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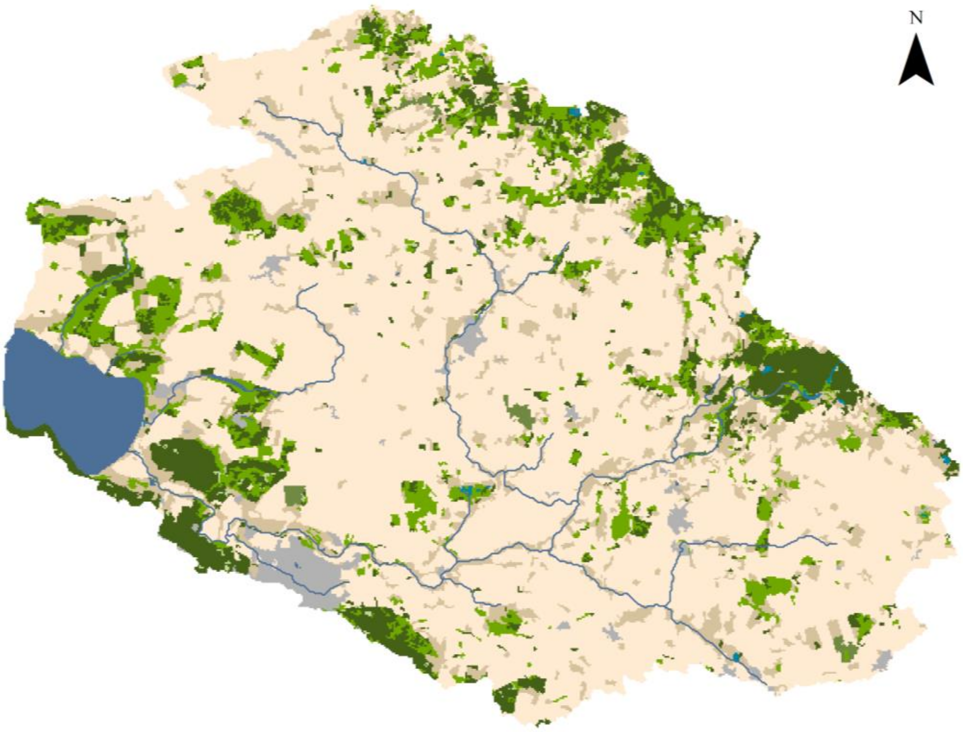

Modelling Impacts of Climate Change and Socioeconomic Development on the Microbial Water Quality of Lake Vomb

Master's thesis in Infrastructure and Environmental Engineering

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DIVISION OF WATER ENVIRONMENT TECHNOLOGY

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Cover:
Land use in lake Vomb watershed used in SWAT simulations, data from Lantmäteriet 2020, see section 3.2.2.
Department of Architecture and Civil Engineering
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ABSTRACT

Anthropogenic and biological activities in a watershed might impose human health risks through faecal contamination of surface waters. Consequently, socioeconomic development is important when predicting microbial water quality. In addition, climate change alters meteorological parameters, thereby affecting flow regimes as well as fate and transport of microorganisms. Therefore, possible risks related to socioeconomic development and climate change were assessed for the drinking water source lake Vomb in Scania. The hydrological model ArcSWAT, and the hydrodynamic model MIKE 3 FM, were used to simulate fate and transport of two microorganisms, i.e. *Cryptosporidium* and *E. coli*, from watershed to water source.

Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) were combined for two time periods, 2040-2050 and 2090-2100, in SWAT, with the aim to simulate both their individual and combined effect on future microbial water quality entering lake Vomb. To cover a broad span of possible future outcomes, one scenario combined an inclusive development pathway respecting environmental boundaries, i.e. SSP1, coupled with a low emission climate scenario, RCP4.5. The other scenario combined an energy and resource intensive development pathway, i.e. SSP5, with a high emission climate scenario, RCP8.5. In MIKE 3 FM, the combined impacts of RCP and SSP on the microbial water quality at the drinking water intake were evaluated for two years, 2050 and 2100.

Results showed low concentrations of *Cryptosporidium* and *E. coli* for all future scenarios in the tributaries of lake Vomb. However, for climate change individually, simulated future concentrations at times reached higher levels than those simulated during the baseline scenario, 2008-2018, in SWAT. This suggests that climate change increase microbial concentrations. On the contrary, socioeconomic development significantly lowered concentration levels, indicating a counteracting effect and suggesting that SSPs are more influential than RCP. This given that the development goes in line with projected changes. Therefore, it is of importance to combine RCP and SSP when simulating future microbial water quality. Furthermore, higher concentrations of *Cryptosporidium* and *E. coli* at the water intake can be expected which might pose a risk to human health in the future.

Keywords: climate change, *Cryptosporidium*, *E. coli*, hydrodynamic modelling, hydrological modelling, MIKE, RCP, socioeconomic development, SSP, SWAT, water quality modelling

Modellering av påverkan från klimatförändring och socioekonomisk utveckling på den mikrobiella vattenkvaliteten i Vombsjön

Examensarbete inom mastersprogrammet Infrastruktur och miljöteknik

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SAMMANFATTNING

Mänskliga och biologiska aktiviteter i ett avrinningsområde kan leda till hälsorisker genom fekal påverkan av ytvatten. Följaktligen är socioekonomisk utveckling en viktig parameter vid modellering av mikrobiell vattenkvalitet. Dessutom påverkar klimatförändringar den hydrologisk cykeln och dess vattenflöden samt överlevnad och transport av mikroorganismer. Därför har risker relaterad till socioekonomisk utveckling och klimatförändringar undersökts för dricksvattentäkten Vombsjön. Den hydrologiska modellen ArcSWAT och den hydrodynamiska modellen MIKE 3 FM användes för att simulera transport av de två mikroorganismerna, *Cryptosporidium* och *E. coli,* från avrinningsområdet till dricksvattenintaget.

Representative Concentration Pathways (RCPs) och Shared Socioeconomic Pathways (SSPs) kombinerades för två tidsperioder, 2040-2050 och 2090-2100, i SWAT. Detta med syftet att simulera deras individuella och kombinerade effekt på den framtida mikrobiella vattenkvaliteten i Vombsjön. För att omfatta ett brett spektrum av framtida utvecklingsscenarier, kombinerades en inkluderande utvecklingsväg där miljögränser respekteras (SSP1) med ett lågt utsläppsscenario (RCP4.5). Dessutom kombinerades ett energi- och resursintensivt utvecklingsscenario (SSP5) med ett högt utsläppsscenario (RCP8.5). I MIKE 3 FM simulerades endast den kombinerade effekten av RCP och SSP på mikrobiell vattenkvalitet vid dricksvattenintaget under januari till december 2050 och januari till december 2100.

Resultaten visar att koncentrationerna av *Cryptosporidium* och *E. coli* ökar som en konsekvens av klimatförändring, detta för båda tidsperioderna i förhållande till jämförelseperioden i SWAT, 2008-2018. I motsättning till detta visar SSP-simuleringar lägre koncentrationer av *Cryptosporidium* och *E. coli,* vilket tyder på en motverkande effekt gentemot RCP. Något som indikerar att socioekonomisk utveckling är mer inflytelserik gällande mikrobiell vattenkvalitet, givet att utvecklingen följer de uppskattade förändringarna. Det är därför av högsta vikt att kombinera både RCP och SSP vid simulering av framtida vattenkvalitet. Utöver detta, visade simuleringarna på en stundtals förhöjd halt av både *Cryptosporidium* och *E. coli* vid dricksvattenintaget vilket medför en ökad hälsorisk.

Nyckelord: *Cryptosporidium, E. coli,* hydrodynamisk modellering, hydrologisk modellering, MIKE, RCP, socioekonomisk utveckling, SSP, SWAT, vattenkvalitetsmodellering

Contents

Preface

This thesis has been carried out with Ekaterina Sokolova and Mia Bondelind as supervisors at the Water Environment Technology division at Chalmers University of Technology, Sweden. It was carried out within the research project ClimAQua funded by Formas (project number: 2017-01413). We would like to thank Mia and Ekaterina for valuable brainstorming and support throughout the entire project. We would also like to thank Viktor Bergion at Chalmers University of Technology for his previous work with lake Vomb that facilitated this project and his help when questions arise. Nor should we forget to thank Associate Professor Nynke Hofstra at Wageningen University for providing literature recommendation regarding socioeconomic development and input regarding modelled scenarios. This project could not have been conducted without DHI kindly proving us with license for MIKE powered by DHI.

Finally, we would like to give our gratitude towards Chalmers University of Technology for five educating years and a memorable time.

Göteborg May 2020

Anna Samuelsson

Ebba Östberg

1 Introduction

The continuous emission of greenhouse gases (GHG) generating from both anthropogenic and natural activities are driving global warming (IPCC, 2019). Since the pre-industrial period, the land surface air temperature has risen twice as much as the global average temperature. As a result, the global climatic stability is decreasing, leading to extreme effects on the hydrological cycle (Larsen *et al*., 2013; Met Éireann, 2013; Rehana & Mujumdar, 2012). Meanwhile, there is an increasing need for food production which has required land use change and land use intensification resulting in increased environmental stress. 23% of the total anthropogenic GHG emissions stems from agricultural processes, forestry and other land use activities (IPCC, 2019). Inevitably, these global changes affects water sources and impact water quality worldwide (Tong *et al.*, 2012), consequently adventuring human health (Bergion *et al.*, 2018). Microbial risks in the form of pathogenic microorganisms in freshwater can be a result of animal or human faeces (Funari *et al.*, 2012). These pathogens can contaminate drinking water sources, cause endemic waterborne illness and waterborne outbreaks of gastrointestinal diseases, resulting in high cost for society (Larsson *et al.*, 2014).

Cryptosporidium is a parasite that accounts for a majority of all waterborne outbreaks worldwide and can cause severe health effects, especially for children (Adler *et al.*, 2017). The route of transmission is mainly via oral ingestion of faecal contaminated water or food. *Cryptosporidium* is frequently occurring in Swedish surface waters and in 2011, *Cryptosporidium* oocysts were found in 11.5% of 200 positive raw water samples. Therefore, it is of importance to monitor the quality of raw water and drinking water to ensure adequate barriers in treatment plants (Adler *et al.*, 2017). However, outbreaks occur, and in November 2010, there was a major outbreak in the city of Östersund, where 27,000 inhabitants were symptomatic (Widerström *et al.*, 2014). This is the largest outbreak in Europe in modern time, and it is expected that climate change will increase the number of *Cryptosporidium* outbreaks in the future.

Furthermore, bacterial pathogens like specific strains of *Escherichia coli (E. coli)* are also of interest because they can, in the same way as *Cryptosporidium,* cause gastrointestinal illness (Harley, 2019). Monitoring the presence of *E. coli* is important to ensure high raw water quality and safe drinking water distribution (Vermeulen & Hofstra, 2014). The bacteria are transmitted through oral ingestion of faecal contaminated food or water. Similar to *Cryptosporidium*, climate change will affect the presence of *E. coli* in water sources worldwide. Consequences related to increasing temperatures and changing precipitation patterns include higher die off rate of microorganisms, increased discharge events and altered dilution.

The combined impact of climate change and socioeconomic development on microbial pollutants is important to evaluate from a human health perspective (Delpla *et al.*, 2009; Howard *et al.*, 2016). Therefore, predictive tools are required to be able to mitigate potential impact, for instance water quality modelling (Oliver *et al.*, 2016). Water quality modelling include both hydrological and hydrodynamic models, where hydrological models simulate the processes within a catchment and hydrodynamic models simulate the processes within a water source (De Brauwere *et al*., 2014; Lewerin *et al.*, 2019). Studies have been made regarding the combined effects on microbial water quality resulting from climate change and socioeconomic development (Molina-Navarro *et al.*, 2014; Coffey *et al.*, 2015; El-Khoury *et al.*, 2015; Islam *et al.*, 2018) however, to our knowledge, none have combined both climate change and socioeconomic development with its projected land use changes with a coupled approach of hydrological and hydrodynamic modelling.

1.1 Aim and objective

The aim was to use hydrodynamic and hydrological modelling to simulate the fate and behaviour of the parasite *Cryptosporidium* and the faecal indicator bacteria *E. coli* in lake Vomb and surrounding catchment under future conditions of climate change and socioeconomic development. The objective was to formulate scenarios representing the combined and individual effect of climate change and socioeconomic development in the catchment of lake Vomb for two time periods, 2040-2050 and 2090-2100. These scenarios combine Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) to investigate microbial water quality. The projected scenarios were modelled using both a hydrological and hydrodynamic model i.e. ArcSWAT and MIKE 3 FM respectively.

1.2 Scope and limitations

The land use changes resulting from the socioeconomic development only include the land use in the 41545 hectares large catchment area of lake Vomb in Scania, Sweden which is the case study area. No measurements were performed to assess the current concentration of *Cryptosporidium* and *E. coli* of lake Vomb, nor any flow measurements in the lake or its tributaries. Finally, due to heavy simulations and time constraints, future scenarios in MIKE 3 FM were represented by two years, 2050 and 2100, instead of the ten-year span used in SWAT.

2 Theoretical background

Following chapter presents observed and projected climate change globally, nationally for Sweden and further, downscaled for Scania. This is followed by a chapter reviewing socioeconomic development and resulting land use changes. Furthermore, the importance of combined impact of climate change and socioeconomic development is discussed. Thereafter follows a description of how *Cryptosporidium* and *E. coli* could be affected by climate change and socioeconomic development. Finally, there is a chapter describing the principles of hydrological and hydrodynamic modelling together with a brief review of how modelling has been used to predict microbial water quality.

2.1 Future climate change

During the last decade, mean land surface air temperature has increased rapidly, almost twice as much as the global average temperature (IPCC, 2019). As a result, frequency, intensity and duration of heat related events have increased leading to desertification and land degradation. The impact and extent of future climate change is largely dependent on continuous emissions of GHG, as well as the effectiveness and development of climate policies. This in turn means that projected climate change is associated with large uncertainties. The Intergovernmental Panel on Climate Change (IPCC) mentions several key factors associated with anthropogenic GHG emissions: economic and population growth, lifestyle and behavioural changes, associated changes in energy use and land use, technology, and climate policy (IPCC, 2019). Some of the key factors, associated with expansion of urban areas, may alter natural cycles. One of the most important being the hydrological cycle (Alaoui *et al.*, 2014; Ning *et al.*, 2016; Abera *et al.*, 2019; Guo *et al.*, 2020). Major impacts on the hydrological cycle are changing temperatures as well as altered evaporation and precipitation patterns. Altogether, climate change will affect water resources and flow regimes around the world, nonetheless, sustainable land use management and climate policies can mitigate consequences of this changing cycle (Wang *et al.*, 2014).

To assess climate change for different development scenarios related to the key factors presented by IPCC, four different pathways known as RCPs have been derived (Ohlsson *et al.*, 2015). This to show what effects different development paths might have on climate change. RCPs are described by the projected level of radiative forcing by 2100, the lowest being 2.6 W/m^2 (RCP2.6) and the highest 8.5 W/m^2 (RCP8.5). Radiative forcing is the net change in the energy balance of the Earth system, i.e. the change in energy radiating down on the planet and energy radiating back out to space (Huang *et al*., 2013). It is often used as a simple quantitative measure for comparing aspects of potential climate response to different imposed agents, especially global mean temperature. Higher forcing means higher imbalance of the earth's energy budget. Additionally, there are two intermediate scenarios, RCP4.5 and RCP6.0. Altogether the radiative pathways cover scenarios both with and without forceful climate policies (SMHI, 2013). See Table 2.1 for some of the underlying assumptions for RCP4.5 and RCP8.5, that will be investigated in this research.

Table 2.1 Underlying assumptions for RCP4.5 and RCP8.5 (SMHI, 2018).

RCP4.5	Minor rise of carbon dioxide emissions culminating 2040
	World population reaches 9 billion by the end of the century
	Low areal need for agriculture as a result of larger crops and changed consumption patterns
	Extensive reforestation programme
	Low energy intensity
	Forceful climate politics
RCP8.5	Carbon dioxide emissions increase threefold to the year 2100 and emissions of methane increase heavily
	World population increases to 12 billion
	Increasing claim on pasture cultivated land for agriculture
	Development of technology towards increased energy efficiency continues, but slowly
	Large dependency on fossil fuels
	High energy intensity
	No additional climate policies

2.1.1 Climate projections for Sweden and Scania

Overall, the trend in Sweden is increasing average annual temperatures where the largest increase can be seen in the north of Sweden for RCP8.5 (Sjökvist *et al.*, 2015). Figure 2.1 and Figure 2.2 show annual observed temperatures in Sweden between 1961-1990, together with predicted temperatures for 2021-2050 and 2069-2098 projected for RCP4.5 and RCP8.5 respectively. Future precipitation scenarios indicate an increase of precipitation until the end of the century where the largest increase is visible in the summits of Lappland, and the northern parts of Sweden. RCP4.5 indicates an increase in precipitation of 10-30% compared to observed data whereas RCP8.5 indicates an increase of 15-40%. Winter and summer are the seasons where the increase is the largest, however in some parts of western summits the precipitation will remain unchanged. During this century the average catchment inflow and the availability of water will increase in most part except in the southeast (Sjökvist *et al.*, 2015). SMHI has downscaled this country specific data to county specific climate projections regarding precipitation and temperature in Scania. The yearly average temperature in Scania today is around 7°C, however, the temperature is expected to increase with 4°C by the year of 2100 (Ohlsson *et al.*, 2015). The yearly precipitation is around 650 mm and is expected to increase with 100-150 mm, resulting in a new yearly average of 800 mm as well as an increased intensity of heavy rains. Furthermore, assessment of future climate change in Scania shows trends of warmer climate during both summer and winter seasons. However, summers will have increasing periods of drought whilst winter will have an increase in events of heavy rain. Projected changes are available for all seasons with Winter being defined as December-February, spring as March-May, Summer as June-August and Autumn as the period September-November.

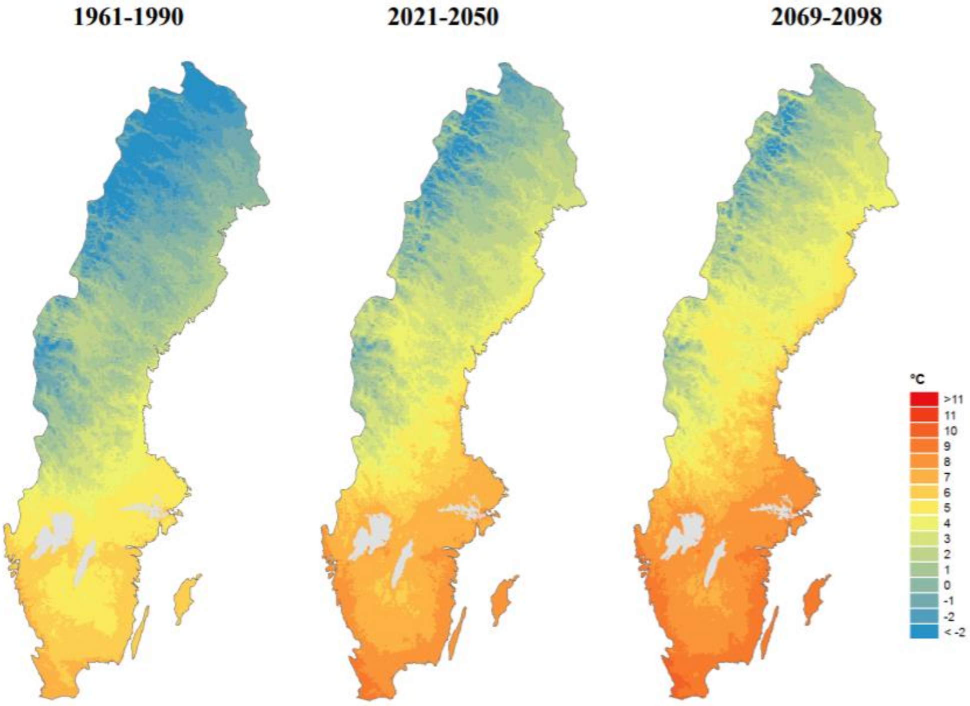

Figure 2.1 Annual average temperature in Sweden, RCP4.5. Published with permission from SMHI (Sjökvist et al., 2015).

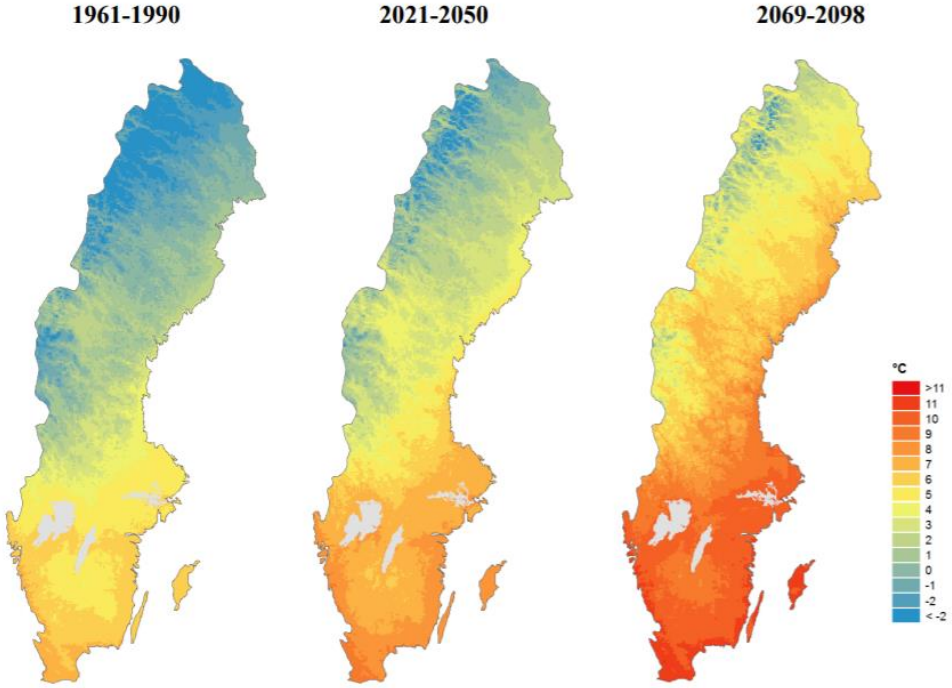

Figure 2.2 Annual average temperature in Sweden, RCP8.5. Published with permission from SMHI (Sjökvist et al., 2015).

2.2 Socioeconomic development and resulting land use changes

Land use in Europe have changed significantly during the last century as a result of changing consumption and production patterns. To ensure proper food production to an ever-increasing population, an agricultural intensification has been required, often at the expense of the environment (European Environment Agency, 2019). Farmers are required to produce larger amounts of food on more concentrated areas due to urbanisation. Urbanisation and other anthropogenic activities are important when considering impacts on the hydrological cycle, where the major effects are changing flows, both volumes and pathways, and alteration of infiltration and evapotranspiration (Guo *et al.*, 2020). Furthermore, urbanisation is causing a sharp increase in runoff due to expanded impermeable surfaces (Li *et al.*, 2018; Zhang *et al.*, 2018).

To assess future land use and socioeconomic development, a set of SSPs have been developed as a joint effort by an international team of climate scientists, economists and energy system modellers (Unece, 2019). SSPs describe and quantify different socioeconomic scenarios likely to occur before 2100 and based on five narratives describing alternative socioeconomic development pathways (Riahi *et al.*, 2017). This includes sustainable development, regional rivalry, inequality, fossil-fuelled development, and middle-of-the-road development. The aim of all five scenarios is to quantify energy and land use development and associated uncertainties for GHG and air pollutant emissions. Main socioeconomic drivers are population, economic activity and urbanisation, while main narratives include resource availability, technology development and drivers of demand such as lifestyle changes. See Table 2.2 for some of the underlying assumptions for SSP1 and SSP5, the pathways that will be combined with RCP4.5 and RCP8.5 in this study.

Table 2.2 Underlying assumptions for SSP1 and SSP5 (Riahi *et al.*, 2017).

SSP1	The world shifts gradually towards a sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries Management of the global commons slowly improves and the emphasis on economic growth shifts toward a broader emphasis on human well-being Inequality is reduced both across and within countries Consumption is oriented toward low material growth and lower resource and energy intensity
SSP5	The world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development Strong investments in health, education, and institutions to enhance human and social capital The push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyle Rapid growth of the global economy Global population peaks and decline in the 21st century Local environmental problems are successfully managed and there is faith in the ability to effectively manage social and ecological systems

The combined impact of climate change and socioeconomic development is necessary to evaluate since both affect the hydrological cycle and microbial water quality (Islam *et al.*, 2018), leading to increased risks for human health. Moreover, future management problems for treatment plants responsible for safe drinking water distribution due to higher peak concentration of pathogens might occur (Schijven *et al.*, 2013; Howard *et al.*, 2016). There is thus a need for predictive tools, such as models, to assess the risks connected to both varying climate and socioeconomic development to adequately predict water quality and quantity trends (Hofstra, 2011; Mellor *et al.*, 2016).

2.3 Effects of climate change and socioeconomic development on microorganisms

Waterborne pathogenic microorganisms include different types of viruses, bacteria and parasitic protozoa (Funari *et al*., 2012) and contamination in surface waters often originates from wastewater treatment plants (WWTP), combined sewer overflows, on-site wastewater treatment systems (OWTS), manure spreading and faecal dropping (Jung *et al.*, 2014). To be of concern for human health, microorganisms must either be emitted into the environment in high numbers or be highly infectious at low doses. Furthermore, microorganism need to remain for long periods in the environment or be resistant to water treatment (Funari *et al.*, 2012). Survival and transport depends mainly on contamination level, land use, size of surrounding area, ability of transport and hydrometeorological conditions (Jung *et al.*, 2014).

Several studies have proven a relationship between hydrometeorological conditions and microbial water quality in connection to future climate scenarios. Shortly after extreme meteorological events such as floods and droughts there is an increased risk of waterborne outbreaks (Delpla *et al.*, 2009; Funari *et al*., 2012; Cann *et al.*, 2013).

2.3.1 Characteristics of *Cryptosporidium*

Cryptosporidium is a persistent parasite protected by an outer shell called oocyst (Funari *et al*., 2012). These oocysts are susceptible to freezing, i.e., with a decreasing number of frozen days the number of oocysts that survives winter will increase. Moreover, increased humidity as a consequence of climate change is another parameter that increases the survival rate of *Cryptosporidium* oocysts. On the contrary, increased temperatures generally accelerates the decay rate. Furthermore, increased precipitation increases the spread of oocysts by mobilisation whilst increase of dry periods decreases the survival but increases their concentration in water (Pozio, 2020). Generally, the survival rate of *Cryptosporidium* benefit from colder water temperatures (Svenskt Vatten, 2008). There are no general guideline values for *Cryptosporidium* in surface water, however, it is suggested that even detection of the parasite indicates inadequate water quality.

2.3.2 Characteristics of *E. coli*

E. coli is a bacteria and member of a broader faecal coliform group commonly used to evaluate possible presence of pathogenic microorganisms in water (United States Environmental Protection Agency, 2012). In Sweden, guidelines suggest that concentration of *E. coli* in surface waters should be below 500 cfu/100 ml (Svenskt Vatten, 2008). With increasing temperatures in surface water, the decay rate of *E. coli* increases, resulting in higher die-off of the microorganism (Vermeulen & Hofstra, 2014). On the other hand, increased precipitation and frequent discharge events, is positively correlated to concentration of *E. coli*. In addition, re-suspension of microorganisms in stream sediment can increase during heavy rainfall. Furthermore, during dry periods, decreased dilution in watersheds may lead to increased concentrations of *E. coli*.

2.4 Hydrological and hydrodynamic modelling

The understanding of hydrology is fundamental in order to understand hydrologic modelling. Hydrology is the science of the occurrence, circulation and distribution of water on earth, including chemical and physical properties (Mariño, 2019). Thus, hydrological modelling is the process of simplifying natural features and characterising them by the use of small-scale physical models, mathematical analogues and computer simulations (Anees *et al.*, 2016). All flows in the hydrological cycle are controlled by different processes related to precipitation; evapotranspiration, interception, infiltration, runoff estimation, groundwater flow, streamflow and transport of substances in flowing water (Kingsley, 2017). Hydrodynamic models on the other hand, describe natural water systems by numerical computation of fluids in motion (TAMU, 2020b). To establish a representative model, input parameters such as land boundaries, bathymetry, wind and atmospheric pressure data, water levels, flow speed and direction are required (Department for Environment Food and Rural Affairs, 2011). Model outputs include strength and direction of currents, temperature and salinity fields, sea levels and particle or sediment transport (Kress, 2019). The accuracy and credibility of hydrological and hydrodynamic models are strongly dependent on model selection, setup, calibration, validation and analysis (Hodges, 2009). To summarize, hydrological models are models that describe processes in the watershed and obtained outputs can be used as inputs in hydrodynamic models which describe processes within the water source (Lewerin *et al.*, 2019).

2.4.1 Hydrological modelling with SWAT

SWAT, a Soil and Water Assessment Tool, was originally developed for the United States Department of Agricultural Research Service to predict impacts of land use on water and sediment in large watersheds over time (Neitsch *et al.*, 2011). SWAT builds a distributed rainfall–runoff model which divides a catchment into smaller units with similar physical properties, i.e. Hydrologic Response Units (HRUs), see Figure 2.3. Therefore, hydrological processes within these HRUs can be treated homogeneously. The behaviour of each sub-basin can be calculated as a result of each respective HRU (Khalid, 2018). SWAT can be used to study microbial transport and enables users to study long-term impacts of microorganisms. Altogether, it is computationally efficient, and simulations can be performed with little time or money. Since SWAT is compatible with GIS software it can be used as an extension in ArcGIS and QGIS (TAMU, 2020a) and it can be downloaded free of charge.

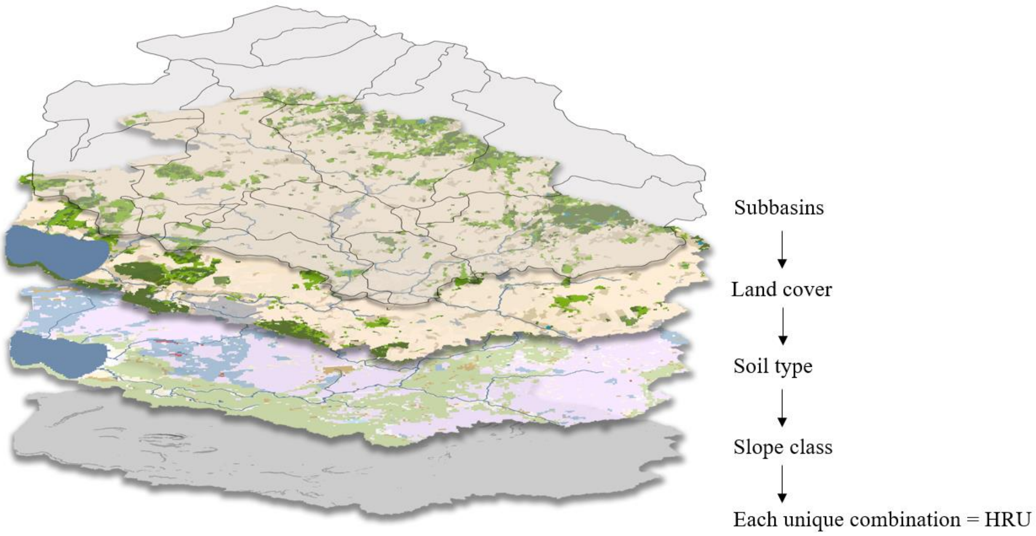

Figure 2.3 Schematic figure of HRU in SWAT. Figure by author with data from ArcSWAT.

2.4.2 Hydrodynamic modelling with MIKE

MIKE 3 FM is a software package (part of MIKE Powered by DHI modelling suite) for 3D modelling of hydrodynamics, sediment dynamics, water quality and ecology (Soudi *et al*., 2019). It focuses on free surface flow with its associated water quality processes. MIKE 3 FM includes modelling of advection-dispersion processes and advanced water quality modelling. The model geometry is based on a flexible, triangular, non-structured mesh and the finite volume method is used to solve the Navier-Stokes equation for an incompressible fluid.

2.4.3 Application of hydrological and hydrodynamic modelling

SWAT has been frequently used to investigate impacts of socioeconomic development and climate change on the hydrological cycle. For instance, Coffey *et al*. (2016) used SWAT to investigate the combined impact of future climate change and socioeconomic development on streamflow and microbial transport in the West of Ireland. During such scenarios results showed that higher microbial pollutant concentrations are likely to encounter. Moreover, Coffey *et al*. (2016) suggests that future land use changes might be equally important as climate change, when considering microbial pollutant loads. In a similar manner, El-Khoury *et al.* (2015), used land use projections and climate change scenarios together with the hydrological model SWAT, to estimate the relative impact of climate and land use change on streamflow, nitrogen and phosphorus loading on a Canadian watershed. Climate change increased monthly streamflow, nitrate and organic phosphorus loads whilst decreasing organic nitrogen and nitrite loads. For land use change, the same patterns were discovered except for organic nitrogen loads, where it had a reverse impact on loading. Furthermore, Iqbal *et al.* (2019) used SWAT to evaluate the effects of future socioeconomic development on *E. coli* loads and concentration in Kabul River, Pakistan. Results suggested that with population and livestock growth in combination with limited treatment of wastewater and manure, simulated *E. coli* concentrations increased. The largest contributor of *E. coli* was point sources followed by non-point sources and upstream loads.

In a similar manner as hydrologic models have been used to investigate impacts of land use and climate in watersheds, hydrodynamic modelling has been used to investigate fate and transport of microorganism in surface waters and rivers. For instance, Sokolova *et al.* (2014) used a three-dimensional hydrodynamic model, MIKE 3 FM coupled with the ECO Lab module, to simulate the spread of *E. coli.* The aim was to describe and forecast microbial water quality of lake Rådasjön in Sweden. Results showed how different discharge sources contributed to *E. coli* concentration in lake Rådasjön. By comparing modelled results to measured concentrations, it was concluded that the model produced reliable results and that the approach can be used for short-term forecasts on microbial water quality. Furthermore, Islam *et al*. (2018) used MIKE 21 FM coupled with the ECO Lab module to simulate the fate and transport of *E. coli* and enterococci within Betna River in Bangladesh. One aim was to use the model to predict microbial water quality in the river for different future wastewater management scenarios. Results suggested that the dominant factors controlling the concentration of *E. coli* and enterococci in the river were bacterial decay, upstream concentrations and untreated wastewater discharge. Less dominant factors were wind and contamination from diffuse sources. It also showed that the climatic inputs had lower influence than the socioeconomic factors.

Lately, hydrodynamic and hydrological models have been combined in studies to get a comprehensive coverage from watershed to water source with regard to microbial water quality. For instance, Mohammed *et al*. (2019) used SWAT in combination with The Generalized Environmental Modelling system for Surface waters, i.e. a hydrodynamic model, to predict impacts of climate change on microbial quality in a Norwegian water source and its tributaries. Results suggested that the temperature at the intake will rise gradually and the number of *E. coli* will increase marginally due to longer autumn circulation, less protected winter season and shorter spring circulation. Furthermore, Lewerin *et al*. (2019) used MIKE together with the hydrological model HYPE, to describe the risk of grazing animals to be exposed to faecal pollutants in natural drinking water sources. It was concluded that animals exposed to such pathogenic microorganisms are troublesome from an animal health perspective. Furthermore, it affects human health as well since faecal dropping can cause further contamination and spread of microorganisms.

Since there is a large variety of software available, the combination of different models varies greatly. Either SWAT or MIKE have been frequently used the impact of climate change and socioeconomic development on microbial water quality.

3 Material and method

This chapter presents the case study site, lake Vomb in Scania. Furthermore, the SWAT-model set up including all data required and calibration of model in SWAT-Cup is presented. Moreover, it includes a description of the MIKE-model set up and validation process. Finally, modelled scenarios are described together with relevant parameters, how these are expected to change in the future and how they can be interpreted for lake Vomb watershed.

3.1 Lake Vomb

Lake Vomb is located in the centre of Scania, the southmost part of Sweden, see Figure 3.1. It is part of Kävlingeån basin (Alström *et al*., 2017). Since 1948, lake Vomb has served as a drinking water source and today, it supplies 350 000 consumers in Malmö, Burlöv, Svedala, Staffanstorp, Vellinge and partly Lund and Eslöv. The daily raw water outtake is 1 m^3/s which accounts for roughly 25% of the total outflow (VISS, n.d.). Remaining 75% is discharged into Kävlingeån (Alström *et al*., 2017). The catchment area is 435 km^2 with an average inflow of 10 $l/(s\ km^2)$. Since the lake is a drinking water source it is a water protection area (Länsstyrelsen Skåne, 2013). Furthermore, a beach stretching along the western part of the lake is protected as a nature reserve and Natura 2000 area (Alström *et al*., 2017). Lake Vomb is considered hypertrophic and due to its nutrient content, the ecological status has been classified as inadequate (VISS, n.d.).

Lake Vomb has three main inflows, the rivers Björkaån, Torpsbäcken and Borstbäcken, see Figure 3.1 (VISS, n.d.). The biggest contributor to the inflow is Björkaån, located in the east part of the lake, accounting for 76% of the total inflow. Furthermore, there are multiple smaller inflows around the lake. The outlet, the river Kävlingeån, is located in the western part of the lake. The surface area of lake Vomb is approximately 12 km^2 with an average depth of 6.6 meters and a maximum depth of 16 meters. The theoretical turnover time in the lake is roughly 0.7-0.8 years (Alström *et al*., 2017).

Figure 3.1 Map of lake Vomb displaying tributaries with red dots.

3.2 Setting up the SWAT model

To set up the rainfall-runoff model in ArcSWAT, ten main types of input data were required which included GIS layers and text files, see Table 3.1. The table also presents each respective format, resolution and where the data was obtained. Reference coordinate system used for the model was SWEREF99_TM. Following subchapters will explain the steps that were performed when setting up the rainfall-runoff model.

Table 3.1 Input data for ArcSWAT.

Input data	Format	Resolution	Reference
Vomb area	Shape-Polygon	-	Lantmäteriet, 2020
DEM	Raster	50 m x 50 m	Lantmäteriet, 2020
Watershed, mask	Shapefile-Polygon	-	Lantmäteriet, 2020 SMHI 2020c
Water course	Shapefile-Line	-	Geological Survey of Sweden, 2016
Land use	Raster	-	Lantmäteriet, 2020
Land use lookup table	Text	-	Viktor Bergion, 2020
Soil type	Raster	-	Geological Survey of Sweden 2016
Land use lookup table	Text	-	Viktor Bergion, 2020
Meteorological data	Text	Daily recordings from three stations	SMHI, 2020b
Private properties	Shapefile- Point	Ca 4000 points	Lantmäteriet, 2020

3.2.1 Watershed delineation

The first step in setting up the SWAT model was to define the watershed. Based on the Digital Elevation Model (DEM), the watercourse file and watershed mask, the software calculated both flow direction, accumulation and defined streams and outlets automatically. Later, Eggelstad measuring station was added as a sub-basin outlet by a pre-written table with coordinates. Furthermore, Björkaån, Borstbäcken and Torpsbäcken were added manually as sub-basin outlets as well. Finally, the outlet of the entire watershed, was selected before automatically delineating the watershed and calculating sub-basin parameters. The modelled watershed area was 41545 ha and included 31 sub-basins.

3.2.2 HRU analysis

Land use, soil and slope data, the latter being derived from the DEM, was combined in the HRU analysis to create HRU units and define threshold limits. The land use raster contained 118 different numerical values and was combined with the land use lookup table, which contained the same numerical values as the raster. With the combined data, SWAT could reclassify it into ten different land use classes. These are presented with respective area and percentage of total area in Table 3.2. SWAT requires effluent from OWTS to be released on land to use the septic water quality database. Therefore, all properties in non-urban areas i.e. approximately 3000 OWTS, were converted from point locations to land use features before running the model. Figure 3.2 displays the land use distribution in the catchment of lake Vomb.

Table 3.2. Land use features in lake Vomb catchment.

Land use	**Area [ha]**	**Percentage of total area [%]**
Agriculture	2520	61
Wetland	57	0.1
Water	1270	0.4
OWTS	2530	3
Urban high density	770	1.9
Grassland	135	0.3
Pasture	4470	11
Forest mixed	167	0.4
Forest evergreen	3510	8.5
Forest deciduous	3450	8.3

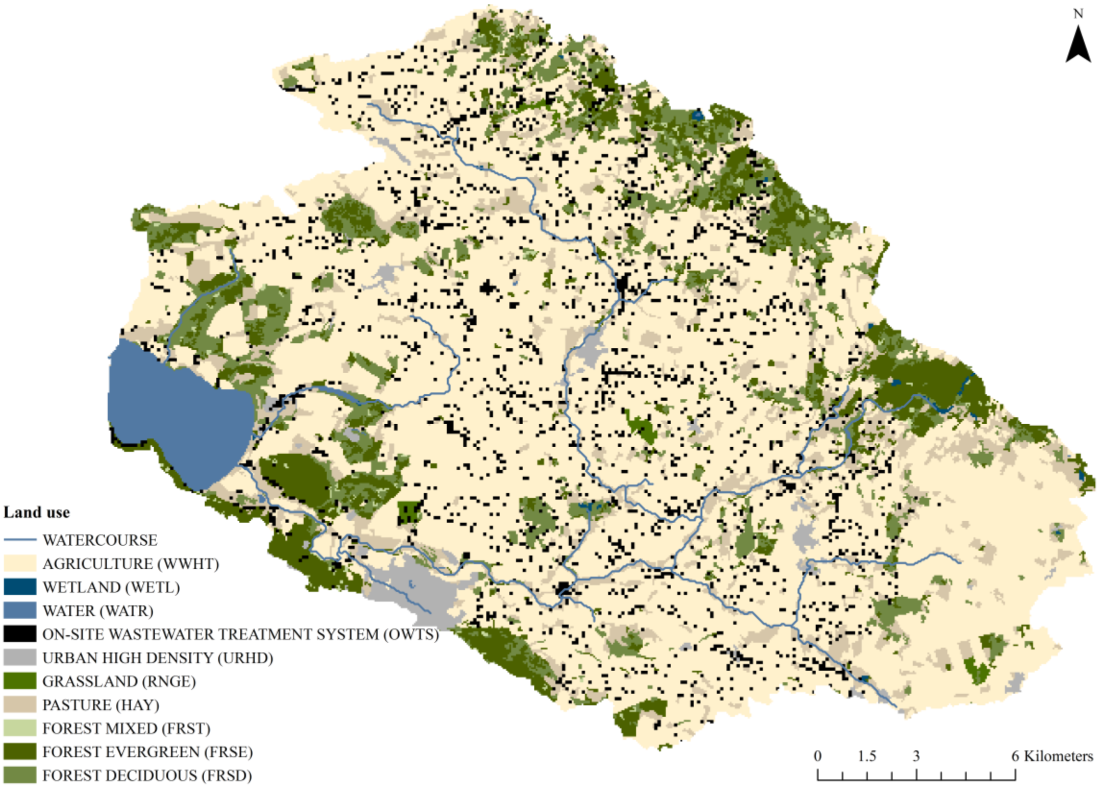

Figure 3.2 Land use classes in lake Vomb catchment obtained from Lantmäteriet (2020).

The soil raster contained 37 different numerical values and, following the same principle as described for land use, SWAT could combine the raster and look up table to reclassify the data into ten different soil classes. These are presented with respective area and percentage of total area in Table 3.3. Since the soil data was obtained from the Geological Survey of Sweden, soil classes were named in Swedish, however, for SWAT to understand how to reclassify the soil, the lookup table needed to be converted into U.S. soil names. A conversion was made by Viktor Bergion at Chalmers University of Technology, through comparison of the Swedish soil content to predefined SWAT soils and renaming them accordingly. Figure 3.3 shows the soil distribution in lake Vomb catchment.

Table 3.3. Soil types in lake Vomb catchment.

Soil type	**Clay (%)**	**Silt (%)**	**Sand (%)**	**Rock (%)**	**Organic content (%)**	**Area [ha]**	**Percentage of total area [%]**
Bucksport	10.0	45	45	0	9.88	1300	3.1
Fredon	14.0	20	66	6	2.65	15200	37
Hinckley	6.0	7	87	22	2.33	7780	19
Kingsbury	38.0	54	7	0	3.49	1080	2.6
Panton	59.5	40	0.5	0	5.81	383	0.9
Pillsbury	7.0	45	47	40	0	926	2.2
Pittsfield	6.0	34	60	40	0	43	0.1
Rock outcrop	-	-	-	-	0	55	0.13
Scarboro	4.0	16	80	20	0	13400	32
Water	-	-	-	-	-	1290	3.1

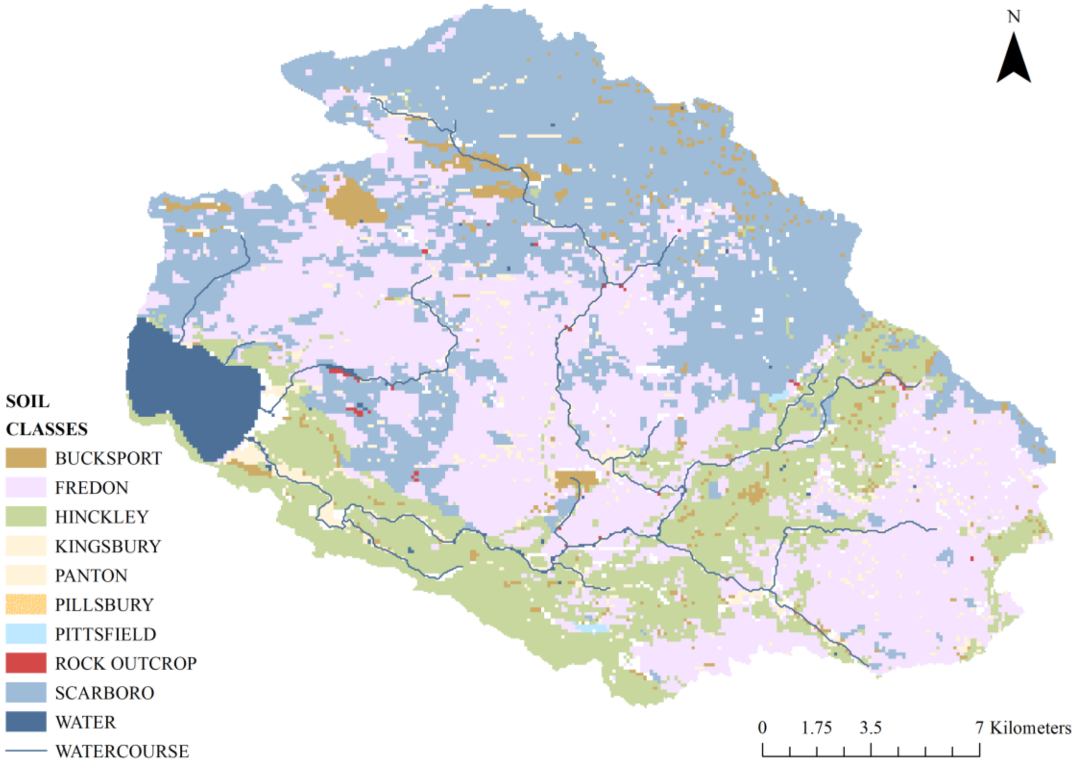

Figure 3.3. Soil types in lake Vomb catchment obtained from Geological Survey of Sweden (2016)

Finally, slope definition was set to three slope classes, 0-10 with an upper class limit of 10%, 10-30 with an upper class limit of 30% and lastly, 30-99 with an upper class limit of 99%. Most of the site is within the class 0-10, and the area can therefore be considered rather flat.

3.2.3 Input tables for meteorological data

The third step was to add meteorological data from different weather stations to the model by writing input tables. To begin with, WGEN_US_FirstOrder, which is a predefined table formatting, was selected as monthly weather database. The uploaded input data included time observations for precipitation, temperature, relative humidity, wind speed and solar radiation obtained from SMHI (2020b). Precipitation values came from Vomb measuring station, whereas temperature, humidity and wind speed were taken from Hörby weather station, and solar radiation was obtained from Lund measuring station since Vomb measuring stations does not record all parameters.

3.2.4 Microbial sub-model and adding operations

The final step before running the model was to edit SWAT inputs such as the microbial sub-model and operations for agriculture and pasture. The data considered impacts of microbial concentrations originating from OWTS, livestock grazing and agricultural activities in the watershed.

3.2.4.1 Microbial sub-model parameterisation

The purpose of the microbial sub-model was to simulate the fate and transport of microbial contaminants, in this case *Cryptosporidium* and *E. coli*. Decay rate for the different microorganisms were calculated by SWAT according to Chick's law of first order decay, see Equation 3.1 (Baffaut & Sadeghi, 2010).

$$C_t = C_0 e^{-K_{20} t \theta (T-20)} \qquad (3.1)$$

where C_t (count/100 ml) is the microbial concentration at time t; C_0 (count/100 ml) is the initial microbial concentration; K_{20} (day^{-1}) is first order die-off rate at 20°C; t (days) is exposure time; θ is the temperature adjustment factor; T (°C) is the temperature.

Microbial parameters in ArcSWAT were updated according to values in Table 3.4, based on a literature study by Löwenström & Hussain (2017). General watershed attributes are defined in the basin input file and control a diversity of physical processes at the watershed level.

Table 3.4 Input data for the bacterial sub-model in SWAT.

Parameter	Value[a]	Definition	Database
		General	
BACTKDDB	0.9	Bacteria partition coefficient (fraction of organism in soil solution, 0 = adsorbed to soil and 1 = in solution)	Fert.dat
BACTKDQ	175	Partition coefficient for bacteria between soluble and sorbed phase in surface runoff (m^3/mg)	.bsn
		Cryptosporidium	
WDPQ	0.005	Die-off factor for persistent bacteria in soil solution (1/day)	.bsn
WDPRCH	0.032	Die-off factor for persistent bacteria in streams at 20°C (1/day)	.bsn
WDPS	0.003	Die-off factor for persistent bacteria adsorbed to soil particles (1/day)	.bsn
WDPF	0.03	Die-off factor for persistent bacteria on foliage at 20°C (1/day)	.bsn
WOF-P	0.8	Wash-off fraction for persistent bacteria (fraction on foliage that washes off during a rainfall event)	.bsn
		E. coli	
WDLPQ	0.092	Die-off factor for less persistent bacteria in soil solution (1/day)	.bsn
WDLPRCH	0.18	Die-off factor for less persistent bacteria in streams at 20°C (1/day)	.bsn
WDLPS	0.023	Die-off factor for less persistent bacteria adsorbed to soil particles (1/day)	.bsn
WDLPF	0.016	Die-off factor for less persistent bacteria on foliage at 20°C (1/day)	.bsn
WOF-LP	0.5	Wash-off fraction for less persistent bacteria (fraction on foliage that washes off during a rainfall event)	.bsn

[a] Löwenström & Hussain, 2017

3.2.4.2 Microbial contribution from livestock

Livestock contributes to pathogenic microbial loads in the catchment through faecal production and dropping during grazing as well as through faecal stored during housed periods and used as manure on agricultural land. To account for these loads, concentrations of *Cryptosporidium* and *E. coli* in livestock faeces were obtained from literature and added in the fertilizer database, see Table 3.5 for baseline values. Since different livestock shed different concentrations of *Cryptosporidium* (Lewerin *et al*., 2019; Sturdee *et al*., 2003), the mean prevalence can be used to simulate the total concentration of *Cryptosporidium* originating from different livestock. For future scenarios, concentrations of *Cryptosporidium* and *E. coli* in faeces stayed the same while the prevalence of *Cryptosporidium* was changed. With greater livestock density, the prevalence is assumed to increase whilst a decreased density results in decreased prevalence (Hill *et al*., 2009). See inputs regarding concentration and prevalence for future scenarios in Appendix I.

Table 3.5. Microbial concentration in livestock faeces, 2008-2018.

Livestock	***E. coli*** **(cfu g^{-1})**	***Cryptosporidium*** **(oocysts g^{-1})**	***Cryptosporidium*** **(mean prevalence[a])**	**Conc. total livestock**
Cattle	2.00E+05[b]	3830	0.515	1970
Calve	4.20E+05[b]	38100	0.283	10800
Pigs	1.20E+07[a]	24.1	0.221	5.00
Sheep	5.90E+06[a]	780	0.346	270
Lamb	6.90E+06[a]	9140	0.524	4790
Horses	5.80E+03[a]	1030	0.100	103

[a] Ferguson *et al.*, 2009
[b] Löwenström & Hussain, 2017

Table 3.6 shows the variety and number of grazing livestock in the municipality of Sjöbo. Furthermore, it shows recommended number of grazing days for Scania and respective faecal production obtained from Atwill *et al*. (2012), a book published by World Health Organization & United States Environmental Protection Agency summarizing microbial contamination from domestic animals. It is assumed that data regarding livestock in Sjöbo is representative for the whole watershed as most of it belongs to the municipality of Sjöbo. The livestock density was therefore calculated based on total grazing area in Sjöbo is 3977 hectares (SCB, 2020b). This data was used in SWAT to set up grazing operations for all different livestock in the management database. The livestock was assumed to be uniformly distributed over all sub-basins containing grazing area and over all underlying soil layers.

Table 3.6. Faecal production during grazing in Sjöbo, 2008-2018.

Livestock	**Number of livestock in Sjöbo[a]**	**Livestock density (animal ha^{-1})**	**Faecal production (kg animal^{-1} day^{-1})[b]**	**Grazing days[a]**	**Faecal production (kg ha^{-1} day^{-1})**
Cattle (milk)	5280	1.33	25.3	120	33.7
Cattle (beef)	7420	1.86	14.4	120	26.8
Calve	6970	1.75	1.65	120	2.89
Sheep	2930	0.74	0.70	120	0.52
Lamb	3020	0.76	0.70	120	0.53
Horses	1590	0.40	18.5	183	7.40

[a] Swedish Board of Agriculture, 2016
[b] Atwill *et al.,* 2012

During livestock housing days it was assumed that all faeces were collected and stored to be used as manure during two periods each year, first on March 15th - 21st and secondly on October 1st - 7th. Die-off of oocysts and *E. coli* in stored manure was not considered. This approach has previously been used by Coffey *et al*. (2010a). The amount of collected manure was calculated through multiplying manure production with number of livestock and their respective housing days. This was divided by 26209 ha, which is the total area of agricultural land in the municipality of Sjöbo (SCB, 2020b) and split in two. In a similar manner as for grazing, the area of agricultural land in Sjöbo was assumed to be representative for the entire watershed.

All input data required for manure application during 2008-2018 can be found in Table 3.7 and for future scenarios see Appendix I. Manure was assumed to be uniformly distributed over all sub-basins containing agricultural land and over all underlying soil layers.

Table 3.7 Manure application on agricultural land 2008-2018.

Livestock	**Number of livestock**[a]	**Manure production [kg×animal^{-1} day^{-1}]**[b]	**Number of housed days**	**Collected manure [kg]**	**Applied manure per application [kg×Ha^{-1}]**
Cattle (milk)	5280	25.3	245	3.27E+07	624
Cattle (beef)	7420	14.4	245	2.62E+07	499
Calve	6970	1.65	245	2.82E+06	54
Pigs	27060	2.70	365	2.67E+07	509
Sheep	2930	0.70	245	5.02E+05	10.0
Lamb	3020	0.70	245	5.18E+05	10.0
Horses	1580	18.5	183	5.36E+06	102

[a] Swedish Board of Agriculture, 2016

3.2.4.3 Water consumption and microbial contribution from OWTS

Although OWTS effluent is not specifically accounted for in SWAT, there are ways to represent this. Coffey *et al*. (2010a) used a continuous fertilisation management operation allowing effluent from OWTS to be incorporated over a constant period of time. This was complemented with an additional use of the septic database in SWAT for the model of lake Vomb. Inputs included number of residents in each house, estimated to 2.3 persons in Scania (SCB, 2020b) with an average consumption of 157 l/d (SCB, 2017). Furthermore, the average area of drain field for each individual system was set to 1 ha and the predefined Conventional Drain field system was used. Concentration of *Cryptosporidium* after treatment was assumed to be 3.7 oocysts/100 ml (Coffey *et al.*, 2010b) and *E. coli* was assumed to correspond to the concentration in untreated sewage with a 2-log reduction i.e. 10^5 cfu/100 ml (Coffey *et al.*, 2010a). For future scenarios, treatment was additionally enhanced, see Table 3.11. Assumed future consumption was partly based on values obtained during a campaign in the municipality of Mörbylånga, Sweden for decreased water consumption (Chonewicz, 2019) and partly on water consumption in the United States (United States Environmental Protection Agency, n.d.). Inevitably, changed water consumption will change the water outtake from lake Vomb, see Table 3.11 for details.

3.3 Calibration and validation of SWAT model

For calibration, validation and sensitivity analysis of the SWAT model, the software SWAT-Calibration and Uncertainty Program (SWAT-CUP), was used with the SUFI-2 preprogramed analysis routine. SUFI-2 accounts for uncertainties in the model, e.g. measured data, parameters, driving variables and the conceptual model (Abbaspour, 2015). In SWAT-CUP, two types of analysis can be performed, local or global sensitivity analyses. For this study, the global sensitivity analysis, which uses a multiple regression approach to quantify the sensitivity of each parameter, was chosen. This since it is considered more reliable than the local sensitivity analysis. The results are shown as relative sensitivities in t-stats, i.e. a t-test, and p-values for each parameter. The t-test identifies the relative significance of each parameter determined by their range of minimum and maximum values whereas the p-values consider each parameters' contribution to the sensitivity of the full model. A large absolute value of t-stat and a small p-value indicates a more sensitive parameter (Abbaspour, 2015). Which parameters that are most important to analyse in SWAT-CUP depends on the specific watershed model and the variable being calibrated (Arnold *et al.*, 2013). Table 3.8 presents the parameters deemed appropriate for lake Vomb watershed based on parameters used in similar studies (Khalid *et al.*, 2016; Arnold *et al*. 2013). Minimum and maximum values for the parameters are default settings in SWAT-CUP based on the hydrological model in ArcSWAT. The five most sensitive parameters were later used in the model calibration, see blue marked boxes, Table 3.8.

Table 3.8. Parameters used in sensitivity analysis of watershed model and the parameters chosen for calibration (blue marked boxes).

Parameter	**Description**	**Method**	**Min**	**Max**	**t**	**p**
CN2[a]	Runoff curve number	Relative	-0.20	0.20	-0.46	0.64
ALPHA_BF[a]	Base flow alpha factor	Replace	0	1	3.70	0
GW_DELAY[a]	Delay time of groundwater	Replace	30.0	450	-23.0	0
GWQMN[a]	Threshold depth of water in the shallow aquifer required for return flow to occur	Replace	0	2	0.42	0.68
ESCO[a]	Soil evaporation compensation factor	Relative	0	1	1.30	0.19
SURLAG[a]	Surface runoff lag time	Relative	0.05	24.0	0.66	0.51
GW_REVAP[a]	Groundwater "revap" coefficient	Relative	0.02	0.20	0.12	0.91
RCHRG_DP[a]	Deep aquifer percolation fraction	Relative	0	1	-0.34	0.73
SOL_AWC[b]	Available water capacity of the soil layer	Relative	0	1	-4.10	0
SOL_K[b]	Saturated hydraulic conductivity	Relative	0	2000	-0.24	0.81
SOL_BD[b]	Moist bulk density	Relative	0.90	2.50	-9.80	0
REVAPMN[a]	Threshold depth of water in shallow aquifer	Relative	0	500	0.06	0.95
EPCO[a]	Plant uptake compensation factor	Relative	0	1	0.30	0.77

[a] Arnold *et al.*, 2013
[b] Khalid *et al.*, 2016

The model was calibrated based on observational data from Eggelstad measuring station during the years 2009-2014 and validated for the years 2015-2018. For the calibration period, an analysis of 500 simulations was carried out. After the simulations, new ranges for the five parameters were suggested by the software and an iteration process began. Depending on the default method for each parameter, the software either replaced or multiplied the existing parameter with a new value for the new calibration. The process was repeated until R^2 and NSE was adequate. R^2 is a statistical measure that provides an estimate of the variance for a dependent variable explained by the variables in the regression model, i.e. how well the variance of the observed values corresponds to the model (Arnold *et al.*, 2013; Hayes, 2020). The range of R^2 is 0 to 1 where 0 indicates no correlation and 1 full correlation. Additionally, NSE values provide a measure of how well the simulated data correspond to measured data, with a range of -∞ to 1. It is suggested that NSE below 0.5 is unsatisfactory, 0.5-0.64 is satisfactory, 0.65-0.74 is good and 0.75-1 is very good (Coffey *et al.*, 2010b). For the calibration period, i.e. 2009-2014, an R^2- value of 0.75 and NSE of 0.72 was obtained, which can be considered good. For the validation period, i.e. 2015-2018, R^2- value of 0.93 and NSE of 0.88 was obtained, which can be considered very good. For calibrated and uncalibrated flows, see Figure 3.4. All uncalibrated and calibrated results for remaining tributaries, Borstbäcken, Torpsbäcken and Björkaån can be found in Appendix II with respective R^2 and NSE values.

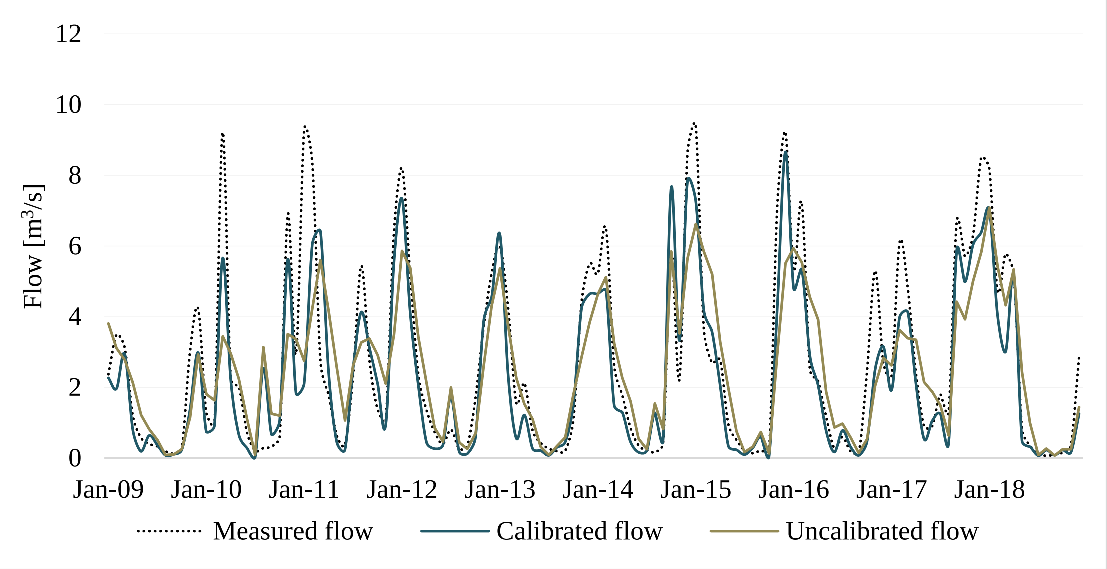

Figure 3.4 Calibrated and uncalibrated flows for Eggelstad measuring station.

3.4 Setting up the MIKE model

The mesh in MIKE 3 Flexible Mesh (FM) is triangular and combines the water depth with different geographical positions and boundary conditions. The mesh for lake Vomb consisted of 817 nodes and 1515 elements with SWEREF99_TM as reference coordinate system. The lake was divided into 10 layers with equidistant distribution. To account for spread of microorganisms in lake Vomb, the ECOLab module was added allowing a visualization of *Cryptosporidium* and *E. coli* discharged into the lake.

3.4.1 Hydrodynamic module

The hydrodynamic module in MIKE 3 FM allows the model to take density variations, bathymetry and forcings into account (DHI, 2017). As these vary depending on which source one models, parameters deemed important for lake Vomb were adjusted. Parameters that were not changed were kept in default. Model equations were based on the numerical solution of shallow water equations and Coriolis forcing were assumed to vary in domain. Boundary conditions were closed, and density was set as a function of temperature. Heat exchange was included with default parameterisation apart from light extension coefficient that was changed to 0.25 as calibrated in a previous study by Sokolova *et al.*, (2012). Meteorological parameters included in the model, as time series, were wind direction and speed, precipitation, air temperature, relative humidity and ice coverage. Moreover, clearness coefficient was set to 40%. All meteorological data was obtained from SMHI (2020b).

All parameters were daily times series except precipitation that was based on hourly data. See section 3.2.3 for detailed information about which measuring stations data was obtained from. Temperature, precipitation, wind speed and wind direction were set to varying in time but constant in domain (no spatial variations).

Borstbäcken, Björkaån, Torpsbäcken, Kävlingeån and the water intake were added as sources with their respective geographical position. Furthermore, flow time series for all tributaries obtained from SWAT were added as well. There are multiple smaller inflows, both from runoff and groundwater, which contribute to the water balance in the lake therefore, one additional source was added to account for the total flow from these diffuse sources. Flow time series for this source is based on all simulated flows in SWAT that are not accounted for in the main tributaries.

Initial conditions for surface elevation were set to 1.25 m based on water level in the lake on January 1st, 2018 and water temperature was 4.9°C (Ekologigruppen Ekoplan AB, 2018). Moreover, two outputs were added, one type 3D volume series showing movement and velocity at the surface of the lake while the other output, 2D area series, simulates the surface elevation.

3.4.2 ECOLab module

The MIKE ECO Lab module was added to describe the fate and transport of *Cryptosporidium* and *E. coli* using advection-diffusion equation accounting for decay and settling. The decay rate, k, for *Cryptosporidium* was described as a function of temperature (T) using Equation 3.2 (Walker & Stedinger, 1999).

$$k = 10^{[(0.058 \cdot T) - 2.68]} \tag{3.2}$$

and the decay rate for *E. coli* was derived from Equation 3.3 (Mancini, 1978)

$$\frac{dC}{dt} = k_0 \cdot \theta_S^{Sal} \cdot \theta_I^{Int} \cdot \theta_T^{(Temp-20)} \cdot C \tag{3.3}$$

where t is the time; C is the *E. coli* concentration; k_0 (1/day) is the decay rate at 20°C for a salinity of 0‰ and darkness; θ_S is the salinity coefficient for the decay rate; *Sal* (‰) is the salinity; θ_I is the light coefficient: *Int* (kW/m^2) is the light intensity integrated over depth; θ_T is the temperature coefficient for the decay rate; *Temp* (°C) is the water temperature. The light and salinity coefficient in Equation 3.3 was 1, temperature coefficient was set to 1.04 and decay coefficient was set to 0.2.

Furthermore, sedimentation of *Cryptosporidium* was simulated according to Equation 3.4 (Walker & Stedinger, 1999).

$$\frac{dC}{dt} = -\frac{v_s}{dz} C \tag{3.4}$$

where *dz* is the thickness of the layer, v_s is the settling velocity and C is the concentration of *Cryptosporidium*. The settling velocity was specified as 0.03 m/day (Medema *et al*., 1998)

Cryptosporidium and *E. coli* concentrations were obtained as daily time series from the SWAT model. These time series were added as sources to the ECO Lab template provided by Ekaterina Sokolova at Chalmers University of Technology, containing eight state variables together with decay rate and settling velocity. The type of time step used was instantaneous, which means that the values are representative at one precise instant (DHI, 2017). Furthermore, the two sources, Kävlingeån and the drinking water intake, without specified concentrations from SWAT were defined as sources with excess concentration. Dispersion was added with scaled eddy viscosity formulation and constant format for all sources whereas the concentrations in precipitation were set to 0. Moreover, two outputs were added, one type 3D volume series which records the concentration of the microorganisms in the entire modelling domain in time. The other output, 3D point series, showed concentration levels at the intake of the Drinking Water Treatment Plant (DWTP) as a function of time.

3.5 Validation of the MIKE model

The hydrodynamic model was calibrated in a previous study by Sokolova *et al.* (2018). Therefore, only validation of the model was performed. This by comparing modelled water levels at the outflow in Kävlingeån with observed water levels obtained from Kävlingeåns vattenvårdsförbund (Svärd, 2013). The model was validated for three months, 2013-05-01 – 2013-07-01, reaching an R^2 of 0.77 and NSE of 0.66 which can be considered good. This period was chosen because Kävlingeåns vattenvårdsförbund started reporting water levels by graph instead of tables in 2014, making levels harder to read and thereby making results more uncertain. For the validated period, initial water level was set to 0.5 m and temperature was set to 10.95°C (Svärd, 2013).

3.6 Input parameters and modelled scenarios

Two different scenarios were modelled as a combination of SSP and RCP. The motivation for choosing these two scenarios was that they are contrasts of one another and therefore cover a broad span of possible outcomes depending on climate change and socioeconomic development.

1. SSP1/RCP4.5
2. SSP5/RCP8.5

SSP1 is considered a green scenario where the world is moving towards a sustainable path regarding equality, environment, consumption and management. This development is likely in Sweden with agreements and protocols in place today such as the Paris agreement (United Nations, n.d.-b) and the United Nations' Sustainable Development Goals (United Nations, n.d.-a). The predicted socioeconomic development for SSP1 is associated with limited GHG emissions (van Vuuren *et al.*, 2011), thus making it appropriate to combine with RCP4.5. Therefore, the combination of SSP1 and RCP4.5 have been frequently used in the scientific world (Iqbal *et al.*, 2019). There is one more stringent RCP-scenario, RCP2.6, aiming to limit the increase of global mean temperature to 2ºC. For this scenario, emissions need to be reduced rapidly and stringent reduction strategies are required in the current decade. CO_2-emissions also need to decline, starting in 2020 (SMHI, 2018) and it is uncertain if they will do so globally, therefore RCP2.6 was not further investigated.

SSP5 is a fossil fuelled driven scenario, where high levels of GHG emissions and large challenges to reduce them are expected (Kriegler *et al.*, 2017). It is currently the only SSP scenario that can result in RCP8.5 and according to Geological Survey of Sweden (Geological Survey of Sweden, 2020) it is the scenario closest to today's emission pathway. There is also a less extreme scenario, RCP6.0, however, since RCP4.5 and RCP8.5 overlap and thereby cover the span of RCP6.0 (Iqbal *et al.*, 2019) it was neglected.

In Scania there is an increase in young people moving to the larger cities in line with the global trend of urbanization. However, during 2018-2027, also the smaller municipalities in western Scania are expected to have a high percentage increase in population (Region Skåne, 2019). For urban land to expand and meet the demand of growing populations, there is often a need to impose on other land covers (European Environment Agency, 2018). Generally, in EU development of buildings and other artificial surfaces claim land used for agricultural activities and, to a smaller extent, forest and natural land. For SSP1, natural land and forests are assumed to grow due to environmental awareness and reforestation. As a part of the SSP1 storyline, urban land take is assumed to only impose on agricultural land. At the same time, technology is improved, and the focus lies on renewable energy and increasing yield resulting in less land required to produce the same amount of crops. Furthermore, improved technology is assumed to enhance manure treatment and thereby decrease the presence of microorganisms in applied manure. Moreover, livestock numbers in lake Vomb watershed are expected to decrease as a result of the underlying assumption of changing diets and consumption patterns.

For SSP5, agricultural land will presumably decrease during the entire century, however, not to the same extent as in SSP1. This could be a consequence of enhanced technology and increased yield. Similar to SSP1, increased technology was assumed to enhance manure treatment and decrease pathogenic microbial concentration in applied manure. Due to the underlying assumption of a meat rich diet and increased food demand, the number of livestock will increase during the first part of the century. During the latter part of the century, there is a decline in livestock instead. Presumably, Natural land and forest are not protected to the same extent in SSP5 as in SSP1, therefore they presumably increase slightly during the first part of the century and then stagnate.

As livestock density changes for both SSP1 and SSP5, manure applied on agricultural land and faecal droppings during grazing are assumed to change accordingly. Another factor that affects the microbial concentration in lake Vomb is effluent from OWTS in the watershed. With enhanced technology for SSP1 and SSP5 it is assumed that sewage treatment will be improved by the end of the century. Furthermore, the number of OWTS in the watershed will decrease due to expanding urban areas and additional households connected to the municipal sewage network. Presumably, water consumption will also change for SSP1 and SSP5 and, as a result, effluent from OWTS will change accordingly.

Table 3.9 and Table 3.10 summarize the relevant parameters for SSP1 and SSP5, expected changes in the future and how the parameters can be interpreted for lake Vomb watershed.

Table 3.9 Parameters included in SSP1 and expected changes of these parameters (Van Vuuren et al., 2011) and interpreted effect on the area of lake Vomb.

SSP1		
Parameter	**Expected development**	**Interpretation for the area of lake Vomb**
Population growth	High	According to population forecast of Scania, higher in the beginning of the century and lower in the end
Governance and institutions	Effective both nationally and internationally	Working towards sustainable development goals and follows international agreements. Cooperation between the municipalities responsible for lake Vomb
Technology	Rapid, translated into assumptions for efficiency e.g. renewable technologies and yields	Decreased number of on-site wastewater treatment systems (OWTS) with enhanced treatment plus enhanced treatment of manure, all driven by renewable energy
Consumption/production preferences	Promotion of sustainable development and change in consumption patterns	Water demand per person decreases due to environmental awareness, food and livestock demand decline during the entire century, higher decline rate during the second half
Land use (incl. crops and livestock)	50% reforestation, less agricultural land due to effective crop yield, natural land increases	Abandonment of agricultural and pasture areas, forest increases as a result of reforestation
Emission pathway	Low	Motivation for choosing the combination of SSP1 and RCP4.5

Table 3.10 Parameters included in SSP5 and expected changes of these parameters (Kriegler et al., 2017) and interpreted effect on the area of lake Vomb.

Parameter	**SSP5**	
	Expected development	Interpretation for the area of lake Vomb
Population growth	Low	Stable increase during the century
Governance and institutions	Effective for development, limited for environment. Absence of climate policies	Reactive and not proactive approach to climate policies, regulations and goals. Action is taken when absolutely necessary.
Technology	Rapid, directed towards fossil fuel	Decreased number of OWTS with enhanced treatment plus enhanced treatment of manure, all driven by fossil fuel, thus resulting in high emissions
Consumption/ production preferences	Intensive consumption, materialism, meat rich diet, increasing global food demand and energy demand	Water demand per person increases, increasing food demand and meat resulting in higher livestock population during the first part of the century and decreases during the second.
Land use (incl. crops and livestock)	Resource intensive, rapid increase in productivity and crop yield. Slow decline in deforestation, land-use change is incompletely regulated.	Agricultural and pasture increase in the surrounding area, forest increases slightly during the first part of century and then stagnates
Emission pathway	High	Motivation for choosing the combination of SSP5 and RCP8.5 as modelling scenario 2

Input data regarding changes of temperature and precipitation for the different scenarios was obtained from SMHI. This data contains average yearly change per season from the period 1961-1990 up until the year 2100. As the modelled baseline scenario of this study, 2008-2018, differed from that of SMHI, average change occurring from 1961-1990 up until 2008-2018 was subtracted to discard changes which have already occurred before 2008. The average change between the new baseline scenario and the two 10-year periods, 2040-2050 and 2090-2100, were then added to the current meteorological data to simulate future climate scenarios. The year 2040 and 2090 are based on data from 2008 with projected changes from SMHI, likewise 2050 and 2100 are based on data from 2018 with projected changes. According to a study by Hanzer *et al.*, (2018), relative humidity change according to the same pattern as precipitation, however climate scenarios show no significant change globally (S. Tainamo, SMHI, personal communication, May 11, 2020). On the contrary, greater changes are visible regionally in areas where global warming leads to dryer soil and decreased relative humidity. Therefore, the future change of relative humidity is still uncertain (SMHI, 2019). Furthermore, wind speed is suggested to increase globally (Harvey, 2019), however, as for relative humidity, SMHI suggests that changes in wind speed are hard to predict and that there are unambiguous results (SMHI, 2020a). As a consequence, neither relative humidity nor wind speed were hanged for the simulated future scenarios to reduce uncertainties. Another parameter remaining unchanged was solar radiation as this is mostly determined by cloudiness yet how this will change in warmer climate is unclear (S. Tainamo, SMHI, personal communication, May 11, 2020). Moreover, the number of days when ice cover lake

Vomb will decrease for RCP4.5 and RCP8.5. This was based on calculated decreasing number of days per year for lake Mälaren since it is the closest lake with projected change in ice days for respective RCP scenario and for the two reference periods (Stensen *et al.*, 2017). Table 3.11 summarizes modified parameters for the different RCP and SSP scenarios in comparison to baseline scenario 2008-2018.

Table 3.11 Projected socioeconomic development and climate change for the two modelled scenarios.

	SSP1/RCP4.5		**SSP5/RCP8.5**	
	2040-2050	2090-2100	2040-2050	2090-2100
Land use (%)				
Agricultural land[a]	-11	-15	-4	-5
Forest/Natural land	8[a]	13	1[a]	-
Urban land	6	8	6	10
OWTS	-3	-6	-3	-5
Water use (%)				
Consumption	-20[b]	-30	240[c]	180[c]
Outtake	-20	-30	150[d]	150[d]
Microbial treatment				
Removal rate OWTS	-	+ 1-log	-	+ 1-log
Manure application (%)				
Livestock[a]	-5	-17.5	8.5	-9
Prevalence[e]	-10	-10	20	-10
Manure treatment (%)				
Anaerobic digester (removal rate: 90%)	75	90	60	85
No treatment	25	10	40	15
Temperature (ºC)[f]				
Winter	0.90	1.73	0.69	3.05
Spring	0.54	1.24	0.69	2.59
Summer	0.50	1.27	0.48	2.70
Autumn	0.56	1.41	0.53	3.10
Precipitation (%)[f]				
Winter	3.84	9.17	3.44	22.19
Spring	-1.69	5.92	3.41	14.06
Summer	-1.09	1.58	2.70	1.09
Autumn	4.99	5.82	3.10	13.38
Days with ice coverage (%)[g]				
	-36	-35	-49	-79

[a] International Institute for Applied Systems Analysis, 2018
[b] Chonewicz, 2019
[c] United States Environmental Protection Agency, n.d.
[d] Sydvatten, n.d.
[e] Sokolova *et al.*, 2018
[f] SMHI, n.d.
[g] Stensen *et al.*, 2017

See Appendix III for change in number of days with ice coverage for each respective scenario and year and Appendix IV for a visualization of climate change relative to baseline.

To summarize, 13 different simulations were performed with SWAT. One for the baseline 2008-2018 including a warm-up year and three for each of the future scenarios, 2040-2050 and 2090-2100. This since climate features and socioeconomic features were first modelled separately before being combined. The purpose was to see if they contributed equally to the total change in microbial concentration or if it was possible to distinguish any differences between the two. In total, five different simulations were performed with MIKE, one baseline scenario for the year 2018, using inputs from the SWAT model and two simulations per combination of SSP and RCP for 2050 and 2100 respectively.

4 Results

First, results from SWAT are presented where the individual impact on microbial concentration resulting from climate change is presented for Björkaån. Similar trends were observed for Borstbäcken and Torpsbäcken as well, see Appendix V for results. This is followed by a subchapter where the individual impact of socioeconomic development with its related land use change is presented. After this, the combined impact on microbial water quality of climate change and socioeconomic development is presented followed by concentrations of *Cryptosporidium* and *E. coli* at the water intake, simulated in MIKE.

4.1 Climate change effects on microorganisms entering lake Vomb

Generally, all five scenarios follow the same trend throughout the year with slightly varying peak concentrations. Scenarios representing the end of the century have higher fluctuations in concentration than scenarios representing mid-century. Occasionally, all future scenarios exceed baseline concentrations, indicating that climate change can increase microbial contamination in the tributaries. However, there are still periods when baseline concentrations exceed projected future concentrations. The maximum concentration occurs between year 7 and 8 and then decrease somewhat before stagnating at lower levels at the end of year 10. For *E. coli*, there is an increasing number of dominant peaks compared to *Cryptosporidium*, see Figure 4.1 and 4.2. The highest peak is 550 cfu/100 ml for RCP8.5 and the year 2046, but generally high peaks are also noticeable for RCP4.5 during mid-century. Note that the unit for *Cryptosporidium* is oocysts/10 litres and the concentrations for both *Cryptosporidium* and *E. coli* are displayed as a monthly average, derived from the daily concentrations rendered by SWAT. Daily concentrations fluctuated greatly over 10 years and monthly average was thereby chosen to easier interpret trends and patterns.

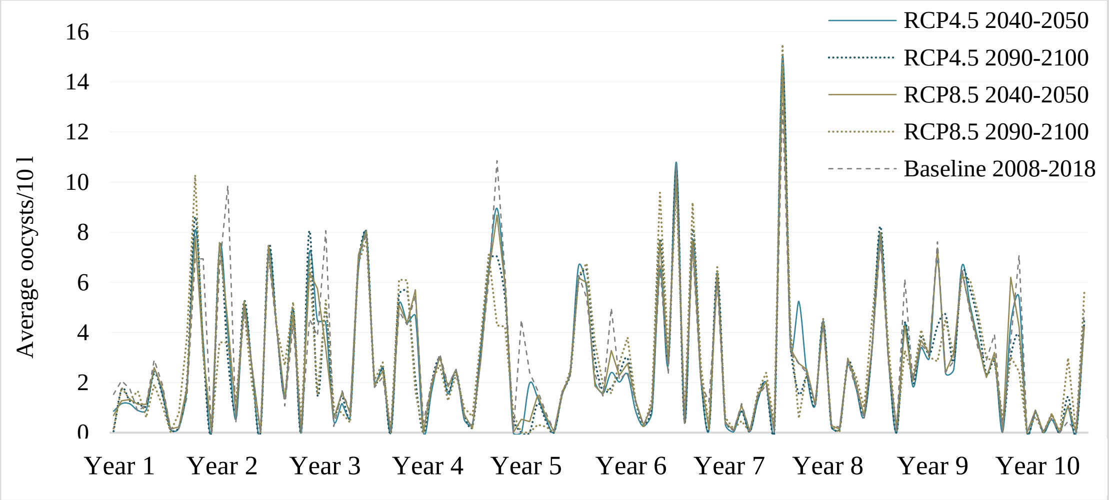

Figure 4.1 Simulated concentrations for Cryptosporidium under future climate scenarios in Björkaån.

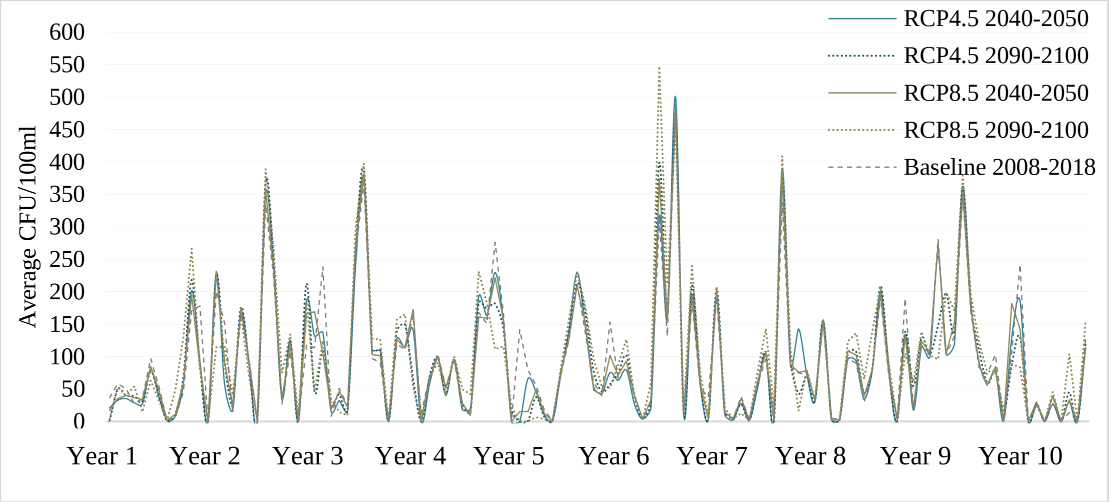

Figure 4.2 Simulated concentrations of E. coli under future climate scenarios in Björkaån.

4.2 Socioeconomic development effects on microorganisms entering lake Vomb

All four socioeconomic development scenarios result in *Cryptosporidium* concentrations lower than those simulated for the baseline scenario, see Figure 4.3. However, there are differences in their relative impact. By mid-century, higher concentrations can be expected for both SSPs, with SSP5 2040-2050 displaying the highest levels throughout the time period and a maximum average concentration of 8 oocysts/10 litres. Decreased concentrations by the end of the century can be explained by significantly enhanced manure treatment and sewage treatment. By the end of the century 90% and 85% of all stored manure was treated with anaerobic digestion for SSP1 and SSP5 respectively, see Table 3.11. Furthermore, OWTS performance was enhanced by 1-log each for both SSP scenarios. Similar trends are visible for simulated *E. coli* concentrations with a maximum average concentration of 240 cfu/100 ml for SSP5 2040-2050 which is a decrease compared to the simulated baseline period, displaying a maximum average of 500 cfu/100 ml. Concentrations obtained under different socioeconomic development scenarios generally predict significantly lower concentrations for both *Cryptosporidium* and *E. coli* compared to concentrations obtained under climate change scenarios, see Figure 4.3 and 4.4. This indicates that the impact of SSP on microbial concentrations is stronger compared to RCP.

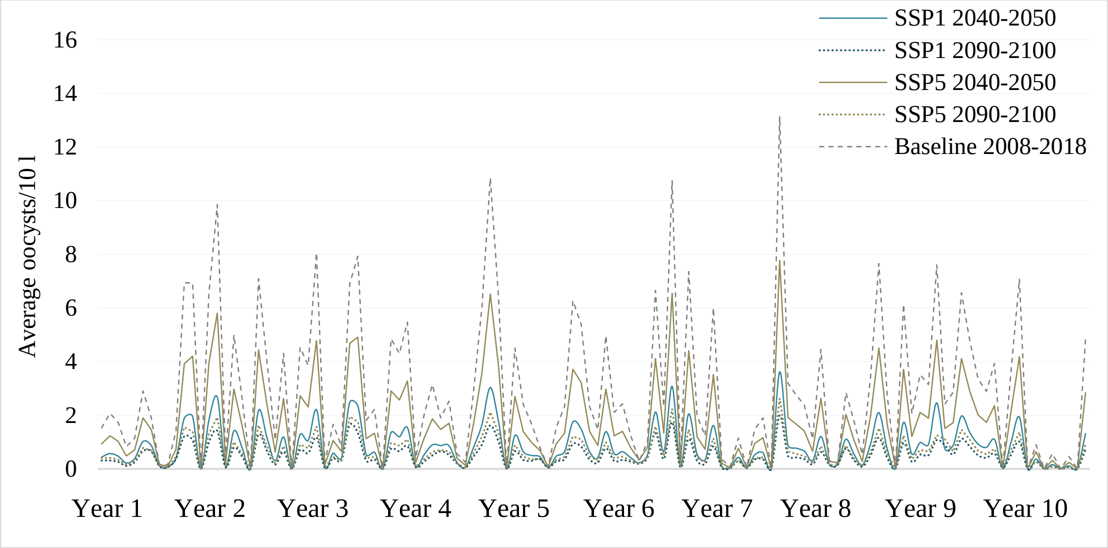

Figure 4.3 Simulated Cryptosporidium concentration under future socioeconomic development in Björkaån.

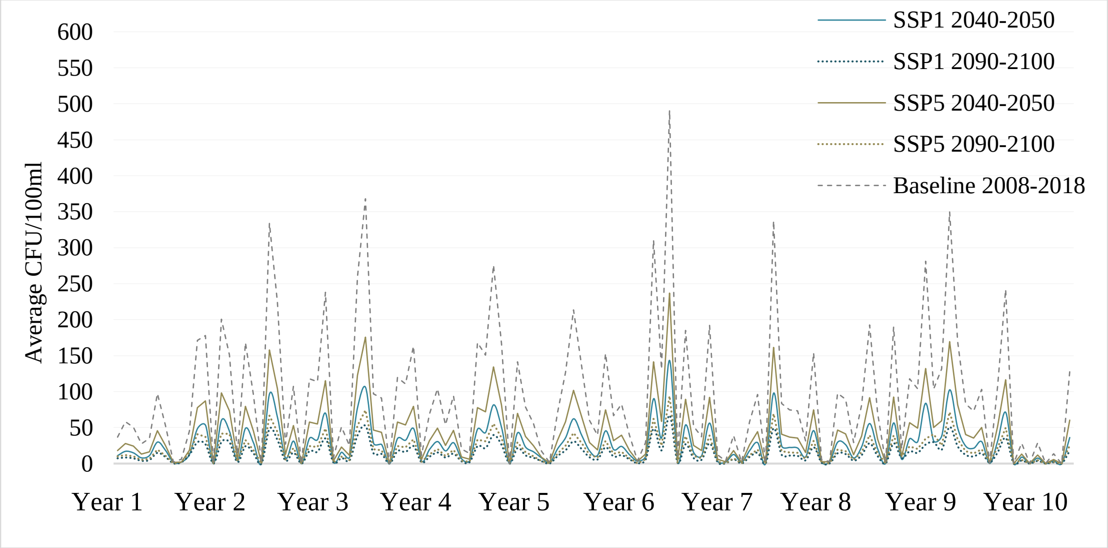

Figure 4.4 Simulated E. coli concentration under future socioeconomic development in Björkaån.

4.3 Combined effects on microorganisms entering lake Vomb

When combining climate change and socioeconomic development scenarios, none of the simulated concentrations for *Cryptosporidium* and *E. coli* exceed the baseline scenario, see Figure 4.5 and Figure 4.6, for maximum concentrations see Appendix VI. Similar to the results obtained when investigating socioeconomic development individually, SSP1/RCP4.5 2040-2050 and SSP5/RCP8.5 2040-2050 simulate the highest concentrations. Whereas by the end of the century, for both scenarios, lower concentrations can be expected. The largest difference between the four scenarios are visible during concentration peaks. Furthermore, when combining SSP and RCP, results are more in line with magnitudes obtained under the individual socioeconomic development scenarios than the climate change scenarios. This indicates that SSP is more influential than RCP when it comes to simulated *Cryptosporidium* and *E. coli* concentrations in the tributaries.

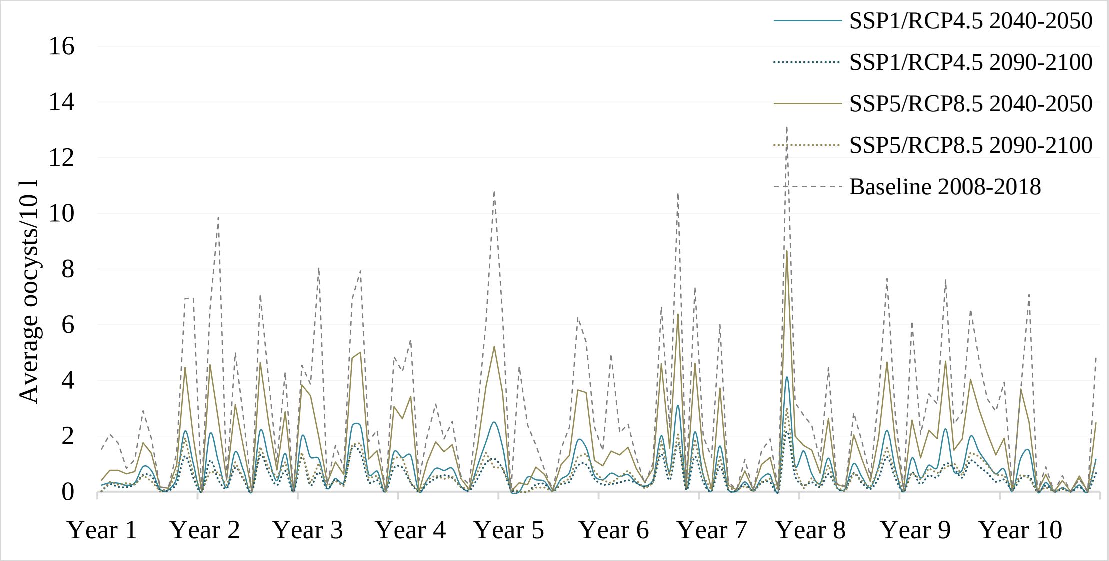

Figure 4.5 Simulated Cryptosporidium concentrations under both climate change and socioeconomic development in Björkaån.

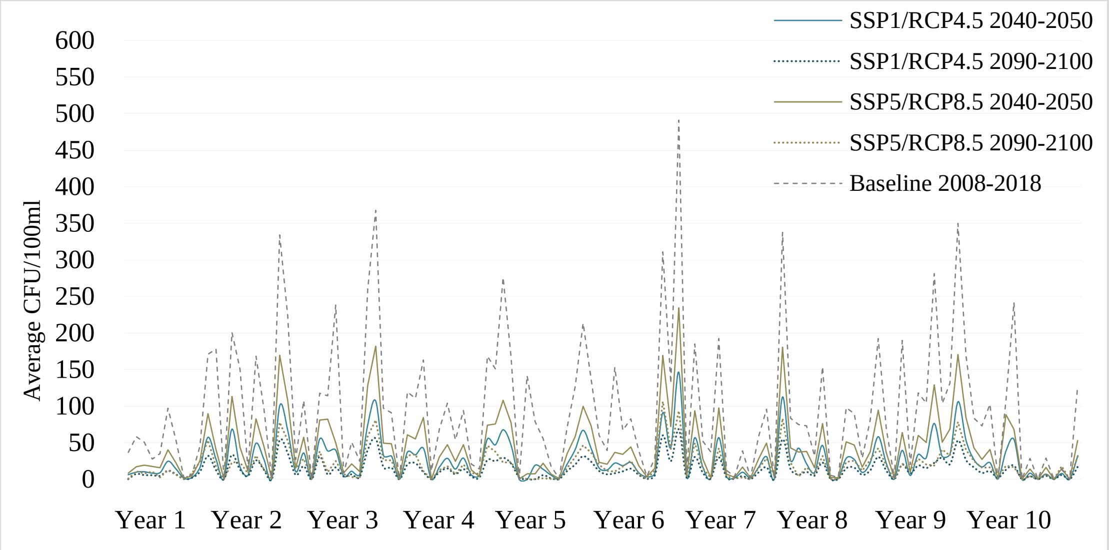

Figure 4.6 Simulated E. coli concentrations under both climate change and socioeconomic development in Björkaån.

4.4 Combined effects on pathogen concentration in lake Vomb

Concentrations of *Cryptosporidium* and *E. coli* at the water intake show somewhat similar trends throughout the year with increasing concentrations staring in January and culminating in April, see Figure 4.7 and 4.8 This is evident for all five scenarios. Thereafter, concentrations decline gradually until August before stagnating closer to 0 during fall. In November and December, i.e. the beginning of winter, concentrations start increasing again.

Generally, all future scenarios simulate *Cryptosporidium* concentrations below the baseline scenario. However, *Cryptosporidium* is detectable during most part of the year and can therefore pose a risk to human health (Svenskt Vatten, 2008), depending on treatment processes in the DWTP. On the contrary, simulated *E. coli* concentrations exceed the baseline scenario for both SSP1/RCP4.5 2050 and SSP5/RCP8.5 during the entire century. For the SSP5/RCP8.5-scenarios, *E. coli* concentrations are also above the guideline value of 500 cfu/100 ml in March and early April, indicating an elevated risk on human health and safe drinking water distribution.

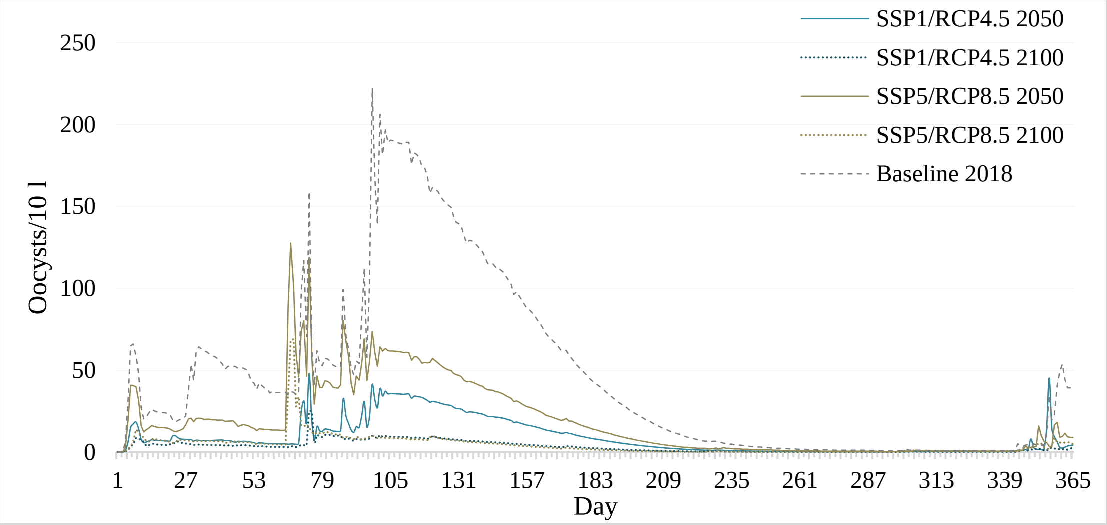

Figure 4.7 Simulated concentrations of Cryptosporidium at the intake of the DWTP for all combined scenarios.

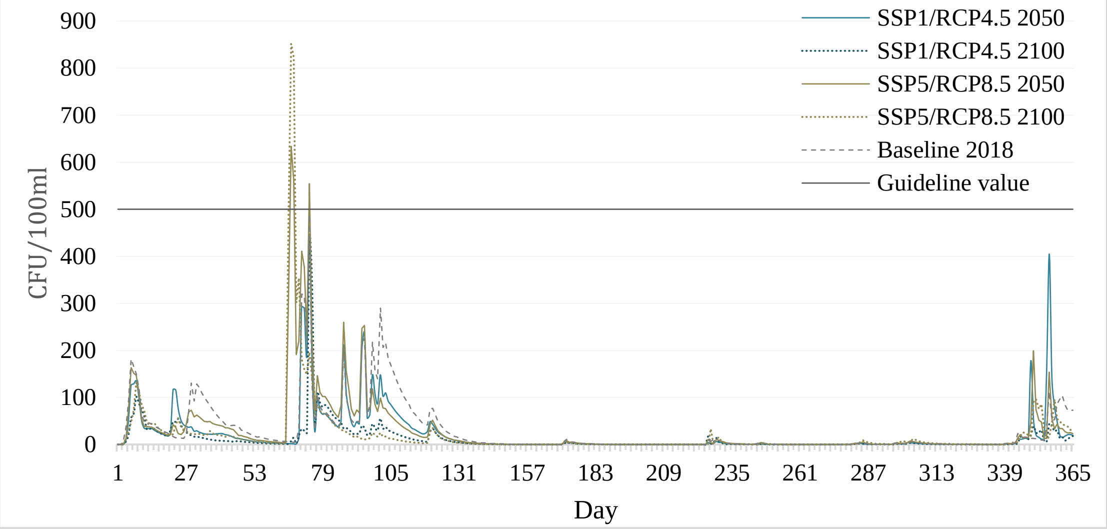

Figure 4.8 Simulated concentrations of E. coli at the intake of the DWTP for all combined scenarios.

5 Discussion

This chapter will discuss obtained results regarding future water quality of lake Vomb, how assumptions and method might impact these results, uncertainties in both method and results as well as recommendations for future studies in the area.

5.1 Projected future microbial water quality

Results from this study show that simulations with SWAT give higher concentrations for RCP scenarios individually compared to the combination of SSP and RCP, where resulting concentrations are more in line with those obtained for SSP scenarios, see Table 4.1-Table 4.6. Results from Mohammed *et al.*, (2019) showed that increased temperatures in their water source increased concentrations of *E. coli*. A trend that is also visible in this study on lake Vomb, where *E. coli* concentrations occasionally increased for RCP4.5 and RCP8.5, during both time periods, as opposed to SSP1 and SSP5, which showed lowered concentration compared to simulated baseline period during all time periods. Furthermore, our results indicate that SSP is more influential compared to RCP when it comes to microbial water quality. This confirms the results by Islam *et al*. (2018), suggesting that socioeconomic development is more important than climate change for future microbial water quality. With this in mind, results are based on assumptions that technology will be improved, with regard to on-site wastewater treatment systems and their removal efficiency as well as manure treatment, see table 3.11. Moreover, it is assumed that livestock density and thereby faecal production will decrease for all scenarios except SSP5/RCP8.5 2040-2050. If these improvements would not be implemented, future concentrations could be higher than simulated in this study. Measures should therefore be taken to improve both sewage and manure treatment to avoid future problems regarding microbial water quality. Since the results are strongly affected by the SSP storyline, one could expect that activities like fertilization would increase simulated concentrations. However, there is no significant peak during fall when fertilizers are applied, rather the peaks are higher during wintertime when it is colder compared to during the fertilization periods. This could be a consequence of increased survival rate for *Cryptosporidium* when in slightly colder weather conditions (Svenskt Vatten, 2008). However, during springtime significant peaks are visible which is also when fertilizers are applied. Hence, it is difficult to say to what extent fertilizing contributes to microbial contamination in lake Vomb. One important factor in transporting the fertilizer to the tributaries is precipitation, which therefore plays a large role in dominant peaks.

Looking at the relative impact of the modelled future scenarios in SWAT, SSP5/RCP8.5 2040-2050 is the most critical with highest simulated concentrations. This can be interpreted as a consequence of the SSP5 storyline, where policies are more reactive than proactive and development is driven by fossil fuels, see Table 3.10. Furthermore, it is the only scenario where the amount of livestock increases, see Table 3.11, resulting in larger faecal production and increased prevalence of *Cryptosporidium*. Additionally, SSP1/RCP4.5 2090-2100 renders the lowest concentrations of *Cryptosporidium* and *E. coli*. This was expected since it is the most stringent RCP scenario with a SSP storyline working towards sustainable development. The amount of livestock was significantly reduced together with extensive manure treatment while at the same time technology is driven by renewable energy resulting in reduced GHG emissions. However, all combined SSP and RCP scenarios simulate concentrations lower than the baseline scenario, indicating that

Cryptosporidium and *E. coli* concentrations will decrease in the tributaries entering lake Vomb. Furthermore, the average *E. coli* concentration is below 500 cfu/100ml for all time periods. Moreover, maximum concentrations for all three tributaries are significantly smaller compared to baseline, even for the most critical scenario SSP5/RCP8.5 2040-2050, see Appendix V. However, all maximum daily concentrations exceed the guideline value of 500 cfu/100ml (Svenskt Vatten, 2008), indicating that occasionally, concentrations in the tributaries can pose a health risk. With this in mind, combining SSP5 with RCP8.5 might underestimate the climatic impact since SSP5 is driven by fossil fueled development, which in turn increases the combustion of fossil fuels, thus resulting in even more GHG emissions, not accounted for in RCP8.5. Furthermore, water quality is not only determined by the concentration of *Cryptosporidium* and *E. coli* but is regulated by other parameters as well. For instance, water temperature, turbidity, phosphorus, nitrogen and traffic related contaminants are all affected by both SSP and RCP as well but these factors were not included in this research. Therefore, even though microbial concentrations are below baseline, further research is required to determine the overall water quality in the tributaries. However, the results can indicate which aspects are important to consideration when analyzing future microbial water quality.

When analyzing results rendered by MIKE, the critical period occurs during spring when concentrations of both *Cryptosporidium* and *E. coli* are at their maximum. This could be due to favorable temperature conditions for both microorganisms and fertilizing processes occurring at that time. *Cryptosporidium* is detected almost throughout the year and can therefore pose a threat even at low concentrations depending on treatment processes in the DWTP. Furthermore, it was evident that concentrations started to increase during colder period, culminating in April and slowly decreased during warmer period. This goes in line with research by Svenskt Vatten (2008). In addition, the concentration curve for *Cryptosporidium*, Figure 4.7, declines during summer, which could be a result of stratification of the lake due to limited mixing during this period. However, the results obtained in MIKE do not show any large differences in temperature between the surface and deeper layers of the lake. The peaks are more likely explained by favorable conditions and fertilizer application during spring. It could also be a result of periods with and without ice coverage. For *E. coli* on the other hand, simulated concentrations are generally above baseline concentrations except occasionally, suggesting that climate change and socioeconomic development will increase microbial concentration in lake Vomb. Furthermore, *E. coli* concentrations exceeds guideline values of 500 cfu/100 ml by the end of March and beginning of April meaning that there will be an elevated risk to human health for the two SSP5/RCP8.5 scenarios during the entire century, see Figure 4.8. Why *E. coli* concentration exceed baseline concentrations at the water intake but not for the tributaries could be explained by the fact that concentrations in the tributaries are displayed as average concentrations while at the water intake it is displayed as daily times series.

5.2 Uncertainties in the results and method

Some common uncertainties in watershed modelling, is interaction between surface and groundwater, unaccounted water diversion, unknown wastewater discharges into water streams from factories and wastewater treatment plants, amongst other (Abbaspour, 2007). For instance, there is a WWTP located in the watershed, however, it does not discharge any effluent into the tributaries. Nevertheless, it is possible that some discharge is transported via groundwater to lake Vomb which is not accounted for. During calibration of the SWAT-model, the most sensitive parameters were related to groundwater and soil characteristics, therefore by calibrating flows with respect to these parameters, uncertainties are decreased. Furthermore, the WWTP might need to discharge into adjacent streams during sewer overflows which would affect the microbial concentrations entering lake Vomb. This was not included in the SWAT-model either. Moreover, wastewater from factories or industries could affect both flow patterns and microbial concentration, however, this was not accounted for, and all urban areas were treated as homogenous. Unaccounted water diversion could also influence flows and concentrations reaching lake Vomb, nevertheless, the SWAT model is based on a DEM which should reduce uncertainties related to diversion.

Generally, using RCPs is a strategic way to quantify climate change, however, these are projections associated with some uncertainty which is transferred to the results. Likewise, SSPs are also associated with assumptions and uncertainties. Therefore, it is of importance to discuss uncertainties associated with results presented in this study.

It was assumed that for the baseline scenario, no manure was treated before application to agricultural land. This due to lack of information regarding current manure treatment in the area. It is likely that some farmers treat part of stored manure, so this assumption might lead to an overestimation of *Cryptosporidium* and *E. coli* in manure for the baseline scenario. Furthermore, die-off of oocysts and *E. coli* in stored manure was not considered which might lead to an overestimation of microbial concentrations. For future scenarios, it was assumed that manure treatment will be developed, but at which pace this technology will do so and how effective it will be is uncertain. It is possible that development of this technology will be slower or implemented at smaller scales than assumed in this study, depending on how legislation and technology will develop in the coming years, which would then make the results an underestimation of the concentrations. Furthermore, it was assumed that stored manure was applied to all agricultural land in the watershed simultaneously over a course of one week, two times a year. It is more reasonable in common agricultural practice to apply manure on different parts of the agricultural area in the watershed over a course of weeks (Coffey *et al.*, 2010a; Coffey *et al.*, 2010b), however this would be complex to incorporate in the SWAT model. This simplification could lead to an overestimation of microorganisms on the application dates, thereby affecting the daily concentration of microorganisms. However, this assumption does not affect as much the monthly average concentrations as presented in Table 4.1- Table 4.6.

Furthermore, it is likely that the OWTS in the watershed differ somewhat, which also means that different loads of *Cryptosporidium* and *E. coli* are emitted from each household, however there is no available data on type of treatment or system used, therefore, all OWTS were treated in the same way.

Moreover, it is suggested that increased humidity increases the survival rate of *Cryptosporidium* oocysts (Funari *et al.*, 2012). However, to what extent relative humidity will change for different RCPs is not certain. Hanzer *et al.*, (2018) suggests that it will increase to the same extent as precipitation whereas SMHI (S. Tainamo, SMHI, personal communication, May 11, 2020) means that it is not certain how relative humidity will change in the future. Therefore, relative humidity remained unchanged for future scenarios, nonetheless this could affect the results. Not altering the humidity data, thus means that the concentrations of oocysts entering lake Vomb in future scenarios might be underestimated.

There is no projection on how ice coverage will change for different RCP-scenarios in lake Vomb specifically. Therefore, an assumption that the percentual change in ice days for lake Mälaren could be applied to lake Vomb was made. However, since lake Mälaren is located further north in Sweden, one could expect colder climate and more days with ice cover, resulting in an overestimation of ice coverage. There are already recorded winters in Scania with no ice (Eklund, 1999), which under the chosen RCPs could increase. Decreased number of frozen days can increase the number of oocyst that survive winter (Funari *et al*., 2012) and thereby potentially increase the concentration of *Cryptosporidium* in lake Vomb. Moreover, as air temperature increases, so does the water temperature, which was simulated in the MIKE model. However, since there are no predictions for water temperature from SMHI for the different RCPs, the same initial water temperature was used for all simulations. By increasing water temperature, the number of ice days could decrease, consequently leading to higher survival of oocysts during winter. On the contrary, higher temperatures during the rest of the year could decrease the survival rate of both *Cryptosporidium* and *E. coli.*

All uncertainties regarding assumptions made for socioeconomic development scenarios in SWAT consequently apply for modelling in MIKE as well. Furthermore, the MIKE-model was calibrated by Sokolova *et al*. (2012) with flows modelled by SMHI. However, in this study, flows were obtained from the SWAT-model. If calibration had been performed with flows obtained from SWAT, the model could be further improved and thereby increasing the reliability of the results. Moreover, simulations in MIKE were limited to one-year period, whereas in SWAT the simulated periods corresponded to ten years. In SWAT, results showed varying concentrations during the ten-year periods, indicating that results obtained in MIKE would differ if a different year was chosen for simulation. However, results do give an indication on how concentrations at the water intake vary throughout the year.

5.3 Suggestions for future research

To further improve models regarding fate and transport of microorganism entering lake Vomb, it is recommended to conduct measurements regarding both flow and concentration in all tributaries. This would enhance flow calibration and enable adequate calibration of microbial concentration. Furthermore, it would give a more accurate baseline scenario to compare future scenarios with. Moreover, there were uncertainties regarding both treatment type and extent of OWTS in the watershed, therefore it is recommended to survey all OWTS and use this data in future models for lake Vomb.

In SWAT concentrations during the ten-year period differed somewhat while for MIKE the results are only representative for one-year period. This means that running longer time periods in MIKE would be beneficial to see if the concentrations differ. It is also recommended to use longer time periods for validation and calibration of the model.

Since ice coverage and water temperature are important in relation to *Cryptosporidium* and *E. coli* survival, reliability of the baseline results would be enhanced by measuring these parameters and investigating how these will change in the future for lake Vomb specifically.

Additionally, it would be interesting to perform a sensitivity analysis of the socioeconomic development parameters, to see which parameters affect the results most. This to see how technical solutions and behavioral patterns can be changed in order to establish how to best mitigate the consequences of socioeconomic development.

Finally, since it is known that lake Vomb already have high nutrient concentration (VISS, n.d.), it would be interesting to see how nutrient concentrations were to change for future scenario. Agricultural activities include phosphorous and nitrogen which drives eutrophication and both parameters are possible to simulate in SWAT and MIKE. Furthermore, since the lake is considered hypertrophic (VISS, n.d.), it would be of interest to investigate how algae blooms and related toxins will be affected by climate change and socioeconomic development in the future.

6 Conclusion

The four future scenarios represented possible development pathways with regard to socioeconomic development and climate change for the chosen time periods, 2040-2050 and 2090-2100. One inclusive development pathway respecting environmental boundaries, SSP1, coupled with a low emission climate scenario, RCP4.5, and one energy and resource intensive development pathway, SSP5, coupled with a high emission climate scenario, RCP8.5, were studied. Modelled results showed generally lower concentrations of *Cryptosporidium* and *E. coli* under the different socioeconomic development scenarios compared to concentrations obtained under climate change scenarios. When assessing the impact of climate change individually, concentrations were occasionally above simulated concentrations for the baseline 2008-2018. However, when combining socioeconomic development scenarios with climate change, resulting concentrations were more in line with those obtained for the individual SSP scenarios. This suggests that socioeconomic development is important to include when investigating future microbial water quality. This also means that combining the socioeconomic development with climate change is important to study since they might have a counteracting effect.

Furthermore, results showed detectable levels of *Cryptosporidium* for all future scenarios and *E. coli* concentrations were occasionally above guideline values as well as baseline concentrations at the drinking water intake. Thus, safe drinking water distribution may be at risk if development follows the path of SSP5/RCP8.5. It is also suggested that, since *E. coli* concentrations are above baseline concentrations, climate change and socioeconomic development might increase microbial concentrations in lake Vomb for both SSP5/RCP8.5 scenarios as well as for SSP1/RCP4.5 by the middle of the century. Important to note is however that concentrations at the water intake are based on one year simulation. For the results to be more reliable, it is recommended to simulate several years in MIKE as well.

To conclude, this research shows a relatively hopeful future regarding microbial water quality entering lake Vomb from its tributaries whereas at the water intake both concentrations of *Cryptosporidium* and *E. coli* might pose a risk to human health. However, this is under the assumption that development follows the projected changes in this research with significant technological development and implementation. Furthermore, other parameters and aspects to consider beyond *Cryptosporidium* and *E. coli* are important as well with regard to overall water quality.

7 References

Abbaspour, K. (2015). SWAT-Calibration and uncertainty programs (CUP). *Neprashtechnology.Ca*. https://doi.org/10.1007/s00402-009-1032-4

Abbaspour, K. C., Vejdani, M., & Haghighat, S. (2007). SWAT-CUP calibration and uncertainty programs for SWAT. *MODSIM07 - Land, Water and Environmental Management: Integrated Systems for Sustainability, Proceedings*.

Abera, W., Tamene, L., Abegaz, A., & Solomon, D. (2019). Understanding climate and land surface changes impact on water resources using Budyko framework and remote sensing data in Ethiopia. *Journal of Arid Environments*. https://doi.org/10.1016/j.jaridenv.2019.04.017

Adler, S., Widerström, M., Lindh, J., & Lilja, M. (2017). Symptoms and risk factors of Cryptosporidium hominis infection in children: data from a large waterborne outbreak in Sweden. *Parasitology Research*. https://doi.org/10.1007/s00436-017-5558-z

Alaoui, A., Willimann, E., Jasper, K., Felder, G., Herger, F., Magnusson, J., & Weingartner, R. (2014). Modelling the effects of land use and climate changes on hydrology in the Ursern Valley, Switzerland. *Hydrological Processes*. https://doi.org/10.1002/hyp.9895

Alström, T., Holmström, K., Holmström, C., Davidsson, T., & Björklund, H. (2017). *Vombsjön - Faktasammanställning 2017*. http://kavlingean.se/rapporter/Vombsjoen_Faktasammastaellning_2017_03_30.pdf

Anees, M. T., Abdullah, K., Nawawi, M. N. M., Ab Rahman, N. N. N., Piah, A. R. M., Zakaria, N. A., Syakir, M. I., & Mohd. Omar, A. K. (2016). Numerical modeling techniques for flood analysis. In *Journal of African Earth Sciences*. https://doi.org/10.1016/j.jafrearsci.2016.10.001

Arnold, J. G., Kiniry, J. R., Srinivasan, R., Williams, J. R., Haney, E. B., & Neitsch, S. L. (2013). Soil & Water Assessment Tool: Input/output documentation. version 2012. *Texas Water Resources Institute, TR-439.*

Atwill, E. R., Li, X., Grace, D., & Gannon, V. (2012). Zoonotic waterborne pathogen loads in livestock. In *Animal Waste, Water Quality and Human Health*.

Bergion, V., Lindhe, A., Sokolova, E., & Rosén, L. (2018). Risk-based cost-benefit analysis for evaluating microbial risk mitigation in a drinking water system. *Water Research*. https://doi.org/10.1016/j.watres.2017.12.054

Baffaut, C. & Sadeghi, A. (2010). Bacteria Modeling with SWAT for Assessment and Remediation Studies: A Review. *Transactions of the ASABE*, *53*(5), 1585–1594. https://doi.org/10.13031/2013.34907

Cann, K. F., Thomas, D. R., Salmon, R. L., Wyn-Jones, A. P., & Kay, D. (2013). Extreme water-related weather events and waterborne disease. In *Epidemiology and Infection*. https://doi.org/10.1017/S0950268812001653

Chonewicz, J. (2019). *Dimensionerande vattenförbrukning och alternativa vattenkvaliteter*. http://lup.lub.lu.se/luur/download?func=downloadFile&recordOId=8987717&fileOId=8987719

Coffey, R., Cummins, E., Bhreathnach, N., Flaherty, V. O., & Cormican, M. (2010a). Development of a pathogen transport model for Irish catchments using SWAT. *Agricultural Water Management*. https://doi.org/10.1016/j.agwat.2009.08.017

Coffey, R., Cummins, E., O'Flaherty, V., & Cormican, M. (2010b). Analysis of the soil and water assessment tool (SWAT) to model Cryptosporidium in surface water sources. *Biosystems Engineering*. https://doi.org/10.1016/j.biosystemseng.2010.04.003

Coffey, R., Benham, B., Kline, K., Wolfe, M. L., & Cummins, E. (2015). Modeling the impacts of climate change and future land use variation on microbial transport. *Journal of Water and Climate Change*. https://doi.org/10.2166/wcc.2015.049

Coffey, R., Benham, B., Wolfe, M. L., Dorai-Raj, S., Bhreathnach, N., O'Flaherty, V., Cormican, M., & Cummins, E. (2016). Sensitivity of streamflow and microbial water quality to future climate and land use change in the West of Ireland. *Regional Environmental Change*. https://doi.org/10.1007/s10113-015-0912-0

De Brauwere, A., Ouattara, N. K., & Servais, P. (2014). Modeling fecal indicator bacteria concentrations in natural surface waters: A review. In *Critical Reviews in Environmental Science and Technology*. https://doi.org/10.1080/10643389.2013.829978

Delpla, I., Jung, A. V., Baures, E., Clement, M., & Thomas, O. (2009). Impacts of climate change on surface water quality in relation to drinking water production. In *Environment International*. https://doi.org/10.1016/j.envint.2009.07.001

Department for Environment Food and Rural Affairs. (2011). *Hydrodynamic modelling*. http://www.estuary-guide.net/guide/analysis_and_modelling/hydrodynamic_modelling.asp?fbclid=IwAR2v9QWozm8SFvNS9j2YjeamJp-jaNAA-z-3WfJWTRbsRg-Y2XmXampniM0

DHI. (2017). *MIKE 21 & MIKE 3 Flow Model FM - Hydrodynamic Module*. https://manuals.mikepoweredbydhi.help/2017/Coast_and_Sea/MIKE_FM_HD_Step_By_Step.pdf%0D

European Environment Agency. (2018). *Urban land take*. https://www.eea.europa.eu/airs/2018/natural-capital/urban-land-expansion/?fbclid=IwAR0B-sJlaGt3FoRXja56iIdAqoFe4RWKgvrNC18f97fTny05N3fvtyr_gF8#footnotesand-references

European Environment Agency. (2019). Land and soil in Europe. Why we need to use these vital and finite resources sustainably. In *Eea Signals 2019*. https://doi.org/10.2800/779710

Eklund, A. (1999). *Isläggning och islossning i svenska sjöar*. *81*. SMHI.

Ekologigruppen Ekoplan AB. (2018). *Kävlingeån vattenkontroll 2018*. http://www.kavlingeans-vvf.com/wp-content/uploads/2019/12/Kavlingean-recipientkontroll-arsrapport-2018.pdf

El-Khoury, A., Seidou, O., Lapen, D. R. L., Que, Z., Mohammadian, M., Sunohara, M., & Bahram, D. (2015). Combined impacts of future climate and land use changes on discharge, nitrogen and phosphorus loads for a Canadian river basin. *Journal of Environmental Management*. https://doi.org/10.1016/j.jenvman.2014.12.012

Ferguson, C. M., Charles, K., & Deere, D. A. (2009). Quantification of microbial sources in drinking-water catchments. In *Critical Reviews in Environmental Science and Technology*. https://doi.org/10.1080/10643380701413294

Funari, E., Manganelli, M., & Sinisi, L. (2012). Impact of climate change on waterborne diseases. *Annali Dell'Istituto Superiore Di Sanita*. https://doi.org/10.4415/ANN_12_04_13

Geological Survey of Sweden. (2016). *Geokartan*. https://apps.sgu.se/geokartan/#mappage

Geological Survey of Sweden. (2020). *Vårt framtida klimat*. https://www.sgu.se/om-geologi/ett-klimat-i-standig-forandring/vart-framtida-klimat/%0D

Guo, Y., Fang, G., Xu, Y. P., Tian, X., & Xie, J. (2020). Identifying how future climate and land use/cover changes impact streamflow in Xinanjiang Basin, East China. *Science of the Total Environment*, *710*, 136275. https://doi.org/10.1016/j.scitotenv.2019.136275

Hanzer, F., Förster, K., Nemec, J., & Strasser, U. (2018). Projected cryospheric and hydrological impacts of 21st century climate change in the Ötztal Alps (Austria) simulated using a physically based approach. *Hydrology and Earth System Sciences*, *22*(2), 1593–1614. https://doi.org/10.5194/hess-22-1593-2018

Harley, J. P. (2019). Escherichia coli outbreaks. In *AccessScience*. McGraw-Hill Education. https://doi.org/10.1036/1097-8542.241950

Harvey, C. (2019). The World's Winds Are Speeding Up. *Scientific American*. https://www.scientificamerican.com/article/the-worlds-winds-are-speeding-up/%0D

Hayes, A. (2020). *R-Squared Definition*. https://www.investopedia.com/terms/r/r-squared.asp

Hill, A. E., Green, A. L., Wagner, B. A., & Dargatz, D. A. (2009). Relationship between herd size and annual prevalence of and primary antimicrobial treatments for common diseases on dairy operations in the United States. *Preventive Veterinary Medicine*. https://doi.org/10.1016/j.prevetmed.2008.12.001

Hodges, B. R. (2009). Hydrodynamical Modeling. In *Encyclopedia of Inland Waters*. https://doi.org/10.1016/B978-012370626-3.00088-0

Hofstra, N. (2011). Quantifying the impact of climate change on enteric waterborne pathogen concentrations in surface water. In *Current Opinion in Environmental Sustainability*. https://doi.org/10.1016/j.cosust.2011.10.006

Howard, G., Calow, R., Macdonald, A., & Bartram, J. (2016). Climate Change and Water and Sanitation: Likely Impacts and Emerging Trends for Action. *Annual Review of Environment and Resources*. https://doi.org/10.1146/annurev-environ-110615-085856

Huang, J., Mendoza, B., Daniel, J. S., Nielsen, C. J., Rotstayn, L., & Wild, O. (2013). Anthropogenic and natural radiative forcing. *Climate Change 2013 the Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, *9781107057*, 659–740. https://doi.org/10.1017/CBO9781107415324.018

International Institute for Applied Systems Analysis. (2018). *SSP Database*. https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=welcome

IPCC. (2019). Special Report on Climate Change and Land. *Ipcc*.

Iqbal, M. S., Islam, M. M. M., & Hofstra, N. (2019). The impact of socio-economic development and climate change on E. coli loads and concentrations in Kabul River, Pakistan. *Science of the Total Environment*, *650*, 1935–1943. https://doi.org/10.1016/j.scitotenv.2018.09.347

Islam, M. M. M., Iqbal, M. S., Leemans, R., & Hofstra, N. (2018). Modelling the impact of future socio-economic and climate change scenarios on river microbial water quality. *International Journal of Hygiene and Environmental Health*, *221*(2), 283–292. https://doi.org/10.1016/j.ijheh.2017.11.006

Jung, A. V., Cann, P. Le, Roig, B., Thomas, O., Baurès, E., & Thomas, M. F. (2014). Microbial contamination detection in water resources: Interest of current optical methods, trends and needs in the context of climate change. In *International Journal of Environmental Research and Public Health*. https://doi.org/10.3390/ijerph110404292

Khalid, C. (2018). Hydrological modeling of the Mikkés watershed (Morocco) using ARCSWAT model. *Sustainable Water Resources Management*. https://doi.org/10.1007/s40899-017-0145-0

Khalid, K., Ali, M. F., Rahman, N. F. A., Mispan, M. R., Haron, S. H., Othman, Z., & Bachok, M. F. (2016). Sensitivity Analysis in Watershed Model Using SUFI-2 Algorithm. *Procedia Engineering*, *162*, 441–447. https://doi.org/10.1016/j.proeng.2016.11.086

Kingsley, J. (2017). *Difference between hydrology and hydraulics*. https://www.linkedin.com/pulse/difference-between-hydrology-hydraulics-john-kingsley/?fbclid=IwAR2kLP3iC6RI9_t5YxJDKA2UFG9AGE24F7I0kf-0vdsqeEt944WWIDMSZzo

Kress, N. (2019). Desalination Technologies. In *Marine Impacts of Seawater Desalination*. https://doi.org/10.1016/b978-0-12-811953-2.00002-5

Kriegler, E., Bauer, N., Popp, A., Humpenöder, F., Leimbach, M., Strefler, J., Baumstark, L., Bodirsky, B. L., Hilaire, J., Klein, D., Mouratiadou, I., Weindl, I., Bertram, C., Dietrich, J. P., Luderer, G., Pehl, M., Pietzcker, R., Piontek, F., Lotze-Campen, H., … Edenhofer, O. (2017). Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st century. *Global Environmental Change*. https://doi.org/10.1016/j.gloenvcha.2016.05.015

Länsstyrelsen Skåne. (2013). *Skånes dricksvattenförsörjning -Kan riksintresseinstrumentet skydda anläggningar och vatten?* http://www.lansstyrelsen.se/skane/SiteCollectionDocuments/Sv/publikationer/2013/Skanesdricksvattenforsorjning2013.pdf

Lantmäteriet. (2020). *Geodataportal*. https://geodata.chalmers.se/

Larsen, M. C., Hamilton, P. A., & Werkheiser, W. H. (2013). Water Quality Status and Trends in the United States. In *Monitoring Water Quality: Pollution Assessment, Analysis, and Remediation*. https://doi.org/10.1016/B978-0-444-59395-5.00002-9

Larsson, C., Andersson, Y., Allestam, G., Lindqvist, A., Nenonen, N., & Bergstedt, O. (2014). Epidemiology and estimated costs of a large waterborne outbreak of norovirus infection in Sweden. *Epidemiology and Infection*. https://doi.org/10.1017/S0950268813001209

Lewerin, S. S., Sokolova, E., Wahlström, H., Lindström, G., Pers, C., Strömqvist, J., & Sörén, K. (2019). Potential infection of grazing cattle via contaminated water: A theoretical modelling approach. *Animal*, *13*(9), 2052–2059. https://doi.org/10.1017/S1751731118003415

Li, C., Liu, M., Hu, Y., Shi, T., Qu, X., & Walter, M. T. (2018). Effects of urbanization on direct runoff characteristics in urban functional zones. *Science of the Total Environment*. https://doi.org/10.1016/j.scitotenv.2018.06.211

Löwenström, C., & Hussain, S. (2017). *Hydrological and microbial modelling using Soil and Water Assessment Tool - Lake Vomb and uMgeni catchment*. Chalmers University of Technology.

Mancini, J. L. (1978). Numerical estimates of coliform mortality rates under various conditions. *Journal of the Water Pollution Control Federation*.

Mariño, M. A. (2019). Hydrology. In *AccessScience*. McGraw-Hill Education. https://doi.org/10.1036/1097-8542.329800

Medema, G. J., Schets, F. M., Teunis, P. F. M., & Havelaar, A. H. (1998).

Sedimentation of free and attached Cryptosporidium oocysts and Giardia cysts in water. *Applied and Environmental Microbiology*. https://doi.org/10.1128/aem.64.11.4460-4466.1998

Mellor, J. E., Levy, K., Zimmerman, J., Elliott, M., Bartram, J., Carlton, E., Clasen, T., Dillingham, R., Eisenberg, J., Guerrant, R., Lantagne, D., Mihelcic, J., & Nelson, K. (2016). Planning for climate change: The need for mechanistic systems-based approaches to study climate change impacts on diarrheal diseases. In *Science of the Total Environment*. https://doi.org/10.1016/j.scitotenv.2015.12.087

Met Éireann. (2013). Ireland's climate: the road ahead. In *Ireland's climate: the road ahead.*

Mohammed, H., Tveten, A. K., & Seidu, R. (2019). Modelling the impact of climate change on flow and E. coli concentration in the catchment of an ungauged drinking water source in Norway. *Journal of Hydrology*. https://doi.org/10.1016/j.jhydrol.2019.04.021

Molina-Navarro, E., Trolle, D., Martínez-Pérez, S., Sastre-Merlín, A., & Jeppesen, E. (2014). Hydrological and water quality impact assessment of a Mediterranean limno-reservoir under climate change and land use management scenarios. *Journal of Hydrology*. https://doi.org/10.1016/j.jhydrol.2013.11.053

Neitsch, S. ., Arnold, J. ., Kiniry, J. ., & Williams, J. . (2011). Soil & Water Assessment Tool Theoretical Documentation Version 2009. *Texas Water Resources Institute*. https://doi.org/10.1016/j.scitotenv.2015.11.063

Ning, T., Li, Z., & Liu, W. (2016). Separating the impacts of climate change and land surface alteration on runoff reduction in the Jing River catchment of China. *Catena*. https://doi.org/10.1016/j.catena.2016.06.041

Ohlsson, A., Asp, M., Berggreen-Clausen, S., Berglöv, G., Björck, E., Johnell, A., Axén Mårtensson, J., Nylén, L., Persson, H., & Sjökvist, E. (2015). *Framtidsklimat i Skånes län - enligt RCP-scenarier*. https://www.smhi.se/pd/klimat/rcp_scenario/county_analysis/rapporter_kartor/12_Skane/Rapport/Framtidsklimat_i_Skåne_Län_Klimatologi_nr_29.pdf%0D

Oliver, D. M., Porter, K. D. H., Pachepsky, Y. A., Muirhead, R. W., Reaney, S. M., Coffey, R., Kay, D., Milledge, D. G., Hong, E., Anthony, S. G., Page, T., Bloodworth, J. W., Mellander, P. E., Carbonneau, P. E., McGrane, S. J., & Quilliam, R. S. (2016). Predicting microbial water quality with models: Over-arching questions for managing risk in agricultural catchments. In *Science of the Total Environment*. https://doi.org/10.1016/j.scitotenv.2015.11.086

Pozio, E. (2020). How globalization and climate change could affect foodborne parasites. In *Experimental Parasitology*. https://doi.org/10.1016/j.exppara.2019.107807

Region Skåne. (2019). *Skånes befolkningsprognos*.

Rehana, S., & Mujumdar, P. P. (2012). Climate change induced risk in water quality control problems. *Journal of Hydrology*. https://doi.org/10.1016/j.jhydrol.2012.03.042

Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J. C., KC, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., … Tavoni, M. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*. https://doi.org/10.1016/j.gloenvcha.2016.05.009

SCB. (2017). *Vattenanvändningen i Sverige 2015*. https://www.scb.se/contentassets/bcb304eb5e154bdf9aad3fbcd063a0d3/mi0902_2015a01_br_miftbr1701.pdf%0D

SCB. (2020). *Statistikdatabasen*. http://www.statistikdatabasen.scb.se/pxweb/sv/ssd/START__HE__HE0111

Schijven, J., Bouwknegt, M., de Roda Husman, A. M., Rutjes, S., Sudre, B., Suk, J. E., & Semenza, J. C. (2013). A Decision Support Tool to Compare Waterborne and Foodborne Infection and/or Illness Risks Associated with Climate Change. *Risk Analysis*. https://doi.org/10.1111/risa.12077

Sjökvist, E., Mårtensson, J. A., Dahné, J., Köplin, N., Björck, E., Nylén, L., Berglöv, G., Brunell, J. T., Nordborg, D., Hallberg, K., Södling, J., & Clausen, S. B. (2015). Klimatscenarier för Sverige - Bearbetning av RCP-scenarier för meteorologiska och hydrologiska effektstudier. *Klimatologi*, *15*(15). https://www.smhi.se/polopoly_fs/1.95649!/Menu/general/extGroup/attachmentColHold/mainCol1/file/Klimatscenarier_för_Sverige-v1-Klimatologi_15.pdf

SMHI. (n.d.). *Klimatscenarier*. Retrieved April 15, 2020, from https://www.smhi.se/klimat/framtidens-klimat/klimatscenarier/%0D

SMHI. (2013). *Snabbguide till IPCC:s RCP-scenarier*. https://www.smhi.se/polopoly_fs/1.140001!/Snabbguide till IPCCs RCP Scenarier.pdf

SMHI. (2018). *Vad är RCP?* https://www.smhi.se/klimat/framtidens-klimat/vagledning-klimatscenarier/vad-ar-rcp-1.80271

SMHI. (2019). *Luftfuktighet*. https://www.klimatanpassning.se/hur-klimatet-forandras/klimateffekter/luftfuktighet-1.35753

SMHI. (2020a). *Klimatförändringen är tydlig redan idag*. http://www.smhi.se/kunskapsbanken/klimat/klimatet-forandras/klimatforandringarna-marks-redan-idag-1.1510

SMHI. (2020b). *Ladda ner meterologiska observationer*. https://www.smhi.se/data/meteorologi/ladda-ner-meteorologiska-observationer#param=airtemperatureInstant,stations=all

SMHI. (2020c). *Vattenwebb*. https://vattenwebb.smhi.se/station/%0D

Sokolova, E., Lindström, G., Pers, C., Strömqvist, J., Lewerin, S. S., Wahlström, H., & Sörén, K. (2018). Water quality modelling: Microbial risks associated with manure on pasture and arable land. *Journal of Water and Health*. https://doi.org/10.2166/wh.2018.278

Sokolova, E., Pettersson, T. J. R., & Bergstedt, O. (2014). Hydrodynamic modelling and forecasting of microbial water quality in a drinking water source. *Journal of Water Supply: Research and Technology - AQUA*. https://doi.org/10.2166/aqua.2013.216

Sokolova, E., Åström, J., Pettersson, T. J. R., Bergstedt, O., & Hermansson, M. (2012). Estimation of pathogen concentrations in a drinking water source using hydrodynamic modelling and microbial source tracking. *Journal of Water and Health*. https://doi.org/10.2166/wh.2012.183

Soudi, M., Ahmadi, H., Yasi, M., Sibilla, S., Fenocchi, A., & Hamidi, S. A. (2019). Investigation over the capability of MIKE 3 flow model FM to simulate the hydrodynamics and salinity distribution of hypersaline lakes: Lake Urmia (Iran) as case study. *Coastal Engineering Journal*. https://doi.org/10.1080/21664250.2019.1636474

Stensen, K., Tengdelius-brunell, J., Sjökvist, E., Andersson, E., & Eklund, A. (2017). *Vattentemperaturer och is i Mälaren Beräkningar för dagens och framtidens klimatförhållanden*. *46*. http://www.smhi.se/polopoly_fs/1.128133!/Klimatologi_46.pdf

Sturdee, A. P., Bodley-Tickell, A. T., Archer, A., & Chalmers, R. M. (2003). Long-term study of Cryptosporidium prevalence on a lowland farm in the United Kingdom. *Veterinary Parasitology*. https://doi.org/10.1016/S0304-4017(03)00261-9

Svärd, C. (2013). *Kävlingeån 2013*.

Svenskt Vatten. (2008). *Råvattenkontroll -Krav på råvattenkvalitet*. http://www.svensktvatten.se/globalassets/dricksvatten/ravatten/ravattenkontroll---krav-pa-ravattenkvalitet-20081208.pdf

Swedish Board of Agriculture. (2016). *Statistikdatabas*. http://statistik.sjv.se/PXWeb/pxweb/sv/Jordbruksverkets statistikdatabas/Jordbruksverkets statistikdatabas__Lantbrukets djur__Antal lantbruksdjur/JO0103G6.px/?rxid=5adf4929-f548-4f27-9bc9-78e127837625

Sydvatten. (n.d.). *Vombsjön*. Retrieved May 18, 2020, from https://sydvatten.se/vombsjon/

TAMU. (2020a). *SWAT*. https://swat.tamu.edu/software/arcswat/

TAMU. (2020b). *TMAUCC*. https://cbi.tamucc.edu/cbi/Predictions/Hydrodynamic-Modeling/

Tong, S. T. Y., Sun, Y., Ranatunga, T., He, J., & Yang, Y. J. (2012). Predicting plausible impacts of sets of climate and land use change scenarios on water resources. *Applied Geography*. https://doi.org/10.1016/j.apgeog.2011.06.014

Unece. (2019). *Shared Socioeconomic Pathways (SSPs)*. https://www.unece.org/fileadmin/DAM/energy/se/pdfs/CSE/PATHWAYS/2019/ws_Consult_14_15.May.2019/supp_doc/SSP2_Overview.pdf%0D

United Nations. (n.d.-a). *Sustainable Development Goals*. https://sustainabledevelopment.un.org/?menu=1300

United Nations. (n.d.-b). *The Paris Agreement*. Retrieved March 10, 2020, from https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

United States Environmental Protection Agency. (n.d.). *How We Use Water*. Retrieved May 5, 2020, from https://www.epa.gov/watersense/how-we-use-water

United States Environmental Protection Agency. (2012). *Fecal Bacteria*. https://archive.epa.gov/water/archive/web/html/vms511.html

van Vuuren, D. P., Stehfest, E., den Elzen, M. G. J., Kram, T., van Vliet, J., Deetman, S., Isaac, M., Goldewijk, K. K., Hof, A., Beltran, A. M., Oostenrijk, R., & van Ruijven, B. (2011). RCP2.6: Exploring the possibility to keep global mean temperature increase below 2°C. *Climatic Change*. https://doi.org/10.1007/s10584-011-0152-3

Vermeulen, L. C., & Hofstra, N. (2014). Influence of climate variables on the concentration of Escherichia coli in the Rhine, Meuse, and Drentse Aa during 1985-2010. *Regional Environmental Change*. https://doi.org/10.1007/s10113-013-0492-9

VISS. (n.d.). *Vombsjön*. Retrieved January 20, 2020, from https://viss.lansstyrelsen.se/Waters.aspx?waterMSCD=WA93795099

Walker, F. R., & Stedinger, J. R. (1999). Fate and transport model of Cryptosporidium. *Journal of Environmental Engineering*. https://doi.org/10.1061/(ASCE)0733-9372(1999)125:4(325)

Wang, R., Kalin, L., Kuang, W., & Tian, H. (2014). Individual and combined effects of land use/cover and climate change on Wolf Bay watershed streamflow in southern Alabama. *Hydrological Processes*. https://doi.org/10.1002/hyp.10057

Widerström, M., Schönning, C., Lilja, M., Lebbad, M., Ljung, T., Allestam, G., Ferm, M., Björkholm, B., Hansen, A., Hiltula, J., Långmark, J., Löfdahl, M., Omberg, M., Reuterwall, C., Samuelsson, E., Widgren, K., Wallensten, A., & Lindh, J. (2014). Large outbreak of Cryptosporidium hominis infection transmitted through the public water supply, Sweden. *Emerging Infectious Diseases*. https://doi.org/10.3201/eid2004.121415

Zhang, Y., Xia, J., Yu, J., Randall, M., Zhang, Y., Zhao, T., Pan, X., Zhai, X., & Shao, Q. (2018). Simulation and assessment of urbanization impacts on runoff metrics: insights from landuse changes. *Journal of Hydrology*. https://doi.org/10.1016/j.jhydrol.2018.03.031

Appendix I

Table I.1 Microbial concentration in livestock feaces: SSP1 2040-2050 & 2090-2100, SSP5 2090-2100.

Livestock	***E. coli*** **(cfu g^{-1})**	***Cryptosporidium*** **(oocysts g^{-1})**	***Cryptosporidium*** **(mean prevalence[a])**	**Conc. total livestock**
Cattle	2.00E+05[b]	3830	0.464	1775
Calve	4.20E+05[b]	38100	0.255	9710
Pigs	1.20E+07[a]	24.1	0.199	5.00
Sheep	5.90E+06[a]	780	0.311	240
Lamb	6.90E+06[a]	9140	0.472	4310
Horses	5.80E+03[a]	1030	0.090	93.0

Table I.2 Microbial concentration in livestock faeces: SSP5 2040-2050.

Livestock	***E. coli*** **(cfu g^{-1})**	***Cryptosporidium*** **(oocysts g^{-1})**	***Cryptosporidium*** **(mean prevalence[a])**	**Conc. total livestock**
Cattle	2.00E+05[b]	3830	0.618	2367
Calve	4.20E+05[b]	38100	0.340	12950
Pigs	1.20E+07[a]	24.1	0.265	6.00
Sheep	5.90E+06[a]	780	0.415	320
Lamb	6.90E+06[a]	9140	0.629	5744
Horses	5.80E+03[a]	1030	0.120	120

Table I.3 Manure application: SSP1 2040-2050.

Livestock	**Number of livestock**	**Manure production [kg*animal^{-1} day^{-1}][b]**	**Number of housed days**	**Collected manure [kg]**	**Applied manure per application [kg*Ha^{-1}]**
Cattle (milk)	5015	25.30	245	3.10×10^7	593
Cattle (beef)	7045	14.40	245	2.48×10^7	474
Calve	6619	1.65	245	2.68×10^6	51
Pigs	25703	2.70	365	2.53×10^7	483
Sheep	2783	0.70	245	4.77×10^5	9
Lamb	2870	0.70	245	4.92×10^5	9
Horses	1504	18.50	183	5.09×10^6	97

Table I.4 Manure application: SSP1 2090-2100.

Livestock	**Number of livestock**	**Manure production [kg*animal^{-1} day^{-1}][b]**	**Number of housed days**	**Collected manure [kg]**	**Applied manure per application [kg*Ha^{-1}]**
Cattle (milk)	4355	25.30	245	2.70×10^7	515
Cattle (beef)	6118	14.40	245	2.16×10^7	412
Calve	5748	1.65	245	2.32×10^6	44
Pigs	22321	2.70	365	2.20×10^7	420
Sheep	2416	0.70	245	4.14×10^5	8
Lamb	2492	0.70	245	4.27×10^5	8
Horses	1306	18.50	183	4.42×10^6	84

Table I.5 Manure application: SSP5 2040–2050.

Livestock	Number of livestock	Manure production [kg*animal^{-1} day^{-1}]^{b}	Number of housed days	Collected manure [kg]	Applied manure per application [kg*Ha^{-1}]
Cattle (milk)	5728	25.30	245	3.55×10^{7}	677
Cattle (beef)	8046	14.40	245	2.84×10^{7}	542
Calve	7559	1.65	245	3.06×10^{6}	58
Pigs	29356	2.70	365	2.89×10^{7}	552
Sheep	3178	0.70	245	5.45×10^{5}	10
Lamb	3278	0.70	245	5.62×10^{5}	11
Horses	1718	18.50	183	5.81×10^{6}	111

Table I.6 Manure application: SSP5 2090–2100.

Livestock	Number of livestock	Manure production [kg*animal^{-1} day^{-1}]^{b}	Number of housed days	Collected manure [kg]	Applied manure per application [kg*Ha^{-1}]
Cattle (milk)	4804	25.30	245	2.98×10^{7}	568
Cattle (beef)	6749	14.40	245	2.38×10^{7}	454
Calve	6340	1.65	245	2.56×10^{6}	49
Pigs	24621	2.70	365	2.43×10^{7}	463
Sheep	2665	0.70	245	4.57×10^{5}	9
Lamb	2749	0.70	245	4.71×10^{5}	9
Horses	1441	18.50	183	4.87×10^{6}	93

Table I.7 Faecal production: SSP1 2040–2050

Livestock	Number of livestock	Livestock density	Grazing days	Faecal production [kg/ha*d]
Cattle (milk)	5015	1.26	120	31.90
Cattle (beef)	7045	1.77	120	25.51
Calve	6619	1.66	120	2.75
Sheep	2783	0.70	120	0.49
Lamb	2870	0.72	120	0.51
Horses	1504	0.38	183	7.00

Table I.8 Faecal production: SSP1 2090–2100.

Livestock	Number of livestock	Livestock density	Grazing days	Faecal production [kg/ha*d]
Cattle (milk)	4355	1.10	120	27.71
Cattle (beef)	6118	1.54	120	22.15
Calve	5748	1.45	120	2.38
Sheep	2416	0.61	120	0.43
Lamb	2492	0.63	120	0.44
Horses	1306	0.33	183	6.08

Table I.9 Faecal production: SSP5 2040–2050.

Livestock	Number of livestock	Livestock density	Grazing days	Faecal production [kg/ha*d]
Cattle (milk)	5728	1.44	120	36.44
Cattle (beef)	8046	2.02	120	29.13
Calve	7559	1.90	120	3.14
Sheep	3178	0.80	120	0.56
Lamb	3278	0.82	120	0.58
Horses	1718	0.43	183	7.99

Table I.10 Fecal production: SSP5 2090-2100.

Livestock	Number of livestock	Livestock density	Grazing days	Faecal production [kg/ha*d]
Cattle (milk)	4804	1.21	120	30.56
Cattle (beef)	6749	1.70	120	24.44
Calve	6340	1.59	120	2.63
Sheep	2665	0.67	120	0.47
Lamb	2749	0.69	120	0.48
Horses	1441	0.36	183	6.70

Appendix II

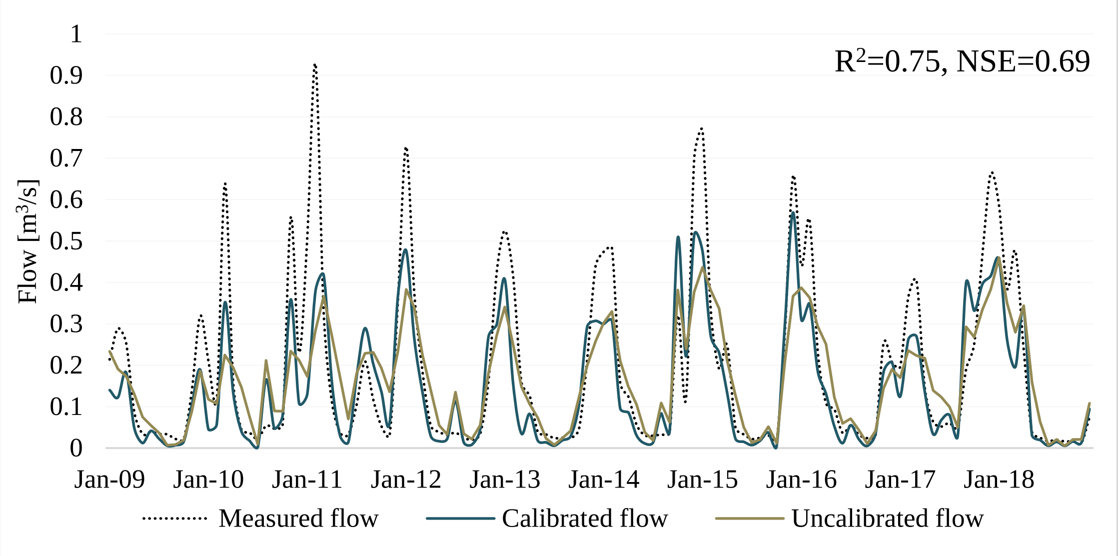

Figure II.1 Calibrated and uncalibrated flow for Borstbäcken.

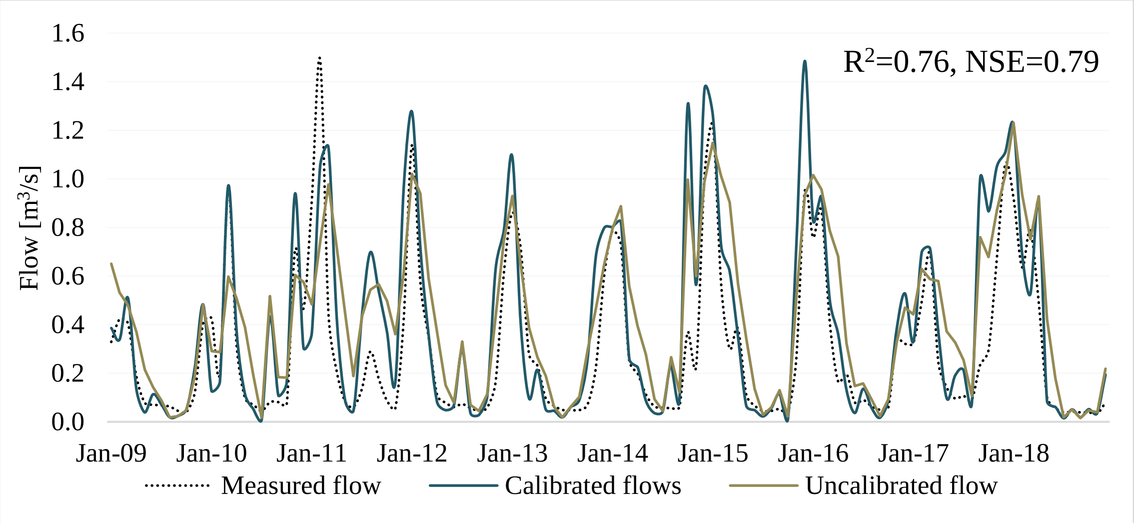

Figure II.2 Calibrated and uncalibrated flow for Torpsbäcken.

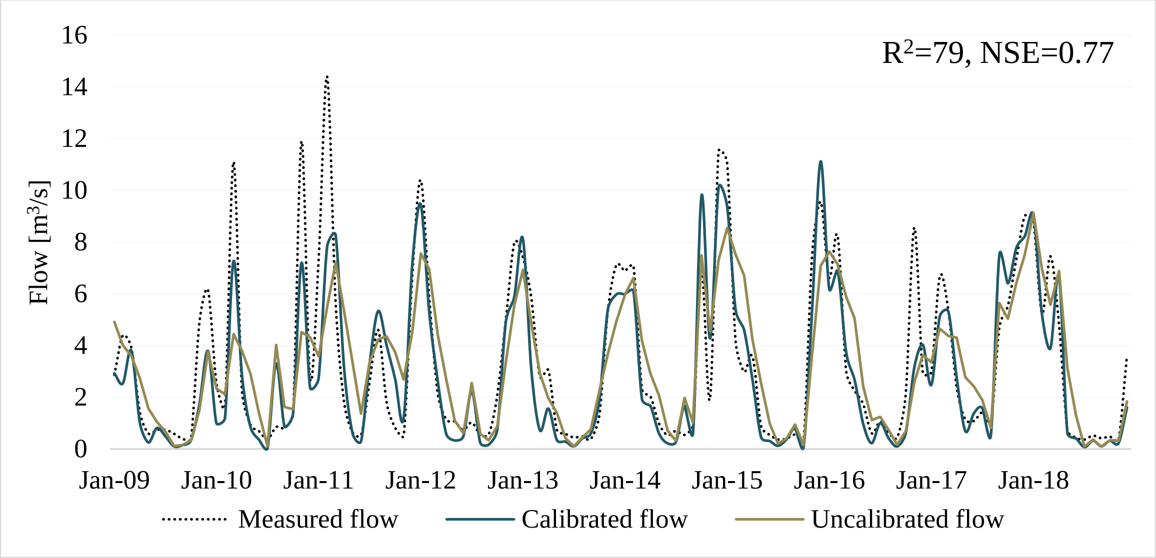

Figure II.3 Calibrated and uncalibrated flows for Björkaån.

Appendix III

Table III.1 Period of ice cover for all scenarios simulated in MIKE and the years 2018, 2050 and 2100 with start and end date.

Simulated scenario	**Start date of ice coverage**	**End date of ice coverage**
Baseline 2018	January 31st	February 15th
RCP4.5 2050	February 3rd	February 13th
RCP4.5 2100	February 3rd	February 13th
RCP8.5 2050	February 3rd	February 11th
RCP8.5 2100	February 6th	February 9th

Appendix IV

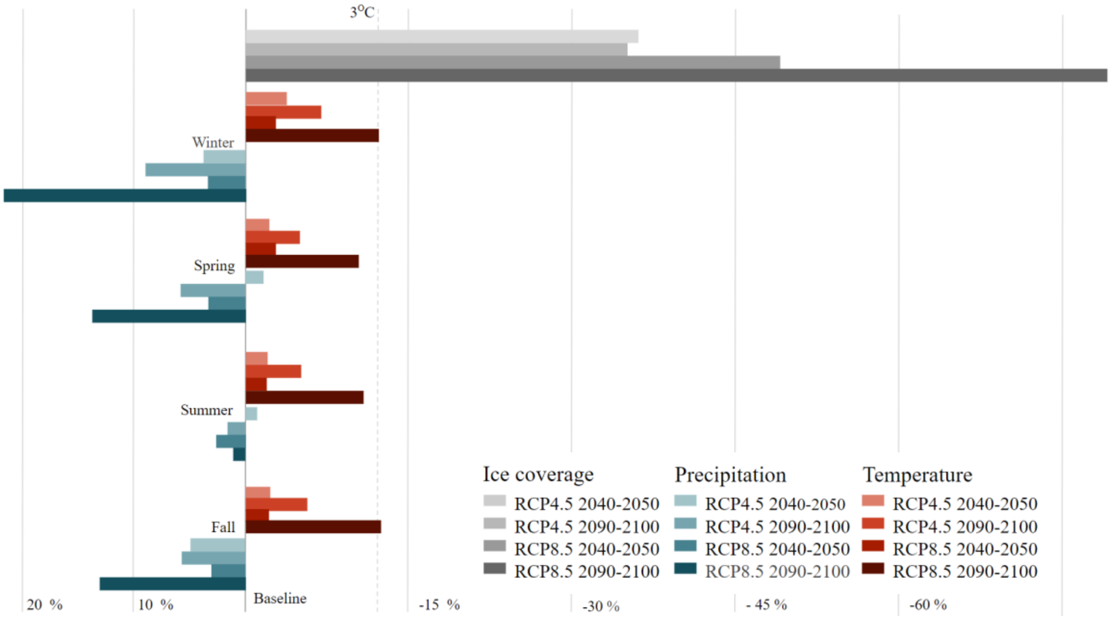

Figure IV.1 Precipitation, temperature and ice coverage projections for all RCP scenarios and all seasons relative to baseline scenario for lake Vomb catchment. Ice coverage and precipitation presented as percentual change while temperature is presented as change in degrees Celsius.

Appendix V

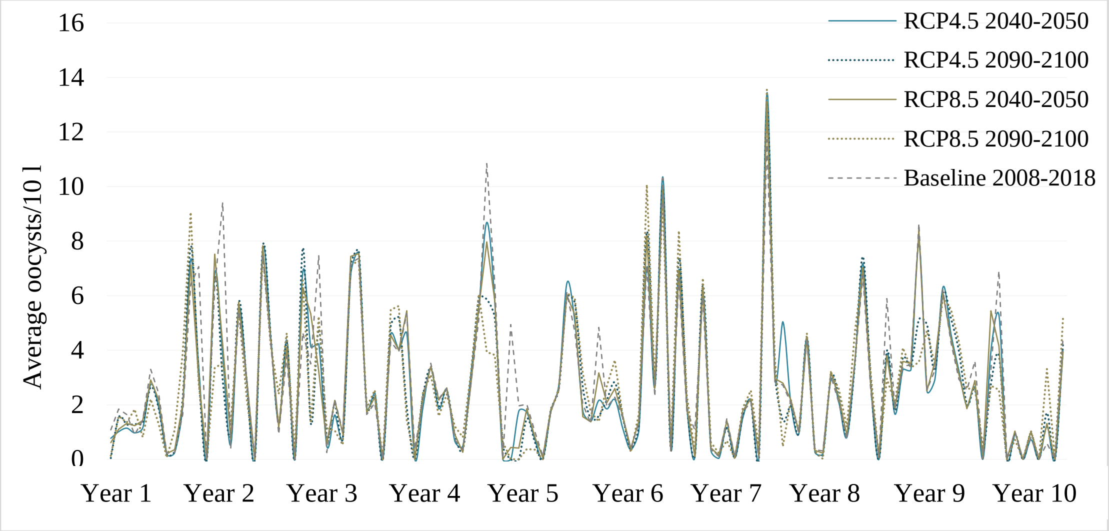

Figure V.1 Simulated concentrations for Cryptosporidium under future climate scenarios in Borstbäcken.

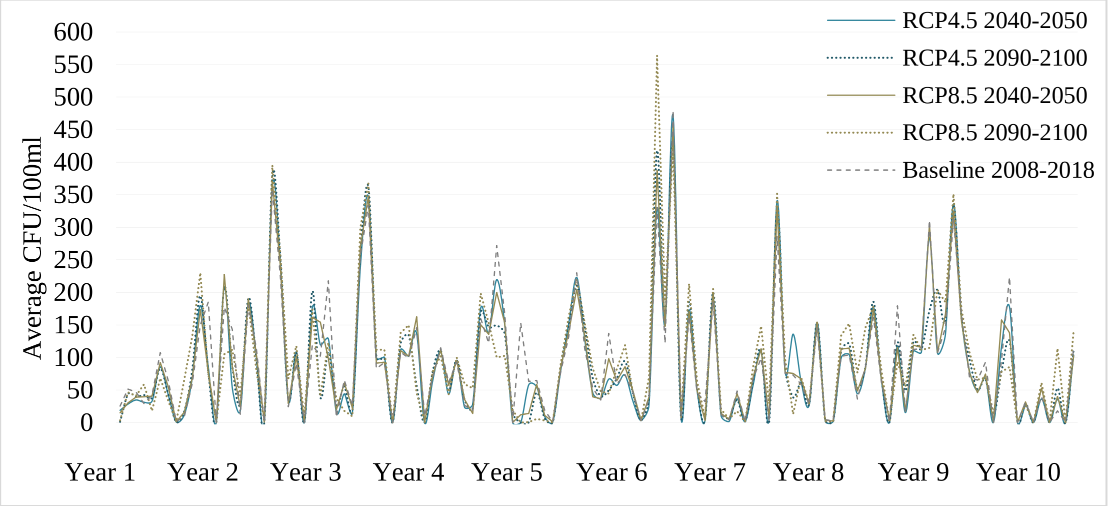

Figure V.2 Simulated concentrations for E. coli under future climate scenarios in Borstbäcken.

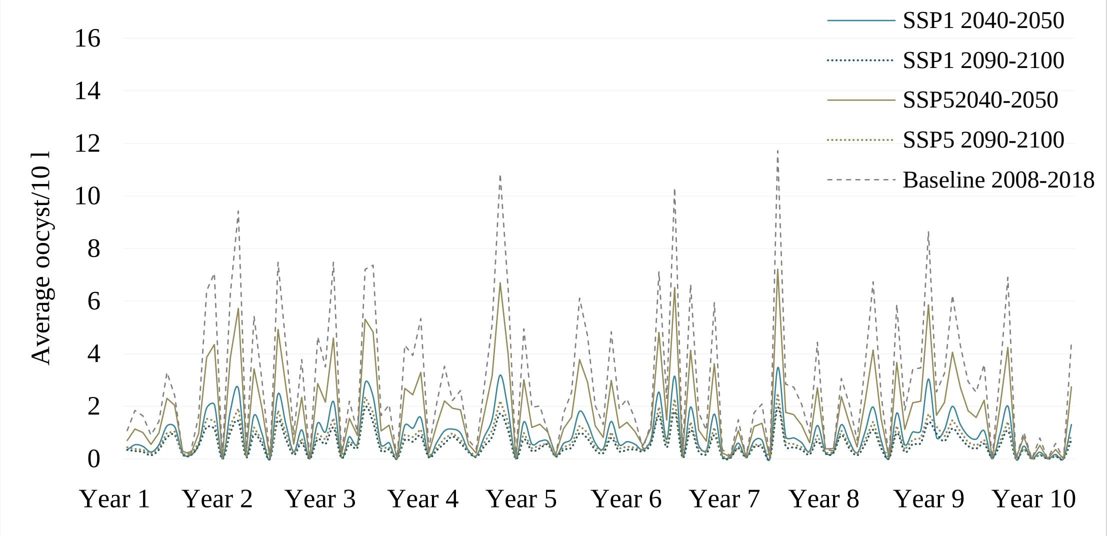

Figure V.3 Simulated concentrations for Cryptosporidium under socioeconomic development scenarios in Borstbäcken.

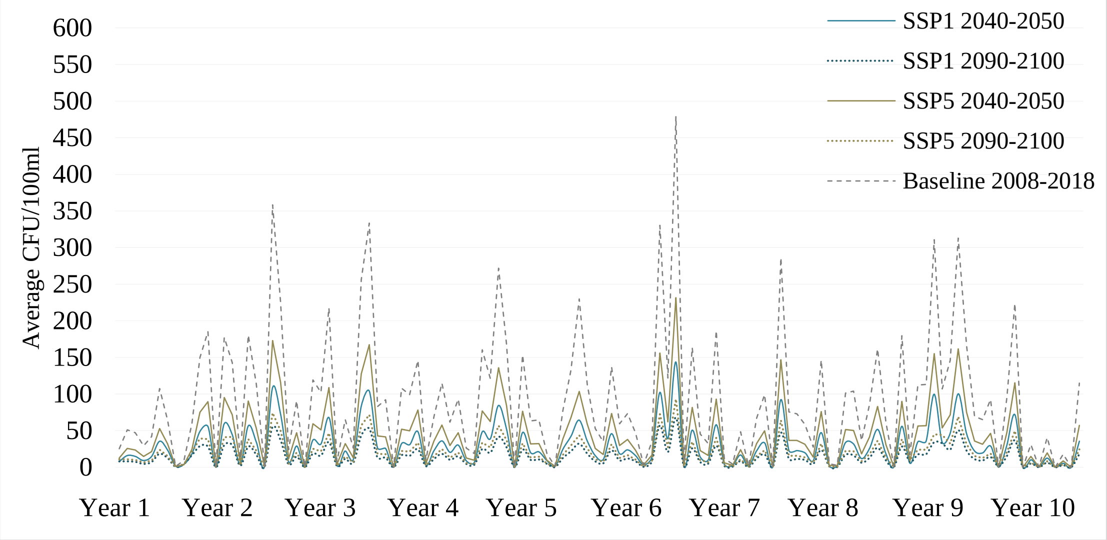

Figure V.4 Simulated concentrations for E. coli under socioeconomic development scenarios in Borstbäcken.

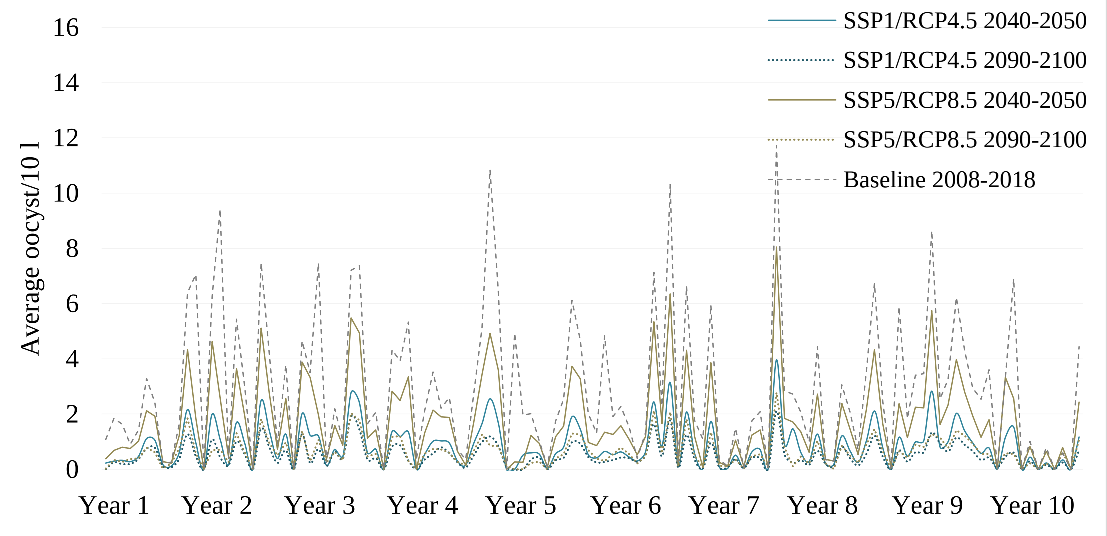

Figure V.5 Simulated concentrations for Cryptosporidium under both climate change and socioeconomic development in Borstbäcken.

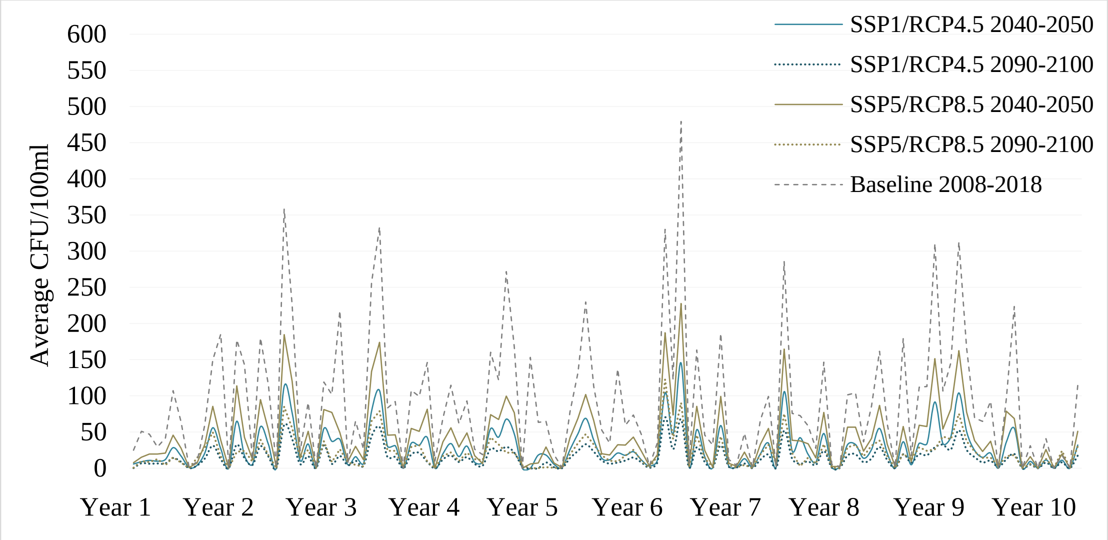

Figure V.6 Simulated concentrations for E. coli under both climate change and socioeconomic development in Borstbäcken.

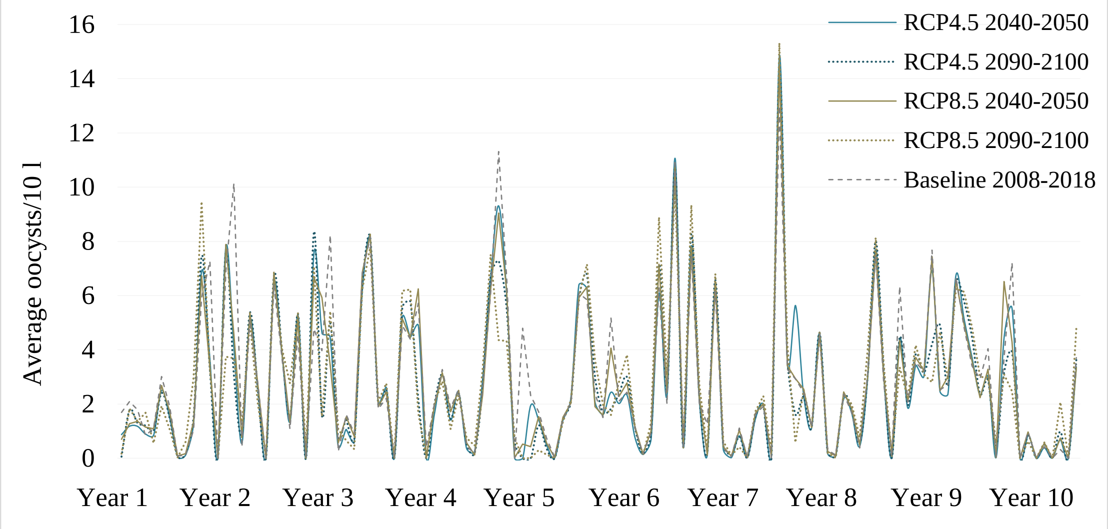

Figure V.7 Simulated concentrations for Cryptosporidium under future climate scenarios in Torpsbäcken.

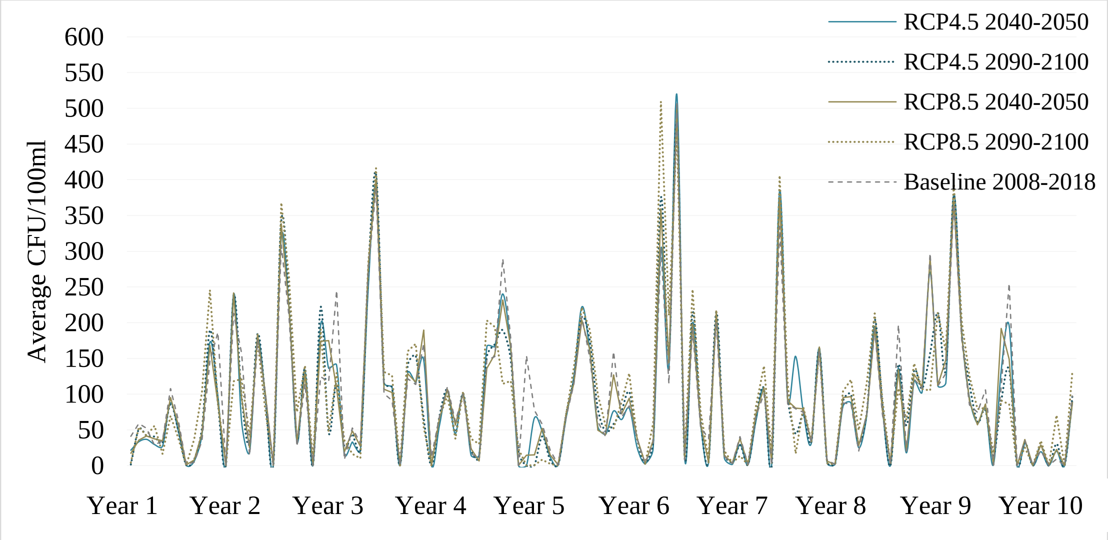

Figure V.8 Simulated concentrations for E. coli under future climate scenarios in Torpsbäcken.

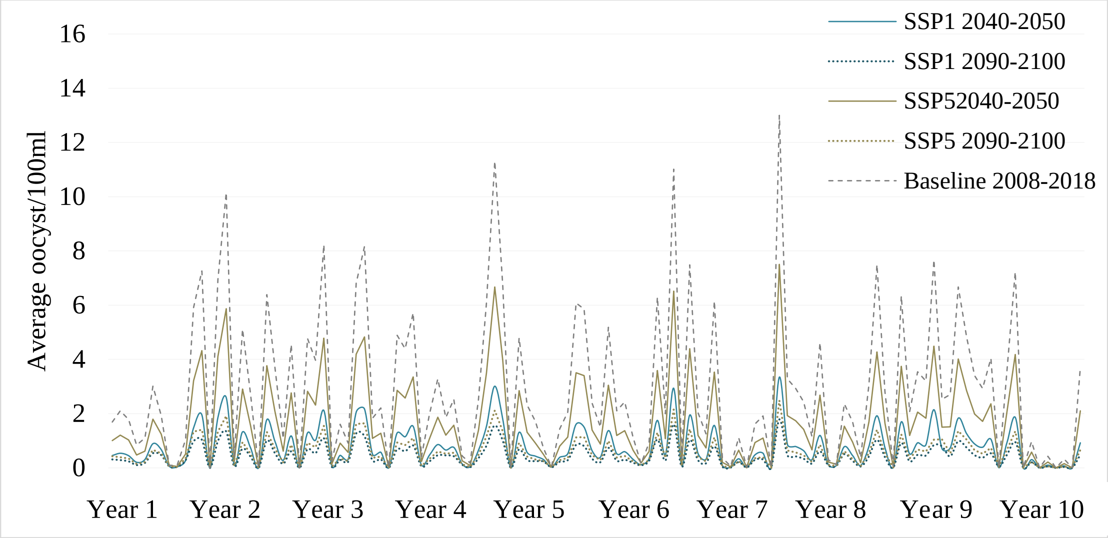

Figure V.9 Simulated concentrations for Cryptosporidium under socioeconomic development scenarios in Torpsbäcken.

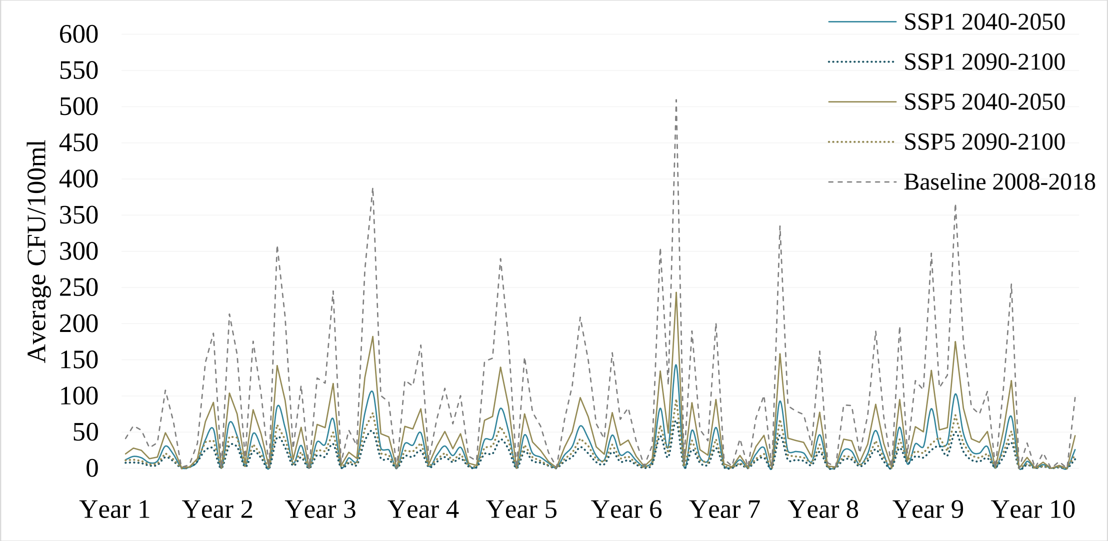

Figure V.10 Simulated concentrations for E. coli under socioeconomic development scenarios in Torpsbäcken.

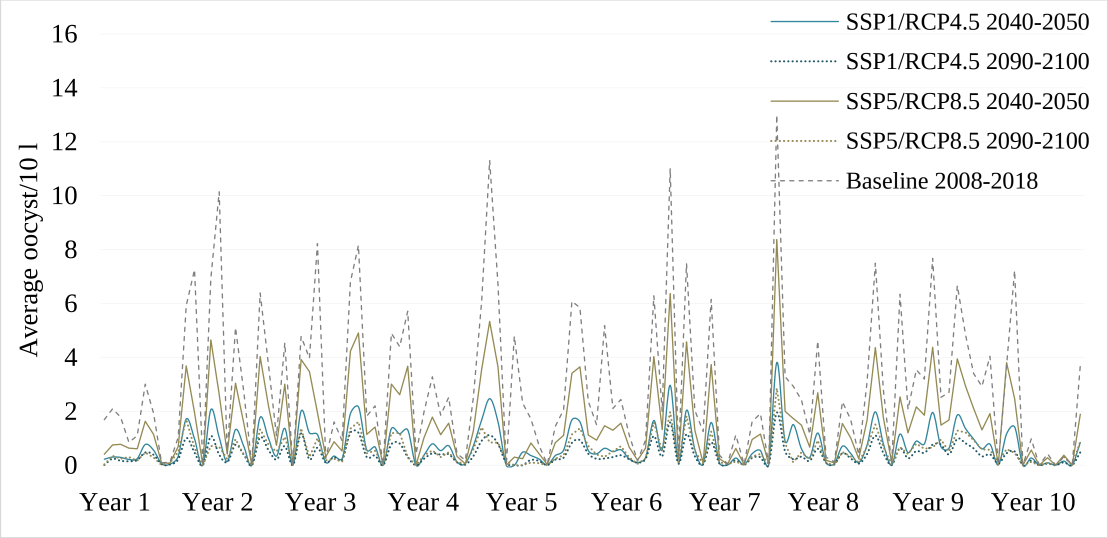

Figure V.11 Simulated concentrations for Cryptosporidium under both climate change and socioeconomic development in Torpsbäcken.

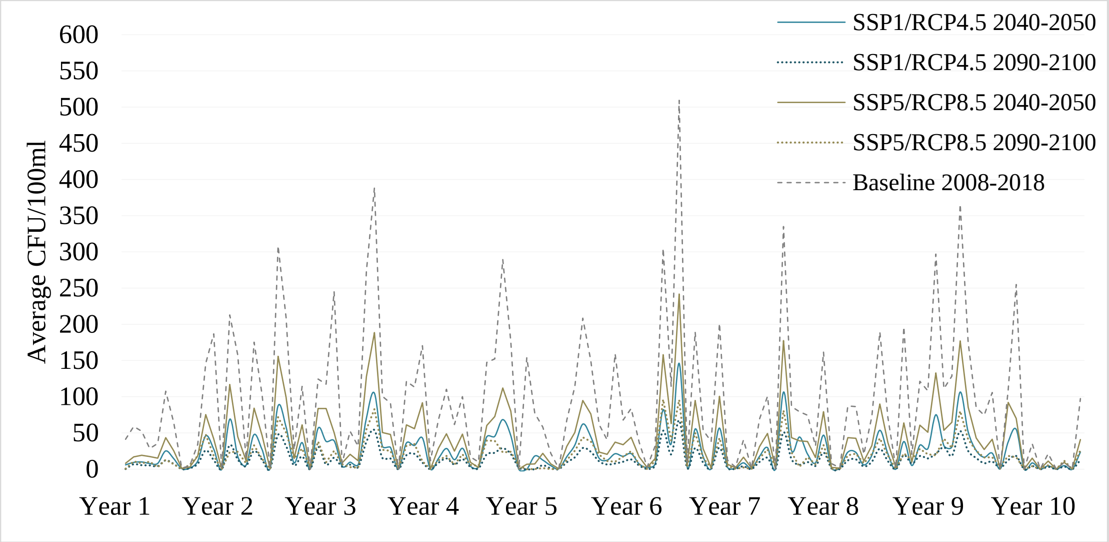

Figure V.12 Simulated concentrations for E. coli under both climate change and socioeconomic development in Torpsbäcken.

Appendix VI

Table VI.1 Maximum concentration of Cryptosporidium and E. coli in Björkaån, Borstbäcken and Torpsbäcken for all scenarios.

Max concentration	**Baseline 2008-2018**	**SSP1/RCP4.5 2040-2050**	**SSP1/RCP4.5 2090-2100**	**SSP5/RCP8.5 2040-2050**	**SSP5/RCP8.5 2090-2100**
			Björkaån		
Oocysts/100ml	1.396	0.345	0.1869	0.7158	0.2471
E. coli/100ml	4510	1354	595.7	2145	814.9
			Borstbäcken		
Oocysts/100ml	1.532	0.3546	0.1925	0.7626	0.2542
E. coli/100ml	4749	1362	606.7	2102	825.5
			Torpsbäcken		
Oocysts/100ml	1.486	0.3397	0.1708	0.7353	0.2356
E. coli/100ml	4772	1334	595.6	2234	837.7

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