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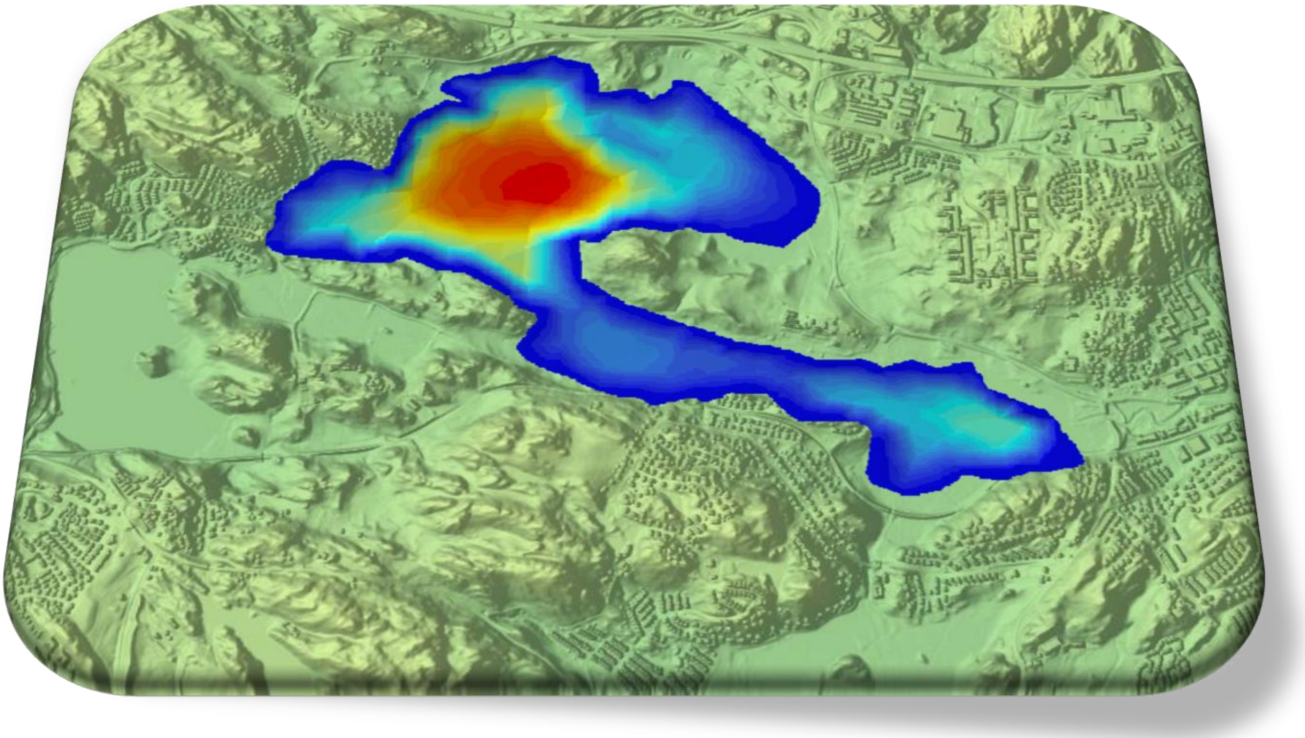

Modelling the circulation and spread of pollution in Lake Rådasjön under conditions of climate change

Master's thesis in Infrastructure and Environmental Engineering

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Cover:

Digital elevation model of Lake Rådasjön used to model the hydrodynamics of the lake with the software MIKE 3 FM.

Göteborg, Sweden 2019

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ABSTRACT

Climate change could degrade water quality with changes in precipitation patterns and in combination with urbanisation and further land uses, such as agriculture production. These changes could accelerate the transport of pathogens into water bodies.

The aim of this study is to model the circulation and spread of pollution in Lake Rådasjön due to climate changes. Lake Rådasjön is the selected study area since it is the source of raw water for the cities of Gothenburg and Mölndal. A hydrodynamic model was set up, and impacts on circulation and spread of *E. coli* under climate change were evaluated to identify increased risk for the water intake. Air temperature was the most significant variable for the study. The scenarios for climate change were based on two Representative Concentration Pathways (RCP), the RCP 4.5 and RCP 8.5.

The results showed that the water temperature in the lake would warm-up for the years 2040 and 2100 on average 1.5°C and 3.5°C, respectively. The major impact from climate change was observed to be the reduction of ice coverage on the lake, and based on the modelling results for water temperature, there would be a prolongation of the summer regime and shortening of the winter regime for the lake. Thus, inversion of the lake in spring would occur earlier, and inversion after summer would occur later. The results showed that during spring the pollutant *E. coli* could reach deeper into the lake and for a longer period due to the shorter period of ice coverage on the lake since the winter season would be warmer, increasing the risk at the water intake at that time. Whereas for the rest of the year it would be seen a longer summer, thus decreasing the risk for a much longer period and leading to an even later autumn inversion.

Keywords: Climate change, *E. coli*, hydrodynamic model, lake inversion, safe drinking water.

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Gothenburg, June 2019

Erwin Diener

ABBREVIATIONS

DBS – Distribution Based Scaling

DWTP – Drinking Water Treatment Plant

E. coli – *Escherichia coli*

GHG – Greenhouse Gas

IPCC – Intergovernmental Panel on Climate Change

RCP – Representative Concentration Pathway

SMHI – Swedish Meteorological and Hydrological Institute

WHO – World Health Organization

WWTP – Wastewater Treatment Plant

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1 Introduction

Climate change is currently a great concern for the world. The United Nations Intergovernmental Panel on Climate Change (IPCC) has communicated that global warming would likely reach 1.5 ºC above pre-industrial levels between 2030 and 2052 (IPCC, 2018) if no further actions are taken. Therefore, in recent years, research has focused on the possible impacts of climate change that could shape the future of human activities in order to be better prepared for them, and what could be done from now on in order to limit the consequences and/or even reverse some effects.

With a rapid urbanisation, cities would seem to be better prepared when it comes to water management, separating and securing new sewer systems. But at the same time, they could be facing higher vulnerabilities with extreme precipitation events if these are not taken into account (Delpla et al., 2009; Willems et al., 2011). Different studies (Willems et al., 2011; Hofstra et al., 2016; Alamandari et al., 2017; Mohammed et al., 2019a) have shown the probable impacts of climate change, where increase of precipitation in combination with urbanisation and further land uses, such as agriculture production, could accelerate the transport of pathogens into water bodies (Hofstra et al., 2016) and consequently increase the risk for waterborne diseases. Then, understanding our environment is the key to be prepared and account for such difficult uncertainties when it comes to climate change, e.g. higher frequency of rainfalls, drastic temperature changes and increase of solar radiation (IPCC, 2018).

The Swedish Meteorological and Hydrological Institute (SMHI) studied and modelled the impacts of climate change for Sweden and Europe, and showed an increase in run-off in the north of Europe due to an increase in rainfall, and a decrease in run-off and rainfalls in the south (Koutroulis et al., 2018).

Lake Rådasjön with its catchment was selected as the study area. Located in the county of Västra Götaland of Sweden, the lake is a drinking water source for Mölndal and a reserve water source for Gothenburg. Drinking water treatment plants (DWTP) may face difficult times in the future, since they must be able to supply safe drinking water to consumers despite the potentially increased load of microbial pollutants in their raw water sources.

Modelling is one method to assess changes in the environment, such as climate change, and evaluate the risks from faecal pollution. This has been done for different cases (Sokolova et al., 2013; Alamandari et al., 2017; Mohammed et al., 2019b). For the selected area of study, Lake Rådasjön, a hydrodynamic model was set-up in an earlier study (Sokolova et al., 2013). In the current study, this hydrodynamic model was used to assess circulation and spread of pollution under climate change conditions described for the study area by Berglöv et al. (2015).

1.1 Aim

The aim of this project was to model the circulation and spread of *E. coli* in Lake Rådasjön under conditions of climate change.

1.2 Objectives

i. Describe the effects of climate change on the lake;
ii. Evaluate the circulation and temperature effects due to climate change;
iii. Simulate the spread of *E. coli* in the lake from a wastewater source;
iv. Evaluate the risk of *E. coli* reaching the water intake of a drinking water treatment plant.

1.3 Limitations

This research focused on the microbial load discharged into and spread in Lake Rådasjön from sewer discharges as a source of pollution and risk for the drinking water source. Thus, only the discharges from the urban source were modelled and consequently, no hydrological processes or influences of rural/agricultural catchments were considered.

The data to be used for the hydrodynamic models included bathymetry, meteorological data, water flow and microbial parameters for *E. coli*. The data were obtained from the authorities (e.g. Geological Survey of Sweden and Swedish Meteorological and Hydrological Institute), water producers and previous studies (Sokolova et al., 2013). No measurements nor field studies were performed.

2 Background

2.1 Climate change

The climate is evidently changing (IPCC, 2014), unprecedented changes have been observed during the last century, the atmosphere and ocean are warmer, snow and ice diminished, and the sea level has risen. The last three decades have been warmer than any previous decade since 1850. The Northern Hemisphere, from 1983 to 2012, most likely experienced the warmest 30-year period of the last 800 years. The concentrations of greenhouse gas (GHG) in the atmosphere have been found to be the highest in history, therefore continued emissions will cause further warming and long-lasting changes on the climate system (IPCC, 2014).

Four Representative Concentration Pathways (RCPs) have been developed by The United Nations Intergovernmental Panel on Climate Change (IPCC) to represent GHG emissions and atmospheric concentrations, air pollutant emissions and land use: a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0), and one scenario with very high GHG emissions (RCP8.5). For all four scenarios the surface temperature is expected to rise, and it is very likely that heat waves and extreme precipitation events will occur more often and with higher intensity. The ocean will warm up and acidify, and global sea level will rise (IPCC, 2014).

SMHI studied the future climate in the county of Västra Götaland in Sweden using observations and calculations based on the two cases, RCP4.5 and RCP8.5 (Table 1). SMHI chose to use these cases since they cover a wide range of variations in terms of future concentrations of GHG in the atmosphere and are the most used in research. Consequently, they represent the most complete basis for regional climate calculations (Berglöv et al., 2015). For the middle of the century, both RCPs show a warming of approximately 2°C compared to the period 1961-1990. At the end of the century, RCP4.5 shows a warming of about 3°C, while RCP8.5 shows a warming of up to around 5°C.

Table 1 Assumptions of RCP 4.5 and 8.5 (Berglöv et al., 2015)

RCP 4.5	**RCP 8.5**
- Emissions of carbon dioxide increase slightly and culminate around 2040. - Earth’s population slightly below 9 billion at the end of the century. - Low area requirement for agricultural production, partly as a result of larger harvests and changed consumption patterns. - Extensive forest planting program. - Low energy intensity. - Powerful climate policy.	- Carbon dioxide emissions are three times higher than currently estimated at 2100 and methane emissions are increasing abruptly. - Earth's population increases to 12 billion, increasing the need of land for pasture and agricultural production. - Technology development driven to increase energy efficiency continues, but slowly. - Great dependence on fossil fuels. - High energy intensity. - No additional climate policy.

With a warmer atmosphere there will be higher evaporation and faster circulation, resulting in more precipitation (Berglöv et al., 2015). The annual average precipitation is expected to increase by 12% for RCP4.5 and 25% for RCP8.5. Rainfall increases most in winter, and at the end of the century RCP8.5 shows an increase of 40%. The heavy rainfall also increases, and maximum daily rainfall can increase by 10-20% depending on the RCP.

2.2 Risks and management of drinking water – climate change

Diseases caused by pathogenic bacteria, viruses and parasites (e.g. protozoa and helminths) are the most common health risk associated with drinking water, although other sources of exposure may also be of importance such as person-to-person contact and food (WHO, 2017). The effects in human health can go from mild gastroenteritis to severe and even fatal diarrhoea, dysentery, hepatitis and typhoid fever.

E. coli is a thermotolerant coliform and considered to be the most suitable indicator of faecal contamination, since it can be found in the normal intestinal flora of animals and humans, where normally it would not cause harm, but in other parts of the body can cause diseases such as meningitis, urinary tract infections and bacteraemia (WHO, 2017). *E. coli* is the first organism of choice for monitoring drinking water quality, since indication of presence could mean faecal contamination, thus further actions are recommended, such as investigating potential sources and enhance sampling (WHO, 2017).

Human activities of urban, industrial and/or agricultural origin are related to water pollution, and climate change could degrade water quality as an indirect consequence of these activities. Climate change impacts (i.e. changes in the precipitation patterns) could increase the diffuse pollution with urban or agricultural runoff (Delpla et al., 2009). Also, heavy rainfalls could overflow the sewer system leading to emergency discharges into water bodies (Delpla et al., 2009; Willems et al., 2011).

2.3 Modelling water sources and climate change

Modelling can be broadly categorised as empirical or mechanistic. An empirical model focuses on describing the data with few assumptions, while the mechanistic does not only rely on known records but instead works with the mechanisms surrounding the data (Case et al., 2017), making it more adaptable but also more data demanding.

The hydrodynamics and microbial dynamics can be linked in a mechanistic model and have been used to simulate the fate and transport of faecal indicators before (Sokolova et al., 2013; Alamdari et al., 2017; Mohammed et al., 2019a).

It is suggested that water quality could be degraded due to climate change (Tung et al., 2012) and has been modelled finding it to be the case (Liu et al., 2016), where dissolved oxygen concentrations would go down and concentrations of carbonaceous biochemical oxygen demand, ammonium nitrogen and total phosphorus would increase.

In hydrodynamic modelling the findings also suggest changes due to climate change (Alamdari et al., 2017; Mohammed et al., 2019a; Weinberger et al., 2012). The main parameters used in hydrodynamic models are inflows (precipitation and runoff) and outflows, salinity values and daily mean water temperature, light extinction coefficient, wind and albedo. Then when it comes to including climate change into the models, they have taken into account short and long wave radiation, air temperature, precipitation, wind speed, vapour pressure, total cloud cover and relative humidity, which are all values with a strong influence in a lake. Weinberger et al. (2012) showed that, in comparison with observed stratifications in the past (period of 1985-2011), the simulated stratification for the period 2041-2050 occurred earlier in the year, due to a shorter winter season, and lasted longer, due to the warmer climate.

Mohammed et al. (2019a) and Weinberger et al. (2012) recommended the use of regional climate models with bias-correction and concluded that the models are suitable to estimate impacts of climate warming on lake ecosystems. In Sweden, the Rossby Centre at SMHI carried out a regional modelling with the regional climate model RCA4 with a resolution of 50×50 km^2, then using the method DBS (Distribution Based Scaling) increased the resolution to 4×4 km^2 and presented air temperature and precipitation results with a higher resolution for scenarios RCP 4.5 and RCP 8.5, making the data suitable for modelling at a local level.

3 Methodology

3.1 Study Area – Lake Rådasjön

Lake Rådasjön (Figure 1) and its catchment constituted the selected study area. Located in the county of Västra Götaland of Sweden, the lake is a drinking water source for Mölndal and a reserve water source for Gothenburg. The surface area of the lake is around 2 km^2 and its catchment area is approximately 15 km^2. Its main inflow is from the river Mölndalsån in the east side and its outflow to Lake Stensjön is located at the west. River Mölndalsån varies its flow during a year from 1 to 20 m^3/s and the average is approximately 4 m^3/s. Currently the water level of Mölndalsån is regulated due to floods that occurred in 2006 and 2007.

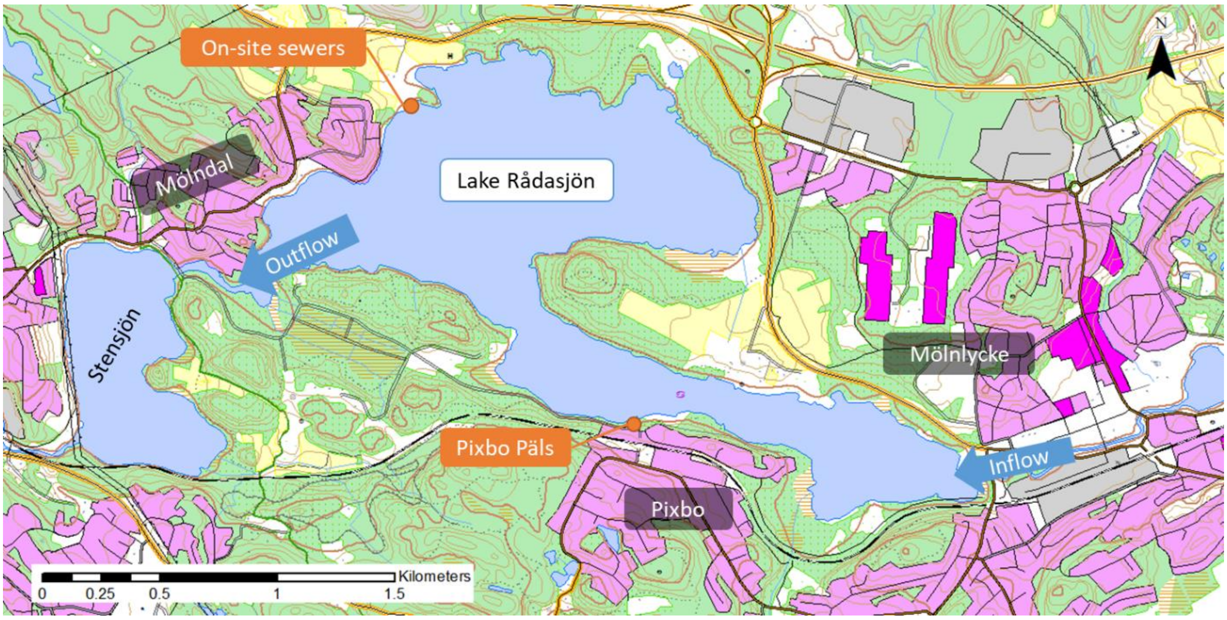

Figure 1 Lake Rådasjön

The lake is exposed to different sources of contamination, mainly from wastewater, bathing, agricultural and farming activities in its catchment area, thus, *E. coli* at the raw water intake is regularly monitored as a main indicator. One of the identified main sources of pollution is the emergency discharges at Pixbo Päls due to hydraulic overloads (Figure 1 and Figure 2). On-site sewer discharges (Figure 1) are also another source of concern due to the closeness to the water intake. There are also records of other sorts of accidents (e.g. construction sites, pipe maintenance, etc) that have led to polluting the lake and hence the importance of monitoring the levels of *E. coli* in the lake.

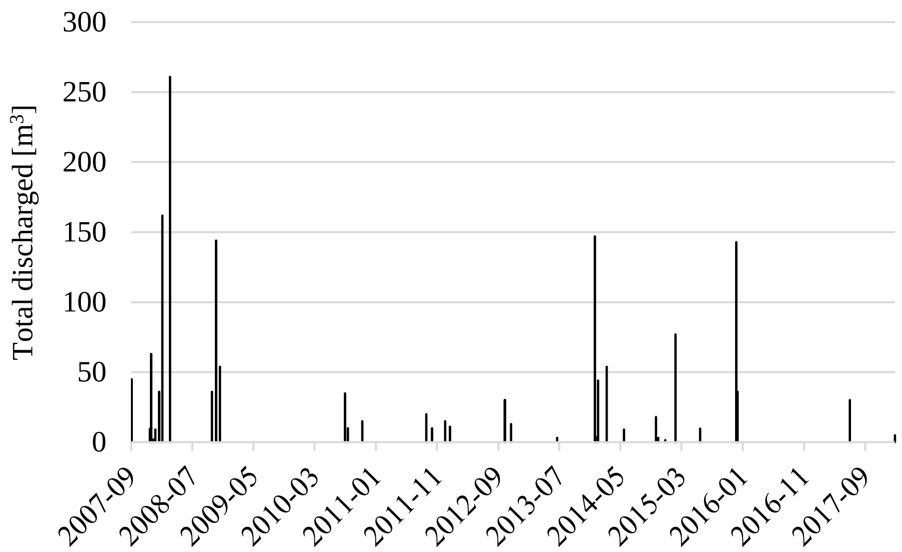

Figure 2 Sewer overflows due to hydraulic overload from Pixbo Päls (Municipality of Härryda, 2018)

3.2 Scenarios and assumptions

In this study a hydrodynamic model of Lake Rådasjön was used. The model was initially set-up and calibrated from the period 2007-2011 (Sokolova et al., 2013). The selected model to be used as base case covers the year 2010, this model is from here on referred to as 'base model'. Using this model as a base model, several scenarios were defined.

The scenarios were formulated using the base model 2010 and the conditions of climate change based on data for RCP 4.5 and RCP 8.5 from SMHI. RCP 4.5 behaves similar to RCP 8.5 until the year 2040 (Figure 3), after that, RCP 4.5 starts to stabilise, while RCP 8.5 does not, therefore, four scenarios were defined (Table 2).

To evaluate the results of water temperature and circulation, and spread of E. coli in the lake, a point P located in the deepest part of the lake was studied (Figure 6); the location of the water intake was not used in this study due to security reasons.

3.2.1 Circulation and water temperature

It has become clear that from the last half century air temperature (Figure 3 A) and precipitation (Figure 3 B) have gradually increased in the county of Västra Götaland (Berglöv et al., 2015), with a projected increase in precipitation of 12% for RCP4.5 and 25% for RCP 8.5 by the end of the century. In this thesis, the impacts of RCP 4.5 and RCP 8.5 on Lake Rådasjön for the years 2040 and 2100 were investigated. Since the circulation of the lake varies according to the seasons, the period to study for each scenario was a complete calendar year.

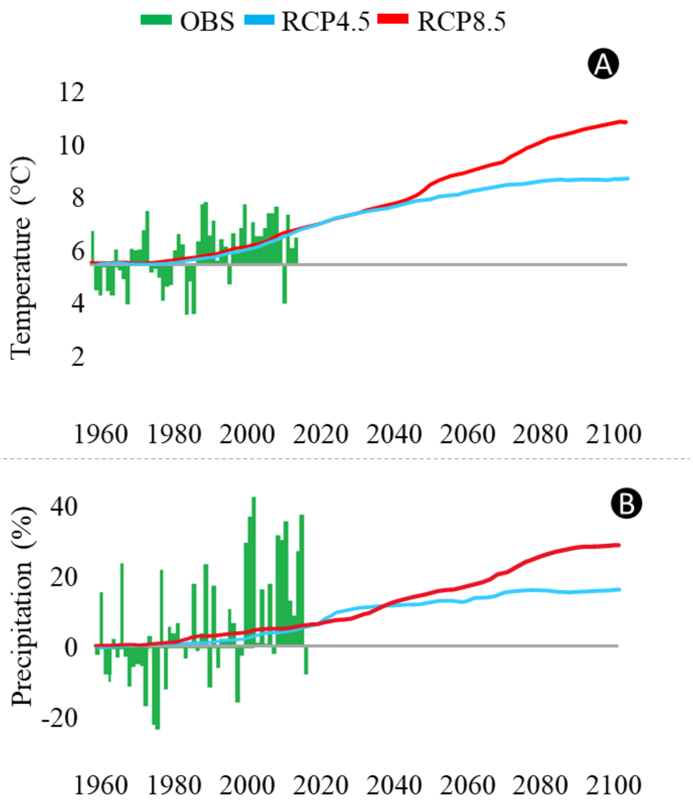

Figure 3 Annual average (A) air temperature and (B) precipitation increments results from observations (OBS), modelling RCPs 4.5 and 8.5 for the county of Västra Götaland (Berglöv et al., 2015)

The main variables that define the different scenarios are air temperature, as the main conditional to weather and microbial decay rate, precipitation, and ice coverage (Table 2), where the ice coverage of the lake during winter season (January–March) is assumed according to low air temperature records from the simulated period 2007-2011, where for the year 2010 there were 60 days of ice and the reduction on days for future years are assumed from the studied Lake Mälaren (Stensen et al., 2017) that presented similar conditions.

The possible increase of inflow from the river Mölndalsån is not taken into consideration, since currently its flow is regulated to avoid floods, hence it can be assumed that it would not affect the scenarios.

Table 2 Variation of values from the base model 2010 implemented to each scenario

Scenario	**Season**	**Air temperature [°C]**	**Precipitation [%]**	**Ice coverage [days]**
RCP4.5 – Year 2040	Winter (Dec. to Feb.)	+1.82	+22.27	-21
	Spring (Mar. to May)	+1.10	+22.01	
	Summer (Jun. to Aug.)	+0.92	+20.28	
	Autumn (Sep. to Nov.)	+1.24	+18.01	
RCP8.5 – Year 2040	Winter (Dec. to Feb.)	+1.37	+25.13	-21
	Spring (Mar. to May)	+0.64	+23.42	
	Summer (Jun. to Aug.)	+1.15	+20.72	
	Autumn (Sep. to Nov.)	+1.39	+22.87	

RCP4.5 – Year 2100	Winter (Dec. to Feb.)	+2.33	+26.95	-35
	Spring (Mar. to May)	+1.88	+29.32	
	Summer (Jun. to Aug.)	+2.57	+23.90	
	Autumn (Sep. to Nov.)	+2.36	+25.04	
RCP8.5 – Year 2100	Winter (Dec. to Feb.)	+4.08	+41.86	-56
	Spring (Mar. to May)	+2.85	+36.77	
	Summer (Jun. to Aug.)	+4.37	+30.07	
	Autumn (Sep. to Nov.)	+4.25	+35.03	

Other parameters such as cloudiness, wind and relative humidity were assumed not to change from the base model, due to the lack of data on the potential future changes for these parameters. SMHI has studied their implications and has found that they do not impact significantly, and they can be obviated (Stensen et al., 2017).

3.2.2 Contamination spread and risk

There is no clear method to determine the reasons behind the emergency discharges into the lake that have already occurred (Figure 2). The discharges could be caused by many situations, such as storm events, human errors, snow melting, unclogging, etc. Therefore, it was assumed in the model that the discharges of wastewater were constant over time, in order to assess how the new modified circulation of the lake (from the worst case scenario defined in Table 2, RCP8.5 – Year 2100) could affect the pollutant's fate and whether the risk will increase.

3.3 Hydrodynamic model MIKE 3 FM and microbial spread with ECO Lab

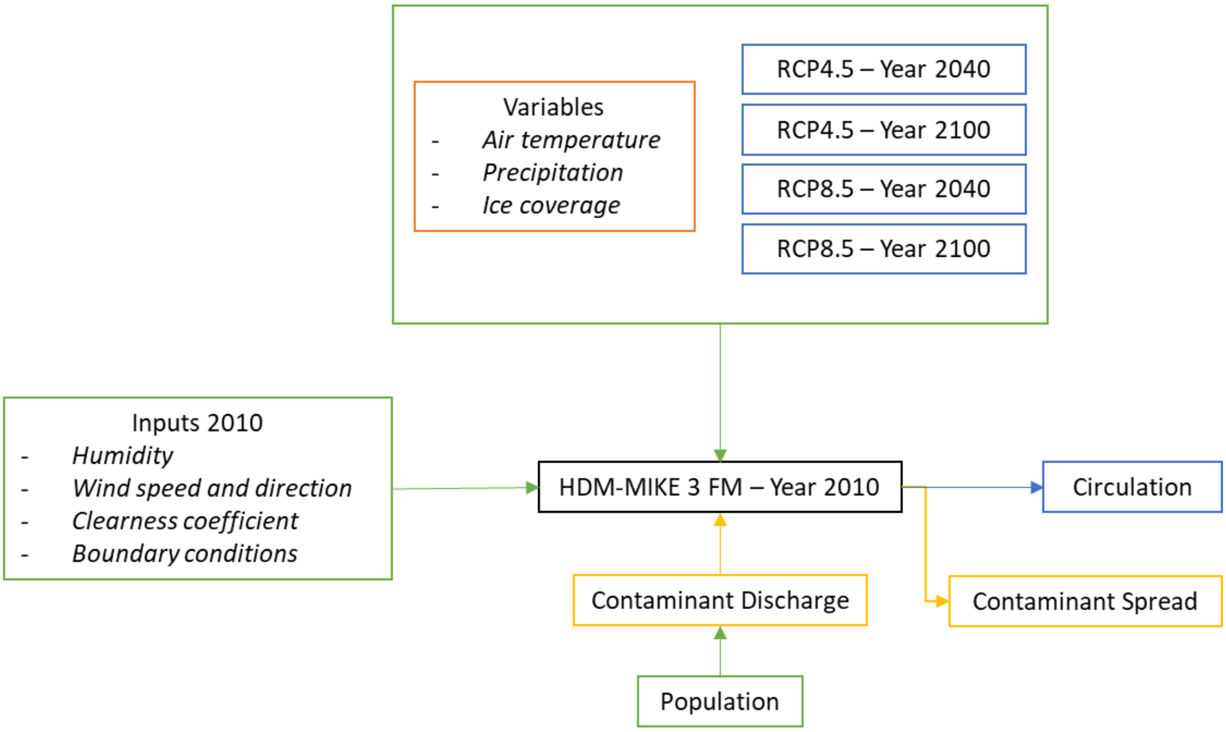

Figure 4 Modelling Method

This study uses the year 2010 as the base hydrodynamic model of the lake when simulating each scenario. Therefore, some data were not changed, such as 'Inputs 2010' in Figure 4. Air temperature, precipitation and ice coverage were changed for each scenario, to obtain the circulation for each scenario.

For the spread of the contaminant, the assumptions of discharges and concentrations of *E. coli* were added to the model. The same assumption for discharges was used for the base model 2010 and for 2100 RCP 8.5. The two scenarios were compared to estimate how the climate change impacted the circulation and the decay of *E. coli* in the lake.

3.3.1 Hydrodynamic model – MIKE 3 FM

The model of the lake was set up to simulate the water behaviour in the lake using a three-dimensional time-dependent hydrodynamic model MIKE 3 FM. The hydrodynamic model MIKE 3 FM is based on the numerical solution of three-dimensional incompressible Reynolds averaged Navier–Stokes equations using Boussinesq and hydrostatic assumptions, and consists of continuity, momentum, temperature, salinity and density equations, and is closed using a turbulent closure scheme (DHI, 2011)

The model was initially set up and calibrated for the period 2007-2011 (Sokolova et al., 2013), thus, the simulation for future scenarios were also based on and set up using the parameters from this earlier study.

The model of the year 2010 was selected as the base model, since it presented the best agreement with the measured data among the simulated years. As can be seen in Figure 5, the simulated data ('Simulated') were in agreement with the measurements ('Reported') done by Göta älv's water conservation association in the lake (Göta älvs vattenvårdsförbund, 2011).

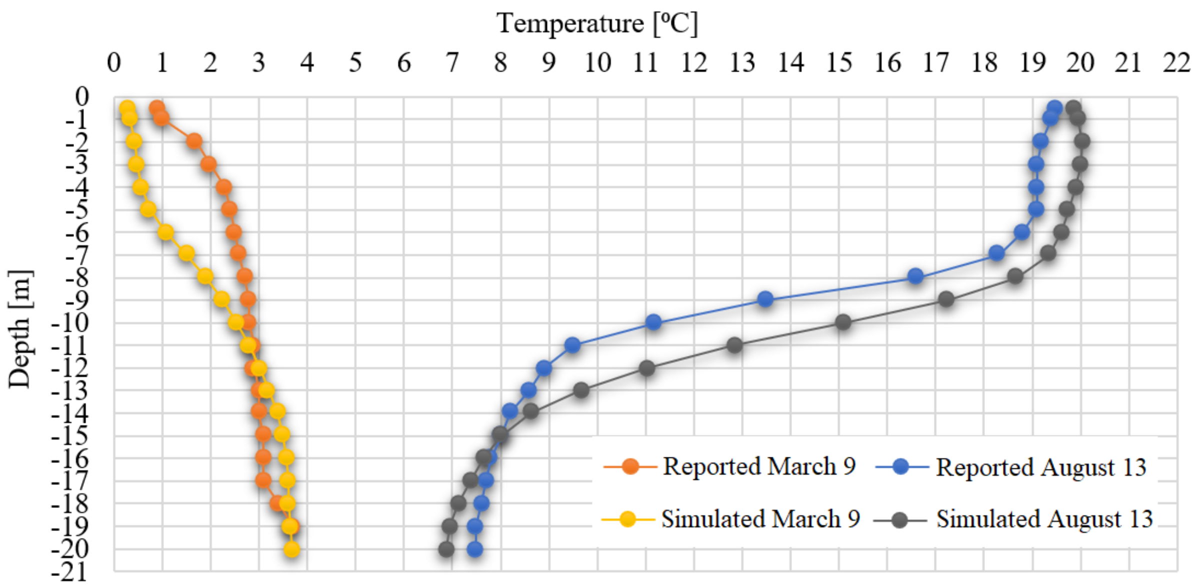

Figure 5 Comparison between the reported and simulated water temperature values for the year 2010

The simulated period starts for each scenario on the 17th of December of the previous year and runs until the last day of December of the studied year (380 days in total). This is in order to allow for a start-up period, i.e. time for mixing and heat exchange, to start the actual year of the scenario with a lake under stratified conditions, since a homogeneous temperature was assumed in the domain as initial condition.

The initial conditions in the lake were defined by the constant surface elevation and the flow velocity was set to zero. The open boundary conditions were defined by the discharge into the lake from the river Mölndalsån and by the water level in Lake Stensjön, located downstream of Lake Rådasjön. The land boundary was defined by zero normal velocity. The temperature on the open boundaries was described as zero gradients.

The model is set-up to account for hydrometeorological conditions (wind and precipitation on the lake surface), and to simulate the heat exchange between the atmosphere and the lake (Table 3). The parameterisation of the model is set according to the calibrated model 2010 (Sokolova et al., 2013).

Table 3 Input data for hydrodynamic modelling

Data	Resolution	Source
Precipitation[1]	1 day	SMHI Miljöövervakning Luft - LuftWebb
Air temperature[1]	3 h	SMHI Meteorologiska observationer - Öppna Data
Ice coverage[1]	1 day	Assumed by the simulated years (Sokolova et al., 2013)
Wind speed	3 h	SMHI Meteorologiska observationer - Öppna Data
Wind direction	3 h	SMHI Meteorologiska observationer - Öppna Data
Relative air humidity	3 h	SMHI Meteorologiska observationer - Öppna Data
Clearness coefficient	1 h	SMHI MESAN Data

Inflow Rådasjön	1 day	Mölndalsån.se - Vattenrapport Mölndalsån
Stensjön level	1 day	Mölndalsån.se - Vattenrapport Mölndalsån

[1]Varies according to their corresponding scenario.

3.3.2 Microbial water quality model – ECO Lab

The microbial water quality model ECO Lab was coupled with the hydrodynamic model to simulate the spread of the contaminant in the lake. The module ECO Lab describes the decay of bacteria as function of temperature and concentration, the contaminant concentration, the initial concentration in the lake and the boundary conditions (concentrations in the inflow to the lake and the outflow from the lake). ECO Lab uses flow fields from the hydrodynamic model to calculate the concentrations of the faecal indicators in the lake. The fate and transport of the faecal contamination were simulated using *E. coli* bacteria as a faecal indicator.

The inactivation of *E. coli* in the lake due to temperature and sunlight was described by the decay rate model of Mancini (1978):

$$\frac{dC}{dt} = -k_0 \cdot \theta_S^{Sal} \cdot \theta_I^{Int} \cdot \theta_T^{(Temp-20)} \cdot C \tag{1}$$

Where: *t* is time; *C* is the *E. coli* concentration; k_0 (1/day) is the decay rate at 20 ºC for a salinity of 0‰ and darkness of 0‰; 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* (ºC) is the water temperature.

The different parameters were previously studied and determined for Lake Rådasjön (Sokolova et al., 2013) and hence the same values were used. Thus, for equation (1) light coefficient (θ_I) was set to 1; the salinity coefficient (θ_S) to 1; the temperature (θ_T) to 1.04 and the decay rate (k_0) to 0.2.

The concentration of *E. coli* is was assumed to be constant at 2×10^6 No/100 ml, which is the median value calculated from Pixbo Päls' untreated wastewater discharges (Sokolova et al., 2013). The on-site sewer W (Figure 6) was of the most interest since it is located close to point P; it was assumed that a population of 36 people were connected to the source W discharging 8.3×10^{-5} m^3/s continuously. To assess the circulation of the lake, the source E was also defined using same characteristics as for the source W. In the model, the discharges from these two sources were simulated separately, this way it can be seen how the spread from one source differs from the other.

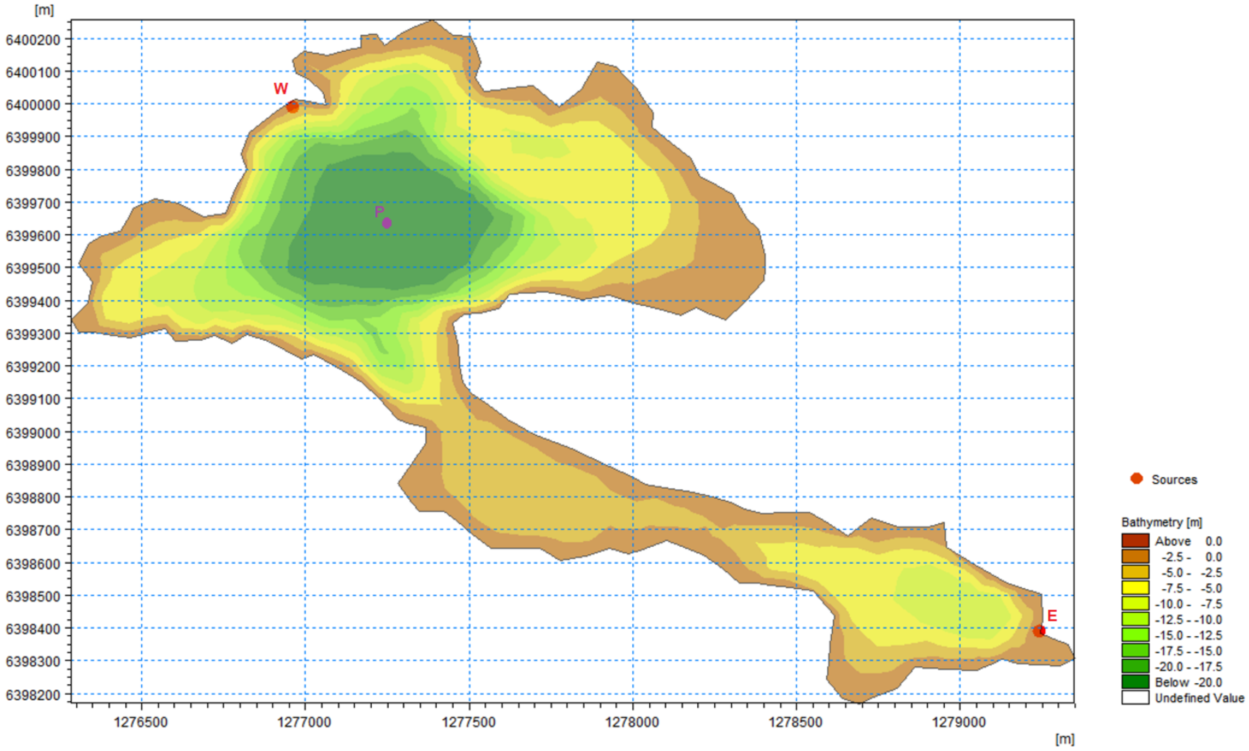

Figure 6 Sources of contamination E and W, and point of monitoring P

4 Results

4.1 Water Temperature

The modelling results of scenarios RCP 4.5 and 8.5 for the period 2040 (Figure 7) showed that they are not very different from each other when it comes to the water temperature in the lake. Therefore, 2040 RCP 8.5 is used for further discussion as 2040 since 2040 RCP 4.5 was similar.

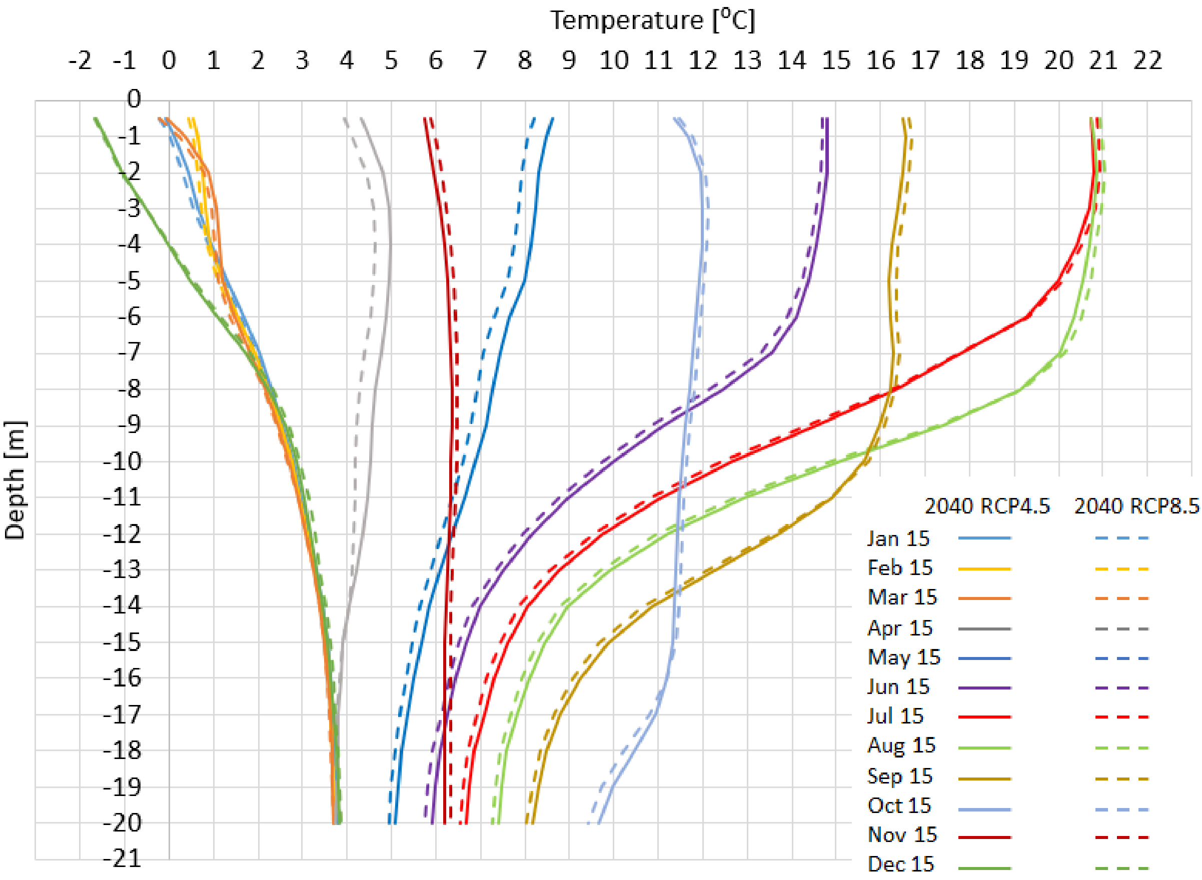

Figure 7 Vertical water temperature profiles for RCPs 4.5 and 8.5 in 2040 at point P

The most difference between RCPs in 2040 (Figure 7) was observed for April and May, for which the differences in water temperatures between scenarios were in the range of 0.3-0.5°C warmer for RCP 4.5. The results showed colder water temperatures for RCP 8.5 in winter (in February, RCP 8.5 is on average 0.1°C colder than RCP 4.5), hence it is understandable that in this scenario it took longer for the lake to warm in April and May in comparison to RCP 4.5. Later, with the start of the summer season, RCP 8.5 got warmer than RCP 4.5. In July, RCP 8.5 surpassed RCP 4.5 by 0.1°C until December, when the water temperatures were a bit colder for RCP 8.5 than for RCP 4.5.

Modelling results showed higher water temperatures by the end of the century (Figure 8), but the thickness of the epilimnion did not change. The water temperatures increased the most in the epilimnion. Scenarios 2040 RCP 4.5 and 2100 RCP 4.5 were very similar, reflecting the fact that after 2040 the scenario RCP 4.5 stabilises (section 3.2).

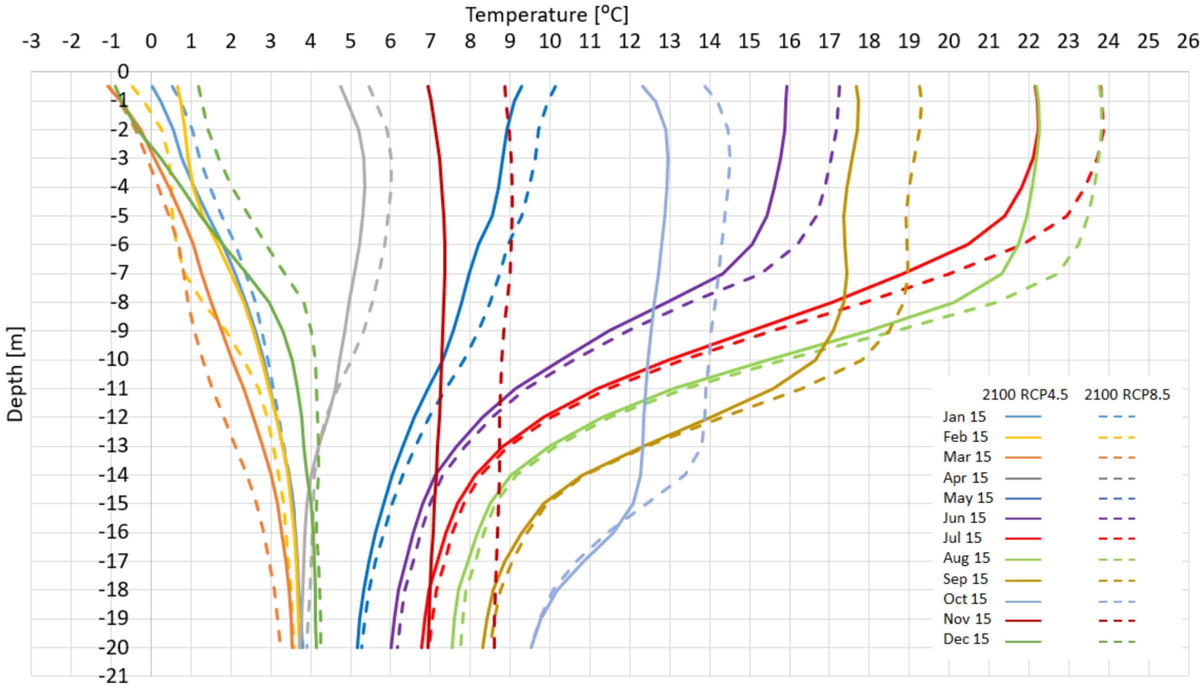

Figure 8 Vertical water temperature profiles for RCPs 4.5 and 8.5 in 2100 at point P

Comparing the year 2010 with 2040 RCP 8.5 (Figure 9), was observed a warming up of the epilimnion by approximately 1°C during the entire year 2040 and by up to approximately 2°C between 2040 and 2100, but the thickness of the epilimnion did not change for all years.

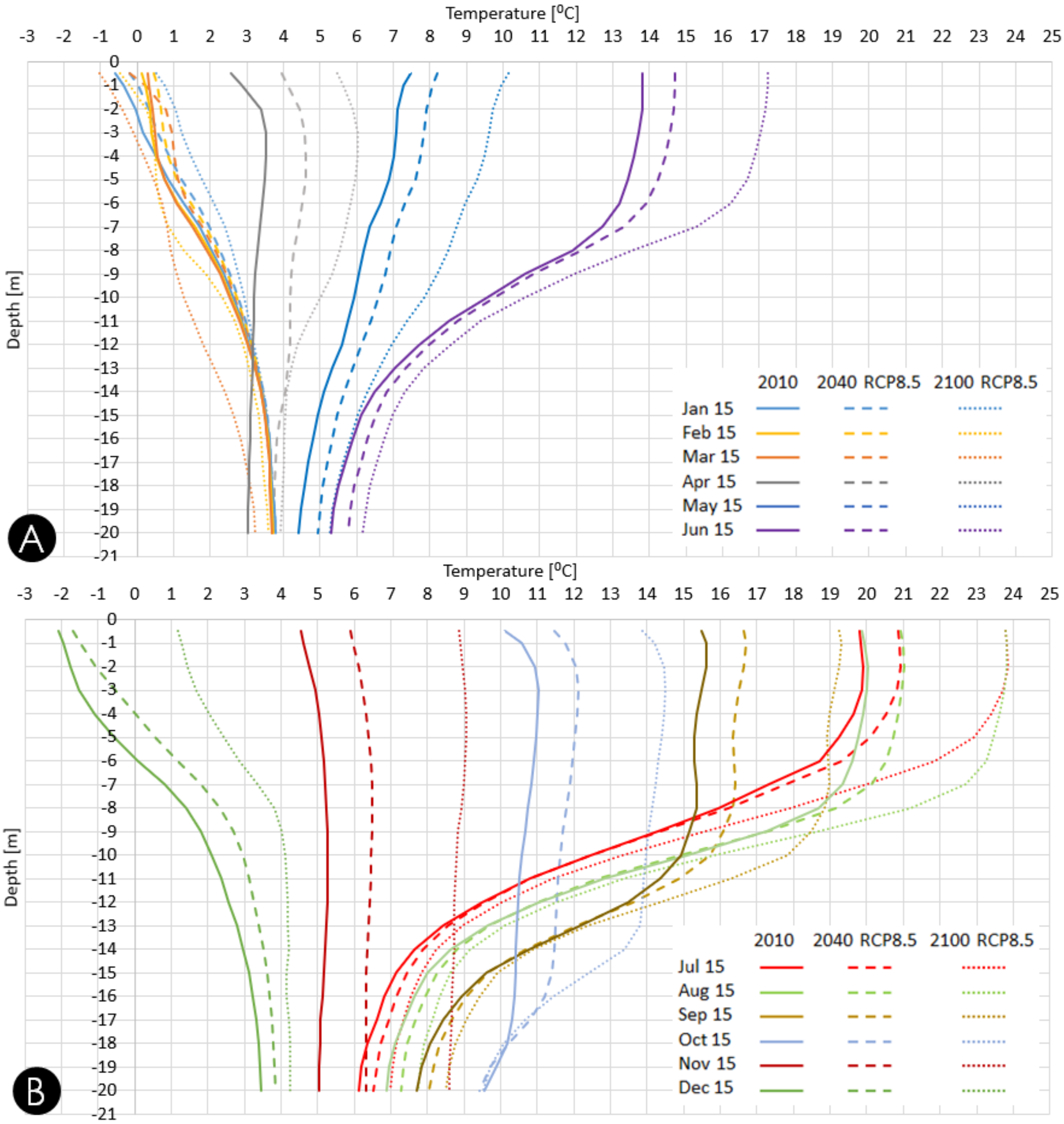

Figure 9 Vertical water temperature profiles in 2010 and RCP 8.5 for 2040 and 2100 at point P. Figure (A) shows from January to June and (B) from July to December

4.2 Inversion of the lake

The modelling results showed that the inversion of the lake for scenarios RCP 4.5 and 8.5 in years 2040 and 2100 respectively, happened approximately within two weeks of difference compared to the year 2010 (Figure 10). Due to reduced duration of ice coverage for 2040 and 2100 in comparison to 2010, the spring inversion occurred around 10 days earlier for 2040 and 13 days for 2100 RCP 8.5, but for 2100 RCP 4.5 it also occurred around the same time that it did with 2040.

Due to a longer period with high air temperatures, the autumn inversion occurred approximately five days later in 2040 than it did in 2010, for 2100 RCP 4.5 happened also similar than it did in 2040, but for 2100 RCP 8.5 it happened 16 days later than 2010.

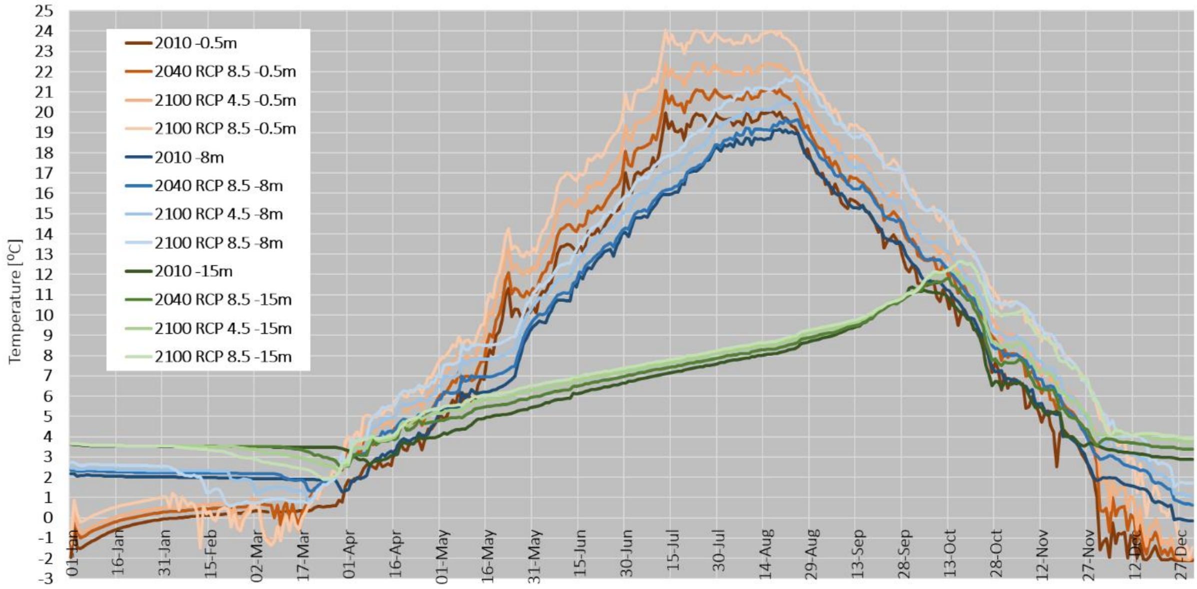

Figure 10 Water temperature at depths of 0.5m (top layer), 8m (medium layer) and 15m (bottom layer) for the years 2010, 2040 and 2100 at point P

The spring inversion in 2010 happened on the 31st of March, the top layer warmed up reaching 1.5°C and the bottom 3.4°C (Figure 11 A). For the scenario 2040 RCP 8.5, the spring inversion happened on the 20th of March, when the top layer reached 1.3°C and the bottom 3.2°C (Figure 11 B). The spring inversion occurred approximately at the same time for 2100 RCP 4.5 as it did with 2040 RCP 8.5, on the 20th of March the top layer reached 0.8°C and the bottom 2.8°C (Figure 11 D). As expected, since scenario RCP 4.5 stabilised after the year 2040. For the scenario 2100 RCP 8.5, the spring inversion happened on the 18th of March, when the top layer reached approximately 0.2°C and the bottom 2.4°C (Figure 11 C).

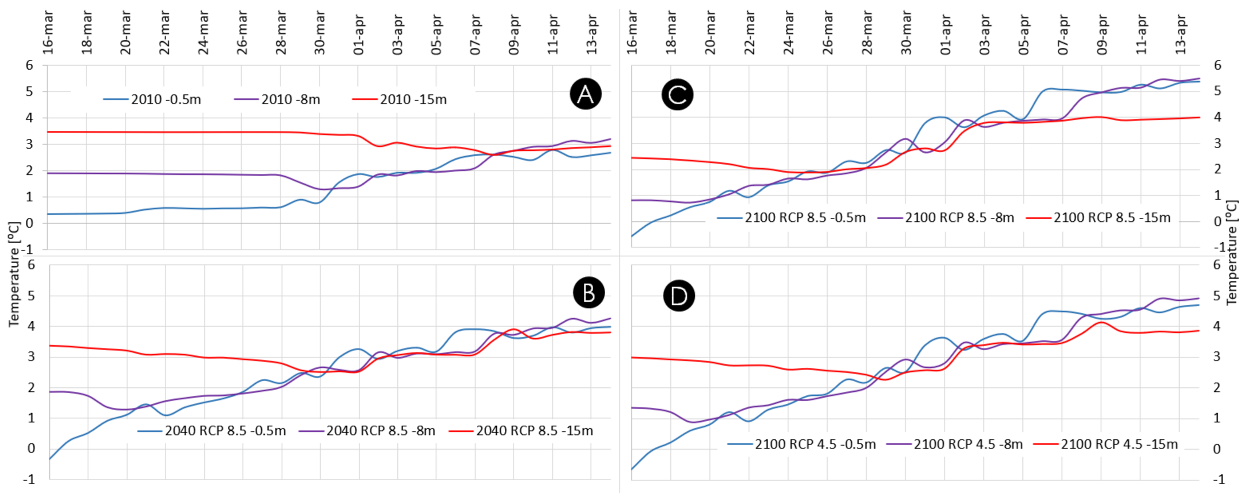

Figure 11 Inversion of the lake during spring. The figure shows: (A) 2010, (B) 2040 RCP 8.5, (C) 2100 RCP 8.5 and (D) 2100 RCP 4.5

The autumn inversion for 2010 happened on the 28th of September (Figure 12 A), when the top layer reached 12.8°C and the bottom 10.8°C. For 2040 RCP 8.5, the autumn inversion happened on the 2nd of October, when the top layer reached 13.5°C and the bottom 11.2°C (Figure 12 B). The scenario 2100 RCP 4.5, like 2040 RCP 8.5, showed an autumn inversion on the 5th of October, when the top layer reached 13.6°C and the bottom 11.7°C (Figure 12 C).

For 2100 RCP 8.5, the autumn inversion happened on the 13th of October, when the top layer reached 14.3°C and the bottom 12.2°C (Figure 12 D).

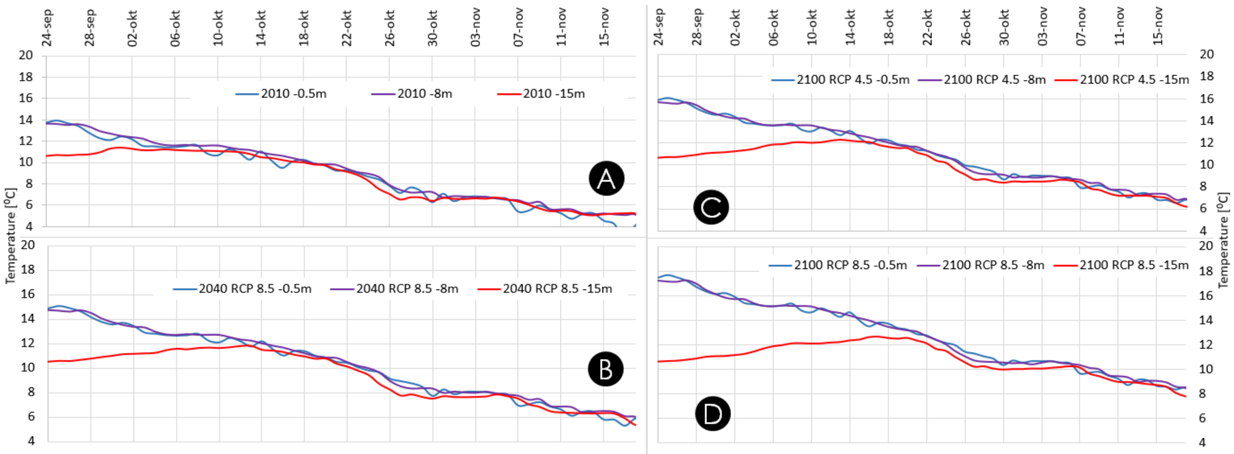

Figure 12 Inversion of the lake during autumn. The figure shows: (A) 2010, (B) 2040 RCP 8.5, (C) 2100 RCP 4.5 and (D) 2100 RCP 8.5

Therefore, considering that the scenarios in comparison to 2010 showed an earlier spring inversion and later autumn inversion, it can be said that the hydrodynamics of the lake would be under a longer summer and shorter winter regime. The year 2010 had 181 days in between inversions, whereas for the different scenarios this period was: 2040 RCP 8.5 197 days, 2100 RCP 4.5 200 days and 2100 RCP 8.5 210 days.

4.3 Spread of *E. coli* in the lake

The spread of *E. coli* was modelled for the scenarios 2010 and 2100 RCP 8.5 with and without decay. Three combinations of discharge points were used: single W, single E and combined W+E.

The modelling results showed that *E. coli* without decay from the source W accumulated at the north side of the lake, and from the source E accumulated at the southeast side (Figure 13). Therefore, *E. coli* from source W was more likely to reach point P than contamination from source E.

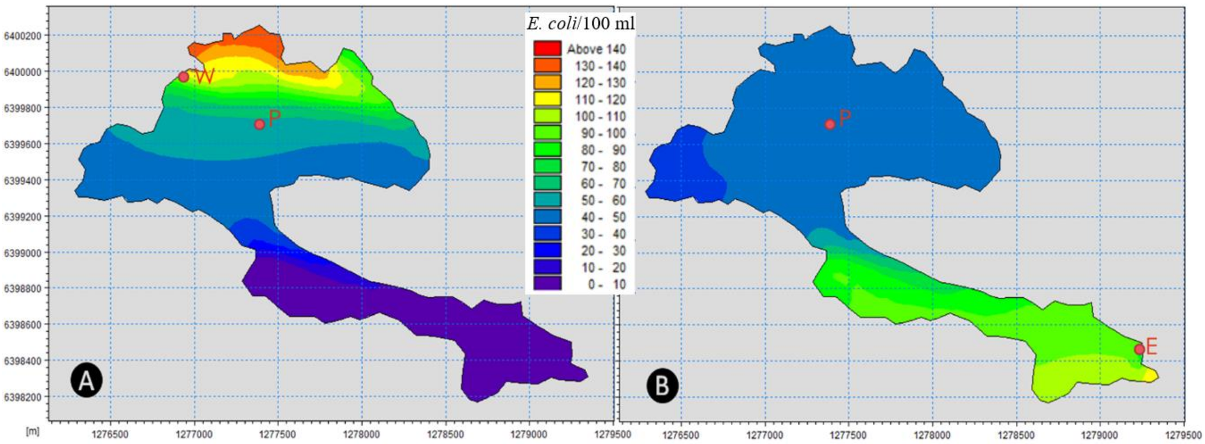

Figure 13 Spread of *E. coli* at the top layer on December 31 of 2010 (assumption of no decay). Figures (A) and (B) show the spread from sources W and E respectively

The hydrodynamic results showed that *E. coli* without decay from E mostly flows from the east to the southwest of the lake, henceforth not reaching so much at point P, unlike W that mostly goes to the north side of the lake (Figure 14 and Figure 15).

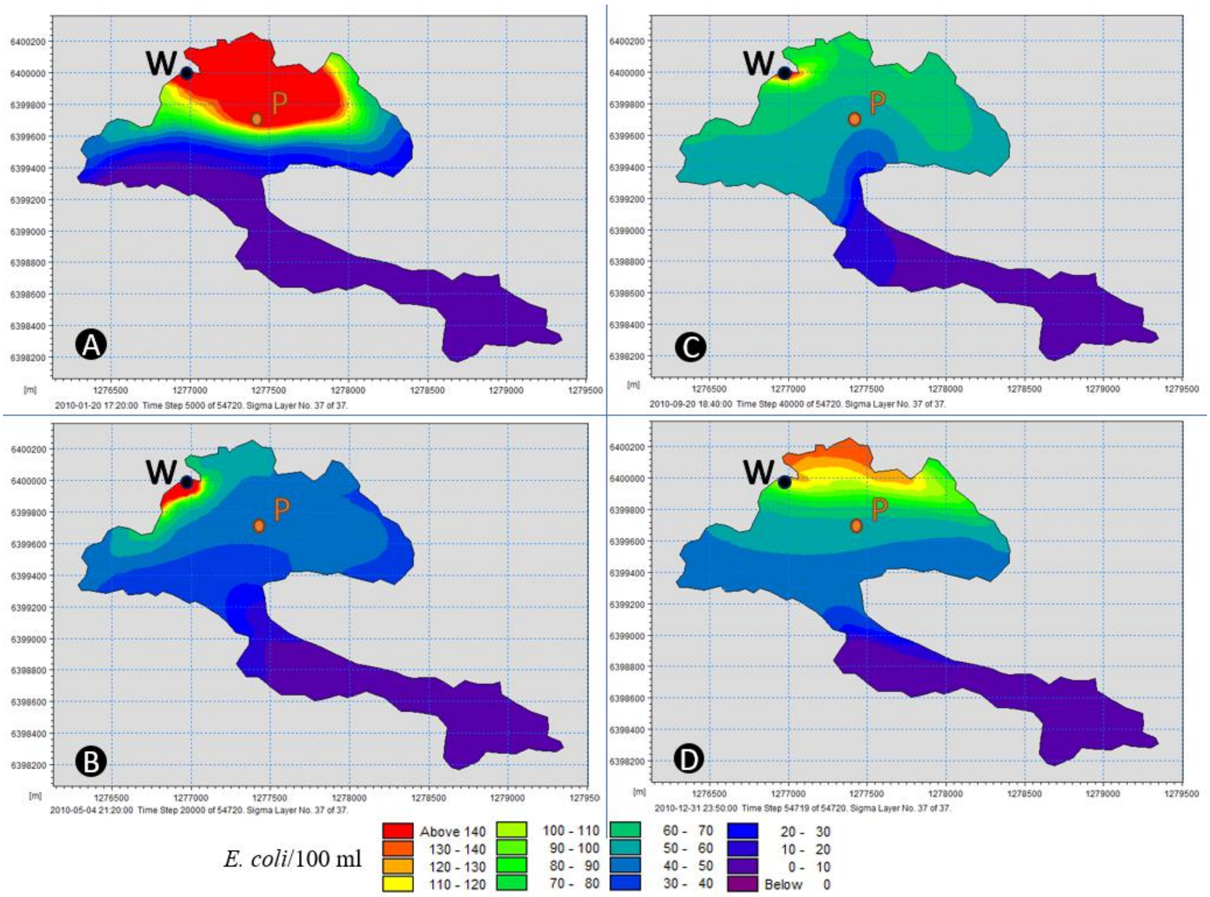

Figure 14 Concentrations of *E. coli* from source W not decaying at the top layer in 2010. Figure (A) shows January 20, (B) May 4, (C) September 20 and (D) December 31

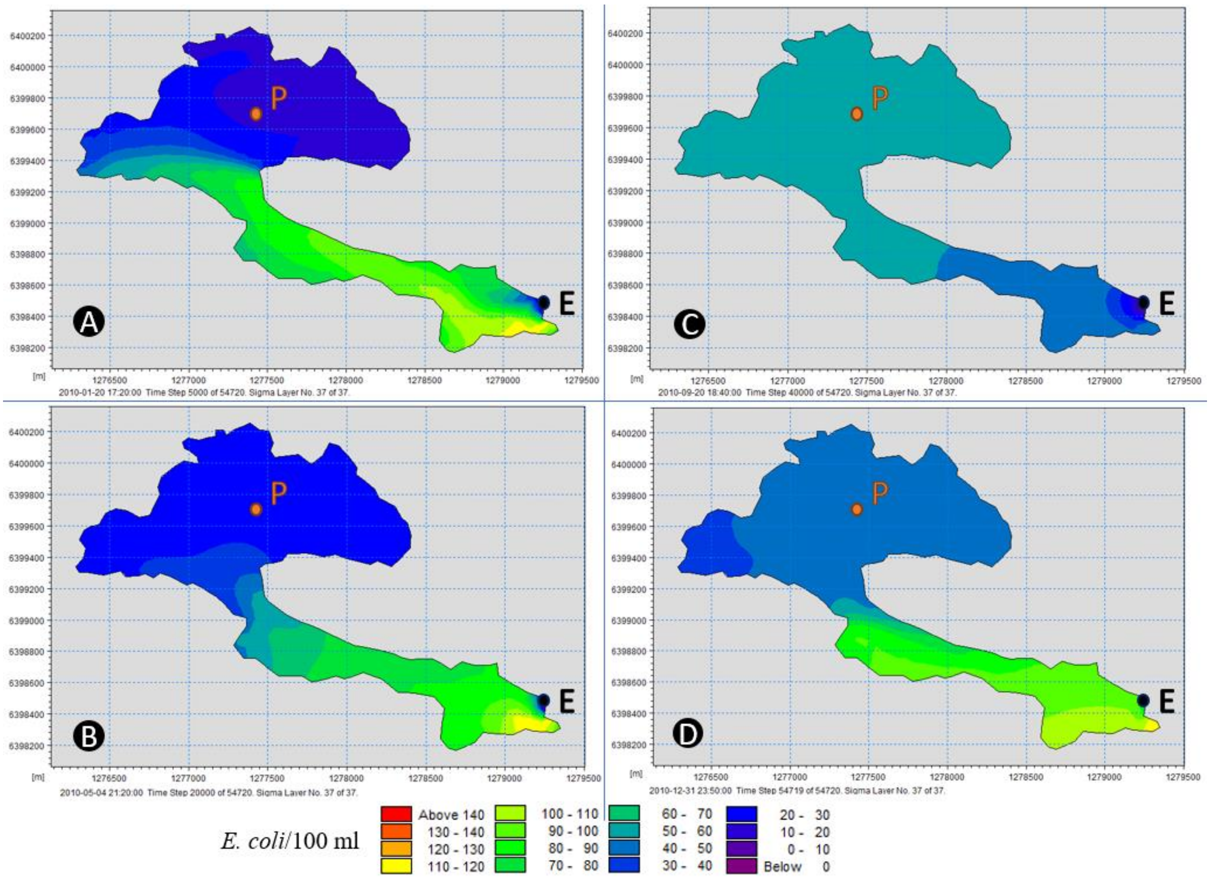

Figure 15 Concentrations of *E. coli* from source E at the top layer in 2010 (assumption of no decay). Figure (A) shows January 20, (B) May 4, (C) September 20 and (D) December 31

For the scenarios 2010 and 2100, assuming no decay of *E. coli*, the total concentrations from both sources (W+E) at point P started to accumulate already at the beginning of the year. This can be explained by the presence of ice on the lake and stratified conditions (Figure 16) with higher concentrations in the top layer than at the bottom of the lake. However, differences were found in concentrations between the scenarios due to the decrease of ice coverage in 2100 compared to 2010. For 2100, *E. coli* reached deeper in the lake at the beginning of February and, in comparison to 2010, the concentrations were lower at the surface of the lake and higher at the deeper layers. Later, due to the vertical mixing during the spring inversion in April, *E. coli* concentrations were similar in the top layer and at the bottom of the lake for both scenarios. Then, during the formation of summer stratification, the concentrations increased and by the end of July reached a maximum value of approx. 220 No/100 ml in the top layer of the lake. During August, the concentrations in the top layer started to decrease, and reached similar levels as at the bottom of the lake due to the autumn inversion.

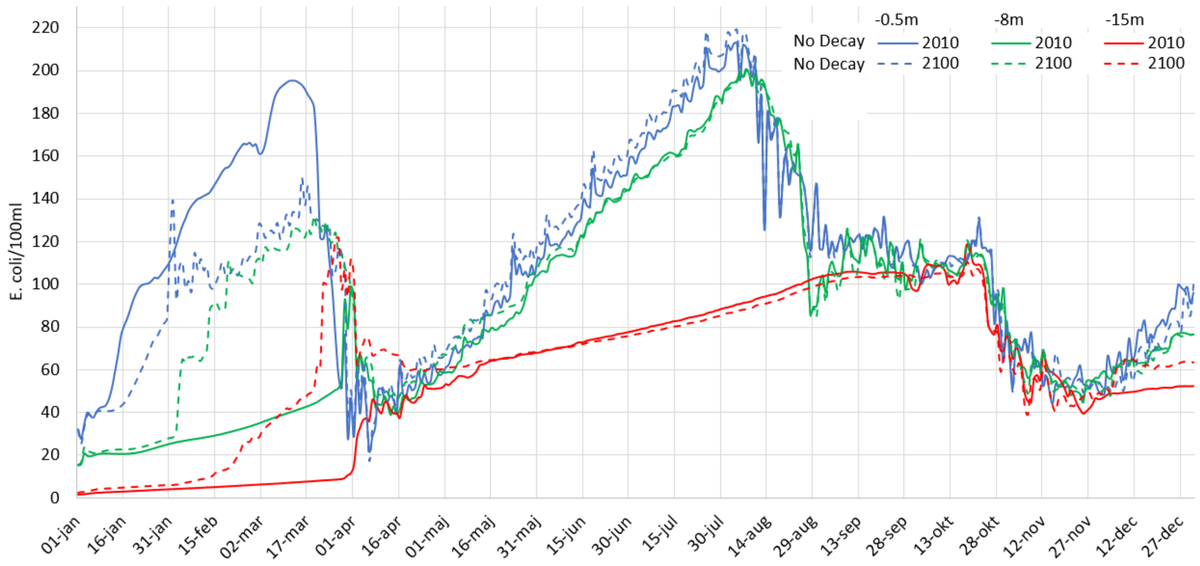

Figure 16 Total concentrations of *E. coli* (W+E), no decay, at point P in 2010 and 2100

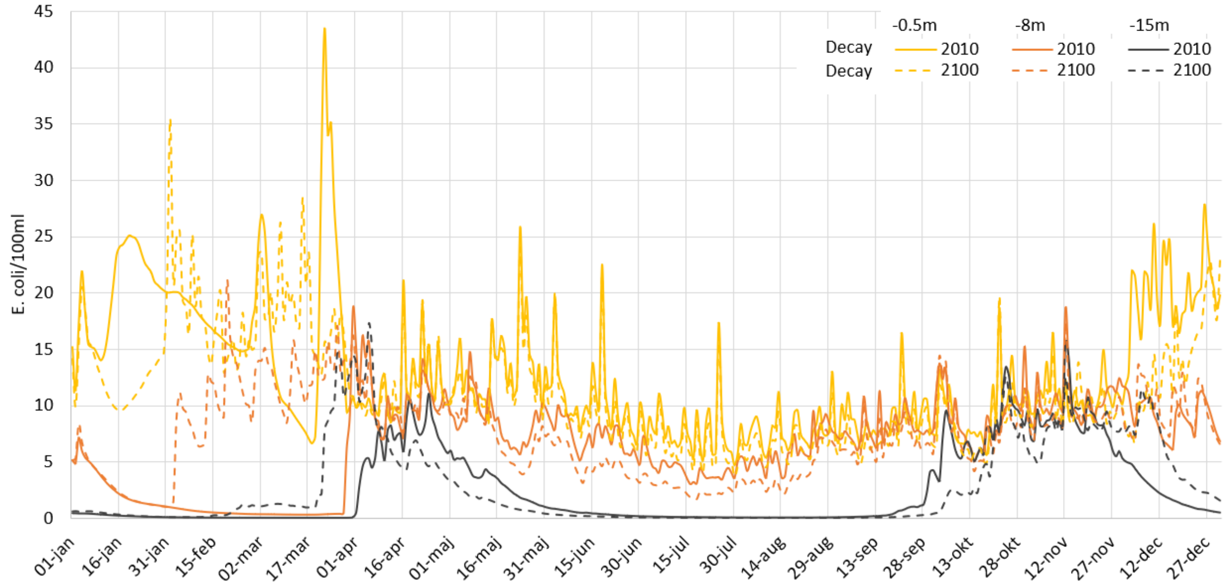

Figure 17 Total concentrations of *E. coli* (W+E), with decay, at point P in 2010 and 2100

For the scenarios taking into account the decay of contaminant, the simulated concentrations in the lake were much lower than for the scenarios assuming no decay (Figure 16 and Figure 17). The modelling results taking into account the decay of contaminant showed major differences between 2010 and 2100 in the beginning of the year from January to April, and in the end of the year from October to December. These differences were caused by the differences in ice cover and water temperature.

In the end of January (Figure 17), the concentrations at depths 8 m and 15 m were higher for 2100 than for 2010, due to the lack of ice cover. Also, higher peak concentrations of around 15 No/100 ml were observed earlier in 2100 comparing with 2010 that showed peaks of 10 No/100 ml. The main reason for this is the earlier spring inversion in 2100.

It is observed that on the 19th of March 2100, the *E. coli* concentration at 15 m deep started to rapidly increase due to the mixing process of the lake, and for 2010 it started on the 1st of April. Scenario 2100 starts to decrease *E. coli* levels earlier than scenario 2010 since the inversion of the lake happened earlier. On June both scenarios reach zero levels of *E. coli* concentrations. Therefore, the results for 2100 shows that *E. coli* contamination can be found for a longer time at 15 m depth.

Due to the stratification during the summer period (Figure 17), for both scenarios, the levels of *E. coli* at the bottom were zero, and most of *E. coli* was found in the top layer of the lake. However, warmer water temperature in 2100 resulted in faster decay in comparison to 2010. The summer period lasted longer in 2100 than in 2010, and the autumn inversion of 2100 started later than in 2010.

For 2010, the levels of *E. coli* at 15 m depth started to increase on the 28th of September until the 27th of November when they started to decrease. For 2100, the same process started on the 4th of October and ended on the 8th of December, hence lasted 5 days longer than 2010.

5 Discussion

The climate change that the future is facing is still not precisely known or defined. However, being able to develop complex studies at a much faster rate nowadays, we might get to be prepared for the change. It is for this reason that studies, such as looking into the risk for raw water sources (Delpha et al., 2009; Sokolova et al., 2013; Mohammed et al., 2019a), are of so much importance. As it has been found for Lake Rådasjön, in this thesis, for 2040 and 2100, the spring inversion happened earlier, and the autumn inversion started later compared to 2010. A longer summer regime and a shortened winter regime is to be expected, then the spread of *E. coli* could more easily reach deeper sections of the lake on earlier days of a year due to having a warmer climate in the future. This would occur due to the lack of ice coverage, causing an increased risk of contamination at the water intake. Whereas for the longer summer period of 2100 would decrease the risk for more time than 2010 until the autumn inversion happens, which is later for 2100 than 2010. The stratification period changes are found to be consistent with Weinberger's study (2012).

It is important to mention that the increased risk of contamination at the water intake is based in the worst-case scenario, the RCP 8.5. Where the climate would warm up drastically from the current period of time 2010 to 2100, leading to a warming up of the water in approximately 3.5°C in the lake, that would decrease ice coverage. But still the scenario RCP 4.5 would also increase the water temperature in approximately 1.5°C, therefore, changes can be expected in the hydrodynamics of the lake, thus, the risk is latent for any scenario.

The spread of *E. coli* was based on the assumption of having 36 people connected to a discharging stream of wastewater. Therefore, how real is the risk for the water intake, it is needed to be further studied. The population and urbanisation can be expected to change in the future, as well as the land use (e.g. for agricultural production), thus it is important to study the other sources surrounding the lake that could pose risks to the water quality.

Many assumptions and uncertainties have been made, such as not using solar radiation values and other weather parameters. Also, the same air temperature and precipitation, were used for every scenario. It was found that the most significant factor of the present thesis was the ice melting due to the increased air temperature, leading to an earlier inversion in spring and longer summer. Therefore, more research on other variables, such as wind, solar radiation and atmospheric pressure is recommended, since they can inflict significant impacts in the hydrodynamic distribution of microorganisms, through changes in the stratification of the lake (Mohammed et al., 2019b).

The future is uncertain, but there are strategies being in place to reduce the risk of contamination of water bodies in the region from emergency discharges and surface run-off. The municipalities surrounding Lake Rådasjön are working on separating the pipe network, having a sewer dedicated for wastewater that should not reach water bodies and be properly treated in a WWTP, and the storm-water being distributed to proper treatment facilities developed specially for it (Härryda Kommun, 2019; Mölndals Stad, 2019). Therefore, it is also recommended to research more the different type of sources that can be found in an area like Lake Rådasjön, such as from human activities (e.g. sailing and bathing) and surface run-off that can find its way to the lake and increase the risk of contamination. It is also recommended to study more meteorological variables and even combine them since they can present different effects in the environment, especially in urban areas (Cho et al., 2010).

6 Conclusions

In this project, the effects of climate change on circulation and spread of *E. coli* in Lake Rådasjön were modelled. The conclusions are:

- The main variable used to describe the climate was air temperature, and it had an effect on the ice coverage in the lake, leading to a shorter winter and longer summer regime. The year 2010 had 181 days in between inversions, whereas for the different scenarios this period was: 2040 RCP 8.5 197 days, 2100 RCP 4.5 200 days and 2100 RCP 8.5 210 days.
- The water temperature in the epilimnion of the lake showed major increases in temperature, by up to approximately 1.5°C between 2010 and 2040 for both RCPs, and by up to approximately 2°C between 2040 and 2100 for RCP 8.5, while for RCP 4.5 it barely increased 1°C between 2040 and 2100. The water temperature in the hypolimnion barely increased from 2010 to 2100, it went up in approximately 0.4°C for RCP 4.5 and to 0.8°C for RCP 8.5 at the end of the century, while for the case of 2040 it did not changed from 2010.
- The circulation results showed that a source from the west side of the lake, source W, will more easily reach the water intake than a source from the east side, such as the modelled source E, due to the natural flow of the lake.
- The decay of *E. coli* had a major impact on the simulated concentrations. Peaks of over 200 *E. coli*/100 ml were modelled in the simulation assuming no decay, while the concentrations were rarely over 30 *E. coli*/100 ml in the results of the simulation with decay.
- With higher air temperature due to climate change, *E. coli* levels will also decay faster, thus the concentrations during summer may be lower in the future than in 2010.
- The major increased risk for the water intake in the future is the earlier spring inversion that can cause *E. coli* to reach deeper in the lake.

Scenarios RCP 8.5 and RCP 4.5 are mainly based in a warmer atmosphere due to the higher concentrations of GHG, thus increasing air temperature. With the findings in this thesis, it can be concluded that an increase of air temperature will facilitate the spread of *E. coli* in Lake Rådasjön during spring due to a shorter winter period with the inversion occurring earlier, increasing in this way the risk of finding contamination at the water intake during this period. This is due to the assumption of ice coverage reduction, while other variables could have a significant impact in the model too, such is irradiation levels from the sun that are related to cloudiness, therefore it is recommended to further study the interaction of meteorological variables to reinforce the hydrodynamic model.

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