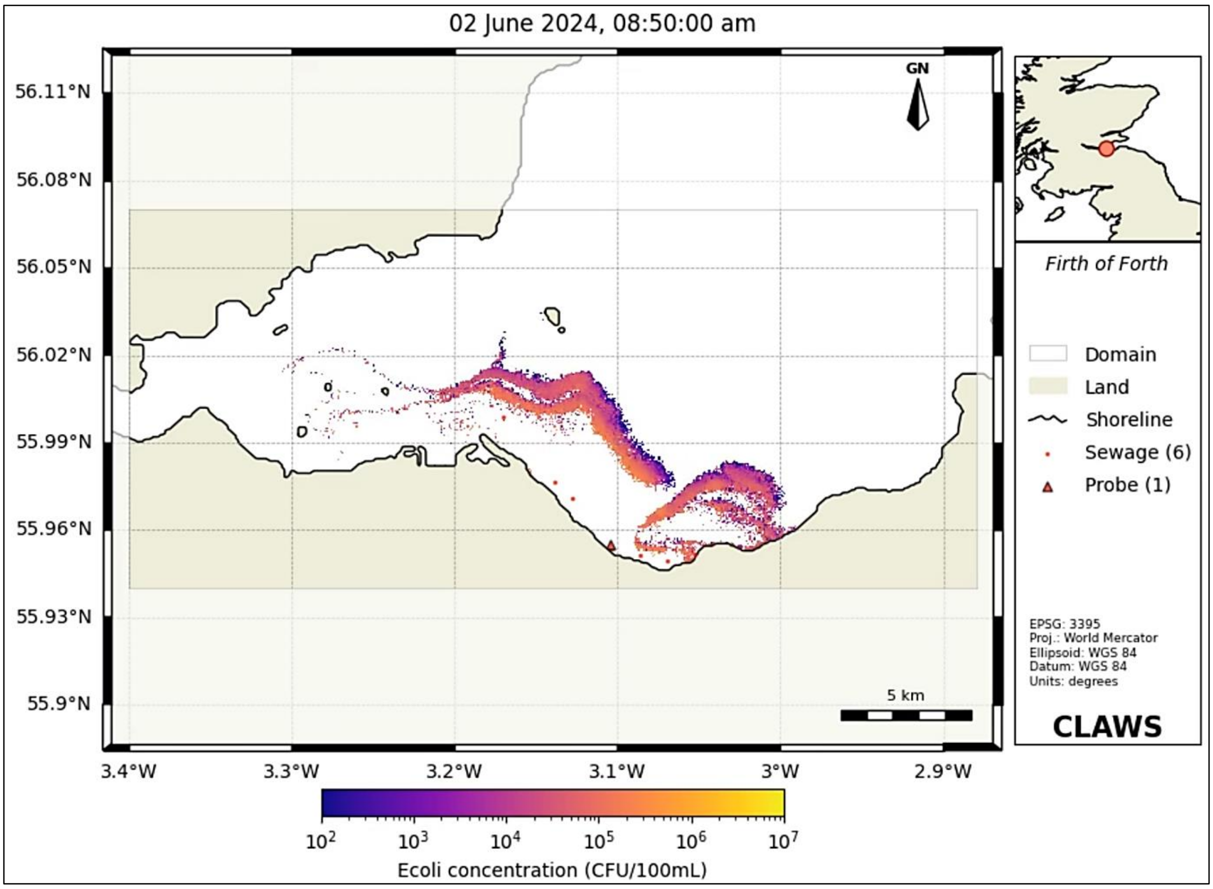
A Hydrodynamic and Biological (E.coli) Model of the Firth of Forth

Dr Tom Scanlon, Dr Matt Stickland

MTS-CFD Limited

Email: mtscfd@gmail.com

Web: www.mts-cfd.com



Executive Summary

A detailed hydrodynamic and biological model of Escherichia coli (E.coli) has been developed in order better understand the E.coli dispersion from Combined Sewer Overflows (CSOs) in the Firth of Forth and assess the risk that bathers and other recreational water users may be harmed by E.coli emanating from CSO's in the area.

A 24-hour raw sewage spill from 6 CSOs in the area surrounding Portobello beach has been modelled over 4-days in May 2023. Results for the average E.coli field show that there is evidence of dispersion over a wide area of the Firth of Forth.

Snapshots of the instantaneous E.coli concentration fields show how the E.coli is likely to evolve with time and provide evidence of high spatial and temporal variability, constantly dynamic and highly transient in nature.

E.coli levels decay as a function of salinity, temperature and light with peak concentrations taking around 2.2 days from the end of the spillage to fall below acceptable environmental quality standards (EQS).

Virtual probes in the model near Portobello beach indicate that E.coli concentrations in excess of the acceptable EQS are likely to persist for just over 2 days.

It may be possible to run the hydro-biological model for each month of the year and create a simple App to inform users of the likely time to wait before safely entering the water following a CSO spillage.

About the Report Authors

Dr Tom Scanlon *BEng PhD CEng MIMechE, Engineering Consultant, MTS-CFD.com*

Tom is a chartered professional engineer with over 25 years' experience in applied computational mechanics. After a first degree in Environmental Engineering at the University of Strathclyde, Tom undertook a Ph.D in Vortex Shedding Flowmeter Pulsating Flow Computational Fluid Dynamics (CFD) Studies at the same university. Subsequently, he was awarded a JM Lessels scholarship from the Royal Society of Edinburgh for a one-year post-doctoral position at the Institute de Mécanique des Fluides de Toulouse, France in the field of numerical oceanography. The IMechE presented Tom with the Alfred Rosling Bennett Premium and Charles S Lake Award in 2003 for CFD in applied aerodynamics. In 2013 Tom returned from an EPSRC-funded sabbatical in the USA, where he carried out fundamental research in rarefied gas dynamics at the University of Michigan and the Lawrence Berkeley Laboratory in California. From 1994-2017 he was a Senior Lecturer in the Department of Mechanical and Aerospace Engineering at the University of Strathclyde specialising in heat transfer, fluid mechanics and applied CFD. His work is reported in over 50 refereed journal and conference publications. He is currently a director at the engineering consultancy firm MTS-CFD.

Dr Matt Stickland *BSc PhD CEng FIMechE, Engineering Consultant, MTS-CFD.com*

After a first degree in Aeronautical Engineering at the University of Manchester, Matt worked for BAE Systems (Military Aircraft) at Warton in Lancashire in the Wind Tunnel Department working on projects which included EAP, EFA (Typhoon), Tornado and HOTOL. After leaving BAE in 1990 Matt worked for YARD Consulting Engineers in Glasgow modelling the heat and fluid flows in Advanced Gas Cooled reactors during on-load refuelling. In 1991 Matt accepted a senior lectureship in the Department of Mechanical Engineering at the University of Strathclyde where his research interest covered both experimental and computational heat transfer and fluid dynamics. He was awarded a PhD for his research into 3D imaging and its application to fluid flow visualisation. For his research in the field of experimental and computational fluid dynamics he was awarded the 2003 AR Bennett Premium/CS Lake Award and the 2004 T A Stewart-Dyer Prize/Frederick Harvey Trevithick Prize from the Institute of Mechanical Engineers. In 2022 Matt left the University of Strathclyde to take a directorship with the Engineering consultancy firm MTS-CFD. Matt is a Chartered Engineer and a Fellow of the Institute of Mechanical Engineers. He has published his research in over 100 papers in refereed journal and conference proceedings.

1 Introduction and Motivation

The Firth of Forth, a prominent estuary in eastern Scotland, is a vital ecological zone and recreational area. However, it faces significant environmental challenges, particularly concerning the contamination of its waters by Escherichia coli (E. coli) bacteria. E. coli, commonly found in the intestines of warm-blooded organisms, often enters aquatic environments through sewage, Combined Sewer Overflows (CSOs), and agricultural runoff. This contamination poses substantial risks to both wildlife and human health, especially around popular coastal areas such as Portobello, Joppa and Musselburgh.

1.1. *Sources of E. coli Contamination*

1. **Sewage Discharges:** Inadequate sewage treatment facilities or infrastructure failures can lead to the direct discharge of untreated or partially treated sewage into the Firth of Forth. This sewage often contains high levels of E. coli, significantly contaminating the water.

2. **Combined Sewer Overflows (CSOs):** CSOs are designed to handle excess rainwater by mixing it with sewage before releasing it into water bodies during heavy rainfall. Unfortunately, this practice also releases E. coli and other contaminants, especially during periods of intense or prolonged precipitation.

3. **Agricultural Runoff:** Runoff from agricultural lands, particularly those practicing intensive livestock farming, can carry significant amounts of E. coli from animal faeces. This runoff enters the Firth of Forth through rivers and streams, further contributing to bacterial contamination.

1.2 *Impact on Local Beaches*

The beaches at Portobello and Musselburgh are renowned for their natural beauty and recreational opportunities, attracting swimmers, water sports enthusiasts, and nature lovers. However, the presence of E. coli in these waters raises serious health concerns. Swimmers and other recreational users are at risk of waterborne illnesses, which can manifest as gastrointestinal infections, skin rashes, and more severe health issues in vulnerable individuals.

The ecological impact is also significant. Elevated E. coli levels can disrupt local ecosystems, harming marine life and degrading the natural habitat. The overall water quality decline can affect the biodiversity of the Firth of Forth, posing a threat to various aquatic species.

1.3 *Mitigation and Public Awareness*

Efforts to mitigate E. coli contamination in the Firth of Forth involve improving sewage treatment infrastructure, enhancing agricultural practices to reduce runoff, and implementing better stormwater management systems. Public awareness campaigns are crucial to inform both locals and visitors about the potential health risks and promote environmentally responsible behaviours.

Addressing E. coli contamination in the Firth of Forth is essential to safeguarding the health of its ecosystems and ensuring the safety and enjoyment of its recreational waters. Protecting areas like the Portobello and Musselburgh beaches requires coordinated action from government agencies, Scottish Water, environmental organizations, and the community at large.

1.4 *A New Hydrodynamic and Biological Model*

In an attempt to better comprehend the above issues and inform thinking, MTS-CFD has created a detailed hydrodynamic and biological computer model of the Firth of Forth.

The key features and goals of the new hydrodynamic/E.coli model may be summarised as follows:

1) Provide a better understanding of the effects of combined sewer overflow (CSO) E.coli pollution events using state-of-the-science computer modelling.
2) Any number of CSOs can be included in the model.
3) Farm run-off effects can be included.
4) Virtual probes may be placed at key water locations to predict the likely E.coli level at any instant in time.
5) Year-round pollution modelling may be shared with the public so that better decisions can be made regarding safety, possibly by creating a simple App.

In general terms, the model simulates water levels and flows (i.e., currents, tides and wind effects), which govern the transport of E.coli emanating from Combined Sewer Overflows (CSOs) in the Firth of Forth.

In order to represent the E.coli, virtual "biological" particles are released at each CSO outlet and allowed to disperse into the marine environment. Each particle represents a certain concentration of E.coli based on standard CSO levels found in the literature [SELMEUS_2018] or measured levels on-site. A modelling technique based on the current SEPA screening approach for salmon lice [SEPA_2025] has been adopted and the biological nature of E.coli degradation as a function of salinity, temperature and light are included in the model. The particles were restricted to exist in the top 2 m of the water column which is considered appropriate for recreational human activities.

The use of hydrodynamic modelling to drive particles representing biological material (e.g. marine zooplankton, pesticides, farmed salmon faeces) is increasingly common, particularly in Norway [Johnsen_2020], [Asplin_2020], [Smyth_2016], [North_2008], [CLAWS_2025]. Marine Scotland and SEPA [SEPA_2025] are working on similar projects in Scotland. The integrated biological model presented in this report draws on the methods and assumptions used by Scottish and Norwegian modellers working for government agencies, as well as other peer-reviewed research.

The flow conditions (sea currents) driving the E.coli particles come from a validated hydrodynamic model that has been detailed elsewhere [CLAWS_2025] and is only summarised in this document.

The risk of harm to human health from waterborne E.coli exposure varies according to the local concentration level of E.coli. A value of 500 Colony Forming Units (CFU) per 100 mL or less is considered "satisfactory" for exposure in coastal waters [SELMEUS_2018]. At each CSO outlet, an initial concentration level of 9.0×10^6 CFU/100 mL is considered appropriate [SELMEUS_2018].

In this report the model outputs are presented in three ways, to demonstrate how the E.coli concentration and therefore the apparent risk vary:

1. E.coli concentrations averaged over a suitable period in May 2023, shown as a heat map
2. Virtual probes at specific locations to measure how instantaneous E.coli concentrations vary locally with time.
3. E.coli concentration levels (CFU/100 mL) calculated every 20 mins and shown as an animated series of E.coli density maps. These are the peak levels that recreational swimmers are likely to encounter. During their swimming period through the coastal waters, they may pass through multiple areas of high E.coli concentrations.

2 Hydrodynamic model

2.1 *Model Extent*

The flow conditions (river and estuary currents) that drive the E.coli particles come from a validated hydrodynamic model of the Forth estuary that has been reported elsewhere [CLAWS_2025]. The extent of this model is shown in Figures 1 and 2 and extends from the Kincardine bridge in the West into the North Sea covering coastal areas to the North coast of Fife and Eyemouth in the East. The hydrodynamic model contains the influence of wind forcing on the estuary water surface and stratification through the salinity and temperature fields. It offers general insight into the spatial and temporal variation in the flow environment in the Firth of Forth and the hydrodynamic model also provides a suitable basis for modelling E.coli dispersion.

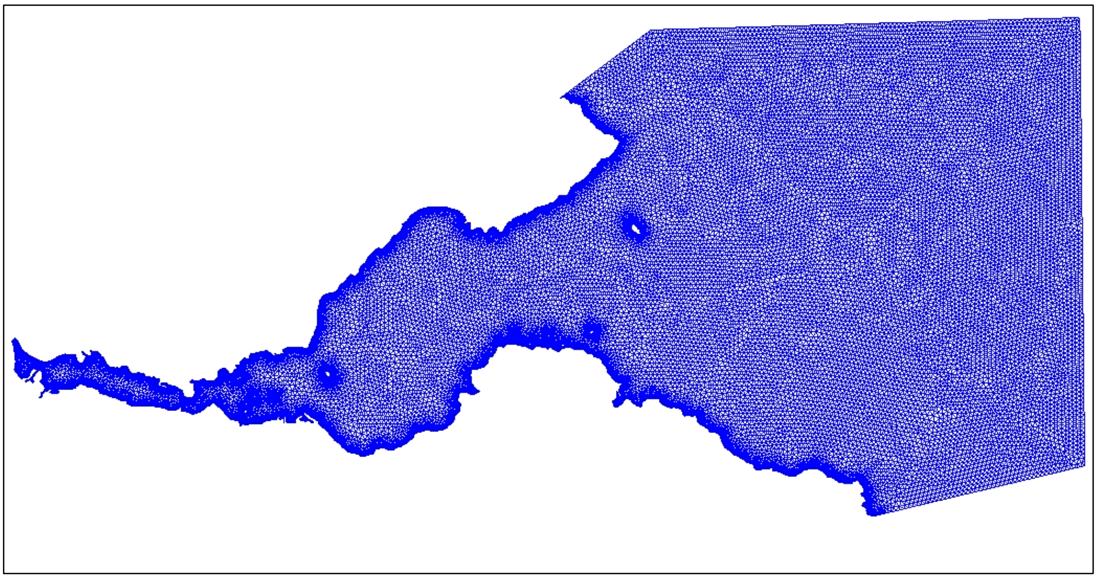


Figure 1 *Hydrodynamic model mesh for the Firth of Forth.*

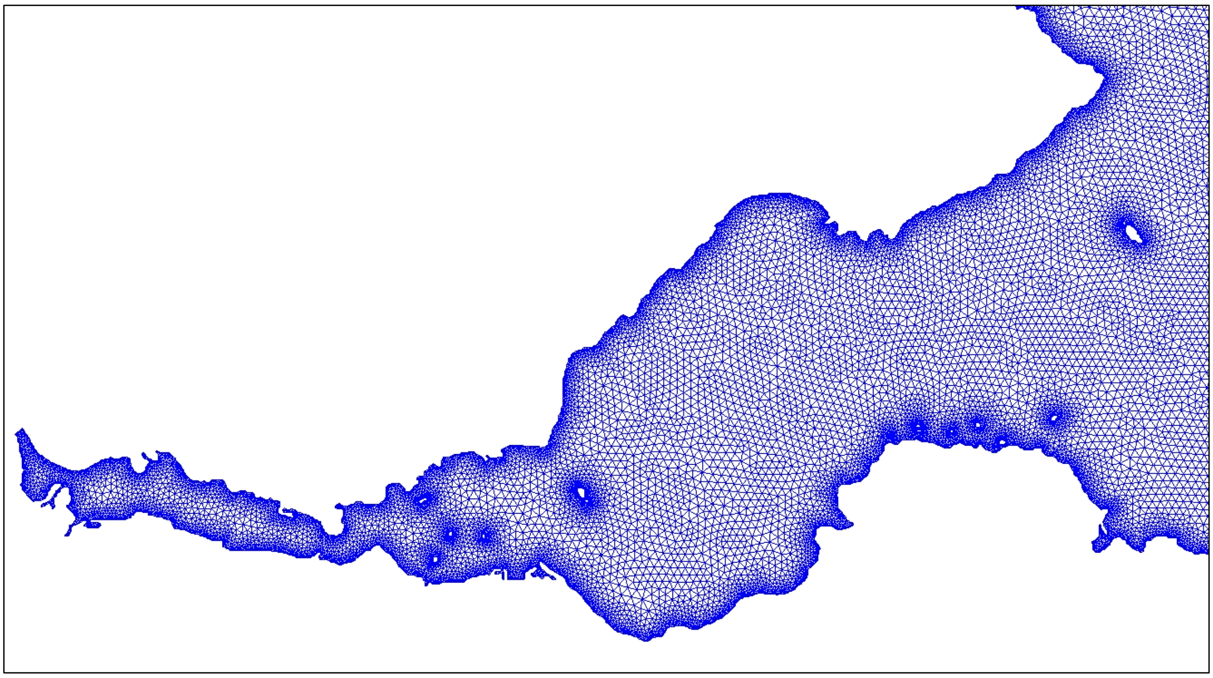


Figure 2 *Hydrodynamic model mesh for the Firth of Forth (zoomed).*

2.2 *Flow fields*

Figures 3 and 4 show snapshots of the near-surface flow patterns in the Firth of Forth on a flood and ebb tide, respectively, and highlight the complexity of the flows due to the competing effects of tides, wind and stratification.

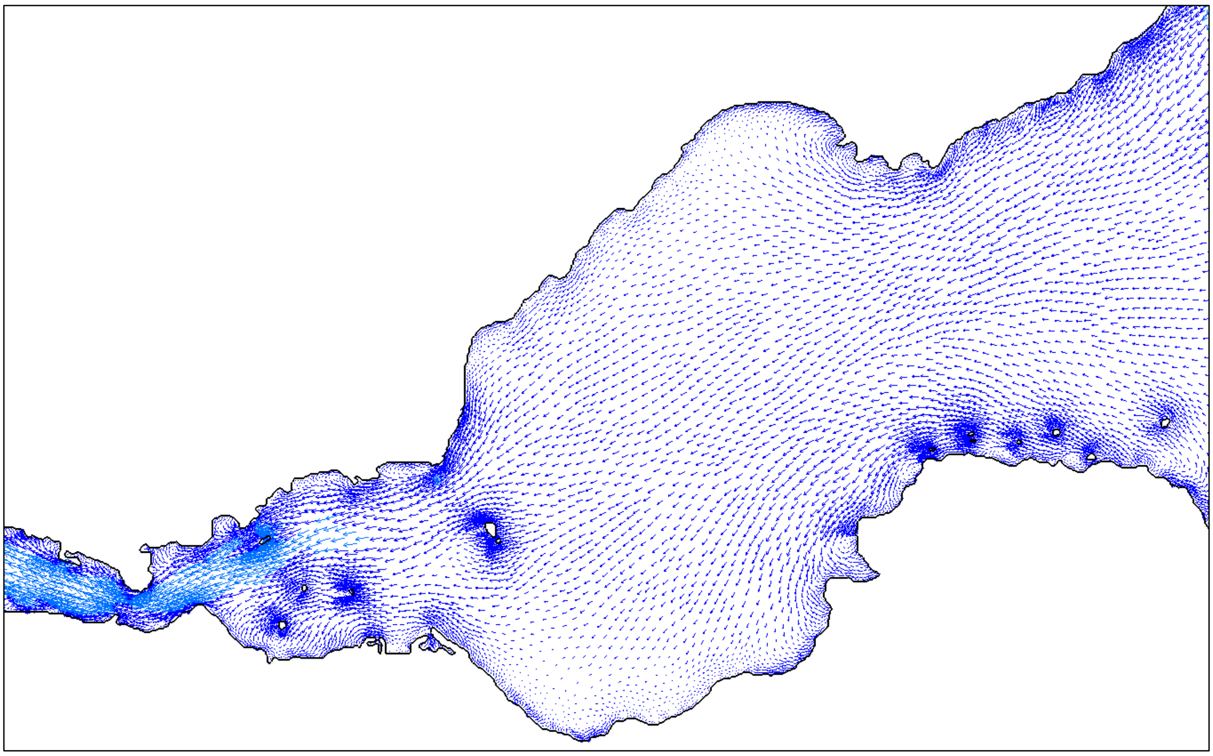


Figure 3 *Snapshot of surface flow patterns in the Forth Estuary on a flood tide.*

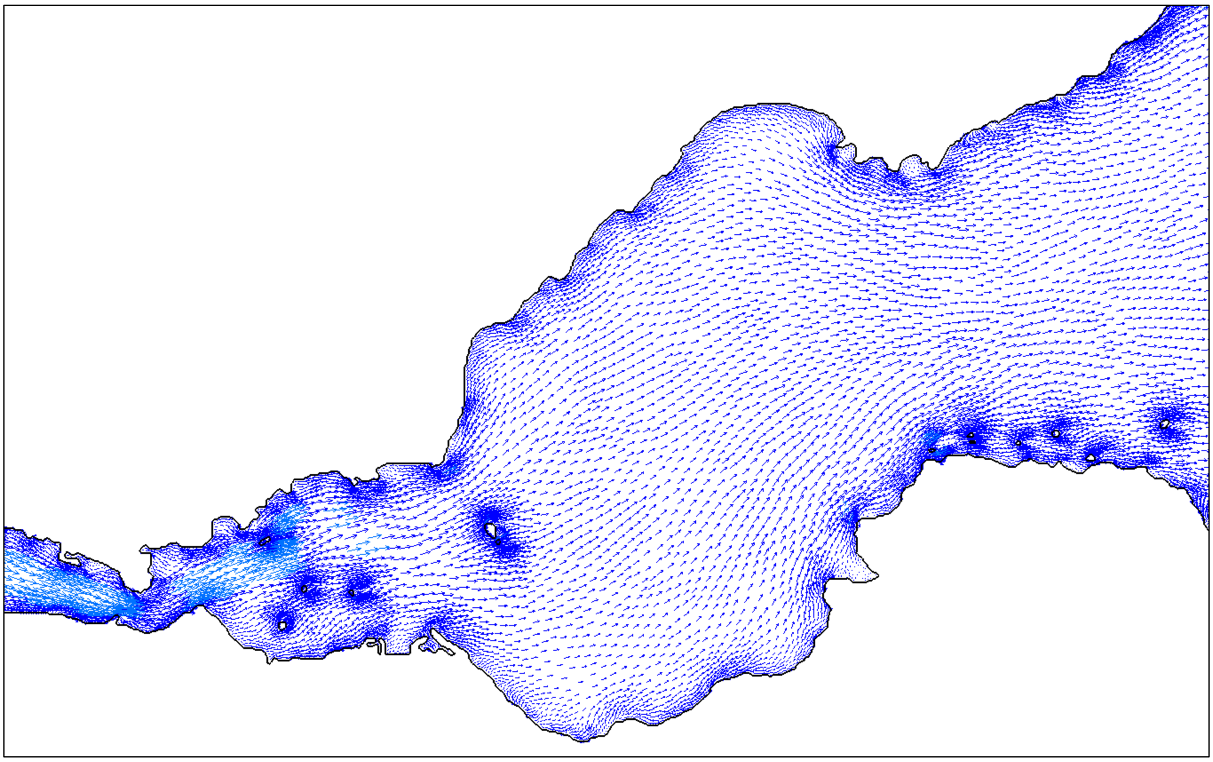


Figure 4 *Snapshot of surface flow patterns in the Forth Estuary on an ebb tide.*

3 Biological E.coli Model

3.1 *Model description*

Degradation of E.coli in the marine environment is a function of the local values of salinity, temperature and light [SELMEUS_2018] according to equation 1:

$$\boxed{C_{E.coli} = C_{E.coli_0} * e^{(-((a_T*T-k_{m0})+(S_m*\frac{(b_T*T+K_{L0})}{(a*S_m-(\frac{1}{a})*S)})*(I_0*e^{-(-ln(\frac{0.15}{SD}))*z}))*t)}} \quad (1)$$

In order to compare our model results against the analytical values based on equation 1, a simple virtual experiment was constructed. This was based on the experiment of Crosbie [CROSBIE_2019] to study salmon lice where a glass tube of 6 cm diameter and depth of 80 cm was filled with heated, saline water and it’s top free-surface exposed to a light source of known irradiance. The experiment is shown in Figure 5:

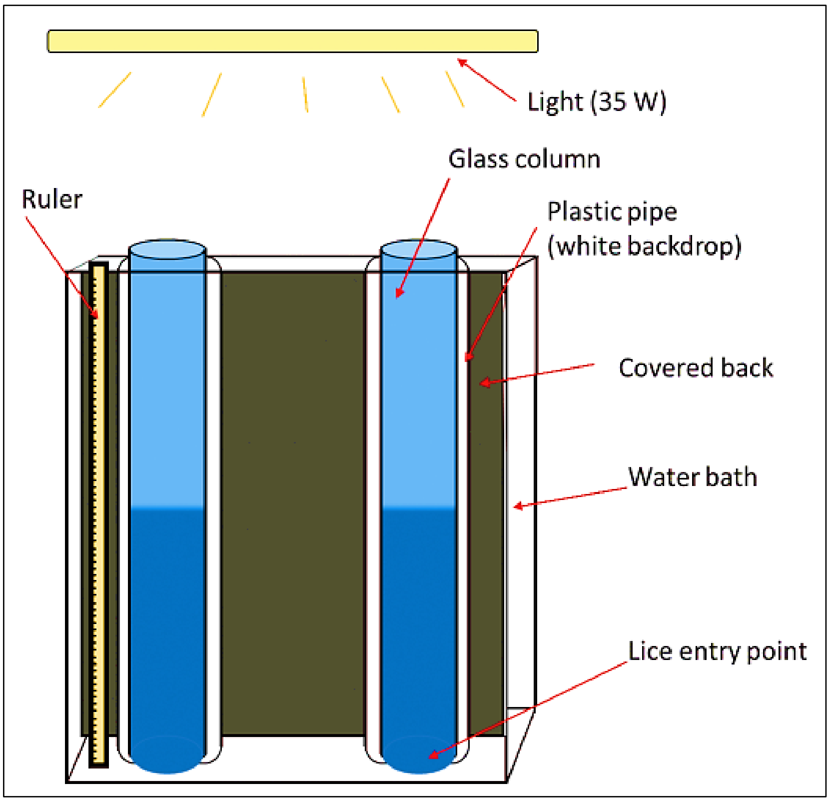


Figure 5 *Crosbie experiment for salmon lice.*

For the model, E.coli particles were seeded into an environment with temperature conditions of 12 ^oC, salinity 33 PSU, a light exposure of 10 W/m^2 and an initial E.coli concentration of 9 $\times 10^6$ CFU/100 mL. The model was run for a time period of 72-hours and Figure 6 shows the comparison of the analytical results based on equation1 (red dots) with the model predictions (blackline) and excellent agreement is found. This means that there is confidence that the programming of the decay equation 1 in the model has been correctly implemented.

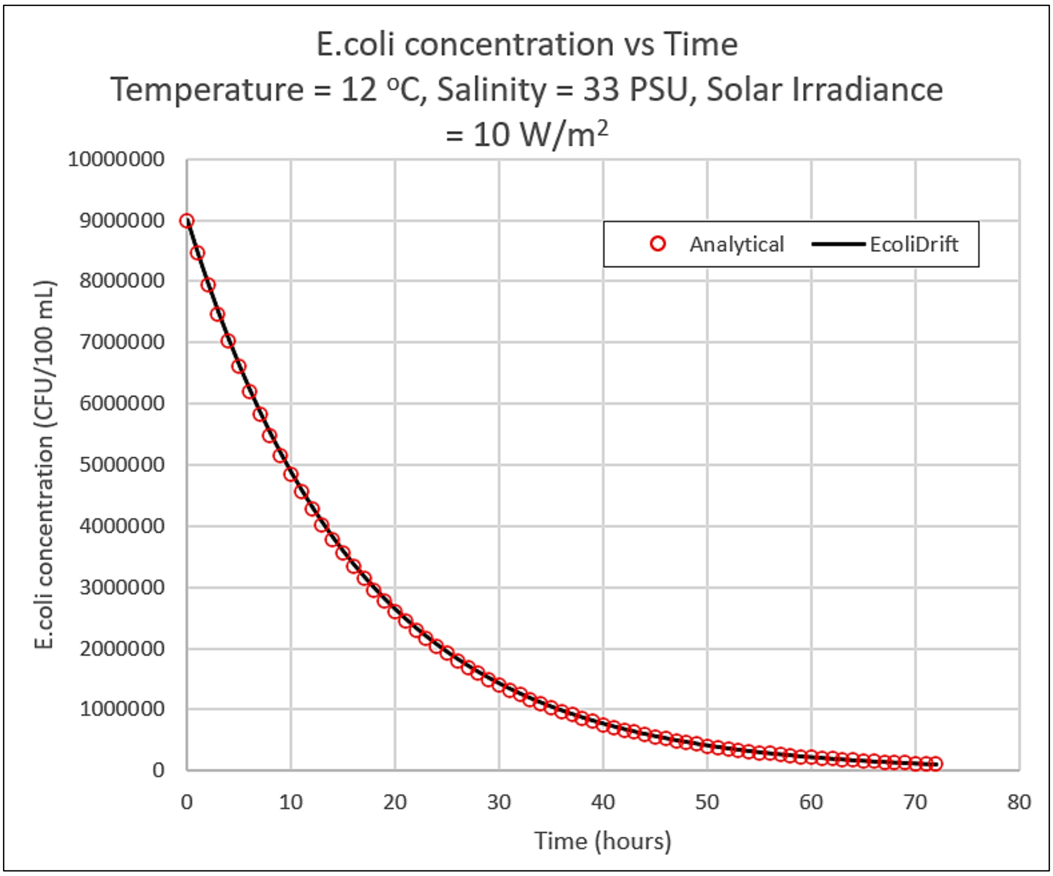


Figure 6 *Comparison of analytical E.coli decay (eq. 1, red dots) against model predicted results (black line) over a 72-hour time period.*

3.2 *Model test case*

The integrated biological model presented in this report draws on the methods and assumptions used by Scottish and Norwegian modellers working for government agencies, as well as other peer-reviewed research [Johnsen_2020], [Asplin_2020], [Smyth_2016], [North_2008]. A methodology similar to the current SEPA screening model for salmon lice [SEPA_2025] has been employed. In this approach, biological "E.coli" particles are released into the marine environment from 6 CSO outlet sites in the vicinity of Leith, Portobello, Joppa and Musselburgh. Details of each CSO release outlet are shown in Table 1 [FORTH_RIVERS_TRUST_2025].

Table 1 *Details of the 6 Combined Sewer Overflow (CSO) Outlet Sites*

CSO Name	Longitude (deg)	Latitude (deg)
LEITH_VICTORIA_QUAY	- 3.170322	55.998821
LEITH_ALBERT_ROAD	- 3.138221	55.976351
CRAIGENTINNY_FILLYSIDE	- 3.127922	55.971068
JOPPA_EAST	- 3.085908	55.951490
MUSSELBURGH_NEW_STREET	- 3.069471	55.949376
MUSSELBURGH_ESK	- 3.053077	55.951995

Figure 7 shows the location of the 6 CSO outlets.

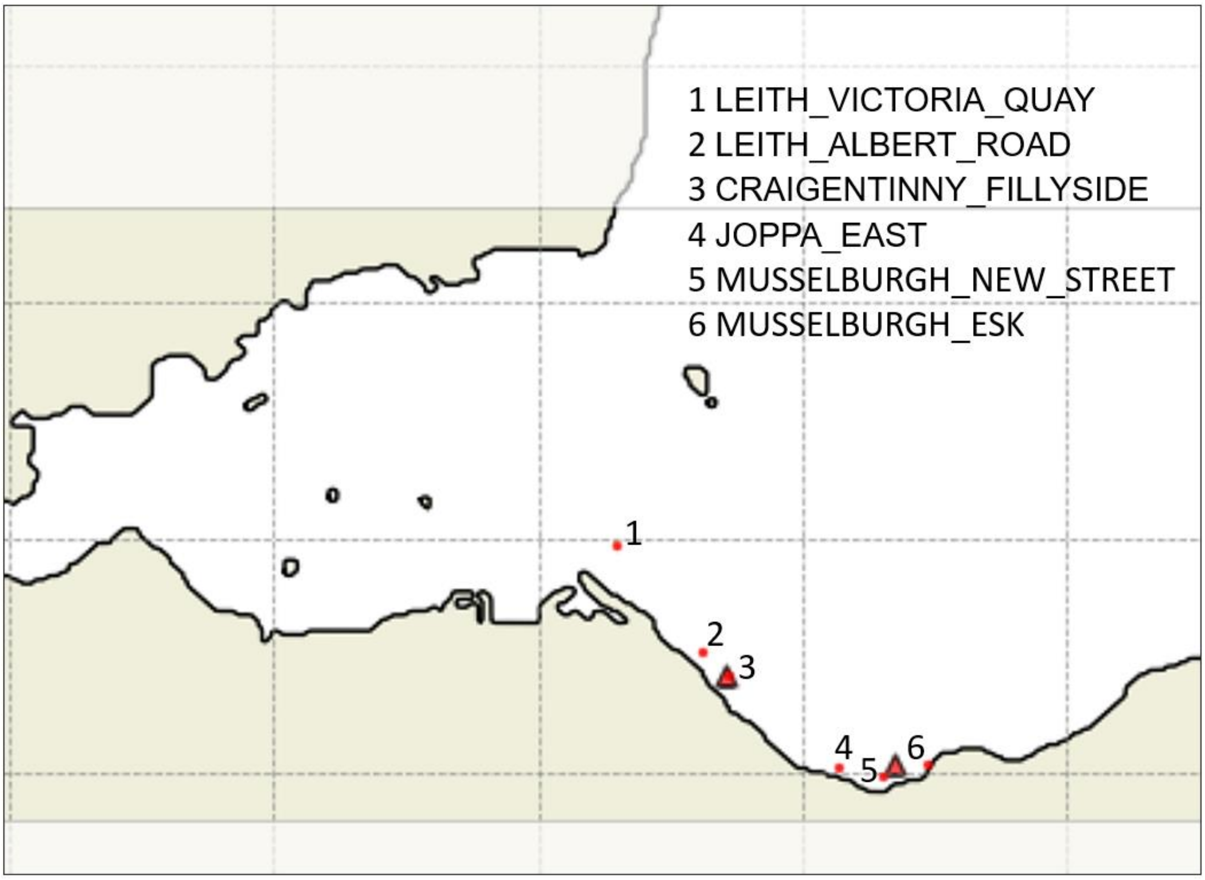


Figure 7 *Location of the 6 CSO outlets (red circles). Triangles are virtual probe points to measure instantaneous E.coli levels.*

For the hydrodynamics, a “spin-up” period covering 4-days from the 12th May 2023 at 7 p.m. until the 16th May was used to develop the temperature and salinity fields. The solution was then hot-started with E.coli particles introduced from the 16th May 2023 at 7 p.m. until the 20th May in a model run lasting 4-days.

50 E.coli particles were released every 5 minutes from each CSO site over the 24-hour period to simulate a raw sewage spillage event. Initial particle positions were randomly distributed within a volume of radius 0.5 m and depth 0.4 m centred at the lat/lon location of the CSO outlet. E.coli concentration for the raw sewage was taken as 9.0×10^6 [SELMEUS_2018].

In addition to transport by sea currents, E.coli particles were given a random movement component, both vertically and horizontally at each time increment to represent turbulence on a subgrid scale. Particles were dispersed in the horizontal using a dispersion coefficient of 0.1 m^2/s and dispersed in the vertical using a dispersion coefficient of 0.001 m^2/s. This is considered a conservative vertical mixing approach [SEPA_2025]. The particle integration method used was 4th order Runge-Kutta.

Hourly solar irradiance (light) values (W/m^2) as shown in Figure 8 were extracted from the NASA POWER API [NASA_2025] with local values of salinity and temperature coming from the hydrodynamic model. These were the values used in the E.coli decay model of equation 1.

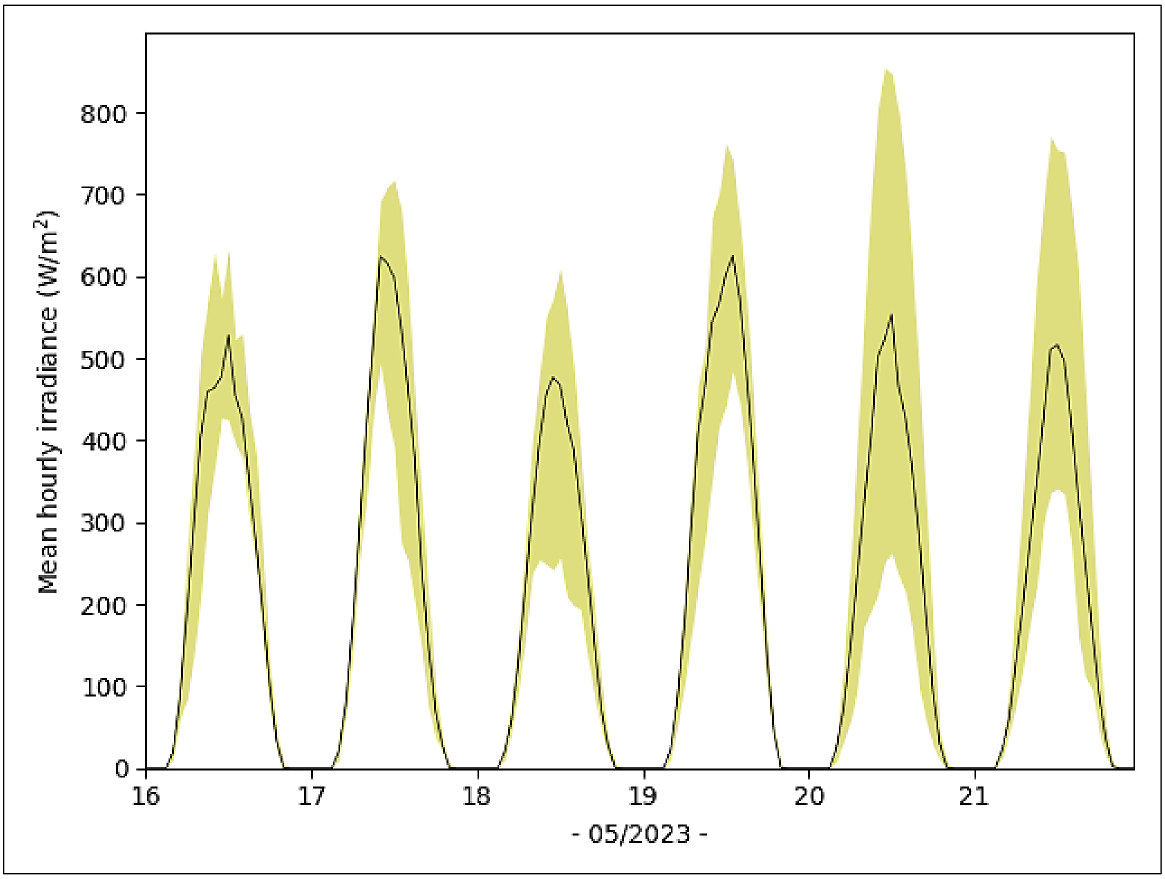


Figure 8 *Mean hourly irradiance (light) values (W/m^2 - black line) used in the E.coli decay equation 1. Data from [NASA_2025]. Yellow area highlights regional variability in hourly irradiance.*

At the end of the 24-hour spillage, there were 87,000 E.coli particles in the system. A cumulative 20-minute average E.coli density field (CFU/100 mL) was post-processed over the 4-day period of 16th-20th May 2023. The averaging took place on a sampling mesh with a bin size of 60 m. The bin depth was restricted to the top 2 m of the water column as this is the most likely depth for human contact.

In addition to the average E.coli concentration fields, instantaneous E.coli densities may be studied quantitatively using virtual probes at specific locations to measure how E.coli concentration varies locally with time. A probe was placed just off Portobello beach for this purpose (see triangle at location 3 in Figure 7).

Finally, the transient E.coli density field may also be interrogated qualitatively by analysing an animated series of particle density maps at 20-minute intervals. These are the peak levels that recreational water users are likely to encounter. During their movement through the coastal waters, they may pass through multiple areas of high E.coli density.

4 Results

4.1 *Average E.coli density plots*

Figure 9 shows the average E.coli concentration plot for the period covering 4-days from the 16th May 2023 at 7 a.m.

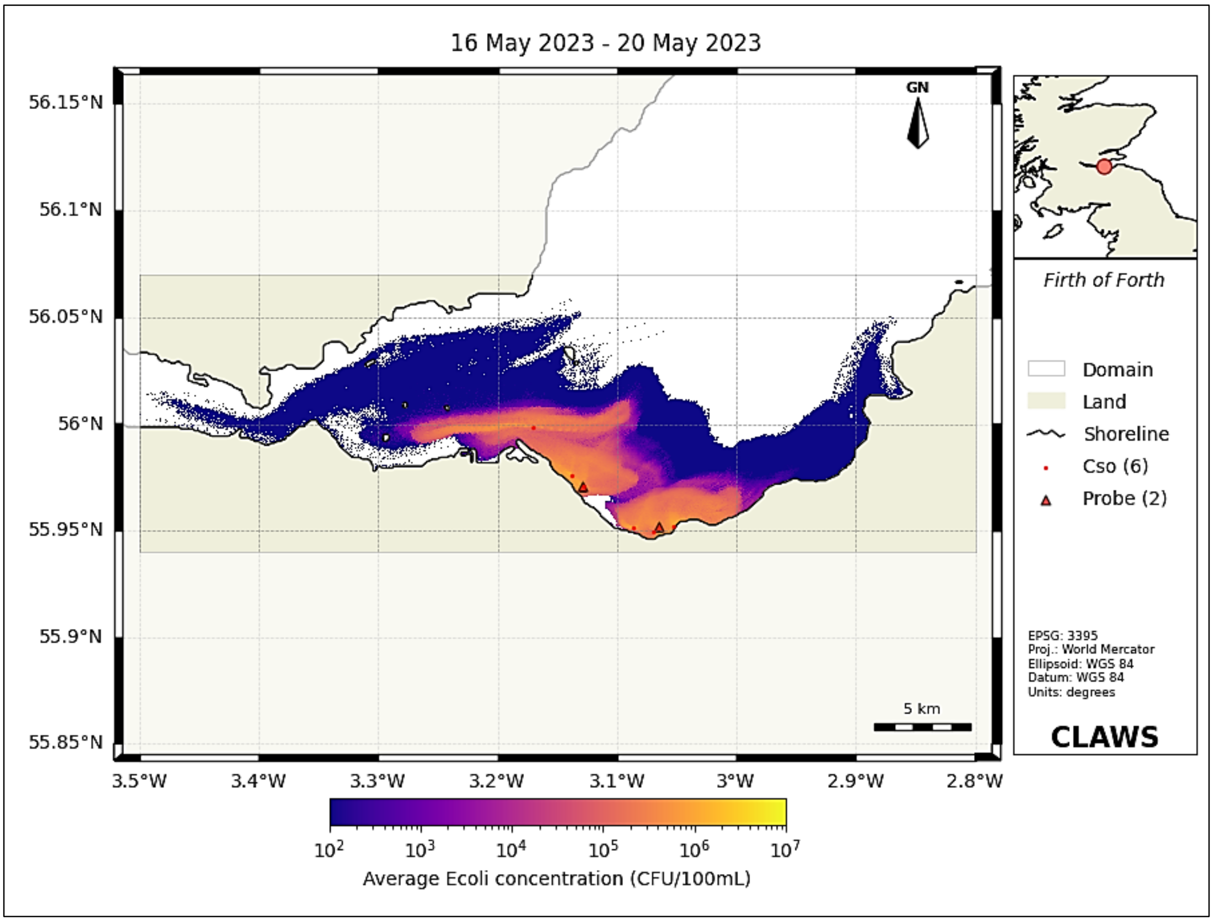


Figure 9 *Average E.coli concentration over 4-days for a 24-hour raw sewage spillage from 6 CSOs showing the extent of dispersal. Red dots show the CSO outlet locations.*

In terms of E.coli distribution, it is evident that the particles are widely dispersed across a large portion of the Firth of Forth. Inclusion of other CSO outlets will likely result in enhanced dispersion.

4.2 *Peak E.coli concentration*

Figure 10 shows the peak E.coli concentration with time across the Forth estuary during the 24-hour spillage event from the 6 CSOs.

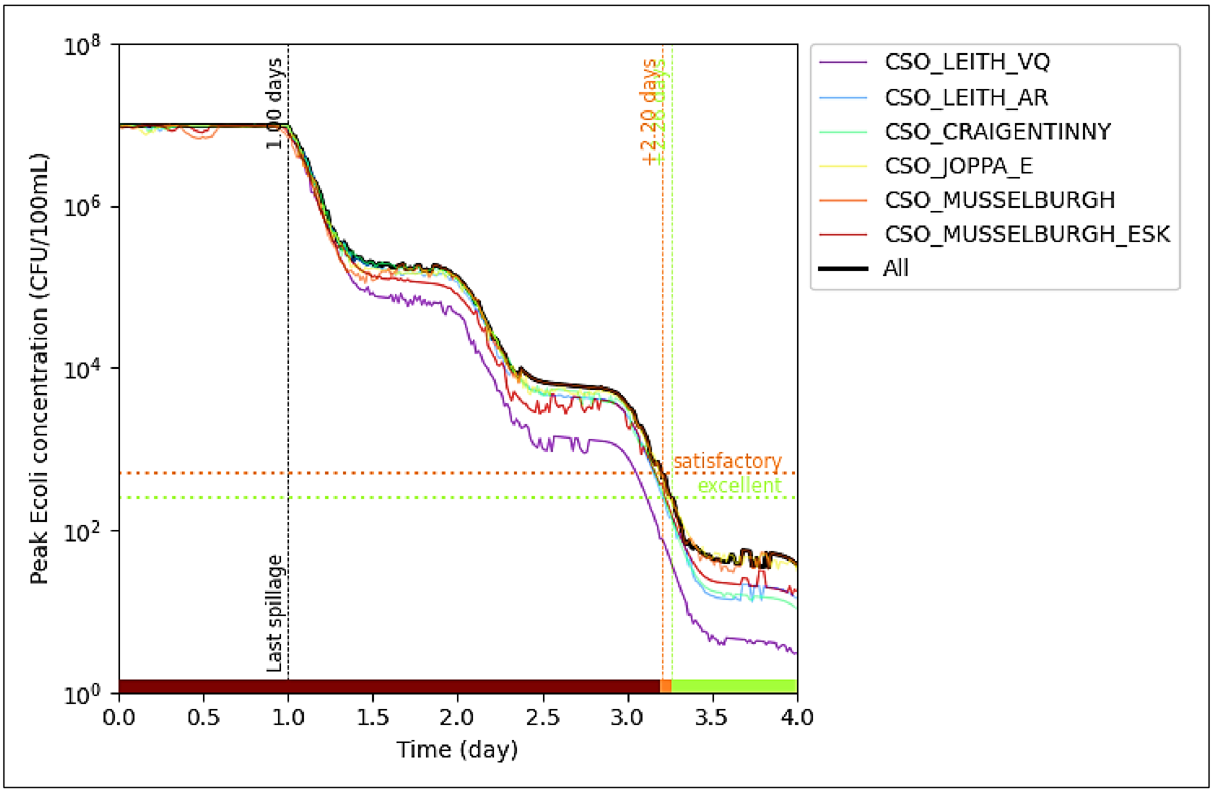


Figure 10 *Peak E.coli concentration (CFU per 100 mL) as a function of time for a 24-hour raw sewage spillage from 6 CSOs around Portobello beach. "Satisfactory" and "Excellent" thresholds correspond to those described in [SELMEUS_2018].*

The model predicts that it is likely to take 3.2 days from the start of the spillage for E.coli levels to achieve "satisfactory" environmental quality standards (EQS) for E.coli – (500 CFU per 100 mL) and 3.26 days for "excellent" conditions (250 CFU CFU per 100 mL). "Satisfactory" and "Excellent" thresholds correspond to those described in [SELMEUS_2018]. Note that the flatter areas in the curves after the last spillage correspond to night conditions when the solar irradiance effect on the E.coli decay is effectively extinct. The plot summarises that it is likely to take around 3.2 days before recreational water users should return to the water across the Forth system based on these spillage and tidal conditions.

4.3 *Virtual Probe*

Figure 11 shows the output from a virtual probe located just off Portobello beach (see triangle at location 3 in Figure 7). The peak concentrations in the plot correspond to occasions when the predicted E.coli cloud swills into the area near the beach on the back of tidal, density and wind effects, then backs away as part of the hydrodynamic cycle. The results show that adverse instantaneous E.coli levels above the EQS are likely to occur at certain instances between the beginning of the 24-hour spillage event and achieve safe levels approximately 3.2 days afterwards.

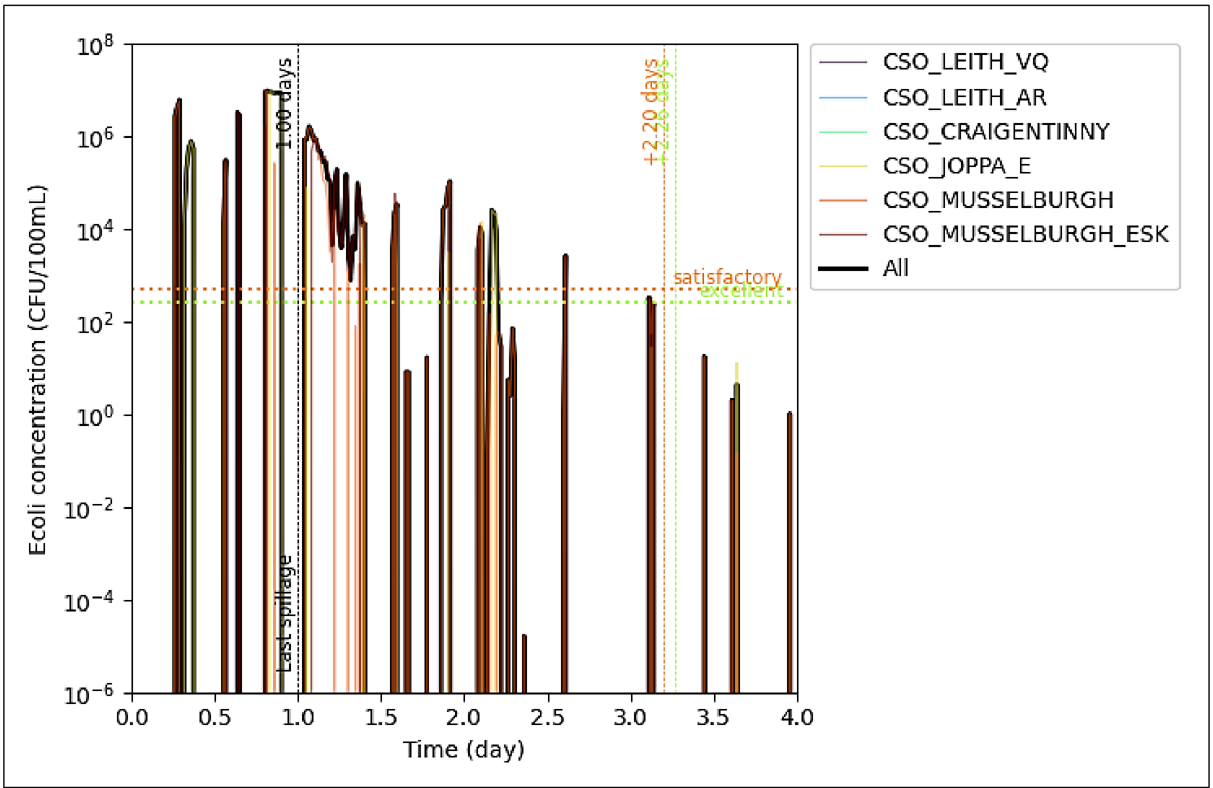


Figure 11 *Instantaneous E.coli concentration (CFU per 100 mL), measured at a virtual probe location off Portobello beach.*

4.4 *E.coli Distribution Snapshots*

In addition to the instantaneous quantitative data provided by the peak and virtual probe results, E.coli concentrations calculated every 20 mins may be shown as an animated series of E.coli density maps. These are the peak levels that recreational swimmers are likely to encounter. During their swim journey through the coastal waters, they may pass through multiple areas of high E.coli density.

The predicted instantaneous E.coli distribution is observed to have a high spatial and temporal variability, constantly dynamic and highly transient in nature.

This qualitative data demonstrates how the E.coli fields evolve with time and provides evidence of large-scale dispersion extending over many kilometres in the Forth Estuary.

Figures 12-14 show sample snapshots of the instantaneous E.coli density fields (CFU/100 mL) in the Firth of Forth for the hydrodynamic period 16th-20th May 2023. Note colours in the plots darken with time as the E.coli degrades in the marine environment based on equation 1.

E.coli animations are also available as part of this study.

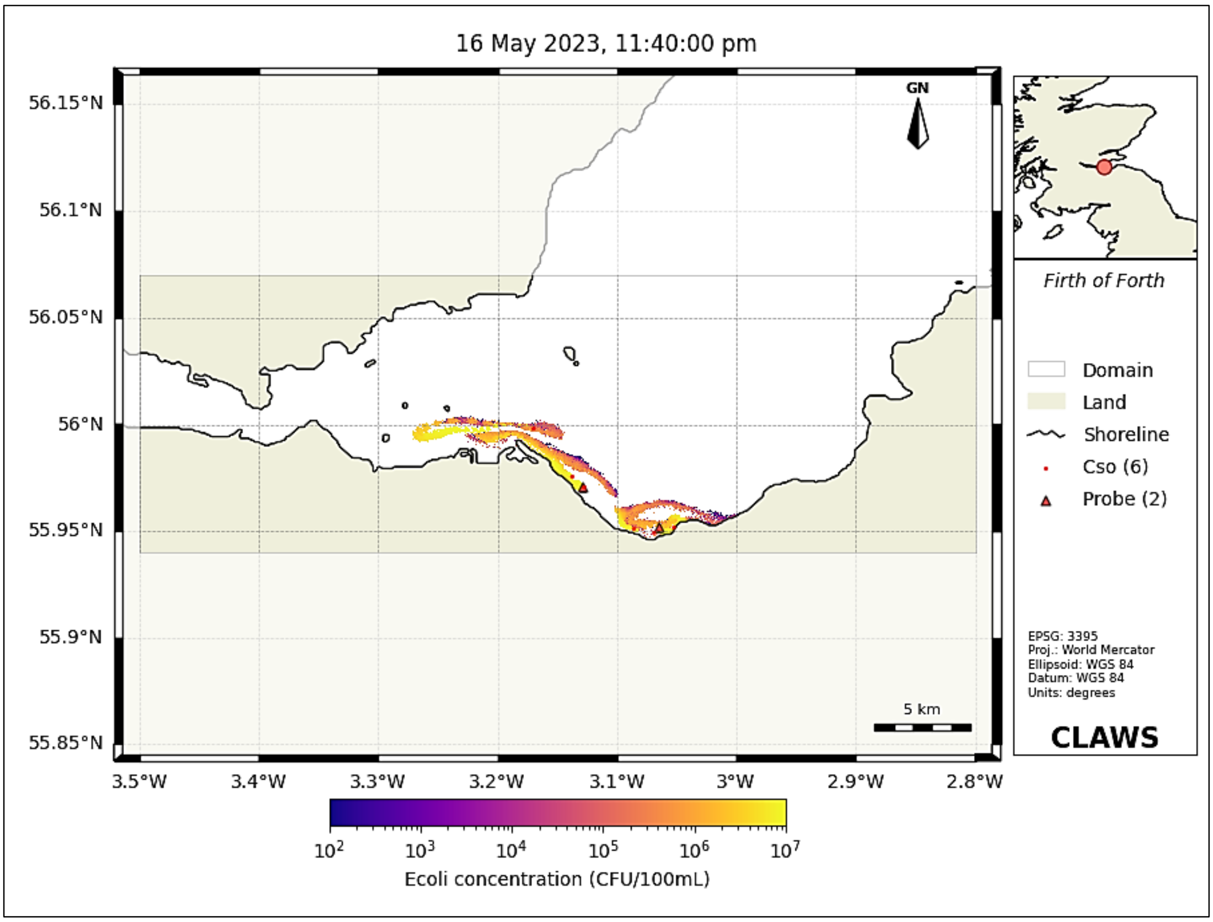


Figure 12 *Snapshot of instantaneous E.coli concentration (CFU/100 mL) on the 16th May 2023 at 11.40 p.m.*

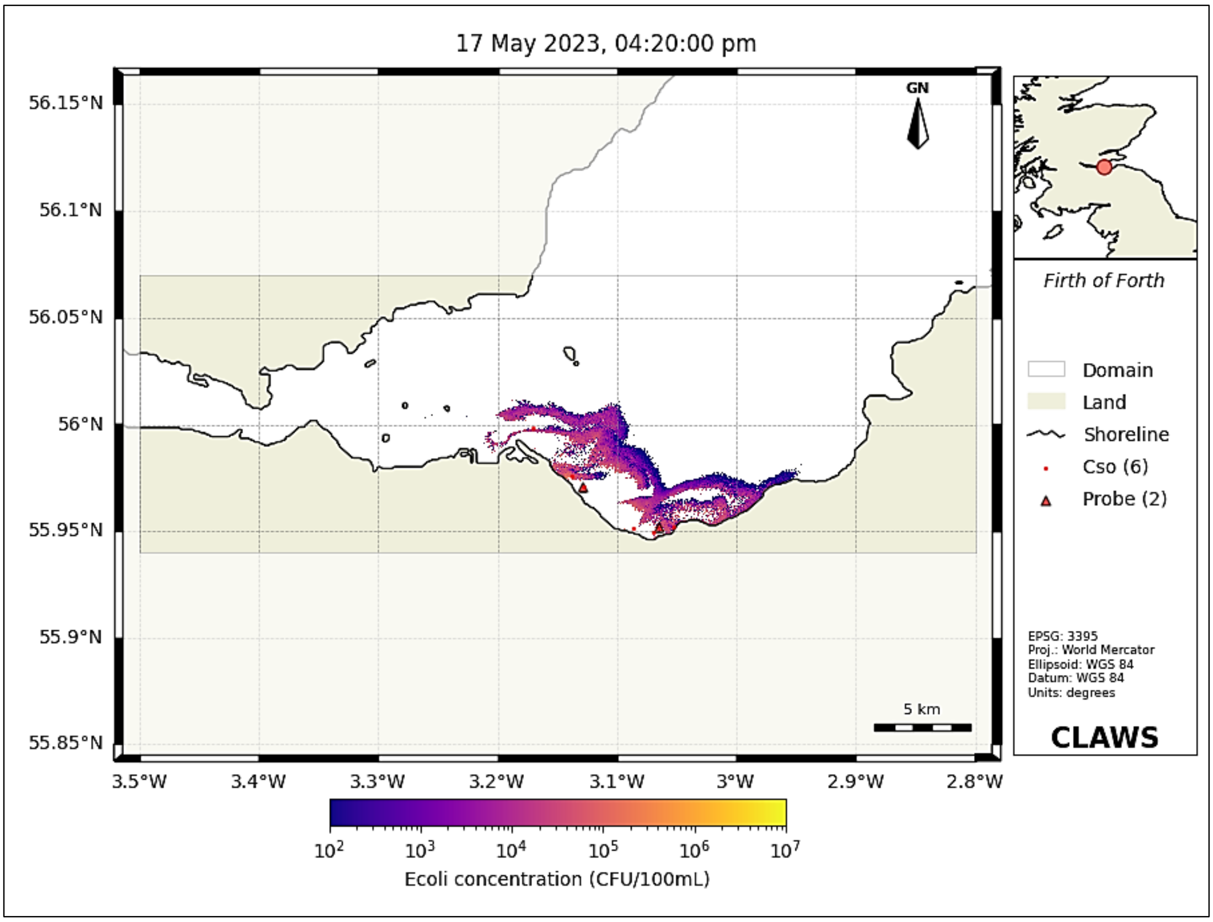


Figure 13 *Snapshot of instantaneous E.coli concentration (CFU/100 mL) on the 16th May 2023 at 12.20 p.m.*

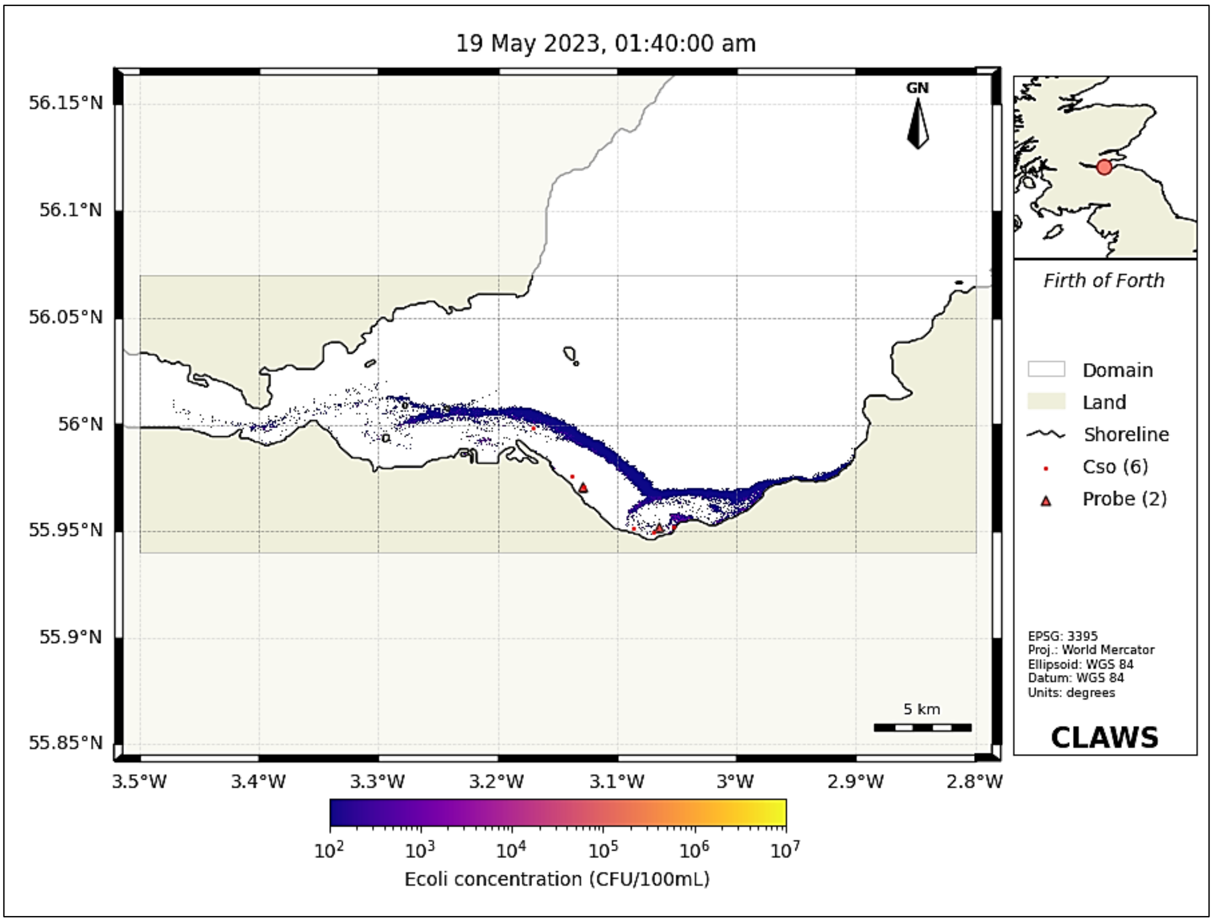


Figure 14 *Snapshot of instantaneous E.coli concentration (CFU/100 mL) on the 16th May 2023 at 12.20 p.m.*

4. Conclusions

A detailed hydrodynamic and biological model of Escherichia coli (E.coli) has been developed in order better understand the E.coli dispersion from Combined Sewer Overflows (CSOs) in the Firth of Forth and assess the risk that bathers and other recreational water users may be harmed by E.coli emanating from CSO's in the area.

A 24-hour raw sewage spill from 6 CSOs in the area surrounding Portobello beach has been modelled over 4-days in May 2023. Results for the average E.coli field show that there is evidence of dispersion over a wide area of the Firth of Forth.

Snapshots of the instantaneous E.coli concentration fields show how the E.coli is likely to evolve with time and provide evidence of high spatial and temporal variability, constantly dynamic and highly transient in nature.

E.coli levels decay as a function of salinity, temperature and light with peak concentrations taking around 2.2 days from the end of the spillage to fall below acceptable environmental quality standards (EQS).

Virtual probes in the model near Portobello beach indicate that E.coli concentrations in excess of the acceptable EQS are likely to persist for just over 2 days.

It may be possible to run the hydro-biological model for each month of the year and create a simple App to inform users of the likely time to wait before entering the water following a CSO spillage.

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