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Hydrodynamic modelling of E. coli along the urban coast of Helsingborg

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Abstract

There is a recurring problem with too high levels of *Escherichia coli* (*E. coli*) at beaches and around the coastline of Helsingborg. *E. coli* is not always dangerous by itself but indicates potential presence of pathogens in the water. This study used the hydrodynamical model MITgcm to model the spread of *E. coli* in three dimensions outside of the urban coastline of Helsingborg in Öresund. In the model, *E. coli* is released from the sediment and from the wastewater outlets. The model uses atmospheric data (such as wind, and temperature), initial conditions (such as stream and salinity) and bathymetry. The simulated scenarios investigated the release of *E. coli* from a wastewater outlet off the urban coast of Helsingborg, the release of *E. coli* from the sediment off the urban coast of Helsingborg, and the release of *E. coli* from wastewater outlets located off the urban coasts of Landskrona, Malmö, Helsingör and Copenhagen. In these scenarios, the location, the depth of release, and the decay of *E. coli* were varied, and the modelling period was from 1 May until 26 September 2019. It was found that *E. coli* released from the sediment could reach the beaches, but the concentrations were not high enough to prevent the recreational use of the water. Nevertheless, the sediment can be a contributing source to the total *E. coli* concentrations at the beaches. *E. coli* from the wastewater outlet in Helsingborg affected the water quality on multiple occasions causing concentrations above 100 cfu/100 ml. The modelling results for the wastewater outlets located in the other cities did not show any impact on the water quality in Helsingborg, but the simulated period was too short and covered unrepresentative stream conditions, necessitating further investigations. The limitations of the model include the coarse computational mesh, lack of input data on the magnitude of the *E. coli* releases, and uncertainties regarding the *E. coli* decay.

Keywords: *Escherichia coli*, Hydrodynamical Model, MITgcm, Sediment, Wastewater

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Referat

Det finns ett återkommande problem med för höga halter av Escherichia coli (*E. coli*) vid Helsingborgs stränder och runt Helsingborgs kust. *E. coli* är inte alltid farligt i sig men indikerar att det kan finnas en förekomst av patogener i vattnet. Denna studie använde den hydrodynamiska modellen MITgcm för att modellera spridningen av *E. coli* i tre dimensioner utanför Helsingborgs urbana kust i Öresund. I modellen släpps *E. coli* ut från sedimentet och från spillvattenrör. Modellen använder atmosfäriska data (som vind och temperatur), initiala förhållanden (som ström och salthalt) och batymetri. De simulerade scenarierna undersökte utsläppet av *E. coli* från ett spillvattenrör utanför Helsingborgs urbana kust, utsläppet av *E. coli* från sedimentet utanför Helsingborgs urbana kust och utsläppet av *E. coli* från spillvattenrör utanför Landskrona, Malmö, Helsingör och Copenhagens urbana kustremsor. I dessa scenarier varierades platsen, djupet och sönderfallet av *E. coli*, under modelleringsperioden 1 maj till 26 september 2019. Det visade sig att *E. coli* som släpptes från sedimentet kunde nå stränderna, men koncentrationerna var inte tillräckligt höga för att förhindra användning av vattnet. Sedimentet kan ändå vara en bidragande källa till de totala *E. coli*-koncentrationerna vid stränderna. *E. coli* från spillvattenröret i Helsingborg påverkade vattenkvaliteten vid flera tillfällen och orsakade koncentrationer över 100 cfu/100 ml. Modelleringsresultaten för spillvattenrören vid de andra städerna visade ingen påverkan på vattenkvaliteten i Helsingborg, men den simulerade perioden var vid dessa scenarier för kort och innehöll ogynsamma strömförhållanden, vilket krävde ytterligare undersökningar. Modellens begränsningar inkluderar det grova beräkningsnätet, bristen på indata om storleken på *E. coli*-utsläppen och osäkerheter angående *E. coli*-nedbrytning.

Keywords: *Escherichia coli*, hydrodynamisk modellering, sediment, spillvatten, MITgcm

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Populärvetenskaplig sammanfattning:

Ironin bakom en sommarstad vars badsugna turister inte kan använda vattnet sjunger högt i Helsingborg. Flera somrar i rad har kvalitén på vattnet inte varit tillräckligt bra i Helsingborg för att vara badvänligt. Problemet med vattnet är att det finns för mycket indikatorbakterier vid många av Helsingborgs badstränder, det överskrider nämligen gränsvärdena för *E. coli* som ligger på 100 cfu/100 ml för att vattenkvalitén ska klassificeras som ”tjänlig med anmärkning”. *E. coli* är en förkortning för *Escherichia coli* vilket är bakterier som kommer från tarmen, så kallade fekalier. Med vardagligt språk benämns dessa bakterier som bajs. För mycket *E. coli* i vattnet *indikerar* existensen av fekala bakterier och patogener, vilka inte bör konsumeras av människan då det kan vara farligt för hälsan. Dessa bakterier kan ha sitt ursprung från flera olika källor, men främst kommer de från tarmen av varmblodade däggdjur och fåglar. Bakterierna ansamlas sedan i reningsverket och därefter i de olika spillvattenrören som är kopplade till reningsverket.

Eftersom Helsingborgs kommun lägger stor vikt på att inte utsätta människorna som badar för hälsofarliga bakterier är dem enligt lag tvungna att stänga dessa stränder när för höga halter *E. coli* råder. För att ta reda på vad det är som ställer till det med vattenkvalitén har Helsingborgs kommun gjort studier över hur *E. coli* sprids från reningsverkets olika spillvattenrör. Dessa tidigare gjorda studier har använt hydrodynamiska modeller (ett datorverktyg som analyserar och studerar hur vattnet, och det som finns i vattnet, rör sig med tiden) för att visa att det finns flertal rör och spillvattenutsläpp som kan ha orsakat dessa förändringar i strändernas badvattenkvalitet. Något de dock noterade var att deras modellerade scenarion från de olika rören och utsläppen inte nådde lika höga nivåer som i verkligheten hade uppmätts vid stränderna.

Detta är märkligt i och med att utsläppen i studien är baserade på data både från reningsverket och tidigare erfarenheter, vilket leder till frågan, vart kommer alla extra bakterier ifrån? I studien kom dem fram till två slutsatser: de nyttjade koncentrationerna samt volymerna av utsläppen i modellen var för låga, eller så kommer bakterierna från sedimentet (det övre jord/lerlagret av bottnen). Forskaren Catherine Paul och hennes kollegor vid Lunds universitet fick upp ögonen för den senare teorin och undersökte därmed om de bakterier som fanns vid stränderna var av samma typ som de som finns i sedimentet runt ett av spillvattenrören. Undersökningen visade att detta stämde, bakterierna i sedimentet var av samma typ som de som kommit från spillvattenröret.

Den här studien undersökte huruvida bakterierna från sedimentet, *E. coli,* påverkar badsträndernas vattenkvalitet och när detta sker om så är fallet, samt hur mycket *E. coli* som i detta fall når stränderna och hur stor spridningen är. Dessutom undersöktes hur stora koncentrationen av *E. coli* skulle vara vid stränderna om utsläppsröret flyttas 450 meter längre ut i havet. Detta gjordes genom att använda oceanografen Göran Broströms uppsättning av det hydrodynamiska modelleringsverktyget MITgcm, på området runt Helsingborg och Öresund under perioden mellan 1 maj och 26 september 2019. Verktyget MITgcm använder flera olika meteorologiska och hydrologiska data såsom vind, lufttemperatur, strömdata och salthalt i vattnet för att modellera de hydrodynamiska processerna.

Resultaten visade att sedimentet runt spillvattenröret höjer halterna av *E. coli* vid stränderna, men som individuellt utsläpp är detta inte tillräckligt för att utgöra den observerade extra mängden bakterier som överskrider gränsvärdena i Helsingborg. Dock om utsläppet är tillräckligt stort, kan det i kombination med andra utsläpp påverka badvattenkvalitén. Resultaten visade också att om röret släpper ut större mängder *E. coli* höjs koncentrationerna vid stränderna.

Därmed består den inledande frågan: är volymerna från utsläppsröret för små, eller underskattas sedimentets påverkan? Det som kan konstateras är att koncentrationerna av *E. coli* vid stränderna minskar om vattnet släpps ut längre från kusten. I modellen görs detta genom att placera utsläppsröret 450 meter längre ut i vattnet (det minsta avståndet modellen tillåter) vilket resulterar i att utsläppsmängderna under några tillfällen fortfarande sänker badvattenkvaliteten, men de maximalt uppnådda värdena är mycket lägre.

Den här studien har fött flera intressanta möjligheter till vidare undersökningar och studier. Ett exempel på en vidare studie skulle kunna vara att undersöka sedimentet och dess utbredning närmare. En annan undersökning som vore intressant är att genomföra en korrekt bedömning av de volymer och koncentrationer som släpps ut från sedimentet och hur snabb nedbrytningstakten för *E. coli* egentligen är. Om dessa undersökningar genomförs bör en modellering över spridningen av *E. coli* utanför Helsingborgs kust med stor exakthet kunna möjliggöras.

Simon Gudmundsson

Contents

1. Introduction

Water is a cornerstone for human life and is used in many different industries, infrastructure and constructions designed to make towns and cities habitable (SCB 2020). One of its primary uses that often gets overlooked, at least in my experience as a (soon to be) water engineer, is namely recreational activities. Since Sweden has a vast coastline, it naturally contains a lot of places for recreational seaside activities such as bathing, and some of the coastal cities' attraction stems from their closeness to the sea. One of the main challenges of coastlines cities with their recreational waters is that the quality of water must meet the EU standards for it to be safe to use, regarding the concentration of indicator bacteria, such as *E. coli* (EU 2006). If these criteria are not met, then the recreational water by the beach is closed to the public. Indicator bacteria are usually not dangerous, but these bacteria, as the name suggests, indicate that there is faecal matter in the water which can contain pathogens. If these pathogens are present in large enough quantities, the water is deemed too dangerous for humans to come in contact with (ICMSF 1996).

One way to help with predicting the spread and concentrations of these indicator bacteria is to use modelling tools, which use the hydrodynamics of the sea to simulate the spread of a released volume of wastewater (Wolska et al 2022). The modelling results could then be analysed and compared to the observed concentrations of indicator bacteria. In a modelling study conducted by Wolska et al. (2022), the authors looked at different parametrisations of *E. coli* decay to be able to better predict the spread of *E. coli* releases from a wastewater treatment plant (WWTP) outlet. While the decay parametrisations showed promise, it was difficult to create a model which considered the large fluctuations and variability of water quality parameters (Wolska et al 2022). Another study conducted by Dumasdelage et al. (2015) used a high-resolution model to show the spread of *E. coli* from combined sewer overflows (CSOs) with very high accuracy. The authors found that while the model produced interesting and highly accurate flow patterns which could match past observed values of indicator bacteria, it had problems acting as a prediction model. The authors concluded that the problems with acting as a prediction model were due to large intervals between weather data observations (Dumasdelage et al 2015).

The city of Helsingborg is one of the largest cities in Skåne and is a very popular city to visit during the summers, in part due to its many beaches and closeness to the sea (SCB 2022). The municipality of Helsingborg had in recent years issues with poor water quality at some of their beaches (SWR 2023). The water at these beaches occasionally had the concentrations of indicator bacteria that exceeded the allowed limit for bathing (Paul et al. 2023). The source for the high concentrations of indicator bacteria at the beaches of Helsingborg may be the WWTP, which releases treated wastewater in the vicinity of the beaches, as well as CSOs. Recent investigations (DHI 2018) raised a question whether there may be other sources apart from the WWTP outlet and CSOs.

According to a study conducted by Paul et al. (2023), the source could be the sediment outside of Helsingborg's urban coastline. The sediment could be acting as a source if the bacteria have ways to nourish themselves and this means that unless the source of nourishment is found or the sediment is treated, the beaches could have problems with contamination for a long time. Previous studies have reported similar findings where the sediment acted as source for *E. coli* and affected the water quality by resuspending (Drummond et al. 2019). In a modelling study done by Drummond et al. (2019), the authors created a mathematical modelling tool, which could accurately predict and describe the movement of resuspended *E. coli* from the sediment. It was found that *E. coli* can grow in the sediment and that resuspension could occur more easily than predicted (Drummond et al. 2019). In a review study by Weiskerger et al. (2019), it was reasoned that with climate change there may be an increase in sediment *E. coli* and that it may spread closer to the beaches and increase the risk to human health. The authors reasoned that this may be because of increases in water temperature, increased urbanisation, and increased water levels (Weiskerger et al. 2019). Cromar et al. (2004) found that *E. coli* survives in the sediment, and that its decay is slower in the sediment compared to the open water, making resuspension of *E. coli* from sediments a risk to water quality.

To determine the reach and origin of faecal pollution, one could use a hydrodynamical model to simulate the movement of the currents in the sea to see the spread of the indicator bacteria. These models can be one dimensional, as in the case of the mathematical model used by Drummond et al. (2019). Alternatively, it can be a three-dimensional model, such as TELEMAC3d used by Dumasdelage et al. (2015) in their modelling of *E. coli* from CSOs. Using a model such as Massachusetts Institute of Technology general circulation model (MITgcm) would provide a view over the spread of the indicator bacteria, as well as answering if the indicator bacteria in the sediment can reach the urban coastline and the beaches.

1.1 Aim

The aim of this study was to model the Öresund straight's hydrodynamics in three dimensions outside of Helsingborg's urban coastline to visualise the spread of the indicator bacteria *E. coli* to deduce if the bacteria from the sediment and from the WWTP outlet by the coastline can reach the recreational areas and compromise the water quality.

Scenarios were modelled using Göran Broström's (Institution of Marine Sciences, University of Gothenburg) hydrodynamic model of Öresund set up using MITgcm. The data for the indicator bacteria *E. coli* was obtained through collaboration with Catherine Paul (Faculty of Engineering, Lund University). During this study, these questions were answered:

1. How does the spread of *E. coli* outside of Helsingborg coast look like?
2. How and when do *E. coli* reach the coastline and recreational areas?
3. Do the simulated *E. coli* concentrations at the beaches of Helsingborg reach the levels considered dangerous for human health in the model?

The modelled spread of *E. coli* shows how the concentrations of the indicator bacteria move and whether the bacteria affect the water quality by the beaches of Helsingborg. It is important to know how and when the indicator bacteria reach the water by the beaches and if these concentrations are high enough to cause a reduction in water quality, to know if the water is dangerous for humans. To model the hydrodynamics and the spread of indicator bacteria, data on hydrodynamical conditions affecting the direction and speed the flow (Haber 2022) as well as on the microbial decay (ISMCF 1996) are required.

1.2 Hydrodynamic modelling using MITgcm

MITgcm is a general circulation model developed at Massachusetts Institute of Technology and first presented in 1995. The model is designed for ocean modelling as well as for small scale hydrodynamic processes. MITgcm is mostly used as a research model for different atmospheric and ocean scenarios. Since MITgcm is open source, it is constantly upgraded, and more functionality is added continuously (MITgcm 2023).

MITgcm's flexibility in functionality makes it possible to add and remove processes to better suit the task of a model setup to make it more efficient and accurate (MITgcm 2023). For example, in this model setup it is required to add transport equation for bacteria and to add decay to the *E. coli* concentrations to describe the survival of the indicator bacteria in open water.

The model uses the Boussinesq approximation and a hydro-static version of Navier-Stokes fluid-dynamical equation which solves the flow of water from each cell of the grid to adjacent grid cells. The Boussinesq approximation of the Navier-Stokes equations is a method to solve flow of fluid that is not constant in temperature, which is convenient since it does not need to solve for the whole set of the Navier stokes equation (COMSOL 2023). Boussinesq approximation ignores all the differences in density except when the differences are multiplied by the earth's gravitational acceleration constant g. In the equations below, g is found in the "equation of state", or equation 1.4. With this approximation the inertia differences can be ignored since they are not sufficiently large, whilst the difference in specific weight between two cells of water is large enough to cause an interchange of water between them. The most important parameters when it comes to differences in density are salinity and potential temperature (Hendriks 2010).

One of the major advantages with MITgcm is that even though it is using a hydro-static version of Navier-Stokes equations it can be used "non-hydro-statically", which allows it to be used in the context of both small and large areas. This feature has not been used in this study, but it could be used for a more detailed study with the purpose of creating and studying fine-scale flow patterns very close to the coast of Helsingborg (MITgcm 2023). The model uses *finite volume* to solve the Navier-Stokes partial differential equations. Since it is a finite volume method, it employs a mouldable grid to support the irregular geometries which exist at the oceans bottom. These irregular geometries affect the modelling which means that the shape of the bottom is considered during flow equations (Larsson 2013)

The following equations and their variables (Table 1) are the main driving equations (or model forcing) that MITgcm uses in the model, these equations are the Boussinesq approximation of the Navier-Stokes equations, with the hydrostatic approximation.

Table 1: Different parameters and variables in use in the driving equations

ϕ = geopotential	b = buoyancy	Q_θ = forcing and dissipation of θ
t = time (seconds)	θ = potential temperature	Q_s = t forcing and dissipation of S
$\vec{v}$ = velocity (x, y, z)	S = salinity	α = decay constant.
$\overrightarrow{\Omega}$ = rotation of the earth	$\vec{F}$ = forcing and dissipation of $\vec{v}$	$\hat{k}$ = vertical unit vector

$$\frac{D\vec{v}_h}{Dt} + (2\overrightarrow{\Omega} \times \overrightarrow{v})_h + \nabla_h \phi = \vec{F}_h \quad (1.1)$$

$$\frac{D\dot{r}}{Dt} + \hat{k} \cdot (2\overrightarrow{\Omega} \times \overrightarrow{v}) + \frac{\partial y}{\partial r} + b = F_r \quad (1.2)$$

$$\nabla_h \cdot \vec{v}_h + \frac{\partial \dot{r}}{\partial r} = 0 \quad (1.3)$$

$$b = b(\theta, S, r) = \frac{g}{\rho_c}(\rho(\theta, S, r) - \rho_c) \quad (1.4)$$

$$\frac{D\theta}{Dt} = Q_\theta \quad (1.5)$$

$$\frac{DS}{Dt} = Q_s \quad (1.6)$$

Where the vertical coordinate is denoted by r and the horizontal coordinate is denoted by h.

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + \vec{v} \cdot \nabla \qquad (1.7)$$

$$\nabla = \nabla_h + \hat{k}\frac{\partial}{\partial r} \qquad (1.8)$$

Equation 1.1 is the horizontal momentum, 1.2 is the vertical momentum, 1.3 is the equation of continuity, 1.4 is the equation of state, also called buoyancy, 1.5 the potential temperature, 1.6 is the and salinity equation, 1.7 is the total derivate, 1.8 is the "grad" operator and 1.9 is the equation of decay. $\vec{F}$, Q_θ and Q_s are provided in a MITgcm package called 'physics' and are equations that describe how and where these equations are forced (change in direction, size and volume) (MITgcm 2023).

The decay for the bacteria concentration, C, reads.

$$C = C_0 \cdot e^{-\alpha/t} \qquad (1.9)$$

Where α the decay constant.

The setup in this study required a supercomputer to make the model function at a reasonable amount of time. A supercomputer contains very powerful computational hardware that can handle a large quantity of complex calculations (Britannica 2024). The one used in this examination report is a setup created and maintained by Göran Broström and is powered by 32 cored 2x Intel Xeon Gold 6130 processors that are available for research at NSC. NSC stands for "Nationellt superdatorcentrum" and is a supercomputer maintained by Linköping's Universitet, and SNI. In this project one or two nodes are used for the modelling, the cluster which was used is called Tetralith (NSC 2023).

1.3 Data and data sources

The data that is entered into the model is called driving data, or forcing, and it is the main contributor to the Navier-Stokes equations different inputs. The different meteorological data listed below affects parameters such as the velocity of the fluid $\vec{v}$, the buoyancy b and the geopotential ϕ.

The database called Emodnet or the European Marine Observation and Data network is a network of organizations supported and kept together by the EUs maritime policy. Their bathymetry data is available for free at their website (Emodnet, 2024). The boundary conditions and initial conditions used in the model come from Copernicus Marine, which is the marine branch of the European Union's space programme, their data is also available for free on their website (Copernicus 2024).

ERA5 (ECMWF 2024) provides atmospheric, land-surface and sea-state data across Europe and is maintained and produced by the ECMWF (European centre for medium range weather forecasts), which in turn is a branch of Copernicus and the European Union's space programme. The ERA5 data acts as the spatial limiter for the model, since that area of data is smaller than the bathymetry and initial and boundary conditions.

Below, is a short chapter containing thorough information about the data that affects how the model behaves, if the reader is familiar with the subject, he/she is invited to skip to the Method chapter

1.3.1 Temperature, Salinity, and Density

Both the temperature and salinity act as variables in a thermodynamic function of state for the water which affects the most important feature of the ocean's circulation, density. The density depends on the different levels of salinity and temperature. The density of the water increases when the salinity is increased and when the temperature decreases. The density is usually lowest at the surface, where the water mixes with the air temperature making it warm. The density in the water increases until it reaches the pycnocline where both temperature and density stabilise. When the density of the surface water changes, circulation occurs, primarily when the surface water cools which then causes the surface water to sink because of its higher density. This in turn affects the temperature at lower depths in the water, when the sinking volumes exchange heat with the rest of the water (Webb 2023).

1.3.2 Bathymetry

Bathymetry is a heightmap of the bottom of the ocean or lake (Sjöfartsverket 2023). The shape of the bottom affects the interaction between friction and momentum of moving volumes of water and therefore bathymetry is also responsible for the overall flow of water in the basin/control volume. The friction of the water differs depending on the incline of the bottom, the material of the bottom as well as its roughness. The bathymetry file changes the vertical grid and depth of the ocean in the model. It is read as a 2D grid file spanned over x-y coordinates, the file contains a map of data with the vertical highs and depths of the ocean or lake bottom (MITgcm 2023).

1.3.3 Wind

The wind strongly affects the flow within the oceans' surface layer and consequently it indirectly controls the flux of heat and the transport of momentum between atmosphere and ocean. Since the wind is turbulent, it translates its turbulent movement onto the oceans' surface layer and creates fluxes and flows in the top layer as well as gravity waves at the surface (Wu 2022). In the model this is represented with a turbulence factor and, the data that affects the model's behaviour is the velocity and direction of the wind (MITgcm 2023). In MITgcm, the wind is applied through forcing terms affecting the momentum in the "top layer" of the model, in other words the surface layer of the ocean. These momentums are added in the form of zonal and meridional flow (MITgcm 2023).

The air temperature is important to the calculations between air sea fluxes and inhabit many of the same equations in which the wind is added. The temperature affects the speed of the flow and the exchange rate of water between the different volumes of the grid. Generally, a higher temperature promotes exchange since the particles are moving faster whilst lower temperatures see lower exchange because of the slower speed of the particles. The temperature is first introduced to a forcing equation that operates on the surface layer of the ocean (MITgcm 2023).

1.3.4 Relative humidity

Relative humidity affects the air temperature which in turn influences mixing and layering because of its interactions with the surface layer of the ocean. In the model relative humidity is represented by a budget equation between the moisture and the temperature for each grid cell. The calculation considers the precipitation, evaporation, pressure, humidity, and temperature affecting the model for each grid cell (MITgcm 2023).

1.3.5 Long and shortwave radiation

The short and longwave radiation are used to calculate the heating from the sun due to the absorption of water vapor and atmospheric gasses. Without an added physics package, the model uses basic Newtonian cooling. Newtonian cooling follows newtons law of cooling and is stated in words as: "The rate of heat loss of a body is directly proportional to the difference in temperature between the body and its environment". In the model The Newtonian cooling has specific heating rate equations (such as different heat transfer coefficients) depending on the kind of light and radiations in the modelled scenario.

These heating rate equations are obtained from a grouped table with the UV light and the visible regions of light. The longwave radiation uses a different table of light wavelengths and equations for the cooling rate of water vapor and atmospheric gasses (MITgcm 2023). The cloud coverage affects the short-wave radiation more than the long wave radiation because of its high albedo. The higher albedo the more short-wave radiation is reflected into space, causing the amount of radiation to go down (Graham, 1999). Long and short-wave radiation only affect the temperature and humidity in the model and does not affect the chemistry or biomechanics of the ocean, although such functionality can be added (MITgcm 2023).

1.4 Microbial water quality

Water with the presence of microbes in the form of pathogenic viruses, bacteria, or other microorganisms poses a risk to human health (WHO 2023). The risk of getting sick when one consumes or interacts with recreational water is relatively small if there is little to no contamination (which usually is the case). Since a contamination of water sometimes occur in nature and infrastructure the risk is not zero, and if the contamination is large, the risk of getting sick is greater (Abrahamsson 2019) The most common reason water gets contaminated is that faecal matter enters the water, either from humans or animals. (WHO 2023). The capacity of the wastewater treatment plants must be big enough to handle large, unexpected flows of incoming wastewater to limit the number of instances where untreated water, which is rich in bacteria and faecal contaminants, is released into an adjacent water body to limit the spread of faecal contaminants (NSVA 2022).

E. coli and other indicator bacteria are often used to examine and determine water quality. These bacteria are found in the faecal waste of humans and animals and are therefore used to monitor potential contamination of water, to assess if there is a risk to human health. Subsequently, many routine tests of sea, lake, stream and drinking water are made to check if there is any contamination. The dangers from *E. coli* usually stems from two strands (STEC and *E. coli* O157:H7) which can cause harm to humans (there are more strands, but these two are the most common), but as the name suggests of, these bacteria are an indicator of other pathogens and bacteria which are considered contaminants (ICMSF 1996).

Other indicator bacteria that could be used for this study instead of *E. coli* could be enterococci. Enterococci is another indicator bacteria found in the intestines of humans and animals. The presence of enterococci can be used as an indicator for faecal contamination since their detection is an indicator of a spread of faecal matter. Enterococci are found in smaller quantities than *E. coli* and they are more resilient to environmental stress than *E. coli* making them useful in assessing water quality. Although Enterococci and *E. coli* are indicator bacterium, certain strains can be harmful. Pathogenic *E. coli* (The strains mentioned in the last paragraph) and Enterococcus faecalis can cause food poisoning and urinary tract infection. The pathogens that indicator bacteria "indicate" are for example, Salmonella and Campylobacter, which causes diarrhoea, fever, and abdominal cramps. The larger the concentrations of indicator bacteria are, the greater the risk of danger to human health (Saxena et al. 2014).

This study uses *E. coli* bacteria for its modelling purposes. For recreational and bathing water the following water quality classification is used when it comes to coast and ocean water in the transition zone, according to the regulations set up by the EU (2016):

Table 2: Different parameters and variables in use in the driving equations

	E. coli in cfu/100ml
Utmärkt kvalitet	< 250
Bra Kvalitet	250 < x < 500
Tillfredställande Kvalitet	500 with 95% certainty
Dålig kvalitet	> 500

Anything above "Dålig kvalitet" has a large presence of *E. coli* bacteria and the water should not be used for bathing or recreational purposes (EU 2016). Nag et al. (2021) noted that one exposure to concentrations at and above 500 cfu/100 ml had a 10% chance of illness caused by the presence of contaminants.

For this study, water quality was defined by the EU (2016) guidelines but the Swedish authorities uses different regulations (HVMFS 2023) Currently the water quality is defined in Sweden as less than 100 is "Utmärkt kvalitiet", 100-1000 is called "tjänligt med anmärkning" and means that it is good enough to use but should done so sparingly, and 1000 and above (cfu/100 mL) is unacceptable (HVMFS 2023).

There are a multitude of sources that can cause contamination of recreational water quality, such as faecal matter from bird populations, people, other animal sources and overflow stormwater from CSOs (Marsalek 2004). Combined sewer overflows (CSOs) are usually the culprit when it comes to microbes and organic micropollutants in waterbodies which exceed the environmental quality standards (Mutzner 2016). This is because the water released from CSOs is untreated and contains pollutants such as faecal matter or pharmaceuticals, and these releases can reach concentrations which are more than 10 times higher than treated wastewater (Gasperi 2012). Contamination can also occur from treated and partly treated wastewater from WWTPs (Philips 2012).

E. coli bacteria face many abiotic and biotic challenges when existing and traveling in open water. The most important abiotic factors for the survival in open water are light, nutrients, and temperature. These factors affect the ability of *E. coli* to expand its bacterial colony and survive in open water. Usually, the growth of the colony stops in the first few days of being in the open water since there is usually not enough of the necessary factors for growth. However, the bacteria can survive for up to a month in open water, sometimes even longer if the conditions are favourable (Rozen et al. 2001). In the sediment, the conditions for growth are much more favourable (Paul et al. 2023).

This has not been the first-time sediment has acted as a store for *E. coli.* In October of 2021 Drummond et al. (2022) found that the sediment in a system of streams in Spain also acted as a source for *E. coli.* The authors hypothesised that the source of nourishment for the sediment

E. coli was the nearby wastewater treatment plant outlet (Drummond et al. 2023). Exactly like the source for *E. coli* in the Helsingborg sediment (Paul et al. 2023).

In a study by Boano et al. (2014) the authors showed that a high exchange rate between the benthic sediment (the top 3-10cm of the sediment) and the stream water and vice versa, increased the nutrients in the benthic zone, leading to increased amounts of bacterial growth. The bacterial growth occurred because it was downstream from a wastewater outlet, since that water contains high concentrations of indicator bacteria and nutrients (Boano et al. 2014).

Drummond et al. (2022) figured that similar phenomena occurred for them and caused the water downstream from the WWTP outlet to have increased growth potential in the benthic zone. During baseflow *E. coli* are transported into and out of the sediment at a similar rate. During low flow conditions there was much less resuspension from the sediment into the water, thus the sediment acted as a store. The opposite occurred during stormflow; the sediment acted as a source as much more of the pathogens got re-suspended into the stream because of the tumultuous water conditions (Drummond et al. 2023).

Similar conditions have caused the sediment by the outlet in Helsingborg to act as a continuous source of indicator bacteria in the water. The *E. coli* in the sediment adjacent to WWTP outlet is being nourished by the wastewater, either from the treated and partly treated wastewater or because of the CSOs (Paul et al. 2023).

DHI (2018) concluded in their report that it was during large events of CSOs that the concentration of indicator bacteria was large enough to cause a reduction in water quality at the beaches adjacent to the urban coastline of Helsingborg. These releases of wastewater were also theorized to partly have sunk to the bottom of the sea, causing the sediment to form *E. coli* colonies (DHI 2018).

The largest concentration of untreated wastewater observed was, according to DHI (2018) above 100 000 cfu/100 ml, which came from a CSO (DHI 2018). The largest amount of concentration measured in partly treated and treated wastewater from WWTP outlet is 29 000 cfu / 100 ml, (DHI 2018). The largest amount of *E. coli* found in the sediment was 3000 cfu/100 ml (Paul et al. 2023).

1.5 Other hydrodynamical *E. coli* modelling studies

Wolska et al. (2022) conducted a study based on their application of the PM3Dhydrodynamic model, which the authors used to predict levels of *E. coli* concentrations from a wastewater treatment plant outlet. Their study described the problems encountered with modelling a release of treated wastewater into the brackish water of the gulf of Gdansk. The authors found that choosing different methods of parametrization, the survival rate (or decay) of *E. coli* in the water changed. The following parametrization was found to fit observed values the best:

$$\mathbf{k} = (0.8\ + 0.11\,\mathbf{S} + 0.0086\,\mathbf{I})1.07\mathbf{T} - 20 \qquad (1.10)$$

Where k, is the same as alpha in equation (1.9), S is the salinity, I irradiance (long and shortwave radiation), and T temperature of the water. The authors compared three different methods for calculating k (or alpha), and the resulting spread of *E. coli* greatly differed between the different parametrisations (Wolska et al. 2022).

In the model Wolska et al. (2022) used, different spatial resolutions for different areas of the Baltic Sea were used to save computer power. The area of study (the Vistula estuary) was made to have a high spatial resolution of the order 100 – 200 meters around the WWTP outlet. The closer to the outlet, the finer the resolution was. The rest of the Gulf of Gdansk, and the Baltic Sea, had a spatial resolution of 1 km. The authors concluded that most of the problems with using a model to predict water quality is the variability of the water quality variables, such as rainfall, stream currents and volume/concentration release of wastewater, which can change quickly. These qualities are difficult to accurately add to a model and was probably the reason why the models' concentrations were not as large as the observed ones (Wolska et al. 2022).

In another study, conducted by Dumasdelage et al. (2015), TELEMAC3d was used to create a modelling tool which could be used to forecast the spread of indicator bacteria from CSOs from a wastewater plant located in Nice, France. The mesh size around the area of study differed depending on the proximity to the wastewater outlet. It was divided in to two zones, the close zone adjacent to the outlet, which saw a resolution of three meters, whilst the area further away had a resolution of eight meters. Their model was validated with measurements from the wastewater outlet located at a depth of 38 meters (Dumasdelage et al. 2015).

The fine resolution used in Dumasdelage et al. (2015) study allowed for detailed results, showing highly accurate vertical diffusion and advection of the released indicator bacteria, this vertical diffusion and advection occurred because of differences in temperature, salinity, and density of the wastewater release compared to the sea water. Their model was accurate with past observed measurements, but somewhat failed as forecast tool since the concentrations of *E. coli* were lower in the model when used to forecast *E. coli* concentrations compared to observed concentrations. The authors concluded that the models inaccurate forecasting was because the wind and water currents were not represented accurately enough in the model, because of a lack of meteorological data. Their results showed that the magnitude of which *E. coli* differed from the observed values was at its "worst" around 10 000 cfu/100 ml (Dumasdelage et al 2015).

2. Method

2.1 Study area

The area of study is mainly the urban coastline outside of the city of Helsingborg located in the southern Swedish province of Scania (NE 2023). But since the faecal matter can travel large distances in the ocean if there is a prominent flow of water (Drummond 2023), the area of interest may be the whole Öresund. Therefore, the modelling area that is considered is a large part of Öresund. The area of interest can be seen in Figure 1, and the modelling area can be seen in Figure 2.

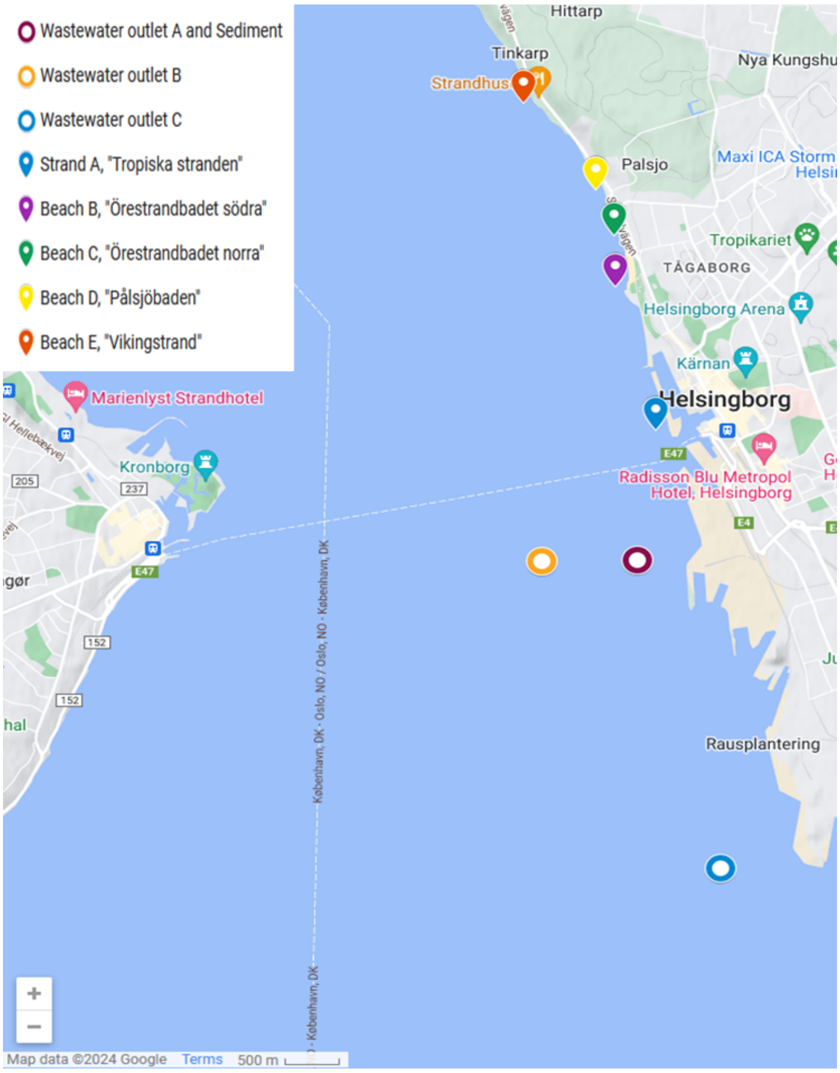

Figure 1. Location of the wastewater outlets, the sediment is located below wastewater outlet A. The beaches A – E are different beaches with compromised water quality. Beach A is 1.2 km from wastewater outlet A and 1.4 km from wastewater outlet B. Beach E is 4.5 km from wastewater outlet A and 4.4 km from wastewater outlet B.

The municipality of Helsingborg has previously had problems with high concentrations of *E. coli* that prevented recreational use of the water by beaches A-E (Figure 1). An investigation was performed by DHI (2018) to confirm where the source of the *E. coli* was located. DHI suspected that it may be the outlet of the wastewater treatment plant. In their investigation, DHI concluded that the most probable source of the *E. coli* is CSOs from "Öresundsverket" ÖV2000b (which is wastewater outlet A in Figure 1).

2.2 Causes of pollution and sediment

In a study by Paul et al. (2023) from Lunds Universitet, sediment samples were collected from the bottom of Öresund in March of 2019, since it was suspected that the sediment may also act as a source for the *E. coli.* The sampling locations varied in distance from the wastewater outlet ÖV2000b where some locations where close by to the outlet and some were closer to the beaches, where high concentrations of indicator bacteria had been detected. The authors collected 16 samples during March of 2019, from the harbour and the urban coast of Helsingborg. 10 ml of sediment was mixed with 20 ml of sterile "MilliQ" and then the samples underwent extraction of the *E. coli* bacteria. The *E. coli* concentrations measurements from around area of the wastewater outlet were collected on 19 March 2019 (Paul et al. 2023), but the city of Helsingborg has had problems with their water quality since at least 2016 (DHI 2018).

DHI concluded that the worsening of water quality is not always the case when a wastewater outlet by the urban coast of Helsingborg releases wastewater. It is also dependent on the direction of the stream and the weather conditions (DHI 2018). The total amount of wastewater released during the summer of 2019 is unknown, but it is assumed that the concentrations are the same as during 2017, as it is stated by Paul et al. (2023) the yearly mean from the main wastewater outlet (wastewater outlet A in the model, Figure 1) is 53,7 m^3 per 24h (Paul et al. 2019). This causes the yearly total mean volume to be 19.600 m^3 which is lower than the 55.000 m^3 used by DHIs model (DHI 2018). These differences could be explained by the fact that on most days there is no combined sewer overflow (CSO) release, but when it occurs, there can be very large volumes of water released. This study does not use a CSO release in the model but instead assumes a continual release. The volume for the continual release of wastewater from ÖV2000b (or wastewater outlet A, Figure 1) is around 1.86 m^3/s (DHI 2018). In the model, this is set to 2 m^3/s for simplicity.

The observed concentration of *E. coli* from wastewater outlets varies somewhat depending on what sort of wastewater outlet it is, the volume of the wastewater release and what type of release (ergo continual or CSO). This study focuses on a smaller continual release from treated wastewater and did not use a varying *E. coli* concentration (ergo not a CSO release, or a fluctuating volume and concentration). According to DHI the release from the outlet should contain *E. coli* concentration around the magnitude of 6000 – 10000 cfu/100 ml. Other studies show that untreated wastewater can reach concentrations of a size of 10^6 - 10^7, where the treated wastewater then reaches around the sizes of 10^3 - 10^4 (Raboni 2016). In another study about the occurrence and removal of antibiotic resistant *E. coli* in the wastewater, the concentrations reached between the sizes of 10^3 - 10^4 (Le et al. 2023).

It is not impossible for the water quality at Helsingborgs beaches (beaches A – E, Figure 1) to be affected by other WWTP outlets from other cities and their and untreated and treated wastewater. If wastewater releases would affect the water quality at the beaches in Helsingborg (beaches A – E, Figure 1) then the wastewater outlets are probably close by. These wastewater outlets are probably located at nearby large cities, cities such as Helsingör and Landskrona, but could include cities as far south as Malmö and Copenhagen since the stream in Öresund is generally northbound (SMHI 2023).

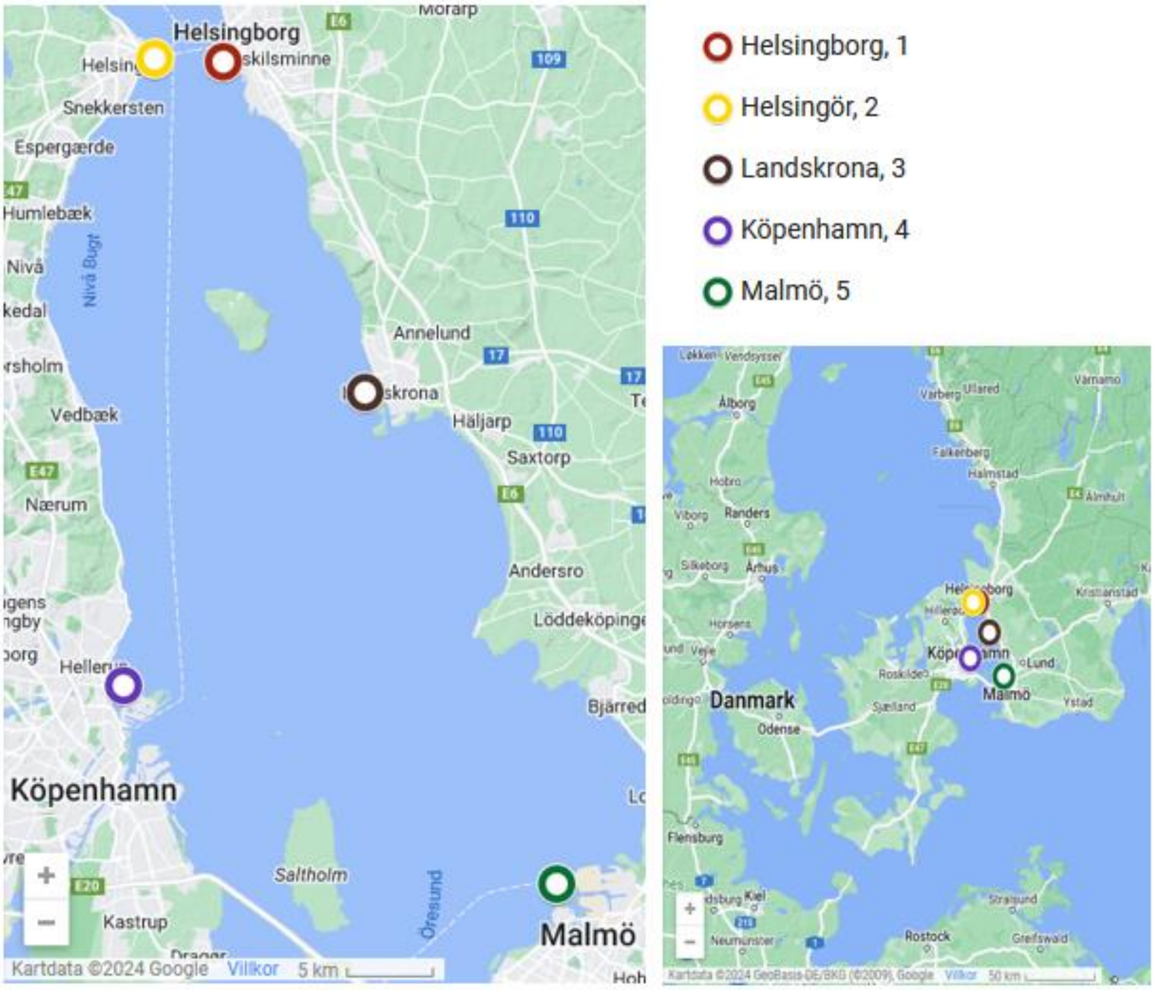

Figure 2. Map of the whole modelled area in the rightmost figure, and other release locations outside of Helsingborg in the leftmost figure.

2.4 Settings and Modelling with MITgcm

The data the model requires (which can be seen in table 2) was uploaded to the supercomputer NSC Tetralith at Linköping, where a version of the model is maintained by Göran Broström, supervisor of this study. The amount of meteorological data the model requires is quite large since it needs to cover a large area of Skagerrak and the Baltic Sea (see Figure 2). All data is of the year 2019, to match the period of interest, which was the summer of 2019. The data collected from the different meteorological databases consists of mean data notations over a temporal period, where an average is taken of all the measured points, after the period has passed (ECMWF 2024).

Table 2. Different driving data that is required by MITgcm: data type, database (Emodnet, ERA5 or Copernicus Marine), and temporal resolution of data.

Driving Data	Emodnet	ERA5	Copernicus Marine	Temporal
Incoming direction and velocity of water streams (“Stream”, in the text)			X	Sub hourly

Air Temperature		X		Hourly
Rainfall		X		Hourly
Bathymetry	X			Constant
Wind		X		Hourly
Salinity and water temperature			X	Sub hourly
Relative Humidity		X		Hourly
Long wave radiation		X		Hourly
Short wave radiation		X		Hourly
Cloud coverage		X		Hourly
Air pressure		X		Hourly

The resolution in the model was 656 pixels in the X direction (longitude), 896 pixels in the Y direction (latitude) and 70 pixels in the Z direction (which can be seen in Figure 3). Because of the shape of the earth, the cells vary in size depending on where the cells are located within the boundaries of the model. Therefore, the MATLAB code to visualise the results had to be written in accordance with the growth of the cells to analyse the results correctly. In the X direction (longitude) the cells grow from 493.2429 meters in width to 524.0178 meters and it grows with 0.008 degrees per cell. In the Y direction (latitude) the cell size is constant, with a length of 444.7 meters (Broström 2024).

The cells size in the z-direction (the depth) grows exponentially in the model. The first cell at sea level is 0.5512 meters deep, and the deepest cell in the model is 3.6815 meters deep, which is the longest cell in the vertical direction. This makes the maximum depth the model can apply 110 meters, although this depth is rarely used since it is limited by the bathymetry (Broström 2023). The maximum observed depth that exists is 130 meters in Kattegat, and in the model this depth is limited at 110 meters. The depth around that area is called "den djupa rännan" and is on average 100 meters deep, so a total depth of 110 meters maximum is deemed sufficient for the purposes of the modelled scenarios, since the part where that depth is exceeded is very small and assumed to not affect the hydrodynamics in a major way, since it is far away from Helsingborg (Broström 2023).

One iteration of the model forward is three hours of time in the model. The data for the model is added from between the period May the first to the 26th of September. The data used is limited to one input every hour, since the ERA5 data is added to the database hourly. Most of the modelled scenarios (see chapter 2.7) ran from May the 1st to the 19th of June, except for one scenario, which ran from June the 19th to September the 26th, the year 2019. The scenario during the period June the 19th to September the 26th was made to compare the concentrations and the spread of *E. coli* at beaches A-E (Figure 1) during the early and late summer. The dates between May the first and the 19th of June were deemed enough to yield all the interesting results. After that amount of time a general direction of the spread could be noticed and a heatmap of the *E. coli* could be produced. The time it took for the supercomputer to run the model was between 2 – 4 days, depending on the modelled scenario and how many users were using the supercomputer.

The boundary and initial conditions (see table 1) used in the model contain which parameters and driving forces the model should use at the beginning of the modelled scenario. The limits of the modelled water body consist of Skagerrak in the north and the Baltic Sea to the east. It is at these boundaries the model uses information about data collected from the “initial conditions”, as to mimic the real world and not a closed box. The information used in the model at the boundaries is stream data, salinity and ocean level (MITgcm 2024).

The model makes a difference between cells that are considered water and land cells by controlling the amount of water that covers the area of said cell. If the cell contains more than 75% water, it is considered a water cell and if not, it is considered a land cell. For MATLAB to be able to visualize the output data from the model one needs to separate the data cells containing water and the ones containing land. This is done by attaching a small value to all the water cells to 1e-26 to turn blue and by changing the value for the land cells from NaN (not a number) to zero to make them white and create a contour (MATLAB 2023).

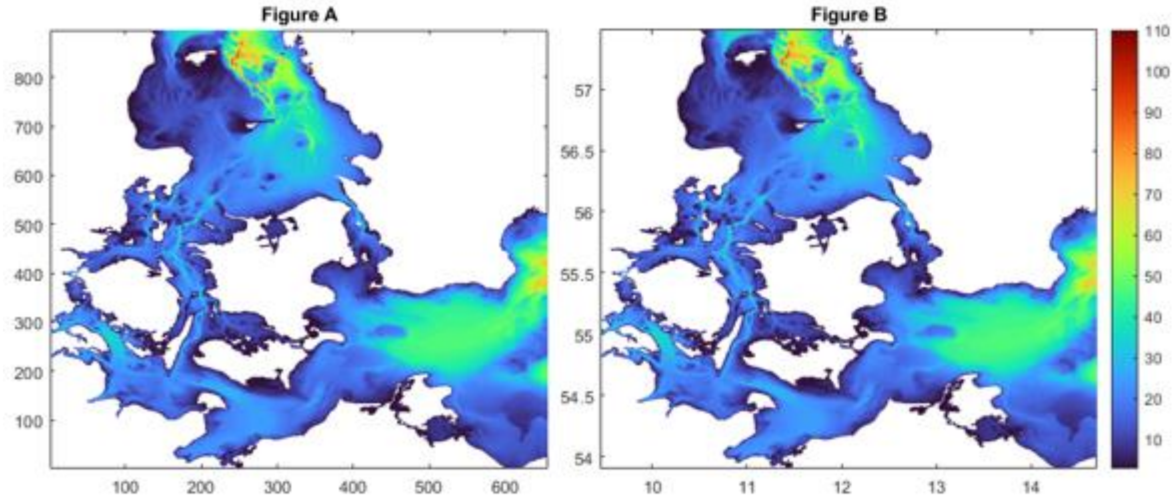

Figure 3. Bathymetry of the modelling domain. The extent of the domain is described in A) cells and B)latitude and longitude..

2.5 Validating the model

This model configuration has previously been employed in another project conducted by Göran Broström, the supervisor of this study. Figure 4 compares the observed salinity data from weather station 7 “Flinten” for the period from June 1 to September 31, 2019, at depths of 2 meters (blue line) and 8 meters (red line), with the model results (black line). It is evident that the model generally aligns with the observed data. However, the model's salinity values are slightly higher than the observed values. This discrepancy is likely due to the model's initial conditions, which are somewhat saline (refer to Figure 4 for examples of mean salinity in the model) and subject to fluctuations based on flow direction.

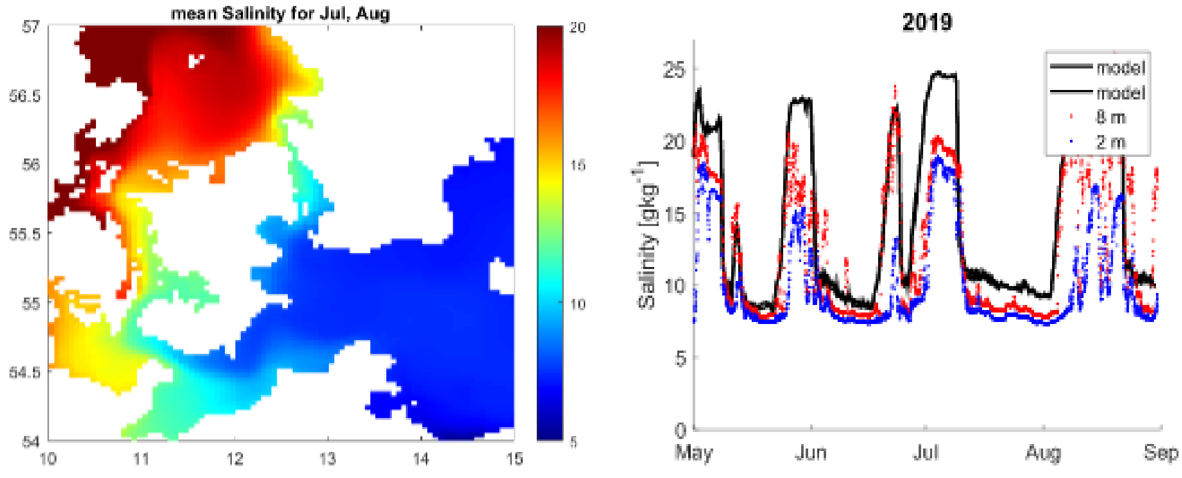

Figure 4. Left: Mean salinity for Kattegat and the Baltic Sea collected from SMHI (the salinity is around 10 g kg^{-1} in the Baltic Sea and about 20 g kg^{-1} in Kattegat). Right: Observed salinity (red and blue lines)and modelled salinity (black line) during Jun-Sep 2019.

When the streamflow is directed northward, the salinity is low, resembling the levels found in the southwestern Baltic Sea at Flinten. Conversely, when the flow shifts southward, salinity increases to levels typical of the southern Kattegat. Despite some discrepancies, the model effectively captures the general flow patterns. The observed misalignment is likely due to the low-resolution (4 km) open boundaries used to define the boundary conditions. Overall, the model adequately represents the large salinity fluctuations, leading to a conclusion that it accurately simulates the transport of Kattegat water through the Öresund and therefore accurately simulates the hydrodynamics of the modelled area (Broström 2023).

2.6 Decay and location of release in the model

E. coli thrives in environments that provide essential nutrients for its survival and growth. Such environments, like the intestines of humans and animals, are typically dark, warm (around 37°C, but tolerable between 5°C and 45°C), and neutral (pH 7). They offer a consistent supply of carbon, phosphorus, nitrogen, and essential metals, such as iron and magnesium, which are crucial for the bacteria's sustenance (Rozen et al. 2021). Additionally, *E. coli* requires certain vitamins (e.g., biotin, thiamine) and amino acids (e.g., valine, leucine) for growth (Kaiser 2016). In wastewater outlets, the sediment provides a conducive environment for *E. coli* growth. Nutrients tend to settle in the sediment, creating a richer resource pool compared to the open sea. The sediment's darker and warmer conditions, along with its higher nutrient concentration, make it an ideal habitat for *E. coli* (Davies et al. 1995).

The open water does not provide the necessary conditions for the *E. coli* bacteria to grow larger colonies, but the *E. coli* bacteria can usually survive for some time, depending on the bacteria's growth history, access to sunlight and salinity of the water. If the *E. coli* bacteria had seen rapid exponential growth, the bacteria were less resistant to environmental factors and the lack of sustenance compared to ones that had grown more stationary. If the *E. coli* bacteria are exposed to sunlight, the lights UV component can cause damage to the DNA, cell membranes and proteins of the *E. coli* bacteria, which reduce their viability. The salinity of the water also reduces the viability of *E. coli* where a more saline environment provides worse conditions for survival (Rozen et al. 2001).

Open water environments typically do not provide the ideal conditions for *E. coli* to form large colonies. However, *E. coli* can survive for a period, depending on their growth history, exposure to sunlight, and water salinity. Bacteria that have experienced rapid exponential growth tend to be less resilient to environmental stresses and nutrient deficiencies compared to those that have grown more slowly. Exposure to sunlight can be negative to *E. coli* as ultraviolet (UV) radiation may damage their DNA, cell membranes, and proteins, thereby reducing their viability. Additionally, higher salinity levels negatively affect *E. coli* survival, with more saline environments proving less hospitable (Rozen et al. 2001).

Since there are many different strands of *E. coli* which differs in resilience to the factors which cause growth and decay of *E. coli*, it is difficult to assess exactly how quickly the decay of *E. coli* in open sea water may be. Different studies have used different ratios of decay, ranging from a couple of days to months, depending on their resilience (Jozic et al. 2016).

Considering the different factors which affects lifetime of the *E. coli*, a decision was made with co-supervisor Catherine Paul to include three different times of decay in the module: 6, 13 and 26 days. The different decay times were used since it is unknown exactly how long the *E. coli* from the sediment can survive. It is suspected that these *E. coli* bacteria (based on the data of the strands of *E. coli* found in the sediment in the study conducted by (Paul et al 2023)) will survive for a maximum of a month, which was why 26 days was the longest decay time (Paul 2024).

In relation to the decay equation, for instance, after 5 days, 37% of the original *E. coli* concentration remains. This is represented in equation 1.9 by an alpha value of 0.05 for 5 days, 0.1 for 10 days, and 0.2 for 20 days. For a 90% decay, the corresponding values are 6 days, 13 days, and 26 days.

The point of release for *E. coli* in the model is the wastewater outlet A, as shown in Figure 1. This outlet is positioned as close as possible to the WWTP outlet ÖV2000b and the sediment located below wastewater outlet ÖV2000b. The coordinates for this wastewater outlet are GPS-DD: 56.032917 (Latitude) and 12.684383 (Longitude). The sediment shares these coordinates but is situated deeper in the sea, beneath the outlet. In the model, the outlet is approximately 8.2 meters below the surface, while the sediment is located at a depth of 11.3 meters. Although the exact depths of the wastewater outlet and the sediment are unknown, they are considered adequate by co-supervisor Catherine Paul (2024) based on observed depths (Paul 2024).

Additionally, another wastewater outlet, termed wastewater outlet B, is included in the model. This outlet is located 450 meters (or one cell) to the west of wastewater outlet A, as illustrated in Figure 1. This second outlet does not exist in reality and is used in the model to compare *E. coli* concentrations at beaches A – E between wastewater outlet A (aligned with ÖV2000b) and the theoretical wastewater outlet B.

To simulate *E. coli* release scenarios, a MATLAB script (MATLAB script 1 in the appendix) was developed to read, interpret, and modify data in the model. For the script to function properly, the "rdmds" script must be downloaded from the supercomputer (or from the MITGCM documentation) to the local machine. The rdmds script converts binary data from the model's output into MATLAB-readable data using metafiles. The rdmds script is crucial for analysing the results and serves as the foundation for all other scripts (rdmds can be found in the appendix as script 2).

2.7 Simulating scenarios with MITgcm

Table 3 shows all of scenarios which where modelled and simulated in this study with MITgcm.

Table 3. The different scenarios modelled and their respective details.

	90% Decay At 6 days	90 % Decay At 13 Days	90% Decay At 26 Days	Cfu/100ml	Period 05/01-06/20	Other Period	Continuous	Depth of release
Release point A, Outlet Scenario 1	X			20000	X		Continual release volume of $2\ m^3/_s$	9 meters
Release point A, Outlet Scenario 2		X		20000	X		Continual release volume of $2\ m^3/_s$	9 meters
Release point A, Outlet Scenario 3			X	20000	X		Continual release volume of $2\ m^3/_s$	9 meters
Release point A Sediment, Scenario 4	X			3000	X		Continual release volume of $0.1 m^3/_s$	12 meters
Release point A, Sediment Scenario 5		X		3000	X		Continual release volume of $0.1 m^3/_s$	12 meters
Release point A, Sediment Scenario 6			X	3000	X		Continual release volume of $0.1 m^3/_s$	12 meters
Release point A, Sediment Scenario 14			X	1500	X		Continual release of volume of $0.01\ m^3/_s$	12 meters
Release point B, Outlet Scenario 10			X	20000		Dates: 06/19 – 08/26	Continual release volume of $2\ m^3/_s$	9 meters
Release point B, Outlet Scenario 10b			X	20000	X		Continual release volume of $2\ m^3/_s$	9 meters

Copenhagen			X	Logarithmic		05/01-05/20	Continual Arbitrary release	4.3 meters
Malmö			X	Logarithmic		05/01-05/20	Continual Arbitrary release	5 meters
Landskrona			X	Logarithmic		05/01-05/20	Continual Arbitrary release	3.7 meters
Helsingör			X	Logarithmic		05/01-05/20	Continual Arbitrary release	9 meters

Several scripts were written to interpret and analyse the results.

- A script which created a timelapse of the spread of *E. coli* concentration from wastewater outlet A, B and the sediment
- A script which showed heatmaps based on the maximum amount of *E. coli* concentration reached in each cell during the modelling period.
- A script which plotted the *E. coli* concentration in the cells which contained beaches A – E (see Figure 1) over time.

All the scripts can be found in the appendix. The 13 scenarios modelled were the following:

- 2 releases of *E. coli* from wastewater outlet B, with a decay of 90% at 13 days, to simulate a release further into the sea.
- 3 releases of *E. coli* from wastewater outlet A, with a decay of 90% at 6, 13 and 26 days respectively from a depth of 8.2 meters, to simulate the release of wastewater from the outlet.
- 4 releases of *E. coli* below outlet point A, with a decay of 90% at 6, 13 and 26 days respectively from a depth of 12 meters to simulate the release of *E. coli* from the sediment.
- 4 releases from other points of interest, Copenhagen, Malmö, Helsingör and Landskrona which may, although unlikely, affect the water quality in Helsingborg.

The release of *E. coli* in the scenarios from wastewater outlet A and B consisted of a *E. coli* concentration of 20000 cfu/100 ml with a continual release of 2 $m^3/_s$. This is based on the previous literature (Rabani 2016) (Le et al. 2023) as well as DHIs ideas about future studies. The release DHI used in their modelling were deemed by them to be too small to reach the levels of *E. coli* observed at beaches A-E (see Figure 1) and considered that the concentrations used in a future study should use at least double the amount of *E. coli* (6000 – 10000 cfu/100 ml was released in the study by DHI) that they released in their model (DHI 2018).

The sediment has a maximum concentration of around 3000 cfu/100 ml and an unknown release volume. Based on information about hyporheic exchange and resuspension, the number of sampling sites which Paul et al. (2023) took of the sediment, the volume of *E. coli* from the sediment can be assumed to consist of a smaller release, around 0.1 – 0,5 $m^3/_s$ (Drummond 2023). All the releases of *E. coli* are constant, which means that the point of origin, volume and concentration of the *E. coli* release never changes during the modelling period. The model releases *E. coli* every new forward iteration, or three hours forwards in time.

2.8 Visualizing scenarios and data with MATLAB

A script which created a timelapse of the spread of *E. coli* from the different modelled scenarios (Script 4 in the appendix) was created. For each iteration of the model, one Figure was created, which acted as a frame in the timelapse. Each of these frames were then used to create an mp4 file which could be viewed as a movie, using built in windows applications.

The heatmaps (Script 3 in the appendix) were created with the purpose of visualizing where the peak values the *E. coli* concentration were located, for each cell in the model. With a heatmap like this the area that is most affected by the *E. coli* and potential danger zones are highlighted. The MATLAB script (Script 3 in the appendix) works by: Creating a loop which went through the *E. coli* concentration files from start to finish, and making a note every time a new maximum concentration in that cell was reached. The larger the concentration of *E. coli* were the more highlighted it became in the plot.

The graphs of concentration over time were made to show what the concentration of *E. coli* was at beaches A-E (see Figure 1), at all times during the modelled period. The graphs were made to have the concentration of *E. coli* on the Y-axis and the date on the X-axis. Two lines were added at 100 cfu/100 ml and 500 cfu/100 ml to represent the two limits of compromised water quality used in this study.

3. Results

3.1 Spread of *E. coli* from wastewater outlet A

The modelling results for the wastewater outlet A (ÖV2000b) scenario showed large fluctuations in the concentration of *E. coli* above the outlet (Figure 5). These fluctuations occurred during the first modelled month, May, and were caused by hydrodynamic conditions during this period. The scenario with the lowest decay showed the largest concentration above the outlet (Figure 5). In the timelapses which show the spread of *E. coli*, it can be observed that the water travelled mostly southward, then rapidly switched northward, followed by being stagnant for some time.

The spread of *E. coli* looked different depending on modelling scenario and during different periods, as can be seen in Figure 5 between the different releases from outlet A. For example, the spread from the scenarios in Figure 5 had a predominantly southern direction (see timelapses 1 – 3) during the first 20 days. A southern stream was uncommon, as most of the time the water ran north, largely because of the larger amounts of water in the Baltic Sea, compared to the Atlantic (SMHI 2023).

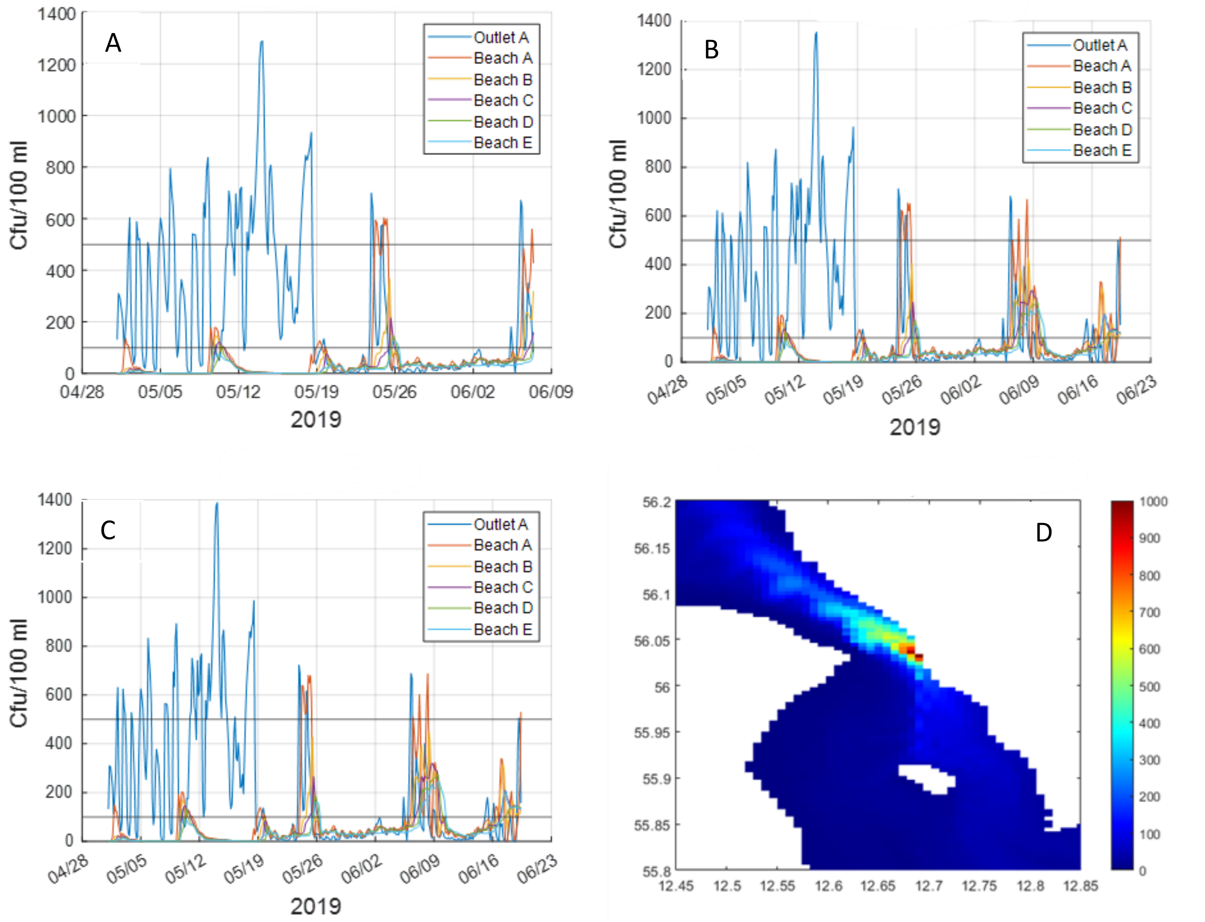

Figure 5. Release from wastewater outlet A. Plot A shows scenario 1 with a decay of 90% by 6 days (note that the timeframe is shorter in plot A because of a crash at the supercomputer and the lack of time to recreate the results). Plot B shows scenario 2 with a decay of 90 % by 13 days. Plot C shows scenario 3 with a decay of 90% by 26 days. Plot D shows the heatmap of maximum concentrations (CFU/100 ml) in scenario 3 at the water surface registered during the entire simulated period at each computational cell, in order to visualise where the highest concentrations occur.

After the first 20 days of southward stream, the water generally began travelling northward. High *E. coli* concentrations were observed when the stream outside of Helsingborg stagnated or switched direction. This can be observed in the timelapse for scenario 1 between second 2 - 6. The physical process driving *E. coli* toward the surface was the mixing between the saline water from Kattegat and the less saline water of outlet A and Baltic Sea, this difference in salinity can be seen in Figure 4. Similar process with less dense wastewater released into a more saline water environment is explained in the study by Dumasdelage et al. (2015) about hydrodynamical modelling of CSOs in Nice, France. The difference in salinity between the released water and the water environment caused a difference in density, which drove *E. coli* from the wastewater outlet upward. The heavier more saline water sank, and the lighter less saline wastewater rose (Dumasdelage et al. 2015).

The pattern of rising wastewater can be observed in the timelapses for all the modelled scenarios, for example, in scenario 1. The stream slowed down, or changed direction, which gave rise to larger accumulation of *E. coli* which then travelled to the beaches. In timelapse "SpridDecay5ytaHavStor" a zoomed out timelapse of scenario 1 can be viewed, in which the flow of the stream is more apparent. The accumulated concentrations of *E. coli* quickly reached the different beaches when the stream changed direction and became northward-bound. The fastest it took for the *E. coli* to reach one of the beaches was one step forward in time in the model, corresponding to three hours, for the *E. coli* concentrations to reach beach A (Figure 1) and two steps forward in time, or 6 hours, to reach the beach furthest away, beach E. This was expected to happen, since the stream of water generally traveled rapidly towards the north.

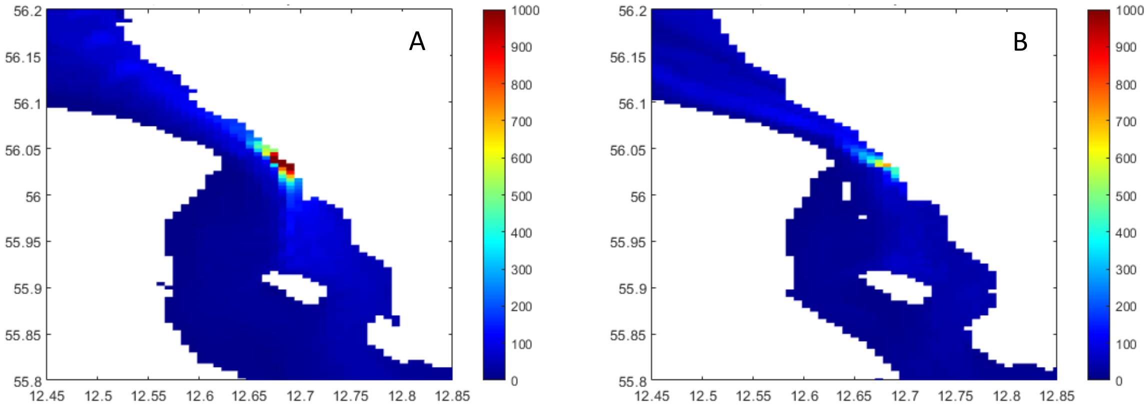

Figure 6. Release from wastewater outlet A, scenario 3 with a decay of 90% by 26 days. The heatmaps (CFU/100 ml) show the maximum concentrations registered during the entire simulated period at each computational cell, in order to visualise where the highest concentrations occur. Plots A and B show the maximum concentrations at the depth of outlet and at the bottom by the sediment, respectively.

By the outlet, *E. coli* spread to adjacent cells but did not extend far from the initial cell at that depth. Instead, *E. coli* generally travelled upward toward the surface and then northward, as indicated by the concentrations shown in the heatmaps in Figure 6. This behaviour can be explained by the mixing of water masses: the less dense water containing *E. coli* flowed upward in a plume towards the surface and subsequently flowed northward toward the beaches.

3.2 Spread of *E. coli* from wastewater outlet B

In Figure 7, wastewater outlet B was positioned one cell to the west, or 450 meters, from outlet A. The results show lower *E. coli* concentrations at the beaches for this scenario, suggesting that relocating the outlet might enhance water quality at the beaches. Although the wastewater outlet was placed at the same depth (9 meters) for both outlet A and outlet B, the deeper water at outlet B could alter hydrodynamics, particularly affecting the mixing processes and the travel time from the outlet to the surface. Additionally, the greater distance of *E. coli* release from the beaches at outlet B contributed to the lower concentrations observed at the beaches.

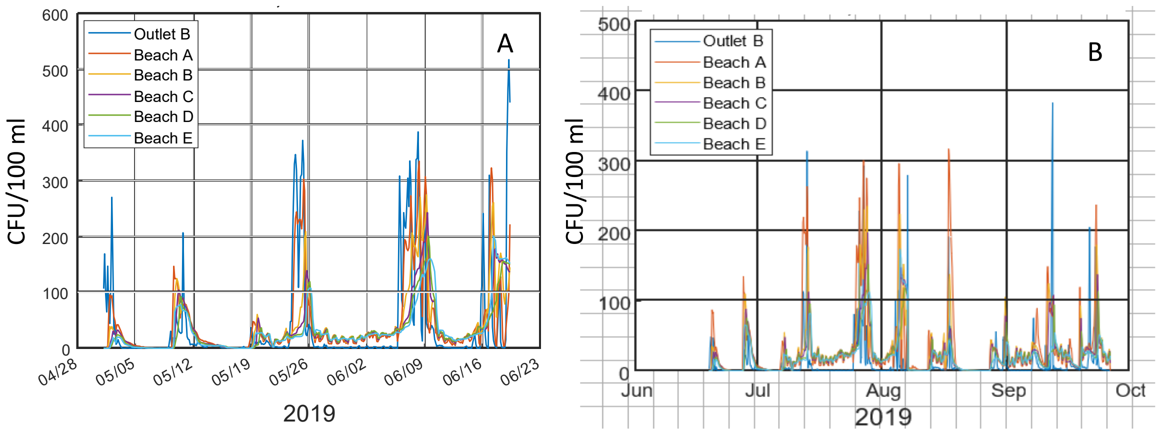

Figure 7. Release from wastewater outlet B located 450 m to the west from wastewater outlet A. Plot A shows the period from 1 May to 19 June 2019; Plot B shows the period from 19 June to 26 September 2019.

Placing the outlet further away may also decrease the amount of *E. coli* in the sediment since the distance between wastewater outlet B and the bottom is larger than in the case of wastewater outlet A (Figure 3). The difference between the dense water and the less dense wastewater from the release may be large enough to make it unlikely for *E. coli* to sink to the bottom. The plume from outlet B spreads toward the north, similarly to outlet A, and the concentrations of *E. coli* are also of similar magnitude (see Figure 6 and Figure 8), the cells in which the beaches are located exhibit a much darker blue hue in Figure 8, indicating that the maximum concentration is lower in comparison to releases from the outlet A.

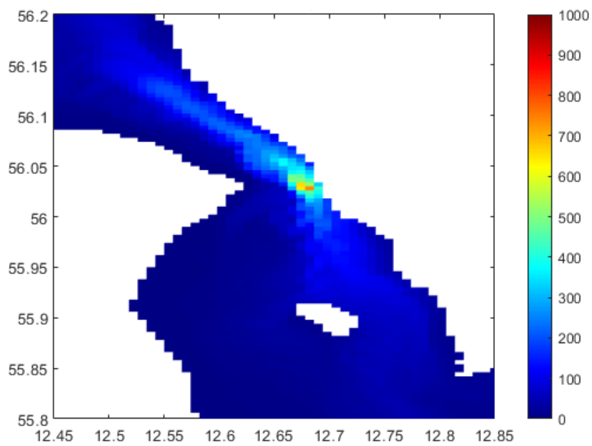

Figure 8. Release from wastewater outlet B located 450 m to the west from wastewater outlet A. Heatmap of E. coli concentrations (CFU/100 ml) in the surface layer shows the maximum concentrations registered during the entire simulated period at each computational cell, in order to visualise where the highest concentrations occur.

3.3 Spread of *E. coli* from the sediment

The sediment scenarios exhibited the similar patterns as the outlet scenarios (notice the peaks in Figure 9 and Figure 5). A notable difference between these figures is that, while the peaks at outlet A on May 26 and June 9 show comparable *E. coli* concentrations, the sediment scenarios in Figure 9 reveal significant variation in *E. coli* levels on those dates. In scenario 14 (plot D in Figure 9), a smaller release from the sediment was modelled, resulting in less pronounced peaks and lower concentrations compared to other scenarios (Figure 9, plot D). Although *E. coli* reached the beaches in all sediment scenarios, the concentrations were insufficient to compromise water quality on their own. However, in combination with other releases or during large resuspension events, these concentrations could potentially accumulate and lead to high levels of *E. coli.*

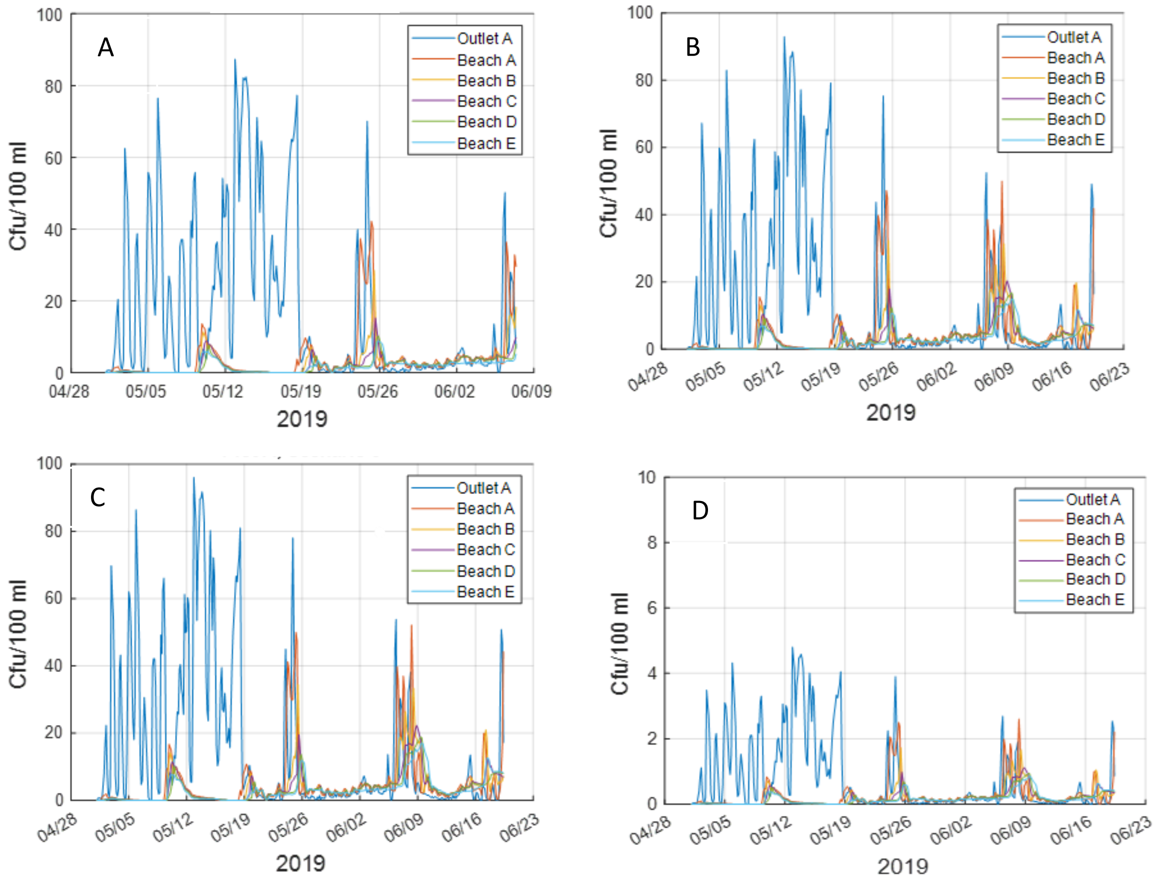

Figure 9. Release from the sediment. Plot A shows scenario 4 with a decay of 90% by 6 days (note that the timeframe is shorter in plot A because of a crash at the supercomputer and the lack of time to recreate the results). Plot B shows scenario 5 with a decay of 90 % by 13 days. Plot C shows scenario 6 with a decay of 90% by 26 days. Plot D shows scenario 14, which used a smaller release of 1500 cfu/100ml and a volume of 0.01 cubic meters per second, while the other scenarios shown in plots A, B and C used concentrations of 3000 cfu/100 ml and a volume of 0.1 cubic meters per second.

The concentrations were the largest by the bottom of the sea where the sediment is located (Figure 10). At this depth there was some spread around the area, where the cells closest to the release show high concentrations of *E. coli* above 200 cfu/100 ml (Figure 10), indicating that there is a spread caused by the stream at this depth.

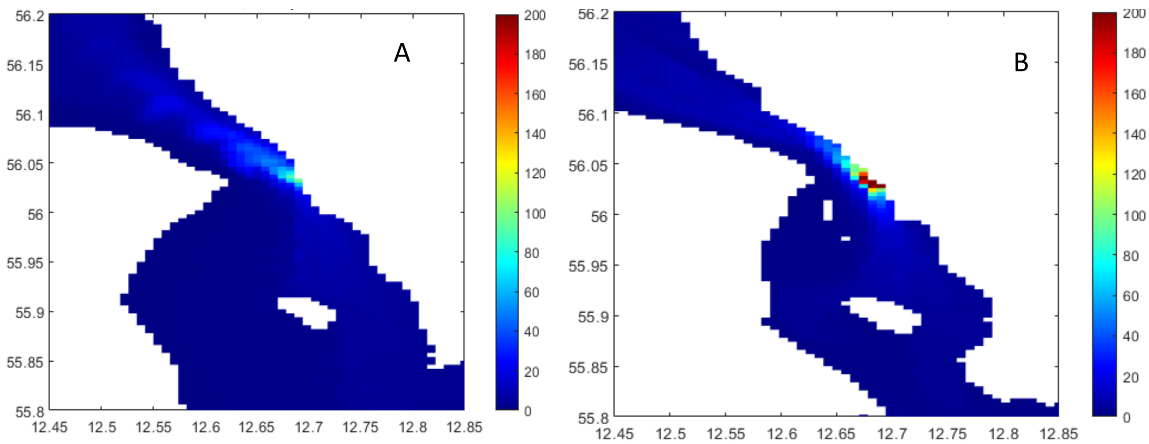

Figure 10. Release from the sediment. Heatmaps from sediment scenario 6 with a decay of 90% by 26 days. Heatmaps in Plots A and B shows the maximum E. coli concentrations (CFU/100 ml) registered during the entire simulated period at each computational cell, in order to visualise where the highest concentrations occur at two different depths, the surface (0.55 meters) and the bottom (12 meters), respectively.

3.4 Releases from outside of Helsingborg

The simulations of releases from cities outside Helsingborg (Figure 11) were limited to a 20-day period due to a supercomputer crash, which precluded further simulations. Figure 11 illustrates an arbitrary release to demonstrate the spread of *E. coli*. During this 20-day period, the flow was predominantly southward, providing limited information on whether and how *E. coli* might reach Helsingborg's beaches. However, based on the observed plumes in Helsingör, Malmö, and Landskrona (Figure 11), it is possible that *E. coli* could potentially reach the beaches of Helsingborg.

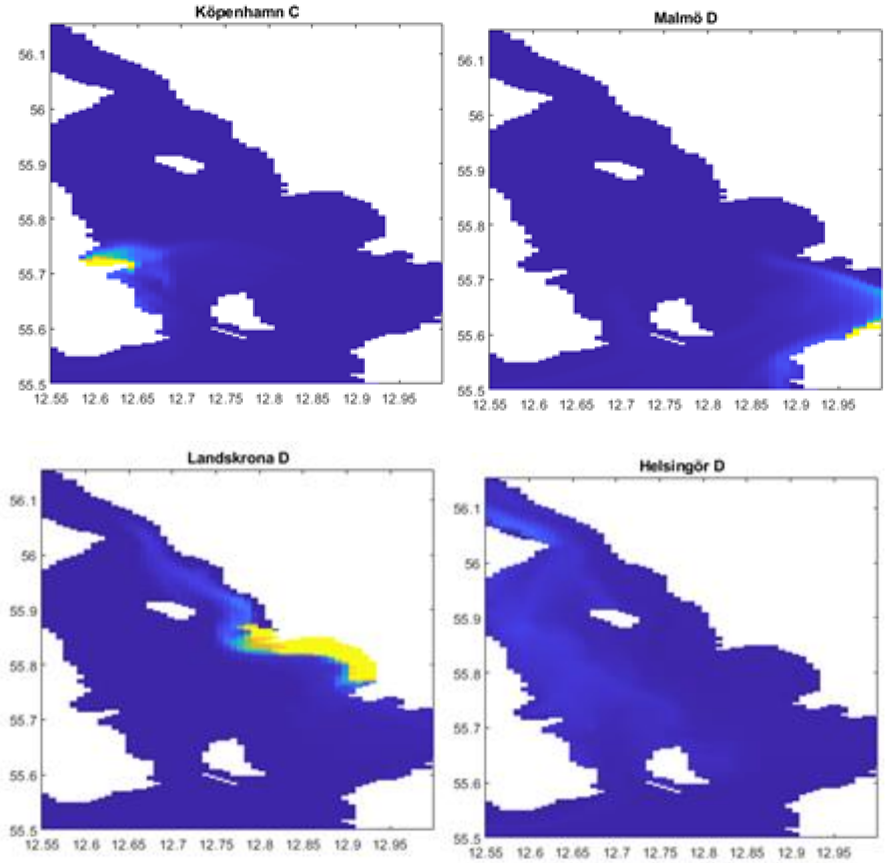

Figure 11. Releases from the cities Copenhagen, Malmö, Landskrona and Helsingör. The four plots show snapshots for time point when the concentrations were at their largest spread northward toward the beaches in Helsingborg. The colour shows the spatial pattern of the spread, and the concentrations cannot be directly interpreted in this simulation.

If the stream would travel north from the Baltic Sea instead of south, it is a possible that a large release could affect the water quality in Helsingborg, but more studies must be done. The stream is usually directed northward from the Baltic Sea because of the difference in water level (SMHI 2023), so most of the time of the stream conditions should theoretically allow a release of *E. coli* to travel from one of these cities to Helsingborg. More information about the size of releases and *E. coli* decay would be needed for a further study, since if the release is small, and decay is high, the concentrations may not reach Helsingborg.

3.5 Effects on water quality in the model

The concentrations near wastewater outlet A (Figure 5) frequently exceeded the limit of 500 cfu/100 ml set in this study. After May 19, these high concentrations were observed less frequently, occurring only three times. Figure 5 illustrates a travel effect where concentrations at the beaches reach 500 cfu/100 ml shortly after the outlet does, due to the time required for *E. coli* to travel through the water. During the first 20 days, this travel effect is seldom observed, except a few instances at 100 cfu/100 ml (Figure 5), because the stream generally flowed southward, preventing *E. coli* from reaching the beaches. Decay rates also influence this, with lower decay allowing higher concentrations to travel farther. However, varying decay rates did not significantly affect the number of times water quality at the beaches was compromised, which was unexpected and warrants further investigation.

Scenarios 1-3 displayed consistent patterns regarding water quality at beaches A-E (Figure 5). The highest *E. coli* concentrations were observed at beach A, occasionally exceeding 500 cfu/100 ml, the limit used in this study. Beaches B and C sometimes experienced *E. coli* concentrations well above 100 cfu/100 ml but never above 500 cfu/100 ml (Figure 5). Generally, the risk of compromised water quality decreased with increasing distance from the outlet. Peak timings were similar for sediment and wastewater outlet scenarios (Figures 5, 7, and 9), but *E. coli* concentrations from sediment scenarios did not exceed 100 cfu/100 ml (Figure 9).

In scenarios involving wastewater outlets A and B, cells around the depth of the outlets displayed darker blue colours further from the outlets (Figures 6 and 8), indicating minimal plume formation at those depths and suggesting that spread mainly occurs at the surface. The water rose from the outlet to the surface and then often travelled northward due to stream direction. At the bottom near the sediment, *E. coli* concentrations were lower compared to those around the outlet depth and surface (Figure 6). This is expected because the wastewater in the model is not saline, causing it to move upward when it mixes with the saline seawater.

Sediment scenarios showed higher *E. coli* concentrations at a depth of 12 meters compared to wastewater outlet A scenarios (Figures 6 and 10). *E. coli* from the sediment did not compromise water quality at beaches A-E. The highest concentrations in sediment scenarios were around 90 cfu/100 ml at the surface of the release cell in scenario 6 (Figure 9, Plot C). When combined with other sources, such as additional *E. coli* colonies in sediments from other wastewater outlets or releases from cities outside Helsingborg, these concentrations might be sufficient to compromise beach water quality. For instance, *E. coli* concentrations from scenarios 1-3 (Figure 5) on June 16 at beaches A and B were close to 100 cfu/100 ml. Adding *E. coli* from scenarios 4-6 (Figure 9) on the same day could result in total concentrations that compromise water quality.

Comparison of Figures 5 and 9 reveals similar patterns of *E. coli* concentration over time for sediment and wastewater outlet releases. Both figures show the highest concentrations above the release cell during the first 20 days, with lower concentrations thereafter. The timing of increases in *E. coli* concentrations at beaches A-E is consistent across sediment and wastewater outlet scenarios (Figures 5 and 9). Despite differences in volume, concentration, and depth, the hydrodynamic processes affecting *E. coli* spread are similar for both release types.

4 Discussion

These results indicate that Helsingborg may continue to see worsened water quality if there is a release of wastewater of the size that was modelled in this study. The sediment may also be a reason for the worsened water quality, as if it gets resuspended in the water, it can travel to beaches A-E (see Figure 1). If the releases of *E. coli* from the sediment and wastewater outlets A and B in this study accurately depict the spread of *E. coli* in Helsingborg, then the problems with compromised water quality may continue to affect beaches A – E (see Figure 1).

It has been shown in this study and in the study by DHI (2018) that *E. coli* released from different sources affect the water quality of many beaches in Helsingborg, especially to the north. This in turn hinders the recreational use of beaches A – E (see Figure 1) because of the compromised water quality and the potential risk to humans and animals that use the water (Nag et al. 2021). Since the release of wastewater from the outlet ÖV2000b (outlet A in the model, Figure 1) causes problems by sometimes compromising the water quality of beaches A – E (Figure 1 and Figure 5) (DHI 2018) and is the direct cause of the *E. coli* in the sediment (Paul et al. 2023), a solution to these problems could be of interest. As seen in this study, one solution could be to move the wastewater outlet 450 meters to the west (or one cell), which reduced the concentration of *E. coli* by beaches A – E compared to wastewater outlet A (see Figures 5 and 7).

The method used in this study yielded results suitable to answer the research questions stated in the introduction, and the method was applicable to visualise the spread of *E. coli* from a release point very close in latitude and longitudinal coordinates to that of wastewater outlet ÖV2000b. The results presented in this study show the effect of the release of *E. coli* from the wastewater in terms of spread and concentration of *E. coli* at the beaches adjacent to the urban coast of Helsingborg. To obtain the results that are even more accurate than the ones presented in this study, there are in retrospect improvements that could be made to the method.

These improvements include using a longer modelling period, to cover the whole of summer, preferably from the 1st of May to 31st of August. It would also have been useful to model the same period but of other years, to be able to compare the hydrodynamics and resulting *E. coli* concentrations at the beaches, between the different years. Another improvement to the model would be to increase the resolution of the grid to create more detailed results, although that would mean that more computer power must be used which may increase the computational time. The increase in computational time can be mitigated by decreasing the area of study in the model by setting the boundaries closer to the area of interest (Helsingborg in the case of this study); in this case, the input data at these new boundaries would need to be revised. The initial conditions at these new boundaries would have to be interpolated to fit the new area of study, as well as the finer resolution. Since the seawater current moves quickly outside of Helsingborg, a finer time scale could have been used instead of three hours, to achieve a finer temporal resolution. A finer time scale could have provided interesting results since the water quality fluctuates quickly mostly based on the direction and speed of the stream and the wind. Since this modelling results were generated using a coarse grid, they are not as accurate as the results would have been for a particle model with a more detailed resolution. Although the particle tracking function is less suitable to assess the concentrations of *E. coli* but would improve the the trajectories of the spread.

Another modelling study conducted on water quality in the area around the urban coast of Helsingborg was done by DHI (2018) and concluded that *E. coli* that affect the water quality at the beaches A – E (Figure 1) originate from the continual release from ÖV2000b (wastewater outlet A, Figure 1), CSO releases from ÖV2000b, or from other wastewater outlets north of wastewater outlet A (DHI 2018). In the study by DHI (2018), different reasons to why the water quality is poor on some days and not others were explored. The study concluded that except for the volume and duration of a wastewater release, the effect on the beaches is largely dependent on the weather and direction of the stream (DHI 2018). *E. coli* only rises vertically to the surface in concentrations large enough to compromise water quality by beaches A – E when the stream outside of the urban coast of Helsingborg changes direction or slows down. When the *E. coli* reaches the surface, it is the speed and direction of the stream and the wind which cause the *E. coli* to travel to the beaches. The conditions that appear to reduce water quality the most are when the stream is directed northward toward Kattegat, and the wind is from the west, causing *E. coli* to travel toward the beaches.

In the report by DHI (2018) it was discussed that the chosen concentrations of wastewater had been too low to account for the measured *E. coli* by the beaches and it was suggested that if further studies are conducted the concentrations of *E. coli* in the released wastewater should be at least doubled. The concentrations for the wastewater outlets A and B in the current study were 20000 cfu/100 ml and a continual release of 2 cubic meters per second, while the DHI study used a concentration of 10000 cfu /100 ml and a maximum flow of 1.86 cubic meters per second (DHI 2018). In retrospect the value used in this study could have been set to a value corresponding to literature about *E. coli* released from Swedish WWTP outlets.

According to HVMFS (2023,) the current limits for bad water quality is 1000 cfu/100ml and not 500 cfu/100 ml which was used in this study. If the limits of 1000 cfu/100 ml are used, then only "outlet A" sees a disallowed (in the sense that it must be closed according to law) water quality. The other beaches will still see a compromised water quality according to the limits used by HVMFS (2023) which is at or above 100 cfu/100 ml.

In the study by DHI (2018), the maximum value of *E. coli* concentrations reached in their model was around 250 cfu /100 ml at the location of "Pålsjöbaden" from ÖV2000b (In this study Pålsjöbaden is at beach D and wastewater outlet A, Figure 1). However, the observed values for *E. coli* at Pålsjöbaden and the other beaches, according to DHI (2018), were supposed to be higher. Something that this study does not account for is the added effect of the other sources of *E. coli*, which could be other wastewater outlets or resuspension from *E. coli* colonies in other sediment acting together, which is likely the case for the observed values. Other wastewater outlets were included in the study by DHI (2018), contributing to the total amount of *E. coli* found at the beaches. These other wastewater outlets and their addition to the total amount of *E. coli* were not considered in this study.

Paul et al. (2023) performed source tracking on 16 different sampling locations that contained *E. coli* affected sediment. These sediment samples differed in concentrations of *E. coli* and most of the sediment samples which contained high concentrations where close to the wastewater outlet ÖV2000b (Paul et al. 2023). From the DHI study (DHI 2018) it is known that there is enough sheer stress at the bottom to cause hyporheic exchange and resuspend the sediment in the area (DHI 2018). In retrospect, the one release of *E. coli* from the sediment, as assumed in this study, may not have been enough to account for the full effect the sediment may have on the water quality. The scenario in this study used a large release in one cell to account for all the small releases that could occur all over the bottom. For a better understanding and more accurate results, a finer grid, with particle releases from the sediment at different locations representing the actual concentration of *E. coli* would yield more accurate results.

Improvements could be made to the amount of *E. coli* released from the wastewater outlet. The released concentrations should be based on literature about concentrations of *E. coli* released from WWTP in Sweden instead of increasing the amount DHI (2018) used in their study, since this study uses a different method and time period.

The impact of *E. coli* decay on the simulated concentrations was less than expected. Only some increases could be noticed due to decay, particularly the differences between scenarios 1-3 at "Outlet A" concentrations during the first 20 days (Figure 5). Either the decay was implemented wrongly in the model, or it was due to high velocity of the stream (SMHI 2023) so that the effect of the decay could not be noticed. Further investigations into the decay impacts on the *E. coli* spread in this area are needed.

In the study conducted by Wolska et al. (2022) their decay constant greatly affected the resulting spread of the *E. coli* bacteria. In a future study, a decay constant like the one used by Wolska et al. (2022) (see K in equation 1.10) could be implemented as an improvement. It is important to note that their model used chemical interactions between the indicator bacteria and the sea and was more complex compared to this version of MITgcm. This functionality can be added to MITgcm as well (Broström 2024) for a more detailed/accurate representation of the *E. coli.* The limitation of the study by Wolska et al. (2022) was the difficulty in using the model as a forecast tool to predict the spread of *E. coli.* The variability of water quality variables, such as rainfall, stream currents and the volume and concentration of released wastewater, can quickly change and cause increased and decreased concentrations of *E. coli* in the model.

The vertical and horizontal spread of *E. coli* as a function of hydrodynamic conditions determined the concentrations at the beaches. The vertical spread is affected by the density, and the horizontal spread is affected by the speed and direction of the stream in water and wind. Salinity and water temperature cause a change in the water density in the cell and drive the vertical transport of *E. coli* (Table 1). The horizontal speed is determined by the speed and direction of the stream, which stems from the initial conditions. The direction and speed of the stream is dependent on the difference in water levels between Baltic Sea and Kattegat (SMHI 2023), but also the speed and direction of the wind. When *E. coli* spread vertically to the water surface, the speed and direction of the stream and the wind determined the spread of *E. coli.* The input data to the model (Table 1) affected these driving forces, for example, through the density calculations or the speed and direction of the wind and stream (MITgcm 2023).

The fine resolution of Dumasdelage et al. (2015) study of *E. coli* shows the vertical travel of the *E. coli* bacteria (which is released from a wastewater outlet located 38 meters below the surface). This may be a good illustration of how the *E. coli* bacteria rises vertically from the wastewater outlets and from the sediment. The fine resolution used in the study by Dumasdelage et al. (2015) is possible because of their smaller area of study -the place called “Paiole” on the coast of Nice, France. In their study the plume of *E. coli* travels from the bottom of the sea toward the surface almost undisturbed, because of the low impact from the seawater currents, and then spreads towards the beaches by the coast of Nice, because of the effect of wind on the movement of surface water. When there is a greater effect by the ocean currents on the plume, the *E. coli* dilutes more into the sea leading to less impact on water quality, compared to when the effect of the current was low (Dumasdelage et al. 2015). Similar phenomenon was observed in this study: the vertical travel of *E. coli* caused by density differences and the dilution of *E. coli* caused by stream currents.

Future studies could focus on a particle model for the different sediment releases based on an actual accurate estimation of *E. coli* decay. Also, an accurate description of the decay should be implemented in the model. It could also be of use to model summer period in different years. Something that also may be interesting is the releases of *E. coli* from the coastal cities southward, such as Malmö and Copenhagen. Since the stream is mostly towards the north it is not impossible that wastewater discharges from the neighboring cities could impact the water quality at Helsingborg. It would also be interesting to know the actual concentrations of *E coli* released from the WWTP outlet ÖV2000b.

5. Conclusions

1. The closer the beach is to the wastewater outlet (either wastewater outlet A, or B) or the sediment, the more *E. coli* can be seen affecting the beach.
2. *E. coli* released from the sediment does reach the beaches, but the levels of *E. coli* in the model are not large enough to decrease the water quality to the level of 100 cfu/100 ml by beaches A-E.
3. Moving the wastewater outlet further into the sea would lead to lower concentrations of *E. coli* reaching the beaches.
4. The MITgcm model yields valuable results about the transport of *E. coli* and could with a finer spatial resolution, more years modelled, and revised decay process produce more accurate results.

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Appendix

In the appendix, the different MATLAB scripts which was used during the study is presented. The code in script 2, called rdmds is an open-source code which can be found on the MITgcm website (MITgcm 2024).

Script 1:

```
%% Geometri
   o=40075e3 % Jordens omkrets
   0.004*o/360
   0.008*o/360*cos(55*pi/180)
% Baltikum 400 m

mit.lon=rdmds('./grid/XC');

   mit.lat=rdmds('./grid/YC');

   z=squeeze(rdmds('./grid/RC'));

   dz=rdmds('./grid/DRC');

   D=rdmds('./grid/Depth');
   D(D==0) = NaN;


   figure; pcolor(D'); shading flat; colorbar

     figure; pcolor(mit.lon,mit.lat,D); shading flat; colorbar
```

```
     Nx=656; x=((1:Nx)-1)*0.008+9.45;

     Ny=896; y=((1:Ny)-1)*0.004+53.9;

     Nz=70; dz=0.6+exp((1:Nz)/30); dz=dz*110/sum(dz); z=-cumsum(dz)+(dz/2);
%figure; plot(dz,z)
```

Script 2:

```
function [AA,itrs,MM] = rdmds(fnamearg,varargin)
% RDMDS Läser MITgcmUV meta/data
%
% A = RDMDS(FNAME)
% A = RDMDS(FNAME,ITER)
% A = RDMDS(FNAME,[ITER1 ITER2 ...])
% A = RDMDS(FNAME,NaN)
% A = RDMDS(FNAME,Inf)
% [A,ITS,M] = RDMDS(FNAME,[...])
% A = RDMDS(FNAME,[...],'rec',RECNUM)
%
%   A = RDMDS(FNAME) reads data described by meta/data file format.
%   FNAME is a string containing the "head" of the file names.
%
%   eg. To load the meta-data files
%       T.0000002880.000.000.meta, T.0000002880.000.000.data
%       T.0000002880.001.000.meta, T.0000002880.001.000.data
%       T.0000002880.002.000.meta, T.0000002880.002.000.data
%       T.0000002880.003.000.meta, T.0000002880.003.000.data
%   use
%      >> A=rdmds('T.0000002880');
%      >> size(A)
%   ans =
%      64    32     5
%   eg. To load a multiple record file
%      >> A=rdmds('pickup.0000002880');
%      >> size(A)
%   ans =
%      64    32     5    61
%
%
%   A = RDMDS(FNAME,ITER) reads data described by meta/data file format.
%   FNAME is a string containing the "head" of the file name excluding the
%   10-digit iterartion number.
%   ITER is a vector of positive integers that will expand to the 10-digit
%   number in the file name.
%   If ITER=NaN, all iterations were read.
%   If ITER=Inf, the last (highest) iteration were read.
%
%   eg. To repeat above operation
%      >> A=rdmds('T',2880);
%   eg. To read multiple time steps
%      >> A=rdmds('T',[0 1440 2880]);
%   eg. To read all time steps
%      >> [A,ITS]=rdmds('T',NaN);
%   eg. To read the last time step
%      >> [A,IT]=rdmds('T',Inf);
%   Note: this form can not read files with no iteration count in file name.
```

```
%
%
%   A = RDMDS(FNAME,[...],'rec',RECNUM) reads individual records from
%   multiple record files.
%
%   eg. To read a single record from a multi-record file
%      >> [A,IT]=rdmds('pickup.ckptA',11);
%   eg. To read several records from a multi-record file
%      >> [A,IT]=rdmds('pickup',Inf,'rec',[1:5 8 12]);
%
%
%   A = RDMDS(FNAME,ITER,MACHINEFORMAT) allows the machine format to be
%   A = RDMDS(FNAME,MACHINEFORMAT)
%   specified which MACHINEFORMAT is on of the following strings:
%     'n' 'l' 'b' 'd' 'g' 'c' 'a' 's'  - see FOPEN for more details
%

% $Header: /u/gcmpack/MITgcm/utils/matlab/rdmds.m,v 1.27 2013/05/15 23:10:49 jmc
Exp $
% $Name:  $

AA=[];
itrs=[];
MM=[];

% Default options
ieee='b';
fname=fnamearg;
userecords=0;
recnum=[];

% Check optional arguments
for ind=1:size(varargin,2);
 arg=varargin{ind};
 if ischar(arg)
  if strcmp(arg,'n') | strcmp(arg,'native')
   ieee='n';
  elseif strcmp(arg,'l') | strcmp(arg,'ieee-le')
   ieee='l';
  elseif strcmp(arg,'b') | strcmp(arg,'ieee-be')
   ieee='b';
  elseif strcmp(arg,'c') | strcmp(arg,'cray')
   ieee='c';
  elseif strcmp(arg,'a') | strcmp(arg,'ieee-le.l64')
   ieee='a';
  elseif strcmp(arg,'s') | strcmp(arg,'ieee-be.l64')
   ieee='s';
  elseif strcmp(arg,'rec')
   userecords=1;
  else
   error(['Optional argument ' arg ' is unknown'])
  end
 else
  if userecords==1
   recnum=arg;
  elseif isempty(itrs)
  if isnan(arg)
   itrs=scanforfiles(fname);
   disp([ sprintf('Reading %i time levels:',size(itrs,2)) sprintf(' %i',itrs) ]);
```

```
   elseif isinf(arg)
    itrs=scanforfiles(fname);
    if isempty(itrs)
     AA=[];itrs=[];return;
    end
    disp([ sprintf('Found %i time levels, reading %i',size(itrs,2),itrs(end)) ]);
    itrs=itrs(end);
 % elseif prod(double(arg>=0)) & prod(double(round(arg)==arg))
 % elseif prod(arg>=0) & prod(round(arg)==arg)
   elseif min(arg)>=0 & isempty(find(round(arg)~=arg))
    if arg>=9999999999
     error(sprintf('Argument %i > 9999999999',arg))
    end
    itrs=arg;
   elseif length(arg) == 1 & arg == -1
    itrs=arg;
   else
    error(sprintf('Argument %i must be a positive integer',arg))
   end
   else
    error('Multiple iterations should be specified as a vector')
   end
  end
 end

 if isempty(itrs)
  itrs=-1;
 end

 % Loop over each iteration
 for iter=1:size(itrs,2);
  if itrs(iter)>=0
   fname=sprintf('%s.%10.10i',fnamearg,itrs(iter));
  end

 % Figure out if there is a path in the filename
  NS=findstr('/',fname);
  if size(NS)>0
   Dir=fname(1:NS(end));
  else
   Dir='./';
  end

 % Match name of all meta-files
   %fprintf(' search for file "%s".*meta\n',fname);
  allfiles=dir( sprintf('%s.*meta',fname) );

  if size(allfiles,1)==0
   disp(sprintf('No files match the search: %s.*meta',fname));
  %allow partial reads%  error('No files found.')
  end

 % LOOP SOM FIXAR ALLA FILER ISTÄLLET FÖR EN
  for j=1:size(allfiles,1);
   %fprintf(' file # %3i : %s\n',j,allfiles(j).name);

 % Read meta- and data-file
   [A,N,M,mG] = localrdmds([Dir allfiles(j).name],ieee,recnum);
```

```
%- Merge local Meta file content (M) to MM string:
  if j > 0, %- to comment out this block: "if j < 0" (since j is always > 0)
   ii=findstr(M,' timeStepNumber');
   if isempty(ii), ii1=0; ii2=0;
   else ii1=ii; ii2=ii+min(findstr(M(1+ii:end),'];')); end
   ii=findstr(M,' timeInterval');
   if isempty(ii), jj1=0; jj2=0;
   else jj1=ii; jj2=ii+min(findstr(M(1+ii:end),'];')); end
   if iter==1 & j==1,
    MM=M; ind1=0; ind2=0; is1=ii1; js1=jj1; M3='';
    if ii1*jj1 > 0,
     %ind1=min(ii1,jj1); ind2=max(ii2,jj2);
     %if ii1 < jj1, ii3=ii2+1; jj3=jj1-1;
     %else  ii3=jj2+1; jj3=ii1-1; end
      order=sort([ii1 ii2 jj1 jj2]);
      ind1=order(1); ii3=order(2)+1; jj3=order(3)-1; ind2=order(4);
      M2=M(ii1:ii2); M4=M(jj1:jj2); M3=M(ii3:jj3);
    elseif ii1 > 0,
      ind1=ii1; ind2=ii2;
      M2=M(ii1:ii2); M4='';
    elseif jj1 > 0,
      ind1=jj1; ind2=jj2;
      M4=M(jj1:jj2); M2='';
    end
    M5=M(1+ind2:end);
    %fprintf(' ii1,ii2 = %i %i ; jj1,jj2= %i %i ;', ii1,ii2, jj1,jj2);
    %fprintf(' ii3,jj3= %i %i ; ind1,ind2= %i %i\n',ii3,jj3,ind1,ind2);
    %fprintf('M(1:ind1)=%s<\n',M(1:ind1));
    %fprintf(' M2=%s<\n',M2);
    %fprintf(' M3=%s<\n',M3);
    %fprintf(' M4=%s<\n',M4);
    %fprintf(' M5=%s<\n',M5);
   else
    if ii1*jj1 > 0,
        order=sort([ii1 ii2 jj1 jj2]);
        ind=order(1); ii3=order(2)+1; jj3=order(3)-1; ind2=order(4);
    else ind=max(ii1,jj1); ind2=ii2+jj2; end
    compar=(ind == ind1);    ii=0;
    if compar & ind1 == 0,   ii=1; compar=strcmp (MM,M); end
    if compar & ind1 > 0,    ii=2; compar=strncmp(MM,M,ind1) ; end
    if compar & ind1 > 0,    ii=3; compar=strcmp(M5,M(1+ind2:end)); end
    if compar & ii1*jj1 > 0, ii=4; compar=strcmp(M3,M(ii3:jj3)); end
    if ~compar,
     fprintf('WARNING: Meta file (%s) is different (%i) from 1rst one:\n', ...
              allfiles(j).name,ii);
     fprintf(' it=%i :MM:%s\n',itrs(1),MM);
     fprintf(' it=%i :M :%s\n\n',itrs(iter),M);
    elseif ind1 > 0,
     if ii1 > 0,
      Mj=M(ii1:ii2); ii=findstr(Mj,'['); Mj=Mj(1+ii:end);
%   add it-number from Mj to M2 (if different):
      if isempty(findstr(M2,Mj)), M2=[deblank(M2(1:end-1)),Mj]; end
     end
     if jj1 > 0,
      Mj=M(jj1:jj2); ii=findstr(Mj,'['); Mj=Mj(1+ii:end);
%   add time interval from Mj to M4 (if different):
      if isempty(findstr(M4,Mj)), M4=[deblank(M4(1:end-1)),' ;',Mj]; end
     end
    end
```

```
   end
%  save modifications:
   if ind1>0 & j==size(allfiles,1) & iter==size(itrs,2),
     if ii1 < jj1, MM=[MM(1:ind1-1),M2,M3,M4,M5];
     else          MM=[MM(1:ind1-1),M4,M3,M2,M5]; end
   end
  end

%- put local data file content in global array AA:
  bdims=N(1,:);
  r0=N(2,:);
  rN=N(3,:);
  ndims=prod(size(bdims));
  if j==1 & iter==1, AA=zeros([bdims size(itrs,2)]); end
  if mG(1)==0 & mG(2)==1,
    if      (ndims == 1)
     AA(r0(1):rN(1),iter)=A;
    elseif (ndims == 2)
     AA(r0(1):rN(1),r0(2):rN(2),iter)=A;
    elseif (ndims == 3)
     AA(r0(1):rN(1),r0(2):rN(2),r0(3):rN(3),iter)=A;
    elseif (ndims == 4)
     AA(r0(1):rN(1),r0(2):rN(2),r0(3):rN(3),r0(4):rN(4),iter)=A;
    elseif (ndims == 5)
     AA(r0(1):rN(1),r0(2):rN(2),r0(3):rN(3),r0(4):rN(4),r0(5):rN(5),iter)=A;
    else
     error('Dimension of data set is larger than currently coded. Sorry!')
    end
  elseif      (ndims == 1)
     AA(r0(1):rN(1),iter)=A;
  else
%- to debug: do simple stransfert (with a loop on 2nd index);
%  will need to change this later, to improve efficiency:
   for i=0:rN(2)-r0(2),
    if (ndims == 2)
     AA(r0(1)+i*mG(1):rN(1)+i*mG(1),r0(2)+i*mG(2),iter)=A(:,1+i);
    elseif (ndims == 3)
     AA(r0(1)+i*mG(1):rN(1)+i*mG(1),r0(2)+i*mG(2), ...
                               r0(3):rN(3),iter)=A(:,1+i,:);
    elseif (ndims == 4)
     AA(r0(1)+i*mG(1):rN(1)+i*mG(1),r0(2)+i*mG(2), ...
                   r0(3):rN(3),r0(4):rN(4),iter)=A(:,1+i,:,:);
    elseif (ndims == 5)
     AA(r0(1)+i*mG(1):rN(1)+i*mG(1),r0(2)+i*mG(2), ...
            r0(3):rN(3),r0(4):rN(4),r0(5):rN(5),iter)=A(:,1+i,:,:,:);
    else
     error('Dimension of data set is larger than currently coded. Sorry!')
    end
   end
  end

 end % files
end % iterations

%-----------------------------------------------------------------------------

function [A,N,M,map2glob] = localrdmds(fname,ieee,recnum)

mname=strrep(fname,' ','');
```

```
dname=strrep(mname,'.meta','.data');

%- set default mapping from tile to global file:
map2glob=[0 1];

% Read and interpret Meta file
fid = fopen(mname,'r');
if (fid == -1)
 error(['File' mname ' could not be opened'])
end

% Scan each line of the Meta file
allstr=' ';
keepgoing = 1;
while keepgoing > 0,
 line = fgetl(fid);
 if (line == -1)
  keepgoing=-1;
 else
% Strip out "(PID.TID *.*)" by finding first ")"
%old  ind=findstr([line ')'],')'); line=line(ind(1)+1:end);
  ind=findstr(line,')');
  if size(ind) ~= 0
    line=line(ind(1)+1:end);
  end
% Remove comments of form //
  line=[line,' //']; ind=findstr(line,'//'); line=line(1:ind(1)-1);
% Add to total string (without starting & ending blanks)
  while line(1:1) == ' ', line=line(2:end); end
  if strncmp(line,'map2glob',8), eval(line);
  else allstr=[allstr,deblank(line),' '];
  end
 end
end

% Close meta file
fclose(fid);

% Strip out comments of form /* ... */
ind1=findstr(allstr,'/*'); ind2=findstr(allstr,'*/');
if size(ind1) ~= size(ind2)
 error('The /* ... */ comments are not properly paired')
end
while size(ind1,2) > 0
 allstr=[deblank(allstr(1:ind1(1)-1)) allstr(ind2(1)+2:end)];
%allstr=[allstr(1:ind1(1)-1) allstr(ind2(1)+3:end)];
 ind1=findstr(allstr,'/*'); ind2=findstr(allstr,'*/');
end

% This is a kludge to catch whether the meta-file is of the
% old or new type. nrecords does not exist in the old type.
nrecords = NaN;

%- store the full string for output:
M=strrep(allstr,'format','dataprec');

% Everything in lower case
allstr=lower(allstr);
```

```
% Fix the unfortunate choice of 'format'
allstr=strrep(allstr,'format','dataprec');

% Evaluate meta information
eval(allstr);

N=reshape( dimlist , 3 , prod(size(dimlist))/3 );
rep=[' dimList = [ ',sprintf('%i ',N(1,:)),']'];
if ~isnan(nrecords) & nrecords > 1 & isempty(recnum)
 N=[N,[nrecords 1 nrecords]'];
elseif ~isempty(recnum) & recnum>nrecords
 error('Requested record number is higher than the number of available records')
end

%- make "dimList" shorter (& fit output array size) in output "M":
 pat=' dimList = \[(\s*\d+\,?)*\s*\]';
 M=regexprep(M,pat,rep);
%  and remove double space within sq.brakets:
ind1=findstr(M,'['); ind2=findstr(M,']');
if length(ind1) == length(ind2),
 for i=length(ind1):-1:1, if ind1(i) < ind2(i),
  M=[M(1:ind1(i)),regexprep(M(ind1(i)+1:ind2(i)-1),'(\s+)',' '),M(ind2(i):end)];
 end; end
else error('The [ ... ] brakets are not properly paired')
end

if isempty(recnum)
 recnum=1;
end

if isnan(nrecords)
% This is the old 'meta' method that used sequential access

A=allstr;
% Open data file
fid=fopen(dname,'r',ieee);

% Read record size in bytes
recsz=fread(fid,1,'uint32');
ldims=N(3,:)-N(2,:)+1;
numels=prod(ldims);

rat=recsz/numels;
if rat == 4
 A=fread(fid,numels,'real*4');
elseif rat == 8
 A=fread(fid,numels,'real*8');
else
 sprintf(' Implied size in meta-file = %d', numels )
 sprintf(' Record size in data-file = %d', recsz )
 error('Ratio between record size and size in meta-file inconsistent')
end

erecsz=fread(fid,1,'uint32');
if erecsz ~= recsz
 sprintf('WARNING: Record sizes at beginning and end of file are inconsistent')
end

fclose(fid);
```

```
A=reshape(A,ldims);

else
% This is the new MDS format that uses direct access

 ldims=N(3,:)-N(2,:)+1;
 for r=1:size(recnum(:),1);
 if dataprec == 'float32'
  A(:,r)=myrdda(dname,ldims,recnum(r),'real*4',ieee);
 elseif dataprec == 'float64'
  A(:,r)=myrdda(dname,ldims,recnum(r),'real*8',ieee);
 else
  error(['Unrecognized format in meta-file = ' format]);
 end
 end

 A=reshape(A,[ldims size(recnum(:),1)]);
 if size(recnum(:),1)>1
  N(1,end+1)=size(recnum(:),1);
  N(2,end)=1;
  N(3,end)=size(recnum(:),1);
 end

end

%-------------------------------------------------------------------------------

% result = RDDA( file, dim, irec [options] )
%
% This routine reads the irec'th record of shape 'dim' from the
% direct-access binary file (float or double precision) 'file'.
%
% Required arguments:
%
%   file  - string  - name of file to read from
%   dim   - vector  - dimensions of the file records and the resulting array
%   irec  - integer - record number in file in which to write data
%
% Optional arguments (must appear after the required arguments):
%   prec  - string  - precision of storage in file. Default = 'real*8'.
%   ieee  - string  - IEEE bit-wise representation in file. Default = 'b'.
%
% 'prec' may take the values:
%       'real*4' - floating point, 32 bits.
%       'real*8' - floating point, 64 bits - the efault.
%
% 'ieee' may take values:
%    'ieee-be'     or 'b' - IEEE floating point with big-endian
%                           byte ordering - the default
%    'ieee-le'     or 'l' - IEEE floating point with little-endian
%                           byte ordering
%    'native'      or 'n' - local machine format
%    'cray'        or 'c' - Cray floating point with big-endian
%                           byte ordering
%    'ieee-le.l64' or 'a' - IEEE floating point with little-endian
%                           byte ordering and 64 bit long data type
%    'ieee-be.l64' or 's' - IEEE floating point with big-endian byte
%                           ordering and 64 bit long data type.
```

```
%
% eg.   T=rdda('t.data',[64 64 32],1);
%       T=rdda('t.data',[256],4,'real*4');
%       T=rdda('t.data',[128 64],2,'real*4','b');
function [arr] = myrdda(file,N,k,varargin)

% Defaults
WORDLENGTH=8;
rtype='real*8';
ieee='b';

% Check optional arguments
args=char(varargin);
while (size(args,1) > 0)
 if deblank(args(1,:)) == 'real*4'
  WORDLENGTH=4;
  rtype='real*4';
 elseif deblank(args(1,:)) == 'real*8'
  WORDLENGTH=8;
  rtype='real*8';
 elseif deblank(args(1,:)) == 'n' | deblank(args(1,:)) == 'native'
  ieee='n';
 elseif deblank(args(1,:)) == 'l' | deblank(args(1,:)) == 'ieee-le'
  ieee='l';
 elseif deblank(args(1,:)) == 'b' | deblank(args(1,:)) == 'ieee-be'
  ieee='b';
 elseif deblank(args(1,:)) == 'c' | deblank(args(1,:)) == 'cray'
  ieee='c';
 elseif deblank(args(1,:)) == 'a' | deblank(args(1,:)) == 'ieee-le.l64'
  ieee='a';
 elseif deblank(args(1,:)) == 's' | deblank(args(1,:)) == 'ieee-be.l64'
  ieee='s';
 else
  error(['Optional argument ' args(1,:) ' is unknown'])
 end
 args=args(2:end,:);
end

nnn=prod(N);

[fid mess]=fopen(file,'r',ieee);
if fid == -1
 error('Error while opening file:\n%s',mess)
end
st=fseek(fid,nnn*(k-1)*WORDLENGTH,'bof');
if st ~= 0
 mess=ferror(fid);
 error('There was an error while positioning the file pointer:\n%s',mess)
end
[arr count]=fread(fid,nnn,rtype);
if count ~= nnn
 error('Not enough data was available to be read: off EOF?')
end
st=fclose(fid);
%arr=reshape(arr,N);

%
function [itrs] = scanforfiles(fname)
```

```
itrs=[];
allfiles=dir([fname '.*.001.001.meta']);
if isempty(allfiles)
 allfiles=dir([fname '.*.meta']);
 ioff=0;
else
 ioff=8;
end
for k=1:size(allfiles,1);
 hh=allfiles(k).name;
 itrs(k)=str2num( hh(end-14-ioff:end-5-ioff) );
end
itrs=sort(itrs);
```

Script 3

```
repts = 795;
Cmax = zeros(Nx, Ny, Nz);
freq_1 = zeros(Nx, Ny, Nz);
clear Ser; clear Ser2; clear Ser3; clear Ser4;clear Ser5;clear Ser6;clear Ser7;
for i = 1:repts
    P = rdmds('PTRACER01',(i * 360))*14000;
    Cmax = max(Cmax, P);
    is = find(P > 500);
    %Ser(i,:)=P(403,532,:); %Utsläpp A
    Ser1(i,:)=P(403,533,:); %Utsläpp B
    Ser2(i,:)=P(403,539,:); %örestrandbadet södra, strand B
    Ser3(i,:)=P(403,540,:); % -11- norra strand C
    Ser4(i,:)=P(404,536,:); %%Tropiska stranden, strand A
    Ser5(i,:)=P(402,542,:); %Pålsjöbadet Strand D
    Ser6(i,:)=P(401,543,:); %Vikingstrand E
    %Ser7(i,:)=P(406,527,:); %Utsläpp C, skit utloppet
    if ~isempty(is)
        freq_1(is) = freq_1(is) + 1;
    end
end

%%

freq_1 = freq_1 / repts;
iz = 1; %1 13 18
Cmax(id)=NaN;
Cmax_2D = max(Cmax, [], 3);
figure;
pcolor(Cmax_2D');
pcolor(permute(Cmax(:,:,iz), [2, 1]));
pcolor(mit.lon,mit.lat,Cmax(:,:,iz));
shading flat;
colorbar; %använd jet
colormap jet;
title('Plot B, Scenario 9, at depth 0.55 meters') %0.55, 8.2 meters, 12 meters
clim([0 1000])
xlim([12.45 12.85]);
ylim([55.8 56.2]);


%%
```

```
axes ('FontSize',[12])
hold on;
Y=Ser1(:,1); Y2 =Ser4(:,1); Y3 = Ser2(:,1); Y4=Ser3(:,1); Y5=Ser5(:,1); Y6 =
Ser6(:,1);
%Y1=Ser1(:,1);
X1=(1:repts)*3*3600/86400+datenum(2019,6,19);
plot(X1,Y,X1,Y2,X1,Y3,X1,Y4,X1,Y5,X1,Y6,'LineWidth',1)
yline(500)
yline(100)
datetick;
grid on;
xlabel('2019','FontSize',[16]);
ylabel('Cfu/100 ml ','FontSize',[16]);
title('Plot A, Scenario 10')
legend('Outlet A', 'Beach A', 'Beach B','Beach C', 'Beach D','Beach E')
%%
axes ('FontSize',[12])
hold on;
Y1=Ser1(:,1);
X1=(1:repts)*3*3600/86400+datenum(2019,5,1);
plot(X1,Y1)
yline(0.05)
datetick;
grid on;
xlabel('2019','FontSize',[16]);
ylabel('Cfu*10^-4/100 ml ','FontSize',[16]);
title('Concentrations at outlet A')
legend('Surface', 'Middle, 5.4 m', 'Bottom, 11.3 m');
%%
axes ('FontSize',[12])
hold on;
Y1=Ser1(:,1); Y2 =Ser1(:,11); Y3=Ser1(:,22);
X1=(1:repts)*3*3600/86400+datenum(2019,5,1);
plot(X1,Y1,X1,Y2,X1,Y3,'LineWidth',1)
yline(0.05)
datetick;
grid on;
xlabel('2019','FontSize',[16]);
ylabel('Cfu*10^-4/100 ml ','FontSize',[16]);
title('Concentrations at outlet B')
legend('Surface', 'Middle, 6.8 m', 'Bottom, 15.5 m');
%%
axes ('FontSize',[12])
hold on;
Y1=Ser2(:,1); Y2 =Ser2(:,4); Y3=Ser2(:,7);
X1=(1:repts)*3*3600/86400+datenum(2019,5,1);
plot(X1,Y1,X1,Y2,X1,Y3,'LineWidth',1)
yline(0.05)
datetick;
grid on;
xlabel('2019','FontSize',[16]);
ylabel('Cfu*10^-4/100 ml ','FontSize',[16]);
title('Concentrations at beach B, 5.65 km from the outlet')
legend('Surface', 'Middle, 2.3 m', 'Bottom, 4.1 m');
%%
axes ('FontSize',[12])
hold on;
Y1=Ser3(:,1); Y2 =Ser3(:,3); Y3=Ser3(:,6);
X1=(1:repts)*3*3600/86400+datenum(2019,5,1);
```

```
plot(X1,Y1,X1,Y2,X1,Y3,'LineWidth',1)
yline(0.05)
datetick;
grid on;
xlabel('2019','FontSize',[16]);
ylabel('Cfu*10^-4/100 ml ','FontSize',[16]);
title('Concentrations at beach C, 6.14 km from outlet')
legend('Surface', 'Middle, 1.7 m', 'Bottom, 3.5 m');
%%
axes ('FontSize',[12])
hold on;
Y1=Ser4(:,1); Y2 =Ser4(:,4); Y3=Ser4(:,8);
X1=(1:repts)*3*3600/86400+datenum(2019,5,1);
plot(X1,Y1,X1,Y2,X1,Y3,'LineWidth',1)
yline(0.05)
datetick;
grid on;
xlabel('2019','FontSize',[16]);
ylabel('Cfu*10^-4/100 ml ','FontSize',[16]);
title('Concentrations at beach A, 4.3 km from outlet')
legend('Surface', 'Middle, 8.2 m', 'Bottom, 19.45 m');
%%
axes ('FontSize',[12])
hold on;
Y1=Ser5(:,1); Y2 =Ser5(:,2); Y3=Ser5(:,5);
X1=(1:repts)*3*3600/86400+datenum(2019,5,1);
plot(X1,Y1,X1,Y2,X1,Y3,'LineWidth',1)
yline(0.05)
grid on;
datetick;
xlabel('2019','FontSize',[16]);
ylabel('Cfu*10^-4/100 ml ','FontSize',[16]);
title('Concentrations at beach D, 6.6 km from the outlet')
legend('Surface', 'Middle, 1.1 m', 'Bottom, 2.9 m');
%%
axes ('FontSize',[12])
hold on;
Y1=Ser6(:,1); Y2 =Ser6(:,2); Y3=Ser6(:,5);
X1=(1:repts)*3*3600/86400+datenum(2019,5,1);
plot(X1,Y1,X1,Y3,'LineWidth',1)
yline(0.05)
datetick;
grid on;
xlabel('2019','FontSize',[16]);
ylabel('Cfu*10^-4/100 ml ','FontSize',[16]);
title('Concentrations at beach E, 7.53 km from the outlet')
legend('Surface', 'Bottom, 2.9 m')
```

Script 4:

```
%%
v = VideoWriter("Scenario 9","MPEG-4");
WriterObj.FrameRate = 3;
iz = 1;
WriterObj.Quality = 10;
open(v);
repts = 795;
Cmax = zeros(Nx, Ny, Nz);
freq_1 = zeros(Nx, Ny, Nz);
```

```
clear Ser; clear Ser2; clear Ser3; clear Ser4;clear Ser5;clear Ser6;clear Ser7;
for i = 1:repts
    P = rdmds('PTRACER01',i*360)*14000; %14000 för rör, 2000 för sediment?
    Cmax = max(Cmax, P);
    is = find(P > 500);
    Ser(i,:)=P(405,533,:); %Utsläpp A
    Ser1(i,:)=P(402,533,:); %Utsläpp B
    Ser2(i,:)=P(403,539,:); %örestrandbadet södra, strand B
    Ser3(i,:)=P(403,540,:); % -11- norra strand C
    Ser4(i,:)=P(404,536,:); %%Tropiska stranden, strand A
    Ser5(i,:)=P(402,542,:); %Pålsjöbadet Strand D
    Ser6(i,:)=P(401,543,:); %Vikingstrand E
    %Ser7(i,:)=P(406,527,:); %Utsläpp C, skit utloppet
    if ~isempty(is)
        freq_1(is) = freq_1(is) + 1;
    end
    P(id)=NaN;
    h = figure(1);
    clf;
    pcolor(mit.lon,mit.lat,P(:,:,1));
    shading flat;
    colorbar;
    clim([0 1000])
    %quiver on;
    time=datenum(2019,6,19,00,00,00)+(3600*(3*(i-1))/86400);
    title(['Ptracer time: ',datestr(time,'yyyy mm dd hh'),': z=
',num2str(z(iz),'%.1f'),'m'])
    xlim([12.45 12.85]);
    ylim([55.8 56.2]);
    drawnow;
    frame = getframe(gcf);
    writeVideo(v,frame);
    %saveas(h,sprintf('FIG%d.png',i));
    %hold on
end
close(WriterObj);
thisimage=imread
%% Filmz

P = rdmds('PTRACER01',360);
P(P==0)= NaN;
id = isnan(P);
%P(id)=NaN;
h = figure(1);
pcolor(mit.lon,mit.lat,P(:,:,1));
shading flat;
    colorbar;
    clim([0 2]*1e-2)
    title(['Helsingborg A'])
    time=datenum(2019,5,1,0,00,00)+(3600*(i-1)/86400);
   xlim([12.45 12.85]);
   ylim([55.8 56.2]);

    drawnow;

%%
P = rdmds('PTRACER02',6480);
%P(P==0)= NaN;
%id = isnan(P);
```

```
P(id)=NaN;
h = figure(1);
P1=P*1300;
pcolor(mit.lon,mit.lat,P1(:,:,1));
shading flat;
    colorbar;
    clim([0 50])
    title(['Helsingborg A'])
    time=datenum(2019,5,1,0,00,00)+(3600*(i-1)/86400);
   xlim([12.45 12.85]);
   ylim([55.8 56.2]);

    drawnow;
    %%
    P = rdmds('PTRACER04',36720);
%P(P==0)= NaN;
%id = isnan(P);
P(id)=NaN;
h = figure(1);
pcolor(mit.lon,mit.lat,P(:,:,1));
shading flat;
    colorbar;
    clim([0 2]*1e-2)
    title(['Malmö C'])
    time=datenum(2019,5,1,0,00,00)+(3600*(i-1)/86400);
    xlim([12.55 13.00]);
    ylim([55.5 56.15]);
    drawnow;
    %%
    P = rdmds('PTRACER04',54720);
%P(P==0)= NaN;
%id = isnan(P);
P(id)=NaN;
h = figure(1);
pcolor(mit.lon,mit.lat,P(:,:,1));
shading flat;
    colorbar;
    clim([0 2]*1e-2)
    title(['Malmö D'])
    time=datenum(2019,5,1,0,00,00)+(3600*(i-1)/86400);
    xlim([12.55 13.00]);
    ylim([55.5 56.15]);
    drawnow;
```

Script 5:

```
       Nx=656; x=((1:Nx)-1)*0.008+9.45;

       Ny=896; y=((1:Ny)-1)*0.004+53.9;

       Nz=70; dz=0.6+exp((1:Nz)/30); dz=dz*110/sum(dz); z=-cumsum(dz); %figure;
plot(dz,z)

   S(1:Nx,1:Ny,1:Nz,1:100)=1e-30;

   S(405:406,525:526,1:Nz,1:10)=1/86400;

   fid=fopen('ecoli1.bin','w','b');
```

```
   fwrite(fid,S,'real*4');

   fclose(fid); %helsingborg



   S(1:Nx,1:Ny,1:Nz,1:10)=1e-30;

   S(418:419,482:483,1:Nz,1:10)=1/86400;

   fid=fopen(['ecoli2.bin'],'w','b'); fwrite(fid,S,'real*4');  fclose(fid);
%landskrona



   S(1:Nx,1:Ny,1:Nz,1:10)=1e-30;

   S(398:399,528:529,1:Nz,1:10)=1/86400;

   fid=fopen(['ecoli3.bin'],'w','b'); fwrite(fid,S,'real*4');  fclose(fid);
%helsingör


   S(1:Nx,1:Ny,1:Nz,1:10)=1e-30;

   S(417:418,428:429,1:Nz,1:10)=1/86400; %malmö

   fid=fopen(['ecoli4.bin'],'w','b'); fwrite(fid,S,'real*4');  fclose(fid);%malmö

   S(1:Nx,1:Ny,1:Nz,1:10)=1e-30;

   S(396:397,458:459,1:Nz,1:10)=1/86400;

   fid=fopen(['ecoli5.bin'],'w','b'); fwrite(fid,S,'real*4');  fclose(fid);
%Copenhagen

   % Hitta gridpunkt
%%
xm = mit.lon;
%12.685450 12.685950 12.678867]; % xm matris med lon
ym = mit.lat;
%56.030650 56,029017 56.031750]; % ym matris med lat

   pos.lon=[12.85]% 12.45]
   pos.lat=[56.2]%55.8]

   for ii=1:1; pos.i=ii;y

     dmin=min(min(sqrt((pos.lon(pos.i)-xm).^2+(pos.lat(pos.i)-ym).^2)));

     [dix,diy]=find(dmin==sqrt((pos.lon(pos.i)-xm).^2+(pos.lat(pos.i)-ym).^2));

     disp([pos.i dix diy])

     pos.ix(ii)=dix; pos.iy(ii)=diy;

   end
```