KOMPETENZZENTRUM
WasserBerlin

REPORT

Final draft, **Date: 12.06.2012**

Cicerostr. 24
D-10709 Berlin
Germany
Tel +49 (0)30 536 53 800
Fax +49 (0)30 536 53 888
www.kompetenz-wasser.de

Risk assessment of Braunschweig wastewater reuse scheme

by
Wolfgang Seis
Kompetenzzentrum Wasser Berlin gGmbH
Cicerostr. 24 10709 Berlin
for
Kompetenzzentrum Wasser Berlin gGmbH

Preparation of this report was financed in part through funds provided by
Veolia Water and Berliner Wasserbetriebe

VEOLIA WATER Berliner Wasserbetriebe

Berlin, Germany
2012

Important Legal Notice

Disclaimer: The information in this publication was considered technically sound by the consensus of persons engaged in the development and approval of the document at the time it was developed. KWB disclaims liability to the full extent for any personal injury, property, or other damages of any nature whatsoever, whether special, indirect, consequential, or compensatory, directly or indirectly resulting from the publication, use of application, or reliance on this document. KWB disclaims and makes no guaranty or warranty, expressed or implied, as to the accuracy or completeness of any information published herein. It is expressly pointed out that the information and results given in this publication may be out of date due to subsequent modifications. In addition, KWB disclaims and makes no warranty that the information in this document will fulfill any of your particular purposes or needs. The disclaimer on hand neither seeks to restrict nor to exclude KWB's liability against all relevant national statutory provisions.

Wichtiger rechtlicher Hinweis

Haftungsausschluss: Die in dieser Publikation bereitgestellte Information wurde zum Zeitpunkt der Erstellung im Konsens mit den bei Entwicklung und Anfertigung des Dokumentes beteiligten Personen als technisch einwandfrei befunden. KWB schließt vollumfänglich die Haftung für jegliche Personen-, Sach- oder sonstige Schäden aus, ungeachtet ob diese speziell, indirekt, nachfolgend oder kompensatorisch, mittelbar oder unmittelbar sind oder direkt oder indirekt von dieser Publikation, einer Anwendung oder dem Vertrauen in dieses Dokument herrühren. KWB übernimmt keine Garantie und macht keine Zusicherungen ausdrücklicher oder stillschweigender Art bezüglich der Richtigkeit oder Vollständigkeit jeglicher Information hierin. Es wird ausdrücklich darauf hingewiesen, dass die in der Publikation gegebenen Informationen und Ergebnisse aufgrund nachfolgender Änderungen nicht mehr aktuell sein können. Weiterhin lehnt KWB die Haftung ab und übernimmt keine Garantie, dass die in diesem Dokument enthaltenen Informationen der Erfüllung Ihrer besonderen Zwecke oder Ansprüche dienlich sind. Mit der vorliegenden Haftungsausschlussklausel wird weder bezweckt, die Haftung der KWB entgegen den einschlägigen nationalen Rechtsvorschriften einzuschränken noch sie in Fällen auszuschließen, in denen ein Ausschluss nach diesen Rechtsvorschriften nicht möglich ist.

Colofon

Title
Risk assessment of Braunschweig wastewater reuse scheme

Authors
Wolfgang Seis, Kompetenzzentrum Wasser gGmbH

Quality Assurance
Christian Remy, Kompetenzzentrum Wasser Berlin
Boris Lesjean, Kompetenzzentrum Wasser Berlin
Christoph Siemers, Stadtentwässerung Braunschweig
Bernhard Teiser, Abwasserverband Braunschweig

Publication / Dissemination approved by technical committee members:
Regina Gnirss, Berliner Wasserbetriebe
Christine Mesek, Stadtentwässerung Braunschweig
Bernhard Teiser, Abwasserverband Braunschweig
Andreas Hartmann, Kompetenzzentrum Wasser Berlin
Norbert Dichtl, ISWW der TU Braunschweig
Christophe Sardet, Veolia Wasser
Emmanuelle Trouvé, Veolia Eau

Deliverable number
D 2.6

Final version ☒
Date: 21.01.2013

Abstract (English)

Risk-based management approaches are more and more used in the water sector and are promoted by the WHO. As a first step towards an overall risk-based management approach of the agricultural wastewater reuse concept of Braunschweig this report conducts quantitative microbial risk assessment (QMRA) and quantitative chemical risk assessment (QCRA) of heavy metals. Scenarios for microbial risks are conducted for fieldworkers, nearby residents and children ingesting soil using a 1000 trial Monte Carlo Simulation. As a tolerable value of risk an additional disease burden of 1 µDALY is set following the current WHO guidelines. For heavy metals impacts on the terrestrial and aquatic ecosystems as well as on human health are assessed using the methods outlined in the *European Union Technical Guidance Document on Risk Assessment (TGD)*. Concerning microbial risks risk-based targets are set in terms of additional required pathogen reduction in the STP Steinhof. Based on the model results an additional reduction of 1.5log units is derived for viruses, for which the highest annual risks of infection per person per year (pppy) is calculated in all scenarios. Concerning heavy metals the model indicates an increasing tendency of soil concentrations over time and identifies Cd as the only metal which is currently of concern. Risk reduction measures should be considered for this metal. Recommendations are given concerning necessary validation and additional monitoring for eliminating uncertainties within the model.

Abstract (German)

Diese Arbeit befasst sich mit der Risikobewertung des landwirtschaftlichen Abwasserwiedernutzungskonzeptes der Stadt Braunschweig und soll als erster Schritt in Richtung eines risikobasierten Managementansatzes dienen. Ein solcher findet im Wassersektor vermehrt Anwendung und wird von der Weltgesundheitsorganisation (WHO) gefordert. Eine quantitative mikrobielle Risikobewertung (QMRA) dient zur Abschätzung von Infektionsrisiken für verschiedene Bevölkerungsgruppen (Feldarbeiter, Anwohner, Kinder). Das Model nutzt den probabilistischen Ansatz der Monte Carlo Simulation (1000 Versuche). Als tolerierbares Risiko wird der von der WHO festgesetzte Wert von einem zusätzlichen µDALY pro Person pro Jahr herangezogen. Risiken, welche durch den Eintrag von Schwermetallen in Boden und Oberflächenwasser für das aquatische und terrestrische Ökosystem sowie für die menschliche Gesundheit entstehen, werden durch eine quantitative chemische Risikobewertung abgeschätzt (QCRA). Der methodische Ansatz folgt dem Richtliniendokument für Risikobewertungen der Europäischen Union (TGD). Die Studie zeigt, dass das höchste Infektionsrisiko von den betrachteten Viren ausgeht und das eine zusätzlich Keimreduktion um 1.5 logarithmische Stufen nötig ist, um den von der WHO festgesetzten Wert einzuhalten. Bezüglich möglicher ökologischer und gesundheitlicher Risiken durch Schwermetalle weist das Modell auf steigende Schwermetallkonzentrationen im Boden hin. Cd wird als einziges derzeitig relevantes Schwermetall identifiziert, für das Risikoreduktionsmaßnahmen erarbeitet werden sollten. Abschließend werden Empfehlungen gegeben inwieweit die erhaltenen Ergebnisse validiert werden sollten und zusätzliches Monitoring bestehende Unsicherheiten zu verringern vermag.

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

The social, economic and environmental importance of a safe and sound water resource management as well as of the issue of energy efficiency and security can hardly be overestimated. On a global scale, growing water stress, population growth and diminishing resources will lead to a further increase of the significance of water and energy issues.

The reuse of wastewater in agriculture may be one option to cope with the problem of water scarcity, as the pressure on other water resources decreases (Salgot et al. 2004). Furthermore, nutrients like nitrogen and phosphorus can be reused by applying wastewater on agricultural areas, reducing the need for industrial fertilizers. The reduction of resource requirements in this manner leads not only to economical benefits but also reduces adverse environmental effects resulting from fertilizer production. Moreover, benefits for public health and the environment may result, since wastewater is no longer discharged to surface waters. This implicates an improvement of the overall water quality and ecological status of the receiving water body and thus protects downstream living populations which are dependent on the respective surface water as a source for drinking water (WHO 2006).

In addition to the mentioned benefits of agricultural wastewater reuse, the production of energy plants on wastewater irrigated areas may reduce the need for fossil fuels and, thus, mitigate carbon emissions. This kind of “energetic wastewater reuse” may be of special interest for European sewage treatment plants, since the European “Energy Package” demands a reduction of energy requirements from 20-40% throughout all industrial sectors. In this context, wastewater treatment was identified to imply the highest potential of energy reduction concerning the water sector (Lesjean et al. 2010).

Therefore, the research project “CoDiGreen”, a cooperation between Stadtentwässerung Braunschweig (SEIBS), Kompetenzzentrum Wasser Berlin (KWB) and the Technical University of Braunschweig, aims to identify optimization options concerning energy efficiency of the wastewater treatment concepts of Berlin (B) and Braunschweig (BS) as well as to reduce their external energy requirements. Within this project, experimental research is conducted on laboratory scale and in full scale trials, on how to increase gas yields due to different variations and modifications of the sludge digestion process. Furthermore, Life Cycle Assessment (LCA) of the sanitation schemes of Berlin and Braunschweig is conducted in order to determine the carbon and environmental footprint of the respective concepts and to identify the steps which incorporate the highest reduction potential (Lesjean et al. 2010).

In contrast to the Berlin sanitation concept the sanitation concept of Braunschweig is close to be energy autarkic (Lesjean et al. 2010). A main factor, which significantly contributes to this energy autarky, is the extensive reuse of treated wastewater and digested sewage sludge in agriculture for the growth of energy plants and the use of the produced biogas. 66% of the treated wastewater and about 50% of the digested sludge are reused for agricultural irrigation (Lesjean et al. 2010).

Despite all the mentioned benefits, from nutrient reuse to energy autarky of sewage treatment plants, wastewater reuse may also lead to adverse effects on human health and/or the environment. Wastewater contains a variety of potentially harmful chemical and microbiological agents, like heavy metals, organic chemicals, viruses and bacteria.

Recalcitrant chemicals may accumulate in soil, causing adverse environmental effects on terrestrial ecosystems. Furthermore, chemicals may be taken up by plants and thus enter the food chain. Bioaccumulation may lead to adverse effects on higher trophic levels like animals and humans. Moreover, fecal contamination of water is one of the leading causes for infectious disease (WHO 2006), and wastewater reuse may increase the probability of direct contact of humans with wastewater or wastewater contaminated media, like soil or plants. In conclusion, the reuse of wastewater in agriculture has to be carefully managed in order to maximize benefits while minimizing potential adverse effects.

The World Health Organization states that *"the most effective means of consistently ensuring safety in wastewater use is through the use of a comprehensive risk assessment and risk management approach that encompasses all steps of the process […]"*((WHO 2006), p. 16, chap. 2.6, l. 4).

Therefore, it is an additional objective within the "CoDiGreen" project and the major topic of this report to *"initiate an environmental and health risk analysis of the sanitation scheme in Braunschweig […] based on the methodology of Waster Safety Plans"* (WSPs) (Lesjean et al. 2010).

Chapter 2

The WSP methodology applied to wastewater systems

The project objective of the initialization of an environmental and human health risk analysis based on the WSP methodology has to be concretized in order to define where the initialization starts and where it ends.

In order to do so, it is necessary focus on the background, objectives, principles and methodology of Water Safety Plans.

2.1 The Stockholm Framework and water-related guidelines

The name Stockholm Framework relates to the WHO publication *Water Quality: Guidelines, standards and health - assessment of risk and risk management for water-related infectious disease (Fewtrell and Bartram 2001).*

The focus of this document lies on water-related human health issues related to the exposure of microbial pathogens (disease-causing microorganisms). Although focusing on microbiological hazards, it can readily be applied to the exposure of toxic chemical agents as well (WHO 2006). The framework promotes a harmonized risk based approach for the assessment and management of water systems (Figure 1).

The application of risk-based methods shall lead to a more process based control of water systems, replacing the current practice of end-product quality testing. The main disadvantage concerning the latter one is that for example drinking water may already be distributed when a sample is identified to be of intolerable quality (Schmoll 2003).

The Stockholm framework promotes the so-called HACCP concept (Hazard Analysis and Critical Control Points). This management concept is already applied in the food industry. It determines critical control points during the production process in order to guarantee that the risk concerning identified hazards will be within the tolerable range.

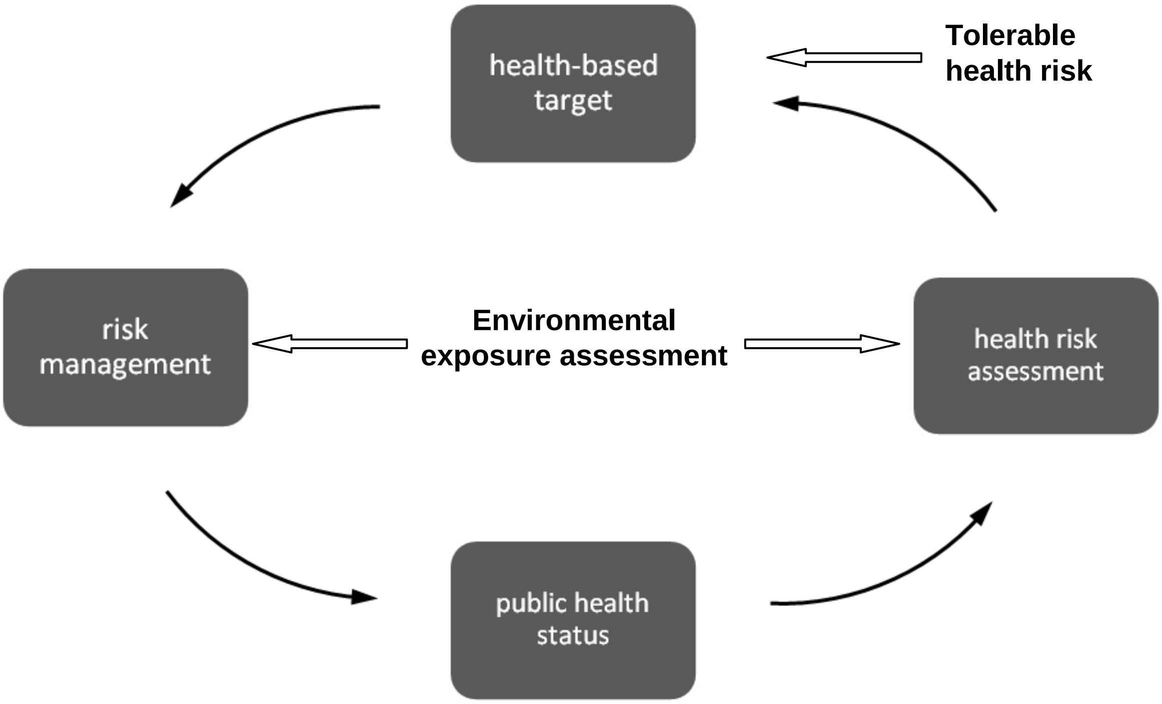


Figure 1: overview of the harmonized approach outlined in the Stockholm Framework on how to develop health-based guidelines and standards for the effective control of microbiological hazards in water and sanitation systems. (adapted from (WHO 2006))

At the basis of the Stockholm approach stands the assessment of health risks due to environmental exposure of humans to hazards related to the water system of interest as well as the derivation of tolerable (acceptable) health risks. Subsequently, health-based targets are set taking the current actual health risk as well as the derived tolerable health risk into account. In order to ensure and monitor those targets sound risk management plans have to be developed and, finally, its impacts on the overall public health status to be examined and evaluated.

Systems have to be periodically reassessed as conditions, scientific evidence or the availability of data change. The effectiveness of the implemented risk reduction measures has to be verified and the system might have to be completely reanalyzed if they fail to achieve the set health-based targets.

From this framework document the WHO derived guidance documents for the respective water sectors, namely the *Guidelines for Drinking-water Quality*, the *Guidelines for safe use of wastewater and excreta in agriculture and aquaculture* and the *Guidelines for safe recreational water environments*. The guideline documents apply the general approach of the Stockholm Framework to the specific water sectors.

The “Water Safety Plan concept” in turn is described and promoted in chapter 4 of the *Guidelines for Drinking Water Quality* published by the WHO in 2011 (WHO 2011) On this basis a Water Safety Plan Manual for practitioners was published to ease the application and implementation of the overall guideline document.
Figure 2 gives an overview of the hierarchic relationship between the different guideline documents. All of the guidance documents in the middle segment of
Figure 2 are based on the HACCP concept.

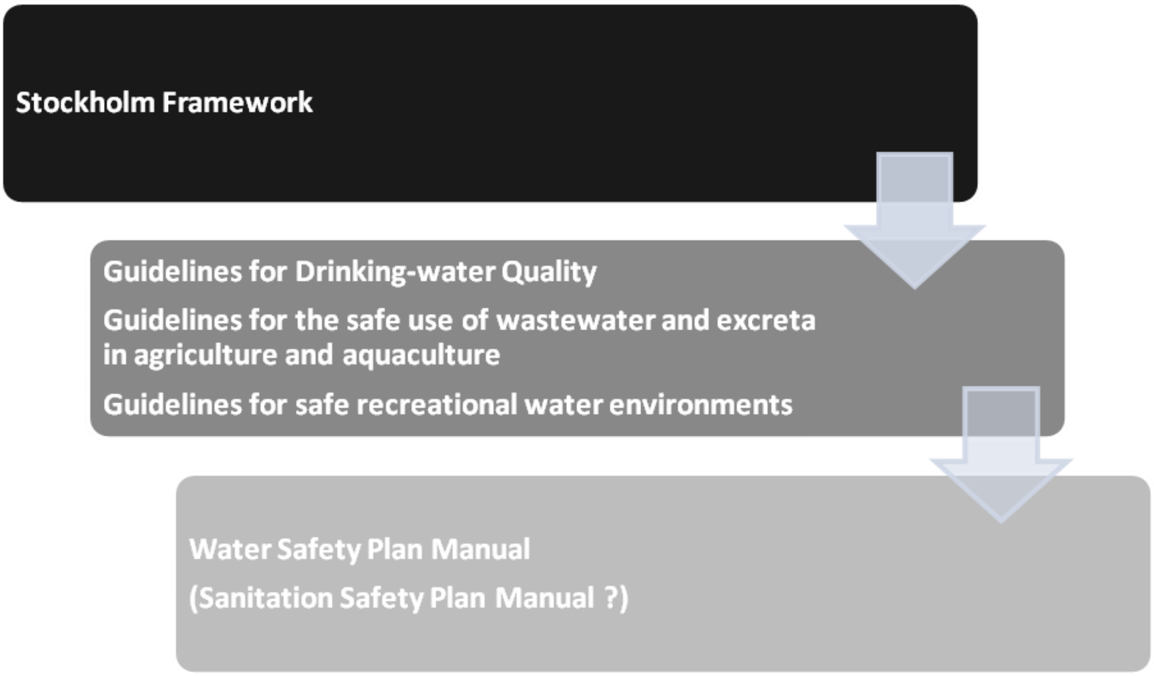


Figure 2: Hierarchy of guidance documents published by the World Health Organization (WHO)

2.2 From Water Safety Plans towards Sanitation Safety Plans

As mentioned above risk analysis in this report shall be initiated using the methodology of Water Safety Plans (WSPs). The focus of WSPs lies on drinking-water systems. The approach includes at least three steps.

A *system assessment* is necessary in order to determine if the water supply system is capable of delivering safe drinking water. This includes risk assessment and the assessment of reduction measures in place.

The introduction of effective *operational monitoring* for each reduction measure has the task to ensure that the performance target of the respective reduction measure is met and that underperformance is detected rapidly.

Finally, *management and communication plans* shall document the system under normal and incident conditions as well as document the system assessment, including upgrading and management options ((WHO 2011),chap.4).

Whereas WSPs are included in the *Guidelines for Drinking-water Quality,* the development of something like a Sanitation Safety Plan (SSP) has not yet been finished. SSPs would be the equivalent to WSPs concerning the sanitation and wastewater sector. A first approach towards Sanitation Safety Plans has been elaborated in a concept note by Barrenberg and Stenström in 2010 (Barrenberg and Stenström 2010). Within this note main similarities and differences between WSPs and SSPs are illustrated (Table 1).

Table 1: similarities and differences between WSPs and SSPs. This summary is adapted from the concept note of Barrenberg and Svenström in 2010 (Barrenberg and Stenström 2010)

Sanitation Safety Plans	Water Safety Plans
Similarities	
[To be] derived from the Guidelines for safe use of wastewater and excreta in agriculture and aquaculture	Derived from the Guidelines for Drinking-water Quality
Incremental risk analysis approach based on HACCP concept and the Stockholm Framework	Incremental risk analysis approach based on HACCP concept and the Stockholm Framework
Essential actions: • system assessment • operational monitoring • management	Essential actions: • system assessment • operational monitoring • management
Differences	
The systematic approach expands to downstream health and environmental effects	The systematic approach remains confined to the drinking-water supply chain
Considers multiple routes of exposure and multiple groups in relation to microbial and chemical risks	Focuses mainly on drinking-water ingestion, considering microbial, chemical and radiation risks
Objectives: • reduce the exposure and negative health and environmental impact of wastewater, excreta or greywater disposal and use • prevent wastewater from contaminating fresh water sources and produce	Objectives: • Prevent drinking-water of being contaminated

2.3 Scope of this report

As Sanitation Safety Plans have not yet been fully developed this report is based on the *Guidelines for the safe use of wastewater, excreta and greywater in agriculture and aquaculture* (WHO 2006), which translate the outcomes of the Stockholm Framework to their specific application in wastewater reuse systems.

Within the WHO guidelines' overall approach for ensuring acceptable water quality for irrigation, the assessment of the current system is the initial step (see Table 1, Figure 1).

This involves:

1. A description of the current system
2. Identification of hazards and assessment of risks against the background of present risk reduction measures

In order to assess present risks a variety of methods exists. Risk assessment can be conducted qualitatively or qualitatively. Quantitative methods in turn may be based on point estimates, probabilistic methods or fuzzy logic (Haas et al. 1999). Single methods are not concretized in the WHO guidelines. Moreover, the guidelines do not address quantitative environmental risk assessment.

Therefore, additional objectives of this report are to illustrate a methodological approach for the concrete implementation of the initial steps of the WHO guidelines by applying it to the concrete case of the wastewater reuse system of Braunschweig. Additionally, environmental risks shall be addressed.

Chapter 3

System description

Wastewater reuse has a long tradition in Braunschweig. The first irrigation fields (Rieselfelder) were constructed in 1895. Until 1954, these areas were used for the production of vegetables and cereals. Today they serve as an additional final treatment step of the sewage treatment plant (STP) Steinhof and as a water reservoir (Eggers 2008).

Since the population of the region grew the capacity of the irrigation fields of 100000PT (total number of inhabitant and population equivalents) did not suffice any more. Instead of enlarging existing irrigation fields, mechanically treated wastewater was from 1954 on used for irrigation of 3000ha of agricultural areas (Hartmann et al. 2010).

In 1979 the sewage treatment plant Steinhof was built. Today, solely purified wastewater and treated sewage sludge is used for agricultural irrigation. Figure 3 gives an overview of the wastewater reuse area.

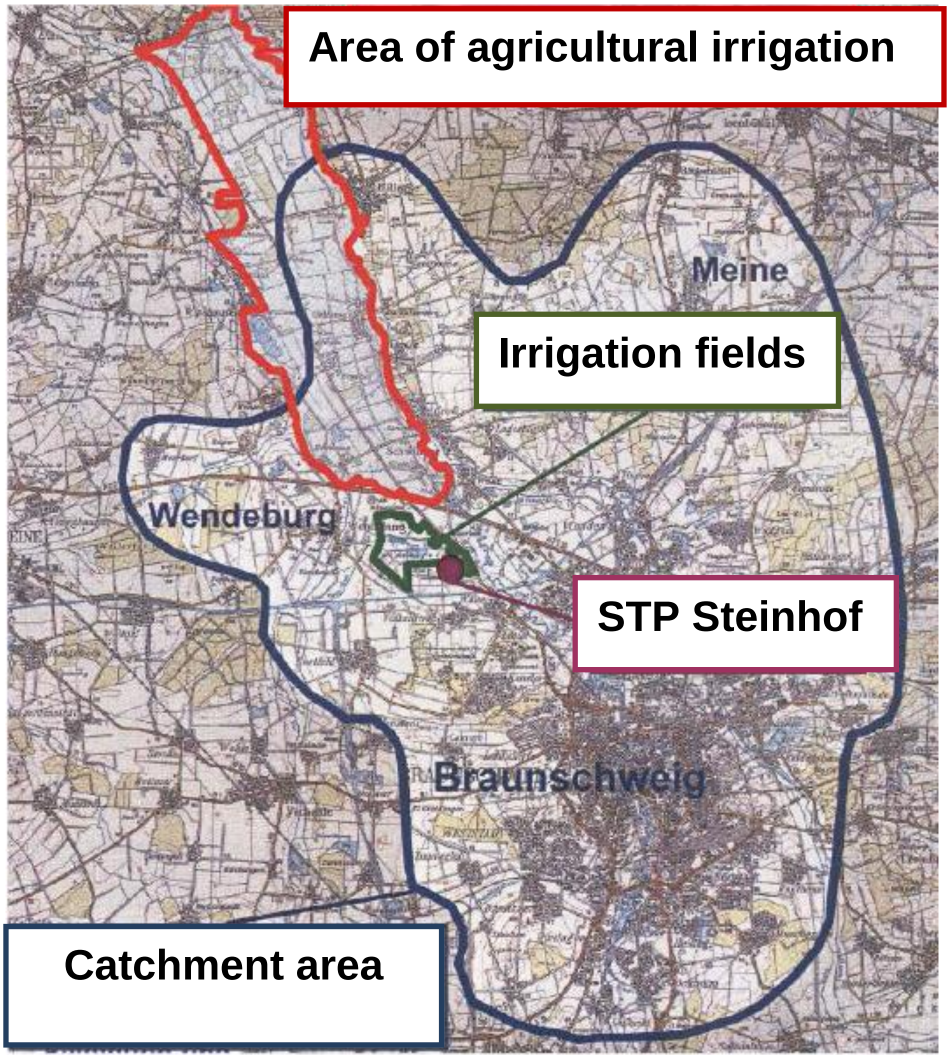


Figure 3: wastewater reuse area of Braunschweig, including the sewage treatment plant (STP) Steinhof, irrigation fields and the area of agricultural irrigation.

3.1 Current practice

The STP has a capacity of 350,000PT and treats an average volume of 21,000,000 m³ wastewater each year. The treatment plant includes primary sedimentation as well as activated sludge treatment for the removal of bulk organic carbon. The nutrients nitrogen and phosphorus are partially removed biologically. Two third of the treated wastewater, an average amount of 15,000,000m³ per year, is used for the irrigation of the 3000ha of agricultural area of the sewage association Braunschweig (AVBS). The remaining third enters irrigation fields as a final treatment step, before it is discharged into the Aue-Oker-Canal.

The produced sludge from primary sedimentation and the activated sludge process is digested in an anaerobic treatment step in order to reduce its volume as well as to generate methane, which is used for energy production. During summer the digested sludge is mixed with the effluent of STP and is used for the irrigation of agricultural areas. In winter the sludge is dewatered and used as fertilizer on agricultural areas other than the ones of the AVBS. By this practice about 50-60% of the annually produced sludge is applied to the area of the AVBS (Ripke). The current practice of the wastewater treatment and reuse system of Braunschweig is illustrated in **Fehler! Ungültiger Eigenverweis auf Textmarke.**.

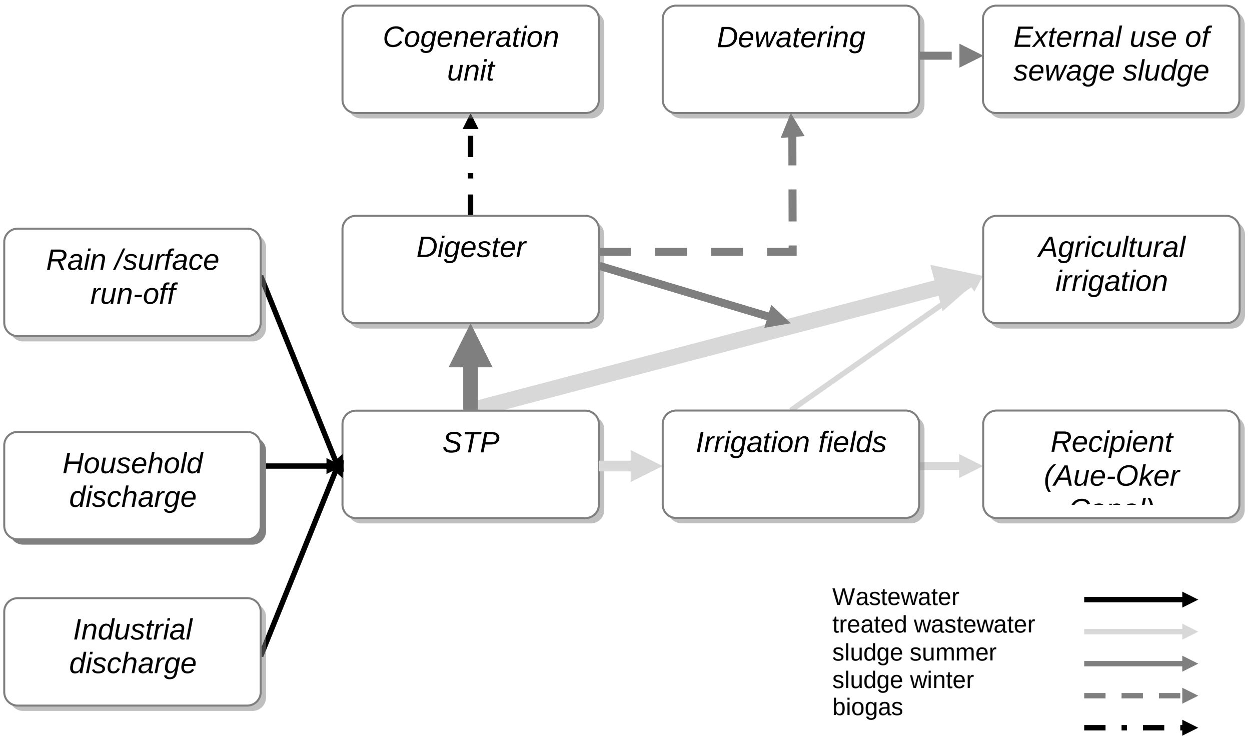


Figure 4: current practice of the wastewater reuse concept of Braunschweig. The thickness of the arrows for water and sludge streams indicates the volume factions of the respective flows (adapted from (Hartmann et al. 2010))

3.2 Agricultural practice

On the agricultural areas of the AVBS wastewater irrigation is restricted, meaning that on these areas no products are grown, which are consumed without further processing. The composition of the grown products is illustrated in Table 2.

Table 2: agricultural products grown on the areas of AVBS in the year 2007 (Ripke).

Product	Percentage
Corn	38
Cereals	30
Potatoes	6
Sugar beet	19
other	7

The majority of the crops are used as energy crops in biogas production. About 1% of the produced corn is used as fodder for milk producing animals. Cereals are also used for bread production (Ripke, personal correspondence).

3.2.1 Legislative boundaries

The legislative permission for wastewater reuse in BS is given by the district government of Braunschweig (Weikert 2001). According to this permission a maximum amount of 60000m³ can be used for irrigation each day. From November 15th to January 31st no sewage sludge may be distributed. In February sludge distribution depends on weather conditions.

Wastewater may just be used for irrigation if no odor problems occur and if it is at least partly treated (chemical oxygen demand (COD) ≤ 75mg/l). For irrigation in winter COD values have to be ≤ 50mg/l.

Moreover, the permission defines minimum distances between the irrigation machine and the landed properties of local residents. The minimum distance depends on the size of the nozzle outlet of the irrigation machine, wind direction and the presence of protective hedges.

Table 3: minimum distances from landed properties of local residents in dependence of the diameter to the nozzle outlet of the irrigation machine as well as to the presence of protective hedges.

Diameter nozzle outlet [mm]	Minimum distance [m] (Protective hedges)	Minimum distance [m] (No protective hedges)
16-24	115	150
10-16	30	100
0-10	10	60

The fieldworkers in charge of the irrigation management, so-called Regenmeister, have to carry wind speed analyzers to optimize irrigation and to prevent that wastewater is carried out of the areas of the AVBS.

3.2.2 System boundaries of this assessment

The extensive use of treated effluent in addition to digested sludge makes the wastewater reuse scheme of BS unique in Germany. Although in the neighboring city of Wolfsburg (WOB) a similar concept exists, there are no products grown in WOB, which are used as fodder for animals or which are consumed by humans.

As treated wastewater as well as digested sludge contains both microbiological and chemical agents the following questions shall be addressed in this report:

1. Does the extensive use of treated effluent and digested sludge lead to intolerable risks for human health due to pathogens?
2. Does the extensive use of treated effluent and digested sludge lead to intolerable risks for human health due to chemical agents?
3. Does the extensive use of treated effluent and digested sludge lead to intolerable risks for the terrestrial ecosystem due to chemical agents?

Before conducting hazard identification and risk assessment, first, the necessary theoretical background on risk and risk analysis shall be provided.

Chapter 4

Theoretical Background-Risk analysis

This section provides the necessary background information on risk, risk assessment, tolerable risk as well as on health based and environmental targets. Furthermore, important idioms will be explained.

4.1 Hazards and Risk

Risk is a term which is used in different contexts like economy, technical processes, public health or environmental safety. In general, risk always relates to a certain system, process or action, which has a certain objective.
The objective of an investment may be the increase of productivity and/or the generation of profit. The objective of the technical process of drinking water treatment may be to guarantee a certain water quality without generating too many costs. Actions in the areas of public health and environmental safety have the objective to ensure a certain level of health and environmental protection.

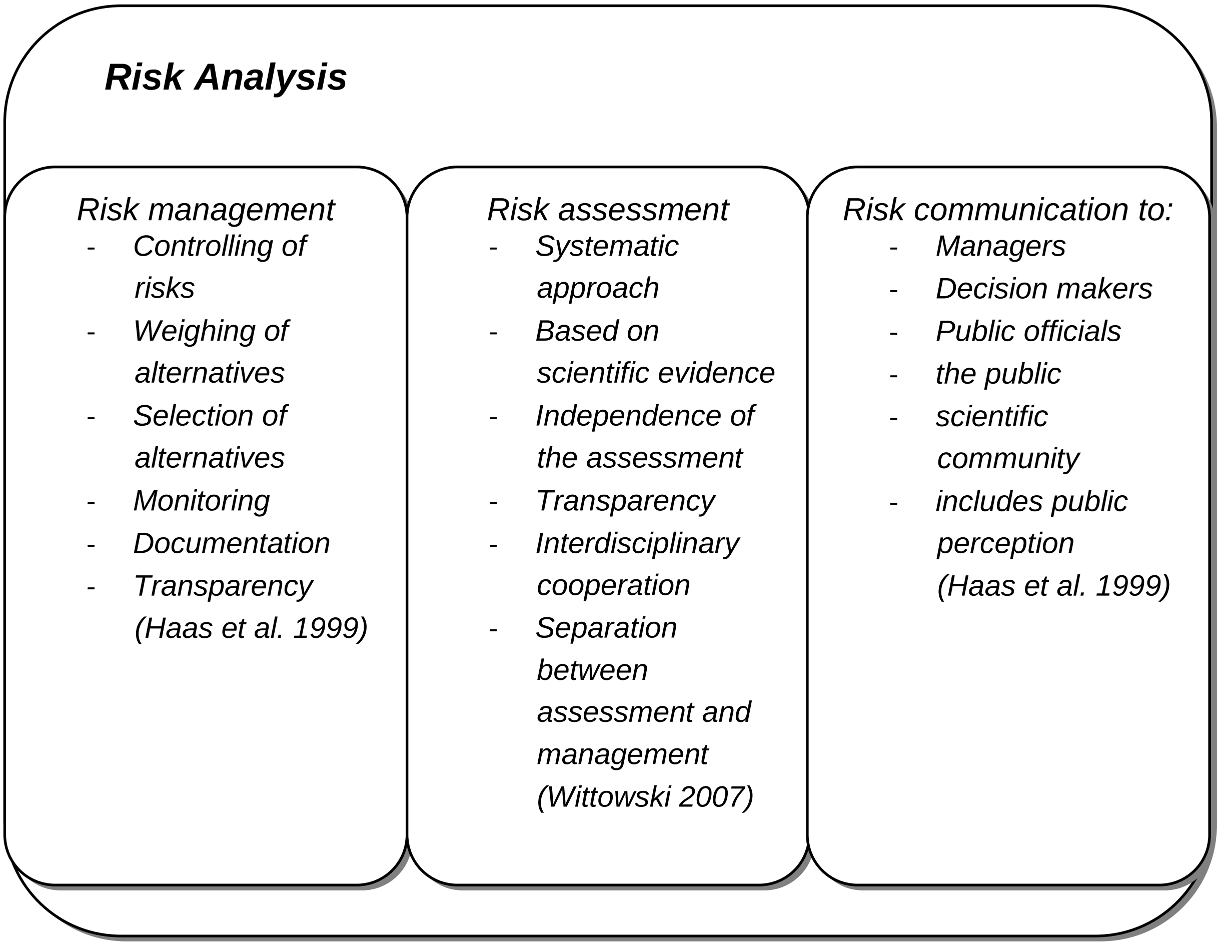
A ***hazard*** is an event, a condition, a chemical or microbial agent which may cause a failure of the system or action, meaning that it is no longer capable of fulfilling its respective objective. A drastic example of a hazard concerning the economic area may be a stock market crash like in 2008. Referring to the technical sector a malfunctioning component may have the consequence that the required performance is not achieved.
For the area of human health the European regulation EC 178/2002 which deals with matters of food safety defines a hazard as *“a chemical, biological or physical agent in, or condition of, food or feed with the potential to cause an adverse health effect”(EU 2002).*
Thus, in the broader context of public health and environmental safety hazards are chemical, biological and physical agents, which potentially cause at least one adverse effect on the environment and/or human health.

Against this background *“**risk** (R) is a function of the probability (P) of an adverse health* [or environmental] *effect and the severity (S) of that effect, consequential to a hazard” (EC 178/2002,(EU 2002))*, or mathematically:

$$R(P,S) = P * S$$

4.2 Risk analysis

The term ***risk analysis*** *“includes risk assessment, risk management, and risk communication”* ((Haas et al. 1999), chap. 3, l. 9). The single parts in turn include certain methods and objectives (Figure 5).



Risk Analysis

Risk management

- *Controlling of risks*
- *Weighing of alternatives*
- *Selection of alternatives*
- *Monitoring*
- *Documentation*
- *Transparency*

(Haas et al. 1999)

Risk assessment

- *Systematic approach*
- *Based on scientific evidence*
- *Independence of the assessment*
- *Transparency*
- *Interdisciplinary cooperation*
- *Separation between assessment and management*

(Wittowski 2007)

Risk communication to:

- *Managers*
- *Decision makers*
- *Public officials*
- *the public*
- *scientific community*
- *includes public perception*

(Haas et al. 1999)

Figure 5: different components of risk analysis. Within the three smaller boxes objectives and characteristics for the management, assessment and communication of environmental and human health risks are listed.

Risk assessment is a science-based, systematic approach in order to quantitatively or qualitatively assessing risks resulting from specific hazards. As various fields of study are often involved in the assessment of certain risks, risk assessment is dependent on interdisciplinary cooperation. Risk assessment is always part of ***risk communication***. Therefore, it has to be written in a transparent and understandable manner, so that the information is accessible to all relevant stakeholders (Wittowski 2007). In order to ensure objectivity in risk analysis, risk assessment should be independent from ***risk management***. The purpose of the latter one is to select, plan, establish and monitor risk reduction measures. In order to decide if additional risk reduction measures are necessary the present risks have to be quantified and compared to a level of risk which is considered to be acceptable or tolerable.

4.3 Tolerable/acceptable risks

Setting levels of tolerable risk may be done through the use of different indicators or measures depending on the type of hazards (chemical, microbial) and the respective endpoint (environment, humans).

4.3.1 Tolerable health risk

The WHO's approach towards a level of tolerable health risk concerning microbial hazards is based on the DALY measure as a metric for expressing the burden of disease within a population. DALY stands for *"disability adjusted life years".*

The DALY is a health gap indicator for the status of health of a population expressed as burden of disease due to a specific disease or risk factor (Alan D. Lopez 2006). The DALYs caused by a specific disease or risk factor are calculated by:

$$DALY = YLD + YLL$$

YLD are the years lived with disability and YLL are the years of life lost through premature mortality due to the respective disease. In other words, the DALY is the sum out of the morbidity (YLD) and the mortality (YLL) caused by a specific disease (Alan D. Lopez 2006).

The calculation of YLL essentially accounts for the number of cases or incidents of a specific cause (*c)* of death, sex (*s)* and age (*a)*. The number of incidents (N) is multiplied with the so-called loss function (L), which is a function of age and sex.

$$YLL(c,a,s) = N(c,a,s) * L(a,s)$$

The loss function defines the standard life expectancies for various age groups in so-called standard life tables. The standard life expectancy for newborns is set to 82.5 years for females and 80 years for males, which is the highest observed life expectancy observed in the mid-nineties (Japan).

The YLD is calculated by multiplying the number of cases of disease (C), the average duration of the disease (D) and a severity factor (SF), which ranges from 0 (perfect health) to 1 (death). The weights used account mainly for the objective adverse effects on body functions and the loss of quality of life (Alan D. Lopez 2006).

$$YLD(c,a,s) = C(c,a,s) * SF(c,a,s) * D(c,a,s)$$

By the use of severity factors for different diseases, the DALY indicator makes different health outcomes comparable.

The DALY indicator can be used to set a level of tolerable risk. As adverse health effects lead to additional DALYs, a tolerable level of risk is expressed by a tolerable number of additional DALYs.

For drinking water WHO considers an additional burden of disease of $\leq 10^{-6}$ DALYs per person per year (pppy) to be safe. This corresponds to an additional risk of developing fatal cancer due to drinking water consumption of 10^{-5} (one in 100000) or a mild illness which occurs more often. For a mild diarrhea the additional risk of disease which corresponds to an additional burden of disease of 1µDALY is 10^{-3}pppy ((WHO 2006), chap. 4.1). The WHO states that concerning wastewater use *"the overall levels of health protection should be comparable with those for other water-related exposures"* ((WHO

2006), chap.2.4, I.3). Thus, within the WHO wastewater guidelines the level of tolerable risk is also set to 1 additional µDALY per person per year.

For human health risks due to the exposure to chemical substances tolerated levels are most commonly expressed as tolerable daily/weekly intake or acceptable daily/weekly intake (TDI, TWI, ADI, AWI). Moreover, the safety parameters upper intake level (UL) and margin of exposure (MOE) are used. The values are the result of toxicological studies and define the dose of a chemical below which adverse health effects are considered not to occur.

4.3.2 Tolerable environmental risk

Levels of tolerable environmental concentrations of a substance are the result of eco-toxicological testing. Commonly used measures of eco-toxicological test are:

- No Observed Effect Concentration (NOEC): concentration up to which no adverse effect was observed
- Lethal concentration 50 (LC50): concentration at which 50% of the exposed test organisms die
- Effective concentration 50 (EC50): concentration at which 50% of the test organisms show adverse effects

The WHO wastewater guidelines do not cover environmental issues in detail. In the *European Union Technical guidance document on Risk assessment (TGD)* the so-called Predicted No-Effect-Concentration (PNEC) is used, which is derived from the eco-toxicological measures above (EU 2003). The PNEC is the concentration in a certain compartment below which an adverse effect is considered to be unlikely.

In order to derive the PNEC additional assessment factors are applied to the outcomes of the eco-toxicological tests. The value of the respective assessment factor of a certain substance depends on the amount of conducted eco-toxicological tests and the number of covered trophic levels. Thereby uncertainties concerning the transfer of laboratory results to the real environment are considered. PNEC values are substance and endpoint specific.

Table 5 and
Table 4 illustrate how PNEC values for water and soil are derived from eco-toxicological data. For a more detailed description of how to derive PNEC values for the respective endpoints see (EU 2003) pp. 93-131.

Table 4: derivation of PNEC values for the aquatic compartment from eco-toxicological results (EU 2003).

Available data	Assessment factor
At least one short-term L(E)C50 from each of three trophic levels of the baseset (fish, Daphnia and algae)	1000
One long-term NOEC (either fish or Daphnia)	100
Two long-term NOECs from species representing two trophic levels (fish and/or Daphnia and/or algae)	50
Long-term NOECs from at least three species (normally fish, Daphnia and algae) representing three trophic levels	10
Species sensitivity distribution (SSD) method	5-1(to be fully justified case by case)
Field data or model ecosystems	Reviewed on a case by case basis

Table 5: derivation of PNEC values for the soil compartment from eco-toxicological results (EU 2003).

Available data	Assessment factor
L(E)C50 short-term toxicity test(s) (e.g. plants, earthworms, or microorganisms)	1000
NOEC for one long-term toxicity test (e.g. plants)	100
NOEC for additional long-term toxicity tests of two trophic levels	50
NOEC for additional long-term toxicity tests for three species of three trophic levels	10
Species sensitivity distribution (SSD method)	5 – 1, to be fully justified case-by-case
Field data/data of model ecosystems	case-by-case

4.4 Risk assessment

As explained in the previous section, risk refers to different kinds of hazards in different areas. At this place, focus is put on the assessment of environmental and human health risks, due to chemical and microbial hazards. Risk assessment can be conducted quantitatively, semi-quantitatively or qualitatively. The main purpose of risk assessment in the context of the WHO guidelines is to compare the outcomes to the level of tolerable risk and to derive operational health-based and environmental targets.
The basic structure of any human health or environmental risk assessment consists of four steps.

- Hazard identification
- Hazard characterization
- Exposure Assessment
- Risk characterization

4.4.1 Hazard identification

The purpose of hazard identification is to build a causative correlation between a certain chemical or microbiological agent and a certain adverse effect for human health or the environment (disease, eco-toxic effects). This field of study is covered by numerous disciplines, like clinical microbiology, epidemiology, environmental chemistry and toxicology ((Haas et al. 1999), chap. 4). The objective is to give a detailed description of the mechanisms and the cause of the actual adverse effect, e.g. the adverse health effect due to an EHEC infection (enterohemorrhagic *Escherichia Coli)* is not due to the infection itself but due to the toxins the organism produces. Furthermore, hazard identification includes the detection of a specific hazard in the system of interest, e.g. a sewage treatment plant.

4.4.1.1 Microbial hazards in wastewater systems

Municipal wastewater contains a variety of microbial agents, like viruses, bacteria and protozoa, which are capable to cause adverse human health effects (Klages et al. 2009). Table 6 gives an overview on detected pathogens in wastewater. The task of hazard identification is to identify pathogens present in the specific wastewater system.

Table 6: overview of selected viral, bacterial and protozoan pathogens found in wastewater (WHO 2006, chap. 2.7.1)

Agent	Disease
Viruses	
Adenovirus	Respiratory disease, eye infections
Astrovirus	Gastroenteritis
Calicivirus	Gastroenteritis
Coronavirus	Gastroenteritis
Coxsackievirus A and B	Herpangina, aseptic meningitis, respiratory illness, fever, paralysis, respiratory, heard and kidney disease
Echovirus	Fever, rash, respiratory and heard disease, aseptic meningitis
Enterovirus	Gastroenteritis, various
Hepatitis A and E	Infectious hepatitis
Norovirus	Gastroenteritis
Parvovirus	Gastroenteritis
Poliovirus	Paralysis, aseptic meningitis
Reovirus	Not clearly established
Rotavirus	Gastroenteritis
Bacteria	
Campylobacter jejuni	Gastroenteritis, long-term sequelae (e.g. arthritis)
Escherichia Coli	Gastroenteritis
EHEC	Bloody diarrhea, haemolytic-uraemic syndrome (HUS)
Leptospira spp.	Leptospirosis
Salmonella	Salmonellosis, Gastroenteritis, diarrhea, long-term sequelae (e.g. arthritis)
Shigella	Shigellosis (dysentery), long-term sequelae (e.g. arthritis)
Vibrio cholera	Cholera
Yersinia enterocolitica	Yersiniosis, Gastroenteritis, long-term sequelae (e.g. arthritis)
Protozoa	
Cryptosporidium parvum	Cryptosporidiosis, diarrhea, fever
Giardia intestinalis	Giardiasis

4.4.1.2 Chemical hazards in wastewater systems

Wastewater contains both organic and inorganic chemical agents, which may cause adverse environmental human health and/or environmental effects. Major inorganic hazards are heavy metals (Table 7).

Table 7: relevant heavy metals in wastewater

Metal	Chemical symbol
Cadmium	Cd
Copper	Cu
Chromium	Cr
Lead	Pb
Mercury	Hg
Nickel	Ni
Zinc	Zn

The identification of organic hazards is less straightforward. This has several reasons:

- The number of substances is extremely high
- Organic substances may transform in the environment to unknown more hazardous substances
- The effect of some organic substances may be high even at low concentrations (e.g. endocrine disruptors)
- Organic substances are hard to detect at low concentrations
- The application and thus the sources of organic substances are very divers (medical products, cleaning agents, personal care products, solvents etc.)
- Environmentally adverse effects are often unknown

4.4.2 Hazard characterization

After a certain agent is identified as a hazard, the step of hazard characterization collects information on its characteristics, e.g. distribution, physic-chemical properties, main sources of emission (Henning et al. 2010). A crucial point of this step is to determine dose-response relations, or concentration-effect relations. Within this procedure it is determined, at which concentrations or doses an adverse effect occurs and if there is a threshold level below which no adverse effect will result. Again, numerous fields of research may be involved in this process, like chemistry, microbiology and immunology.

4.4.2.1 Dose-response relations of pathogens

Dose-response relations of pathogens build a mathematical functional relationship between the number of pathogens someone is exposed to and the probability of the specific adverse effect. The functional relation is pathogen specific. The values for probability lie between zero (no adverse effect) and one (adverse effect is certain). The probability may relate to different outcomes, like infection, illness or death. Someone is infected if the pathogen multiplies inside the body. Infection may be detected by examining the presence of the pathogen within the feces or the development of antibodies. A fraction of the infected people may develop illness like fever or gastroenteritis (morbidity ratio). Infectious where no symptoms occur are called asymptomatic. A certain percentage of the illness developing people will die (mortality ratio). Dose-response assessment focuses mainly on the early step of infection ((Haas et al. 1999), chap.7).

The simplest dose-response model is formulated by an exponential relationship.

$$P_I(d) = 1 - e^{-r*d}$$

$$-r = \frac{\ln(0.5)}{N_{50}}$$

$P_I(d)$ = probability of infection

d = dose

r = infectivity constant

N_{50} = median infectious dose

The exponential model assumes that the probability of infection is constant for all pathogens of the same kind as well as for all people exposed to that kind of pathogen (Haas et al. 1999).

In reality not all pathogens of the same species are equally infective. Moreover, not all human show the same response on the exposure of the same amount of a certain pathogens. Old people as well as children may have a less strong immune system than adults. Consequently, they will be more easily become infected than an adult person. In order to consider such variations other functional relations are used. Often, the Beta-Poisson-model finds application.

$$P_I(d) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)} \sum_{j=1}^{\infty} \left(\frac{\Gamma(\alpha+j)}{\Gamma(\alpha+\beta+j)} * \frac{(-1)^{j-1} * (d)^j}{j!} \right)$$

α, β = Beta-Poisson model parameters

d = dose

(Furumoto and Mickey 1967) approximated the above equation to:

$$P_I(d) = 1 - \left(1 - \frac{d}{\beta}\right)^{-\alpha}$$

The approximation holds true for β ≥ 1 and α ≤ β (Susan Petterson 2006) and low pathogen exposure. The approximation can be rewritten as:

$$P_I(d) = 1 - [1 + \frac{d}{N50}\left(2^{\frac{1}{\alpha}} - 1\right)]^{-\alpha}$$

A more complicated formulation for the dose-response relation, using a confluent hypergeometric function was published by (Teunis et al. 2008) for the infectivity of Norovirus.

$$P_I(d, a, \alpha, \beta) = {}_2F_1\left(\alpha; \frac{-d}{\log(1-\alpha)}, \alpha + \beta, \frac{-a}{1-a}\right)$$

d = dose

α, β = model parameters

a = constant for the aggregation of virus particles

4.4.2.2 Dose-effect / concentration-effect relations of chemicals

The toxicological properties of chemicals are examined via toxicological testing. Outcomes are expressed as tolerable daily/weekly intakes (TDI, TWI etc.) for humans and as EC50, LC50, NOEC values for eco-toxicological surveys (see section 4.3.1 and 4.3.2). The derivation of direct correlations between the exposure to a certain concentration and a specific effect is difficult as not only short-term acute effects but also long- term chronic effects due to the exposure of low chemical doses have to be considered. Moreover, humans and environment are simultaneously exposed to a variety of different substances. Thus, an observed adverse effect is hard to correlate to one specific substance. Currently, dose-effects concentrations refer to the exposure of one specific substance at one specific endpoint.

4.4.3 Exposure Assessment

The purpose of the step of exposure assessment in quantitative risk assessment is to predict the fate of a hazard from its source to the endpoint of interest and the quantity this endpoint is exposed to. Endpoints are points in the modeling process at which the risk is assessed, e.g. the endpoint of human exposure assessments are humans. Concerning the environment, multiple endpoints may be of interests, like surface waters, soil or atmosphere. A main difference between human and environmental exposure assessment is that human exposure assessment calculates the dose a human being is exposed to, whereas environmental exposure assessment calculates concentrations of soil, water or food related to the specific endpoint.

4.4.3.1 Human exposure to microbial hazards via wastewater reuse

This process analyses the different exposure routes of microbial hazards released into the environment via wastewater reuse and their transmission to humans. The main objective is to determine the dose of the respective agents, which people are exposed to. Different groups of people can be exposed to hazards through different pathways (Figure6) (WHO 2006).

Fieldworkers and local communities might be exposed through direct contact with wastewater or wastewater contaminated soil or crops. Furthermore, these groups of people may inhale or ingest wastewater and soil aerosols which contain hazards, especially when sprinkler irrigation is used (WHO 2006). Concerning local communities, children playing on agricultural areas have to be considered as well. Depending on the age, this population group may ingest a higher amount of soil as adults do.

The third group of people which can be exposed to hazards due to wastewater irrigation is the consumers of food, grown on wastewater irrigated fields, drinking water, whose source is influenced by wastewater or animals and animal products, which were contaminated through the application of wastewater.

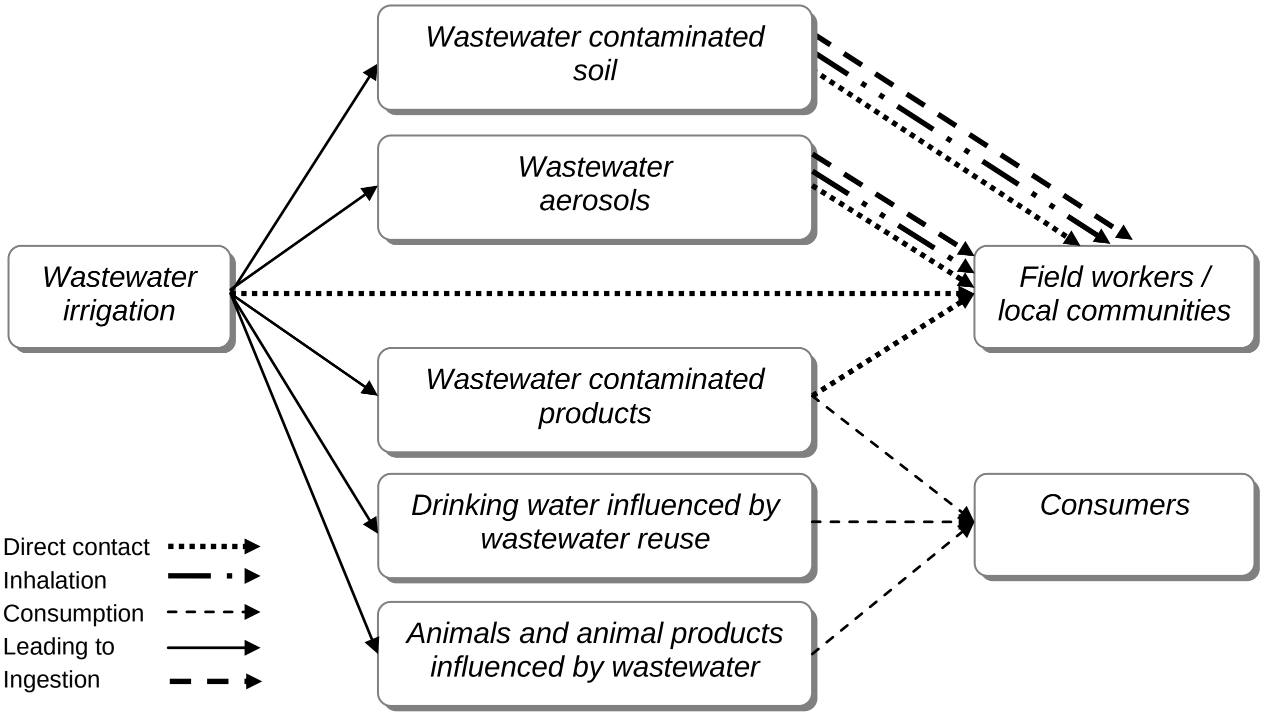


Figure 6: possible exposure of different groups of people to microbial agents due to wastewater irrigation (WHO 2006, chap. 2.2).

4.4.3.2 Exposure of humans and environmental endpoints to chemicals

Once released into the environment chemicals distribute between the different environmental compartments leading to direct adverse effects on these compartments as well as on the organisms living in the respective compartments. Moreover, chemical agents might accumulate through the food chain. Thereby indirect adverse effects to human and animals may result.
Figure 7 illustrates the different fluxes of chemicals agents as well as its direct and indirect effects on humans, animals and ecosystems

Concerning wastewater treatment and irrigation the terrestrial and aquatic ecosystem are of special interest. For these ecosystems, Table 8 summarizes the endpoints and receptors of major concern (Schütze and Spranger 2002)

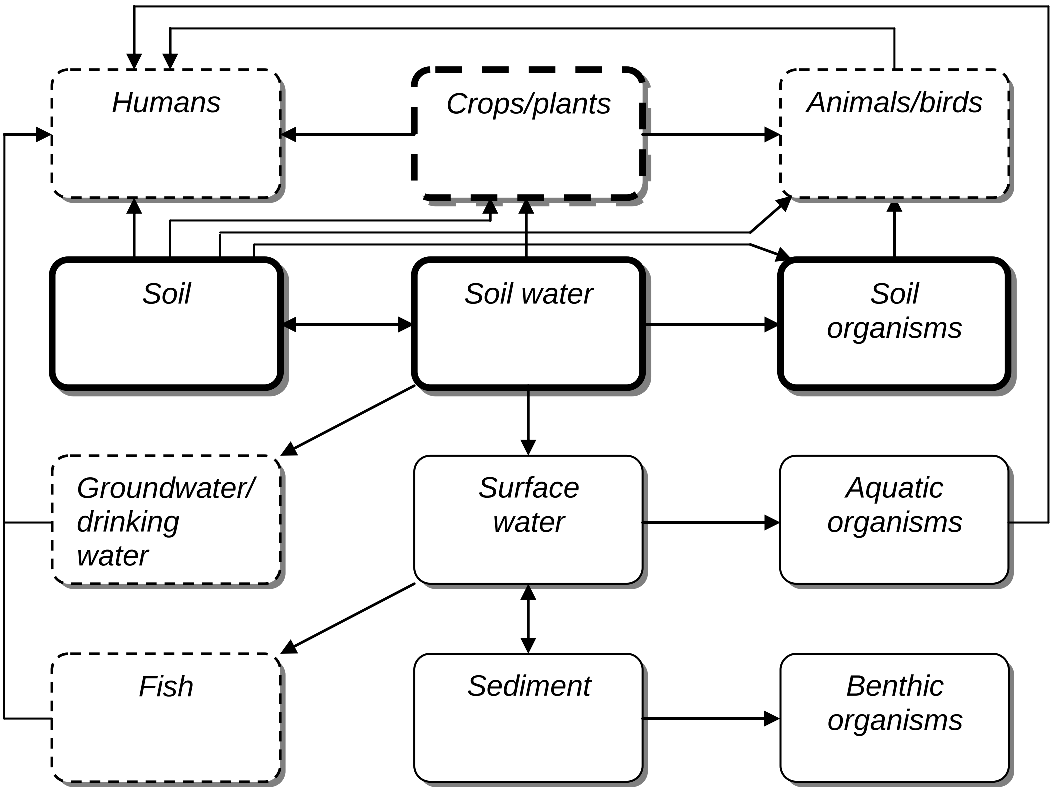


Figure 7: different fluxes and endpoints of chemicals in the environment. Fat frames indicate direct effects on terrestrial ecosystems. Normal solid frames relate to direct impacts on aquatic ecosystems. Dotted frames indicate indirect impacts on human health and animal health due to food chain accumulation. [adapted from ((Schütze and Spranger 2002), p. 32].

Table 8: relevant receptors and the related endpoints of concern for the ecosystems arable land and surface waters [adapted from (Schütze and Spranger 2002), p.33]

Receptors of concern	Type of ecosystem	
	Arable land	Surface waters
Ecosystem (direct effects)		
Soil microorganisms	+	-
Soil invertebrates	+	-
Algae, crustacea	-	+
Human health/animal health (indirect effects)		
Food crops (humans)	+	-
Fodder crops (animals)	+	-
Groundwater (humans)	+	-
Birds/mammals	+	-
Fish (humans)	-	+

4.4.4 Risk characterization

Risk characterization includes all the information of the three previous steps in order to estimate the magnitude of the human health or environmental risk ((Haas et al. 1999), chap. 3). Furthermore, risk characterization evaluates variability and uncertainties within this estimate.

The terms variability and uncertainty refer to the problem of imprecise or not reliable data, which might lead to errors in the overall result. Because of a lack of data, often assumptions have to be made for different scenarios. Variability refers to assumptions in the model, which cannot be improved by further investigation, like human behavior or the analytical error of a specific chemical analysis. Uncertainties on the other hand refer to variations and assumptions within the model, which can be improved by further investigations. There are a variety of methods which can be used for risk characterization. Uncertainties may be discussed on a qualitative basis. Quantitative approaches include methods like Monte Carlo Simulation, sensitivity analysis as well as the calculation of risk quotients. All of these approaches will find application within this report.

4.4.4.1 Risk characterization of microbial hazards

Concerning human health risks due to pathogen exposure risk can be characterized by combining exposure assessment and dose-response models. The risk is expressed as a concrete value for the probability of infection, like 10^{-3} per person per year (pppy). This value is equivalent to one infection per person in 1000 years, one infection per 1000 people each year or 1000 infections per million people each year. Early approaches of quantitative microbial risk assessment (QRMA) were based on point estimates and thus resulted in a single value of risk. In recent years this approach was replaced be the use of Monte Carlo Simulations (MCS) as a more sophisticated probabilistic modeling technique (Drechsel et al. 2010).

The name Monte Carlo Simulation refers to the extensive use of random variables. Instead of calculating risk using point estimates the whole distribution of the respective model parameter is used for calculating risk. This manner of modeling leads to a full risk-distribution instead of a single value. By using the method uncertainties and variability are taken into account. Moreover, more vulnerable groups like children and old people may be considered, by using an upper confidence limit for assessing the risk instead of the mean or median value.

4.4.4.2 Risk characterization of toxic chemicals

Concentration-effect relations concerning chemical exposure are not as clearly mathematically described as pathogen dose-response relations as a single chemical may have various effects on various endpoints. Therefore, risk characterization of chemical exposure is conducted by calculating the ratio between the concentration the respective endpoint is exposed to and the tolerable concentration or dose (PNEC, TDI) for the respective endpoint (see section 7.4). This ratio is called risk factor (RF) or risk quotient (RQ). The result of a risk characterization which is conducted in this manner is “risk” ($RQ > 1$) or “no risk” ($RQ \leq 1$). Uncertainties and variability may be addressed by various methods and validation techniques.

4.5 Risk-based targets

To set risk-based targets the present level of health and environmental risk is compared to the derived tolerable level of risk. Targets are set in a way to reduce the level of risk below the tolerable value. If the actual level of risk is equal or already below the tolerable level no further targets have to be set. Risk-based targets can be different in character. They may be expressed through:

- environmental or public health outcomes, e.g. achievement of a certain surface water quality or incidence reduction of a certain disease
- wastewater quality (concentrations of chemicals or pathogens in the effluent of the STP)
- performance, like removal of pathogens or chemical during wastewater treatment
- a certain technology or process parameters, like minimum temperatures during sludge digestion (WHO 2006)

Chapter 5

Hazard identification and selection

As mentioned in the previous section wastewater contains a variety of different chemical and microbiological agents which potentially cause adverse effects on the environment and human health. Nevertheless, the purpose of this report is to quantify the risks which are the direct result of the extensive reuse of wastewater, which is the major difference of the BS - concept to other wastewater treatment schemes. Thus, some of the potential hazards can be excluded from this risk assessmentasthey are not specific for the BS-concept.
Table 9 summarizes the selected hazards for this risk assessment and gives reason why the specific hazard was selected.

Table 9: Summary and selection of hazards for this report

Hazard	Selected for risk assessment	Reason	Monitoring data available
Pathogens	yes	Wastewater contains a variety of human pathogens which can cause illness in people, and thus pose a direct risk for human health. There is no further treatment step which could reduce to number of pathogens in the STP's effluent	No, but scientific literature allows reasonable assumptions
Heavy metals (HM)	yes	HM are not removed by wastewater treatment and tend to accumulate in soil. Toxic effects are known	Yes, extensive monitoring data available for STP Steinhof as well as for soil contents on the agricultural areas
NO_3	No	The amount of N applied via WW is not sufficient to meet the agricultural demand. The majority of N is added via fertilizers. (Ripke, personal correspondence) Thus, a potential NO_3 contamination of groundwater is not a specific result of WW reuse	Yes, extensive monitoring data available for the STP Steinhof as well as for the drainage waters of the agricultural areas
Soil salinization	No	According to the AVBS, 60 years of WW-application did not lead to salinization problems (Ripke, personal correspondence)	No monitoring data

Pesticides	No	It is assumed that the amount of pesticides directly applied by agriculture exceeds the amount which is applied by WW. Thus, it is not a specific problem of WW reuse	No monitoring data available
Emerging substances (residues of medical products, endocrine disruptors, veterinary medical products)	No	Although this group of chemicals **may pose a significant risk for ecosystems**, there is still a lack of information concerning the chronic effects of low concentrations, on which robust statements could be based. Moreover, the alternative of discharging the STP's effluent into the Aue-Oker Canal would simply transfer the potential impacts from the soil ecosystem towards the freshwater ecosystem.	Single studies on emerging substances available. Since measurements of trace organics is difficult the data lack appropriateness for a robust risk assessment
Other organic compounds (PAK, BETX, Dioxins…)	No	As these substances show an affinity to accumulate in sewage sludge during wastewater treatment, the issue of these chemical is more an issue of agricultural sludge application in general, than a specific risk of the reuse system of BS. It is thus beyond the boundaries of this report	Single studies and measurements available

Chapter 6

Quantitative Microbial Risk Assessment (QMRA)

Wastewater contains a variety of microbial hazards. Because of its high incidence diarrhea infections are assumed to function as a proxy for all infectious diseases (WHO 2006). As a microbial analysis of the wastewater in Braunschweig has not been conducted yet, values are based on assumptions, literature information, as well as official surveillance data. The QMRA follows the general structure of human health risk assessments:

- Hazard identification
- Hazard characterization
- Exposure Assessment
- Risk characterization

6.1 State of the art

In 1992 Asano et al. used the monitoring data for enteric viruses of the chlorinated tertiary effluents of 10 sewage treatment plants (STP) in California to estimate risk of enteric virus infection in four different scenarios. For swimming and golfing, the annual risk of infection varied between 10^{-2}-10^{-7} per person, for the irrigation of food crops and groundwater recharge between 10^{-6}-10^{-11} (Asano et al. 1992). In the following year Shuval published an epidemiological survey in which a correlation between outbreaks of cholera and typhoid fever due to the irrigation of vegetables with raw wastewater is shown (Shuval 1993). In 1997 he estimates the risk of hepatitis infection due to the consumption of vegetables irrigated with raw wastewater to be 10^{-3} (Shuval et al. 1997). In the same year Crabtree et al. conducted a risk assessment study of water related adenovirus infections and come to the conclusion that through recreational water an infection risk of 10^{-3} per exposure event exists (Crabtree et al. 1997). A QMRA (quantitative microbial risk assessment) study, conducted by Hamilton et al. in 2006, examined different vegetables grown on areas where wastewater is used for irrigation. They come to the conclusion that the amount of consumed food is an essential impact factor on the overall risk and that the pathogen survival period partly depends on the surface of the vegetable (Hamilton et al. 2006). A study by Mara and Blumenthal from 2007 directly focuses on the different risks for highly mechanized and labor intensive agriculture. They conclude that for highly mechanized agriculture the effluent concentration of E.Coli bacteria has to be lower than 10^{6} bacteria per 100ml to reduce the risk of Rotavirus infection below a limit of 10^{-2}(Mara et al. 2007). Another study by Mara from the year 2010 states that in order to meet the tolerable level of risk defined by the WHO a log reduction of 5-6 log units is necessary for unrestricted irrigation concerning risks from Norovirus infection(Mara and Sleigh 2010). A study from Westrell et al. from 2004 directly refers to the HACCP concept of Water Safety Plans while she investigates the risks of infection for different groups of sewage workers. Her results show that people working at a belt press for dewatering sludge are at exposed to the highest risk of infection (Westrell et al. 2004). In 2011, Viau et al. derived a risk of Norovirus infection of 10^{-2} through the application of dewatered biosolids and conclude that sludge treatment is a more effective way to reduce present infection risks due to pathogen exposure than the implementation of security distances (Viau et al. 2011b).

6.2 Available local data

6.2.1 Monitoring of infective microorganisms

Infective Microorganisms, so-called pathogens are neither monitored at the STP Steinhof nor at the agricultural areas of the AVBS. According to AVBS there have been some microbial analysis in the past (1970s), but since the results did not give any reason to worry no permanent monitoring program has been established (AVBS, personal correspondence). The mentioned studies were not available for the elaboration of this report.

6.2.2 Existing reduction measures

STP Steinhof uses activated sludge treatment in order to reduce bulk organic carbon. Nitrogen and Phosphorus are reduced biologically. The STP is not designed for the removal of pathogens, meaning that there are no treatment steps with the specific function of disinfection. Nevertheless, primary sedimentation and activated sludge treatment are known to reduce pathogens to a certain extent as a side effect (WHO 2006) (Umweltbundesamt 2011) (see section 6.5.3).

6.3 Hazard identification and selection of reference pathogens

Risk assessment is conducted for relevant reference pathogens. It is assumed that the kind of pathogens most frequently occurring in the STP Steinhof are the pathogens causing the most cases of disease in the region. The approach follows the logic that infected people are excreting the infective pathogen which will thus be found in municipal wastewater.

In order to identify microbial hazards which are typical for the region of Braunschweig surveillance data from the German Robert-Koch-Institute (RKI) were collected for the governmental district of Braunschweig.

Table 10: Monitored infectious diseases by the Robert-Koch-Institute for disease control and prevention (Robert Koch Institute: SurvStat, http://www3.rki.de/SurvStat, deadline: 09.08.2011) (Robert-Koch-Institut 2011)

Adenovirus	Spotted fever	Hepatitis Non A-E	Measles	Salmonellosis
Botulism	Tick-born encephalitis	HUS	Neisseria meningiditis	SARS
Brucellosis	Yellow fever	Influenza	Anthrax	Shigellosis
Campylobacter	Giardiasis	Cryptosporidiosis	MRSA	Rabies
Cholera	Haemophilus influenza	Lassa fever	Norovirus	Suspicion of rabies exposure
CJD	Hantavirus	Louse-born relapsing fever	Ornithosis	Trichinellosis
Dengue fever	Hepatitis A	Legionellosis	Paratyphus	Tuberculosis
Diphtheria	Hepatitis B	Leprosy	Plague	Tularemia
E.-coli-Enteritis	Hepatitis C	Leptospirosis	Poliomyelitis	Typhus
Ebola fever	Hepatitis D	Listeriosis	Q-fever	VHF, other pathogens
EHEC/STEC	Hepatitis E	Marburg virus disease	Rotavirus	Yersiniosis

The RKI collects the incidence rate per year for 55 (Table 10) diseases, which have to be reported in Germany. Those 55 diseases also include diseases which are not common in Germany, e.g. dengue fever, or are not related to water systems like tick-born encephalitis.

In a first step, pathogens which were not reported in the governmental district of Braunschweig during the period from 2001-2010 were neglected. In a second step, the remaining illness causing agents were sorted by category of microorganism, namely bacteria, viruses/prions and protozoa. Prions are disease causing proteins. The only disease caused by prions in this list is the Creutzfeldt-Jakob disease (CJD).

In order to make a selection of relevant pathogens for the wastewater reuse system of Braunschweig three criteria are considered. The selection should:

- be typical for the region of Braunschweig,
- include all three kinds of microorganisms (viruses, bacteria and protozoa)
- consider the number of cases caused by the pathogen

Figure 8, Figure 9 and Figure 10 show the mean numbers of reported disease cases due to the respective pathogens in the period from 2001-2010 in the governmental district of Braunschweig.

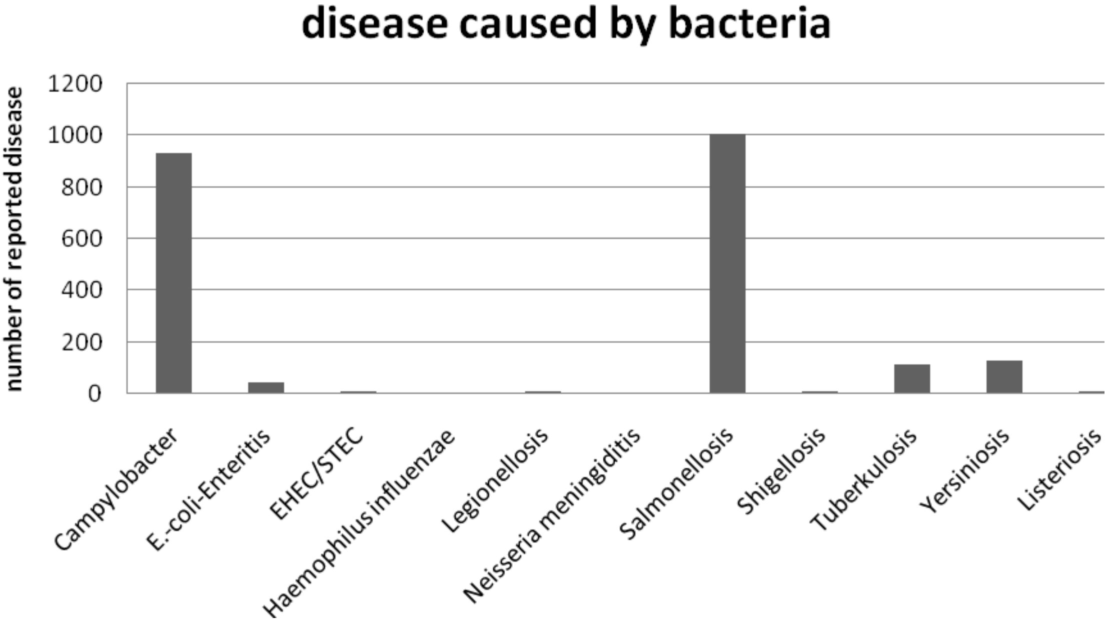


Figure 8: Number of disease incidents caused by bacterial infections. The diagram shows the mean reported number from 2001-2010 in the governmental district of Braunschweig (Robert-Koch-Institut 2011). (Names of diseases were translated by the author)

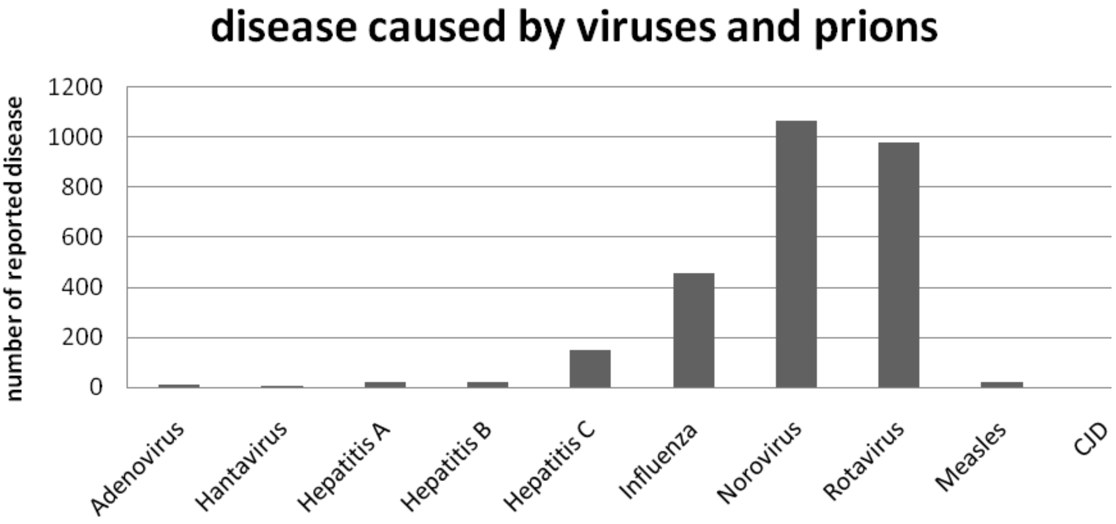


Figure 9: Number of disease incidents caused by viral infections or infections by prions (CJD). The diagram shows the mean reported number from 2001-2010 in the governmental district of Braunschweig (Robert-Koch-Institut 2011). (Names of diseases were translated by the author)

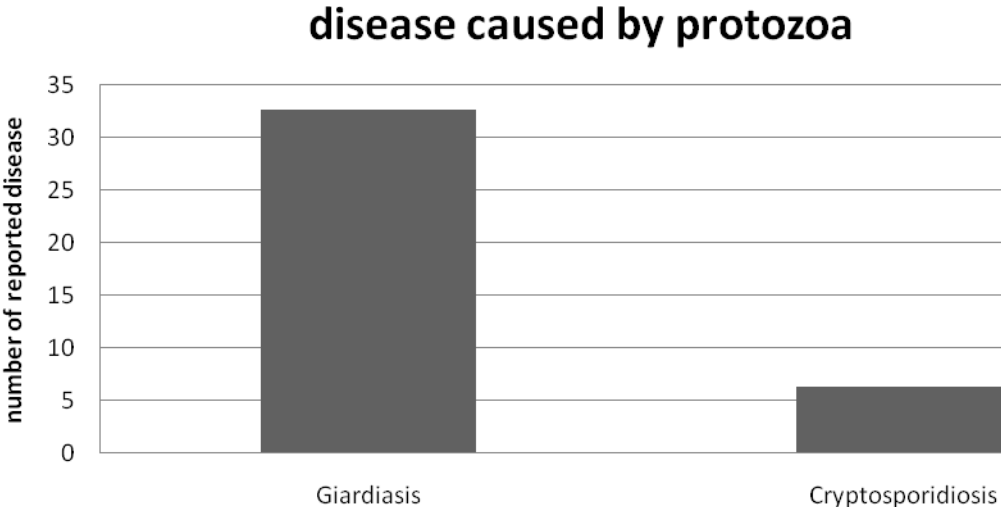


Figure 10: Number of disease incidents caused by protozoan infections of infections by prions (CJD). The diagram shows the mean reported number from 2001-2010 in the governmental district of Braunschweig (Robert-Koch-Institut 2011). (Names of diseases were translated by the author)

Concerning bacteria Campylobacter and Salmonella are the dominant disease causing agents (Figure 8) whereas Noro- and Rotavirus diseases dominate viral infections (Figure 9). These organisms are thus selected as reference organisms. Giardia is selected as the representative of protozoan pathogens (Figure 10).

In addition, enterohemorrhagic *Escherichia Coli* (EHEC) was selected because of the recent outbreak in Germany in 2011. Figure 11 illustrates the significant increase of reported EHEC cases in the governmental district of Braunschweig.

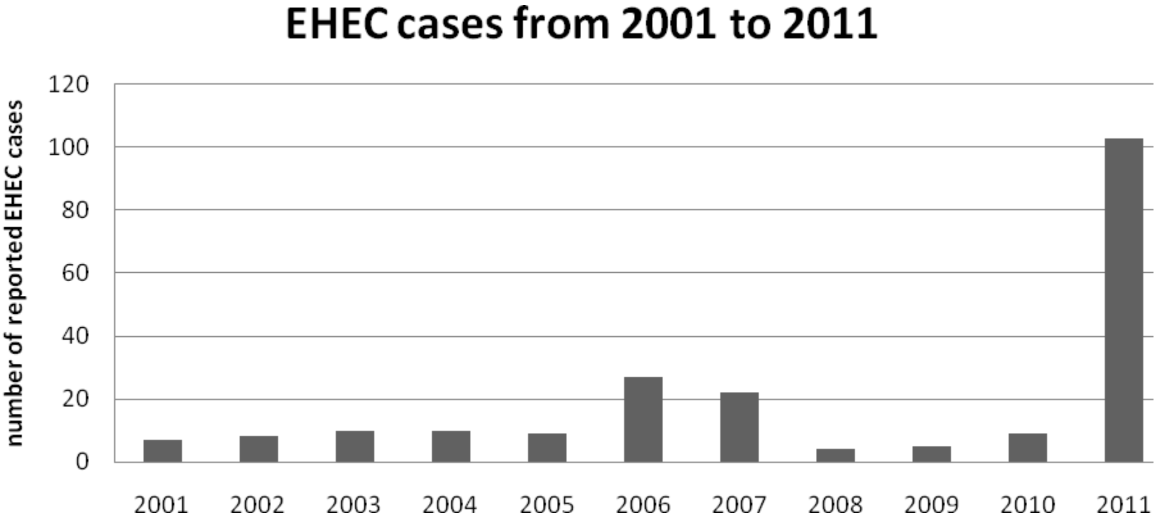


Figure 11: Number of reported EHEC infections. The diagram shows the mean reported number from 2001-2010 in the governmental district of Braunschweig (Robert-Koch-Institut 2011).

6.4 Hazard characterization

This section provides a short general characterization of the selected reference pathogens as well as the respective dose-response parameters and models.

6.4.1 General characterization

Campylobacter

Pathogens of the genus Campylobacter (C.) are gram-negative rod shaped bacteria. Until now there are over 20 species known. The most important pathogenic species are *C.jenuni, C.coli* and *C.lari*.

C.jenuni and *C.coli* are globally distributed. The bacteria colonize a broad spectrum of animals including dogs, cats and pigs. Campylobacter bacteria are able to survive in the environment for a certain time but are not capable of multiplying outside the host.
The main route of human infection is via food consumption, especially due to the consumption of poultry. Infections also occur due to the consumption of and bathing in contaminated water. Human to human infections are rather rare.
Campylobacter infectious are currently the second most frequently reported bacterial infections in Germany causing gastroenteritis. (RKI 1999a)

Enterohaemorrhagic Escherichia Coli (EHEC)

Enterhaemorrhagic Escherichia Coli are gram-negative rod shaped bacteria. All of these bacteria are able to produce certain kinds of cytotoxins, so-called Shigatoxins (Stx). Bacteria, which produce this kind of toxins, are summarized as Shigatoxin-producing E.coli (STEC). Among the STEC those bacteria are regarded as EHEC which are capable of causing illness in humans. The symptoms of EHEC infections range from mild gastroenteritis to severe diseases like HUS.
EHEC infection can be caused via multiple infection routes. All of them are related to fecal-oral exposure to the pathogen. Children younger than nine show the highest prevalence of infection in Germany. Direct contact to ruminants has been identified to be the main cause of infection for this age group. For older people the main route of infection is the consumption of contaminated food. Infection also occurs due to the

consumption of or the bathing in contaminated water. Moreover, direct human-to-human infection occurs (RKI 1999b).

Salmonella

Salmonella are gram-negative, mobile, rod shaped bacteria. Until now there are over 2500 known serotypes. More than 500 of them are known to be pathogenic. Infection is the result of oral intake of the pathogen. 8-48 hours after ingestion typical symptoms are headache, chills, vomiting diarrhea and fever. Usually, the disease resolves within 2-3 days (Madigan and Martinko 2006). After recovery, people keep shedding the pathogen for several weeks.

Non-typhoid Salmonella are the most frequently reported bacterial gastroenteritis causing pathogens in Germany and thus most likely to be present in municipal wastewater. (RKI 2009)

Giardia

The protozoan pathogen *Giardia intestinalis* causes Giardiasis, an acute gastroenteritis. The typical way of transmission is the fecal contamination of water. Moreover, food-borne transmission and transmission via sexual contact have been reported. As a resting stage Giardia forms so-called cysts which are highly resistant. Therefore, Giardia can survive for a long time in the environment outside its host. Symptoms of Giardia infection is an *"explosive, foul-smelling, watery diarrhea, intestinal cramps, flatulence, nausea, weight loss and malaise"*((Madigan and Martinko 2006), chap. 26.6, ll.12-14).

Norovirus

Noroviruses are known since 1972 and belong to the family of the *Caliciviridae*. They are globally distributed and account for the majority of global non-bacterial gastroenteritis cases. Up to 30% of all cases in children and 50% in adults are the result of Norovirus infection. Humans are the only known reservoir of Noroviruses.

Norovirus particles are excreted via feces and vomit and are highly infective. Hand contact of contaminated surfaces or inhalation of aerosol particles suffice for infection. Human-to-human infection is the main cause for the viruses' high prevalence. The virus may also be transmitted via food and contaminated water. Throughout infection the infected person is highly infective. Weeks after recovery, virus particles can still be found in feces (RKI 2000).

Rotavirus

Rotaviruses belong to the family of the *Reoviridae* and are the main cause of gastroenteritis in children. The main routes of infection are human-to-human transmissions as well as the consumption of contaminated food and water (RKI 2002).

6.4.2 Dose-response models

Table 11 gives an overview of the models and model parameters used for the respective pathogen. The respective equations are outlined in section 4.3.1.

Table 11: dose-response modeling parameters used for calculating the probability of infection due to the intake of a specific pathogen dose

Exponential, Beta-Poisson parameters, Hypergeometrical $_2F_1$ (a, α, β)					
Pathogen	k	N_{50}	α	a, β	References
Campylobacter		896	0.145		(Haas et al. 1999), (WHO 2006)
EHEC		1230	0.1778		(Haas et al. 1999)
Giardia	50.23				(Haas et al. 1999), (Rose et al. 1991)
Norovirus			0.04	0.0001, 0.055	(Teunis et al. 2008)
Rotavirus		6.27	0.2531		(Haas et al. 1999), (WHO 2006)
Salmonella		23600	0.21		(Haas et al. 1999)

6.4.3 Tolerable risks of the selected reference pathogens

As mentioned in previous sections the calculated probabilities of infection have to be compared to some tolerable value. As the WHO sets the tolerable value to 1 additional µDALY pppy, the probabilities have to be either expressed as DALYs, or, the other way around, 1µDALY has to be expressed as probability of infection for the specific pathogen.

This part outlines how tolerable levels of risk were derived for the specific pathogens and endpoints.

6.4.3.1 Tolerable risk of infection

As explained in section 4.3 the WHO uses the DALY indicator to set a level of tolerable risk. The tolerable level of additional DALYs due to wastewater reuse is set to be $\leq 10^{-6}$ pppy. In order to make the outcomes of the risk assessment comparable to that value, the DALY measure is translated into a level of tolerable risk of infection.
In order to do so, first, a tolerable risk of disease is calculated for each specific disease caused by the selected reference pathogens.

$$Tolerable\ disease\ risk\ (pppy) = \frac{Tolerable\ \ additional\ DALYs\ pppy}{DALYs\ per\ case\ of\ disease}$$

As not all infected people become ill (see section 4.4.2.1) the calculated tolerable disease risk has to be transferred to a tolerable risk of infection by:

$$Tolerable\ risk\ of\ infection\ (pppy) = \frac{tolerable\ disease\ risk\ pppy}{disease\ per\ infection\ ratio}$$

Data for calculating the amount of additional DALYs per case of disease were taken from literature. For Rotavirus, Norovirus, Cryptosporidium, Campylobacter values were already calculated (WHO 2006; Mara et al. 2010). Giardia is assumed to be comparable to Cryptosporidium. For EHEC and Salmonella data published by (Gokogka et al. 2011) were used. Within this paper the number of DALYs (per million) caused by the respective pathogen as well as the number of infected people (per million) is presented. Thus, the additional DALYs per case of disease due to the respective disease can be calculated by:

$$DALYs\ per\ case\ of\ disease = \frac{Number\ of\ cases\ per\ million\ people}{DALYs\ per\ million\ peolpe}$$

For the disease per infection ratio Salmonella is assumed to be comparable to Campylobacter. For EHEC a worst case scenario is assumed meaning that every case of infection leads to illness (disease per infection ratio = 1).

The following values for the level of tolerable infection risk were derived (Table 12).

Table 12: level of infection risk for various pathogens corresponding to 10^{-6} DALYs per person per year (pppy)

Reference pathogen	DALYs per case of disease	Disease risk pppy equivalent to 1µDALY pppy	Disease/ infection ratio	Tolerable infection risk pppy
Campylobacter[a]	$4.6*10^{-3}$	$2.2*10^{-4}$	0.7	**$3.1*10^{-4}$**
EHEC[d]	$5.4*10^{-2}$	$1.9*10^{-5}$	1	**$1.9*10^{-5}$**
Giardia[c]	$1.5*10^{-3}$	$6.7*10^{-4}$	0.3	**$2.2*10^{-3}$**
Norovirus[b]	$9*10^{-4}$	$1.1*10^{-3}$	0.8	**$1.3*10^{-3}$**
Rotavirus[a]	$1.4*10^{-2}$	$7.1*10^{-5}$	0.05	**$1.4*10^{-3}$**
Salmonella[e]	$4.6*10^{-3}$	$2.2*10^{-4}$	0.7	**$3.1*10^{-4}$**

[a] (WHO 2006), [b] (Mara et al. 2010), [c] data for Cryptosporidium taken from (WHO 2006), [d] calculated, disease infection ratio set to 1 as a worst case assumption, [e] calculated

The lowest tolerable risk of infection is attributed to EHEC, the highest to Giardia infections. Concerning viruses Rotavirus disease leads to a significantly higher value of additional DALYs than Norovirus disease. Due to the low disease per infection ratio of Rotavirus, both viruses show an almost equal tolerable level of annual infection risk. As Salmonella is assumed to be comparable to Campylobacter the specific tolerable level of annual risk is identical.

6.5 Exposure assessment

Figure 6 illustrates possible exposure routes of humans to pathogens due to wastewater irrigation. However, not all of these routes are relevant for the risk assessment in the case of Braunschweig. In Braunschweig water catchment areas for providing drinking water are spatially separated. Therefore, the exposure via drinking water can be neglected. Furthermore, the use of wastewater in agriculture in Germany is not allowed on grassland areas as well as on areas where fruit or vegetables are produced (AbfKlärV 1992). In Braunschweig, following German legislation, no products are grown, which are consumed without further processing. Thus, the pathways through the consumption of animals and animal products as well as direct consumption of crops grown on wastewater irrigated areas are neglected, too.

The remaining groups of concern for the assessment of risk due to pathogen exposure are the people with direct contact to wastewater. Three different scenarios are assumed namely fieldworkers, nearby residents and children ingesting soil.

6.5.1 Model overview

This section describes which exposure scenarios are considered, how pathogen exposure was calculated and on which data the calculations are based. The presented data are either all given as point estimates, distributions or ranges. The reason for presenting distributions and ranges instead of means or medians is caused by the fact that in the subsequent section risk characterization is conducted via Monte Carlo Simulation. Figure 12 gives an overview of the different steps of exposure calculations.

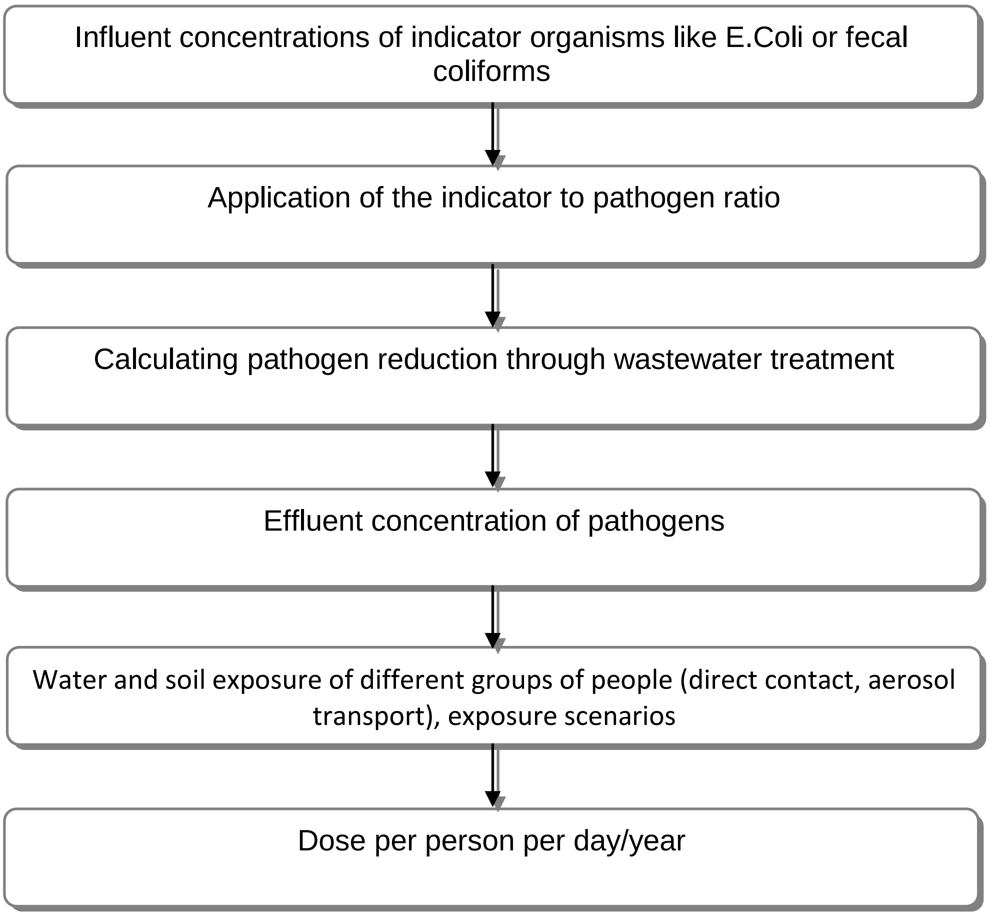


Figure 12: overview of the stepwise calculation of exposure assessment

Starting point is the calculation of influent concentrations of the selected reference pathogens.

6.5.2 Calculation of influent pathogen concentrations

As microbial analysis data for the sewage treatment plant Steinhof as well as for the irrigation site are lacking, data are estimated based on literature review. Microbial analysis of the sewage treatment plant in Bad Tölz measured influent concentrations of total and fecal coliforms between 10^7 and 10^8 per 100ml (Huber and Popp 2005). This corresponds to data published by (WHO 2006), which range from 10^8-10^{10} thermotolerant coliforms per liter. Thus, a log-normally distributed indicator influent concentration is assumed, with a mean (µ) of 7.5 and a standard deviation (σ) of 1.

The indicator concentration is used to estimate pathogen contents. Mara et al. calculated the risk of infection for Norovirus and Rotavirus assuming a ratio of 0.1-1 virus per 10^5 E.coli (Mara et al. 2010). The WHO published the same range for Campylobacter in 2006 (WHO 2006). The estimation for Salmonella concentrations is based on data from Koivunen et al. (2002)(Koivunen et al. 2003). A range from 1-100 Salmonella per 10^5 fecal coliforms was derived. For Giardia a direct relation between indicator and pathogen could not be found. Instead data, directly measured in sewage treatment plants in the Netherlands from Medema and Schijven (2001) are taken (Medema and Schijven 2001). Except from Giardia, influent concentrations for the named pathogens were calculated by:

$$Cpathogen_{influent} = Cindicator_{influent} * \frac{Npathogen}{10^5}$$

$Cpathogen_{influent}$ = Number of pathogens per 100ml of raw wastewater

$Cindicator_{influent}$ = Number of indicator organisms per 100ml of raw wastewater

Npathogen = Number of pathogen per 10^5 indicator organisms

For EHEC no data for wastewater concentrations or relations between EHEC and non-pathogenic E.coli or other indicators could be found. Instead, influent concentrations are based on incidence values [cases/100000]. The incidence of reported EHEC cases for Germany is illustrated in Table 13.

Table 13: Incidence per 100000 of EHEC cases in Germany based on reported cases (Robert-Koch-Institut 2011) Robert Koch Institute: SurvStat, http://www3.rki.de/SurvStat, deadline: <18.8.2011>

2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
1.15	1.38	1.38	1.12	1.41	1.43	1.02	1.02	1.02	1.12	4.95

Using incidence data underreporting has to be considered. The number of underreported cases is highly dependent on the disease itself. The most cases of gastroenteritis are not reported, as people will not always consult a doctor due to diarrhea or do not show any symptoms despite actual infection. For Rotavirus, Norovirus, Campylobacter and Salmonella the Robert-Koch-Institute assumes a factor of 10 for underreporting, but states that this assumption is lacking any scientific foundation. They further state that this factor might be even higher for EHEC as until the recent outbreak laboratories did not analyze the pathogen routinely but just on explicit request of the doctor in charge (RKI, personal correspondence).

Therefore, in order to cope with the problem of estimating EHEC concentrations in raw wastewater, a worst case scenario is applied as a first step. If this scenario leads to an intolerable additional risk of infection the model assumptions will be refined. Otherwise, risk assessment is considered to be finished.

Incidence values from Denmark, which already include a correction for underreporting, published by Schönning et al. in 2007 are used (Caroline Schönning et al. 2007). They promote a normally distributed incidence with a mean of 30 (µ) and a standard deviation of 5 (σ).

On this basis the number of EHEC cases per year is calculated by:

$$EHECcases\ per\ year = Incidence * \frac{PT(Steinhof)}{100000}$$

PT(Steinhof) = total number of inhabitant and population equivalents of the sewage treatment plant Steinhof.

Incidence = EHEC cases per 100000 inhabitants

EHECcases per year = Number of EHEC cases per year in the region of Braunschweig

The number of EHEC cases per year gives no information on the distribution of EHEC cases over the year. The maximum number of EHEC bacteria in wastewater can be calculated, by assuming that all the people are infected on the same day. The number of pathogens excreted by infected people per gram feces is taken from (Caroline Schönning et al. 2007). The average amount of feces excreted by humans is taken from (WHO 1992).

$$Npathogen_{wastewater} = EHECcases\ per\ year * Npathogen_{feces} * Amount_{feces}$$

$Npathogen_{wastewater}$= total number of EHEC bacteria excreted by infected people [N per year]

$Npathogen_{feces}$ = number of pathogens excreted by infected people per gram feces [N per gram wet feces]

$Amount_{feces}$ = mass of wet feces excreted per day

Assuming an average duration of a EHEC gastroenteritis episode of 8 days (Caroline Schönning et al. 2007), this maximum concentration would be present in the sewage treatment plant at 8 days per year. Consequently, on the remaining 357 days the concentration would be zero.

As a worst case scenario the incidence distribution (normal distribution, N (μ, σ), μ=30, σ=5), which refers to the number of cases out of 100000 inhabitants per *year*, is used as a worst case incidence rate per *day*. In order to calculate wastewater concentrations the total number of excreted pathogens is divided by the daily amount of wastewater.

$$Cpathogen_{influent} = \frac{Npathogen_{wastewater}}{V_{wastewater}} * \frac{1}{10000}$$

$Cpathogen_{influent}$ = Number of pathogens per 100ml of raw wastewater

$Npathogen_{wastewater}$ = total number of EHEC bacteria excreted by infected people [N per day]

$V_{wastewater}$ = daily amount of wastewater [m³]

Table 14 summarizes the point estimates and distributions, which were used for the calculation of EHEC concentrations in the influent of the sewage treatment plant Steinhof.

Table 14: used values for the calculation of influent concentrations of EHEC bacteria. N, LN and Tri refer to the distribution, the values in brackets to the parameters necessary to define them. N (mean, standard deviation), LN (ln(mean), ln(standard deviation)), Tri(min, max, modus).

Factor	Distribution	Parameter/values	Reference
Daily amount of wastewater	Point estimate	57534m³	Abwasserverband Braunschweig
EHEC cases per day	Normal	N (30,5)	(Caroline Schönning et al. 2007)
Pathogens per gram feces	Lognormal	LN (5.8,1.2)	(Caroline Schönning et al. 2007)
Excreted feces per day [g/d]	Triangular	Tri (150,400,300)	(WHO 1992)
PT(Steinhof)	Point estimate	350000 PT	Abwasserverband Braunschweig

Table 15 summarizes the distributions of the indicator-pathogen ratios used to calculate pathogen concentrations in the influent of the sewage treatment plant, for Campylobacter Salmonella, Norovirus and Rotavirus as well as the calculated concentration for Giardia and EHEC.

Table 15: Pathogen/indicator ratios and distributions chosen for the present exposure assessment. The triangular distribution is defined by three points. The modus represents the most probable value.

Pathogen	Distribution	Min	Max	Modus
Campylobacter	Triangular	0.1 [10^{-5} E.coli]	1 [10^{-5} E.coli]	0.55 [10^{-5} E.coli]
Salmonella	Triangular	1 [10^{-5} E.coli]	100 [10^{-5} E.coli]	55 [10^{-5} E.coli]
Norovirus	Triangular	0.1 [10^{-5} E.coli]	1 [10^{-5} E.coli]	0.55 [10^{-5} E.coli]
Rotavirus	Triangular	0.1 [10^{-5} E.coli]	1 [10^{-5} E.coli]	0.55 [10^{-5} E.coli]
Giardia	Triangular	2 [$100ml^{-1}$]	200 [$100ml^{-1}$]	20 [$100ml^{-1}$]
EHEC	Triangular	$1.6*10^{-4}$ [$100ml^{-1}$]	1.6 [$100ml^{-1}$]	$1.7*10^{-2}$ [$100ml^{-1}$]

6.5.3 Pathogen reduction of the STP

For the reduction of pathogens during wastewater treatment a triangular distribution is assumed (Haas et al. 1999). Minimum and maximum values for pathogen reduction are taken from (WHO 2006). The modus value to define the triangular distribution is taken from the German Federal Agency for the Environment, Nature Conservation and Nuclear Safety (Umweltbundesamt 2011). The used values are summarized in Table 16.

Table 16: potential pathogen reduction in $\log_{10}$ units for the different wastewater treatment steps and for the sewage treatment plant (STP) as a whole

Treatment step	Distribution	Min [$\log_{10}$]	Max [$\log_{10}$]	Modus[$\log_{10}$]
Primary Sedimentation	Range	0 (Viruses) 0 (Bacteria) 0 (Protozoa)	1 (Viruses) 1 (Bacteria) 1 (Protozoa)	
Activated sludge + secondary sedimentation	Range	0 (Viruses) 1 (Bacteria) 0 (Protozoa)	2 (Viruses) 2 (Bacteria) 1 (Protozoa)	
STP	Triangular	0 (Viruses) 1 (Bacteria) 0 (Protozoa)	3 (Viruses) 3 (Bacteria) 2 (Protozoa)	2 (Viruses) 2 (Bacteria) 1.5 (Protozoa)

6.5.4 Calculation of effluent concentrations

Effluent concentrations are calculated by:

$$log_{10}(C_{effluent}) = log_{10}(C_{influent}) - Reduction$$

Ceffluent	= number of pathogens in the effluent [number per 100ml]
Cinfluent	= number of pathogens in the influent [number per 100ml]
Reduction	= $\log_{10}$ pathogen reduction for the respective type of pathogen

6.5.5 Assumptions for exposure scenarios

In three different exposure scenarios the dose of pathogens to which the respective population groups are exposed to via soil/water intake and inhalation as well as via soil ingestion is calculated. Exposure scenarios differ in the amount of media, to which the respective population is exposed per exposure event as well as the number of exposure events per year. The population groups of interest are fieldworkers, nearby residents and children ingesting soil.

Fieldworkers

Field workers and farmers is the population group most directly exposed to treated wastewater and sewage sludge as they work directly on the irrigation area. A QMRA for wastewater irrigation was conducted by Mara et al. (2005), published by the WHO (WHO 2006). For highly mechanized agriculture, a daily intake of 1-10mg contaminated soil, or 1-10µl treated wastewater are assumed. No die-off is considered. Soil pathogen concentrations are assumed to equal effluent pathogen concentrations (Number per $100ml_{water} \triangleq$ Number of $100g_{soil}$). The number of exposure events per year is set to 100 days per person per year.

Nearby residents

For exposure assessment of nearby residents, the dose of solid and liquid aerosol particles people are exposed to has to be estimated. Viau et al. conducted a QMRA study in 2011, where particle exposure due to biosolid application was modeled. Depending on the wind speed and distance from the site of application they published a range of inhaled PM10 particles from biosolid land application from 0.05µg per application event at a wind speed of 20m/s and a distance of 1000m to 25.3µg per application event at a wind speed of 1.5 m/s and a distance of 5m (Viau et al. 2011a).
The legal permission for wastewater reuse in Braunschweig defines minimum distances between the irrigation machine and the landed properties of local residents (see section 3.2.1).

Depending on the size of the nozzle outlet of the irrigation machine the minimum distance varies between 60 and 150m. The average wind speed for the region of Braunschweig is set to 3m/s (DWD 2004). For this wind speed and distance range Viau et al. published an inhalation dose of PM10 particles produces by biosolid land application form 4.5-6.9 µg per application event (Viau et al. 2011b). The study they conducted focused on the application of dewatered sewage sludge, whereas in Braunschweig liquid sludge is mixed into treated wastewater. Within their publication Viau, Kyle et al. state that "*land-applying dewatered biosolids […] produces an aerosol emission rate approximately 80 greater than emission rates observed for liquid sludge spray application"* ((Viau et al. 2011b), p.5466, ll. 17-20). Thus, an additional exposure reduction of a factor of 80 was applied for the calculation of aerosol exposure of the local communities in Braunschweig.

Soil ingestion by children

Children may play on agricultural areas or may accompany adults while they go for a walk. Especially young children tend to ingest higher amounts of soil. To account for this kind of risk an annual number of exposure events of 10 is applied. The amount of soil ingested is set to 20-100mg per exposure event (Mekel et al. 2007).

6.6 Risk characterization

Risk characterization is conducted by the use of Monte Carlo Simulation. Random variables are created with MATLAB 7. The annual risk of infection per person per year (pppy) is calculated in a 1000 trial simulation. The number of trials for calculating the risk of infection per exposure event depends on the number of exposure events per year.

Fieldworkers are assumed to be exposed 100 days per year. Therefore, 100000 trials were conducted. The 100000 trials are grouped in groups of 100 (number of exposure events per year), resulting in 1000 trials for the total annual risk. This approach follows the improved procedure of Monte Carlo Simulations for wastewater irrigation elaborated by Karavarsamis and Hamilton in 2009, published in ((Drechsel et al. 2010), chap.5).

As local communities are exposed 365 days per year the number of risk per exposure event was calculated in 365000 trials, which again lead to 1000 trials of total annual risk of infection after being grouped in groups of 365.

Analogously, 10000 initial trials per exposure event are conducted for the 10 exposure events per year for the children scenario.

Figure 13 illustrates the procedure of Monte Carlo Simulation used in this report.

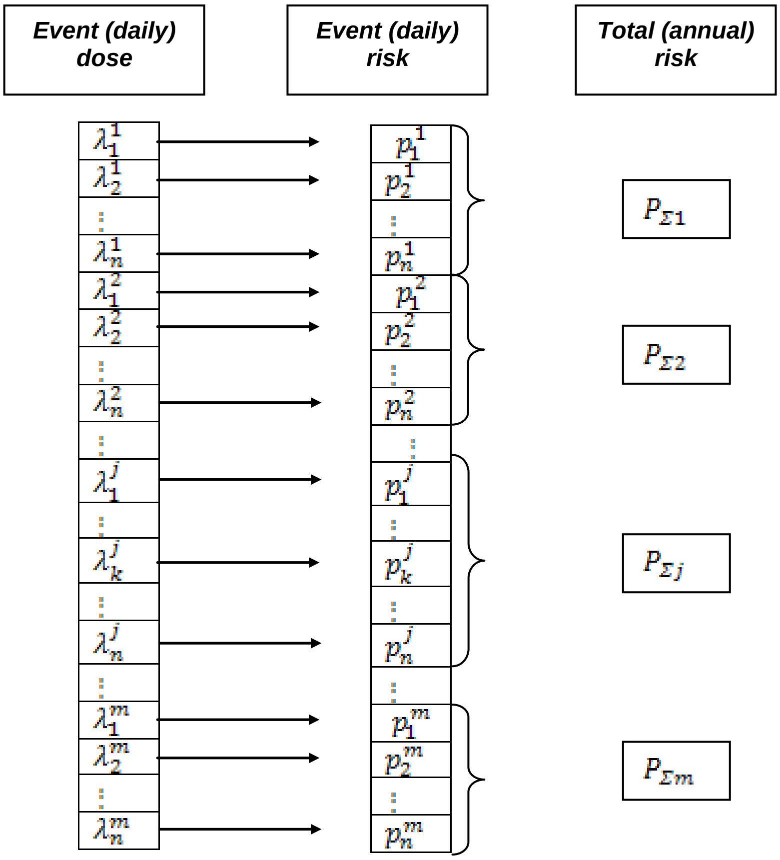


Figure 13: illustration of the Monte Carlo Simulation procedure used in this report elaborated by Karavarsamis and Hamilton. (adopted from ((Drechsel et al. 2010), chap. 5))).

6.6.1 Model results

Based on the model assumptions outlined in the previous section the following pathogen concentrations were calculated:

Table 17: Calculated influent and effluent concentration of the selected reference pathogens in the STP Steinhof

Pathogen	Influent concentration [Number/100ml]	Effluent concentration [Number/100ml]
Giardia	66.5	3.8
Campylobacter	164	1.6
EHEC	$1.7*10^{-2}$	$1.7*10^{-4}$
Salmonella	$1.5*10^{4}$	151.3
Norovirus	164.3	3.3
Rotavirus	164	3.3

Based on the model calculations and scenarios the following doses per exposure event were calculated for the respective scenarios (Table 18).

Table 18: Median dose of pathogens per exposure event for the different exposure scenarios

Pathogen	Scenario		
	Fieldworkers [Number per exposure event]	Nearby residents [Number per exposure event]	Children ingesting soil [Number per exposure event]
Giardia	$2.0*10^{-4}$	$5.1*10^{-6}$	$2.2*10^{-3}$
Campylobacter	$8.4*10^{-5}$	$2.1*10^{-6}$	$9.1*10^{-4}$
EHEC	$8.6*10^{-9}$	$2.1*10^{-10}$	$9.8*10^{-8}$
Salmonella	$7.7*10^{-3}$	$1.9*10^{-4}$	$8.6*10^{-2}$
Norovirus	$1.8*10^{-4}$	$4.3*10^{-6}$	$1.9*10^{-3}$
Rotavirus	$1.7*10^{-4}$	$4.3*10^{-6}$	$1.9*10^{-3}$

By applying the respective dose-response models on the doses the respective population groups are exposed to, the following median values for the risk of infection per exposure were calculated (Table 19).

Table 19: calculated median risk per exposure event per person for the selected reference pathogens and exposure scenarios

Pathogen	Scenario		
	Fieldworkers [per person per exposure event]	Nearby residents [per person per exposure event]	Children ingesting soil [per person per exposure event]
Giardia	$4.0*10^{-6}$	$1*10^{-7}$	$4.4*10^{-5}$
Campylobacter	$1.7*10^{-6}$	$4.3*10^{-8}$	$1.9*10^{-5}$
EHEC	$4.4*10^{-11}$	$1.1*10^{-12}$	$4.8*10^{-10}$
Salmonella	$8.7*10^{-7}$	$2.2*10^{-8}$	$9.3*10^{-6}$
Norovirus	$7.1*10^{-5}$	$1.8*10^{-6}$	$7.8*10^{-4}$
Rotavirus	$1*10^{-4}$	$2.6*10^{-6}$	$1.1*10^{-3}$

After grouping the risks per exposure event by the number of exposure events per year the following median values for the annual risk of infection were calculated (Table 20).

Table 20: calculated median annual risk of infection per person for the selected reference pathogens and exposure scenarios

Pathogen	Scenario			Tolerable risk of infection pppy
	Fieldworkers [pppy]	Nearby residents [pppy]	Children ingesting soil [pppy]	
Campylobacter	$5.1*10^{-4}$	$4.6*10^{-5}$	$5*10^{-4}$	$3.1*10^{-4}$
EHEC	$1.5*10^{-8}$	$3.7*10^{-10}$	$1.4*10^{-8}$	$1.9*10^{-5}$
Giardia	$9.1*10^{-4}$	$2.2*10^{-5}$	$9.9*10^{-4}$	$2.2*10^{-3}$
Norovirus	$3.8*10^{-2}$	$3.5*10^{-3}$	$3.4*10^{-2}$	$1.3*10^{-3}$
Rotavirus	$5.4*10^{-2}$	$5.2*10^{-3}$	$5*10^{-2}$	$1.4*10^{-3}$
Salmonella	$2.4*10^{-4}$	$6.1*10^{-6}$	$2.6*10^{-4}$	$3.1*10^{-4}$

Concerning fieldworkers, the tolerable risk of infection pppy is exceeded for Campylobacter, Norovirus, and Rotavirus.

6.6.2 Risk expressed as additional DALYs pppy

By multiplying the annual risk of infection per person with the amount of DALYs caused per case of disease, the risk can be expressed as the amount of additional DALYs per person per year. Figure 14, Figure 15, Figure 16 illustrate the annual risk as additional µDALYs pppy.
The full distributions including statistical data are presented in Appendix C**Fehler! Verweisquelle konnte nicht gefunden werden.**.

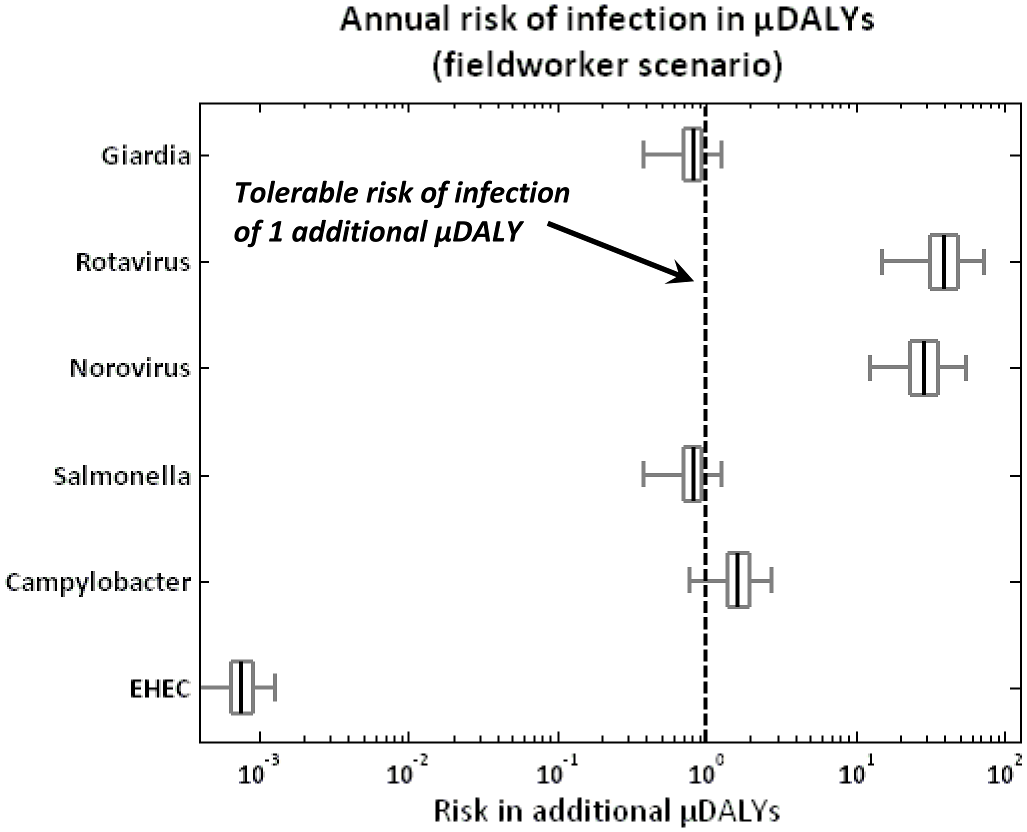


Figure 14: Annual risk of infection per person per year expressed in µDALYs for the fieldworker scenario. The black line represents the median of the respective distribution, the edges of the boxes the respective 25 and 75-percentiles, the grey line the remaining values. The dotted black line represents the level of tolerable risk set by the WHO wastewater guidelines (average amount of µDALYs caused by viruses in Germany pppy, Rotavirus: 110, Norovirus: 14)

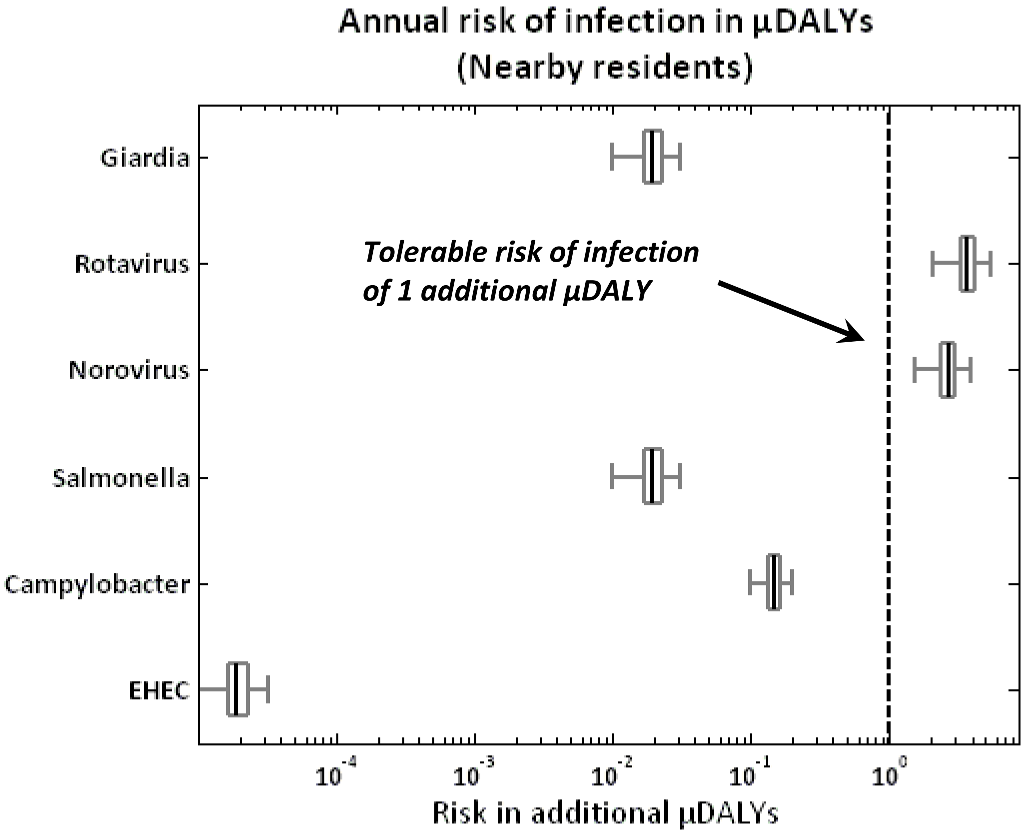


Figure 15: Annual risk of infection per person per year expressed in µDALYs for the nearby residents scenario. The black line represents the median of the respective distribution, the edges of the boxes the respective 25 and 75-percentiles, the grey line the remaining values. The dotted black line represents the level of tolerable risk set by the WHO wastewater guidelines (average amount of µDALYs caused by viruses in Germany pppy, Rotavirus: 110, Norovirus:14)

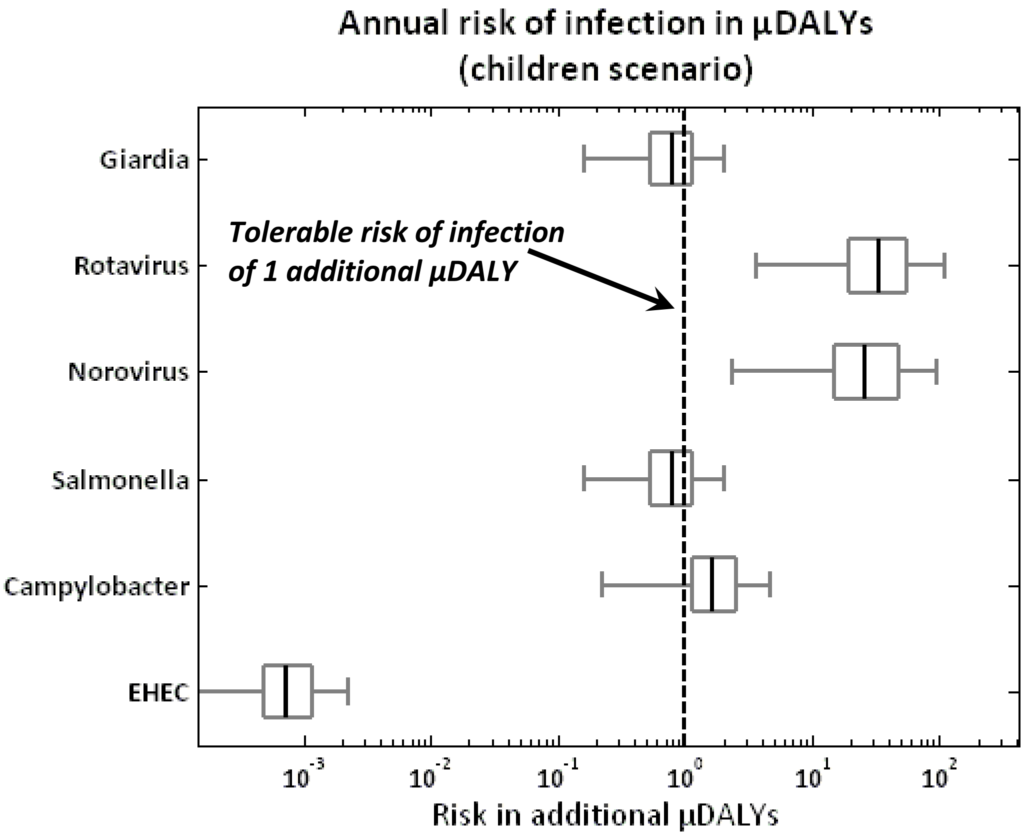


Figure 16: Annual risk of infection per person per year expressed in µDALYs for the children scenario. The black line represents the median of the respective distribution, the edges of the boxes the respective 25 and 75-percentiles, the grey line the remaining values. The dotted black line represents the level of tolerable risk set by the WHO wastewater guidelines (average amount of µDALYs caused by viruses in Germany pppy, Rotavirus: 110, Norovirus:14)

6.7 Evaluation and Discussion

This section critically evaluates the generated results. If it is possible and necessary risk-based targets are defined.

6.7.1 Risk of pathogen infection due to wastewater irrigation

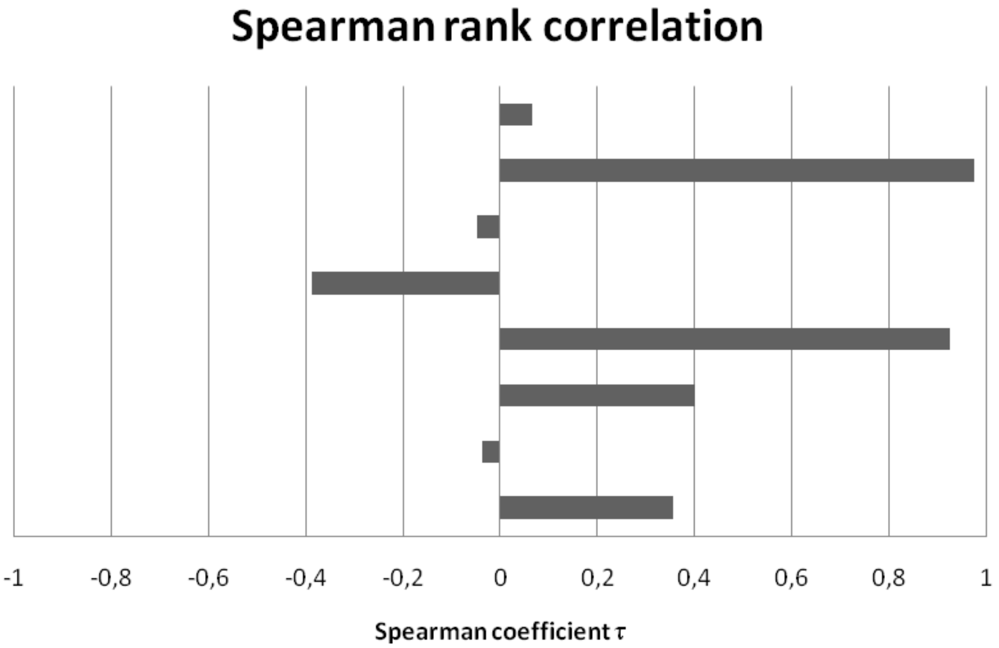
The results of the conducted Monte Carlo Simulations point out that the current practice of wastewater irrigation in Braunschweig result in the highest annual risks of infection for fieldworkers and children. The two scenarios lead to similar results concerning the annual risk of infection. The risk of infection per exposure event is 10 times higher for the children-scenario due to the high intake of soil. Nevertheless, the higher number of exposure events per year in the fieldworker-scenario lead to the overall similar results in the annual risk of infection. Both scenarios exceed the tolerable values for Campylobacter, Norovirus and Rotavirus. For virus infections the modeled annual risk of infection exceeds the tolerable value by a factor 40. For Campylobacter the annual risk of infection exceeds the tolerable value by a factor of 1.6 and is less significant.

Concerning nearby residents the tolerable levels of annual risk of infection are exceeded concerning Noro- and Rotavirus infections. The amount of water and soil aerosols, this population group is exposed to, is the smallest of all scenarios. Nevertheless, the permanent exposure of 365 days per year suffices that the tolerable levels of infection are exceeded for viruses.

For the remaining pathogens the tolerable risk of infection per person per year is not exceeded. It is emphasized that for the EHEC scenario, where influent concentrations as well as the set level of tolerable annual risk are based on worst-case assumptions, the calculated annual risk of infection is still three orders of magnitude below the tolerable value. Thus, as far as EHEC is concerned, intolerable risks resulting from wastewater irrigation can be excluded.

6.7.2 Sensitivity analyses

Sensitivity analysis is conducted by the use of the Spearman rank correlation method, which indicates the correlation between the variation of a specific factor and the final result. As this sensitivity analysis refers to the model and not to the concrete results it is not conducted for all scenarios and pathogens. The fieldworker scenario for Rotavirus is taken as an example as it leads to the highest overall annual risk of infection.



Factor (from top)	τ	Factor (continued)	τ
Daily dose of media (soil, water)	0.07	Effluent concentration RV	0.9
Daily pathogen dose	0.97	Influent concentration RV	0.4
alpha	-0.05	N_{50}	-0.04
Virus reduction in STP	-0.4	*E.Coli* influent	0.35

Figure 17: Spearman rank correlation of the fieldworker scenario respective to the annual risk of Rotavirus (RV) infection. Positive values for τ indicate that an increase of the respective factor lead to an increase of the final result. Negative values for τ indicate that an increase of the respective factor lead to a decrease of the final result.

The dominating model parameter influencing the annual risk of infection is the dose people are exposed to. The reason, that the Spearman coefficient for this parameter does not equal a value of one lies in the variations of alpha and N_{50}, which account for differences in susceptibility of the different single persons exposed to the same number of pathogens.

The factors, which influence the dose of pathogens people are exposed to, are the dose of pathogen containing media and the pathogen concentration in the effluent of the STP Steinhof. In this respect the effluent concentration clearly dominates (τ=0.9) in comparison to the daily dose of media (τ=0.07). The daily dose of media is not influenced by further factors.

In contrast, the effluent concentration of pathogens is dependent on the influent concentration of *E.Coli* as a measure for fecal contamination, the concentration of Rotaviruses, which accounts for the present incidence of infection among the overall population and the pathogen reduction performance of the STP. All three values have similar Spearman coefficients of approximately 0.4. That means that the same effluent concentration can be the result of different conditions. The lowest effluent concentration is the result of a low current incidence among the overall population, low fecal contamination and high performance of pathogen reduction by the STP. The highest is the result of a high incidence, high fecal contamination and low pathogen removal by the STP. Different modifications of the three factors lead to effluent concentrations between these two bounds.

6.7.3 Risk-based targets

Based on the conducted QMRA risk-based targets are expressed as necessary required pathogen reduction for reducing the annual risk per person to its tolerable value. The required additional pathogen reduction is calculated by:

$$\log(Red) = \log\left(P_{I,ann}\right) - \log\left(P_{I,ann,tol}\right)$$

log(Red)	= additional required pathogen reduction in log units
$P_{I,ann}$	= risk of infection per person per year (pppy)
$PI_{,ann,tol}$	= tolerable risk of infection per person per year (pppy)

Virus infections show the highest exceeding of tolerable levels of the annual risk of infection in the conducted QMRA. Therefore, the setting reduction targets for viruses protects simultaneously from other infection risks. The calculated values for additional required pathogen reduction are 1.58 log units for Rotavirus and 1.46 log units for Norovirus. As Norovirus is the main cause of non-bacterial gastroenteritis a risk-based target of 1.5 log units is appropriate. Since the main group at risk is fieldworkers, which are directly exposed to pathogen containing media, the required pathogen reduction has to be achieved by wastewater treatment alone.

6.7.4 Critical discussion

Concerning the methodological approach of risk characterization the conducted Monte Carlo Simulation accounts for a broad spectrum of uncertainties, including different susceptibility of people (model parameters), different incidence rates (indicator to pathogen ratio), fecal contamination (variations of *E.Coli* influent concentrations) and varying doses per exposure event. Thus, uncertainties are considered, integrated in the model calculations and illustrated in a transparent way. The assumptions which are used are not overly conservative and based on reviewed literature. The order of magnitude of the generated results lies within reasonable limits and is comparable to other conducted QMRA studies (WHO 2006; Caroline Schönning et al. 2007; Viau et al. 2011b). A weakness may be that within the children scenario no pathogen die-off is considered. Even if the number of exposure events is 10 times per year, one does not really know when the last irrigation has taken place. Therefore, the results have to be taken as a worst case scenario. On the contrary, the actual probability of infection concerning the fieldworker scenario may be even higher than the calculated ones, as events like accidental wastewater spills were not considered in the scenario. Moreover, secondary infections are not considered, meaning that an infected fieldworker may transmit the pathogen to other persons. This holds especially true for virus infections as person-to-person infections are common. A third factor, which may lead to an underestimation of the actual risk for all scenarios, is that for calculating pathogen reduction it is assumed that just wastewater is used for irrigation. As it is possible that pathogens are just removed by being transferred into the sludge phase, the assumption that just wastewater is used for irrigation, would underestimate pathogen concentrations, since in reality the digested sludge is mixed into the irrigation water.

The lack of measured microbiological data in Braunschweig poses a weakness of the overall results. The assumptions concerning indicator and pathogen concentrations clearly have to be validated by microbiological analysis. Another weakness of the model is that variables are regarded as independent, especially concerning pathogen reduction in the STP. This means that the model creates random values for the STP's log-reduction following the respective distributions for bacteria, viruses and protozoa regardless from the pathogen influent concentration. For example, a randomly created log-reduction of 2 is applied to the influent pathogen concentration regardless if the number of pathogens in the influent is 1000 or 10.

Despite the named weaknesses the results concerning the actual probability of infection per person per year lie within reasonable ranges. The increased risk of infection for people having direct contact to wastewater is not a surprising outcome and has been observed in several studies (see e.g. (Thorn et al. 2002)).

Nevertheless, it is debatable, whether the calculated increased risk of infection poses an "intolerable risk". Referring solely to the WHO approach, which draws the line of the level of tolerable risk at a value of 1 µDALY the calculated results represent an intolerable risk. Nevertheless, the manner in which the WHO level is set as well as how many DALYs are attributed to mild diseases like diarrhea caused by Noro- and Rotavirus infections are currently subject of reasonable criticism.

Concerning the value of 1µDALY as a tolerable level of additional burden of disease Prof. Duncan Mara criticizes that, especially for middle and low income countries, this value is too stringent, as the corresponding probability of infection of approximately 10^{-3} cases pppy is far below the current incidence (Mara et al. 2010). He calculates a current additional burden of disease of 0.0119 DALYs pppy due to diarrhea for middle and low income countries and proposes a tolerable level of additional diseases burden of 10^{-4} DALYs. He states that *"an additional DALY loss of 10^{-4} pppy would increase this to 0.0120 pppy – i.e., an increase of just under 1%. Such an increase is epidemiologically insignificant (and, in any case, would be extremely difficult to detect)."((Mara et al. 2010)p.2, l.24).*

Therefore he concludes that **"[…] it seems perfectly reasonable to accept a maximum additional DALY loss of 10^{-4} pppy for wastewater use in agriculture"**((Mara et al. 2010), p.2, l.26).

As Germany is not a low income country, this criticism shall be examined using current incidence rates for Noro- and Rotavirus of the Robert-Koch-Institute to calculate the additional µDALYs these pathogen currently cause in Germany. A factor of 10 is applied for underreporting (RKI, personal correspondence). Table 21 shows the results.

Table 21: calculated µDALYs caused by Noro- and Rotavirus using incidence data for Germany for the years 2008-2010. Incidence data are taken from SurvStat, http://www3.rki.de/SurvStat, deadline: 04.11.2011

Pathogen	Mean incidence [cases/100000]	Mean probability of disease pppy	Underreporting	DALYs per case of disease	µDALYs pppy
Norovirus	150	0.00150	10	$9.1*10^{-4}$	14
Rotavirus	79	0.00079	10	$1.4*10^{-2}$	110

The calculated additional µDALYs are in the same order of magnitude as the WHO global burden of disease study, which estimates a value of 22 additional DALYs per 100000 people due to diarrheal disease in Germany (WHO 2009). This corresponds to 220µDALYs pppy.

The results show that by applying a tolerable additional burden of disease of 10^{-4} DALYs, which corresponds to 100µDALYs, the DALYs caused by Norovirus would increase by a factor of 8-9 and the ones for Rotavirus would double. Certainly this increase cannot be regarded as *epidemiologically insignificant* as it is for low and middle income countries. Thus, the criticism formulated by Mara has no influence on the final results of this report.

Another criticism on the DALY indicator, which might have consequences on the final results of this study, is formulated by Haagsma et al. 2008, who state that *"because there is no clear exclusion criterion for highly prevalent minimal disease in burden of disease studies its [the DALY indicator's] application may be restricted."*((Haagsma et al. 2008)*,* abstract, l.4).

Their major point is that minor diseases, like a one day diarrhea, are overemphasized in DALY calculations. They used the so-called time trade off (TTO) method to investigate the relevance of 20 different health outcomes. The TTO method asks people if they would trade off some lifetime for avoiding a certain adverse health outcome. If 50% of the people would not trade off any time, the adverse health outcome, like a one day diarrhea, is considered as not relevant and therefore is not used for further DALY calculations. Based on their estimations they recalculated the DALYs caused by a specific pathogen taking the set relevance criterion into account. The DALYs caused by Noro- , and Rotavirus decreased by 94% and 78%, respectively. The DALY values for Salmonella and Campylobacter decreased both by 24%, the ones for EHEC/STEC by 5%.

If those percentages would be applied on the overall results of this study even the µDALYs caused by Noro-, and Rotavirus in the fieldworker scenario would decrease to a value of 1.7 and 2.3 µDALYS pppy, respectively. Against the background of present uncertainties this could hardly be described as a significant exceeding of the tolerable level.

In summary, the setting of an appropriate level of tolerable risk is the crucial point of assessing infection-risks resulting from wastewater reuse in agriculture. The tolerable level of 1µDALY seems appropriate against the background of the current incidence of virus infections and the DALYs they cause in Germany. The criticism of Haagsma et al. concerning the necessity of implementing a further relevance criterion would not increase the overall tolerable level but would reduce the "DALYs caused per case of disease" especially for Norovirus and Rotavirus.

However, if this relevance criterion was applied to the outcomes of this study it would have to be applied to the DALY calculation based on the incidence data by the Robert-Koch-Institute as well. This leads to the same ratio between current DALYs caused by viruses based on incidence data and the calculated DALYs in the different scenarios. The additional burden of disease caused by Norovirus infections is thus still twice as high as for fieldworkers as the burden of disease in the overall society.

Chapter 7

Quantitative chemical risk assessment of heavy metals

The used methodology of quantitative chemical risk assessment (QCRA) follows the methods of the *European Union Technical Guidance Document on Risk assessment (EU 2003).* Like QMRA the conducted QCRA is structured in:

- Hazard identification
- Hazard characterization
- Exposure assessment
- Risk characterization

7.1 Available local data

Annual mean heavy metal concentrations measured in the STP Steinhof are available (Appendix A). Annual loads are calculated by further using the respective measured influent, effluent and sludge rates. Soil metal contents for the four pumping districts are available for the years from 1993-2010 Moreover, Cadmium concentrations in wheat, corn and sugar beet are available for the time span from 1995 to 2010. Data on soil properties (pH, clay content, content of organic carbon) are available from previous research studies (Ternes et al. 2003). Climate data (rain rate, average temperature) as well as atmospheric deposition of heavy metals are available from national surveillance programs (Böhm et al. 2000).

7.1.1 Limit values

The German ordinance for the application of sewage sludge (Klärschlammverordnung,(AbfKlärV 1992)) defines quality limit values for sludge and soil concerning the respective content of heavy metals.

Moreover, a maximum amount 5t of sewage sludge may be applied per hectare of arable land within a three years period. Thus, a maximum annual load of heavy metals is set (Table 22).

Table 22: maximum allowed heavy metal concentrations of sewage sludge and arable soil as well as the calculated maximum annual load considering the maximum amount of applied sludge of 5t/3years. For sandy soils with a low organic carbon content lower limit values for cadmium and zinc are applied. These values are shown in brackets.

Metal	Sludge concentration [mg/kg$_{sludge}$(dw)]	Soil concentration [mg/kg$_{soil}$(dw)]	Maximum annual load [g/ha*a]
Cadmium (Cd)	10 (5)	1.5 (1)	17
Chromium (Cr)	900	100	1500
Copper (Cu)	800	60	1333
Nickel (Ni)	200	50	333
Mercury (Hg)	8	1	13
Lead (Pb)	900	100	1500
Zinc (Zn)	2500 (2000)	200 (150)	4167

According to this ordinance sludge application is prohibited 14 days before harvest (AbfKlärV 1992).

7.1.2 Quality of monitoring data

At the STP Steinhof parameters for nutrients, suspended particles, heavy metals as well as sum parameters for carbon and halogenated organic carbon compounds are measured regularly. Monitoring data are given in Appendix A.

For the risk assessment the data for heavy metals are of special interest. The monitoring program concerning heavy metals is shown in Table 23.

Table 23: Monitoring program of heavy metals at the STP Steinhof

Sampling site	Sample	Parameter	Frequency	Day	Comments
Influent primary treatment	24h-mixed sample	Cd, Cr, Pb, Cu, Zn, Ni	Daily	Mo-Sun	Complete influent STP
		Hg	2x/month		
Effluent activated sludge treatment	24h-mixed-sample	Cd, Cr, Pb, Cu, Zn, Ni	3x/week	Mo, Wed, Fri	Entering irrigation fields
		Hg	2x/month		
Effluent irrigation	24h-mixed-saple	Cd, Cr, Pb, Cu, Zn, Ni, Hg	2x/week	Di, Do	Effluent STP + treated sludge
Primary Sludge	Grab sample	Cd, Cr, Pb, Cu, Zn, Ni, Hg	1x/week	On varying days	Sludge of primary sedimentation
Activated sludge	Grab sample	Cd, Cr, Pb, Cu, Zn, Ni, Hg	1x/week	On varying days	Activated sludge
Effluent Aue-Oker-Canal	24h-mixed-sample	Cd, Cr, Pb, Cu, Zn, Ni, Hg	1x/week	Tue or Wed	Official effluent STP

On the agricultural areas of the AVBS soil contents of Cd, Cr, Cu, Hg, Ni, Pb, and Zn are measured once a year. Additionally, cadmium concentrations in wheat, sugar beet and corn are measured once a year. For monitoring purposes the 3000ha are divided in four districts. Due to the presence of pumping stations in these four districts, the four districts are referred to as Pumping district I, Pumping district II, Pumping district III and Pumping district IV. The single pumping districts are in turn subdivided in 5-7 areas, respectively.

7.1.3 Existing reduction measures

Concerning heavy metals reduction measures have to be applied before the respective metal enters the sewage system as heavy metals are not biodegradable and thus will not be reduced or eliminated in the STP. In Braunschweig SE|BS monitors the industrial discharges into the sewage system. At over 300 sites concentrations of certain contaminants are measured. Industrial discharges with potentially high heavy metal contents are controlled 6-8 times per year (Fiebig 2011). By this control of industrial discharges annual heavy metal loads could be significantly reduced during the last decades (Figure 18).

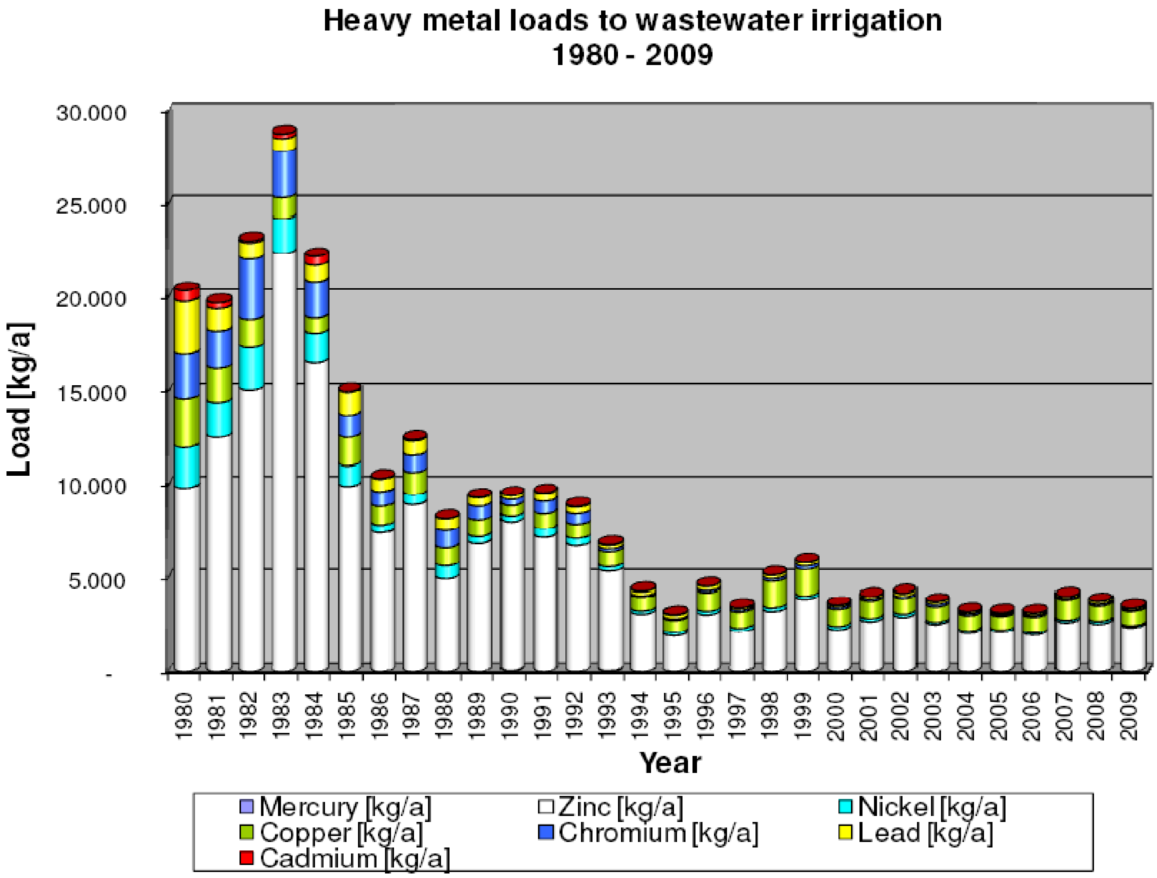


Figure 18: annual loads of heavy metals which were applied on the agricultural areas of Braunschweig (Hartmann et al. 2010).

7.2 Hazard characterization

This section characterizes the different heavy metals concerning their effects on human health and the environment.

7.2.1 General characterization

Cadmium

Cadmium has toxic effects on human health already at very low concentrations. Cadmium accumulates especially in the liver and the kidney. Due to its long half-life time inside the human body Cadmium concentration increase over life time. A critical kidney concentration of approximately 200µg/g (fresh weight) may cause proteinuria ((Scheffer and Schachtschabel 2002), section 7.3.5.3). Painful bone disorders are another effect of Cadmium exposure, including spontaneous bone fractures. Severe bone disorders due to Cadmium exposure have been observed in Japan (Itai-Itai-disease). Cadmium as classified as carcinogenic (Schütze and Spranger 2002).

For Cadmium, no biological function is known. Cadmium is toxic for various terrestrial and aquatic organisms. Cadmium is the metal which shows the highest mobility of all heavy metals at moderate pH levels (<6.5). Due to the combination of high mobility and high toxicity Cadmium is of special concern.

Cadmium is classified as a priority substance of the European Water Framework Directive. Today the major sources of Cadmium emissions to water are the result of urban surface runoff, erosion and drainage of agricultural areas as well as municipal sewage treatment plants (Hillenbrand et al. 2006a).

Mercury

Like Cadmium Mercury is highly toxic to human health. Long term exposure to even very small Mercury concentrations can cause severe neurological disorders and immune-deficiencies (Schütze and Spranger 2002). The biological half-life time inside the human body is about 70 days (Scheffer and Schachtschabel 2002).

As for Cadmium there are no biological function known for Mercury. Mercury is rather immobile and accumulates in the organic layers of the top soil. Because of its immobility plant uptake is of minor importance. Accumulation, especially of organic Mercury-compounds has been found in fish.

Mercury is classified as a priority substance of the European Water Framework Directive. The main sources of Mercury emissions to water are identical to that of Cadmium (Hillenbrand et al. 2006c).

Lead

The level of human toxicity of Lead is far below the ones of Cadmium and Mercury. Lead accumulates in bones, teeth, the liver and the kidney (Scheffer and Schachtschabel 2002). One of the characteristics of long and high lead exposure is anemia. Moreover, lead exposure can lead to hematological and neurological effects as well as to adverse reproductive and development effects (Schütze and Spranger 2002). The biological half life time inside the human body lies between 5 and 20 years. Therefore, lead concentration increases over lifetime (Scheffer and Schachtschabel 2002).

There are no biological functions know for lead in the environment. Lead shows adverse effects on plant and terrestrial microorganisms, but to a lesser extent as Cadmium.

Lead is classified as a priority substance of the European Water Framework Directive. The main sources of Lead emission to water are urban and agricultural surface runoff as well as municipal sewage treatment plants (Hillenbrand et al. 2006b).

Nickel

Human health effects concerning Nickel exposure are mainly known for the respiratory tract. Long term Nickel inhalation may cause chronic bronchitis and a reduction of lung functions. The most important exposure route is via food intake, but as only a small fraction of the Nickel in food is resorbed by the human body (1-2%) there are currently no known adverse human health effects due to Nickel intake via food (Scheffer and Schachtschabel 2002). Nickel is classified as carcinogenic and may cause skin irritation (Hillenbrand et al. 2006d).

Concerning its environmental relevance Nickel shows high phyto-toxicity and may cause adverse effects on soil organisms.

Nickel is classified as a priority substance of the European Water Framework Directive. The main sources of emission to water are surface runoff and drainage of urban and agricultural areas as well as sewage treatment plants (Hillenbrand et al. 2006d).

Chromium

Chromium may be present in the environment as Cr(III) and Cr(VI). Cr(III) is an essential element for human and animals, whereas Cr(VI) is highly toxic. In presence of organic substance Cr(VI) is reduced to Cr(III) in the environment.
Cr(III) is very immobile in the environment. Plants only take up little amounts of the metal via soil solution. Concerning human health issues slightly increased Chromium concentrations in plants would be favorable (Scheffer and Schachtschabel 2002).

Copper

Copper is essential for all living organisms. Chronic effects on human health are rarely known. Nevertheless, in higher concentrations Copper can have phyto-toxic effects on plant and thus may be a hazard for terrestrial ecosystems (Scheffer and Schachtschabel 2002).

Zinc

Zinc is essential for humans, animals and plants. At higher concentrations toxic effects on soil organisms were observed. Adverse effects on human health are currently not known (Scheffer and Schachtschabel 2002).

7.2.2 Tolerable concentrations for human health

Concerning human health risk due to the intake of heavy metals via food, which is grown on the agricultural areas of the AVBS, critical limits in plants and soil are calculated, taking the safety intake parameters (see 4.3.1) and food consumption data as a baseline. From these data tolerable food and soil concentrations are back-calculated.
Tolerable weekly intake values are given in µg/kg$_{bw}$ (bw = bodyweight). An average bodyweight of 70kg is assumed (Schütze and Spranger 2002). The TDI value accounts for all exposure routes, including other than food consumption. Following the approach of the WHO (WHO 2006) and UNECE Expert Meeting (Schütze and Spranger 2002)the tolerable fraction via food intake is set to 50%.
Values for the TWI and UL where taken from (VKM 2009) and are shown in Table 24.

Table 24: safety parameters (tolerable weekly intake, upper intake level) for oral human intake for heavy metals (VKM 2009).

Metals	TWI [µg/kg$_{bw}$]	UL [mg/day]	Other safety parameters [mg/d]	Publishing Institution	Tolerable daily intake [µg/d] (70kg/person)	Tolerable daily intake via food consumption [µg/d]
Cadmium	2.5			EFSA 2009	25	12.5
Chromium			1	VKM 2007	1000	500
Copper		5		SCF 2003	5000	2500
Lead	25			JECFA 2000	250	125
Mercury	5			JECFA 2003	50	25
Nickel	-	-	-		-	-
Zinc		25		SCF 2003	25000	12500

Data about the quantity of food consumption are taken from the national survey of food consumption in Germany (Nationale Verzehrstudie II) conducted by the Max-Rubner-Institute (MRI 2008). Consumption data are shown in Appendix B (section **Fehler! Verweisquelle konnte nicht gefunden werden.**). Wheat is taken as a proxy for all cereals, as it is grown in BS for bread production and because of its affinity of metal accumulation. De Vries at al. state that *“an appropriate indicator for critical load calculation addressing human health effects via food intake is the Cd content in wheat. Keeping a conservative food quality criterion for wheat […] protects at the same time against effects on human health via other food and fodder crops (including also the quality of animal products), since the pathway of Cd to wheat leads to the lowest critical Cd content in soils”* ((de Vries et al. 2005), p. 15, section 2.1, ll. 16-21).

Based on the mean consumption data an average wheat consumption of 400g/d per person is assumed and an amount of 600g/d for high consuming people (95-percentile). The fraction of heavy metals resorbed by the human body is set to 15% (Schütze and Spranger 2002). Thus, the effective amount of metals taken in via food consumption is calculated by:

$$Effective\ consumption = Total\ consumption * 0.15$$

Effective consumption = amount of cereal consumption, whose metal content is completely resorbed [g/d]

Total consumption = total cereal consumption [g/d]

The tolerable heavy metal content in wheat is calculated by dividing the tolerable intake via food consumption (see Table 24) through the effective consumption.

$$Tolerable\ wheat\ concentration = \frac{TDI\ (food)}{Effective\ consumption}$$

Tolerable wheat concentration = tolerable heavy metal concentration in wheat [mg/kg$_{freshweight}$]

TDI (food) = tolerable daily intake attributed to food consumption (see Table 24)

Effective consumption = amount of cereal consumption, whose metal content is completely resorbed [g/d]

In order to calculate tolerable soil concentrations, plant concentration were back-calculated via:

$$Tolerable\ soil\ concentration = \frac{Tolerable\ wheat\ concentration}{BCF}$$

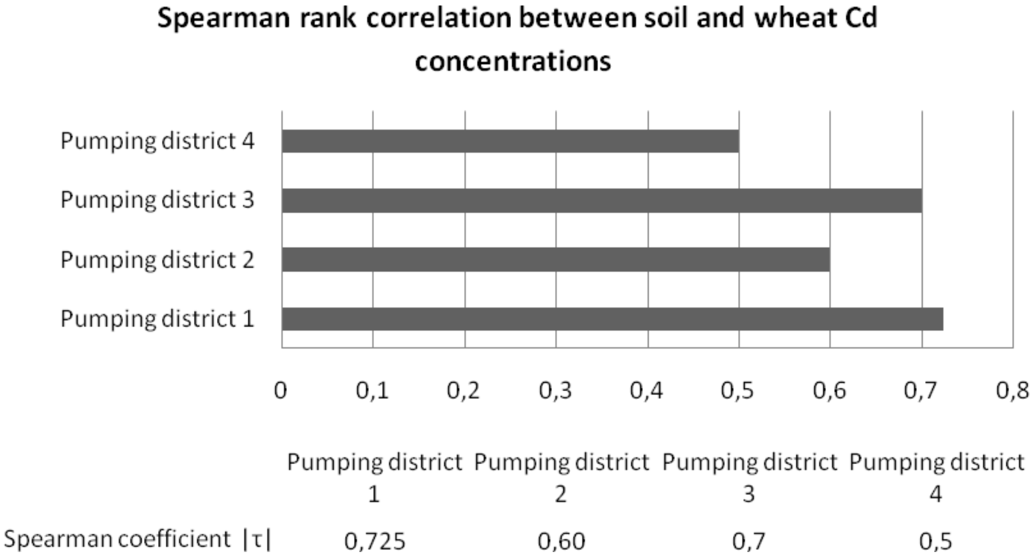
Tolerable soil concentration = tolerable soil concentration for human health [mg/kg$_{soil}$(dw)]

Tolerable wheat concentration = tolerable heavy metal concentration in wheat [mg/kg$_{freshweight}$]

BCF = Bioconcentration factor

The bioconcentration factor (BCF) is defined as the ratio between plant and soil concentration. Since only cadmium plant concentrations are monitored in Braunschweig, BCFs of the remaining heavy metals were taken from literature (VKM 2009).

As soil and wheat concentrations of Cadmium are measured just once a year, the measured data were first checked for correlation, in order to determine if the measured data are reliable enough to calculate a BCF. Correlation was checked using Spearman rank correlation. A Spearman coefficient |τ| ≥ 0.6 indicates correlation ((Haas et al. 1999)) (Figure 19).



	Pumping district 1	Pumping district 2	Pumping district 3	Pumping district 4
Spearman coefficient |τ|	0,725	0,60	0,7	0,5

Figure 19: Spearman rank correlation test for Cadmium soil and wheat concentrations. A Spearman coefficient |τ|≥ 0.6 indicates correlation.

Subsequently, the overall mean wheat concentration was divided by the overall mean soil concentration to determine the BCF. A dry matter content of 86% is applied for wheat (Ripke, personal correspondence).

Both soil and wheat concentrations are measured in Braunschweig. The measurement just takes place once a year. No information is available on the sampling and measurement program. Moreover, paired data of soil and wheat concentrations are just available for the years 1995-1999 and 2009-2010 for the respective pumping districts. Thus, additionally to the soil-wheat relation calculated by the application of a BCF, another soil-wheat relation formulated by De Vries et al. 2003 published in (Schütze and Spranger 2002) is applied to account for present uncertainties.

$$\log(Csoil_{tol}) = \frac{\log\left(c(Cd)_{plant}\right) - 0.35 + 0.15pH + 0.39\log\,(OM)}{0.76}$$

$Csoil_{tol}$ = tolerable soil concentration [mg/kg_{soil}(dw)]

$c(Cd)_{plant}$ = cadmium concentration in wheat [mg/kg_{wheat}(fw)]

OM = fraction of organic matter [%]

Based on these methods the following tolerable wheat and soil concentrations are calculated for average human consumption and high human consumption (Table 25 and 28).

Table 25: derived tolerable wheat and soil concentrations for average food consumption

Metal	Effective consumption (average) [g/d]	Critical wheat concentration [mg/kg$_{freshweight}$]	BCF	Critical soil concentration [mg/kg$_{dw}$]	Critical soil concentration [mg/kg$_{dw}$] (De Vries et al. 2003)
Cadmium	60	0.2	0.29	0.69	0.87
Chromium	60	8.3	0.017	490	
Copper	60	41.7	0.26	160	
Lead	60	2.1	0.0009	2314	
Mercury	60	0.4	0.013	32	
Nickel	60	-	0.06		
Zinc	60	208	0.17	1225	

Table 26: derived tolerable wheat and soil concentrations for high food consumption

Metal	Effective consumption (high) [g/d]	Critical wheat concentration [mg/kg$_{freshweight}$]	BCF	Critical soil concentration [mg/kg$_{dw}$]	Critical soil concentration [mg/kg$_{dw}$] (De Vries et al.)
Cadmium	90	0.14	0.29	0.48	0.54
Chromium	90	5.5	0.017	327	
Copper	90	27.8	0.26	106	
Lead	90	1.4	0.0009	1543	
Mercury	90	0.28	0.013	21	
Nickel	90	-	0.06		
Zinc	90	138	0.17	817	

Due to its low TDI and high plant uptake Cadmium shows the lowest tolerable soil concentration concerning human health risks. Moreover, the differences in the two different formulation of the soil-wheat relation become visible. The equation proposed by De Vries et al. 2003 leads to higher tolerable soil concentrations. Concerning the remaining metals, the highest tolerable soil concentration is attributed to lead, which is hardly taken up by plants. Moderate concentrations are attributed to Copper, Chromium and Zinc. Mercury shows tolerable soil concentrations significantly higher than the ones calculated for Cadmium. As no intake data for Ni was found no tolerable soil concentration could be calculated concerning human health impacts.

7.2.3 Tolerable concentrations for environmental endpoints

Table 8 gives an overview of relevant receptors which are exposed directly or indirectly via the two ecosystems of concern, namely arable land and the aquatic ecosystem. PNECs and critical concentrations for the respective endpoints are collected from literature. For environmental risk assessment relevant receptors are soil microorganisms, soil invertebrates as well as mammals and birds. For the assessment of risks concerning soil microorganisms and soil invertebrates PNEC$_{soil}$ for the respective metals are used as the tolerable value. Mammals and birds are not directly exposed to metals but are exposed indirectly via the food chain. Schütze and Spranger back-calculated critical soil contents from acceptable daily intakes (ADI) for birds and mammals (Schütze and Spranger 2002). The badger was taken as a reference animal for worm eating mammals, whereas for the calculation of critical soil contents for impacts on worm eating birds the black-tailed godwit was chosen. Within this study the authors state that *"the only metal in which indirect impacts due to accumulation in the food chain may cause lower critical soil metal contents […] is Cd"* ((Schütze and Spranger 2002), section 4.1.6, ll.11-12). Therefore, environmental risk assessment due to secondary poisoning of mammals and birds is reduced to Cadmium. For the other metals the $\text{PNEC}_{\text{soil}}$ values are considered to protect also higher trophic levels. Within the European risk assessment report for Cadmium an additional $\text{PNEC}_{\text{soil}}$ for the assessment of mammals and birds exposure is proposed (ECB 2007a). Both are used and compared.

For environmental impacts on the aquatic ecosystem, algae and crustacea are the receptors of concern. To assess risk on these aquatic organisms $\text{PNEC}_{\text{water}}$ values are collected.

Table 27 gives an overview on the used literature for the respective PNECs and critical contents.

Table 27: sources used for the respective critical soil and water contents and concentrations

Metal	Source of $\text{PNEC}_{\text{soil}}$	Source of $\text{PNEC}_{\text{water}}$	Source of critical soil content for birds	Source of critical soil content for mammals
Cadmium	European Chemicals Bureau, 2007	(ECB 2007a)	(Schütze and Spranger 2002), (ECB 2007)	(Schütze and Spranger 2002), (ECB 2007a)
Chromium	European Chemicals Bureau, 2005	(VKM 2009)		
Copper	European Copper Institute, 2008	(ECI 2008)		
Lead	EURAS, 2008	(ECB 2007b)		
Mercury	Euro-Chlor, Voluntary Risk Assessment, Mercury, 2004	(VKM 2009)		
Nickel	Danish Environmental Protection Agency, 2006	(ECB 2008)		
Zinc	VROM, 2008	(JRC 2010)		

The literature review on critical soil concentrations and predicted no effect concentrations (PNEC) for the respective endpoint led to the following values (Table 28).

Table 28: PNECs and critical concentrations for the different environmental endpoints of concern

Metal	$PNEC_{soil}$ [mg/kg_{soil}(dw)]	$PNEC_{water}$ [µg/L]	Critical soil content for birds (black tailed godwit) [mg/kg_{soil}(dw)]	critical soil content for mammals (Badger) [mg/kg_{soil}(dw)]	$PNEC_{soil}$ for mammals and birds (EU) [mg/kg_{soil}(dw)]
Cadmium	1.15	0.08	0.14*	0.067*	0.9**
Chromium	62	3.4			
Copper	89.6	7.8			
Lead	166	7.2			
Mercury	0.3	0.047+BC			
Nickel	50	5			
Zinc	26+BC	7.8+BC			

*calculated by Schütze et al. 2002
**taken from the European Risk Assessment Report for Cadmium Metal (ECB 2007a)

For cadmium impacts on soil organisms and soil invertebrates lead to the highest tolerable concentrations ($PNEC_{soil}$). The tolerable values the European risk assessment report on Cadmium published for animals is approximately 8 times higher than the ones published by Schütze et al. 2002.

For soil organisms as well as for surface waters, Mercury and Cadmium show the lowest PNECs. The highest are attributed to Zinc and Copper.

7.3 Exposure assessment

Tolerable risks for human health concerning heavy metal exposure are a back-calculated to soil and wheat concentrations. For the environmental endpoints soil microorganisms, soil invertebrates, bird and mammals tolerable risks levels via direct and indirect environmental exposure are expressed as critical soil contents as well. Thus, the calculation of soil concentration is the essential step in risk assessment via the terrestrial compartment. Heavy metals are not biodegradable and tend to accumulate in soil. Therefore, the environmental risk is considered to be tolerable if the modeled concentrations and contents do not exceed the PNEC within a hundred years. This approach follows a risk assessment conducted by the Norwegian Scientific Committee for Food Safety (VKM 2009). The 100 years are chosen since this time frame seems to be still imaginable and manageable.

7.3.1 Determination of annual loads

The first step of exposure modeling is the calculation of the average annual loads of the respective metal, which are distributed on the agricultural areas. The measured monitoring data for heavy metals are first checked for plausibility and consistency. For this purpose simplified mass balances for the respective metals are calculated and the ratio between effluent to influent loads determined.

$$Cinf * \dot{V}inf = Ceff * \dot{V}eff + Cps * Mps + Css * Mss$$

Cinf = annual mean influent concentration [mg/L]

Vinf = influent rate [m^3/year]

Ceff = annual mean effluent concentration [mg/L]

Veff = effluent rate [m^3/year]

Cps = annual mean concentration in primary sludge [mg/kg_{sludge}(dw)]

Mps = mass of produced primary sludge [kg_{sludge}(dw)/year]

Css = annual mean concentration in surplus sludge [mg/kg_{sludge}(dw)]

Mss = mass of produced surplus sludge [kg_{sludge}(dw)]/year]

The ratios between influent to effluent loads are shown in Table 29.

Table 29: ratios between effluent and influent loads based on the measured monitoring data in STP Steinhof

Metal	Effluent/influent ratio [%]
Cadmium (Cd)	124
Chromium (Cr)	91
Copper (Cu)	87
Lead (Pb)	54
Mercury (Hg)	532
Nickel (Ni)	89
Zinc (Zn)	106

The results are regarded as plausible if the calculated ratio is between 85 and 115%. For the metals Cd, Cr, Cu, Ni and Zn, thus, measured data were used for further calculations.

Because of its high toxicity for Cd effluent measurements are used. The large gap in the Hg mass balance can be explained by the low concentrations in the effluent of the STP Steinhof as well as in the primary sludge. Both fall below the limit of quantification. One has to mention that the latest data which were available for this study were from 2010. The mass balances for Cd, Hg and Pb for 2011 would fulfill the plausibility criterion.

For Pb and Hg annual loads are therefore calculated based on measured influent concentrations. Effluent and sludge concentration were modeled using the formulas from the TGD ((EU 2003), part 2, section 2.7.1). Calculations are based in measured influent concentrations.

$$Ceff = Cinf * Fstp_{water}$$

Ceff = concentration in the effluent of the STP [mg/L]

$Fstp_{water}$ = fraction of emission directed to water by STP []

$$Csludge = \frac{Fstp_{sludge} * Erate_{water} * 10^6}{sludgerate}$$

Csludge = metal concentration in sewage sludge [mg/kgdw]

$Fstp_{sludge}$ = fraction of emission directed to sewage sludge by STP []

$Erate_{water}$ = metal emission to water [kg/d]

Sludgerate = rate of sewage sludge production [kg_{sludge}(dw)/d]

$$Erate_{water} = \frac{Cinf * \dot{V}inf}{365}$$

$Erate_{water}$ = metal emission to water [kg/d]

Cinf = annual mean influent concentration [mg/L]

Vinf = influent rate [m^3/year]

$$sludgerate = \frac{Mps + Mss}{365}$$

Sludgerate = rate of sewage sludge production [kgdw/d]

Mps = mass of produced primary sludge [kgdw/year]

Mss = mass of produced surplus sludge [kgdw/year]

Values for the fractions of emission directed to wastewater and sewage sludge, respectively, are taken from ((Thornton et al. 2001), p.45)

Table 30: fractions of Lead and Mercury directed to sewage sludge after primary sedimentation and activated sludge treatment (Thornton et al. 2001).

Metal	$Fstp_{sludge}$ [%]
Lead	70
Mercury	80

Table 31 shows the calculated annual heavy metal loads in the STP Steinhof.

Table 31: mean calculated annual load for the STP Steinhof. Influent loads of all heavy metals as well as the annual cumulative loads directed to irrigation for Cadmium, Chromium, Copper, Nickel and Zinc are based on mean measured data. Values for Lead and Mercury were calculated using the models outlined in section 7.3.1.

Metal	Influent load [kg/a]	Effluent load to irrigation [kg/a]	Sludge load to irrigation [kg/a]	Annual load [kg/a]
Cadmium	10.8			5.5
Chromium	226.2			90.9
Copper	1837			828.2
Lead	491.5	48.6	229.8	278.4
Mercury	6.7	0.9	2.9	3.8
Nickel	357			94.8
Zinc	5112			2381.8

7.3.2 Calculation of soil concentrations

Based on the annual heavy metal loads soil concentrations are calculated by using the equations of the Technical Guidance Document model (TGD)((EU 2003), part 2, section 2.3.8.5). The development of soil concentrations of heavy metals is calculated for a time period of a hundred years.

Once released into the soil environment the behavior of heavy metals strongly depends on the environmental conditions. Metal mobility and availability determine to which amounts metals are taken up by plants, being leached into the groundwater or accumulate in the soil. Mobility and availability in turn are depended on both the physical-chemical properties of the respective metal and the surrounding environmental conditions. Therefore, the surrounding conditions have to be determined. The Technical Guidance Document includes a set of default values for environmental conditions for calculating soil concentrations. As far as local data for the respective parameters are available for Braunschweig, the default data are replaced. Values and sources are presented in Table 32.

Table 32: values for surrounding conditions used for the calculation of soil concentrations. Moreover, the respective symbols used in the following calculations and data sources are outlined.

Parameter	Symbol	Value	Unit	Source
Rain rate	*RAINrate*	599	mm/a	Climate data Braunschweig
Temperature	*T_C*	9.2	°C	Climate data Braunschweig
Soil pH	*pH*	5.9		Measured data, (Ternes et al. 2003)
Bulk density of soil	rho_{soil}	1700	kg/m³	((EU 2003), section 2.3.4)
Mixing depth of soil	$Depth_{soil}$	0.2	m	((EU 2003), section 2.3.8.5)
Infiltration rate of rain into soil	$Finf_{soil}$	0.25		((EU 2003), section 2.3.8.5)
Fraction of organic carbon is soil	*Foc*	0.9	%	Measured data, (Ternes et al. 2003)

In order to calculate soil metal concentrations annual inputs and outputs are taken into account.

Inputs

The two main inputs of heavy metals in the conducted calculations are the annual loads applied via wastewater and sewage sludge and atmospheric deposition.

The TGD does not consider permanent wastewater irrigation but solely refers to sludge application. Therefore, for the calculation of soil concentration it is assumed that the total heavy metal load is present in sewage sludge which is applied once in the beginning of the each year. The increase of soil concentrations due to sludge application is calculated by:

$$Csludge_{soil} = \frac{Load_{Metal}}{Depth_{soil} * rho_{soil}}$$

$Csludge_{soil}$	= increase of soil metal concentration due to 1 year of sludge application [mg/kg]
$Depth_{soil}$	= mixing depths of soil [m]
rho_{soil}	= bulk density of soil [kg/m^3]
$Load_{Metal}$	= annual metal load [mg/m^2*a]

The increase of soil concentration due to atmospheric deposition is calculated by:

$$Dair = \frac{DEPtotal_{ann}}{Depth_{soil} * rho_{soil}}$$

$Depth_{soil}$	= mixing depths of soil [m]
Rho_{soil}	= bulk density of soil [kg/m^3]
Dair	= aeral deposition flux per kg of soil [mg/kg*d]
$DEPtotal_{ann}$	= annual average total deposition flux [mg/m^2*d]

Values for the total annual deposition in Germany are shown in Table 33.

Table 33: annual atmospheric deposition of heavy metals in Germany

Source	Cd [g/ha*a]	Cr [g/ha*a]	Cu [g/ha*a]	Hg [g/ha*a]	Ni [g/ha*a]	Pb [g/ha*a]	Zn [g/ha*a]
(Böhm et al. 2000)	2	5	30	0.2	15	40	250

Outputs
The TGD model considers biodegradation, volatilization and leaching as the main output fluxes for chemicals. As metals are neither biodegradable and (except from some single organic Hg-compounds) not volatile those outputs are set to zero.

Thus, the overall output constant k is calculated by:

$$k = kleach$$

k = *first order rate constant for removal from top soil* [d^{-1}]

kleach = *pseudo-first order rate constant for leaching from top soil* [d^{-1}]

kleach is calculated by:

$$kleach = \frac{Finf_{soil} * RAINrate}{Kd_{soil-water} * Depth_{soil} * rho_{soil} * 10^{-3}}$$

$Finf_{soil}$ = *fraction of rainwater that infiltrates into soil []*

RAINrate = *rate of wet precipitation [m/d]*

$Kd_{soil\text{-}water}$ = *soil-water partitioning coefficient* [L/kg_{soil}]

$Depth_{soil}$ = *mixing depth of soil [m]*

kleach = *pseudo-first order rate constant for leaching from top soil* [d^{-1}]

Partitioning coefficients are taken from literature (Table 34).

Table 34: Partitioning coefficients used for calculating leaching processes from top soil

Metal	$Kd_{soi\text{-}water}$[L/kg]	Source
Cd	280	(ECB 2007a)
Cr	3000	(VKM 2009)
Cu	Log Kd = 1.75 + 0.21pH + 0.51log(Foc)	(ECI 2008)
Hg	3000	(VKM 2009)
Ni	Log Kd = 2.86	(ECB 2008)
Pb	6400	(ECB 2007b)
Zn	Log Kd = 3.07	(JRC 2010)

Irrigation represents a water flux additional to the annual rain rate. Therefore, the amount of irrigated water is added to the average annual rain rate

The overall soil concentration over the year is calculated by combining input and outputs via:

$$Csoil(t) = \frac{Dair}{k} - \left[\frac{Dair}{k} - Csoil(0)\right] * e^{-kt}$$

with

$$Csoil(0) = Csludge_{soil} + Cinitial$$

Csoil(0) = Soil metal concentration in the beginning of the year after sludge application [mg/kg$_{dw}$]

Csludge$_{soil}$ = increase of soil metal concentration due to sludge application [mg/kg$_{dw}$]

Cinitial = soil concentration before the first sludge application [mg/kg$_{dw}$]

For the determination of the initial soil metal concentration measured monitoring data of the four pumping districts are used. The overall mean of the available data is taken as the initial soil concentration. As mentioned above the pumping districts are subdivided into 5-7 smaller areas, respectively. In the pumping districts I and II the single areas show comparable mean soil concentrations. In pumping district III two out of 7 areas show elevated heavy metal concentrations, which are already above the limit value for sludge application of 1mg/kg$_{soil}$(dw). Moreover, in pumping district IV one out of 5 areas shows elevated heavy metal concentrations as well. On this area not only the limit for Cd but also the ones for Pb and Zn are exceeded.

The elevated soil concentrations in pumping district III originate from the past, as no wastewater treatment had been in place, yet. In this time wastewater was stored on these areas for the settlement and thus the removal of solid fractions prior to irrigation. On area 5 of pumping district IV the elevated concentrations have a different origin. The metal concentrations in this area are increased because it lies within the flooding area of the river Oker (Ripke, personal correspondence). It happens to be that this river has its source in the Harz Mountains, where extensive mining for metal ores in the past still causes high metal concentrations in the river and its sediment.

Nevertheless, in environmental and human health risk assessment all relevant inputs have to be considered. Statements have to be based on soil concentrations, independently from their origin.

Therefore, the pumping districts III and IV are treated differently from pumping districts I and II. In addition to using mean soil concentrations of the whole district, future soil concentrations are calculated for each single area, using the area specific annual mean concentration, respectively. Table 35 shows the mean measured metal concentrations in top soil in the single pumping districts as well as the values of the single areas.

Table 35: overall mean heavy metal concentrations in top soil for the respective pumping districts and areas: Highlighted (fat, cursive) values indicated that the respective value exceeds the legislative limit value for sludge application

Pumping district	area	Pb	Cd	Cr	Cu	Ni	Hg	Zn
I	1	16.20	0.36	10.00	7.80	5.50	0.07	37.78
I	2	13.60	0.36	8.60	6.70	4.70	0.06	32.30
I	3	15.20	0.35	8.90	7.20	5.00	0.07	37.20
I	4	17.56	0.71	12.00	10.78	7.00	0.11	54.56
I	5	16.60	0.43	10.60	8.80	7.10	0.07	44.40
Pumping district	area	Pb	Cd	Cr	Cu	Ni	Hg	Zn
II	1a	11.20	0.43	7.40	9.30	4.40	0.07	35.30
II	1b	11.00	0.39	7.60	9.30	4.10	0.07	35.70
II	1c	11.90	0.35	6.50	8.50	3.80	0.07	31.10
II	2	12.30	0.51	9.20	11.00	4.20	0.07	41.70
II	3	16.90	0.41	10.00	8.55	5.82	0.07	45.91
II	4	14.70	0.31	9.00	8.70	6.20	0.05	39.90
II	5	13.00	0.23	8.00	6.10	5.60	0.04	35.40
Pumping district	area	Pb	Cd	Cr	Cu	Ni	Hg	Zn
III	1a	20.40	***1.11***	11.90	18.40	6.80	0.18	63.50
III	1b	20.70	***1.15***	11.40	19.90	6.60	0.20	61.10
III	2a	14.90	0.55	9.10	13.40	5.30	0.11	45.40
III	2b	17.30	0.84	11.80	18.30	7.10	0.17	62.70
III	3	14.44	0.76	9.89	11.56	6.11	0.10	46.44
III	4	11.60	0.48	8.50	8.10	4.70	0.07	35.20
III	5	17.00	0.32	11.40	9.90	5.80	0.07	39.10
Pumping district	area	Pb	Cd	Cr	Cu	Ni	Hg	Zn
IV	1	10.20	0.20	5.10	4.00	2.70	0.05	20.50
IV	2	12.90	0.37	7.80	9.00	3.80	0.06	28.90
IV	3	15.30	0.33	8.50	10.20	4.60	0.06	35.30
IV	4	13.80	0.29	7.80	7.90	4.20	0.06	32.20
IV	**5**	***157.30***	***2.20***	28.00	41.20	21.60	0.18	***1107.0***

7.3.3 Calculation of PECsoil for terrestrial ecosystems and plant uptake

Sludge application in this model is treated as a single event in the beginning of the year. Soil concentration changes over the year as leaching and atmospheric deposition are continuous fluxes. Thus, an average value has to be determined. This average concentration is defined as the average concentration over a certain time period. The time period depends on the respective endpoint. For calculating the PECsoil, which is the endpoint concentration for terrestrial ecosystems, birds and mammals 30 days are chosen. For plant uptake an average time of 180 days is applied. The endpoint-specific soil concentrations are calculated by:

$$PECsoil(T)_{endpoint} = \frac{Dair}{k} + \frac{1}{kT}\left[Csoil(0) - \frac{Dair}{k}\right] * \left[1 - e^{-kT}\right]$$

Dair = aeral deposition flux per kg of soil [mg/kg*d]

k = first order rate constant for removal from top soil [d^{-1}]

T = endpoint specific averaging time [d]

$PECsoil(T)_{endpoint}$ = predicted environmental soil concentration for the respective endpoint [mg/kg_{dw}]

7.3.4 Calculation of PECwater due to surface runoff

As mentioned above environmental exposure assessment calculates concentrations instead of doses. The maximum concentration of surface waters as a result of any discharge is the concentration of the discharge itself. If the initial concentration of the surface water is already above the concentration of the respective discharge, the discharge would lead to dilution and thus to a reduction of the general concentration. Since this is rarely the case the TGD model assumes a default value for dilution of 10 (see (EU 2003), section 2.3.8.3). For Zn, Ni, Cu and Cr measured concentration from STP Steinhof for irrigation are used. For Cd, Hg, and Pb the calculated values are used. The annual load of the respective metal is divided by the annual amount of water and sludge as a first estimate for the concentration in irrigation water. The calculation assumes that sewage sludge has a density of 1kg/L.

Since only the dissolved fraction of the respective metal has toxic effect on water organisms, the partitioning between solids and water has to be considered (Kp_{susp}) as well as the amount of suspended matter in the receiving water body ($SUSP_{water}$). For the latter one the default value of the TGD of 15mg/L is used (see (EU 2003), section 2.3.8.3). The partitioning coefficients for the respective metal are taken from literature (Table 36).

Table 36: used partitioning coefficients for heavy metals in surface water

Metal	Kp_{susp} [L/kg]	Source
Cd	130000	(Hillenbrand et al. 2006a)
Cr	150000	Assumed to be comparable to Hg
Cu	30246	(ECI 2008)
Hg	150000	(Hillenbrand et al. 2006c)
Ni	$10^{4.42}$	(ECB 2008)
Pb	$10^{5.34}$	(ECB 2007b)
Zn	81000	(JRC 2010)

In PECwater due to surface runoff from agricultural areas is calculated by:

$$PECwater = \frac{Cwater_{irr}}{\left(1 + Kp_{susp} * SUSP_{water} * 10^{-6}\right) * DILUTION}$$

PECwater	= predicted environmental concentration in surface water [mg/L]
Kp_{susp}	= solids-water partitioning coefficient of suspended matter [L/kg]
SUSPwater	= concentration of suspended matter in the river [mg/L]
DILUTION	= dilution factor
$Cwater_{irr}$	= concentration of the metal in irrigation water [mg/L]

7.3.5 Metal concentrations in surface water

Table 37 shows the calculated surface water concentrations due to surface runoff from agricultural areas.

Table 37: Calculated surface water concentrations due to surface runoff from agricultural areas

Metal	PEC_{water} [µg/L]
Cadmium	0.015
Chromium	0.22
Copper	4.4
Lead	0.47
Mercury	0.0085
Nickel	0.66
Zinc	8.4

7.4 Risk characterization

Risk characterization for humans and environmental endpoints is conducted by calculating the risk quotient for the respective endpoints. Table 38 summarizes the used concentrations which are used for risk characterization.

Table 38: overview of the PECs, PNECs and critical concentrations (CC) used for the calculation of Risk Quotients (RQ) for the respective human and environmental endpoints

Endpoint/receptor	Risk quotient
Humans average consumption (hac)*	$RQ = \frac{PEC_{soil}180}{CC_{hac}}$
Humans high consumption (hhc)*	$RQ = \frac{PEC_{soil}180}{CC_{hhc}}$
Soil organisms	$RQ = \frac{PEC_{soil}30}{PNEC_{soil}}$
Birds (Schütze et al.)*	$RQ = \frac{PEC_{soil}30}{CC_{brd}}$
Mammals (Schütze et al.)*	$RQ = \frac{PEC_{soil}30}{CC_{mm}}$
Animals (EU)	$RQ = \frac{PEC_{soil}30}{PNEC_{soil}(animals)}$
Algae and crustacea	$RQ = \frac{PEC_{water}}{PNEC_{water}}$

*CC = critical concentration

7.4.1 Risk expressed as risk quotients

This section characterizes the environmental and human health risk with respect to heavy metals using Risk Quotients (see section 7.4). As mentioned above different averaging times are used for calculating soil concentrations for environmental and human assessment. Since there is just a slight difference between the two calculated soil concentrations just the soil concentration averaged over 30 days is shown in the following figures. The values for both soil concentrations are shown in Annex IV (section **Fehler! Verweisquelle konnte nicht gefunden werden.**).

7.4.1.1 Risk characterization concerning the terrestrial compartment

Cadmium soil concentrations as well as the points at which the calculated risk quotients for the respective endpoints exceed a value of 1 are illustrated in Figure 20, Figure 21, Figure 22 and Figure 23. Figure 21 shows soil concentrations in contrast to tolerable values concerning human health. Figure 22 focuses on environmental endpoints. The figures 23 and 24 show the area specific soil concentration of the pumping districts III and IV against tolerable human health values.

Concerning pumping district I and II Risk Quotients for birds and mammals from Schütze et al. are exceed the value of 1 from the beginning. The PNECs for soil concerning animals and soil organisms calculated by the European Risk assessment Report are not exceeded over 100 years irrigation. Concerning human consumption the current concentration is below both, the critical soil concentration for high and average consumption and show a stable or decreasing development.

Concerning the mean concentration of pumping district III the Risk Quotients for birds (R_{brd}) and mammals (R_{mm}) from Schütze et al. exceed the critical value of 1 at the beginning. The critical value for animals and soil organisms from the European Risk assessment Report are not exceeded and show in decreasing trend. However, if the areas are investigated separately, area 1 and 1b exceed the critical value from the European Risk assessment Report for animals and does not fall below this value, even not in a hundred years.

When it comes to human health effects the areas 1 and 1b exceed all derived critical soil concentrations for average and high consumption. The trend is decreasing but does not fall below any critical value in 100 years. The initial concentrations on area 2b and 3 lies between the two derived critical concentrations for average human consumption. They are both below the critical concentration derived with the DeVries soil-wheat relation and show a decreasing tendency. Nevertheless, they do not fall below the critical concentration for average human consumption derived with the BCF soil –plant relation. Areas 2a and 4 are not relevant for average human consumption. Area 4 falls below all critical values within 100 years. Area 2a falls below the critical value derived with the DeVries- relation but stays above the one derived with the BCF method. The concentrations on area 5 are not relevant for human health.

Concerning pumping district IV the areas 1-5 exceed the critical soil concentrations for birds and mammals from Schütze et al.. Concerning the remaining critical concentrations for environmental endpoints but also for human health areas 1-4 do not exceed any critical value within 100 years period. In contrast, area 5 exceeds all of them significantly and does not fall below any of them in 100 years.

Concerning lead, copper, Chromium, mercury and nickel in non of the pumping districts wastewater irrigation leads to Risk Quotients ≥ 1 over 100 years wastewater irrigation (Figure 24 to Figure 28).

Concerning zinc the Risk Quotient for soil organisms is exceeded in pumping district IV from the beginning if area 5 is included in the calculations. If not, the exceeding occurs in a time period of 70 years. In the pumping districts I, II, and III Risk Quotients for soil organisms are exceeded within 10 to 35 years. Risk Quotients for human health are not exceeded.

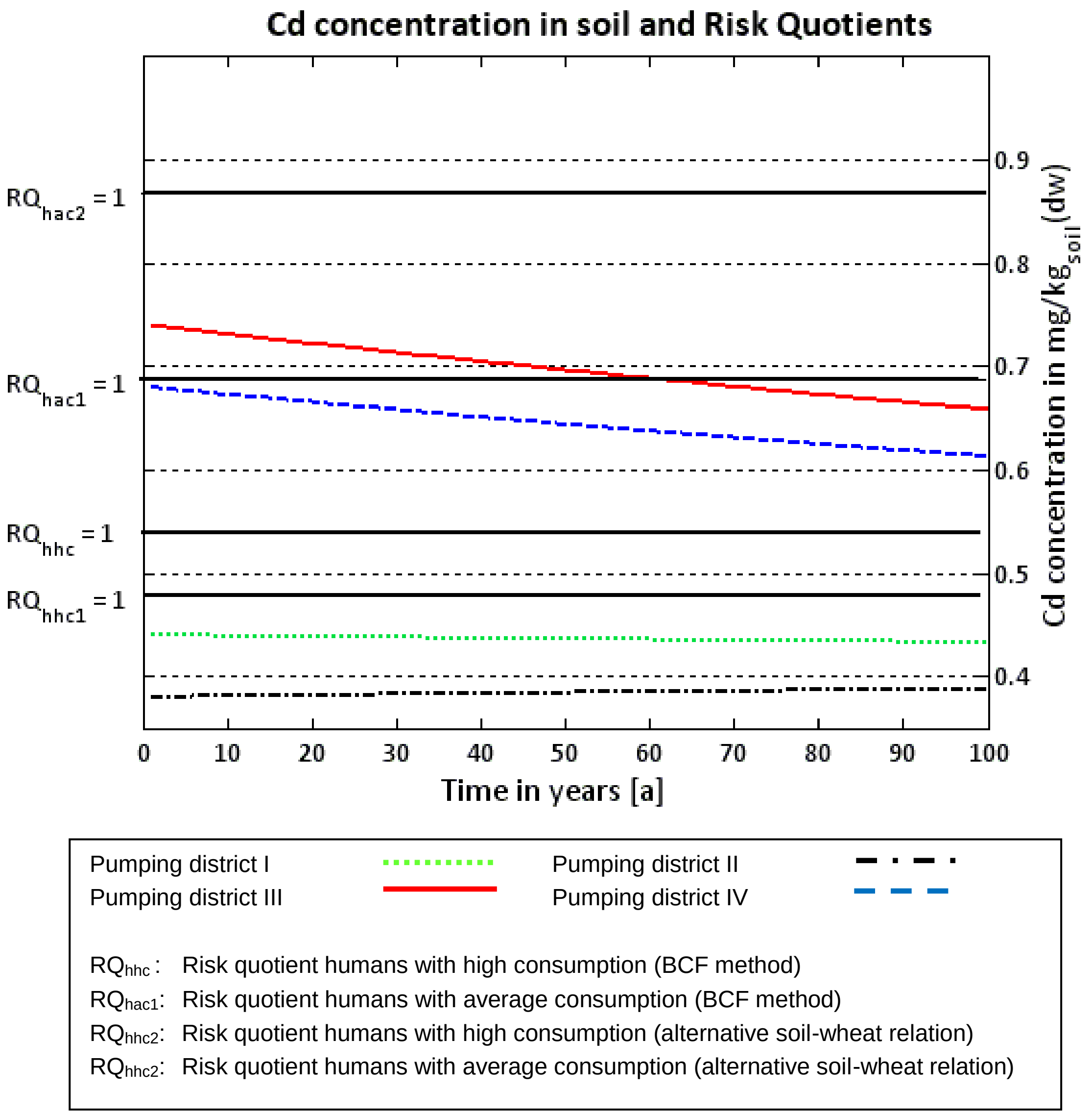


Figure 20: Cd concentrations in top soil over a hundred years time period. On the right x-axis the points are shown at which the Risk Quotients of the respective human endpoints equal one. Concentrations above the respective line indicate risk for the respective endpoint.

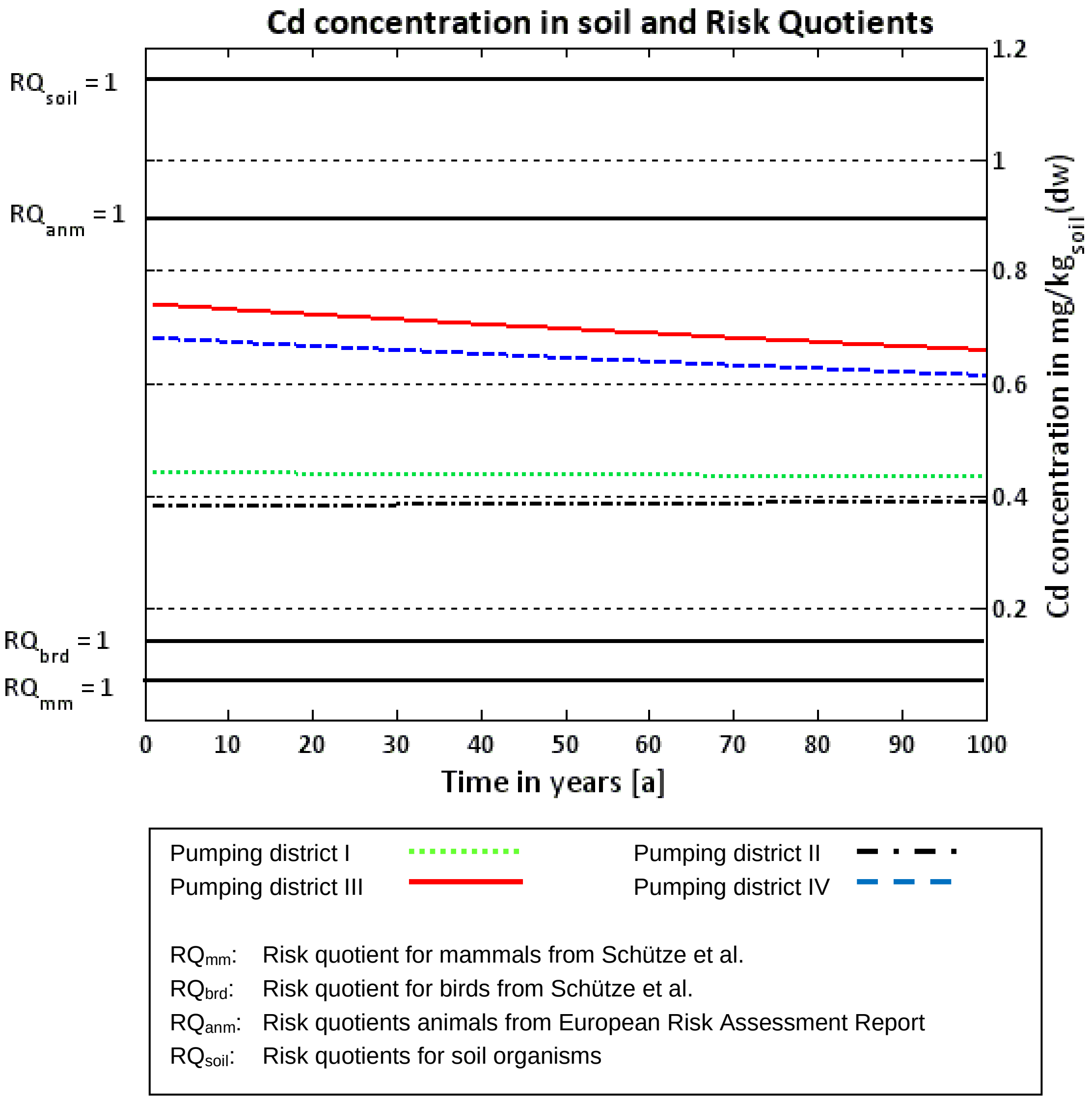
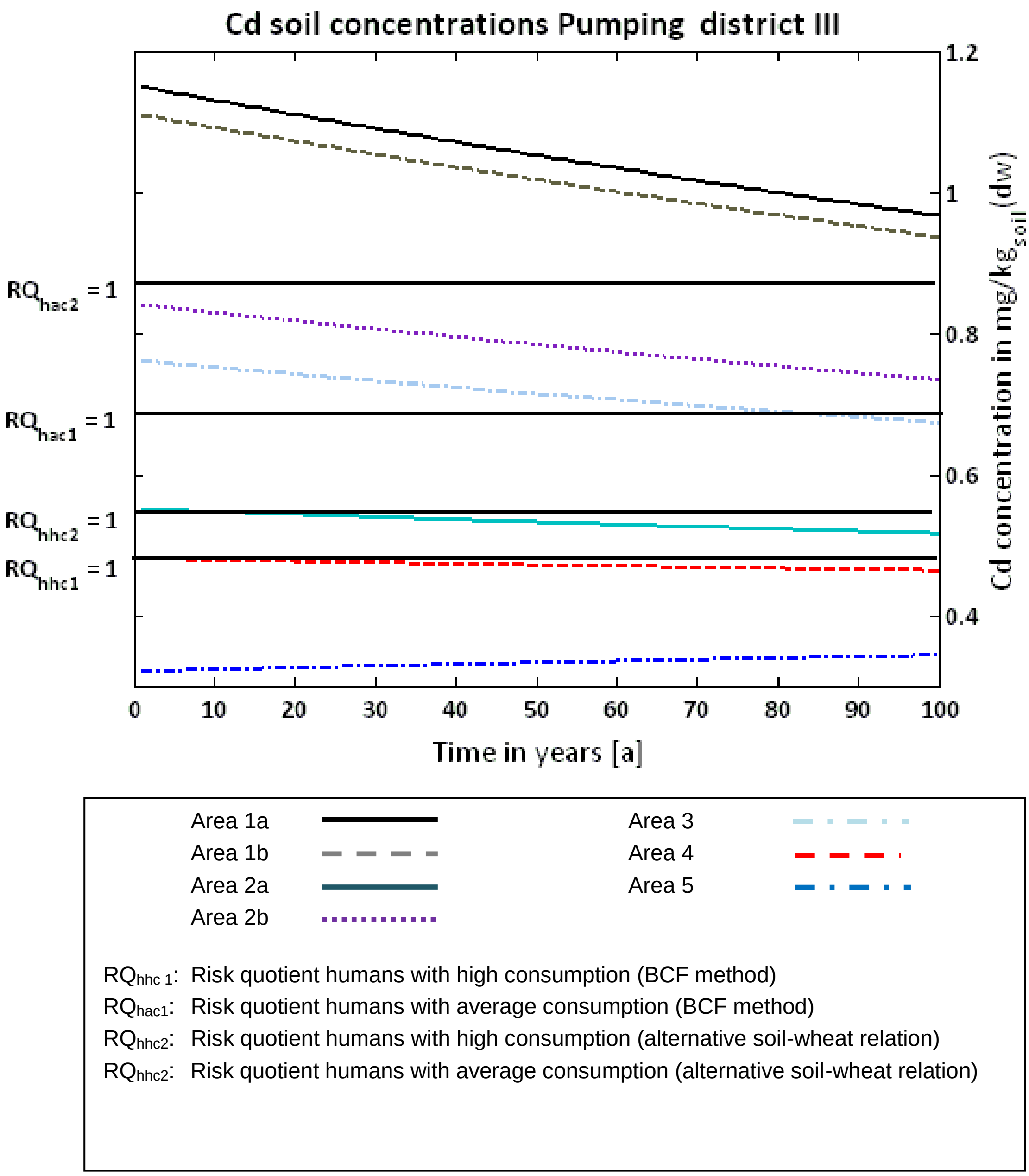
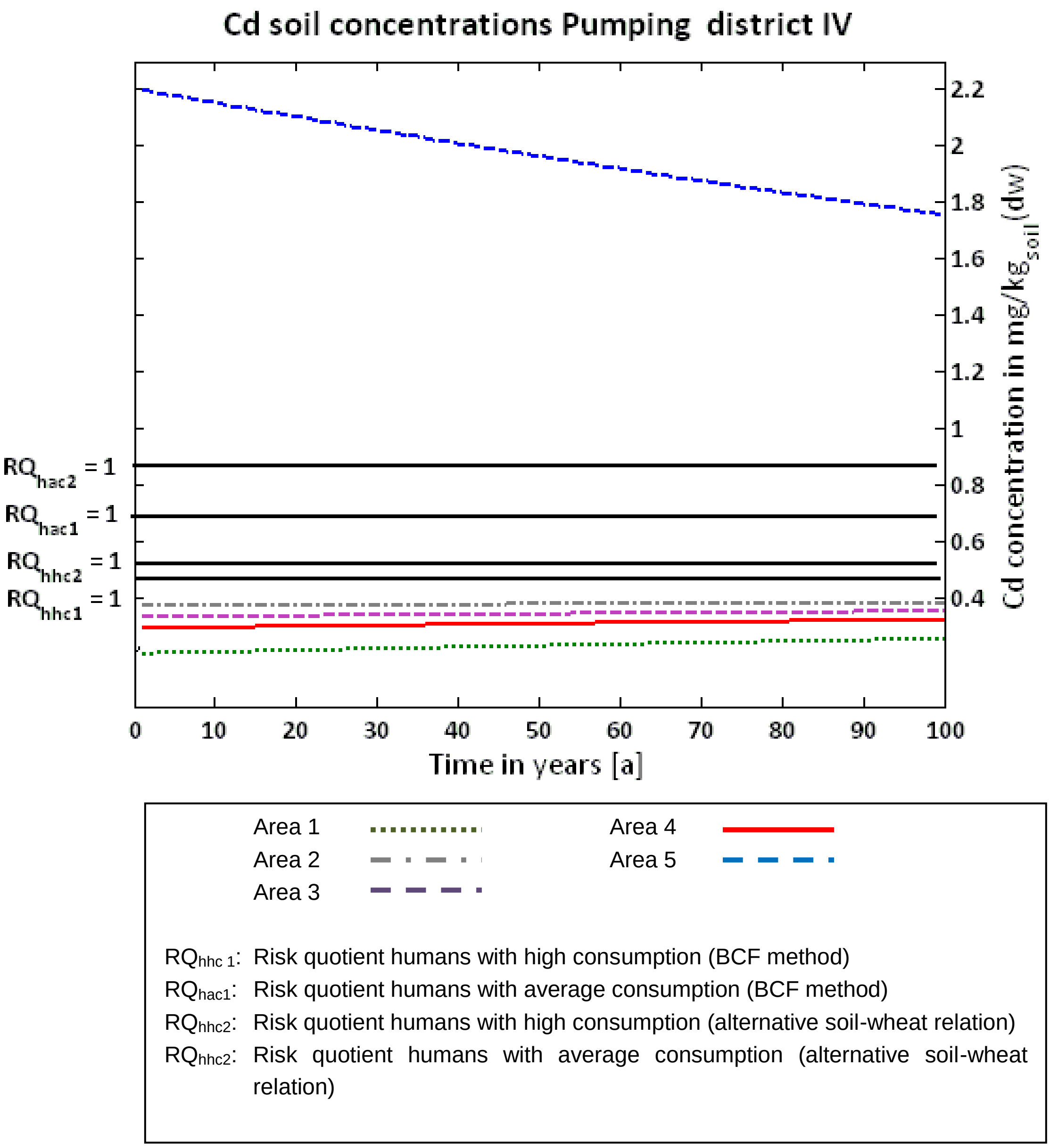


Figure 21: Cd concentrations in top soil over a hundred years time period. On the right x-axis the points are shown at which the Risk Quotients of the respective environmental endpoints equal one. Concentrations above the respective line indicate risk for the respective endpoint.



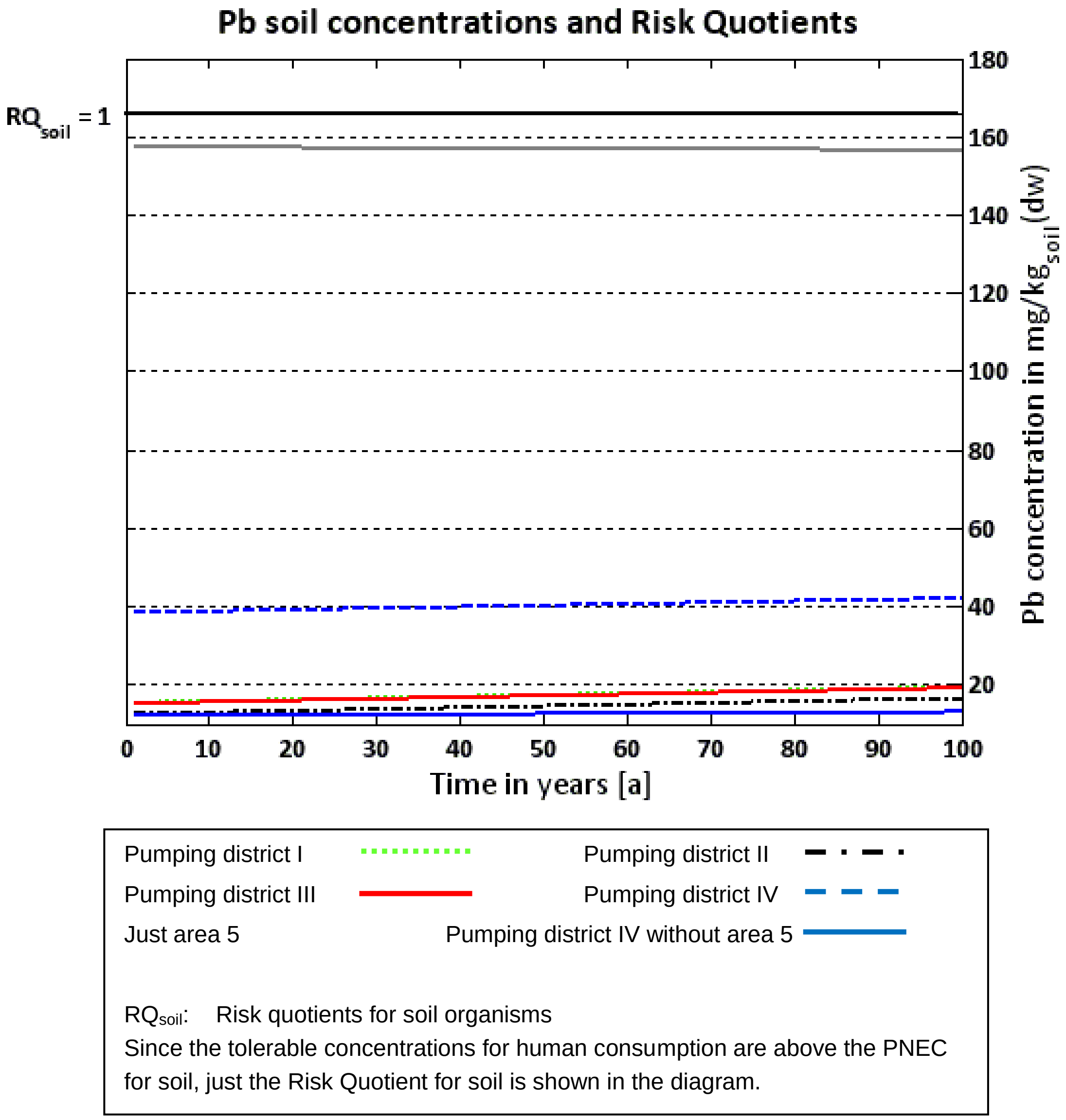
$RQ_{hhc\,1}$: Risk quotient humans with high consumption (BCF method)
RQ_{hac1}: Risk quotient humans with average consumption (BCF method)
RQ_{hhc2}: Risk quotient humans with high consumption (alternative soil-wheat relation)
RQ_{hhc2}: Risk quotient humans with average consumption (alternative soil-wheat relation)

Figure 22: Cd concentrations in top soil over a hundred years time period. On the right x-axis the points are shown at which the Risk Quotients of the respective human endpoints equal one. Concentrations above the respective line indicate risk for the respective endpoint.



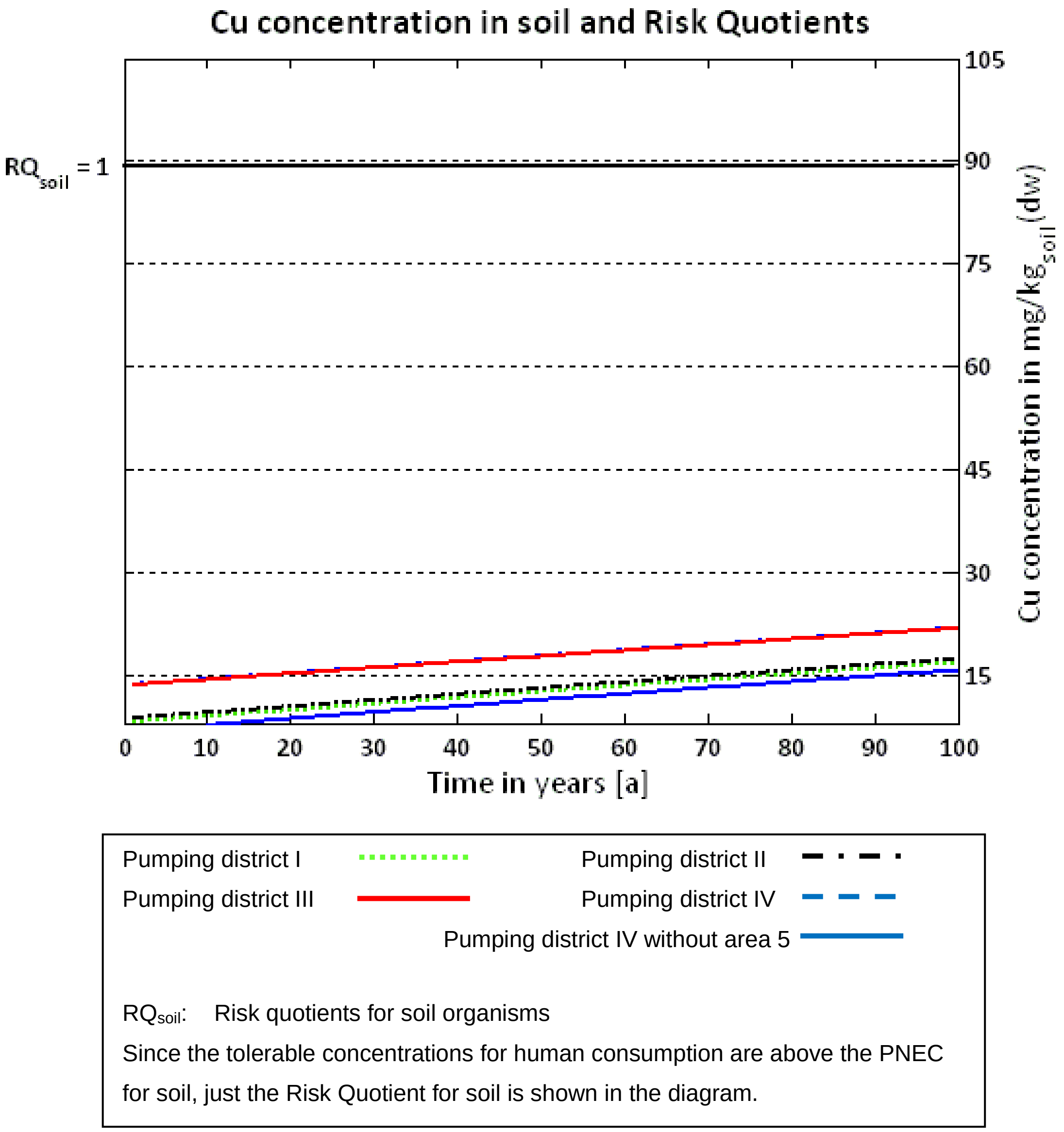
$RQ_{hhc\,1}$: Risk quotient humans with high consumption (BCF method)
RQ_{hac1}: Risk quotient humans with average consumption (BCF method)
RQ_{hhc2}: Risk quotient humans with high consumption (alternative soil-wheat relation)
RQ_{hhc2}: Risk quotient humans with average consumption (alternative soil-wheat relation)

Figure 23: Cd concentrations in top soil over a hundred years time period. On the right x-axis the points are shown at which the Risk Quotients of the respective human endpoints equal one. Concentrations above the respective line indicate risk for the respective endpoint.



RQ_{soil}: Risk quotients for soil organisms
Since the tolerable concentrations for human consumption are above the PNEC for soil, just the Risk Quotient for soil is shown in the diagram.

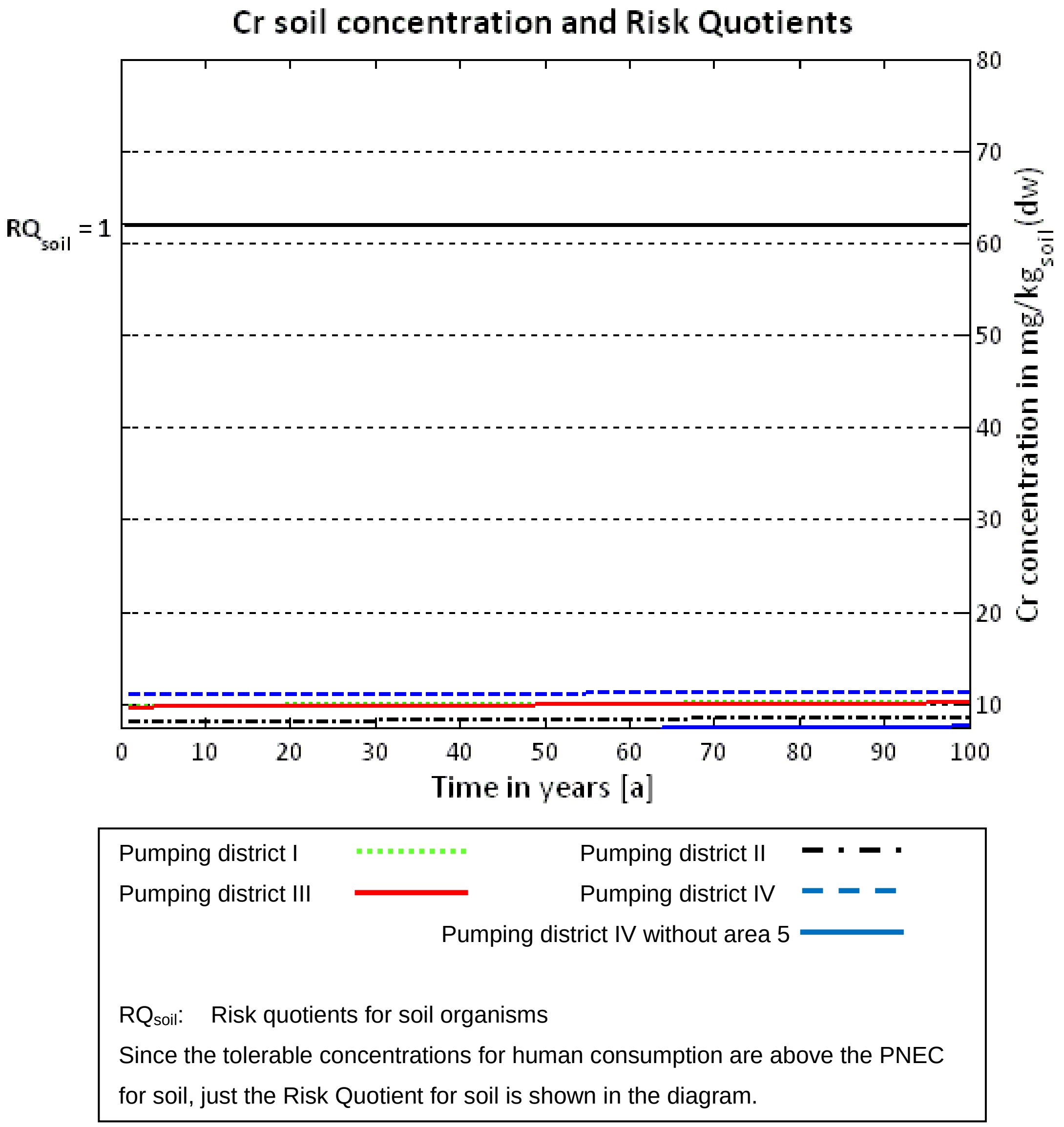
Figure 24: Pb concentrations in top soil over a hundred years time period. On the right x-axis the points are shown at which the Risk Quotients of the respective endpoints equal one. Concentrations above the respective line indicate risk for the respective endpoint.



RQ_{soil}: Risk quotients for soil organisms

Since the tolerable concentrations for human consumption are above the PNEC for soil, just the Risk Quotient for soil is shown in the diagram.

Figure 25: Cu concentrations in top soil over a hundred years time period. On the right x-axis the points are shown at which the Risk Quotients of the respective endpoints equal one. Concentrations above the respective line indicate risk for the respective endpoint.



RQ_{soil}: Risk quotients for soil organisms

Since the tolerable concentrations for human consumption are above the PNEC for soil, just the Risk Quotient for soil is shown in the diagram.

Figure 26: Cr concentrations in top soil over a hundred years time period. On the right x-axis the points are shown at which the Risk Quotients of the respective endpoints equal one. Concentrations above the respective line indicate risk for the respective endpoint.

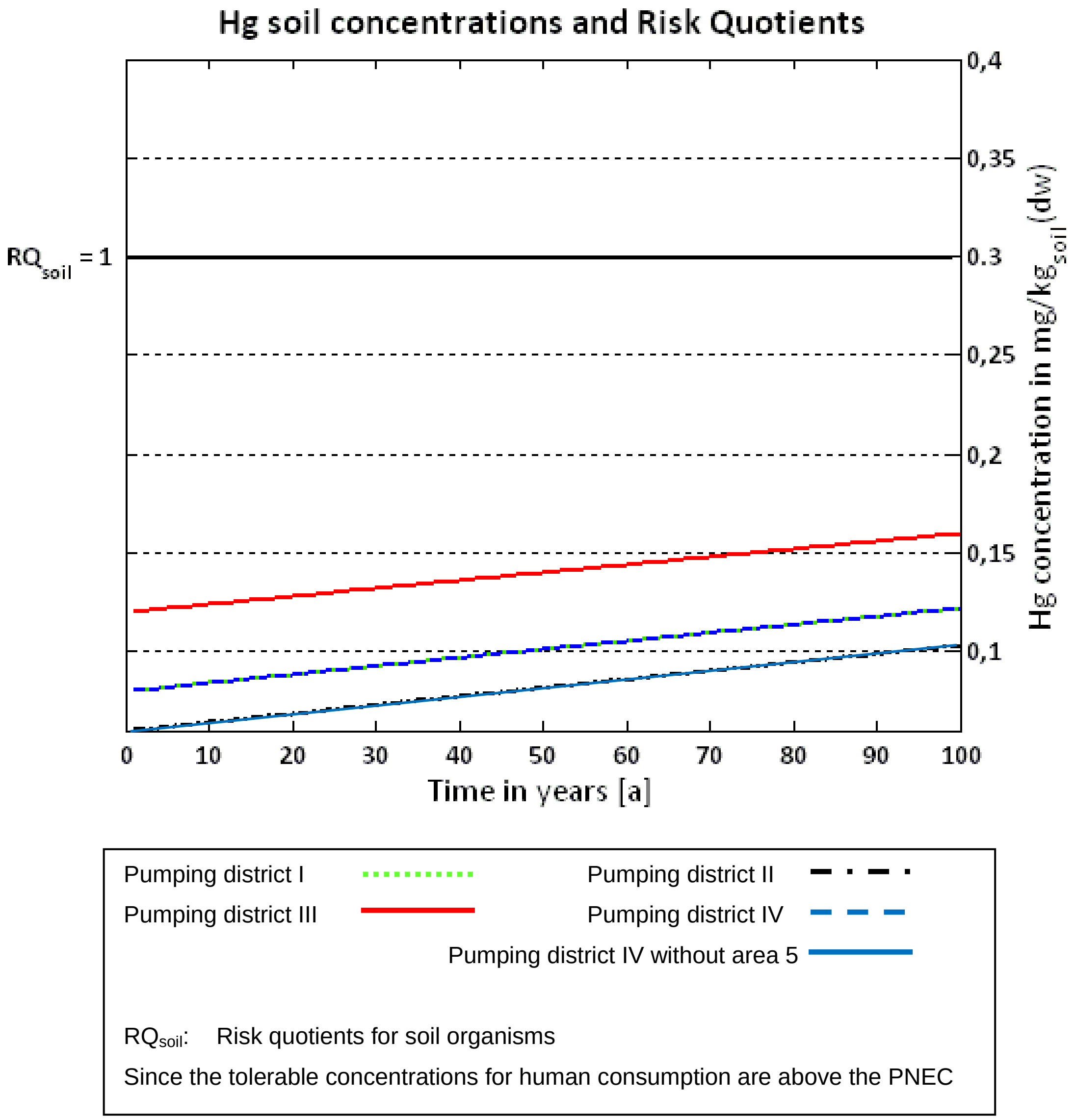
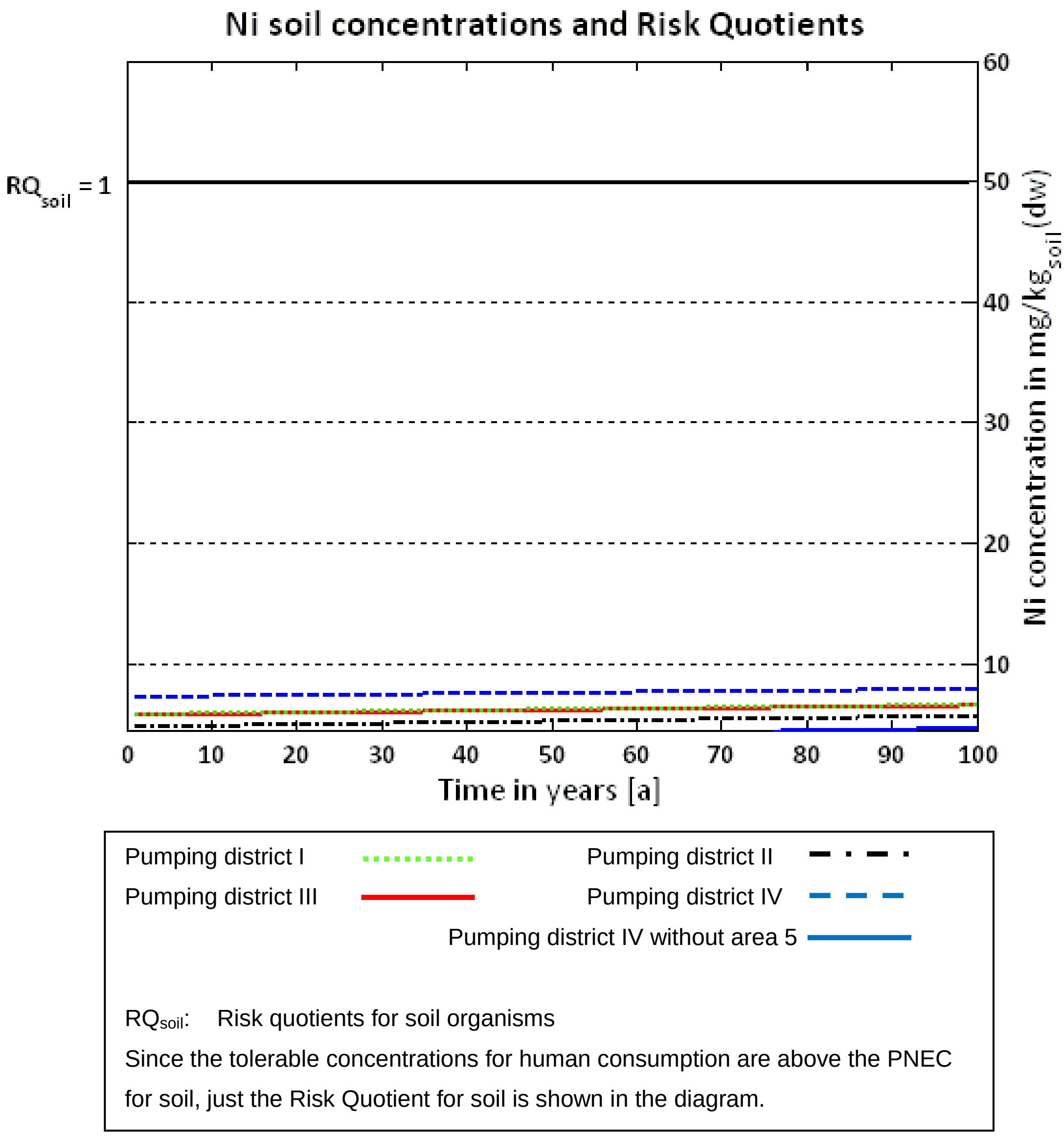


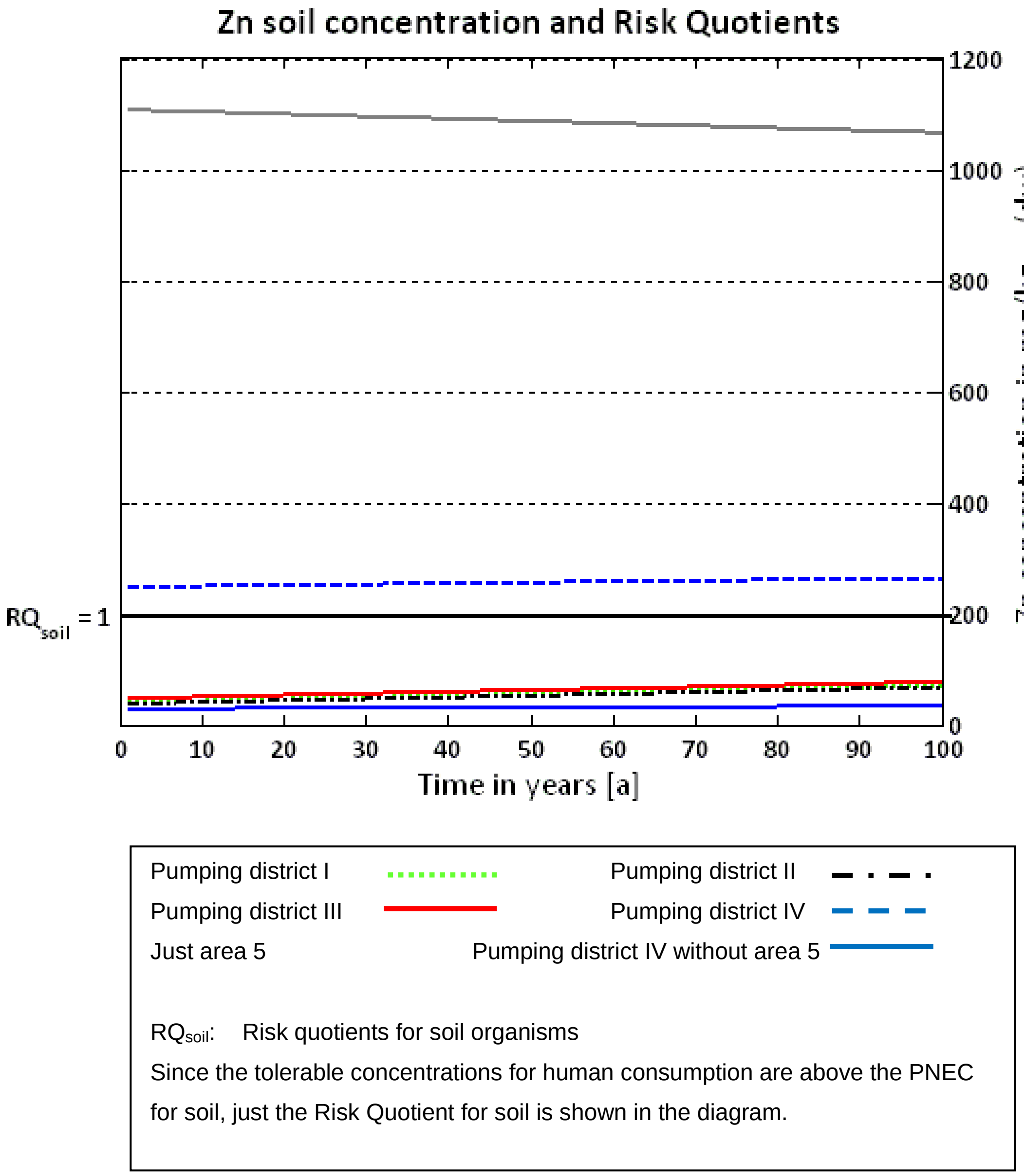
Figure 27: Hg concentrations in top soil over a hundred years time period. On the right x-axis the points are shown at which the Risk Quotients of the respective endpoints equal one. Concentrations above the respective line indicate risk for the respective endpoint.



RQ_{soil}: Risk quotients for soil organisms

Since the tolerable concentrations for human consumption are above the PNEC for soil, just the Risk Quotient for soil is shown in the diagram.

Figure 28: Ni concentrations in top soil over a hundred years time period. On the right x-axis the points are shown at which the Risk Quotients of the respective endpoints equal one. Concentrations above the respective line indicate risk for the respective endpoint.



RQ_{soil}: Risk quotients for soil organisms

Since the tolerable concentrations for human consumption are above the PNEC for soil, just the Risk Quotient for soil is shown in the diagram.

Figure 29: Zn concentrations in top soil over a hundred years time period. On the right x-axis the points are shown at which the Risk Quotients of the respective endpoints equal one. Concentrations above the respective line indicate risk for the respective endpoint.

7.4.1.2 Risk characterization concerning the aquatic compartment

Table 39 shows the calculated risk quotients for heavy metals in surface water due to surface runoff from the agricultural areas in Braunschweig.

Table 39: Calculated Risk Quotients for heavy metals in surface water due to surface runoff from agricultural areas in Braunschweig

Metal	PEC_{water} [µg/L]	$PNEC_{water}$ [µg/L]	$RQ_{surface\ water}$
Cadmium	0.073	0.08	0.1822
Chromium	0.22	3.4	0.0638
Copper	4.4	7.8	0.5679
Lead	0.47	7.2	0.0654
Mercury	0.0085	0.047+BC	0.1817
Nickel	0.66	5	0.1319
Zinc	8.4	7.8+BC	1.0726

Except from zinc all metal are well below the $PNEC_{water}$, resulting in a Risk quotient smaller than 1. Zinc is the only metal exceeding the $PNEC_{water}$.

7.5 Evaluation and discussion

The conducted QCRA of heavy metals show that, except from cadmium and zinc, heavy metals neither exceed the critical soil concentrations for human consumption nor the predicted no-effect concentrations (PNECs) for environmental endpoints.

The present zinc soil concentrations pose no risk for humans. Concerning environmental risks currently the $PNEC_{soil}$ is exceeded in pumping district IV if area 5 is included. The soil concentrations in the other pumping districts as well as when area 5 is excluded will all exceed the $PNEC_{soil}$ in the next 50 to 70 years. The $PNEC_{soil}$ for zinc on area 5 in district IV is exceeded significantly. Soil concentrations thus pose a risk for the terrestrial ecosystem.

Concerning the aquatic environment zinc concentrations exceed the $PNEC_{water}$, leading to a risk quotient of 1.07. The exceeding of the tolerable value (RQ=1) by a value of 0.07 means that modeled zinc concentrations in water pose a risk for algae and crustacea. Nevertheless, against the background of present uncertainties within the model this is not a significant exceeding.

Concerning area 5 in pumping district IV as well as areas 1 and 1b in pumping district III Cadmium concentrations exceed the critical concentrations for all relevant endpoints. Although the concentrations show a decreasing trend, concentrations do not fall below the critical concentrations within 100 years independently from the soil-wheat relation used for deriving tolerable soil concentrations. Against this background Cd poses a risk for human health and the environment on these areas, although present concentrations are not the direct result of present wastewater reuse.

Concerning cadmium concentrations on the other pumping districts the results show that an assessment of present and future risks for the environment and human health depends on the used critical soil concentrations. The critical soil concentration derived by Schütze et al. for mammals and birds lead to present risks for this endpoint, whereas the application of the European predicted no-effect concentration for animals does not.

Moreover, the application of an appropriate soil-wheat relation for deriving tolerable soil concentrations is crucial for the assessment of human health risk concerning area 2b and 3 in pumping district III.

Before making any final statement on the human and environmental risks caused by cadmium, it shall be discussed and derived which of the respective tolerable concentrations for animals and humans is the more appropriate one for this risk assessment.

7.5.1 Tolerable Cd soil concentration for animals

The European Risk assessment Report for cadmium proposes a $\mathrm{PNEC}_{\mathrm{soil}}$ for animals of $0.9\mathrm{mg/kg}_{\mathrm{dw}}$, whereas Schütze et al. calculate a critical soil concentration of 0.14 for the black-tailed godwit as a reference for worm eating birds and a value of $0.062\mathrm{mg/kg}_{\mathrm{dw}}$ for the badger as a reference animal for mammals.

Since both sources are considered to be reliable and trustworthy, the respective outcomes shall not be questioned at this place. Nevertheless, as a personal remark, the critical soil concentrations, which were calculated for badgers and the black-tailed godwit by Schütze et al. are just slightly above or even below the average cadmium concentration in the natural earth crust of 0.1mg/kg ((Scheffer and Schachtschabel 2002)). It may be that even under natural conditions without any anthropogenic influence adverse effects on these two animals may occur. Therefore, the question arises if these two animals are the appropriate reference organisms for assessing environmental risks due to wastewater application. Thus, concerning risk calculation of animals the European PNEC is preferred.

7.5.2 Tolerable Cd soil concentration concerning human health

The result clearly point out that the conclusion, whether present and modeled future soil concentrations pose a risk for humans consuming agricultural products from the areas of the AVBS, depends on the calculated tolerable soil concentration. The calculated Spearman coefficients (see section7.2.2) indicate correlation between soil and wheat concentrations. Nevertheless, this does not give any information whether this correlation is linear or not. The BCF method assumes a linear relationship. Instead, the equation formulated by DeVries et al 2003 results in a graph, where wheat concentration does not increase as strong as soil concentrations (Figure 30).

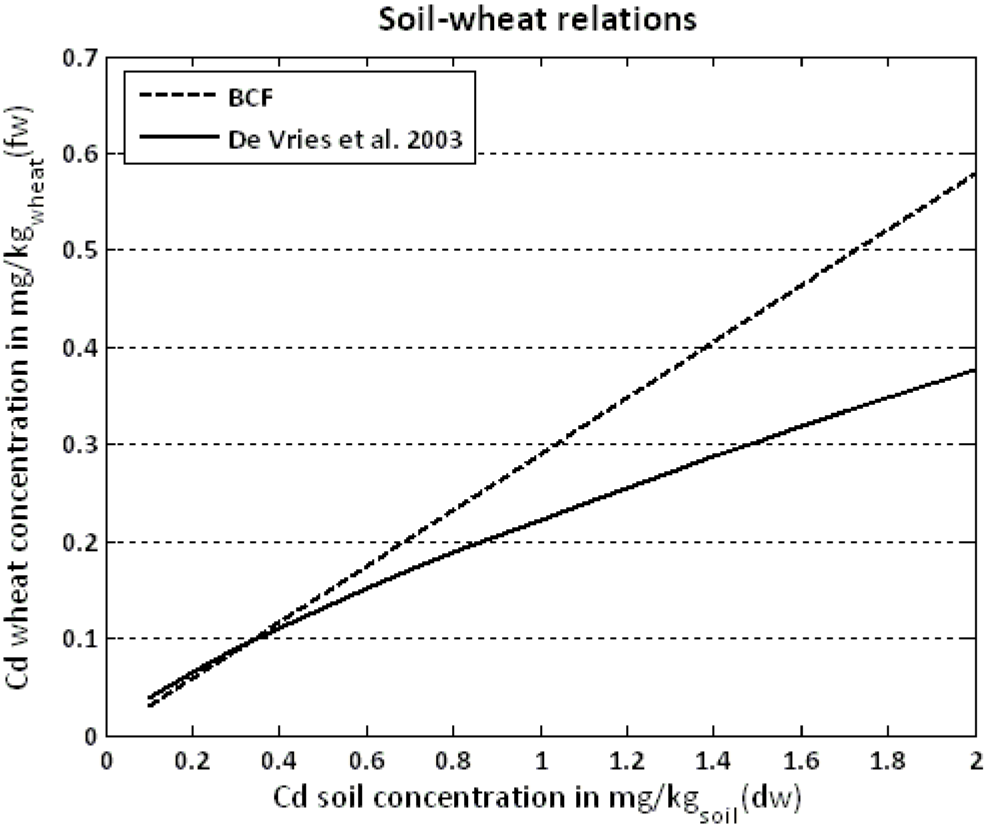


Figure 30: Soil-wheat relation using the BCF method and the equation formulated by DeVries at al 2003

Figure 30 points out that the two approaches lead to similar results up to a soil concentration of 0.3-0.4mg/kg$_{soil}$(dw). Above this value the BCF method leads significantly higher wheat concentrations as the De Vries method does.

Paired data for soil and wheat concentration are available for the years 1995-1999 and 2009-2010. Measurements take place once a year. Depending on the year 1-4 values for wheat concentration are available per pumping district. This is certainly not enough of a data set to calculate reliable mean values. Thus, the quality of the calculated BCF has to be questioned. Moreover, the use of BCFs for calculating soil-wheat relations in general is subject of discussion. Some publications like ((VKM 2009)) use it for all metals, whereas others like (Schütze and Spranger 2002) state that *"only for Cd in wheat some relationship can be discerned. For all other combinations, the BCF concept does not work, since there is simply not such a relationship" (p.51, l.3).*

However, the fact that the BCF method may not be the most appropriate method to calculate tolerable soil concentrations does neither implicate that the equation of De Vries et al. 2003 is a more appropriate approach nor that the BCF methods does not lead to reasonable results for certain cases (e.g. Cd in wheat). Therefore, a comparison is made between the initial modeled wheat concentrations (see Table 40) based on the mean soil concentrations and the measured wheat concentrations of the four pumping districts during the time span from 1995-2010. The values are calculated by using the measured dry matter content and applying a dry matter content of 86% (Ripke, personal correspondence) Data for 2006 are missing. Figure 31 shows the measured data. Modeled values as well as the mean and the median of the measured data are shown in Table 40.

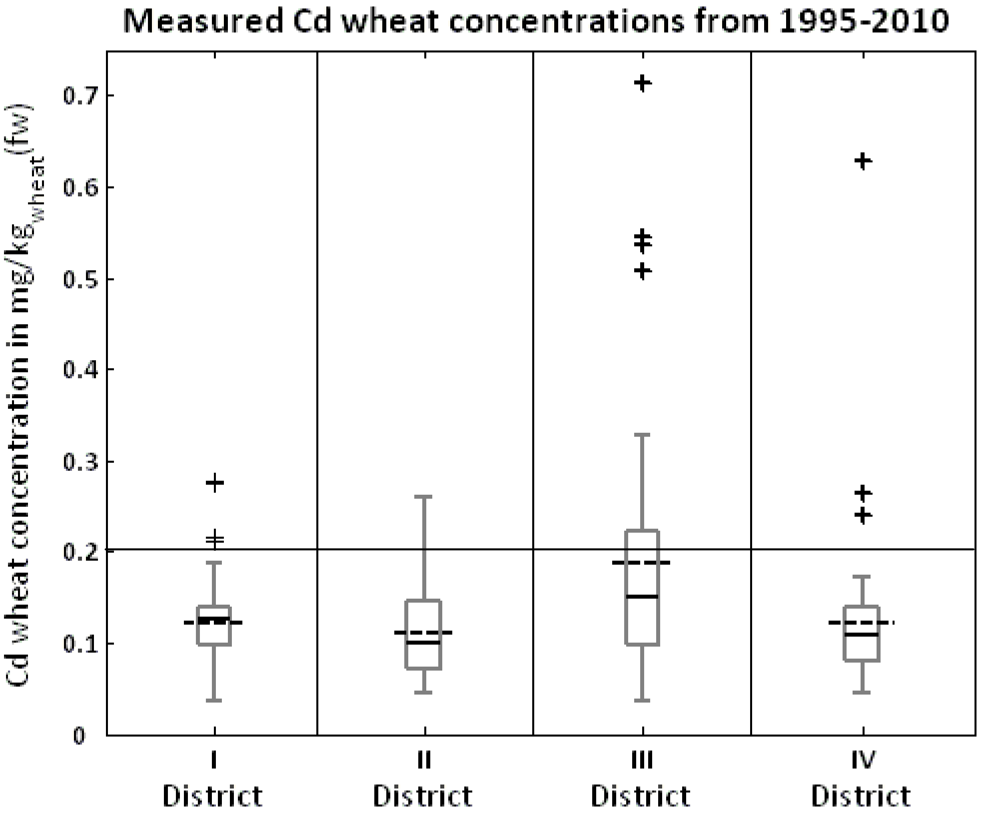


Figure 31: Measured wheat concentrations from 1995-2010. Black solid lines show the median, black dotted lines the mean value. The boxes range from the 25 to the 75 percentile. Black crosses indicate outliers. The horizontal line represents the derived critical wheat concentration. (Pumping district I (n=41), Pumping district II (n=32), Pumping district (n=41), Pumping district IV (n=42))

Table 40: Modeled and measured wheat concentrations in mg/kg$_{wheat}$(fw)

Pumping district	Modeled (De Vries)	Modeled (BCF)	Measured median	Measured mean
I	0.119	0.128	0.126	0.126
II	0.107	0.11	0.099	0.117
III	0.176	0.206	0.151	0.189
IV	0.166	0.197	0.108	0.126
IV without area 5	0.097	0.084	0.108	0.126

The comparison between modeled and measured data shows that for lower Cd soil concentrations (Pumping districts I, II, IV without area 5) the modeled values correspond to the measured ones for both modeling approaches. Concerning pumping district III which shows higher Cd soil concentrations the both modeled concentrations in wheat exceed the median measured value. Concerning the mean measured value the BCF method overestimates measured concentrations, whereas the equation of De Vries et al. 2003 underestimates the measured mean. The De Vries equation shows a deviation of -0.013 mg/kg$_{wheat}$(fw), the BCF method one of +0.017 mg/kg$_{wheat}$(fw).

Nevertheless, it is not only the question if the used model approaches represent reality appropriately, but also if the measured data represent reality in an appropriate way. Within a 15 year time period the number of annual single samples per pumping district ranges from 2 in district II to 3 in the other districts. Assuming that the single pumping districts are equally large, and that cereals are grown on 30% of the agricultural areas of the AVBS (see section 0), than 1 sample represents an area of 225ha. If additionally, other sources of uncertainties, like the annual variations of environmental conditions (weather), the species of wheat, the sampling methods etc. are taken into account, the question arises if these measured data are sufficiently reliable to validate the respective model. Against this background of present uncertainties, none of the models can be described as completely inappropriate by the comparison to measured data.

7.5.3 Environmental and human health risks due to Cadmium

The critical discussion on the formulated tolerable soil concentrations for animals and human health led to the conclusion that the $PNEC_{soil}$ formulated by the European Union for animals seems to be the more appropriate value for assessing environmental risks for this endpoint. Except from area 5 in pumping district IV and the areas 1 and 1b in district III, the $PNEC_{soil}$ is currently not exceeded and also the model results indicate that this will not be the case within the next 100 years in the other pumping districts. Adverse effects are thus unlikely to occur in those districts.

Concerning risks for human health, there are three types of areas. The Cd soil concentrations on area 5 of district IV and on area 1 and 1b in district III clearly exceed the tolerable value independently from the used soil-wheat relation. According to the used methodology these concentrations hence pose a risk for human health if products for human consumption are grown on them.

The second type of areas is area 2b and 3 in district III. Here statements of current risk depend on the used soil- wheat relation. Concerning the tolerable concentration for human health impacts even the comparison to measured wheat concentrations does not give further information, which of the two approaches is the more appropriate one. Both approaches lead to wheat concentrations comparable to the actually measured ones at low soil concentrations. The two models show higher deviations to measured data for the higher soil concentrations. Nevertheless, against the present uncertainties of the monitoring data, this deviation is too small for being a knock-out criterion for one or both of the models.

Taking this information into consideration, on the one hand, a clear statement whether the present Cd soil concentration on these areas poses a risk for human health is hard to derive, since it does, if the BCF method is applied and it does not, if the De Vries method is applied. On the other hand, it can be stated that also these areas are of concern concerning risk from Cd soil concentrations. Definitely, monitoring should be extended to gather a more reliable data set.

The third type of areas is all the remaining ones. Here, Cd concentrations currently do not pose a risk for average human consumption. The model result show that there is a kind of equilibrium concentration at a soil concentration of about 0.4 mg/kg_{soil}(dw), below which concentrations are slightly increasing and above which concentrations decrease. This stable state depends on the used partitioning coefficient between soil and water used in this model. As this value is taken from literature and there is no local value known yet, this statement is uncertain. Nevertheless, against the background of present soil concentrations and decreasing overall Cd emissions in Germany, the statement can be made, that adverse human health effects resulting from wastewater reuse of these areas are unlikely to occur.

7.5.4 Validation of model results

Not only the derived calculated tolerable soil concentration for Cd but also the calculated soil concentrations have to be checked for plausibility. For this purpose the modeled data will be compared to measured soil concentrations. Subsequently, a sensitivity analysis is conducted to examine the robustness of the calculated results.

7.5.4.1 Comparison to measured data

Modeled cadmium concentrations show a decreasing tendency at higher concentrations and an increasing one for lower concentrations. This cannot be confirmed by measured mean values (Figure 32).

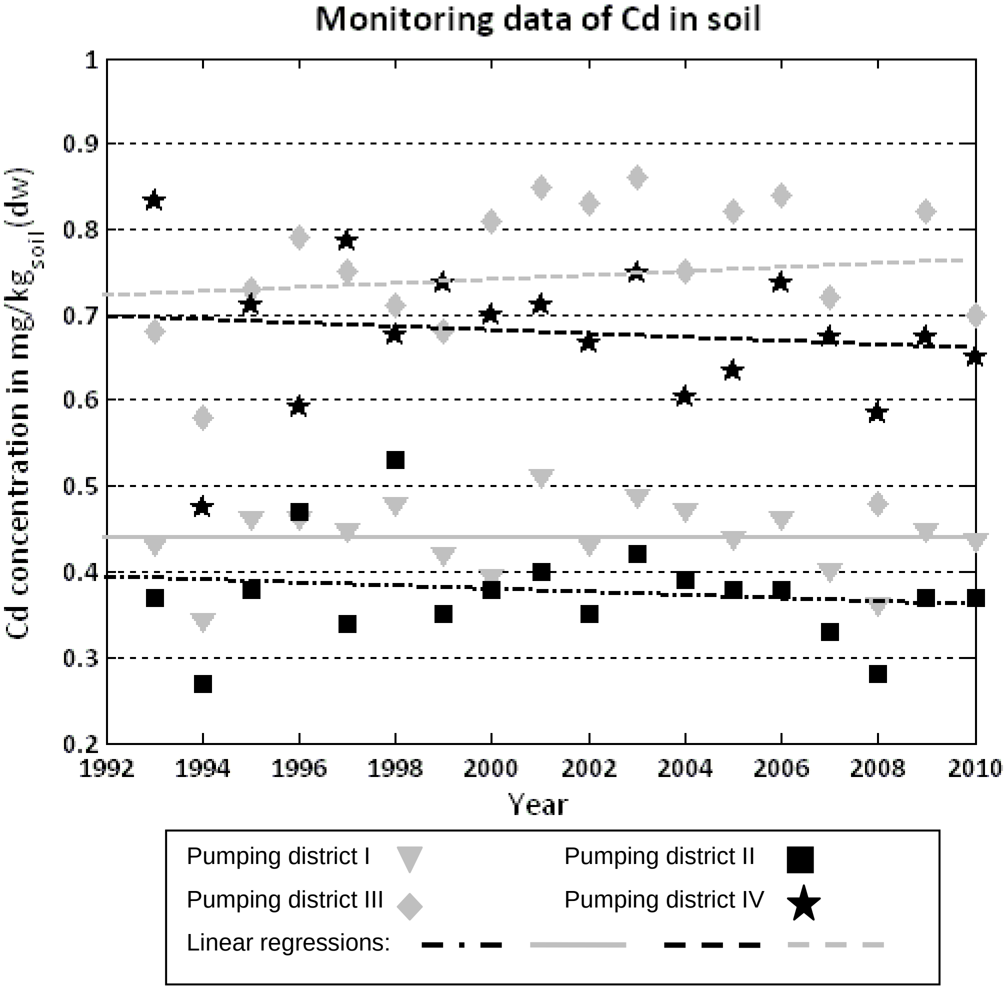


Figure 32: Linear regression of the measured soil concentrations in Braunschweig.

Except from the areas with a high initial concentration, especially area 5 in district IV, the model indicates a rather stagnating development. If the mean data are taken as initial concentration Cd soil concentrations show a change of less than 0.1 mg/kg_{soil}(dw) within 100 years. In contrast measured data show high annual fluctuations of up to 0.2mg/kg_{soil}(dw). Uncertainties like fluctuations in the annual precipitation, different annual cadmium loads and varying sampling locations have thus high impact on the overall results relative to the modeled results. Although the linear regression shows also just slight increases and decreases, respectively, the fit is rather poor and cannot be used for further statements.

7.6 Sensitivity analysis

The model for calculating soil metal concentrations is influenced by several factors, including physical-chemical properties of the respective metal, the surrounding environmental conditions and the annual metal loads which are applied on the agricultural areas. Moreover, the model itself may lead to imprecision with regard to the calculated results.

Cadmium is used as reference as it exceeds the most critical concentrations and PNECs. The factors which are analyzed for their respective impact on the overall results are plant uptake, the annual load of Cd applied on agricultural areas and the partitioning coefficient Kd. It will be examined if a change of the respective factor influences the final result of the assessment.

Plant uptake

The model described in the TGD does not consider the uptake of plants as an output factor. The impact on soil concentrations by including an additional removal rate constant for plant uptake is conducted by assuming that wheat is grown on the whole area, as this plant is known for its high Cadmium accumulation. Based on measured Cd concentrations in wheat and the amount of wheat which is harvested per year an additional removal rate constant is calculated.

$$kplant = \frac{Cwheat * Mwheat * DMwheat}{10 * 365 * Depth_{soil} * rho_{soil}}$$

kplant	= first order rate constant for Cd removal from top soil via plant uptake [mg/kg$_{soil}$*d]
Mwheat	= Mass of wheat harvested per year [kg/ha]
DMwheat	= content of dry matter in wheat [%]
Depth$_{soil}$	= mixing depth of top soil [m]
Rho$_{soil}$	= bulk density of top soil [kg/m^3]

The amount of wheat harvested in Braunschweig is set to 7.8t/ha with a dry matter content of 86%. The overall mean measured Cd concentration is used for Cwheat (AVBS, personal correspondence).
Impacts on the overall result are presented in Figure 33.The results show that although plant uptake influences soil concentrations the differences do not change the general outcomes of the risk assessment as the overall change is approximately 3% due to plant uptake in respect to the initial concentration.

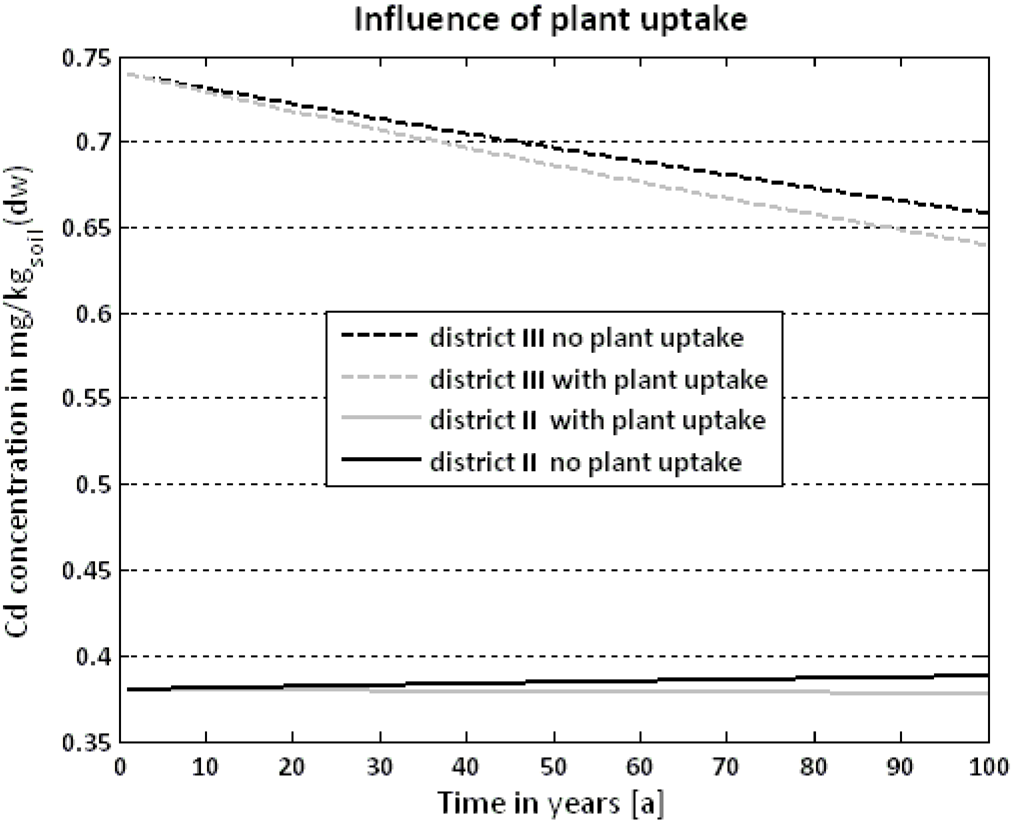


Figure 33: Impact of plant uptake on the overall model results. Results are plotted for the pumping districts II (black) and III (red) is the districts with the highest and lowest initial Cd concentration. The respective lower concentrations are calculated if plant uptake is included.

Annual metal loads

Figure 34 shows how the model reacts when the annual Cd load is changed by +10%, +20%, -10% and -20% respectively. The influence of 20% change of the annual load changes the final concentration after 100 year of wastewater irrigation of just 1% and has thus no influence on the final result.

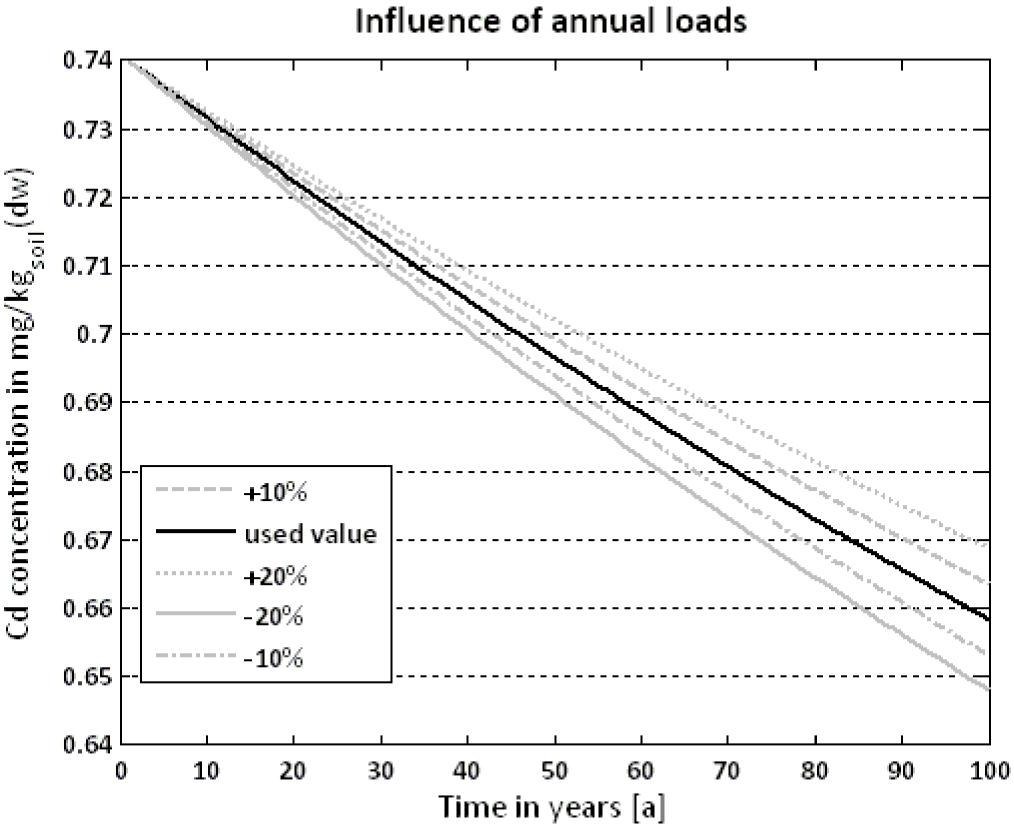


Figure 34: Impact of the annual Cd loads on soil concentrations.

Soil-water partitioning coefficient Kd

The Kd value determines the equilibrium between soil and soil solution and thus the amount of heavy metal which is washed out by leaching processes. The Kd value is dependent of several factors, from which the fraction of organic matter and the pH level are the most important ones. Different functional relationships have been formulated describing the relationship between organic content, pH level and the Kd value (see (ECB 2007a) p.190). The referenced equations are used to calculate different Kd values for this sensitivity analysis. The calculated values range from 139-310 L/kg. The higher the Kd value the higher is the amount of Cadmium remaining in top soil (Figure 35).

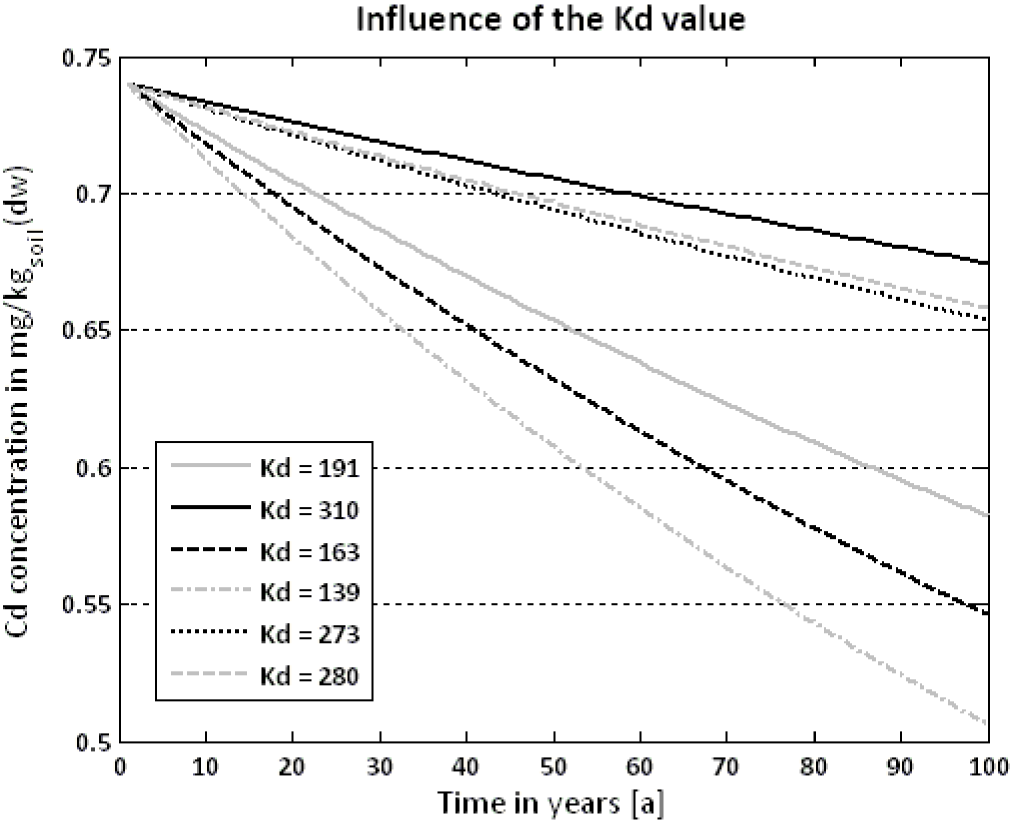


Figure 35: Influence of the partitioning coefficient on the modeled Cd soil concentration in pumping district III. Values for Kd are given in L/kg

Figure 35 shows that the choice of an appropriate Kd value influences the trend of Cadmium concentrations in top soil. A change of the used Kd value by 32% (191kg/L) results in a change of the final result of 11%. The highest calculated Kd value, which corresponds to an increase of 10% in respect to the used value, changed the final result by 2%.

7.6.1 Conclusions on sensitivity

The sensitivity analysis of the single factors showed that Cd soil concentrations are influenced by the partitioning coefficient Kd, plant uptake and the annual Cd loads which are applied on the agricultural areas in Braunschweig. Varying single factors while keeping the other ones constant (like in the conducted calculations) did not lead to changes in soil concentrations, which would change the overall outcome of the risk assessment in a way that final conclusions would have to be changed.

7.6.2 Risk based targets

Taking all the information of the conducted model and the sensitivity analysis into consideration one has to draw the conclusion that risk reduction measures for human health risks due to Cd exposure have to be considered concerning pumping district III (areas 1 and 1b) and area 5 of district IV.

As humans are indirectly exposed to cadmium via food consumption, as a short term action, risks can be reduced by stopping the production of food crops on the respective areas of the agricultural areas of the AVBS. Another option would be to prevent Cd from being taken up by plants. An increase of the soil pH value through liming could be one option to achieve this.

Nevertheless, it became obvious that in order to achieve a more sustainable solution it makes more sense to express risk-based targets in terms of environmental outcomes. A reduction of soil concentrations below all critical concentrations should be achieved. As the annual heavy metal loads of the STP Steinhof are not the only inputs, which have to be considered (atmospheric deposition, Oker), and against the background of present uncertainties concerning the surrounding environment, this target cannot be expressed as a certain tolerable annual Cd load, yet. Nonetheless, as Cd is highly toxic to humans, animals and the environment, any increase is undesirable and releases into the environment should be reduced to its minimum.

Since zinc shows an increasing tendency as well and will reach the PNEC for soil organisms within the next 20-70 years efforts to reduce zinc loads should be considered as well.

7.6.3 Critical discussion

Concerning the methodological approach the model calculations are based on the widely reviewed *European Technical Guidance Document on Risk assessment.* The used calculations are therefore considered to generate acceptable results concerning general outcomes and overall tendencies. However, environmental modeling can be conducted far more complicated and in more detail. The soil-plant relation was identified to be a source of uncertainty in the mathematical approach. Another weakness is that the conducted calculations are based on total metal contents in soil. No differentiation is made between total and reactive metal contents. Moreover, the speciation of the respective metal is not taken into account. This, in turn depends on the local soil pH and redox conditions. Concerning plant uptake certainly this simplification plays an important role, as just the metal content in soil solution can be taken up by plants.
Another weakness is the use of calculated instead of measured metal loads for lead and mercury. As the mass balance currently does not come out even this influence factor implicates a lot of uncertainties. The sensitivity analysis showed that also the correct value for the partitioning coefficient between soil and water has impacts on the overall tendencies of soil metal concentrations. The validity of the results can thus definitely be improved by replacing this value by an actually measured one, which accounts better for the site specific surroundings. Nevertheless, even if a far lower Kd value would be applied it would not change the final conclusions concerning the current indentified risks.

Concerning the derived critical wheat concentrations concerning human health impacts the calculated critical wheat content is not overly conservative, as it is in line with current European food quality standards (0.2mg/kg$_{\text{wheat}}$(fw) (EC 2006)).

The derived critical soil concentrations for Cd are calculated by two different approaches. Since the derived values are within the same order of magnitude as the values set by German legislation (precautionary value 0.4mg/kg$_{\text{soil}}$(dw) (BBodSchV 1999), limit value 1mg/kg$_{\text{soil}}$(dw) (AbfKlärV 1992)), the derived values are considered to be within a reasonable range. Concerning environmental endpoints the used PNECs are based on widely reviewed European Risk Assessment Reports.
In conclusion, against present uncertainties the conducted model is on the one hand not sufficiently precise to make a statement, whether the whole reuse system of Braunschweig is “safe” or “unsafe”. On the other hand, the results are sufficiently good to identify Cd as a priority for risk reduction measures. Moreover, the whole procedure of risk assessment made weaknesses, like the Cd balance of the STP Steinhof, apparent and transparent. Since the identification of weaknesses is the necessary first step towards any improvement the generated results can be used as a first step towards a more risk based management approach.

Chapter 8

Conclusion and recommendations

The major objective of the report was to initiate a risk analysis concerning environmental and human health risks of the sanitation scheme in Braunschweig following the methodology of water safety plans. The methodological approach was realized by using the overall approach of the Stockholm Framework, which, in consensus to Water Safety Plans, is based on the HACCP concept. The whole approach was initialized by conducting the first three steps of the approach, namely risk assessment, setting tolerable levels of risk and the derivation of risk-based targets. Heavy metals were used as reference chemicals of QCRA, the most prevalent gastroenteritis causing pathogens as reference organisms for QMRA. For QCRA the endpoints, soil organisms, mammals and birds, humans with high and average consumption as well as algae and crustacea were considered. For QMRA three different scenarios were applied, fieldworkers, nearby residents and children ingesting soil.

Viruses were identified as the pathogens with the highest annual risk of infection in all scenarios. The tolerable additional burden of disease of 1µDALY was exceeded in all scenarios for viruses. The annual probability of infection exceeds the value of the general German public even if a factor of 10 is applied for underreporting. To reach the WHO objective of 1 µDALY an additional pathogen reduction of 1.5 log units was derived.

Concerning risks resulting from heavy metals it was shown, that Cd soil concentrations in pumping district 3 (area 1 and 1b) and on area 5 of pumping district IV are of concern for human health. Although the model shows a decreasing trend soil concentrations do not fall below the critical soil concentrations within 100 years on these areas. Moreover, zinc soil concentration on area 5 in pumping district IV exceeded the $PNEC_{soil}$ for soil organisms.

Concerning risks resulting from pathogen exposure the following recommendations can be given.

- Pathogen concentrations have to be validated by microbiological analysis. Peaks for virus incidence rates in winter and for bacterial incidence rates in summer should be considered when planning the monitoring program
- Verification monitoring should focus on viruses in wastewater and sewage sludge
- Risks should be communicated pro-actively and transparently
- Additional informational signs should be set up, which provides the information that wastewater is not free of pathogens

Concerning risks from heavy metal exposure the following recommendations are given.

- Cadmium and zinc loads should be reduced as far as possible
- On the areas 1 and 1b in districts III as well as on area 5 of district IV no food or fodder products should be grown, or other reduction measures developed, e.g. production of energy plants only
- The determination of site-specific Kd values is recommended

As final conclusion it can be stated, that, if used in the right manner, this report has the potential to function as a first step towards an overall risk-based management approach of the wastewater reuse concept of Braunschweig and as one additional case study for the development of an overall “sanitation safety plan” concept.

The major objectives of system description, risk assessment, derivation of tolerable risk levels and the derivation of risk-based targets were achieved, although risk-based targets in the chemical risk assessment could not be formulated as concrete annual loads but just as desirable environmental outcomes. The additional objectives of the implementation of environmental concerns and the providing of respective methodological background can be regarded as achieved, too.

Chapter 9

Outlook

By focusing once again on the approach for risk assessment and risk management outlined in the Stockholm Framework (Figure 1), the circular structure illustrates that risk-based management is a permanent and iterative process. Thus, this report has to be regarded as a first initial step.
The model results for both, microbial and chemical risks assessment clearly need to be validated. Special focus concerning the validation of the assumptions made during QMRA should be put on viruses. Concerning heavy metals emphasis should be put on Cd in the STP Steinhof. Based on the outcomes of the validation process the model has to be refined based on local site specific data and, subsequently, potentially necessary risk reduction measures planned and implemented.

Moreover, chemical risk assessment and management has to be extended to other chemical agents, which were not considered in this report, especially organic chemicals. Every year new organic compounds are developed and consequently might enter municipal treatment plants. Environmental effects of organic chemicals (eco-toxic, endocrine disruptive etc.) are subject of intensive research as they are not completely known, yet. Therefore, risks resulting from organic chemicals need to be periodically reassessed if new substances enter the sewage system. Moreover, reassessment has to take place if new information on environmental impacts of a specific chemical agent becomes available. This, once more, underlines the iterative character of risk-based management approaches.

Thus, additionally to validation, initiating risk assessment of organic chemicals would be the next step towards and overall risk-based management approach of the wastewater reuse system of the city of Braunschweig.

Appendix A

Technical and monitoring data STP Steinhof

All data are presented as annual means.

Influent

Paramter	**Chromium**	**Zinc**	**Cadmium**	**Lead**	**Nickel**	**Copper**	**Mercury**
Analytic	**ICP**	**ICP**	**ICP**	**ICP**	**ICP**	**ICP**	**ICP**
Unit	mg/l	mg/l	µg/l	mg/l	mg/l	mg/l	ug/l
LOQ	<0,01	<0,01	<0,2	<0,01	<0,01	<0,05	<0,2
2010	0.012	0.271	0.615*	0.022	0.011	0.091	0.254
2009	0.011	0.262	0.385*	0.025	0.011	0.088	0.226
2008	0.010	0.259	13	0.050	0.011	0.094	0.308
2007	0.011	0.257	10	0.050	0.020	0.102	0.388
2006	0.011	0.232	10	0.050	0.040	0.078	0.467
2005	0.010	0.194	10	0.050	0.014	0.076	0.302
2004	0.010	0.158	10	0.050	0.010	0.060	0.248
2003	0.010	0.175	10	0.051	0.012	0.066	0.342
2002	0.010	0.153	10	0.050	0.011	0.055	0.273
2001	0.012	0.188	10	0.052	0.012	0.066	0.300
2000	0.011	0.216	9	0.050	0.013	0.080	0.700
1999	0.010	0.184	5	0.050	0.011	0.084	0.001
1998	0.013	0.213	6	0.050	0.011	0.090	0.001

Parameter	**AFS**	**AOX**	**CSB-h**	**CSB-f**	**TNb/TKN**	**Pges.**	**PO4-P**	**lipohile Stoffe**
Analytic	**-**	**-**	**-**	**-**	**-**	**ICP**	**Küvette**	-
Unit	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
LOQ	<2	<0,01	<15	<15	<1 / <2	<0,02	<0,05	<10
2010	406	0.073	937	366	70.0	11.3	6.27	51.8
2009	404	0.054	986	410	77.2	12.0	7.06	51.3
2008	387	0.058	917	381	71.9	11.0	6.20	45.7
2007	397	0.067	949	386	64.2	10.5	6.17	45.9
2006	382	0.098	995	456	71.6	12.2	7.60	60.7
2005	288	0.126	886	493	69.1	11.5	7.70	40.9
2004	249	0.139	756	470	65.9	9.6		
2003	220	0.125	650	406	62.3	9.3		
2002	193	0.126	545	316	51.3	7.7		
2001	270	0.130	741	438	67.0	10.3		
2000	323	0.107	832	449	70.3	11.2		
1999	301	0.072	730	430	60.6	9.1		
1998		0.076	717	405	60.4	8.3		
1997	202		609		60.8	9.4		

*Change of the quantification limit down to 0.2µg/L, before 10µg/L

Effluent activated sludge treatment

Parameter	**Chromium**	**Zinc**	**Cadmium**	**Lead**	**Nickel**	**Copper**	**Mercury**
Analytic	**ICP**	**ICP**	**AAS**	**AAS**	**ICP**	**ICP**	-
Unit	ug/l	ug/l	ug/l	ug/l	ug/l	ug/l	ug/l
LOQ	<2	<5	<0,1	<2	<2	<5	<0,2
2010	2.26	16.63	0.11	2.23	3.22	7.60	0.200
2009	2.28	14.16	0.31	2.01	3.22	6.05	0.200
2008	5.06	17.61	2.00	2.15	10.01	6.52	0.200
2007	4.96	16.64	2.00	2.03	8.84	8.29	0.220
2006	5.00	13.31	2.00	2.03	5.51	6.85	0.200
2005	5.00	16.83	2.00	2.03	9.35	8.77	0.200
2004	5.00	20.67	2.00	2.00	10.01	19.14	0.200
2003	5.28	21.91	2.02	2.03	10.26	14.77	0.200
2002	5.08	20.35	2.00	2.00	10.00	13.58	0.200
2001	5.16	17.46	2.00	2.00	10.72	18.81	0.200
2000	5.32	19.68	2.00	2.34	10.80	18.98	0.211
1999	5.40	24.64	2.00	5.11	10.51	14.35	0.414
1998	5.50	30.02	2.00	4.99	11.02	10.13	0.618

Parameter	AFS	AOX	CSB-h	CSB-f	NO3-N	TNb/TKN	Pges.	PO4-P
Unit	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
LOQ	<2	<0,01	<15	<15	<1	<1 / <2	<0,02	<0,05
2010	9.3	0.050	43	32	4.00	9.9	0.98	0.52
2009	7.4	0.047	42	34	4.36	9.1	0.88	0.48
2008	9.7	0.041	44	31	3.66	8.0	0.95	0.40
2007	8.6	0.044	38	29	3.81	7.1	0.83	0.44
2006	6.1	0.051	38	33	3.24	6.6	0.60	0.35
2005	6.2	0.076	40	34	5.37	8.8	0.84	0.55
2004	5.2	0.080	35	31	8.52	12.2	0.62	0.39
2003	5.1	0.091	34	30	5.58	8.5	0.62	0.37
2002	6.2	0.065	31	26	5.16	4.7	0.51	0.29
2001	6.8	0.065	36	32	4.64	3.9	0.58	0.29
2000	8.8	0.064	43	37	4.77	4.5	0.72	0.36
1999	8.4	0.048	42	37	4.46	4.9	0.58	0.31
1998	4.7	0.039	39	33	4.98	5.6	0.73	0.47
1997	7.4		41		4.92	7.4	0.77	

Effluent Aue-Oker-Canal

Parameter	Chromium	Zinc	Cadmium	Lead	Nickel	Copper	Mercury
Analytic	ICP	ICP	ICP	ICP	ICP	ICP	-
Unit	ug/l	ug/l	ug/l	ug/l	ug/l	ug/l	ug/l
LOQ	<2	<5	<0,4	<4	<2	<5	<0,2
2010	2.12	18.23	0.39	3.96	7.00	6.05	0.200
2009	2.28	14.79	0.48	3.56	7.03	6.33	0.200
2008	5.00	19.43	2.00	2.10	10.25	5.16	0.200
2007	5.00	17.47	2.00	2.02	9.67	5.92	0.200
2006	5.00	16.12	2.00	2.02	8.62	6.86	0.240
2005	5.45	19.14	2.00	2.35	10.75	7.27	0.204

Parameter	AFS	AOX	CSB-h	N03-N IC	TNb/TKN	Pges.	PO4-P
Unit	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
LOQ	<2	<0,01	<15	<1	<1 / <2	<0,02	<0,05
2010	11.5	0.044	36	2.75	6.26	0.810	0.35
2009	11.9	0.036	32	2.19	5.18	0.769	0.23
2008	9.8	0.031	30	2.41	5.37	0.811	0.33
2007	13.0	0.034	32	2.77	4.98	0.823	0.36
2006	12.1	0.040	31	2.31	4.81	0.737	0.30
2005	12.3	0.055	33	3.30	6.18	0.796	0.30
2004	13.3		31	3.99	7.75	0.741	0.38
2003	9.0		28	3.34	3.79	0.813	0.40
2002	12.7		32	3.06	3.88	0.737	0.34
2001	11.9		35	2.78	4.63	0.729	0.33
2000	11.9		35	2.78	4.63	0.729	0.33
1999			33	3.01		0.739	0.34
1998			32	3.22		0.944	0.43

Effluent for agricultural irrigation

Parameter	Chromium	Zinc	Cadmium	Lead	Nickel	Copper	Mercury
Analytic	ICP	ICP	AAS	AAS	ICP	ICP	-
Unit	ug/l	ug/l	ug/l	ug/l	ug/l	ug/l	ug/l
LOQ	<2	<5	<0,1	<2	<2	<5	<0,2
2010	7.29	210.9	0.35	9.49	7.85	69.7	0.211
2009	5.59	174.4	0.40	7.27	7.09	55.3	0.228
2008	7.97	195.8	0.41	10.04	10.78	63.3	0.222
2007	7.39	200.8	0.68	9.03	9.79	79.6	0.247
2006	7.51	199.3	0.51	8.19	8.32	67.1	0.286
2005	6.39	162.4	0.36	7.01	9.92	55.5	0.236
2004	7.21	153.7	0.31	7.06	10.67	60.09	0.273

Parameter	AFS	AOX	CSB-h	CSB-f	NO3-N	TNb/TKN	Pges. Spuren
Unit	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
LOQ	<2	<0,01	<15	<15	<1	<1 / <2	<0,02
2010	196	0.064	211	60	4.94	34.4	9.70
2009	155	0.047	157	57	5.45	29.0	8.46
2008	184	0.081	181	59	3.53	27.6	8.65
2007	162	0.051	175	48	3.18	29.0	8.73
2006	156	0.086	236	58	2.96	26.5	8.70
2005	153	0.100	200	61	5.21	24.8	7.67
2004	150	0.106	135	41	10.16	22.51	6.90
2003	177	0.123	223	45	7.44	22.35	8.28
2002	196	0.132	227	46	6.70	23.17	8.42
2001	193	0.088	226	57	4.83	23.10	7.51
2000	269	0.074	350	57	3.57	34.41	9.64
1999	420	0.087	503	51	4.16	37.04	11.81
1998	322	0.084	405	43	4.67	35.11	10.62
1997	299	0.085	292	50	4.17	39.19	7.03

Primary sludge

Parameter	Pges.	TR	Chromium	Zinc	Cadmium	Lead	Nickel	Copper	Mercury
Analytic	ICP		ICP	ICP	ICP	ICP	ICP	ICP	-
Unit	g/kg TS	%	mg/kg TS	mg/kg TS	mg/kg TS	mg/kg TS	mg/kg TS	mg/kg TS	mg/kg TS
LOQ	<0,01	<1	<0,4	<0,2	<0,2	<0,1	<0,2	<0,4	<1
2010	8.30	4.56	11.10	445	0.65	21.1	10.0	109	1.00
2009	8.92	4.30	11.35	489	1.06	28.9	15.5	121	1.01
2008	8.08	4.60	11.12	435	0.77	26.0	8.3	110	1.00
2007	7.81	3.69	12.72	437	0.75	28.6	9.7	107	1.03

2006	7.69	4.71	11.10	421	1.29	26.4	7.9	110	1.13
2005	8.18	4.62	12.16	423	1.00	36.8	9.5	111	1.33

Surplus sludge

Parameter	**Chromium**	**Zinc**	**Cadmium**	**Lead**	**Nickel**	**Copper**	**Mercury**
Analytic	ICP	ICP	ICP	ICP	ICP	ICP	-
Unit	mg/kg TS	mg/kg TS	mg/kg TS	mg/kg TS	mg/kg TS	mg/kg TS	mg/kg TS
LOQ	<0,4	<0,2	<0,2	<1	<0,2	<0,4	<0,2
2010	17.5	657	0.944	24.1	16.0	179	2.5
2009	13.2	628	1.240	24.0	14.3	175	5.2
2008	14.7	570	0.662	20.3	11.1	176	4.9
2007	13.0	601	0.702	23.5	9.5	164	5.0
2006	11.9	510	0.656	20.7	8.5	171	4.8
2005	12.8	496	0.761	18.8	10.4	175	5.0

Parameter	**AFS**	**Ngesamt**	**Pges.**
Unit	g/l	g/kg TS	g/kg TS
LOQ	<2	<10	<0,01
2010	5.2	94.1	32.2
2009	6.4	81.6	35.0
2008	5.8	79.9	32.6
2007	6.3	73.0	30.0
2006	6.0	77.4	34.4
2005	5.9	74.8	32.7

Volume streams

Year	**Influent STP [m³]**	**Effluent AST [m³]**	**Effluent for irrigation [m³]**	**Effluent Aue-Oker-Canal [m³]**	**Primary sludge (tDM)**	**Surplus sludge (tDM)**
2010	23.274.700	22.944.800	12.500.700	12.652.100	3.127	5.828
2009	18.865.700	18.340.300	12.897.300	8.137.400	3.585	5.704
2008	21.750.300	21.279.200	12.586.800	12.439.200	4.088	5.487
2007	21.819.600	20.869.400	12.256.100	12.493.600	4.331	7.029
2006	18.618.200	17.052.000	12.800.600	5.834.600	3.883	5.961
2005	19.826.700	18.275.610	13.215.510	7.326.700	3.349	5.969
2004	21.916.700	20.833.620	14.084.620	10.569.600	3.417	6.471
2003	22.419.200	21.670.370	13.794.130	11.537.400	3.633	5.784
2002	26.017.640	25.558.050	14.457.250	18.159.700	3.694	5.738
2001	21.321.000	19.985.360	14.556.460	8.258.500	4.710	4.976
2000	21.294.000	20.285.100	15.000.400	7.344.600	3.994	4.505
1999	22.751.600	21.657.400	15.298.100	7.810.500	3.491	6.849
1998	23.253.200	22.858.100	14.695.100		3.667	7.656
1997	22.760.000	22.042.800	14.874.500		3.692	6.103
	21.849.181					

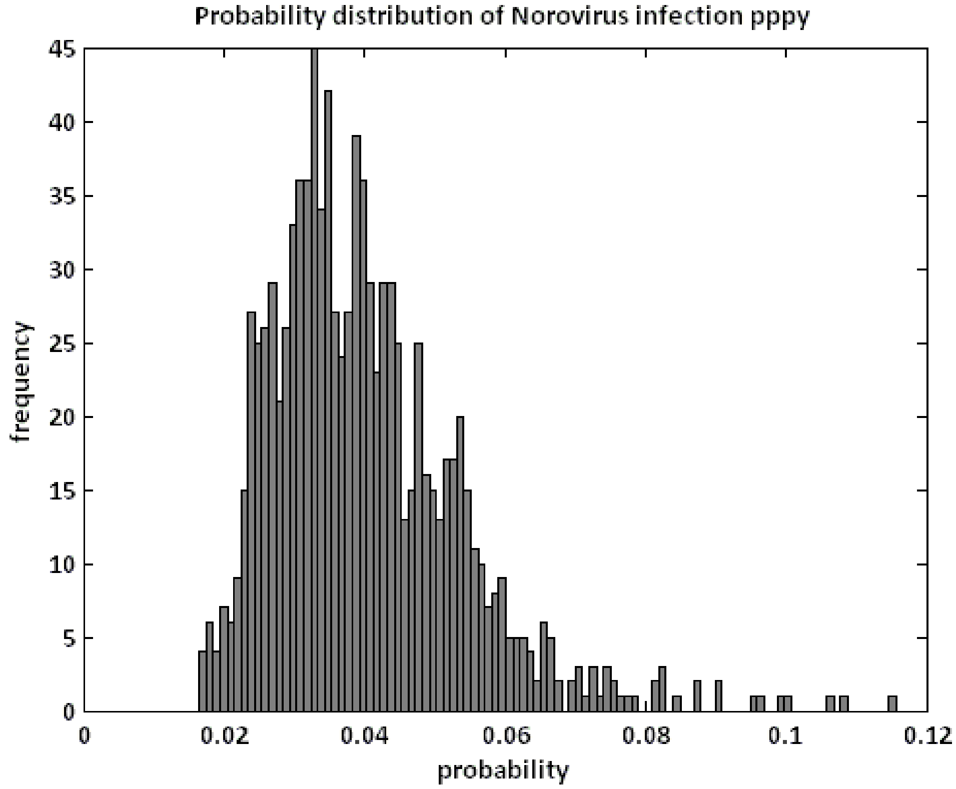
Appendix B

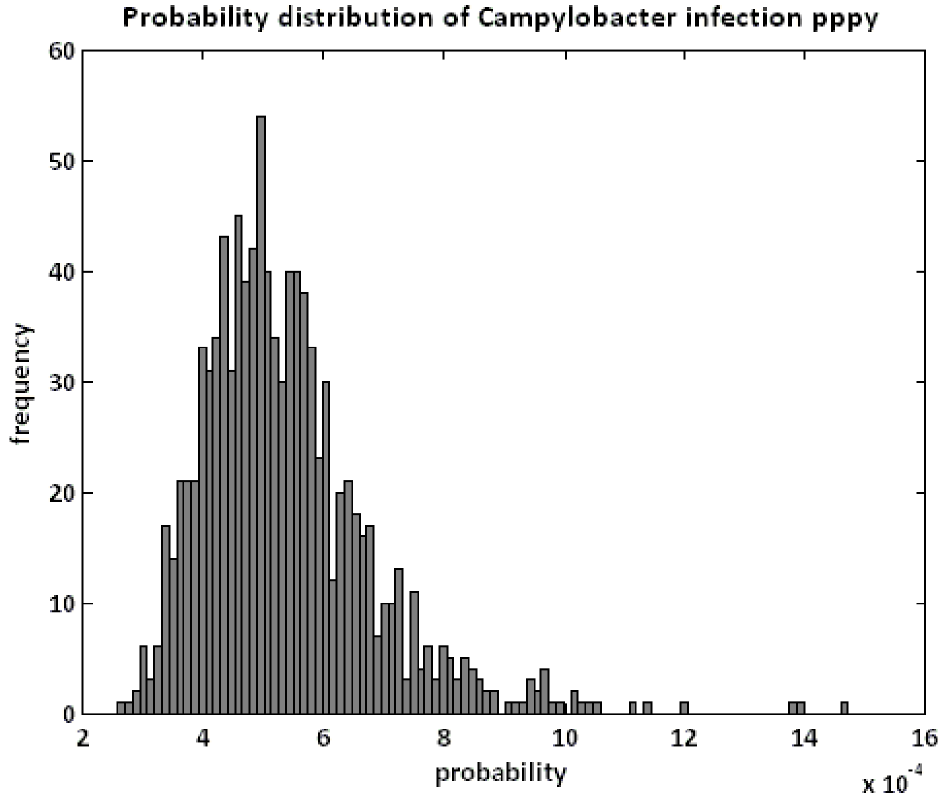
Food consumption data Germany (MRI 2008)

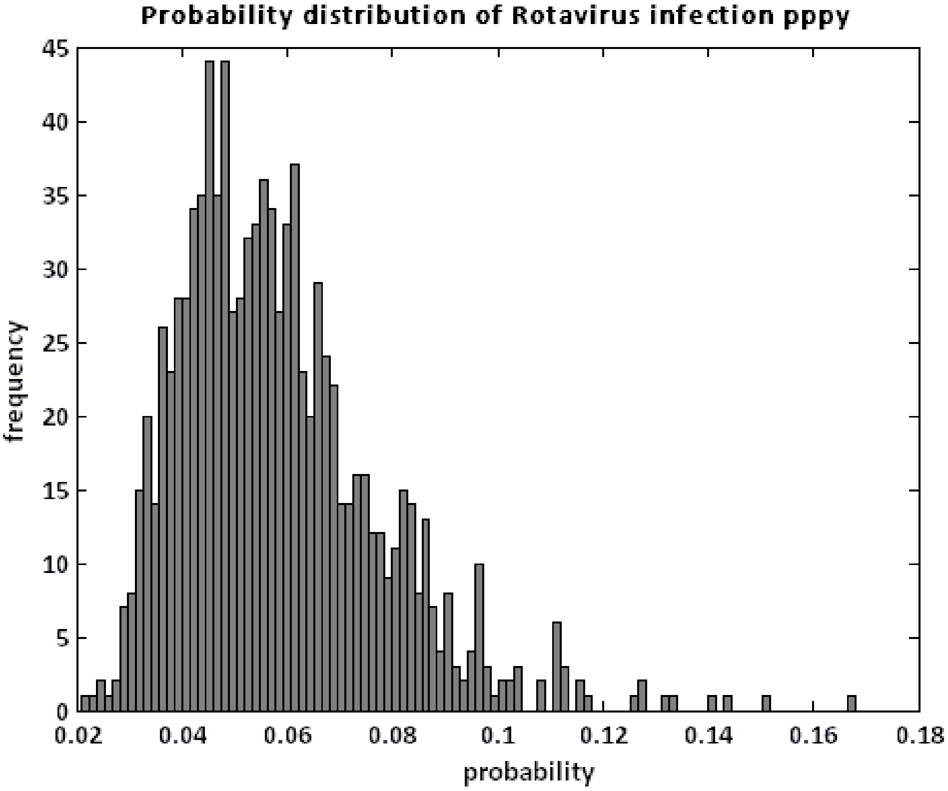
Product		Men		Women	
	Age group	mean	95 percentile	mean	95 percentile
Bread [g/d]					
	14-18	182	383	142	306
	19-24	162	380	118	246
	25-34	175	390	129	267
	35-50	184	391	134	266
	51-64	180	354	135	256
	65-80	171	311	136	257
Cereals [g/d]					
	14-18	43	133	38	111
	19-24	42	163	41	151
	25-34	46	147	39	110
	35-50	38	120	35	110
	51-64	29	100	28	89
	65-80	27	89	23	78
dishes based on bread [g/d]					
	14-18	3	21	3	15
	19-24	3	21	3	14
	25-34	4	23	2	8
	35-50	2	9	1	6
	51-64	1	0	1	0
	65-80	1	0	1	0
dishes based on cereals [g/d]					
	14-18	67	192	52	136
	19-24	75	214	58	162
	25-34	66	197	57	156
	35-50	56	156	46	124
	51-64	37	113	29	90
	65-80	24	78	21	68
backery products [g/d]					
	14-18	61	196	39	119
	19-24	61	174	38	111
	25-34	54	157	39	115
	35-50	47	141	34	99
	51-64	38	119	31	90
	65-80	35	113	28	88

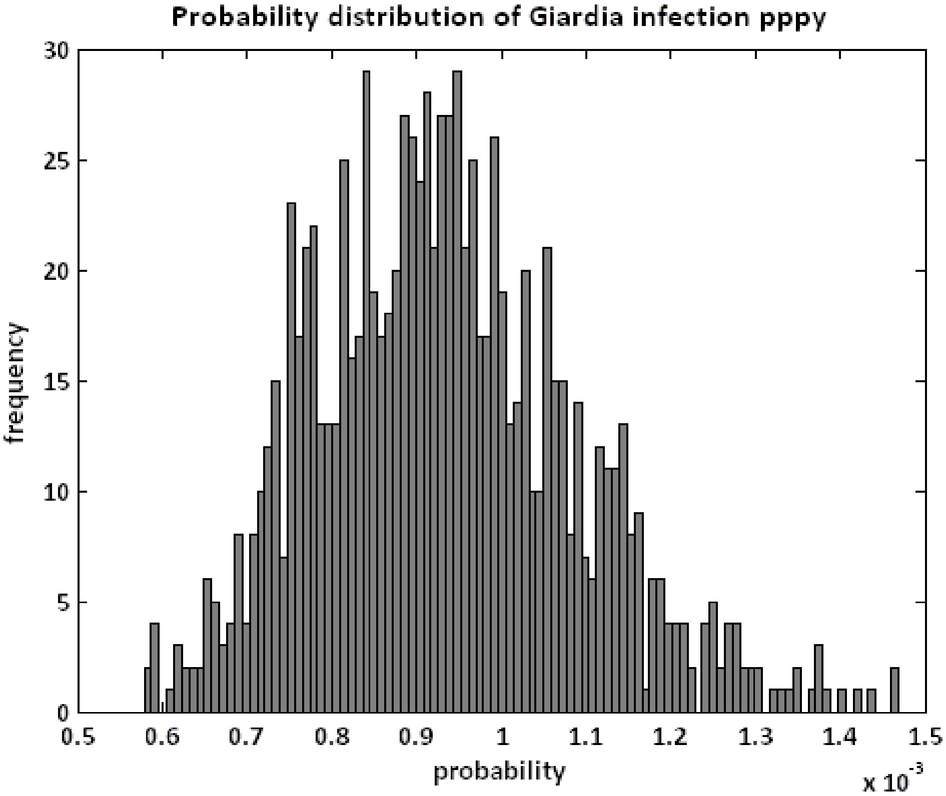
Appendix C

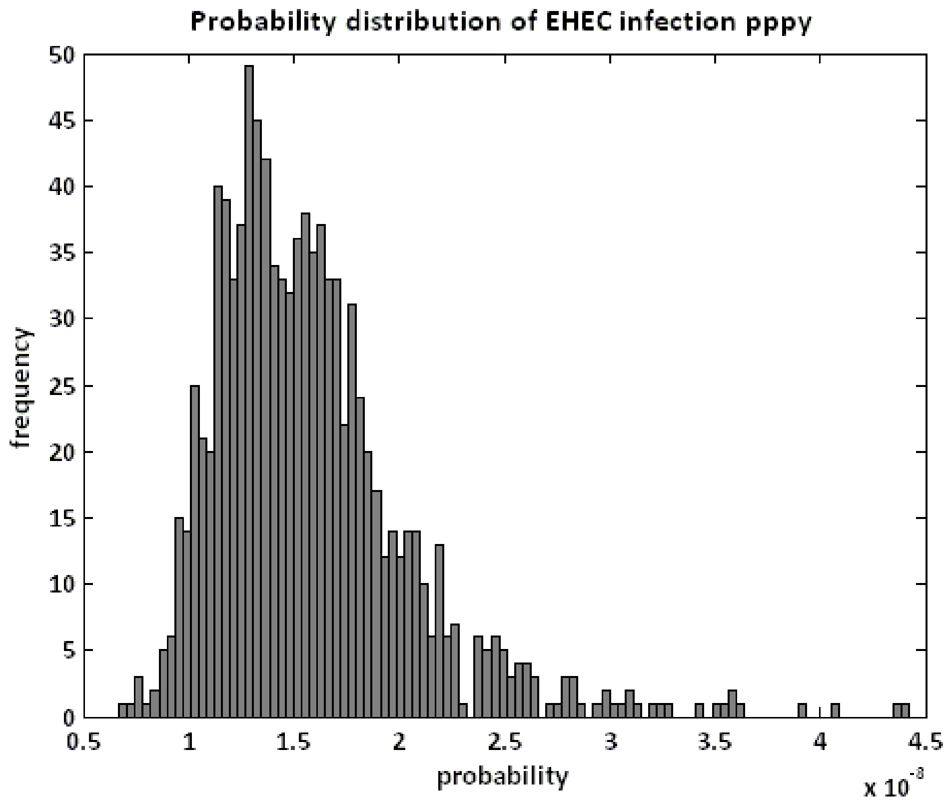
Risk distributions and statistical data for reference pathogens

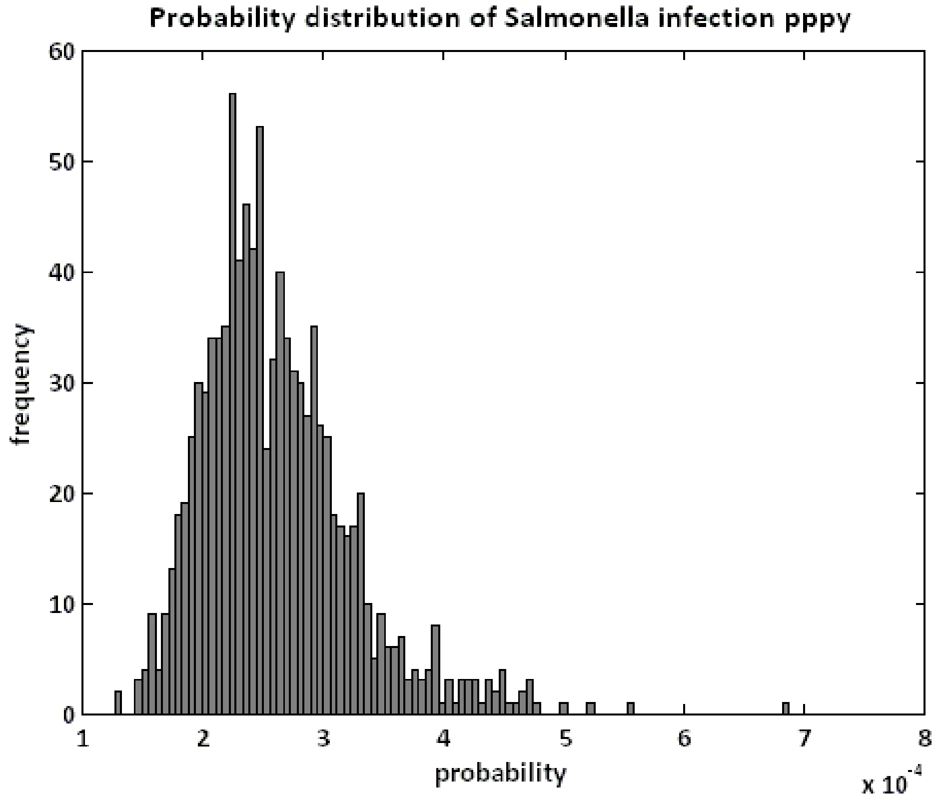




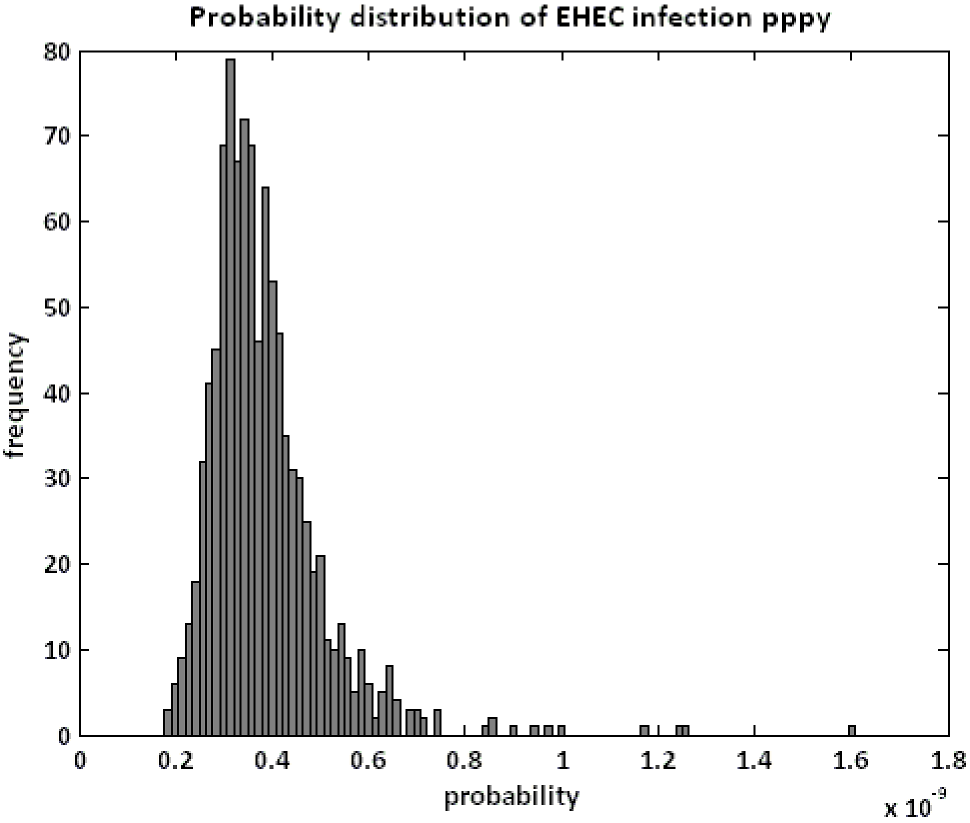

Probability distribution of Rotavirus infection pppy

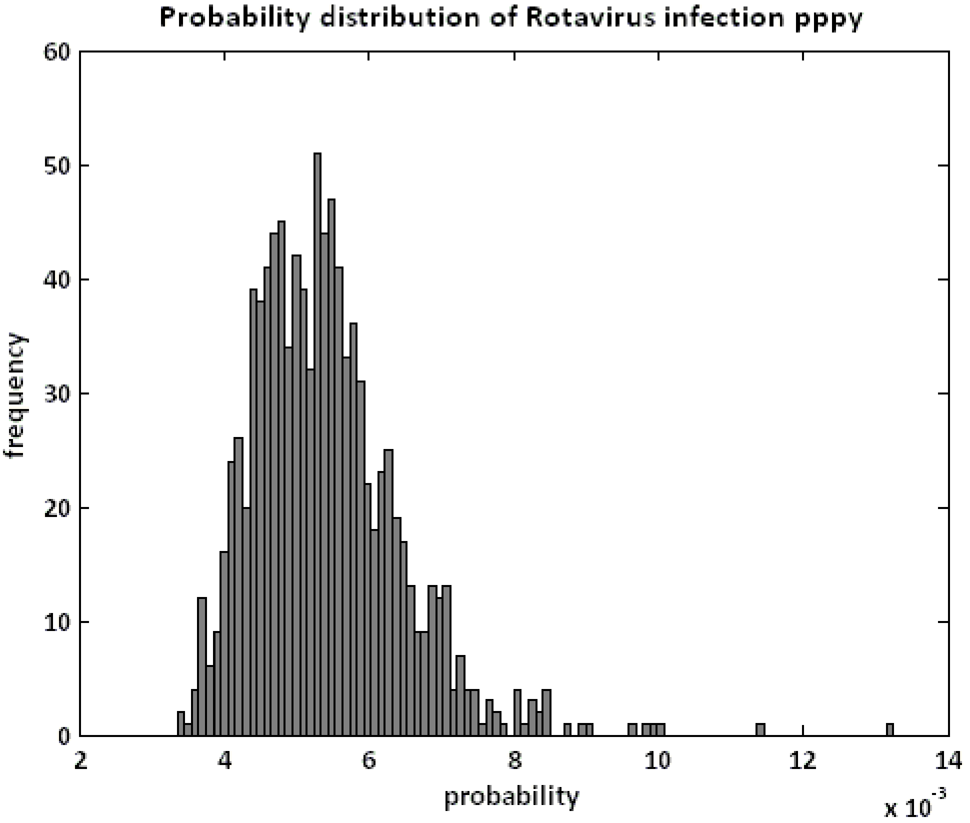

Probability distribution of Giardia infection pppy

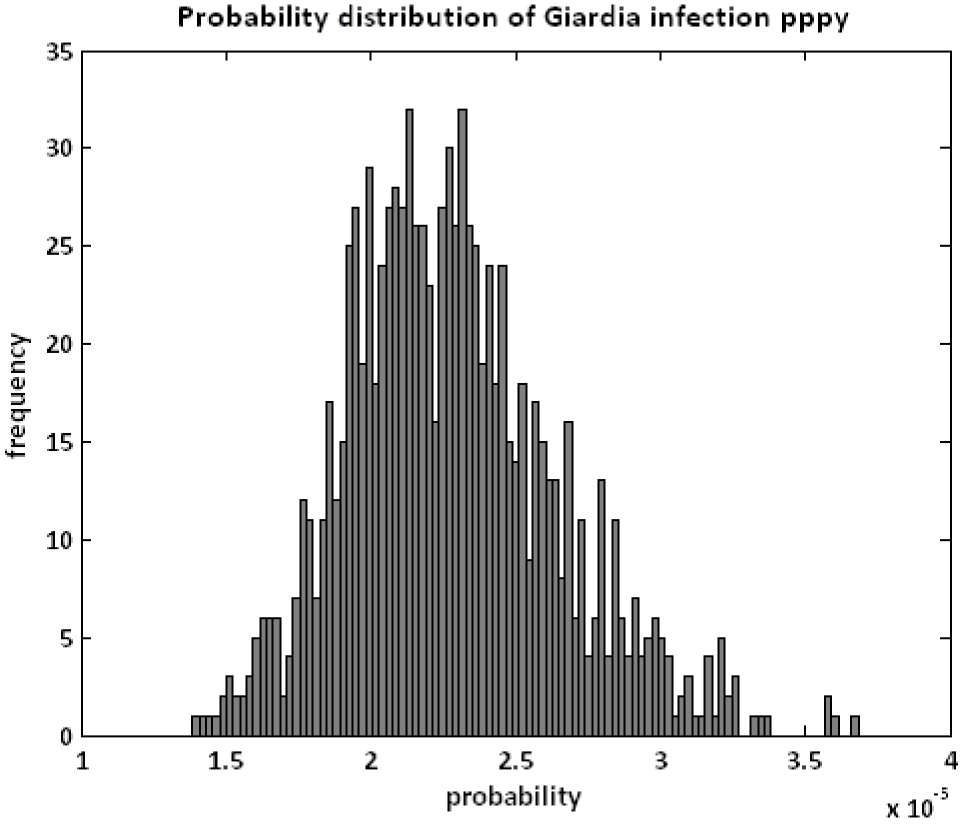

Probability distribution of EHEC infection pppy
frequency
0
5
10
15
20
25
30
35
40
45
50
0.5
1
1.5
2
2.5
3
3.5
4
4.5
probability
x 10^{-8}

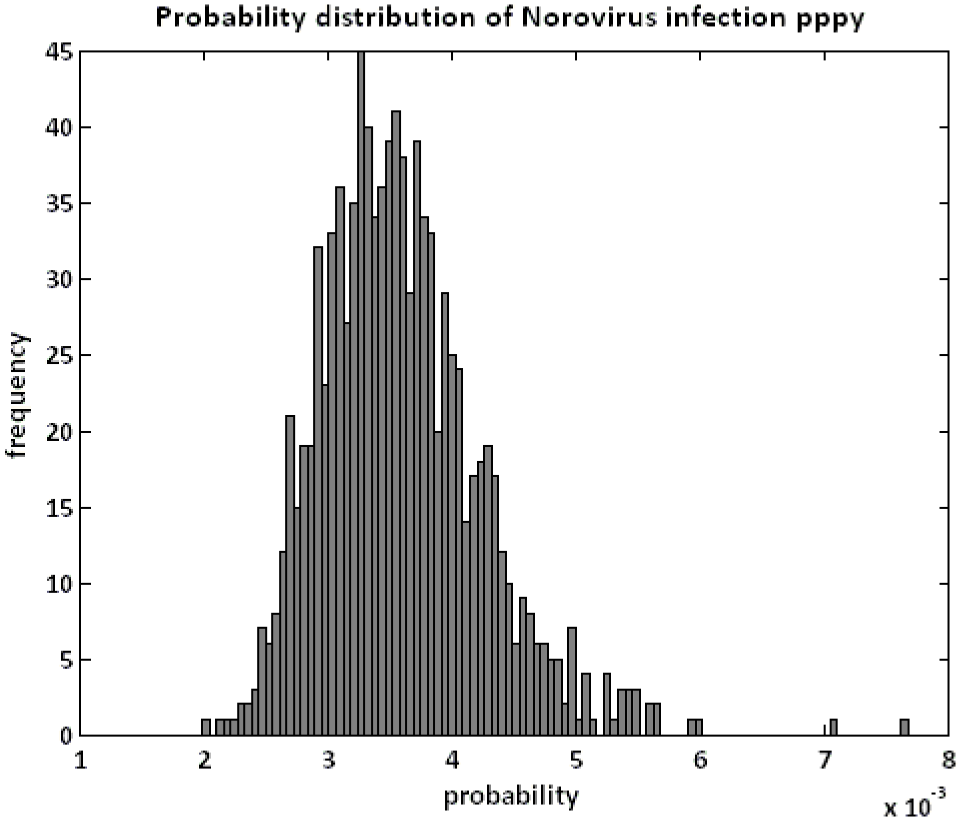

Probability distribution of Salmonella infection pppy
frequency
0
10
20
30
40
50
60
1
2
3
4
5
6
7
8
probability
x 10^{-4}

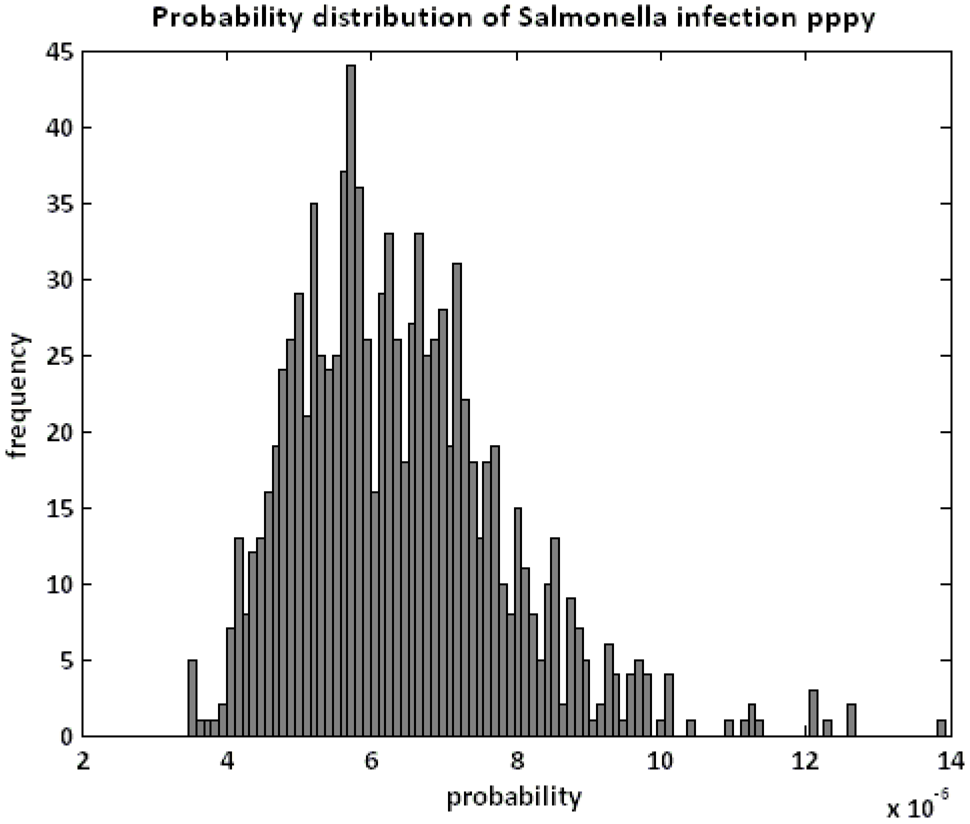
Nearby residents scenario



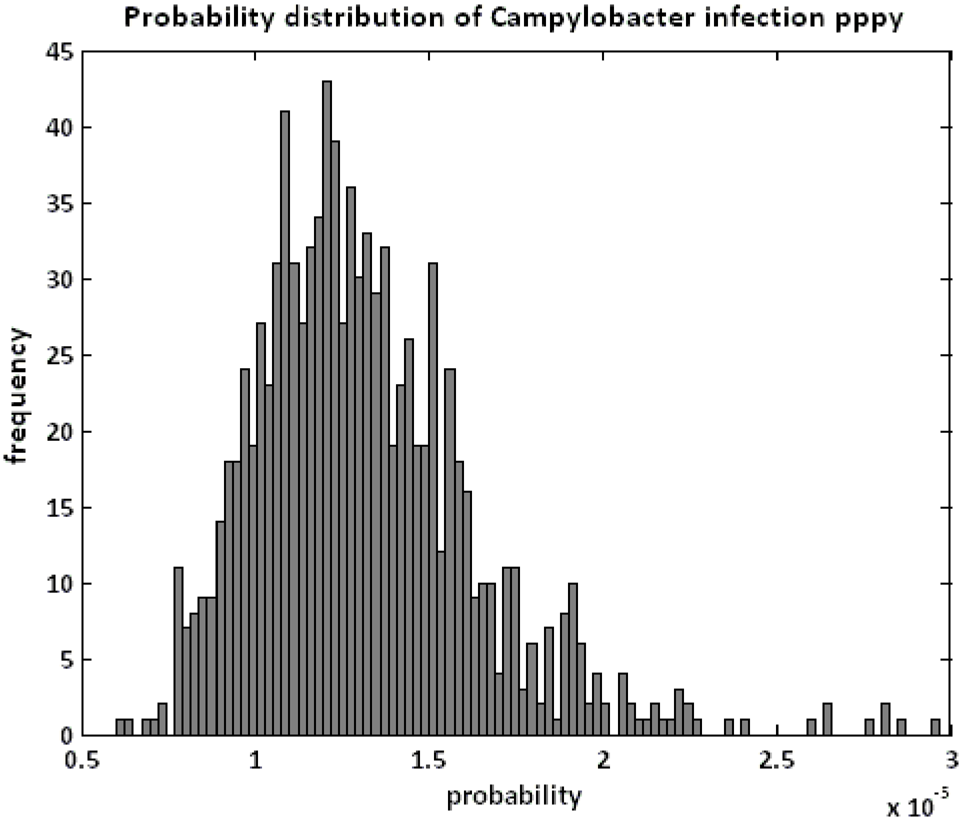



Probability distribution of Giardia infection pppy
frequency
probability
x 10^-5
0
5
10
15
20
25
30
35
1
1.5
2
2.5
3
3.5
4


Probability distribution of Norovirus infection pppy
frequency
probability
x 10^-3
0
5
10
15
20
25
30
35
40
45
1
2
3
4
5
6
7
8

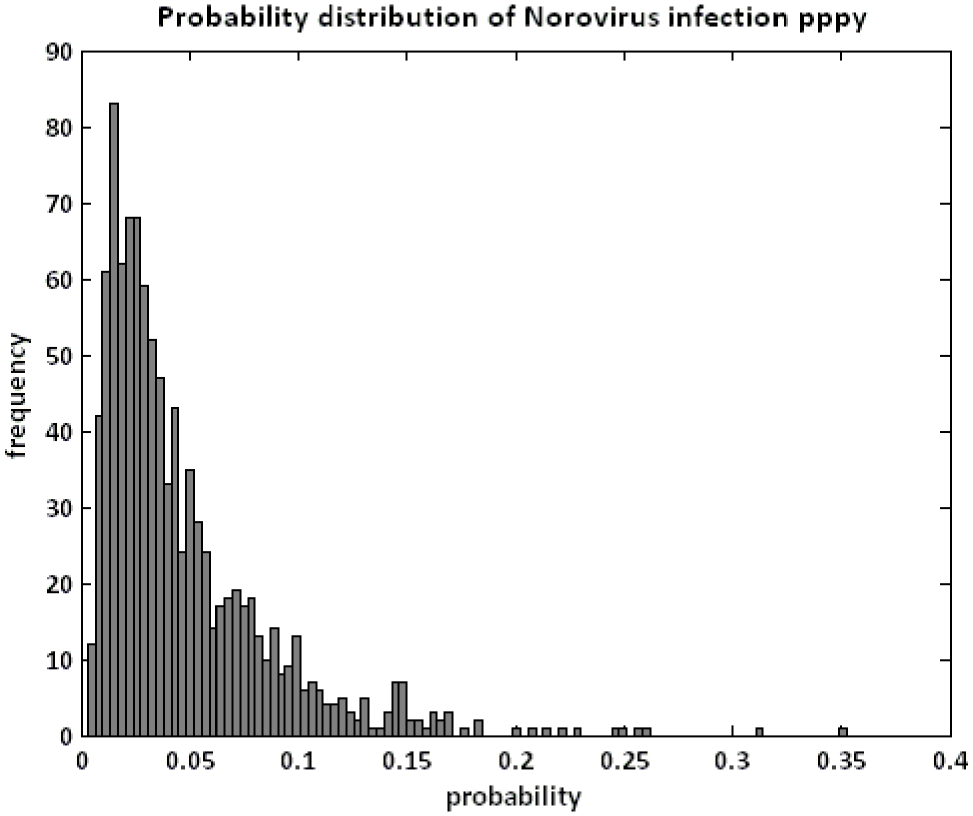


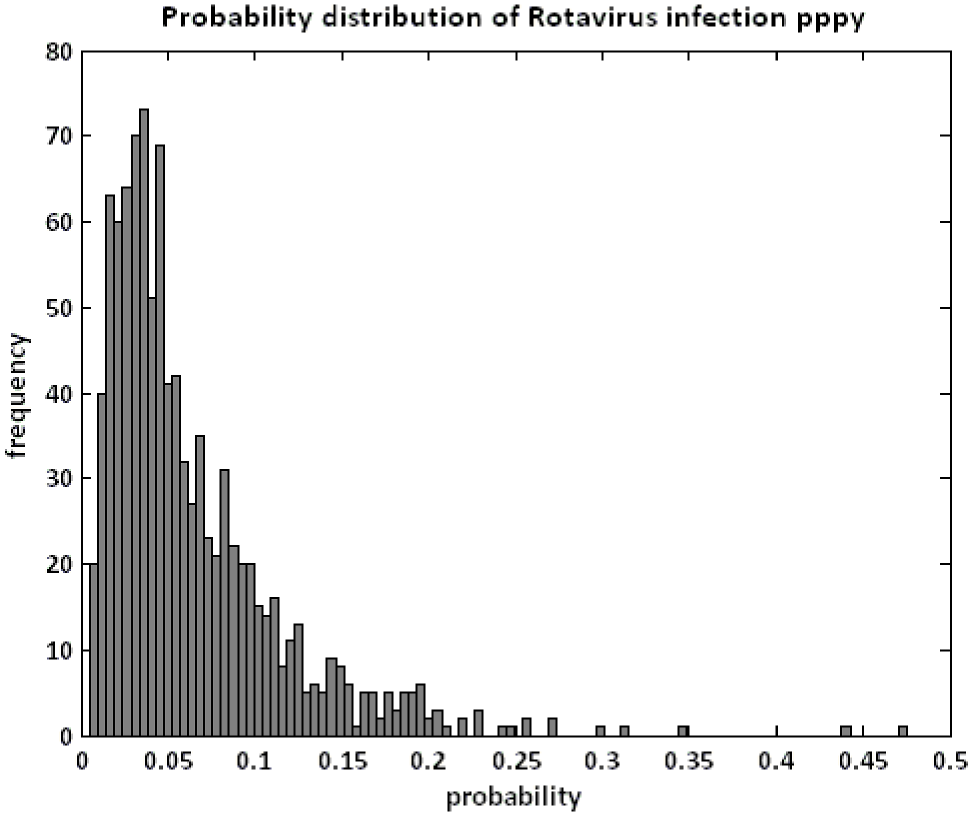
Probability distribution of Salmonella infection pppy

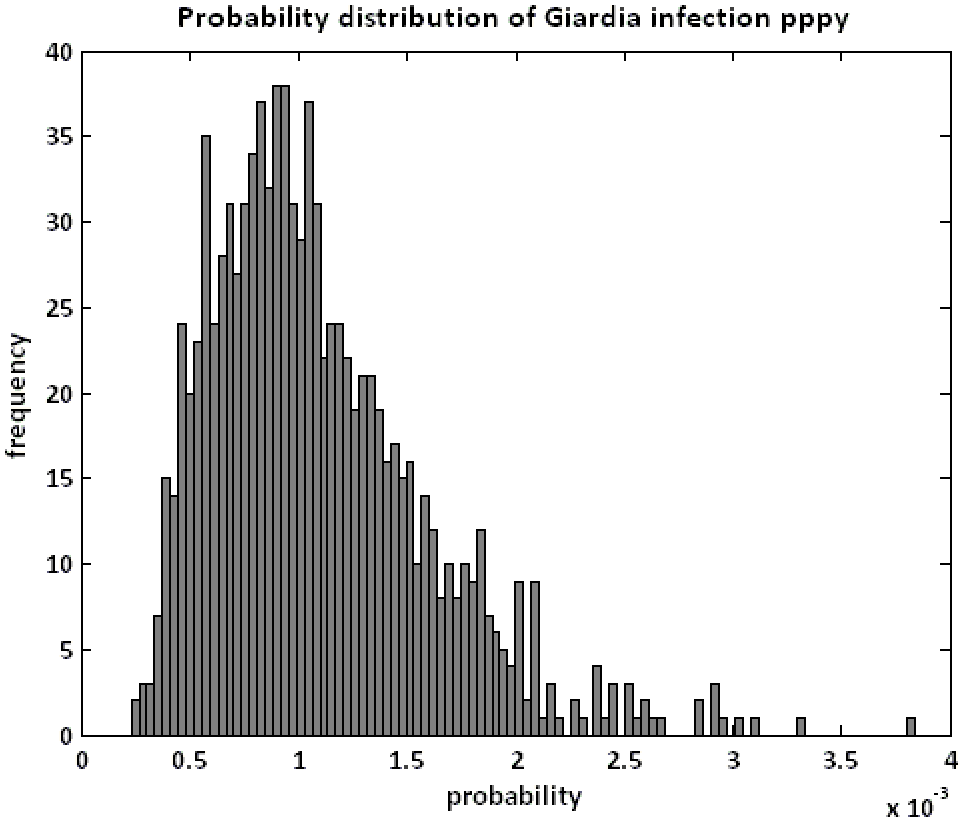


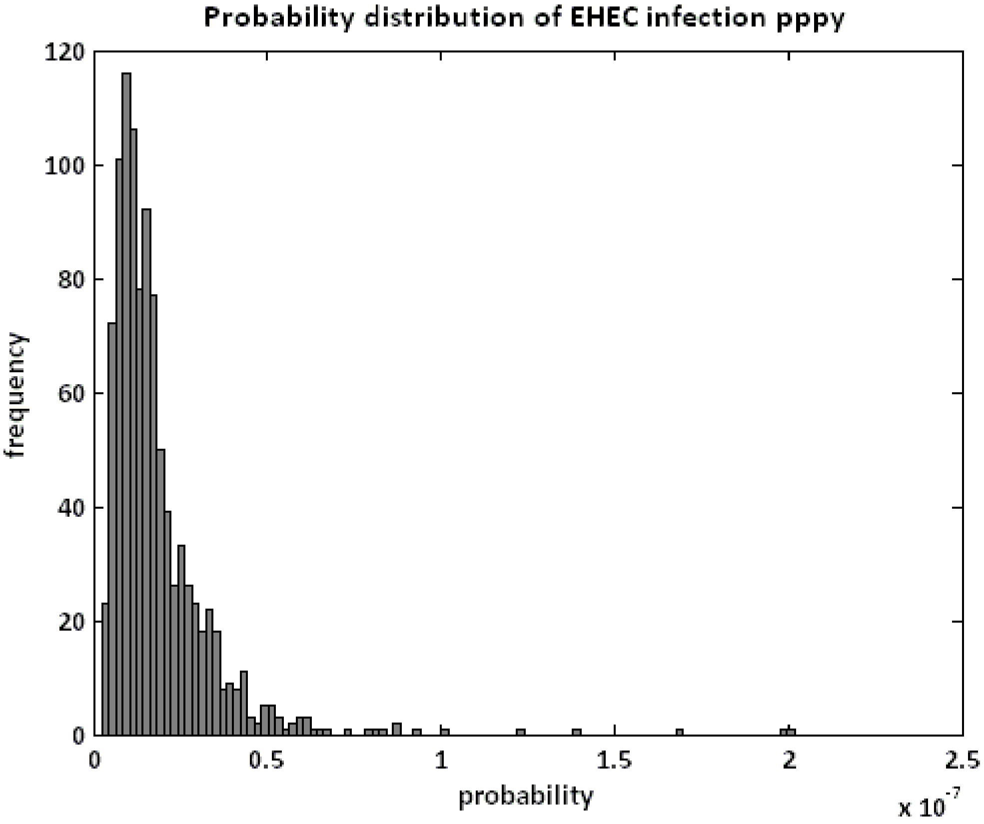
Probability distribution of Campylobacter infection pppy

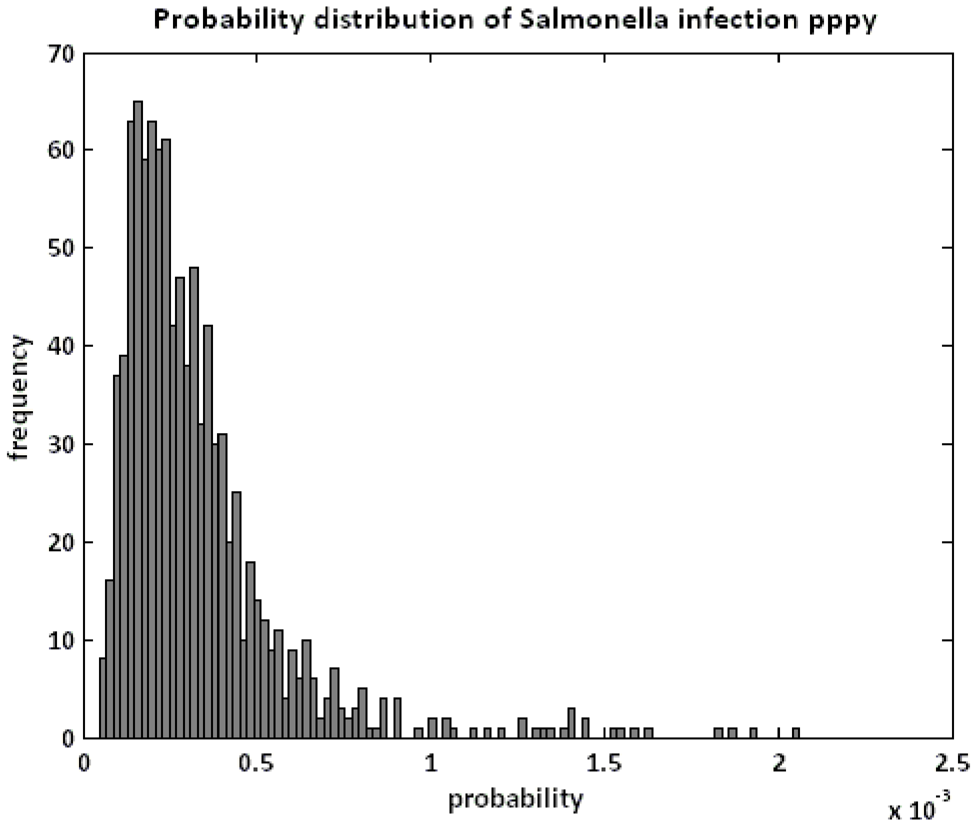
<u>Children scenario</u>

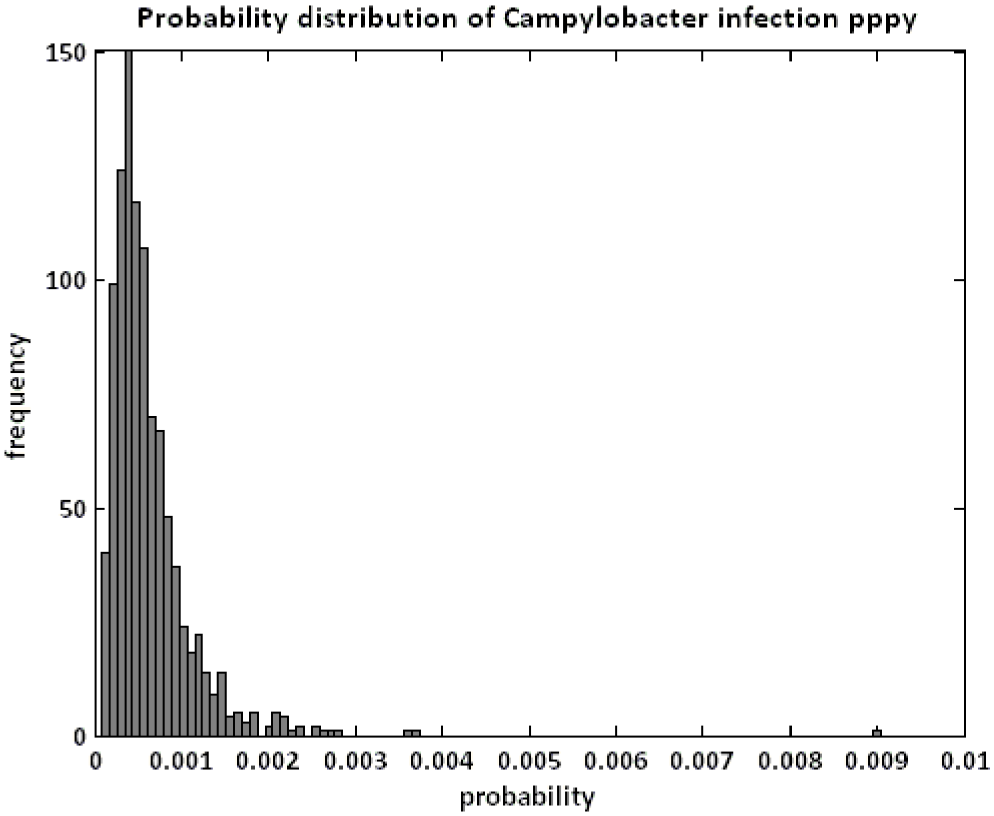





Probability distribution of Giardia infection pppy
frequency
probability
0
5
10
15
20
25
30
35
40
0
0.5
1
1.5
2
2.5
3
3.5
4
x 10^{-3}


Probability distribution of EHEC infection pppy
frequency
probability
0
20
40
60
80
100
120
0
0.5
1
1.5
2
2.5
x 10^{-7}


Probability distribution of Salmonella infection pppy
frequency
70
60
50
40
30
20
10
0
0
0.5
1
1.5
2
2.5
probability
x 10^{-3}


Probability distribution of Campylobacter infection pppy
frequency
150
100
50
0
0
0.001
0.002
0.003
0.004
0.005
0.006
0.007
0.008
0.009
0.01
probability

Annual risk of Rotavirus infection

	fieldworkers	Nearby residents	children
Median	$5.4*10^{-2}$	$5.1*10^{-3}$	$5*10^{-2}$
Mean	$5.6*10^{-2}$	$5.3*10^{-3}$	$6.4*10^{-2}$
Min	$2.1*10^{-2}$	$3.3*10^{-3}$	$3.3*10^{-3}$
Max	$1.3*10^{-1}$	$1.4*10^{-2}$	$4.4*10^{-1}$
Standard deviation	$1.7*10^{-2}$	$1.0*10^{-3}$	0.049
Range	0.113	$1.1*10^{-2}$	0.43

Annual risk of Giardia infection

	fieldworkers	Nearby residents	children
Median	$9.1*10^{-4}$	$2.2*10^{-5}$	$9.9*10^{-4}$
Mean	$9.3*10^{-4}$	$2.3*10^{-5}$	$1.1*10^{-3}$
Min	$5.3*10^{-4}$	$1.4*10^{-5}$	$2.3*10^{-4}$
Max	$1.7*10^{-3}$	$3.7*10^{-5}$	$3.8*10^{-3}$
Standard deviation	$1.5*10^{-4}$	$3.7*10^{-6}$	$5*10^{-4}$
Range	$1.2*10^{-3}$	$2.3*10^{-5}$	$3.6*10^{-3}$

Annual risk of Campylobacter infection

	fieldworkers	Nearby residents	children
Median	$5.1*10^{-4}$	$1.3*10^{-5}$	$5*10^{-4}$
Mean	$5.3*10^{-4}$	$1.3*10^{-5}$	$6.2*10^{-4}$
Min	$2.8*10^{-4}$	$6.0*10^{-6}$	$7.8*10^{-5}$
Max	$1.3*10^{-3}$	$3.0*10^{-5}$	$9.0*10^{-3}$
Standard deviation	$1.3*10^{-4}$	$3.2*10^{-6}$	$5.0*10^{-4}$
Range	$1.1*10^{-3}$	$2.4*10^{-5}$	$9.0*10^{-3}$

Annual risk of EHEC infection

	fieldworkers	Nearby residents	children
Median	$1.5*10^{-8}$	$3.6*10^{-10}$	$1.4*10^{-8}$
Mean	$1.6*10^{-8}$	$3.8*10^{-10}$	$1.8*10^{-8}$
Min	$7.4*10^{-9}$	$1.7*10^{-10}$	$2.4*10^{-9}$
Max	$5.4*10^{-8}$	$1.6*10^{-9}$	$2.0*10^{-7}$
Standard deviation	$5*10^{-9}$	$1.2*10^{-10}$	$1.7*10^{-8}$
Range	$4.7*10^{-8}$	$1.4*10^{-9}$	$2.0*10^{-7}$

Annual risk of Norovirus infection

	fieldworkers	Nearby residents	children
Median	$3.8*10^{-2}$	$3.5*10^{-3}$	$3.3*10^{-2}$
Mean	$4*10^{-2}$	$3.6*10^{-3}$	$4.7*10^{-2}$
Min	$1.7*10^{-2}$	$2.0*10^{-3}$	$3.1*10^{-3}$
Max	$1.2*10^{-1}$	$7.7*10^{-3}$	$3.5*10^{-1}$
Standard deviation	$1.4*10^{-2}$	$6.5*10^{-4}$	0.041
Range	$9.9*10^{-2}$	$5.7*10^{-3}$	0.34

	Annual risk of Salmonella infection		
	fieldworkers	Nearby residents	children
Median	$2.4*10^{-4}$	$6.2*10^{-6}$	$2.6*10^{-4}$
Mean	$2.5*10^{-4}$	$6.4*10^{-6}$	$3.3*10^{-4}$
Min	$1.3*10^{-4}$	$3.5*10^{-6}$	$4.9*10^{-5}$
Max	$8.2*10^{-4}$	$1.4*10^{-5}$	$2.1*10^{-3}$
Standard deviation	$6.4*10^{-5}$	$1.5*10^{-6}$	$2.5*10^{-4}$
Range	$6.9*10^{-4}$	$1.0*10^{-5}$	$2*10^{-3}$

Bibliography

AbfKlärV (1992). Klärschlammverordnung (AbfKlärV), Bundesrepublik Deutschland

Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit

Alan D. Lopez, C. D. M., Majid Ezzati, Dean T. Jamison, Christopher J. L. Murray, Ed. (2006). Global Burden of Disease and Risk Factors. Washington DC, Oxford University press, The World Bank.

Asano, Leong, et al. (1992). "Evaluation of the California Wastewater reclamation criteria using enteric virus monitoring data." Water Science and Technology 26(7-8): 1513-1524.

Barrenberg, E. and T.-A. Stenström (2010). "Sanitation Safety Plans (SSP), A vehicle for Guidline Implementation."

BBodSchV (1999). Bundesrepublik Deutschland, Bundes-Bodenschutz- und Altlastenverordnung (BBodSchV).

Böhm, E., T. Hillenbrand, et al. (2000). Quantification of high priority heavy metal discharges into water. Berlin, Frauenhofer-Institut für Systemtechnik und Innovationsforschung

Caroline Schönning, Therese Westrell, et al. (2007). "Microbial risk assessment of local handling and use of human faeces." Journal of water and health 05(1): 117-128.

Crabtree, C. P. Gerba, et al. (1997). "Waterborne Adenovirus: A Risk Assessment." Water Science and Technology 35(11-12): 1-6.

de Vries, W., G. Schütze, et al. (2005). Calculation of critical loads for Cadmium, Lead and Mercury - Background document to a Mapping Manual on Critical Loads of cadmium, lead and mercury. Wageningen, Alterra.

Drechsel, P., C. Scott, et al., Eds. (2010). Wastewater irrigation and health-Assessing and Mitigating Risk in Low-Income Countries. London, Sterling VA, International Development Research Center, Earthscan.

DWD (2004). Jahresmittel der Windgeschwindigkeit - 10m über dem Grund- in der Bundesrepublik Deutschland. Offenbach, Deutscher Wetterdienst, Abteilung Klima- und Umweltberatung: Statistisches Windfeldmodel, Bezugszeitraum 1981-2000.

EC (2006). Verordnung (EG) Nr. 1881/2006 der Kommission zur Festsetzung der Höchstgehalte für bestimmte Kontaminanten in Lebensmitteln. 1881/2006. E. Kommission.

ECB (2007a). European Union Risk Assessment Report CADMIUM METAL.

ECB (2007b). European Union Risk Assessment Report LEAD METAL,LEAD OXIDE, LEAD TETROXIDE, LEAD STABILISER COMPOUNDS Lead Development Association International.

ECB (2008). European Risk Assessment Report NICKEL AND NICKEL COMPOUNDS.

ECI (2008). European Union Risk Assessment Report VOLUNTARY RISK ASSESSMENT OF COPPER, COPPER II SULPHATE PENTAHYDRATE, COPPER(I)OXIDE, COPPER(II)OXIDE, DICOPPER CHLORIDE TRIHYDROXIDE, European Copper Institute.

Eggers, T. (2008). "Verregnung von geklärtemAbwasser auf 3000ha langwirtschaftlich genutzten Flächen." Wasser(Abwasser 149(13).

EU (2002). REGULATION (EC) No 178/2002 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL. EC 178/2002. E. P. a. Council.

EU (2003). Technical Guidance Document on Risk Assessment, European Commission. 2.

Fewtrell, L. and J. Bartram, Eds. (2001). Water Quality, Assessment of risk and risk management for water-related infectious disease, IWA Publishing, SMITTSKYDDSINSTITUTET, World Health Organization.

Fiebig, B. (2011). Einleiterkontrollen. Braunschweig

Berlin.

Furumoto, W. and R. Mickey (1967). "A mathematical model for the infectivity-dilution curve of tabacco mosaic virus: theoretical considerations." Virology 32(216).

Gokogka, E., M. Reij, et al. (2011). "Risk-based Estimate of Effect of Foodborne Disease on Public Health, Greece." Emerging Infectious Diseases 17(9): 1581-1591.

Haagsma, J., A. Havelaar, et al. (2008). "Disability Adjusted Life Years and minimal disease: application of a preference-based relevance criterion to rank enteric pathogens." Population Health metrics 6(7).

Haas, C. N., J. B. Rose, et al. (1999). Quantitative Microbial Risk Assessment, John Wiley & Sons, Inc.

Hamilton, A. J., Stagnitti, et al. (2006). "Quantitative Microbial Risk Assessment, Models for Consumption of raw vegetables irrigated withi reclaimed water." Applied and Environmental Microbiology 72(5): 3284-3290.

Hartmann, A., D. Klein, et al. (2010). Energie und Nährstoffrückgewinnung in der Abwasserbehandlung-Das Konzept Braunschweig.

Henning, K. J., D. J. Bräunig, et al., Eds. (2010). Leitfaden für gesundheitliche Bewertungen. Rostock.

Hillenbrand, T., F. Marscheider-Weidemann, et al. (2006a). "Prioritäre Stoffe der Wasserrahmenrichtline: Datenblatt Nr.6: Cadmium."

Hillenbrand, T., F. Marscheider-Weidemann, et al. (2006b). "Prioritäre Stoffe der Wasserrahmenrichtlinie. Datenblatt Nr.20: Lead."

Hillenbrand, T., F. Marscheider-Weidemann, et al. (2006c). Prioritäre Stoffe der Wasserrehmenrichtlinie, Datenblatt 21: Mercury.

Hillenbrand, T., F. Marscheider-Weidemann, et al. (2006d). "Prioritäre Stoffe der Wasserrhmenrichtlinie, Datenblatt Nr. 23: Nickel."

Huber, S. and W. Popp (2005). Überprüfung der Abtötung bzw. Inaktivierung ausgewählter Krankheitserreger in Abwasser durch UV-Strahlung im Vergleich zur Reduktion von Fäkalindikatorbakterien und Untersuchungen zur Wiederverkeimung, Bayerisches Landesamt für Umwelt.

JRC (2010). "European Union Risk Assessment Report ZINC METAL."

Klages, S., U. Schultheiß, et al. (2009). Anforderungen an die Novelierung der Klärschlammverordnung unter besonderer Berücksichtigung von Hygieneparametern. F. I. 2.6. Dessau-Roßlau, Umweltbundesamt.

Koivunen, J., A. Siitonen, et al. (2003). "Elimination of enteric bacteria inbiological-chemical treatment and tertiary filtration." Water research 37: 690-698.

Lesjean, B., T. Dockhorn, et al. (2010). "Optimisation of energy and nutrient recovery in wastewater treatment schemes GoDiGreen."

Madigan, M. T. and J. M. Martinko (2006). Brock Biology of Microorganisms, Pearson Prentice Hall.

Mara, D., Blumenthal, et al. (2007). "Health risks in wastewater irrigation: Comparing estimates from quantitative microbial risk analyses and epidemiological studies." Journal of water and health 05(1): 39-50.

Mara, D., C. Hamilton, et al. (2010). WSHH Guidance note 4, More appropriate tolerable additional burdenof disease, Improved determination of annual risks, Norovirus and Ascaris infection risks, Extended health protection control measures,Treatment and non-treatment options. OMS-WSHH-Guidance note, World Health Organisation.

Mara, D. and A. Sleigh (2010). "Estimation of norovirus infection risks to consumers of wastewater-irrigated food crops eaten raw." Journal of water and health 08(1): 39-43.

Medema, G. J. and J. F. Schijven (2001). "Modelling the sewage discharge and dispersion of Cryptosporidium and Giardia in surface water." Water research 35(18): 4307-4316.

Mekel, Mosbach-Schulz, et al. (2007). Evaluation von Standards und Methoden der probabilistischen Expositionsabschätzung. Dessau-Roßlau, Umweltbundesamt.

MRI (2008). Nationale Verzehrsstudie II, Max-Rubner-Institut Bundesforschungsinstitut für Ernährung und Lebensmittel.

Ripke, H. Nutzungalternativer Wasserresourcen für die Zusatzbewässerung, Abwasserverband Braunschweig.

RKI (1999a). "Aktuelle Daten in Informationsn zu Infektionskrankheiten und Public Health, 7.Folge: Campylobacterinfektionen." Epidemiologisches Bulletin 35/99.

RKI (1999b). "Aktuelle Daten und Informationen zu Infektionskrankheiten und Public Health, 6. Folge: EHEC-Infektionen." Epidemiologisches Bulletin 31/99.

RKI (2000). "Aktuelle Daten und Informationen zu Infektionskrankheiten und Public Health, Ratgeber Infektionskrankheiten, 11 Folge: Erkrankungen durch Norwalk-like-Viren." Emerging Infectious Diseases 4/2000.

RKI (2002). "Aktuelle Daten und Informationen zu Infektionskrankheiten und Public Health, Merkblätter für Ärzte, Erkrankungen durch Rotaviren." Epidemiologisches Bulletin 10/2002.

RKI (2009). "Aktuelle Daten und Informationen zu Infektionskrankheiten und Public Health, Merkblätter für Ärzte, Salmonellose (Salmonellen-Gastroenteritis) " Epidemiologisches Bulletin 13/09.

Robert-Koch-Institut (2011). SurvStat, http://www3.rki.de/SurvStat, deadline: 09.08.2011.

Rose, J. B., C. N. Haas, et al. (1991). "Risk Assessment and Control of Waterborne Giardiasis." American Journal of Public Health 81(6).

Salgot, Huertas, et al. (2004). "Wastewater reuse and risk:definition of key objectives." Desalination 187: 29-40.

Scheffer and Schachtschabel (2002). Lehrbuch der Bodenkunde. Heidelberg, Spektrum Akademischer Verlag GmbH.

Schmoll, O. (2003). Das HACCP-Konzept und die Water Safety Plans der WHO, Neue Entwicklungen in der Trinkwasserhygiene?, Umweltbundesamt.

Schütze, G. and T. Spranger (2002). Expert Meeting on Critical Limits for Heavy Metals and Methods for their Application. Berlin, Umweltbundesamt.

Shuval (1993). "Investigation of typhoid fever and cholera transmission by raw wastewater irrigation in Santiago, Chile." Water Science and Technology 27(3-4): 167-174.

Shuval, Lampert, et al. (1997). "Development of a risk assessment approach for evaluating wastewater reuse standards for agriculture." Water Science and Technology 35(11-12): 15-20.

Ternes, T., B. Teiser, et al. (2003). Fallstudie Deutschland, Verhalten von Pharmaka und Körperpflegemittelnnach der Verregnung in Braunschweig.

Teunis, F. M., C. L. Moe, et al. (2008). "Norwalk Virus: How infectious is it?" Journal of Medical Virology 80: 1468-1476.

Thorn, Beijer, et al. (2002). "Work related symptoms among sewage workers: a nationwide survey in Sweden." Occupational and Environmental Medicine 59: 562–566.

Thornton, I., D. Butler, et al. (2001). Pollutants in urban waste water and sewage sludge. I. C. Ltd. London

Luxembourg, European Communities.

Umweltbundesamt (2011). FAQ EHEC. Umweltbundesamt. Dessau-Roßlau.

Viau, E., B. Kyle, et al. (2011a). "Supporting information of "Toward a consensus view on the infecious risks associated with land applying sewage sludge" " Environmental Science and Technology 45.

Viau, E., B. Kyle, et al. (2011b). "Toward a consensus view of the infectious risks associated with land application of sewage sludge." Environmental Science and Technology 45: 5459-5469.

VKM (2009). Risk assessment of contaminants in sewage sludge applied on Norwegian soils. Nydalen.

Weikert, W. (2001). Wasserrechtliche Erlaubnisse; Änderungen der Erlaubnis zur Beregnung mit bahandeltem Abwasser aus dem Klärwerk Braunschweig für den Abwasserverband Braunschweig. 2399/01. B. Braunschweig.

Westrell, Schönning, et al. (2004). "QMRA (quantitative microbial risk assessment) and HACCP (hazard analysis and critical control points) for management of pathogens in wastewater and sewage sludge treatment and reuse

" Water Science and Technology 50(2): 23-30.

WHO (1992). "A guide to the development of off-site sanitation."

WHO (2006). Guidelines for the safe use of wastewater, excreta and greywater, World Health Organization. Volume 2.

WHO (2009). Global burden of disease death daly country estimates 2004, World Health Organization.

WHO (2011). Guidelines for Drinking Water Quality, Fourth Edition, World Health Organization.

Wittowski, R. (2007). Aufgaben der Risikobewertung, Bundesinstitut für Risikobewertung (BfR)