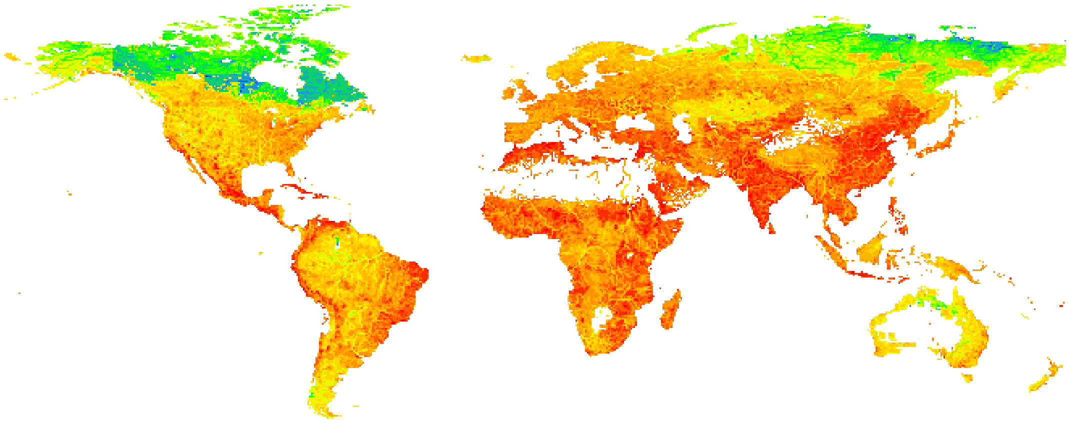
Assessing the Impact of Socioeconomic Development and Climate Change on Global Cryptosporidium Concentrations

A GloWPa Modelling Approach



M.Sc. Thesis by Maurits P. Kuijvenhoven

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A GloWPa Modelling Approach

Master Thesis Water Systems and Global Change Group in partial fulfillment of the degree of Master of Science in International Land and Water Management at Wageningen University, the Netherlands

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Table of contents

Thesis structure and concepts

This MSc thesis does not follow the conventional format typically reserved for students of International Land and Water Management. Instead of following the standard thesis-structure, I will adopt the structure of a research paper. I chose this structure as it was recommended to me by my supervisor and because I wanted to challenge myself while developing the skill of writing a concise research paper. Furthermore, I consider my research to be relevant and novel and I intend to submit it to a scientific journal if the level of my writing allows for that. While a research paper is similar in structure to a traditional thesis format, the research questions, explanation of the concepts and reflection on the conceptual framework are usually left out. To fulfil the requirements of the MSc thesis at the Water Systems and Global Change group for MIL students, I will use this chapter to briefly introduce the sections that are not included in a research paper. At the end of my thesis, I will provide a reflection on my conceptual framework.

This thesis will focus on the effects socioeconomic development and climate change have on *Cryptosporidium* concentrations using a quantitative modelling method. *Cryptosporidium* is a waterborne pathogen, which are microorganisms, such as bacteria, viruses and parasites causing illnesses or diseases when ingested or exposed to contaminated water. *Cryptosporidium* infection can cause diarrhoea and can pose a significant risk to public health. Existing modelling exercises for calculating the concentrations of waterborne pathogen concentrations on a global scale do not use scenarios to study the future impact of socioeconomic development and climate change on these concentrations. Therefore, the objective of this study is to assess future impact of socioeconomic development and climate change on the concentration of *Cryptosporidium*, by using scenarios for future socioeconomic development and climate change. A more in-depth description of the problem definition and objective can be found in the Introduction chapter of the research paper.

Based on the problem definition and the objective, two research question have been developed to complete the objective. These research questions have been specified with sub-research questions, to help answer the research questions. It must be noted that the sub-research questions have not been explicitly answered in the paper, but rather have served as a methodology to get to the answers of the research questions, having made the research more manageable by cutting it up into steps.

1. What is the effect of different socioeconomic scenarios (SSP1, SSP3, SSP5) on *Cryptosporidium* concentrations with the GloWPa model?
    a. How would the future incidence or prevalence of *Crypto*sporidiosis change in the population?
    b. What is the effect on *Cryptosporidium* loads of population changes (number, urbanisation, HDI (Human Development Index)) under different socioeconomic development scenarios?
    c. What is the effect on *Cryptosporidium* loads of prevalence and excretion changes under different socioeconomic development scenarios?
    d. What is the effect on *Cryptosporidium* loads of sanitation and treatment changes under different socioeconomic scenarios?
    e. What is the effect on *Cryptosporidium* loads of agricultural management changes under different socioeconomic scenarios?
2. What is the impact of climate change on *Cryptosporidium* concentrations, using RCP 2.6 and RCP 8.5 with the GloWPa model?
    a. What is the effect of runoff and discharge changes on *Cryptosporidium* concentrations?

b. What is the effect of water temperature and solar radiation changes on *Cryptosporidium* concentrations?

The first research question will be answered in Chapter 2.1.1 This research question is answered by analysing *Cryptosporidium* concentrations under different socioeconomic development scenarios. The second research question will be answered in Chapter 2.1.2, by quantitative modelling of *Cryptosporidium* concentrations under different climate change scenarios.

I will now briefly introduce the conceptual framework and concepts that were used to tackle the research questions. The conceptual framework applied to this research combines the impacts of socioeconomic development and climate change with the GloWPa model, as shown in Figure 1. First the GloWPa models are introduced, thereafter quantification of socioeconomic development and climate change with input variables for these models is introduced. An in-depth introduction to the conceptual framework, models and concepts will be provided in the Supplementary materials S1.

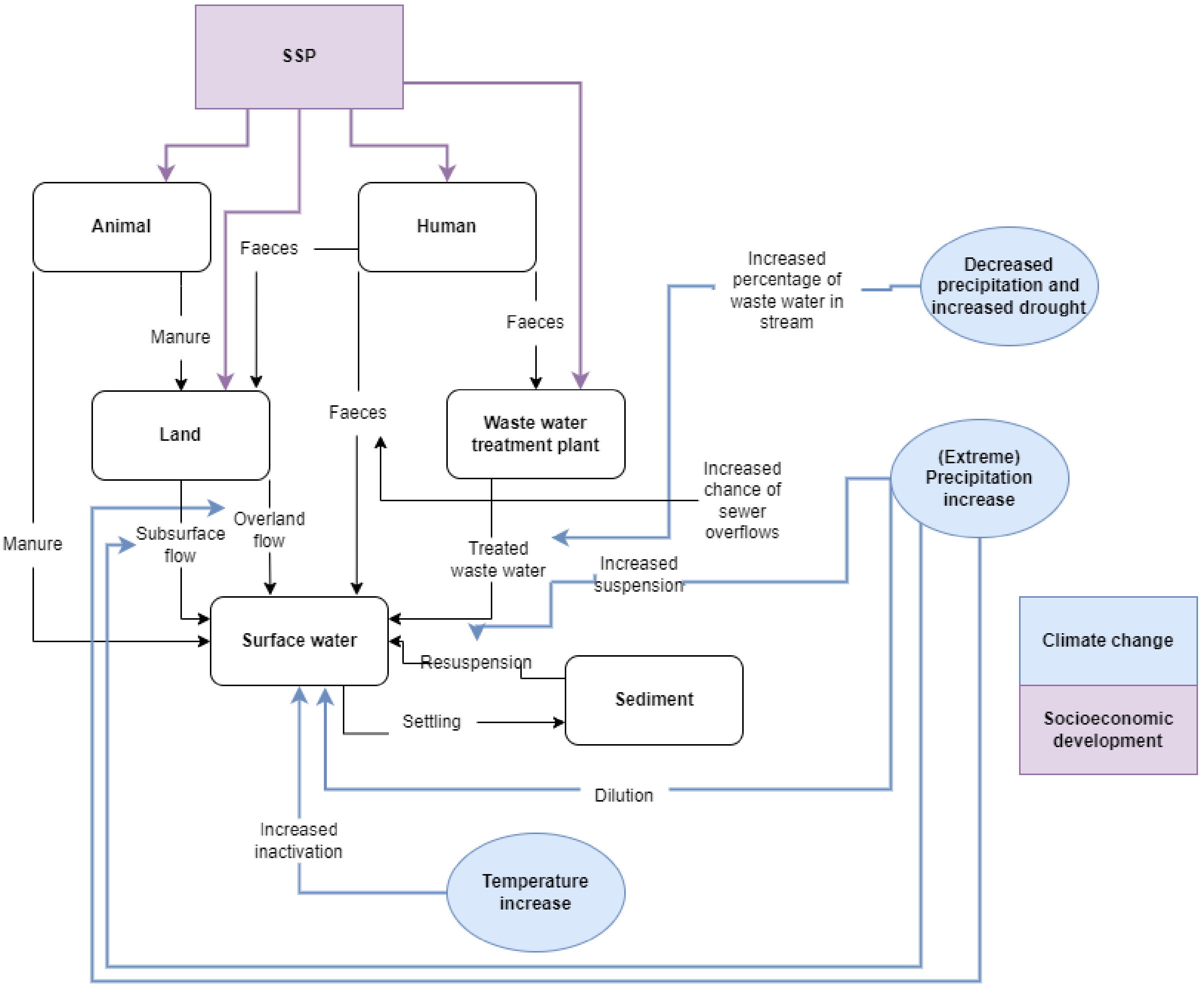

Figure 1: Conceptual model combining the impact of climate change and socioeconomic change scenarios on waterborne pathogen concentrations. Based on the conceptual frameworks by Hofstra (2011) and Hofstra et al. (2019).

The model used is the Global Waterborne Pathogen (GloWPa) model. The GloWPa model is programmed in R, to calculate the global distributions and emissions of pathogens, such as *Cryptosporidium*, to land and rivers from oocyst excretion by humans and livestock on a 30 min grid. This means that each cell is approximately 50 km by 50 km at the equator. Human and livestock oocyst loads are calculated by using the GloWPa-*Crypto* H1 and GloWPa-*Crypto* L1 models respectively. GloWPa-*Crypto* C1 couples output from GloWPa-*Crypto* H1 and L1 with data from the

Variable Infiltration Capacity (VIC) model (Liang et al., 1994), to calculate the mean monthly riverine oocyst concentration. The *Cryptosporidium* loads and concentrations are then appointed to the grids, in accordance with grid-specific data.

The conceptual framework used in this thesis research is based off the GloWPa model and two previous conceptual models, integrating socioeconomic development and climate change (Hofstra, 2011; Hofstra et al., 2013, 2018). Socioeconomic development and climate change are quantified into future change scenarios to be used as model input variables. These model input variables impact either the *Cryptosporidium* loads of humans/livestock or *Cryptosporidium* concentrations in surface water. For socioeconomic development the following model input variables are used: 1) population, 2) prevalence/excretion, 3) sanitation/treatment and 4) agricultural management. For climate change: 1) runoff, 2) discharge, 3) water temperature and 4) solar radiation.

Abstract

Cryptosporidium, a waterborne pathogen causing diarrhoea, poses a risk to global public health and ecological balance by compromising water quality. This paper presents the results of an assessment of the future impact of socioeconomic development and climate change on the global oocyst loads and concentrations of *Cryptosporidium* in rivers. Three models, the GloWPa-*Crypto* H1, L1 and C1, were used to project future loads from humans and livestock to rivers and concentrations in rivers by integrating assumptions and future change scenarios for socioeconomic development (SSP1, SSP3 and SSP5) and climate change (RCP2.6 and RCP8.5) for the years 2010, 2020, 2030 and 2050.

The results show that the majority of global oocyst load is caused by human emissions. Highest human loads are found in East Asia and Pacific and South Asia, accounting for over half of the total human oocyst emission. The study demonstrates the interrelation between oocyst load, population growth and economic development, with population being the biggest contributor to the global human oocyst load. Global livestock emissions, although relatively low compared to global human emissions, contribute substantially to the total oocyst load, with cattle being the dominant contributor followed by chickens and pigs. Animal population changes, rather than agricultural management, emerged as the biggest determinant of livestock loads. Coastal regions with large cities were hotspots with high concentrations, due to their large population. The impacts of the different SSPs show that SSP3 (Regional rivalry – A rocky road) has the highest oocyst loads and concentrations, while SSP1 (Sustainability – Taking the green road) exhibited the lowest. No significant differences were found between the concentrations under RCP2.6 and RCP8.5. This study contributes to the global water quality assessment, signalling more effort is needed to improve sanitation and wastewater treatment practices in all future scenarios.

1. Introduction

Diarrhoea is one of the leading causes of death among children under the age of five, especially in developing countries (World Health Organization, 2017). Diarrhoea can be caused by different pathogens, such as bacteria, viruses or parasites. Enteric pathogens commonly spread via water and food, allowing it to be attributed to unsafe water, poor sanitation and lack of general hygiene interventions (Utaaker et al., 2019). The control of faecal pollution into water has gained attention, for example in the Sustainable Development Goals (SDGs) (Ortigara et al., 2018), more specifically in SDG 6.3.2: "proportion of bodies of water with good ambient water quality" (UN-Water, n.d.). Safely managed sanitation reduces the risk of exposure to these pathogens (Speich et al., 2016). However, in 2012, still 19% of the diarrhoea burden in low and middle income regions could be attributed to inadequate sanitation and 58% of diarrhoea deaths were attributable to inadequate water, inadequate sanitation and inadequate hand hygiene (Prüss-Ustün et al., 2014). *Cryptosporidium* has been attributed to be responsible for the second most cases of diarrhoea in young individuals worldwide after rotavirus (Kotloff et al., 2013).

Cryptosporidium is an enteric protozoan parasite, infecting humans through contaminated water and food. *Cryptosporidium* is a zoonotic pathogen, indicating that it could be transmitted between humans and animals (Khan et al., 2019). Agricultural activities and livestock close to water bodies have been linked to higher *Cryptosporidium* concentrations in the past (Hansen & Ongerth, 1991). Being a waterborne pathogen, *Cryptosporidium* is able to survive for a considerable amount of time in the water (Robertson et al., 1992). Conventional water treatment struggles to effectively remove *Cryptosporidium* from water as the use of advanced treatment processes, such as ozonation or UV irradiation, may be necessary to effectively remove the parasite from water (Betancourt & Rose, 2004). Concentrations may vary seasonally and annually, caused by rainfall events and topography (Boyer & Kuczynska, 2003; Burnet et al., 2014; Ehsan et al., 2015; Hansen & Ongerth, 1991; Hörman et al., 2004; Mons et al., 2009; Tsushima et al., 2003).

Observational data has shown three climatic impacts on waterborne pathogen concentrations in surface water (Hofstra, 2011). First, the water temperature has different effects on the survival/persistence of pathogens. Second, increased precipitation and extreme precipitation events increase (sub-)surface-runoff of manure and faeces and increase the risk of sewer overflows. Third, decreased precipitation and increased incidence of droughts increases the fraction of waste water to the total discharge resulting in increased waterborne pathogen concentrations. Future population growth and urbanisation will likely lead to deterioration of water quality, improvements to sanitation and treatment will improve water quality in the future (Vermeulen, 2018). On the other hand, socioeconomic development can help reduce the incidence of *Cryptosporidium* infection in developing countries (Checkley et al., 2015).

Determining the microbial water quality is important to comply to health standards and legislation. Microbial water quality can be predicted by using data-driven models. It is critical to try to understand the survival, transfer and export of *Cryptosporidium* to enhance the knowledge of microbial water quality and guide decision-making associated with water resources management. Scenario analysis can be used to ask the "what-if" questions to explore uncertainties, shifting the focus away from what is most likely to occur, toward questions of what could happen under certain circumstances (Duinker & Greig, 2007). Scenario development is one such aid to develop alternative visions of the future. O'Neill et al. (2015) developed five long-term socioeconomic development scenarios, describing the future evolution of key aspects of society that together could imply a range of challenges to adaptation and mitigation of climate change. These narratives, or Shared Socioeconomic Pathways (SSPs), offer qualitative descriptions of future changes in demographics, human development, economy and lifestyle, policies and institutions, technology, and environment and natural resources. The Representative Concentration Pathways (RCPs) are a set of scenarios modelling how concentrations of greenhouse gases (GHG) will develop over the future, widely used to understand potential impacts of climate change (Van Vuuren et al., 2011). Four RCPs represent different levels of GHG emissions and concentration trajectories, using assumptions about economic, demographic and technological factors affecting GHG emissions, as well as policies and measures to mitigate emissions. The specific SSPs and RCPs applied to this research will be discussed in depth in the methods section.

Existing modelling exercises for calculating the concentrations of waterborne pathogen concentrations on a global scale do not use scenarios to study the future impact of socioeconomic development and climate change on these concentrations (Hofstra, 2011; Vermeulen, 2018). Furthermore, studies around impacts of socioeconomic development and climate change focus mainly on developed countries, while problems with diarrheal disease are most prevalent in developing countries (Hofstra, 2011; Hofstra & Vermeulen, 2016). This paper, therefore, aims to assess future impacts of socioeconomic development and climate change on the concentration of *Cryptosporidium* spp., by using scenarios for future socioeconomic development and climate change: SSP1, SSP3 and SSP5 and RCP2.6 and RCP8.5 respectively. This paper will consider for socioeconomic development future changes in incidence, population, prevalence and excretion, sanitation and treatment, and agricultural management. For climate change future changes in runoff, discharge, water temperature and solar radiation will be considered. In doing so, this research contributes to a comprehensive worldwide assessment of freshwater quality. This holistic approach provides valuable insights into complex interactions between socioeconomic and environmental aspects, enhancing the understanding of how global waterborne pathogen concentrations may be influenced in the future.

2. Methods

2.1 Model

Here, a brief overview of the Global Waterborne Pathogen (GloWPa) model is presented. More detailed descriptions of the various iterations of the GloWPa models can be found elsewhere (Hofstra et al., 2013, 2018; Hofstra & Vermeulen, 2016; Vermeulen, 2018; Vermeulen et al., 2015). The GloWPa model is programmed in R, to calculate the global distributions and emissions of pathogens to land and rivers from oocyst excretion by humans and livestock on a 30-minute grid. A 30-minute grid is a way of dividing a geographic area into small cells or squares, each of which covers an area of 30 minutes of latitude and 30 minutes of longitude. This means that each cell is approximately 71.9 square kilometres in size at the equator and slightly smaller at higher latitudes. Human and livestock oocyst loads are calculated by using the GloWPa-*Crypto* H1 and GloWPa-*Crypto* L1 models respectively. GloWPa-*Crypto* C1 couples output from GloWPa-*Crypto* H1 and L1 with data from the Variable Infiltration Capacity (VIC) model (Liang et al., 1994), to calculate the mean monthly riverine oocyst concentration.

2.1.1 GloWPa-*Crypto* H1

The GloWPa-*Crypto* H1 model calculates the human emissions of *Cryptosporidium* to the surface water for an annual time step (Hofstra et al., 2013). Excretion rates are dependent on the fraction of people infected by *Cryptosporidium* and the number of oocysts emitted by infected people (Vermeulen, 2018). Data of human population is divided into developed/developing and rural/urban. Depending on sanitation systems used by a specific population group and assumptions on the oocysts removal fractions by sewage treatment, the human emissions to surface water are calculated. In its latest version, used in this research, 13 sanitation types have been developed, including septic tanks and latrines, and decay in septic tanks and management of these systems (Okaali et al., 2022). Differentiation is made in human loads to water and human loads to land. Loads to land represent the load of *Cryptosporidium* onto the land surface, which is for the most part determined by open defecation, which is still practiced in some rural areas, Loads to water represent the load directly into water bodies, such as rivers, lakes, and coastal areas.

2.1.2 GloWPa-*Crypto* L1

The GloWPa-*Crypto* L1 model calculates animal *Cryptosporidium* loads to land for an annual time step (Vermeulen, 2018). Excretion rates depend on livestock population data, prevalence and oocyst excretion by 11 different livestock species (asses, buffaloes, camels, cattle, chickens, ducks, goats, horses, mules, pigs and sheep) (Vermeulen, 2018). The model splits manure excreted directly to land during grazing and manure spread on land after storage, where decay is accounted for in different management systems. Combining the animal population density, the excretion rate by animals and multiplying that by the fraction of oocysts on the land that end up in surface water, the livestock emission is calculated. The model does not account for the timing of the birthing season and the application of stored manure on fields.

2.1.3 GloWPa-*Crypto* C1

The mean monthly riverine *Cryptosporidium* concentrations are calculated in GloWPa-*Crypto* C1 (Vermeulen, 2018). The output from GloWPa-*Crypto* H1 and L1 are combined with output from the VIC model (Liang et al., 1994; Vermeulen, 2018). GloWPa-*Crypto* C1 simulates the number of oocysts that run off the land with surface-runoff. Subsurface flow is not included, because it is not expected to transport a significant number of oocysts due to the filtering capacity of soils (Mawdsley et al., 1996; McLaughlin et al., 2013). A fraction of the oocysts, that depends on the amount of runoff in each grid, reaches the surface water. For the transport of the oocysts through the river network this model accounts for temperature dependent and solar radiation decay and sedimentation.

2.2 Scenario

2.2.1 Shared Socioeconomic Pathways

For scenario analysis on socioeconomic development, the narratives of the Shared Socioeconomic Pathways (SSPs) will be used (O'Neill et al., 2015). SSPs describe different plausible future socioeconomic conditions. SSP1, SSP3 and SSP5 will be used, as these represent the most extreme scenarios. SSP1 (Sustainability – Taking the green road) represents a future world with a strong focus on sustainable development, including high levels of international cooperation, technological innovation and environmental protection. Global population peaks around mid-century and then declines and there is a shift toward a service-based economy with lower levels of material consumption. Energy use is increasingly dominated by low-carbon sources and there is widespread adoption of sustainable land use practices. SSP1 results in low challenges to climate change mitigation and low challenges to climate change adaptation. SSP3 (Regional rivalry – A rocky road) represents a future characterised by fragmented and inward-looking national policies, limited international cooperation and geopolitical tensions. Global population continues to grow throughout the century, with high levels of migration driven by conflicts and climate change impacts. Economic development is unevenly spread; some regions experience rapid growth and others struggle with poverty and instability. Energy use is dominated by fossil fuels and there is little progress in addressing climate change. SSP3 results in high challenges to climate change mitigation and high challenges to climate change adaptation. SSP5 (Fossil-fuelled development – Taking the highway) represents a future with a strong focus on economic growth, technological progress and resource extraction, with limited concern for environmental protection or social equity. The global population continues to grow throughout the century, with high levels of urbanization and industrialization. Energy use is dominated by fossil fuels, with little progress in addressing climate change. SSP5 also includes a high level of inequality, with wealthy elites benefiting from economic growth while the majority of people struggle with poverty and environmental degradation. This scenario results in high challenges to climate change mitigation and low challenges to climate change adaptation.

To quantify socioeconomic development as input for the GloWPa model as described in the SSP narratives, the following parameters have been included: population (urbanisation, HDI and growth), incidence, prevalence and excretion, sanitation and treatment, animal numbers and agricultural management.

2.2.1.a Human emissions

Human emissions are determined by population, excretion, fraction removal and fraction connected to sewer systems (Hofstra et al., 2013). Assumptions about population, incidence, excretion, sanitation and treatment are presented.

The narratives of the SSPs have been implemented with the IMAGE-model (Beusen et al., 2015, 2022; Morée et al., 2013; Van Puijenbroek et al., 2019). Land-use trends of the different SSPs implemented in IMAGE are taken from Doelman et al. (2018). For this paper, data outcomes of IMAGE version 3.0 have been used. Population data from IMAGE (population per country, urbanisation and HDI) is distributed over the grids according to patterns found in the NCAR database (Gao, 2017, 2020).

The original incidence of *Cryptosporidium* used in previous applications of GloWPa-*Crypto* H1, 0.01 in developing countries (HDI <= 0.785) and 0.05 in developed countries (HDI > 0.785), is adjusted to fit the narratives of the SSPs. New incidence is based on the SSP narratives and on trends in diarrheal disease across different world regions (O'Neill et al., 2015; Sellers, 2020). For each SSP it is assumed that the incidence shrinks compared to the original incidence. The incidence under SSP1 and SSP5 shrinks by 0.625% every 10 years for both developing and developed countries. Under SSP3, the incidence shrinks by 0.25% every 10 years for developed countries and by 0.5% every 10 years for developing countries. The excretion is calculated by multiplying the incidence with the shedding rate (10^9), the shedding duration (7 days) and the population (IMAGE-data) (Hofstra et al., 2013). The specific values for the incidence under each SSP and year have been added to the Supplementary materials S2.

Table 1 shows five categories distinguished to group the sanitation types: unimproved, pit latrines, septic tanks, sewers and other. These replace 4 emissions categories grouping the sanitation types considered by the GloWPa-*Crypto* H1 model (Kiulia et al., 2015; Vermeulen, 2018). The sanitation types each contribute to the total human load to water and land, quantified as a fraction. The fractions are determined based on the GDP of each country, which is different under each SSP and year. The fractions for pit latrines and septic tanks are not determined based on GDP, but rather on HDI, which is explained later. SSP specific sanitation data has been updated with the IMAGE-model (Van Puijenbroek et al., 2023).

Table 1: An overview of the sanitation types grouped into five sanitation categories.

Sanitation category	**Sanitation type**
Unimproved	Open defecation, hanging toilet, container based, pit latrine without a slab, bucket latrine, flush open toilet, urban other
Pit latrines	Flush pit latrine, pit latrine with slab, composting toilet
Septic tanks	Flush septic tanks
Sewers	Flush sewers
Other	Other

The level of management applied to pit latrines and septic tanks impacts the potential for oocysts emission. It is assumed that, under different socioeconomic development scenarios and under different levels of HDI, the management of septic tanks and pit latrines will be different. HDI is cut up into four quartiles, making four cut-off points from a 2015 HDI dataset: 1) 0.42, 2) 0.42-0.55, 3) 0.55-0.62 and 4) higher than 0.62 (Cuaresma & Lutz, 2015). The management of septic tanks and pit latrines is adapted according to the narratives of the SSPs (O'Neill et al., 2015). Considering the HDI cut-off points and the narratives from the SSPs, relative weights are assigned to different management levels: poor, satisfactory and excellent. For excellent management of pit latrines these conditions must be met: dual pit, watertight, covered and buried or waste is emptied periodically. For excellent management of septic tanks these conditions must be met: leach field, watertight, emptied periodically. If only two of these conditions is met, the management is satisfactory. If only one of these conditions is met, management will be classified as poor. The relative weights assigned to management of pit latrines and septic tanks are presented in the Supplementary materials S3.

2.2.1.b Livestock emissions

Livestock emissions are determined by the animal population, oocyst excretion per animal species, the fraction of oocysts (Hofstra et al., 2013). Assumptions about agricultural management to calculate the fraction of oocyst on land ending in surface water and animal populations are presented. The oocyst excretion per animal species remains the same.

Animal species specific population data has been generated with the IMAGE-model (Beusen et al., 2022). The narratives of the SSPs have been implemented with the IMAGE-model, with land-use trends of the IMAGE SSPs specifically described in (Doelman et al., 2018). Gridded animal species specific population data was generated for 11 different animal species: cattle (dairy), cattle (meat), buffaloes, pigs, poultry, sheep, goats, horses, mules, asses and camels.

The fraction of oocysts on the land that ends up in the surface water from livestock manure storage can be managed with various strategies. 11 management strategies are considered: pasture/range/paddock, daily spread, solid storage, dry lot, liquid/slurry, uncovered anaerobic lagoon, anaerobic digester, burned for fuel, other systems, pit storage lower than one month (pigs only) and pit storage longer than one month (pigs only) (Vermeulen et al., n.d.). Each of these management strategies are quantified as a fraction, assigning a portion of the total *Cryptosporidium* load of a certain animal species to the manure management strategy. Together these fractions must always add up to 1. Table 2 shows four animal categories that have been established.

Table 2: An overview of the animal species grouped into four animal categories. The categorisation has been made based on the type of faeces and on how the species is typically managed.

Category 1	Category 2	Category 3	Category 4
Cattle (dairy)	Pigs	Poultry	Sheep
Cattle (meat)			Goats
Buffaloes			Horses
			Mules
			Asses
			Camels

The manure management fractions assigned in a previous iteration of GloWPa-*Crypto* L1 to each animal are adapted according to the SSP narratives (Vermeulen, 2018). It is assumed that for categories 1 and 2, there will be an increase in anaerobic digestion fraction and solid storage fraction, the exact figure depending on the specific SSP narrative, year and HDI (cut-off categories remain the same as with sanitation). The assumption of increased anaerobic digestion and solid storage is based on an increase in demand for bioenergy in the future (Holm-Nielsen et al., 2009). If the anaerobic digestion fraction increases, the liquid/slurry fraction is assumed to reduce equally. Similarly, if the solid storage fraction increases, the daily spread fraction reduces. Countries in the lowest HDI cut-off category have less demand for bioenergy in the future than countries in the highest HDI cut-off category, so demand increases with higher HDI cut-off categories. SSP1 and SSP5 reach the same highest demand for bioenergy in 2050, even though SSP5's growth is much more exponential than SSP1's almost linear growth. For example, the fraction of anaerobic digestion for category 1 and 2 has undergone an absolute increase of 0.2, 0.05 and 0.2 for SSP1, SSP3 and SSP5 respectively between 2010 and 2050 for HDI cut-off category 4. In-depth values changes of the manure management under different scenarios are presented in the Supplementary materials S4.

2.2.2 Representative Concentrations Pathways

For scenario analysis on climate change impacting *Cryptosporidium* concentrations, the Representative Concentration Pathways (RCPs) are used (Van Vuuren et al., 2011). Only RCP2.6 and RCP8.5 are used, as they are the most extreme climate scenarios of the four RCPs. RCP2.6 assumes immediate and strong action to reduce GHG emissions, resulting in peak of emissions around 2020 and a decline thereafter. Within this pathway, the goal is to limit global warming to 2°C above pre-industrial levels, a target agreed upon in the Paris Agreement (*The Paris Agreement*, 2015). RCP8.5 assumes GHG emissions continue to increase throughout the 21st century, with no mitigation efforts. In this pathway, global temperature is expected to increase by 4.5°C by 2100.

To quantify the effects of climate change on global *Cryptosporidium* concentrations, solar radiation (short-wave radiation) and water temperature, discharge and surface-runoff are selected as parameters to input in the GloWPa-*Crypto* C1 model. Data for a historic scenario (approximately 2010) and for RCP2.6 and RCP8.5 was gathered from the Variable Infiltration Capacity (VIC) model and the River Basin Model (RBM) for the years 2040-2069 (Liang et al., 1994; Lohmann et al., 1998; M. T.H. Van Vliet et al., 2016; Michelle T.H. Van Vliet et al., 2016; J. Yearsley, 2012; J. R. Yearsley, 2009). To model discharge and surface-runoff, five different climate models were considered: gfdl-esm2m, miroc-esm-chem, noresm1-m, hadgem2-es and ipsl-cm5a-lr. With these five climate models, the average monthly gridded discharge and surface-runoff are calculated, to develop a monthly average scenario of discharge and surface-runoff for both RCP2.6 and RCP8.5. Discharge values below 1 are ignored in this study, in accordance with Vermeulen et al. (2019), as the GloWPa-*Crypto* C1 model was found to not perform well for locations with a discharge lower than 1. The loads from the SSPs were also combined with historic (HIST) hydrology, using the original hydrology from the GloWPa model representing approximately 2010. For scenarios RCP2.6 and RCP8.5, future hydrology for 2040-2069 is used.

In this study SSP1, SSP3 and SSP5 are combined with RCP2.6 and RCP8.5 to calculate *Cryptosporidium* concentrations. According to the SSP narratives, combining for example SSP1 with RCP8.5 would be implausible, as the ‘greenest’ socioeconomic pathway SSP1 would not typically be combined with a high emissions scenario such as RCP8.5. Similarly, a resource intensive pathway, such as SSP3, would typically not be combined with a low emissions pathway such as RCP2.6. Having said that, by combining all possible combinations of these SSPs and RCPs, a comprehensive spectrum of socioeconomic and climatic scenarios can be explored, providing a more robust assessment of potential impacts on *Cryptosporidium* concentrations. While other studies focus on plausible future developments such as Islam et al. (2018), taking implausible futures into account enhances the reliability and applicability of modelling results. Policymakers require comprehensive understanding of the potential future impacts of socioeconomic developments and climate change, to generate insights into the implications of different choices and strategies.

To test the significance of the differences between SSPs and RCPs, a two-tailed t-test is performed. Typically when the value coming from the t-test is below the p-value 0.05, it means that the difference is statistically different. The scenarios meet the conditions for a two-tailed t-test: they are independent of one another, are relatively homogeneous, follow roughly a normal distribution (although not as important in sample sizes greater than 30) and data is obtained from random sampling.

3. Results

3.1 Global oocyst load from humans

The GloWPa-*Crypto* H1 model calculates the total global oocyst load from humans for each of the SSPs combined with the years 2010, 2020, 2030 and 2050. 2010 data for all SSPs is approximately a representation of historic loads. Figure 2 shows how emissions to water are distributed over the world regions for all data years and SSPs. The emissions to water are roughly 10^2-10^7 times bigger than the emission to land, depending on the region. Emissions to land from human source predominantly come from open defecation, which is only practiced in some countries in rural areas. Therefore, human emissions patterns are mostly determined by the oocyst load to water, rather than the oocyst load to land. The Supplementary materials S5. provide an overview per world region on how each sanitation category contributes to the emissions to water and emissions to land for each scenario and year. World regions with more advanced sanitation and treatment, usually due to high HDI and Gross Domestic Product (GDP), have lower emissions. For example, Europe and Central Asia and High-Income Countries have the lowest total water and total land emissions. For all data points, East Asia and Pacific and South Asia together account for more than half of the total oocyst load to water. Between 2010 and 2050, South Asia and Sub-Saharan Africa are the only two world regions projected to have an increased share in the total global oocyst load under all SSPs, predominantly because the population growth and urbanisation rate are highest in those two world regions. East Asia and Pacific's share in the total global oocyst load is decreasing, a result of the stagnating population growth. While world regions with large population size, growth and urbanisation rates have large oocyst emission rates, these world regions tend to also have relatively low HDIs and GDP, thus less advanced sanitation and treatment, further enlarging their emissions. Such a relationship can for example be seen in Sub-Saharan Africa, where large population growth and high urbanisation rates, combined with relatively low HDIs will lead to drastically increased emissions to water between 2010 and 2050.

Under all scenarios, the total global load is growing. The absolute total loads to water for world regions are increasing in all scenarios between 2010 and 2050, with the exception of High-Income Countries and Europe and Central Asia; where decreasing trends for all scenarios can be seen. Under SSP3, the total global oocyst load to water is highest, followed by SSP5 and SSP1 in all years. Regional loads to water are also highest under SSP3 and lowest under SSP1, with the exception of Sub-Saharan Africa, High-Income Countries and South Asia; where in 2050 loads are highest under SSP5.

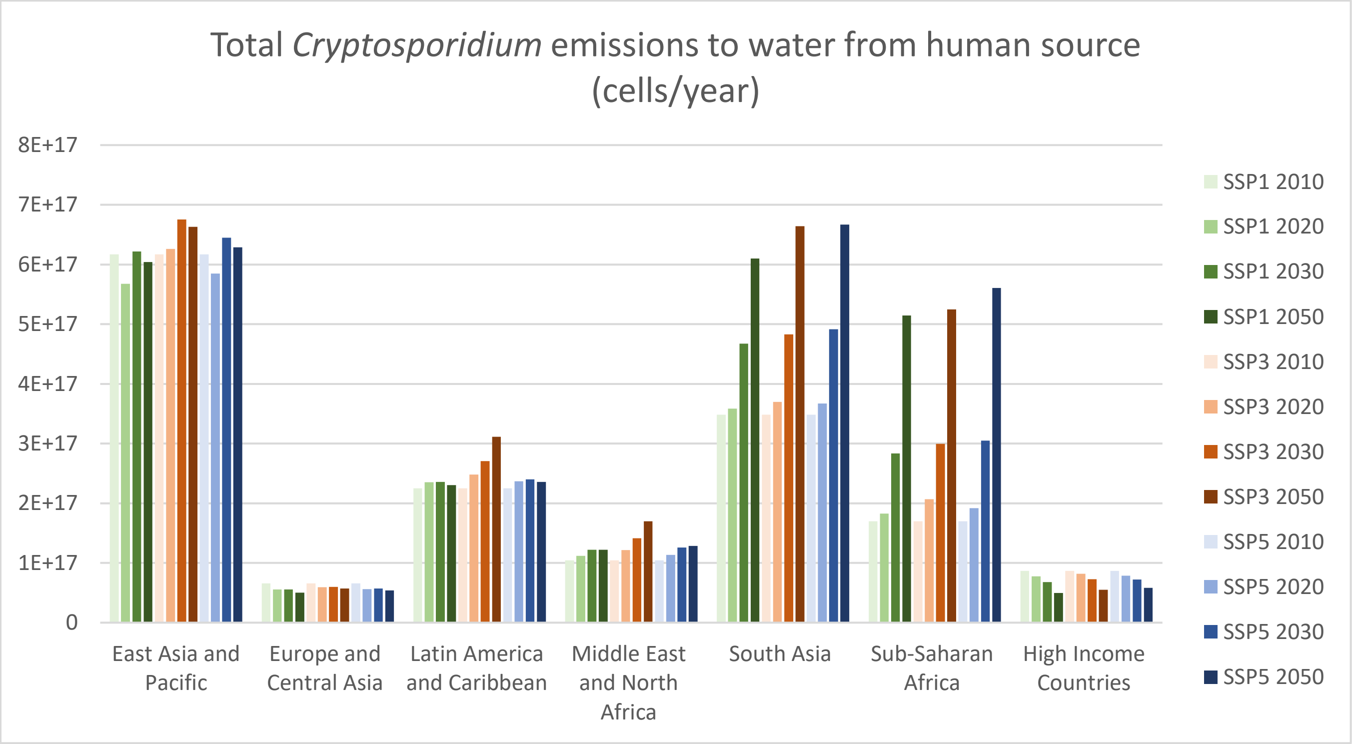

Figure 2: The total regional Cryptosporidium loads to water from a human source in cells per year. Loads have been specified per region, per SSP and per year.

3.2 Global oocyst load from livestock

The GloWPa-*Crypto* L1 model calculates the total global oocyst load from livestock for each of the SSPs combined with the years 2010, 2020, 2030 and 2050. 2010 data for all SSPs is approximately a representation of historic loads. Figure 3 shows for combinations of SSPs and years the regional global oocyst load from livestock. The total global oocyst load from livestock decreases for SSP1 and increases under SSP3 and SSP5. All world regions experience an increase in absolute livestock oocyst load under SSP3 and SSP5 between 2010 and 2050. Under SSP1 Asia, MENA and Oceania experience an increase in absolute load in that time-frame. For all SSPs, Asia has the highest share of global livestock oocyst load, accounting for more than 40% in all scenarios. Oceania has the lowest share for all scenarios and years. Africa, Europe, Latin-America and North-America experience a decrease in their share of the total global livestock oocyst load between 2010 and 2050 under SSP1. Under SSP3: Europe, North-America and Oceania; and under SSP5: Africa, Europe and Oceania. A reduction in the share of the total oocysts from livestock for a world region is predominantly caused by a reduction of animal population. The total emission trends from livestock more closely resemble the trends in animal population, rather than the trends in emissions per head, meaning that changes in manure management have less of an effect.

Cattle has the highest share of the total global oocyst loads (43-52%) over all SSPs and years, followed by chicken (19-27%) and pig (11-15%). Asia has the highest emissions for most animal species: cattle, buffaloes, goats, sheep, chickens and ducks. For pigs, Europe is the biggest emitter with Asia second. Horses and mules' emissions are highest in Latin-America. Emissions of camels and asses is highest in Africa. The Supplementary materials S6. provide an overview per world region how each animal category contributes to the livestock emissions for each scenario and year.

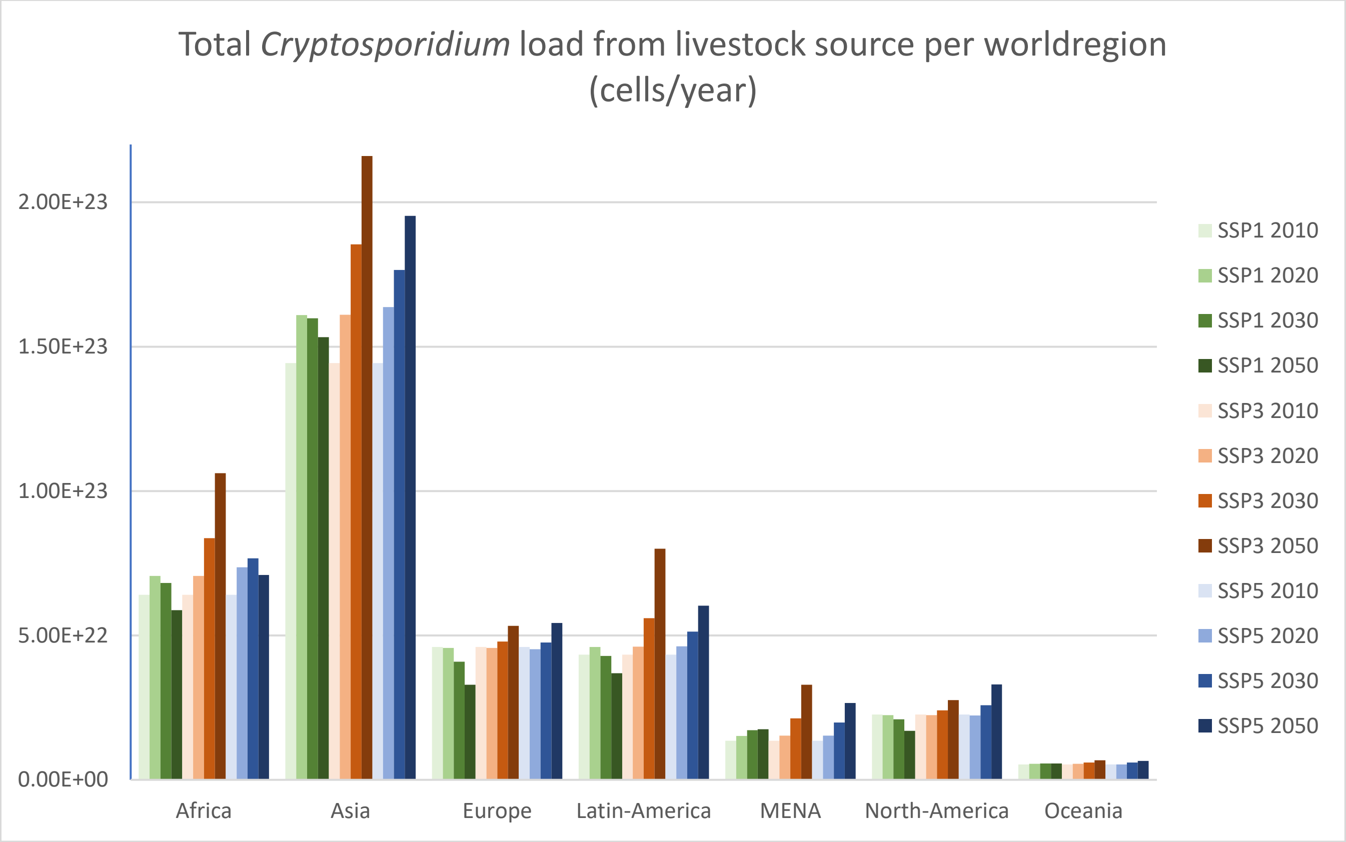

Figure 3: The total regional Cryptosporidium loads to land from livestock sources in cells per year. Loads have been specified per region, per SSP and per year.

3.3 Results concentrations

The total global *Cryptosporidium* concentrations calculated with the GloWPa-*Crypto* C1 model for historic (HIST) scenario (approximately 2010) and for each of the SSPs combined with the years 2010, 2020, 2030 and 2050. Figure 4 shows the monthly average global *Cryptosporidium* concentrations between the years 2010, 2020, 2030 and 2050 for SSP1, SSP3 and SSP5 for RCP2.6, RCP8.5 and HIST. Discharge values below 1 are ignored, in accordance with Vermeulen et al. (2019). Discharge and surface-runoff have been calculated using the original hydrology and multiplying that by the relative difference between past (1971-2000) and future (2040-2069) hydrological data. Hydrological data for RCP2.6 and RCP8.5 projected for 2040-2069 were combined with all SSP years. SSP3 has the highest level of average global concentrations in each of the data years for both RCP2.6 and RCP8.5. The monthly average global concentrations are the same for RCP8.5 and for RCP2.6, as there are no significant differences between the hydrological data of the two RCPs. The socioeconomic scenarios have also been run with the original (HIST) hydrology (representing approximately data from 2010), which results in a near 50% increase compared to the RCP scenarios.

The differences between the average global concentrations in all years are statistically significant between SSP1-SSP3, SSP1-SSP5 and SSP3-SSP5, when a t-test is performed with a p-value of 0.05. The average global *Cryptosporidium* concentrations are projected to go up in all scenarios. Monthly distributions of diffuse *Cryptosporidium* loads show that June, July and August are the highest under all scenarios. It is in those months that the northern hemisphere, where most of the *Cryptosporidium* loads originate from, that the driest months occur. Relatively low runoff in those months results in high concentrations. It is also in those months, that the fraction of concentrations due to diffuse loads is the highest. For point loads, no monthly differentiation can be made, as yearly data has been equally divided over all months.

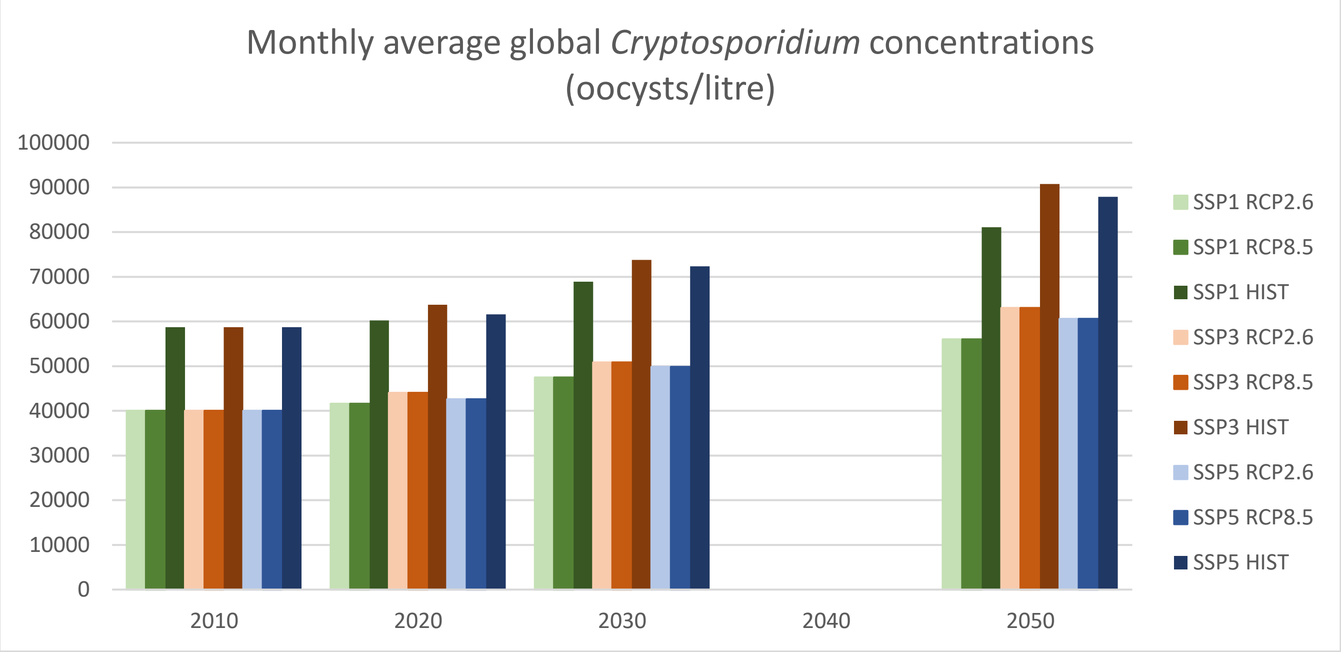

Figure 4: The total global Cryptosporidium concentrations in oocysts per litre. Concentrations have been specified per SSP and RCP combination.

Figure 5 shows the distribution of the average monthly global concentrations of *Cryptosporidium* over the world, for SSP1, SSP3, SSP5 combined with historic hydrology and with RCP8.5 in 2050. RCP2.6 has been left out, as differences between RCP8.5 and RCP2.6 are statistically insignificant. The distribution of concentrations over the world follows the patterns previously seen with *Cryptosporidium* loads for humans and livestock. Asia has the highest concentrations under all scenarios, followed by Africa. Specifically, highly populated areas have higher *Cryptosporidium* concentrations, such as China and India, further underlining the weight human and livestock populations have on *Cryptosporidium* loads and consequently concentrations. High HDI areas have lower *Cryptosporidium* concentrations, due to a combination of lower incidence, better sanitation, better treatment and better agricultural management.

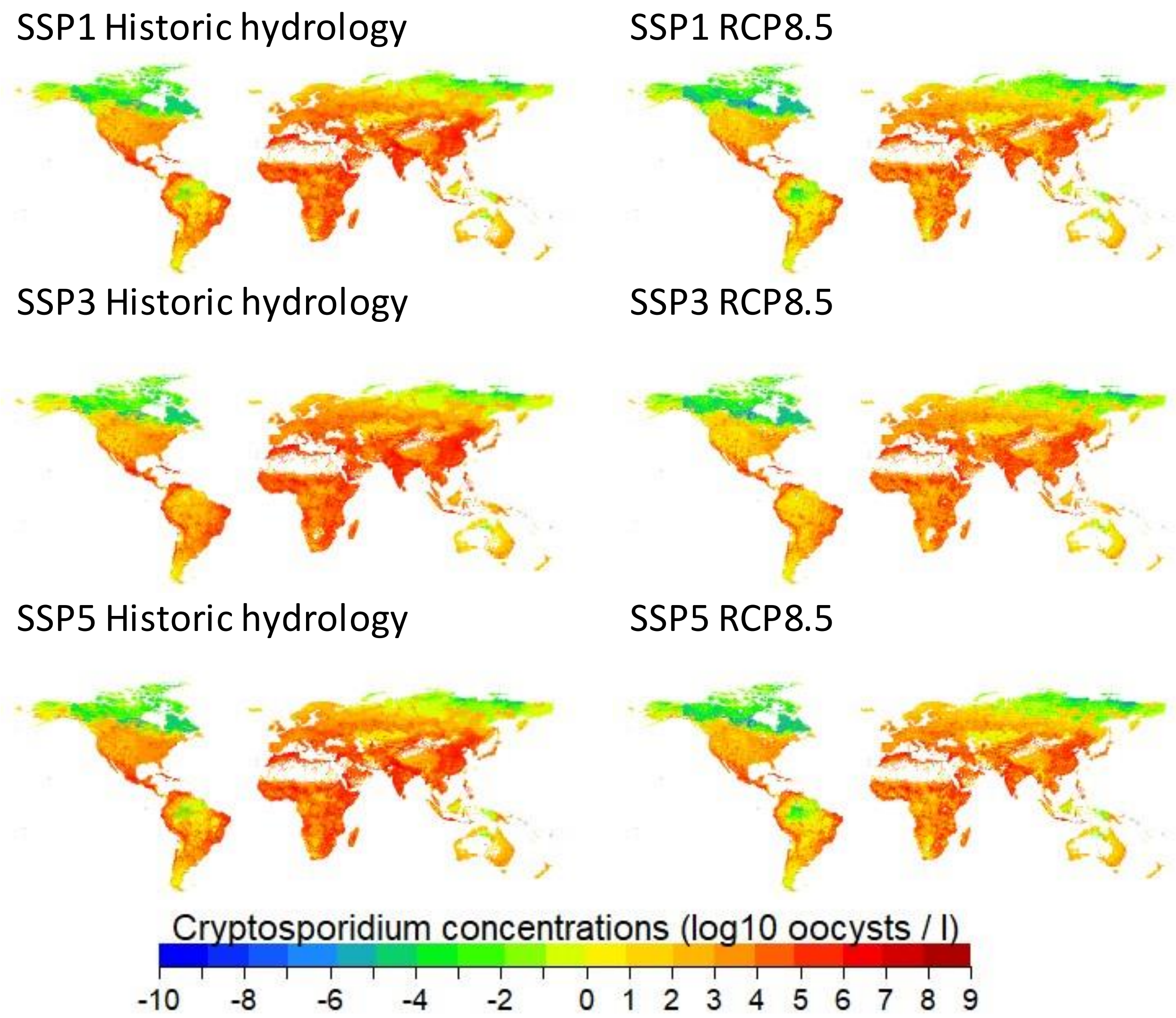

Figure 5: The distribution of the total global concentrations of Cryptosporidium over the world, from oocyst excretion by humans and livestock on a 30 min grid. Distributions are shown for historic data 1971-2000 and for SSP1, SSP3, SSP5 combined with original, historic (HIST) hydrology.

An area is considered a hotspot if the *Cryptosporidium* concentration is above the 95th percentile in 2010, a value slightly different for each scenario. The increase in number of hotspots is calculated by taking the 95th percentile of 2010 and comparing how many grids go over that value in 2010 and 2050. As RCP2.6 and RCP8.5 had the same values in the last run, the number of hotspots are also the same. In 2010 the amount of hotspots is 2700. In 2050 under SSP1 that is 3467, under SSP3 3687 and under SSP5 3665. Therefore, a large increase is found in the number of values above the 95th percentile in 2050 compared to 2010. The increase in the number of hotspots is highest in SSP3 and the absolute number is also highest. Maps visualising the global distribution of the hotspots in 2050 for the different SSPs under RCP8.5 have been added to the Supplementary materials S7.

4. Discussion

This paper presents the results of a study estimating the global oocyst load and concentrations of *Cryptosporidium*, a waterborne pathogen able to cause severe diarrhoea. Three models were used combining different datasets and assumptions to calculate the number of oocysts in surface water: GloWPa-*Crypto* H1, L1 and C1. The models' inputs take into account different socio-economic scenarios and climate changes scenarios, in the form of SSPs and RCPs respectively, to project future trends up to 2050.

Results show that the global human oocyst load to water largely concentrates itself in East Asia and Pacific and in South Asia, accounting for over half of the total human oocyst load. The human oocyst load is highest in areas with large populations combined with relatively low HDIs. In this study, sanitation data is coupled to GDP, determining the level of sanitation and treatment, thus low GDP areas generally have less advanced sanitation and treatment than high GDP areas. There is an interrelation between population growth and economic development or GDP and HDI, as low population growth or even shrink has previously been related to economic development (Myrskylä et al., 2009). This is reflected in High-Income Countries and Europe and Central Asia, where HDI and GDP are high and population growth is low, as the absolute load to water is decreasing between 2010 and 2050. In other world regions, the absolute human loads to water are increasing. Under SSP3, the total global oocyst load to water is highest, followed by SSP5 and SSP1 in all years: a reflection of the narratives by O'Neill et al. (2015). Knowing that the incidence and consequently the excretion has decreased under all scenarios, the rising loads in most world regions show that the decreasing incidence rate may not be sufficient to have a significant impact on the oocyst load levels, nor on the excretion rates. Rather, population variables such as HDI, population growth and GDP may have a much bigger impact on oocyst load from humans. A sensitivity analysis in Vermeulen et al. (2015) concluded that the GloWPa-*Crypto* H1 model was most sensitive to changes in oocyst excretion and number of infections. For the study presented here, a sensitivity analysis was not part of the scope. This study uses the updated GloWPa-*Crypto* H1 from Okaali et al. (2022), for which a sensitivity analysis has not been performed yet. However, we could reasonably assume that the absolute number of infections will go up with a larger population and that the model would also be sensitive to incidence changes and thus oocyst excretion changes.

The human oocyst load to water is much higher than the load to land, because oocyst load to land is determined only by open defecation, which is practiced in some rural areas. Oocyst load to water sources from the other sanitation categories. The addition of septic tanks and pat latrines in this study adds to the load to water. That being said, maximum oocyst total loads found in the world, for example India and Bangladesh, do not exceed 10^{15}, which is similar to Vermeulen et al. (2015). In almost all world regions, sewers account for the largest share of *Cryptosporidium* emission. In addition, Sub-Saharan Africa and South Asia have a relatively large proportion of emissions from unimproved sanitation, whereas High-Income Countries and Europe and Central Asia have the largest proportion from sewers. Combining this notion with the fact that the latter two world regions have the lowest emissions, this further shows the effect of GDP and consequently advanced sanitation systems have on emissions in a world region.

Regional livestock oocyst load is highest in Asia and lowest in Oceania. Cattle accounts for the largest portion of the total global load, followed by chicken and pigs. Taking animal category 1 to compare world regions, which includes cattle and buffalo, we can see that animal head amounts relate to the total livestock emissions: most cattle heads are found in Asia and the least cattle heads are found in Oceania. Generally, global human development is improving, thus also increasing HDI in most areas. As agricultural management is determined by HDI, we would expect a decrease in oocyst emissions from livestock with more advanced manure management. However, most world regions experience an increase in absolute livestock oocyst loads between 2010 and 2050. Overall, the total emission trends from livestock more closely resemble the trends in animal population than for instance the trends in emissions per head. Therefore, animal population is the biggest determinant of livestock emission, rather than agricultural management.

Compared to a previous study on the emissions of livestock to land, the modelling outcomes are in the same order of magnitude in this study (Vermeulen, 2018). Similar conclusions can also be drawn from animal species specific data, where cattle is the dominant emitter, followed by chicken and pig. Animal species that have little contribution to global total oocyst loads also match (e.g., mules, asses and ducks). The distribution of oocyst load from livestock is relatively similar to Vermeulen (2018): the developing world is responsible for the majority of the emissions and the developed world accounts for little more than a quarter of the total global emissions. A sensitivity analysis from the same previous study showed that the GloWPa-*Crypto* L1 model is most sensitive to changes in excretion rates, specifically of young cattle, young goats and young buffaloes. The analysis of monthly diffuse *Cryptosporidium* loads reveal that the highest levels occur in June, July and August. It is in those months that the northern hemisphere, where most of the *Cryptosporidium* loads originate from, the driest months occur. Relatively low runoff in those months could result in high concentrations. The model does not account for the timing of the birthing season and the application of stored manure on fields. Oocyst excretion per animal species remains the same. Kinyua et al. (2016) confirmed that treating manure by anaerobic digestion can lower the risk of cryptosporidiosis from contaminated crops and soil significantly. Therefore, it is reasonable to assume that increase of anaerobic digestion performed in this study under the different scenarios, has led to a reduction in *Cryptosporidium* loads.

Typically, higher surface-runoff and discharge lead to lower concentrations of *Cryptosporidium*. When there is a higher runoff and discharge, there is greater dilution which tends to lower the concentrations. On the other hand, lower runoff and discharge can result in reduced dilution, allowing the concentration of *Cryptosporidium* to be higher in the water. With RCP8.5, more extreme climate conditions are expected than with RCP2.6, thus both discharge and surface-runoff would generally be more extreme. In the data presented for this study, no differences were found between RCP2.6 and RCP8.5 concentrations. This could be having to do with the calculation of the new discharge and surface-runoff, where if the values in the original hydrological files were 0, no changes would be made under RCP2.6 and RCP8.5. An argument could be made that with higher surface-runoff, there is less retention and thus higher concentrations in surface water. In the analysis of hotspots, a large relation between human population numbers and hotspots can be seen. Socioeconomic scenarios run with original (HIST) hydrology result in even higher concentrations, which could be explained by the fact that RCP2.6 and RCP8.5 have more extreme discharge and surface-runoff values.

The point sources are the dominant source of oocysts load for global total concentrations, in accordance with (Vermeulen et al., 2019). Point sources are faeces from humans, diffuse sources are for the most part livestock manure plus a small fraction human faeces from the human population practicing open defecation in rural areas. Human emissions specific to each sanitation category show the growing importance of sewage as a source of *Cryptosporidium* in surface water, the growing importance of sewage is also found in nutrient loading under the socioeconomic pathways in Beusen et al. (2022). Development of large cities in coastal zones further increases this effect, as most of those cities are developed with more advanced sanitation systems such as sewage. Such cities being built in coastal zones reduces the travel times of oocysts from homes to surface water, thus decreasing the time oocysts have to decay. The results of this study support that, as for instance in China, India and North-Africa large hotspots are found in coastal areas (Beusen et al., 2022). Increasing populations with connection to sewage systems further increases its share to the total human oocyst concentrations.

The differences between the SSPs are mostly determined by the loads. SSP3 has the highest level of average concentrations for both RCP2.6 and RCP8.5 in all data years. SSP1 has the lowest level of average concentrations. This is in line with the narratives of O'Neill et al. (2015), from which one would assume that SSP1 has the lowest concentrations and SSP3 or SSP5 the highest. In analysing the average *Cryptosporidium* concentrations, a critical notion has to be placed that hydrological data for RCP2.6 and RCP8.5 were used projected for 2040-2069. Therefore, concentrations in 2050 most accurately represent the scenarios and narratives. A previous study by Beusen et al. (2022) also concluded from nutrient loading research that under all SSPs the loads would increase. Even under the 'green' scenario SSP1, improvements such as in sanitation do not lead to a reduction in total *Cryptosporidium* concentrations. Statistically significant differences are found between average global concentrations when comparing all SSPs in all data years.

Hotspot areas were defined as highly populous areas in other previous studies, specifically mentioning East Asian countries and Sub-Saharan Africa, which is also reflected in the findings of this study due to a combination of large populations and population growth (Hofstra & Vermeulen, 2016; Van Puijenbroek et al., 2023). Future population growth and urbanisation worsen *Cryptosporidium* loads despite improved sanitation (Vermeulen et al., 2015). In this study, the sanitation and treatment are connected to GDP (Van Puijenbroek et al., 2023). However, agricultural management is still connected to HDI. The relationship between GDP and sanitation could be argued to be better than HDI and agricultural management, as one could argue countries with a higher GDP tend to invest more in sanitation, treatment and agricultural management. The same argument could be made the other way, as countries with higher GDP don't necessarily invest more. However, similar to HDI, it remains uncertain whether a country with a higher GDP actually does invest in improved sanitation and treatment. By considering GDP, a country's financial capacity to invest can be better assessed. Countries with higher GDP tend to allocate more funds towards sanitation infrastructure. HDI is able to provide a more holistic view, while GDP is less comprehensive but more specific. For consistency, it would have been better to take either (or both) GDP and HDI for all variables, as each have their advantages.

This research has some limitations and uncertainties, that should be addressed in future research. The assumptions presented in this study are process-based, based on assumptions about the behaviour and interactions of various processes. These assumptions may not hold universally or may be inherently uncertain, contributing to the overall uncertainty of the model results. The assumptions presented in this paper have been process based, mainly on literature and expert knowledge. No specific data, tailoring to the GloWPa model, exists for the SSPs on these assumptions, meaning that more research is needed to confirm these assumptions. A new sensitivity analysis using these assumptions, could conclude which have the greatest effect. Using GDP as a determining factor for both agricultural management and sanitation would allow for a more consistent comparison of economic development between human and livestock emissions. Similarly, using hydrological data specific to each data year would reduce the uncertainty of the concentration results. On the other hand, hydrological data is subject to variation between years, some perhaps much wetter and vice versa. To avoid such variations, hydrological data for the future in this study has been averaged from multiple years. To address and manage these uncertainties in the assumptions, sensitivity analysis, model validation and expert knowledge can be further employed, to test the effect of individual components of various scenarios.

The application of the GloWPa model as in this study also has some limitations that, could affect the results of this study. Behavioural changes are not taken into account in socioeconomic development, such as dietary changes. Less meat consumption could reduce the need for a livestock population for human consumption in the future, meaning that the livestock population would decrease. This could especially affect cattle emissions, the most dominant emitters, as dairy and meat are important food staples from cattle. Future technological development, where all *Cryptosporidium* is treated from water is not considered. The prevalence has not been differentiated between world regions and livestock species, perhaps oversimplifying the assessments of the loads. The incidence has also not been differentiated. Having found no differences between concentrations of RCP2.6 and RCP8.5 in the final results, shows that the change in discharge and surface-runoff have perhaps been oversimplified as well. Furthermore, it is now uncertain whether the surface-runoff for future scenarios also includes sub-surface-runoff.

An avenue for future research could be to explore the impact of other SSPs and RCPs on *Cryptosporidium* concentrations. The current study only looked at SSP1, SSP3 and SSP5 and at RCP2.6 and RCP8.5. To be able to make policy recommendations, all scenarios have to be considered. This research shows that there are significant differences between the average global concentrations between some socioeconomic scenarios. Therefore, other socioeconomic scenarios could also be explored in future research. The added value of exploring more scenarios can be questioned however, as the most extreme scenarios have already been assessed. Between climate change scenarios no statistically significant differences were found, meaning that in future research there is no need to further explore other RCPs. Another avenue for future research would be to look into monthly differences in point source emissions. Factors such as changes in human behaviour could influence the transmission dynamics of *Cryptosporidium* and contribute to seasonal variations. Together with the monthly differences in diffuse source emissions, effects of climate change in different months of the year can be explored. With the added monthly differentiation in point source emissions contributing to concentrations in each month, the effects of climate extremes on *Cryptosporidium* can be evaluated. Data of monthly concentration differentiation could potentially help understand the regional effects of climate change more. The way concentrations are modelled now as monthly data does not allow us to see the extreme events, which could make large differences in the concentrations. Understanding spatial and temporal patterns of *Cryptosporidium* concentrations could help develop management strategies and more targeted interventions.

In the context of global pursuit of clean bodies of water with excellent water quality, this study contributes to the broader discussion on global water quality. It offers projections for future scenarios up to 2050 and provides insights into the current state of water contamination. Understanding factors influencing water quality is critical for strategy development addressing waterborne pathogens and diseases. Studying *Cryptosporidium* loads and concentrations helps assess the impact of socioeconomic and climate change scenarios on water quality, allowing for identification of regions with high concentrations and understanding the underlying factors contributing to this issue, such as in this paper population size and economic development. Knowledge of these contributing factors can guide stakeholders and policymakers in developing and implementing targeted interventions to mitigate water contamination. Findings in this paper have implications for both present and future situations. Presently, areas with large populations and less advanced sanitation infrastructure seem to suffer from higher *Cryptosporidium* concentrations. Advancements in sanitation and treatment are not expected to, according to this study, counteract the effects growing populations and urbanisation trends have on *Cryptosporidium* concentrations. Countries with high GDP and HDI, such as the High-Income Countries, have been able to address these challenges with investments in sanitation systems, improved agricultural management and more advanced water treatment. Trends of increasing concentrations under all socioeconomic scenarios indicate the importance of integrated water management strategies that consider socioeconomic development and climate change adaptation and mitigation measures. Ultimately, the paper presented here contributes to efforts aimed at achieving the SDGs, particularly SDG 6, focusing on clean water and sanitation for all. Being able to understand the factors contributing to *Cryptosporidium* loads and concentrations, policymakers, researchers and stakeholder can collectively make informed decisions to reduce the burden of waterborne diseases. Having seen the current state of water quality, with respect to *Cryptosporidium* concentrations, the need for data-driven approaches, interdisciplinary collaborations and evidence-based policies have been emphasised to ensure sustainable water quality for present and future generations.

5. Conclusion

In this study, the future impacts of socioeconomic development and climate change on *Cryptosporidium* concentrations, a waterborne pathogen that can cause diarrhoea, have been assessed, using three models to calculate the load and concentration of oocysts in surface water, the GloWPa-*Crypto* H1, L1 and C1 models. Socioeconomic development, represented by the Shared Socioeconomic Pathways, indicates that the highest human oocyst load concentrates around East Asia and Pacific, as well as South Asia, accounting for over half of the total human oocyst load. This pattern is attributed to areas having large populations and relatively low Human Development Indexes and Gross Domestic Product. Human Development Index determines the level of management for pit latrines and septic tanks, Gross Domestic Product determines the level of management for other sanitation types. The study highlights the interrelation between economic development, population growth and oocyst loads. While world regions with high Human Development Index and Gross Domestic Product and with low population growth show a future decrease in the absolute load to water from human sources, due to improved treatment, most other world regions experience increasing oocyst load.

Although relatively small compared to human load, livestock oocyst load still is a large contributor, with cattle as the largest contributor to the total global livestock oocyst load, followed by chicken and pigs. Despite improvement in human development and consequently agricultural management, livestock oocyst loads are increasing in most world regions. This study suggests that animal population has a greater impact on livestock emissions than changes in agricultural management. These findings align with previous studies, confirming the order of magnitude of emissions from livestock and the dominance of cattle as the primary emitter.

Furthermore, the importance of point sources, such as human faeces, is emphasised in contributing to oocyst concentrations in surface water. Hydrology subject to climate change, represented by the Representative Concentration Pathways, also play a role in *Cryptosporidium* concentrations. Generally, higher runoff and discharge lead to lower concentrations, but specific impacts may vary per region. The study shows that there are no differences in the average global concentrations between RCP2.6 and RCP8.5. Surface water *Cryptosporidium* concentrations were consistently highest under SSP3, representing a future characterised by fragmented and inward-looking national policies. In all years, concentrations are projected to be lowest under SSP1, in line with the SSP narratives.

This study acknowledges its uncertainties and limitations, such as the various assumptions made for the different scenarios as input in the models. Future studies should consider sensitivity analysis and expert knowledge to address the uncertainties in the assumptions and strengthen the findings. Further exploring the impact of additional socioeconomic development and climate change scenarios, in particular by including extreme events, may enhance our understanding of global *Cryptosporidium* concentrations. Overall, this study highlights the importance of implementing effective measures to reduce *Cryptosporidium* emissions, especially in densely populated areas. Advancements in sanitation and treatment are not expected to, according to this study, counteract the effects growing populations and urbanisation trends have on *Cryptosporidium* concentrations. More effort is need to improve sanitation and wastewater treatment practices, making sure no untreated waste reaches the surface water, in order to achieve progress towards SDG6.3.2; a higher proportion of bodies of water with good ambient water quality.

Reflection on thesis structure and concepts

Before I started writing my thesis, writing it in the format of a publishable research paper seemed a daunting task, but it turned out to be a very rewarding experience. It has required me to take a different approach to my writing compared to a traditional thesis format and it has the potential (if deemed good enough) to lead to publication and wider dissemination of my work. Writing in the style of a research paper, has led me to focus primarily on the clarity and conciseness of my work. The appropriate level of detail to include was the biggest challenge. While a traditional thesis format may include a detailed methodology section, a research paper should be briefer and more focused, yet complete. The methodology, results section and findings had to be tailored to a wider audience than I previously expected, with me having to explain terms that I had gotten quite familiar with, but were relatively unknown in the targeted audience. While I have not yet tailored my work to specific formatting and style guidelines of a certain journal, I have tried to write as concisely as possible. In hindsight, I enjoyed the challenge and at no point did I feel pressured to write in this style, nor did I find it stressful.

When I initially started my research, I included in my research questions that I would also conduct research on rotavirus concentrations. However, as I started running the models and generating data, I ran into some problems, which led me to reconsider my planning. Combining that with the fact that I had an abundance of data for *Cryptosporidium*, I decided in consultation with my supervisor not to include rotavirus in my final product. With the data I generated from *Cryptosporidium* emission and concentrations, I had no issue filling an entire thesis, so I would say in hindsight that has been a good decision.

The GloWPa models have proven a valuable tool to model the future socioeconomic development and climate change, offering a comprehensive framework integrating various factors and making it suited for studying the complex interactions between *Cryptosporidium* concentrations and those changes. Its ability to consider for example hydrological processes and population dynamics allow for good insights into the drivers of water contamination risks. Process based modelling, using the GloWPa models, involves formulas and parameters to analyse data. While it can be a powerful tool to make predictions and gain insights, there is always a level of uncertainty involved. Incomplete and inaccurate models can lead to unreliable results. While I have seen that the GloWPa model works very well to make predictions, it is hard to change parameters based on assumptions without validating the model with those new parameters. Process based models often use a simplification of complex real-world phenomena, such as socioeconomic development and climate change, which makes it hard to capture all the variables that may change under certain scenarios. In a well-designed and accurate model, there is still some degree of randomness and chance involved in the real world, which makes it difficult to model. Even when considering these factors, in my opinion the GloWPa model is a valuable tool for assessment and exploration of broad trends and patterns. However, for more precise, localised analysis, additional models, a more zoomed in version or refinement of the GloWPa model with region-specific factors may enhance the accuracy of the assumptions and thus the results.

Scenario analysis in the form of SSPs and RCPs has been a valuable tool to help model future concentrations of *Cryptosporidium.* Being able to make process-based assumptions and thus construct scenarios backed by literature and expert knowledge made the eventual future scenarios seem quite plausible. Implausible futures, such as combination of SSP1 RCP8.5 and SSP3 RCP2.6 have not had very much added value in hindsight, because of the insignificant differences between the RCPs. Even though implausible futures may seem far-fetched or unlikely, they still hold value in scenario analysis and decision-making. Exploring implausible futures allows us to challenge conventional thinking and expand knowledge, uncovering vulnerabilities, potential risks and opportunities, that might have otherwise gone unnoticed. These scenarios help test the model and serve as stress tests for the systems, being able to identify weaknesses and develop more robust mitigation and adaptation strategies. While implausible futures may not happen and the findings insignificant, the value lies in improving the understanding of the dynamics of the system and the models. Uncertainty of scenario analysis must also be discussed. While the scenarios try to best represent the possible futures, there is always a level of uncertainty. Extreme climate events, societal disruptions such as conflicts are currently not taken into account. I realise it is hard to model such uncertainties, but it would help policy-making to be able to see the “what-if” in the broader sense. Being able to adapt to extreme events, such as low discharges causing much higher concentrations in particular months, could greatly improve the water quality. The scope of this research did not allow to go into depth on these extremes, but it would be valuable to discuss or perhaps study the possibilities for concentration changes in such events in future studies.

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