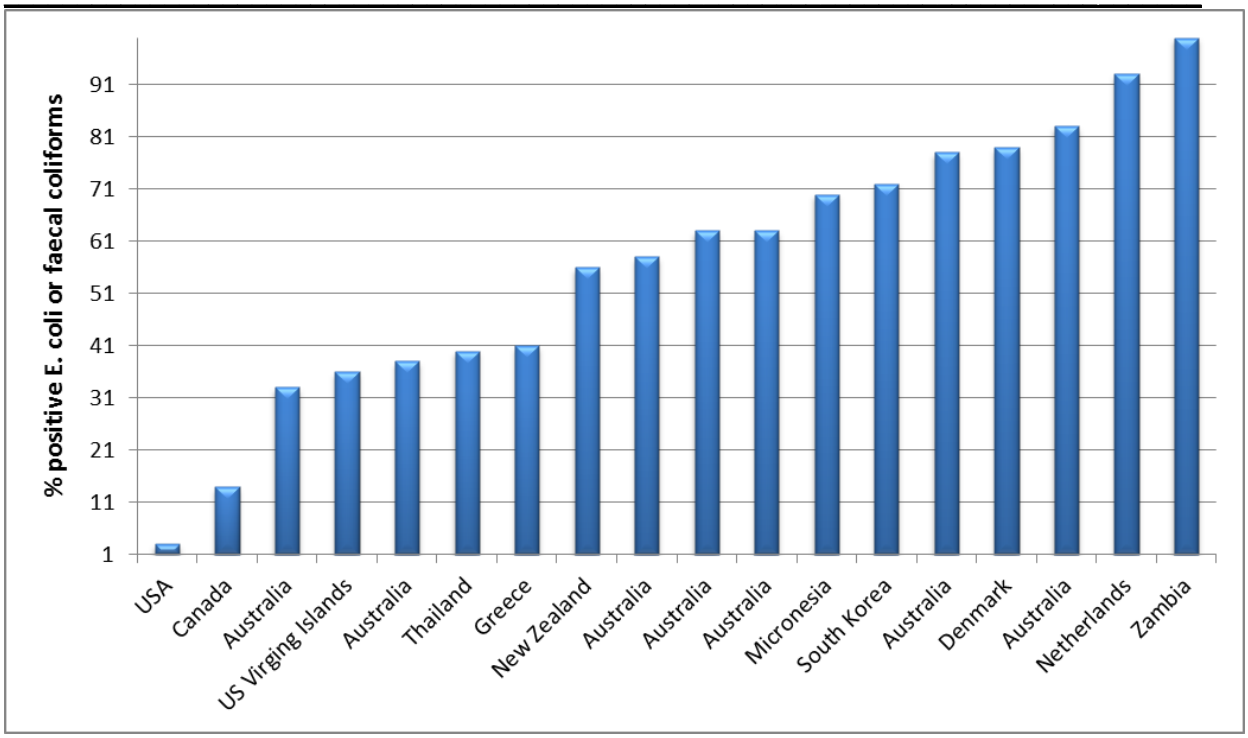

Figure 5.4 ***Reported detection of fecal indicator bacteria in harvested rainwater in various countries***

Birds could be considered the most likely fecal source for harvested rainwater. Using the minimum and maximum concentrations of *E. coli* and *Campylobacter* in gull faeces, their ratio would be in the range of 50 to 1000 (Soller et al. 2010). No *Giardia* , *Cryptosporidium* or enterovirus would be expected based on this data. However Oesterholt (2007), Ahmed et al. (2010) and Albrechtsen et al. (2002) did find both protozoa in harvested rainwater. None of the studies reported on viruses, since no human fecal input is expected for rainwater. Some studies have reported on transportation of human pathogens through air that then contaminate rainwater even before harvesting (Zhu 2004). Table 5.2 provides an overview of estimated concentrations of various pathogens in harvested rainwater.

Table 5.2 Parameters of pathogen concentrations in harvested rainwater for best estimate and conservative risk assessment.

Index pathogen	Range (org/l)	Point estimate (org/l)
***E. coli* ***	10-1000	1000
Enterovirus	0	0.01
Campylobacter	10-1000	100
Cryptosporidium	0-10	1
Giardia	0-10	1

* *E. coli* is not a pathogen, it is included as a reference for the level of fecal contamination

6 CONTAMINATION DURING STORAGE AND DISTRIBUTION

6.1 Concept of contamination in QMRA

Most QMRA studies in drinking water have been performed to assess the required treatment efficacy of surface water supplies (Schijven et al. 2009). In those studies, the source water is contaminated and the removal of pathogens is modelled. QMRA of recontamination of treated water are less common. Some studies addressed the contamination of drinking water distribution systems (Teunis and LeChevallier 2010, Nicole 2014, Blokker 2015). Risk estimation consists of the following components:

- The likelihood that contamination occurs
- The pathogen concentration in the contamination
- The amount of contamination entering the drinking water
- The likelihood that the contaminated water is drunk (not used for showering etc.)

The likelihood of contamination can be estimated from microbial monitoring for FIB. Since contamination events are generally temporal, the likelihood of actually detecting an event is very low. Therefore a correction for underreporting of events and other approaches will also be explored. The occurrence of an event will be modelled binomially as the likelihood that a contamination occurs per day.

The concentration of pathogens in the contamination is a major uncertainty, as was discussed for the groundwater characterization in section 5.2. Here the same approach is taken resulting in two estimates. For each situation a typical concentration representing a plausible contamination is given and a range of concentrations that represent the uncertainty about the concentration.

The amount of contamination depends on the mechanism of contamination. For each situation a plausible amount of contamination is estimated considering that this amount can be present at that location and that contamination can occur unnoticed. For example it is not impossible that a bird dropping falls into an open reservoir unnoticed, but it is unlikely that a septic tank empties into a reservoir without being noticed.

Supplied water is used for many purposes and only a part of it is used for direct consumption. In Western countries daily water use ranges from 100 to 300 litre per capita per day, while consumption of unboiled drinking water ranges between 0.2 and 2 litres per capita per day. Since only 0.07% to 2% of the water is drunk, most of the contamination will be flushed through other uses (shower, toilet, irrigation) without exposing people. In rural India the daily water use can be far less, and a larger proportion of the water is drunk. In the QMRA the consumed proportion of the water will be used to address this in relation to the situation. The proportion will be modelled binomially as the likelihood that the proportion of the water that is contaminated actually is consumed. For a Western type of water use (shower, flushing toilets) this could be 1%, but for water in a household container it can be 100%.

6.2 Water supply reservoirs

Water supply reservoirs are generally covered, however often open entrance lids are observed. Ground level reservoirs allow access or proximity of various animals (dogs, chickens, rats) and leaks at ground or underground level can lead to contamination e.g. during rainfall events. Overhead reservoirs are only vulnerable to birds or human activities. Leakages under the water level will not go unnoticed, but roofs may leak or contain openings that allow bird feces and dust to wash into the reservoir during rainfall. A

typical overhead reservoir volume is 200 m^3, whereas ground level reservoirs can be larger, typically 2,000 m^3. Considering the values in Table 5.1 a single bird dropping (10 grams) in an overhead reservoir can result in 1,000 *Campylobacter* /l . If 10 grams of cow feces near a ground level reservoir is flushed in during a rain event through a leak, this could result in 1,000 *Cryptosporidium* or *Giardia* /l. These scenarios show that small incidents can lead to significant levels of contamination. These events could occur without detection of FIB, since the expected FIB concentrations could be below 1 per 100 ml and samples might not be taken at the right time. These scenario's require a coincidence of infected animals, open or leaking reservoir, location of feces and rainfall event, therefore they are not very likely. These values will be used as an estimate the health effects of a contamination that can occur. To assess the uncertainty associated with this risk, a Gamma distributed concentration with 5 and 95 percentile of 10^{-4} and 10^{4} pathogens/l will be used, representing the 8 log uncertainty about the pathogen content in the contamination source.

Likelihood of a contamination event is expressed per day as a percentage. The frequency of FIB detected in water reservoirs could be used as an estimate of the likelihood of contamination occurring. This could be corrected for underreporting due to the limitations of monitoring frequency. Samples from drinking water reservoirs can currently not be identified in the NRPDW database, therefore one event per 1 year is chosen in the QMRA to demonstrate the principle. This corresponds to a percentage of 1/365=0.27%.

The scenario assumes that the contamination is equally spread over the whole reservoir volume. In rural situations it is common that the water is distributed until the reservoir is empty, which takes less than an hour. People collect and store the water for that day. Therefore all the water that is drunk on that day will be contaminated. Therefore the likelihood for drinking the contaminated water is 100%.

The visited water supply systems did not monitor chlorine residual in the reservoirs and the presence of sufficient residual chlorine is therefore uncertain. The effect of residual chlorine is estimated as nil in the QMRA since even if it is present, the organic substances in the fecal contamination will consume the residual chlorine.

6.3 Drinking water distribution

Lieverloo et al. estimated that the chance of detecting a significant contamination of a drinking water distribution reservoir in a city by the legislative periodical sampling of the distribution system was less than 5%. This was confirmed by Van Vossen who showed that on-line monitoring could improve the chance of detection to 30% or higher. These studies indicate that microbial monitoring data should be corrected for underreporting, depending on the type of system en monitoring program. Alternatively Teunis and LeChevallier modelled pressure transients and resulting ingress of contamination through leaks in distribution systems. These studies identified the pathogen concentration in the contaminating water as the most important uncertainty. Sewage pipes will be near the drinking water pipes in urban situations since sewage is needed to dispose of the used water and both drinking water and sewage pipes are placed under the streets. In rural situations sewers are mostly absent since people use latrines or open defecation, and excess water is simply disposed of in the ground, e.g. to water the garden. Although there are no sewers, fecal contamination of the soil is likely due to open defecation, infiltration from latrines and free roaming cattle, chickens, dogs and other animals. Because the contamination will often have to travel through soil to reach the distribution system, some pathogens will be removed. For the QMRA it is estimated that 1 gram of ruminant feces with high pathogen

concentration (Table 5.1) is diluted in 1 litre of infiltrating water and that 2 log removal occurs due to filtration by the soil before this water enters the drinking water pipe.

Soil may be wet when there is a leak in the distribution pipes, making a 'connection' between fecal contamination at the surface and the water surrounding the distribution pipe. Since water is only distributed for less than one hour per day, the system is without pressure most of the time. Without pressure, the distribution pipes can start working as drainage pipes for contaminated water around leaks. There is no basis to estimate the amount of contaminated water entering the system or the amount of feces in that water. To demonstrate the principle the same amount of contamination as the reservoir contamination in section 6.2 is assumed. An uncertainty range of 10 log units (-7 or +3 logs) is applied to the concentration in the QMRA because the pathogen concentration in feces, the dilution of feces and the effect of soil passage are all uncertain.

When taps are turned on, the contamination is mixed with the first drinking water and then flushed out of the system. It is assumed that 1 litre of contamination is diluted in 1 m^3 of water, and that 100 m^3 of water pass the contamination point. This means the pathogen concentration is diluted 1000 times (3 log) and that it is present in 1% of the water.

The likelihood of drinking the contaminated water is therefore also 1% (assuming that people randomly use the water for different purposes). If this situation is the case it may happen almost every day since water supply is discontinuous. Most distribution systems in rural India have a high leakage rate (that is one of the reasons water is only supplied once per day) and the presence of fecal contamination is also high. A likelihood of 25% will be used in the QMRA for the occurrence of this scenario.

6.4 Secondary transport

Only few houses have taps in their homes. Water is collected at public taps or wells in open pots (codas) which are carried to the home. Studies have shown that contamination occurs between the well and the home resulting in an increase of FIB positive samples and an increase of FIB concentrations (… Kampala conference, Taylor…). The likelihood of contamination of an open pot is estimated as 25% in the QMRA.

The contamination is suspected to come through hands that were not washed properly after defecation or touching animals or contaminated soil or materials. Analogous to the estimation of contamination of groundwater wells, the pathogen concentration is related to the presence of 1 FIB in 100 ml. The estimated pathogen concentration is set to 1.000 pathogens/l to assess the potential risk of a contaminated pot. To identify the knowledge gap, the uncertainty about the pathogen concentration in a contaminated pot (uncertainty about the ratio) the pathogen concentration will be modelled as a Gamma distribution with a 5 and 95 percentile of 10^{-4} to 10^{4} pathogens per litre, based on a detection limit of 1 FIB per 100 ml and the range of possible ratios based on Table 5.1 (5 to -3 log). Since the contamination is spread in the water in the pot, the likelihood of drinking that water is 100%.

Not all secondary transport takes place with open pots. Ground water from private open wells is often pumped to a rooftop tank with a submergible pump. From there the water flows to an in-house tap. Thus contamination through hands cannot occur. The pipes or hoses are above ground, allowing leak detection and repair and therefore ingress of contaminated water is less likely. Therefore no contamination is assumed in the QMRA for this route.

When closed vessels or jerry cans are used for secondary transport, the risk of contamination is much lower. Water vendors generally use 20 l water vessels that can be placed in a water dispenser with a tap in the home. For this type of system also no recontamination is assumed.

6.5 Household storage

The open pots or codas are generally covered in the house with a lid or plate to prevent contamination falling in. However the habit of dipping cups in the codas to fetch water for drinking has been observed. This can lead to recontamination of stored water in the house. Therefore the risk of recontamination of open pots is estimated to be similar as the secondary distribution in open pots (even when covered with a lid).

Storage of drinking water in a rooftop tank is common practice. These are mostly closed plastic tanks, but contamination can take place through the lid (for cleaning) or leaking pipe connections. Monkeys were seen opening such tanks to access the water if they were not properly constructed. The risk of contamination for rooftop tanks is estimated to be similar to overhead tanks, although their volumes are smaller (300 liter). Considering the values in Table 5.1 a single bird dropping (10 grams) in rooftop reservoir can result in $10^{2.4}$ Giardia/l (the estimated contamination of $10^{5.8}$ *Campylobacter* /l is probably more a relevant health risk). Contamination with cow feces is less likely (only indirectly by animals or by poor hygiene).

7 TREATMENT EFFICACY

7.1 Centralized treatment

Treatment efficacy was already discussed in report D2.2 and D4.3. In the QMRA the uncertainty about long term performance will also be taken into account.

7.1.1 Coagulation-sedimentation-rapid sand filtration

Hijnen and Medema (2011) performed an extensive literature review on treatment efficacy resulting in best estimate performance, and reported ranges of performance. For conventional surface water treatment systems they concluded that the particle removal processes of coagulation-sedimentation and rapid sand filtration were best assessed as a whole. Table 7.1 summarizes their findings. Most of the cited literature discussed findings in optimized treatment systems. The observed treatment systems in India don't seem to be optimized. Coagulant dosing is performed by hand, rapid mixers were missing or out of order and treatments are operated discontinuously. Therefore the lower end of the reported range of efficacy from 2.1 to 3.3 log removal was used in the QMRA with a mean of 2.5.

Table 7.1 Efficacy of coagulation-sedimentation-rapid sand filtration (Hijnen and Medema 2011)

Organisms	Data characteristics			MEC (log)		
	Studies	Data	FS-index*	Average	P50	Range
Viruses	7[a,b,d,f,j,z,A]	69	3.6	3.0 (±1.4)	2.5	1.2–5.3
Bacteria[b]	7[d,g,j,q,s,z,A]	54	3.1	2.1 (±0.8)	2.1	1.0–3.4
Bacterial spores	11[f,g,j,m,n,q,r,s,t,v,z]	62	4.7	2.4 (±0.9)	2.1	1.4–4.7
Cryptosporidium	15[e,f,h,i,l,k,o,p,t,v,w,x,y,z,A]	162	3.7	3.2 (±1.3)	2.9	1.4–5.5
Giardia	8[c,e,f,h,l,o,u,z]	67	4.3	3.4 (±0.9)	3.3	2.1–5.1

[a]Foliguet et Doncoeur, 1975; [b]Guy *et al.*, 1977; [c]Logsdon *et al.*, 1981; [d]Payment *et al.*, 1985; [e]LeChevallier *et al.*, 1991: [f]Payment *et al.*, 1993; [g]Hijnen *et al.*, 1994; [h]Nieminski *et al.*, 1994; [i]West *et al.*, 1994; [j]Havelaar *et al.*, 1995; [k]Nieminski *et al.*, 1995; [l]Patania *et al.*, 1995; [m]Rice *et al.*, 1996; [n]Hijnen *et al.*, 1997; [o]States *et al.*, 1997; [p]Yates *et al.*, 1997a; [q,r,s]Hijnen *et al.*, 1998a,c,e; [t]Nobel *etal.*, 1999; [u]Hasimoto *et al.*, 2000; [v]Dugan *et al.*, 2001; [w]Cornwell *et al.*, 2001; [x]Hasimoto *et al.*, 2001; [y]Akiba *et al.*, 2002; [z] Hijnen*et al.*, 2003; [A]Harrington *et al.*, 2003 *FS = full-scale index; the higher the number, the more equivalent with full-scale situation; [b]indicator bacteria (*E. coli,* coliforms, faecal streptococci)

7.1.2 Chlorination

The effect of chlorination depends on the chlorine concentration and contact time, which are combined in the CT value. The efficacy is further impacted by the temperature, pH and chlorine consumption of the water. Hydraulic conditions determine if the dosed chlorine is well mixed with the water and affects the contact time. Types of pathogens respond differently to chlorine disinfection. Bacteria are rapidly inactivated, viruses persist longer while protozoa and Ascaris eggs are hardly affected by chlorine. These inactivation kinetics have been determined in laboratory experiments and inactivation rates are reported in literature (e.g. USEPA 2001). Although bacteria are effectively inactivated under ideal conditions, in full scale systems these conditions cannot be achieved and inactivation largely depends on hydraulic conditions and process control (Smeets et al. 2006). Many different approaches have been published to account for these shortcomings ranging from simple (Ct10 concept) to complex (computational fluid dynamics modelling). The Watershare QMRA treatment calculator provides an overview of inactivation kinetics for the various pathogens and provides two ways to model inactivation. The plug-flow approach calculates the inactivation under ideal conditions, whereas the CSTR approach (continuously stirred tank reactors) provides a more realistic estimate based on full scale conditions

(Smeets et al 2006, KWR 2015). The CSTR approach was therefore chosen to estimate chlorine disinfection efficacy in the QMRA.

Indian operators have indicated that the chlorine dosing is adjusted proportionally to the flow in order to achieve a constant chlorine level of 1 mg/l after dosing. They could not provide more information about the other mentioned aspects that impact the effect of chlorine on pathogens. Since very few details about chlorination conditions are available, chlorination in the QMRA is estimated for assumed typical process conditions. Assuming a CT of 10 min*mg/l, a temperature of 20°C and characterizing hydraulic conditions as 2 CSTR (continuously stirred tank reactors) the inactivation of pathogens was calculated with the Watershare QMRA treatment calculator. Table 7.2 provides an overview of the inactivation used in the QMRA study. When QMRA is used to assess the effect of disinfection optimization, the site specific conditions should be determined in more detail. Smeets et al. (2013) found that improving hydraulic conditions and consistent chlorine residual is generally more effective than increasing the ozone dose.

Table 7.2 Estimated inactivation of pathogens by chlorine disinfection under assumed full scale conditions

	Log inactivation
Enterovirus	2.8
Campylobacter	>5
Cryptosporidium	0
Giardia	0.2
Ascaris	0

7.2 Household treatment

7.2.1 Boiling

Boling of water is a common treatment applied in rural India when the quality of the water is not trusted, or when the water is meant for vulnerable groups (children, ill, visitors). A literature study was performed to determine the effect of boiling on micro-organisms. Boiling is very effective against the waterborne pathogens under study here, generally achieving 'full disinfection'. Model calculations result in >>10 log inactivation of these pathogens when water is boiled for 1 minute. Some spores of microorganisms are more persistent against boiling, however these are not waterborne pathogens.

Table 7.3 Estimated inactivation of pathogens by chlorine disinfection under assumed full scale conditions

	Log inactivation
Enterovirus	>>10
Campylobacter	>>10
Cryptosporidium	>>10
Giardia	>>10
Ascaris	>>10

7.2.2 Ceramic candle filters

Ceramic candle filters are frequently used by homes in India and when handled and applied properly, they can be effective filters for pathogens. Table 7.4 provides an overview of estimated pathogen removal by ceramic candle filters (Franz et al. 2004, Hörer et al. 2004, CAWSTnet 2015)

Table 7.4 Pathogen removal by ceramic candle filters

	Log inactivation
Enterovirus	1
Campylobacter	2
Cryptosporidium	>5
Giardia	>5
Ascaris	>5

7.2.3 Commercial system with membrane filtration and UV disinfection

The use of more advanced home treatment systems that apply membrane filtration and UV disinfection is less common in rural India because of the higher costs and the regular need for replacement parts. However they are used in hospitals there. These systems can be very effective because of the double treatment barrier included, achieving more than six log inactivation of pathogens. The efficacy can be compromised by the use of poor materials (leaking membranes, ineffective lamps), poor construction (leaking seals) or poor maintenance (parts are not replaced in time). No evaluation of the performance of this type of treatment in practice was found in the literature. Some systems in Western countries are certified by organisations such as NSF to verify that (properly installed, operated and maintained) systems achieve treatment standards. Indian systems are sometimes labelled as 'certified' however the certification requirements we not found. Challenge testing can be part of certification, for example the NSF/ANSI 58 standard for RO membrane POU systems requires 99.95% (3.3 log) removal of cysts. Removal of bacteria or viruses is not included since filters are intended for (chlorine) disinfected water. A UF membrane filtration For the purpose of the QMRA it is assumed that the system just meets the certification requirements or that long term performance is compromised and that 0.1% leakage of seals occurs.

NSF/ANSI 55 requires 40 or 16 mJ/cm^2 for A or B level certification of UV disinfection. For Indian POU systems no certification requirements or design doses were found. For the risk assessment we assumed a dose of 10 mJ/cm^2 to be achieved on long term. UV inactivation of the pathogens was then calculated with the Watershare QMRA treatment calculator (KWR 2015), in which the inactivation rate constants are based on Hijnen et al (2006). The resulting limiting removal of pathogens is summarized in Table 7.5.

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Table 7.5 Estimated long term pathogen removal or inactivation by commercial home membrane-UV treatment (Hijnen et al. 2006)

	Membrane filtration RO	UV disinfection 10 mJ/cm^2	Total Log inactivation
Enterovirus	3	0.6	3.6
Campylobacter	3	>4	>7
Cryptosporidium	3	2	5
Giardia	3	1	4
Ascaris eggs	3	[1]0.1	3.1

1 Brownell and Nelson 2006

8 CONSUMPTION AND INFECTIVITY

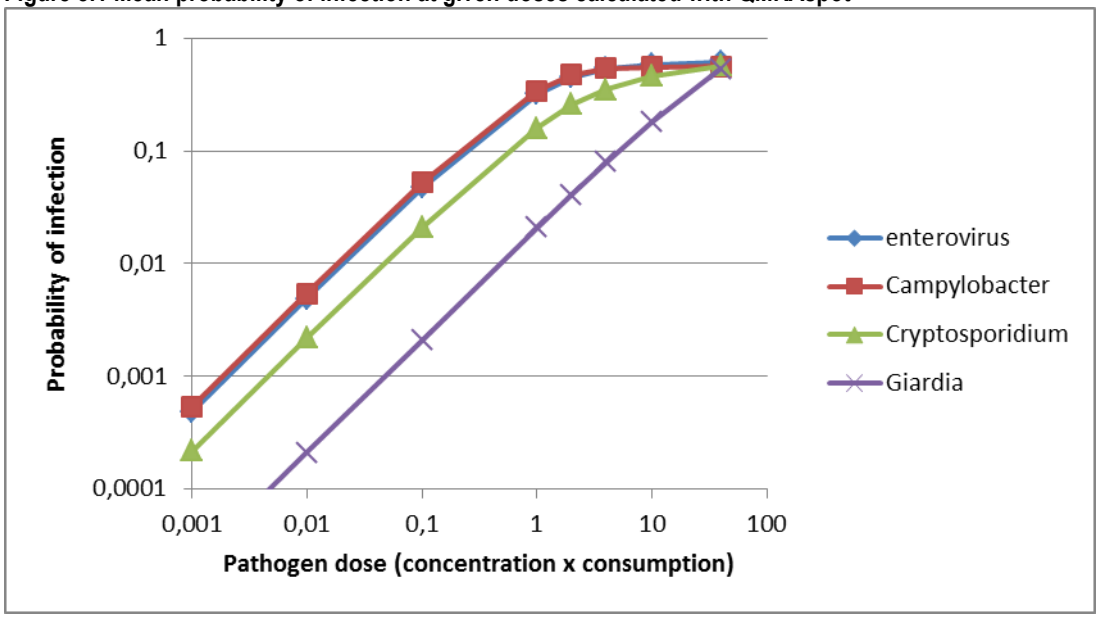
8.1 Consumption

Mons et al (2007) studied available data on consumption of unboiled drinking water. These were all studies from developed countries. Reported mean consumption varied from 0.10 to 1.55 litres per person per day. The data show no clear relation between climate and consumed drinking water as the highest consumption was reported for Sweden (cold climate) and Australia (hot climate). The only factor that seemed to predict the water consumption to some level was performing hard labour under hot conditions. Steel workers consumed 1.8 litres per day in winter up to 3.7 litres in summer. For rural India, one can argue that people generally perform labour under hot conditions and therefore drinking water consumption will be at the higher end of the spectrum. Mondal et al. (2015) used an average consumption of 2 litres per day for their study in Bangladesh. For the current QMRA study a consumption of 2 litres per person per day will also be assumed as a best estimate, and a range of 0.5 to 3.7 litres will be used to assess the impact of uncertainty about average consumption on the risk assessment.

8.2 Dose and probability of infection

The daily dose of pathogens is calculated by multiplying the pathogen concentration with the volume consumed. The probability of developing an infection is higher when more pathogens are ingested. This is expressed as a dose-response relationship. Various pathogens have different dose-response relationships that have been studied based on volunteer experiments and outbreaks. Pettersson et al (2007) provides an overview of these studies. Several researchers have analysed the data from these studies and developed various dose-response models. The most recent work by Teunis et al (2014) resulted in a relatively complex approach, resulting in datasets of 10.000 parameter pairs per pathogen to be implemented in a stochastic estimate of risk using the 1F1 Hypergeometric function. This approach is incorporated in the QMRAspot software tool (Schijven et al. 2011, Schijven et al. 2014). This tool was used in the current QMRA study to determine the mean probability of infection at a given dose, which is shown in Figure 8.1. This data is used in the current QMRA to look up the probability of infection at a calculated dose. A dose below 1 means that there is a chance that the consumed water did not contain a pathogen, therefore the dose-response relationship is linear at doses below 1. Figure 8.1 also shows that even at very high doses there is always a possibility that a person doesn't develop an infection.

Figure 8.1 Mean probability of infection at given doses calculated with QMRAspot



9 SIMULATIONS

9.1 Shimoga case study

The input values for QMRA in the following tables are based on limited data or assumptions. Goal is to demonstrate the principle of the multi-route QMRA approach rather than provide an accurate estimate of risk. More data may be available to improve the estimated parameter values. This case study only considers Giardia as pathogen. The same steps should be followed for other waterborne pathogens (viruses, bacteria and *Cryptosporidium*).

9.1.1 Input parameters

Table 9.1 QMRA parameters Shimoga case study route 1, Giardia

Centralized surface water supply	Unit	Description	Chance	Min (2,5%)	Max (97,5%)
Pathogens in source	log n/l	Tunga river Shimoga		-0,82	0,99
Treatment 1	log	Coagulation-sedimentation-RSF		2,1	3,3
Treatment 2	log	Chlorination		0	0,4
Treatment 3	log	not implemented		0	0,00001
Storage events	%	once per year	0,27%		
Storage concentration	log n/l	Bird faeces 1 g		-4	4
Distribution events		once per month	3,29%		
Distribution concentration	log n/l	Cow faeces 10 g		-3,7	6,3
Secondary distribution events		once per month	3,29%		
Secondary distribution conc.	log n/l	Human faeces 0,01 g		-4	4
Home treatment	log	Candle filter		1	3
Home storage events		once per month	3,29%		
Home storage conc.	log n/l	Human faeces 0,01 g		-4	4
Consumed per day				0,5	3,7
Days used			30		

Table 9.2 QMRA parameters Shimoga case study route 2, Giardia

Private open well	Unit	Description	Chance	Min (2,5%)	Max (97,5%)
Pathogens in source	log n/l	none before contamination		-9	-9,0
Treatment 1	log			0	0,0
Treatment 2	log			0	0,0
Treatment 3	log			0	0,0
Storage events	%	25% of wells contaminated	25,00%		
Storage concentration	log n/l	1 g cow in 500 l		-1,4	5,6
Distribution events		no primary distribution	0,00%		
Distribution concentration	log n/l			-9	-9,0
Secondary distribution events		once per month	3,29%		
Secondary distribution conc.	log n/l	Faeces		0	7
Home treatment	log			0	0,0
Home storage events		in secondary distribution	0,00%		
Home storage conc.	log n/l			-9	-9,0
Consumed per day				0,5	3,7
Days used			300		

Table 9.3 QMRA parameters Shimoga case study route 3, Giardia

Rainwater harvesting	Unit	Description	Chance	Min (2,5%)	Max (97,5%)
Pathogens in source	log n/l	none before contamination		-9	-9,0
Treatment 1	log			0	0,0
Treatment 2	log			0	0,0
Treatment 3	log			0	0,0
Storage events	%	rainwater always contaminated	100,00 %		
Storage concentration	log n/l	1 g bird in 50 l		-1,4	5,6
Distribution events		no primary distribution	0,00%		
Distribution concentration	log n/l			-9	-9,0
Secondary distribution events		once per month	3,29%		
Secondary distribution conc.	log n/l	Faeces		-4	4
Home treatment	log	Advanced candle filter with tap		4	6,0
Home storage events		protected container	0,00%		
Home storage conc.	log n/l			0	0,0
Consumed per day				0,5	3,7
Days used			35		

9.1.2 Calculated risks

The risk was calculated for each individual step in each of the routes to gain insight in how the risk is affected by the various contaminations and measures. In the following sections each of the routes will be discussed and the combined annual risk from all routes is presented. Then the effect of various measures to reduce risks are examined and discussed.

9.1.2.1 Route 1 Centralized river supply

The presence of faecal coliform bacteria shows that river water is faecally contaminated. The constant presence of pathogens is therefore likely. Figure 9.1 shows that it is very likely that you get an infection if you drink the water for 30 days (the period that route 1 is used). The risk is certainly larger than 25% (>$10^{-0.6}$) as indicated by the single bar in the graph.

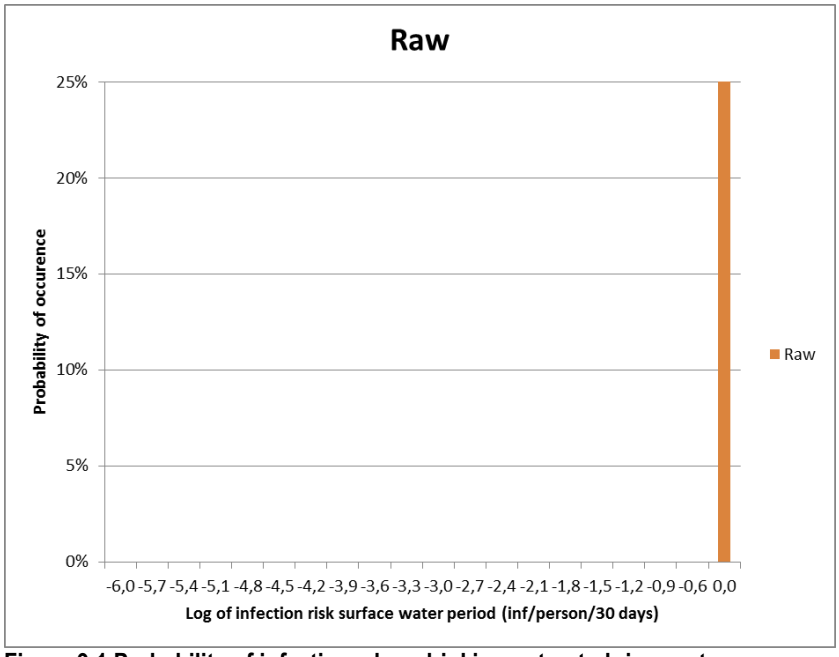


Figure 9.1 Probability of infection when drinking untreated river water

Centralized surface water treatment will reduce the number of pathogens, and therefore the risk of infection. There is some uncertainty in the assessment. The most likely risk is about 10^{-2}, but it may vary between $10^{-2.4}$ and $10^{-0.9}$. This uncertainty is caused by the uncertainty about the pathogen concentration in the river water and their removal by treatment.

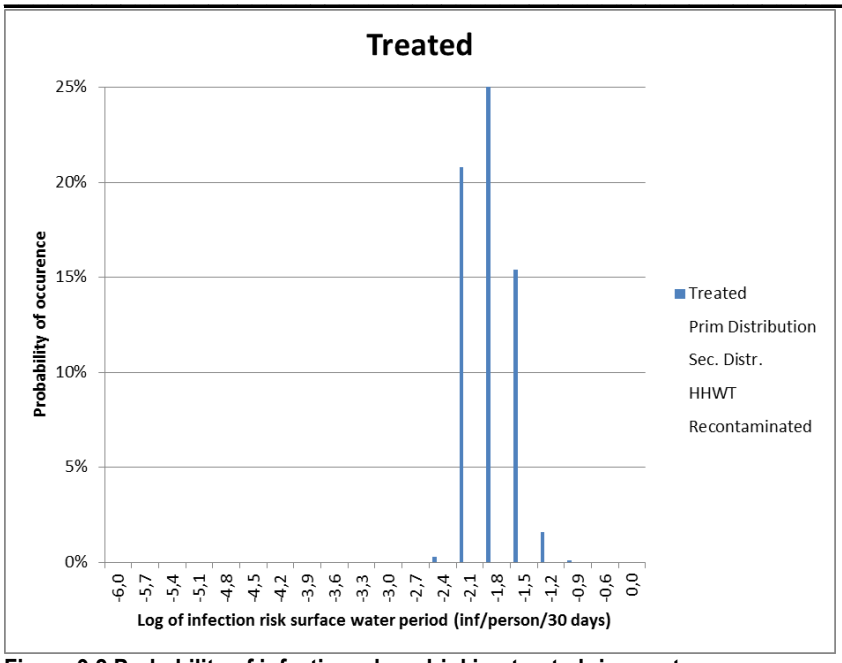


Figure 9.2 Probability of infection when drinking treated river water

During primary distribution the water can become contaminated by intrusion of pathogens from faeces near the water lines without pressure. This can be seen in Figure 9.3 as a 5% chance of a high risk (>10-0.6). Otherwise the risk is comparable to the risk of drinking treated water.

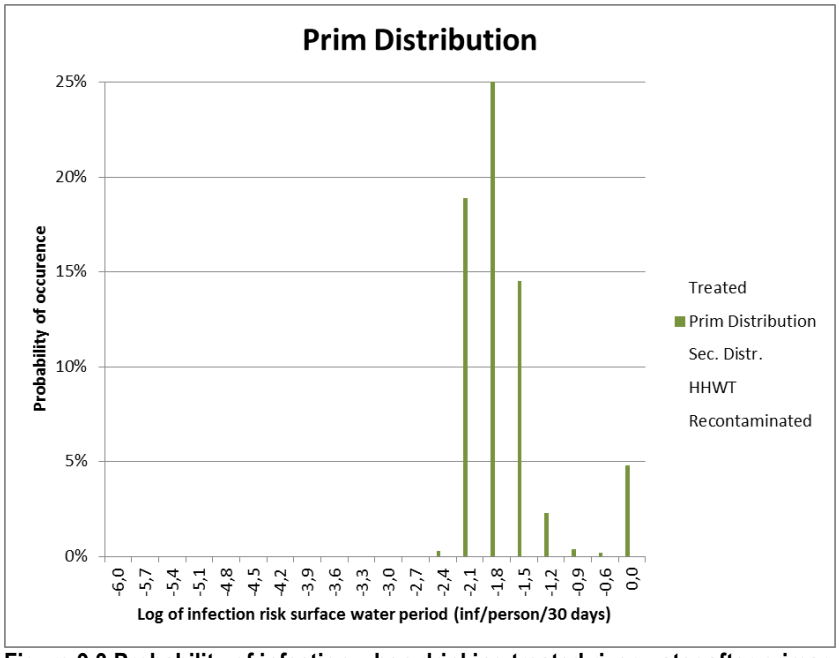


Figure 9.3 Probability of infection when drinking treated river water after primary distribution

During secondary distribution, from the standpipe to the home, there is again a risk of contaminating the water. In Figure 9.4 this can be seen as an increase of the chance that the risk is high from 5% to 13%.

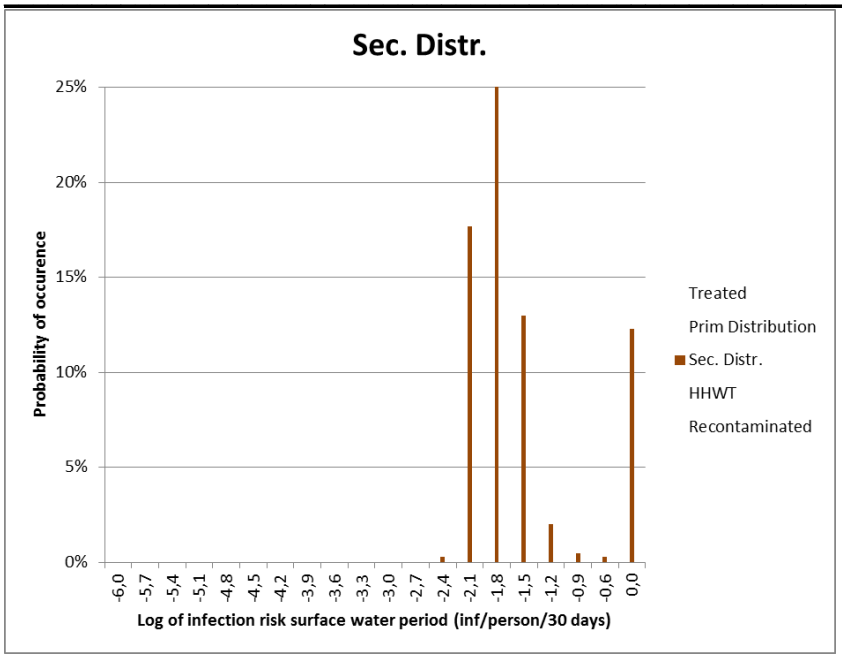


Figure 9.4 Probability of infection when drinking treated river water after primary and secondary distribution

When the water is treated at the point of use in the house, the risk of drinking water is reduced. The risk of infection is most likely around $10^{-4.2}$. The uncertainty about the non-event risk has increased due to the uncertainty about the treatment efficacy. The likelihood of high risk from events during distribution is reduced from 13% to 2% since these contaminations will be reduced by effective treatment. However some high risk remains since the efficiency of POU treatment is uncertain.

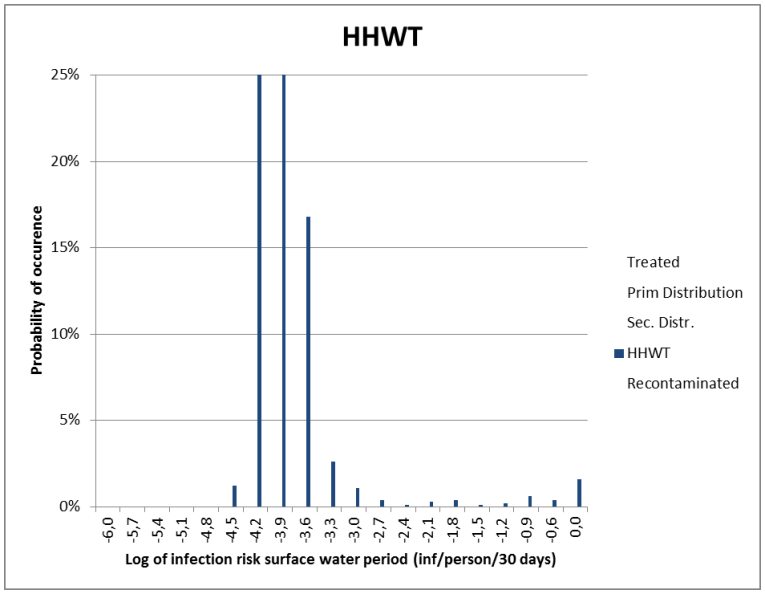


Figure 9.5 Probability of infection when drinking treated and distributed river water after household treatment

After treatment the water may be recontaminated during in-house storage. This leads to an increase of likelihood of a high risk from events, increasing from 2% to 4%. Repeated modelling shows that the number of simulations in the model is resulting in slight variations in the occurrence of all contamination events. Increasing the number of simulations would provide more stable results, but requires more

calculation time, especially since the model was developed in MS excel®, which isn't optimized for such simulations. For the purpose of demonstrating the model and gaining insight in the risks, the limited number of simulations is sufficient.

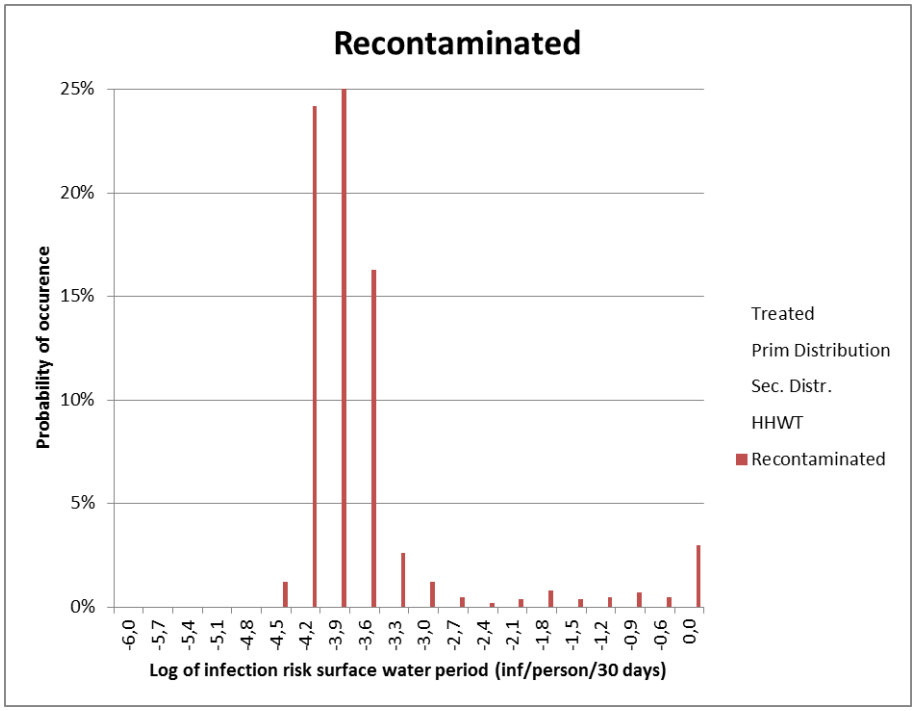


Figure 9.6 Probability of infection when drinking treated, distributed and household treated river water after recontamination in the home

9.1.2.2 Route 2 Private open well

The private open well was simulated in the model as a clear water tank with incidental contamination occurring. In Figure 9.7 one can clearly see that water is assumed to be either clean or contaminated in this simulation.

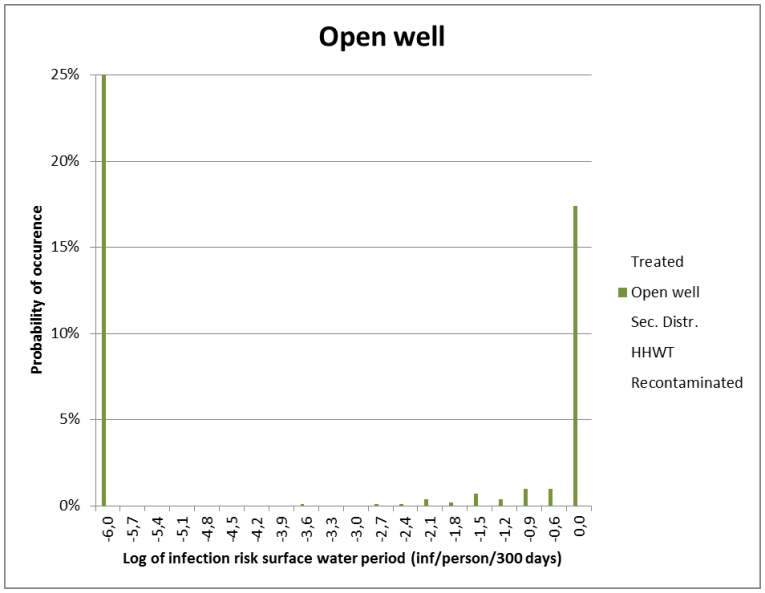


Figure 9.7 Probability of infection when drinking directly from a private open well.

The water may be further contaminated during transportation from the well to the house and in house storage. This is shown in Figure 9.8 by an increase of the likelihood of high infection risk from 17% to 24%

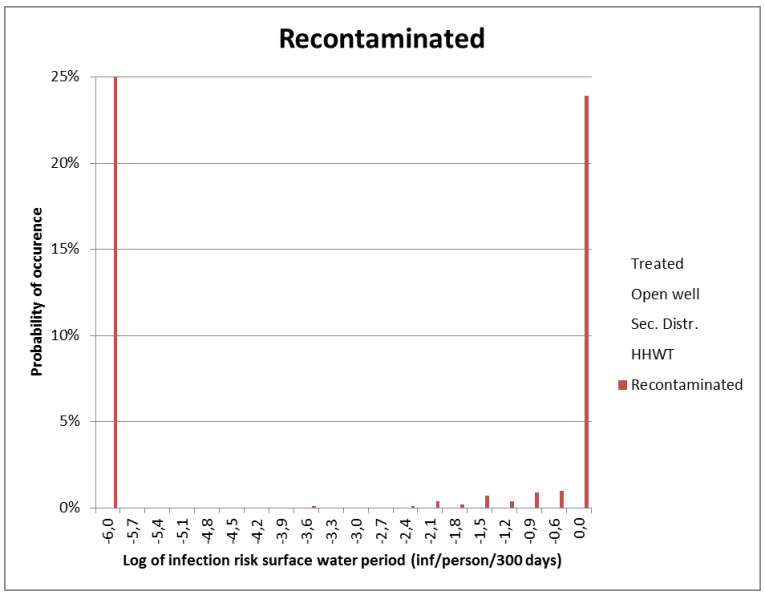


Figure 9.8 Probability of infection when drinking water from a private open well after transport and storage.

9.1.2.3 Route 3 Rainwater harvesting

Harvested rainwater can contain a range of faecal contamination from the roof. This was simulated as contamination of a clear water reservoir in the model. Figure 9.9 shows the clear difference between contaminated and not-contaminated situation, and there is a small range of partially contaminated water from $10^{-3.9}$ to $10^{-0.6}$ risk of infection.

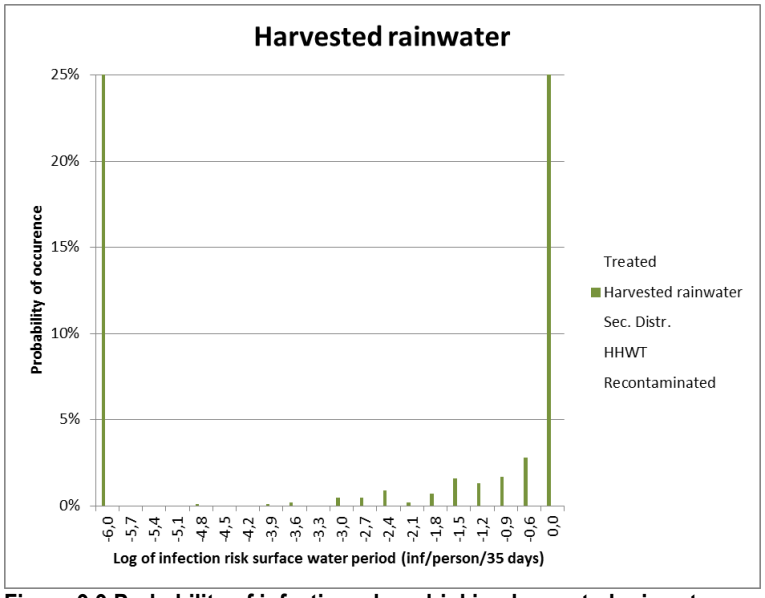


Figure 9.9 Probability of infection when drinking harvested rainwater

After POU treatment in the house the uncertainty about the risk shows a large range due to the uncertainty of the contamination in the harvested water and about the effect of treatment. Since the treated water is directly contained without risk of recontamination in the home, the risk after treatment in equals the risk to the consumer.

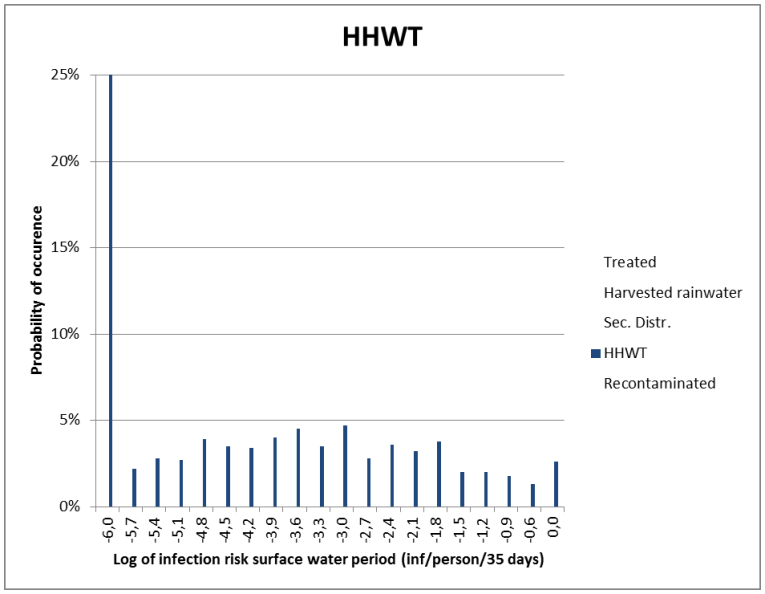


Figure 9.10 Probability of infection when drinking harvested rainwater after POU treatment

9.1.2.4 Combined routes of exposure

The risks to consumers through the various routes was combined in Figure 9.11 which shows the risk for each period the water is used. The figure clearly shows the difference in uncertainty about the risk levels for each route. For open wells it is simply the uncertainty if a well is contaminated or not. Rainwater may be clean, but if it is contaminated the risk largely depends on the (uncertain) effect of treatment. For surface water supply, a range of low risk is likely if the water is also treated in the home. However contamination events during centralized and local distribution and storage still introduce some high risks.

The risks through the various routes were combined in Figure 9.12 to calculate the combined annual risk through all these routes that are used during different periods of the year. The very low risks from open well water and rainwater are compromised by the period that people drink surface water, for which some risk always exists. The high event risks from contaminations, especially the open wells, can easily be recognized in the graph.

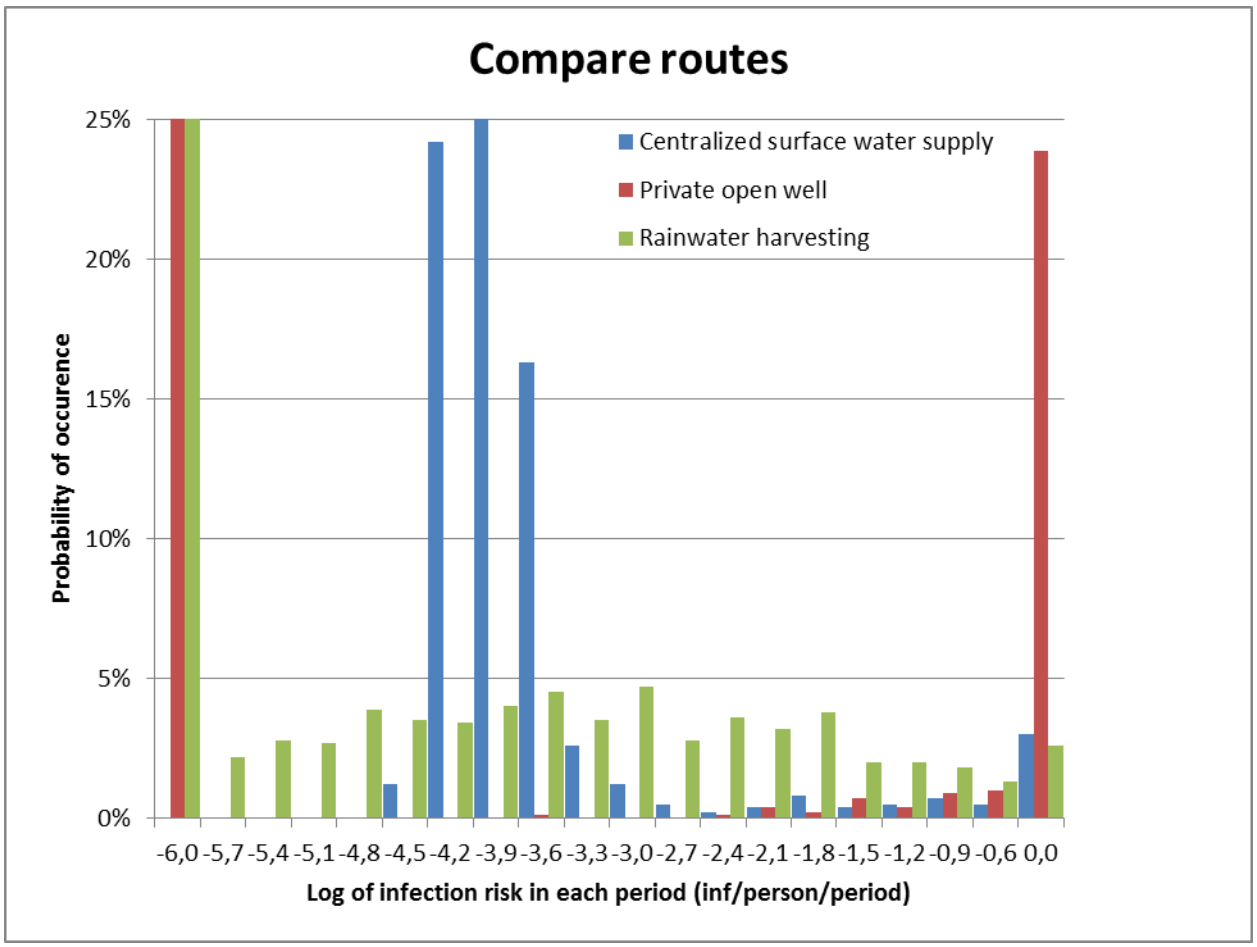


Figure 9.11 Probability of infection from the three exposure routes Shimoga case study

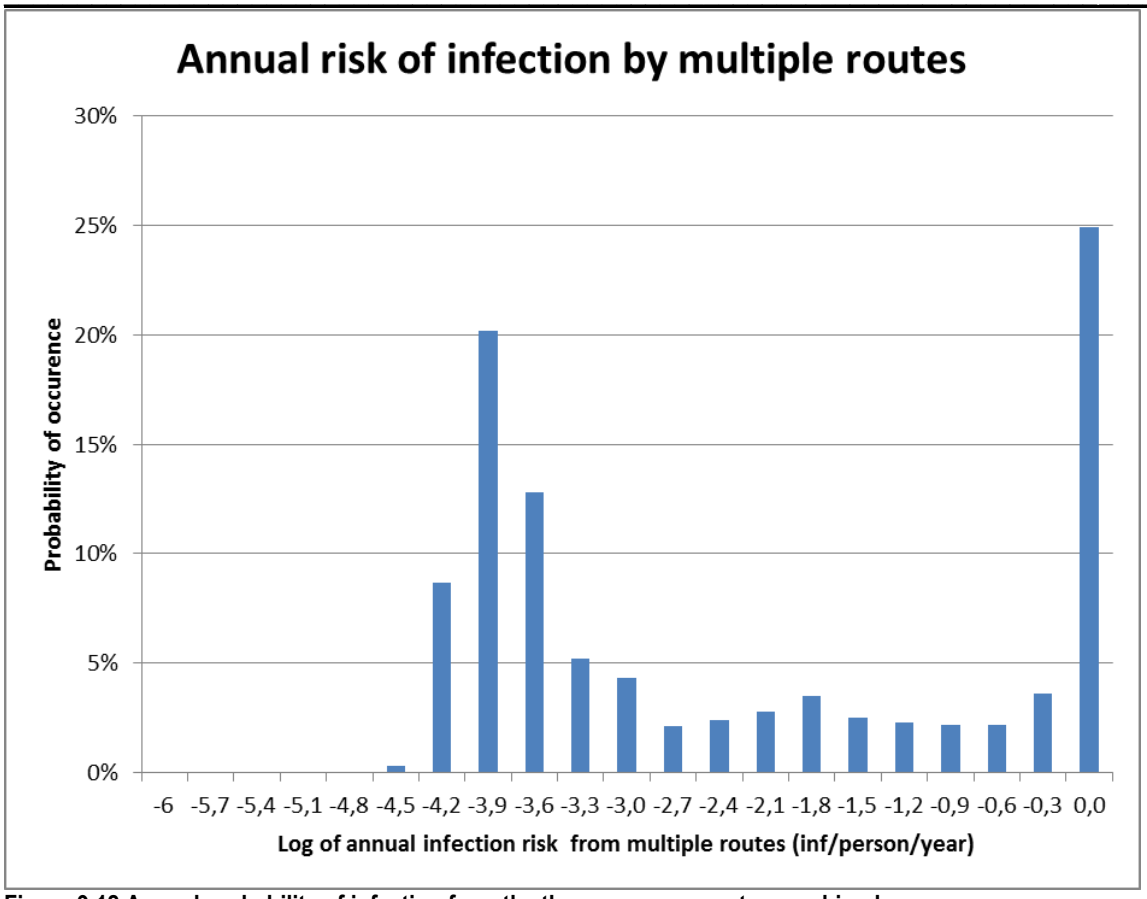


Figure 9.12 Annual probability of infection from the three exposure routes combined

Table 9.4 QMRA outcomes for Simoga case study, daily risk of infection with Giardia

	Route 1	Route 2	Route 3	Annual risk
	Centralized river supply + Recontamination	Private open well	Rainwater harvesting+ Boiling	
Point estimate	$5*10^{-1}$	$5*10^{-1}$	$1*10^{-10}$	1
Mean stochastic	$2*10^{-2}$	$5*10^{-2}$	$<1*10^{-10}$	1
2.5%	$3*10^{-5}$	$<1*10^{-10}$	$<1*10^{-10}$	$1*10^{-3}$
97.5%	$5*10^{-1}$	$5*10^{-1}$	$<1*10^{-10}$	1
No recontamination	$4*10^{-4}$			
No boiling			$7*10^{-3}$	

9.1.3 Gulbarga case study

The approach in the Gulbarga case study is similar to the Shimoga case study, therefore we don't present all the steps in the risk assessment, only the comparison between routes is shown (Figure 9.13). The nominal risk from the centralised groundwater supply is slightly lower than the risk from the public shallow well with handpump. In both these routes, the occurrence of contamination events leads to high risk for a percentage of time or population. The village RO-UV system provides very safe water due to the effect of advanced treatment for the not very contaminated groundwater. Recontamination doesn't occur for this route, because a closed collection, transportation and household storage and dispensing system is used. This illustrates he potential health benefit from such a village system.

Figure 9.13 Probability of infection from the three exposure routes Gulbarga case study

9.1.4 Discussion

The case study of Shimoga was a first attempt to quantify the health risk through multiple routs of exposure including recontamination during transport and storage. The goal was to gain insight into the relative risks and the lack of data and knowledge gaps to assess risks. At this stage the results should not be interpreted as an actual assessment of drinking water risk in India.

Looking at Table 9.4 the estimated daily infection risks for routes 1 and 2 are very high. The calculations resulted in ingestion of Giardia in almost every simulated exposure in these assessments. Such constant exposure can either lead to developing immunity by the local population. Boiling water, as performed in Route 3 clearly provides protection against Giardia . This corresponds with the practice of boiling water for visitors from other villages, as they would not have developed immunity. For the local population the infection risk may over estimated since the dose-response relationship is developed for low exposure levels and doesn't account for high levels of immunity.

The water quality from the surface water supply in route 1 is compromised by the recontamination during distribution as a consequence of lack of constant pressure and leaking pipes. Without this recontamination the water would be much safer. However if this was the only water source the whole year, the annual risk of infection would still be 14%.

The private well scenario in route 2 also results in a high risk estimate. Since FIB are frequently detected in open wells, there is a strong indication that the wells are faecally contaminated. The 95% uncertainty range cover 8 orders of magnitude. It is mostly impacted by the estimated pathogen concentrations based on FIB presence. Research into the sources of these contaminations and the actual presence of pathogens could provide new insights in the actual risks. One also must consider that absence of FIB can mean that FIB concentration is just below detection limit. The corresponding risk then is also just below the estimated level in Table 9.4.

The rainwater harvesting in route 3 results in a very low risk since it assumes that all the consumed water is boiled, and that water isn't recontaminated after boiling. Without boiling the risk from rainwater harvesting is still relatively high. The main uncertainty is the level of contamination on the roof, which can be situation dependent. The presence of animals on the roof that can shed human pathogens, or bring contamination with their paws is a risk factor of concern.

10 CONCLUSIONS

A multiple route QMRA was developed in this study to assess the risk of infection through various drinking water sources, treatments and storage practices. Apart from the QMRA framework, the available data to perform QMRA was evaluated and examples were provided how to estimate missing information.

At this stage the approach is suitable to gain insight into the routes of exposure and their relative importance. Given the uncertainties in the assessment, the risk estimates should not be interpreted as actual health risk through drinking water in India. The uncertainty analysis showed that the translation from FIB data to pathogens introduces uncertainty over multiple orders of magnitude. It is desirable to reduce this uncertainty before using the approach to support decisions on risk mitigation. Although existing data from Western countries provides a first estimate of FIB and pathogens in fecal contamination sources, these estimates need to be confirmed by actual Indian data. This will require targeted sampling programs with more advanced microbial methods to assess pathogens in various water matrices.

This report can be used as a basis for discussion with Indian stakeholders in drinking water quality. They can indicate the questions that need further quantification through QMRA in order to improve risk management. The current framework could then be developed into a tool for stakeholders to perform QMRA themselves.

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