Roger Falconer | Water Consultancy

Independent Review Report

on

Beachbuoy Independent Assessment:
Oceanographic Modelling Review

by

Professor Roger A. Falconer

FREng ForMemCAE FEurASc FICE FCIWEM CEng CEnv C.WEM

November 2023

Report No. SW_Rep_1

Beachbuoy Independent Assessment: Oceanographic Modelling Review

Executive Summary

Southern Water have commissioned an independent review to provide an assessment of the current Beachbuoy system's ability to provide consistent, reliable, and credible near real-time warnings of potential water quality impacts along their coastline from storm overflow releases. The writer has been commissioned as an "Independent Oceanographic Modelling Expert" through Atkins to make an assessment of the coastal models developed for Southern Water and the potential of these models to provide consistent, reliable and credible input data into Beachbuoy, with this system then being able to provide near real-time warnings of potential water quality impacts from storm overflow releases.

Beachbuoy is a tool currently available on Southern Water's website (Beachbuoy (southernwater.co.uk)) which 'displays near real-time storm release activity information relating to (their) coastal bathing waters'. Southern Water are to be congratulated on making this information available to the public, with the proviso that the company 'can't make any safety or water quality recommendations as Beachbuoy is simply a reporting tool. The public are therefore advised to use their own discretion when entering the water'.

In the opinion of the writer Beachbuoy is a valuable resource of data provision to the public, provided the additional statement is made that Beachbuoy currently provides limited information specifically focussed on Southern Water's overflows. The writer understands that Southern Water will investigate the scope for including third party water quality inputs into the coastal models and Beachbuoy in the future. It should be noted that the disadvantage of receiving RED or GREEN warnings too frequently when not appropriate, often results in bathers deciding not to pay too much attention to the warnings; this experience has been quite common in flood alerts. Therefore, it is important that Beachbuoy provides information as accurately as possible relating to the potential impact of Southern Water's assets on bathing water health risks. Furthermore, in the future Beachbuoy could be automated to provide real-time advice on health risks to bathers through being updated online (in real time), based on data accessed from the coastal models. However, the current hourly updating is commendable based on the existing data availability.

The writer has been extensively involved in developing, refining and applying computational models for predicting hydrodynamic, water quality and sediment transport processes in coastal, estuarine and riverine basins for over 45 years, mainly in academe and working in collaboration with water companies, consulting companies and regulatory authorities. His original model DIVAST (Depth Integrated Velocities And Solute Transport) was developed in the early 1980s, and used extensively up to about 2000 by 44 companies (including Atkins) and regulatory authorities for coastal and estuarine hydro-environmental impact assessment projects, both in the UK and internationally; some companies are still using enhanced versions of this model. Since the mid-1990s consulting companies etc. have increasingly used commercial hydro-environmental computational models, which have been developed and documented for project applications by a broader cohort of engineers and scientists, without necessarily having the in-depth experience to develop, refine and apply specialist research tools. More recently, since around the mid-1990s, the writer has been extensively involved in auditing and reviewing the application of commercial computational coastal and estuarine models for predicting hydro-environmental and hydro-bacterial process predictions in coastal waters, particularly in connection with planning long sea outfall design and operation for compliance with the EU Bathing Water Directives. These review and assessment studies have been primarily undertaken for various water companies in the UK and comparable overseas organisations.

The writer has reviewed all the reports provided to him by Atkins and which relate to the extensive coastal modelling studies undertaken by Southern Sciences Ltd., primarily since the mid-1990s to-date. In the experience and opinion of the writer, whilst these models have generally given reasonable agreement between field measured and Admiralty Chart data, compared to comparable hydro-environmental modelling and data monitoring studies there are a number of underlying concerns about the set-up of the coastal models and the over-simplification of some process parameters highlighted in this report. The writer recommends that several key refinements need to be made to the models before a robust assessment of the impact of long sea outfall and CSO plume discharges on bathing water quality can be made. In particular, there are a number of key validation sites, in the coastal models reviewed where the degree of validation does not meet the Foundation for Water Research (FWR) guidelines for good agreement between the measured and predicted data. In the writer's experience these guidelines continue to be widely used by the UK water industry and regulatory authorities and in the writer's opinion there is much scope for improving many of the processes represented in the coastal models, thereby enabling more confidence to be acquired in predicting the bathing water quality at various sites along Southern Water's coastline. If desirable the existing coastal models can continue to be used until a new model is set up for the region (particularly using an unstructured grid and a finer grid resolution in the nearshore coastal waters), taking into account the limitations of the existing model.

The main concerns relating to confidence in the model predictions are summarised briefly below and outlined in more detail in Section 2 of this report:

(i) The coarse grid model using a regular grid size of 2 km is appropriate and reasonably well calibrated with measured and admiralty chart data in offshore waters. However, in the experience of the writer the nesting to finer grids does not reduce to sufficiently fine a grid to predict tidal eddies etc. in the nearshore coastal waters – a typical and complex hydrodynamic process which needs to be predicted accurately for bathing water quality assessment.

(ii) The bed roughness coefficient has been changed in nearshore waters, without anecdotal evidence or field observations to support changes to the roughness parameter.

(iii) The representation of key processes, such as: turbulence, dispersion and diffusion, are based on constant values, thereby excluding key parameter gradients in shallower waters and excluding the dependency of these parameters on the local velocity and depth. These parameters are known from classical analytical derivations and field and laboratory data to be dependent on depth and velocity (as well as bed roughness, wind stress etc.).

(iv) The wind representation and its impact on changing the surface currents and vertical velocity profile appears to be over-simplified in the model studies, with published studies by the writer and many others indicating that relatively high wind speeds (ca. 10+ m/s) can have a marked impact on surface currents, plume trajectories and FIO (Faecal Indicator Organism) concentrations.

(v) The lack of ADCP (Acoustic Doppler Current Profiler) data for the hydrodynamics calibration and validation, and the relatively limited FIO concentration data, are shortcomings in providing confidence in the model predictions, particularly in comparison with the amount and sophistication of data now increasingly being used by the water industry in comparable studies.

Based on these main comments above, along with other review comments in Section 2 of this report, the writer has provided a number of recommendations throughout the report, as listed below, with an indication of the timescale for consideration being identified as Short Term (**ST**): less than 6 months, Medium Term (MT): 6 months to 3 years, and Long Term (**LT**): over 3 years.

Recommendation: 1 - ST

Southern Water consider replacing their existing oceanographic and coastal zone modelling suite with a more refined model, based on an unstructured grid finite volume or finite element structure, and with improved representations of the physical and biological processes in the governing hydrodynamic and solute transport equations, particularly in the shallower near-shore bathing waters. The current unstructured grid finite volume or finite element models widely used include (in alphabetical order): Delft3D Flexible Mesh Suite (Deltares, 2021)*, MIKE 21/3 Flow Model* (Danish Hydraulic Institute, 2017)*, and TELEMAC-MASCARET* (Electricite de France, 2022)*. The models Delft3D and TELEMAC-MASCARET are available as Open Source, but at the time of writing this report MIKE 21/3 is not available in open-source form.*

Note: The writer understands that Southern Water now has a licence for the unstructured MIKE 21/3 model and is about to implement its use.

Recommendation: 2 - ST

It is not clear if the Coriolis slope effect is included in the coarse grid model, either directly or indirectly, along the northern and western open boundaries and the inclusion of this effect should be checked to ensure that if any questions are raised about its inclusion in the model, then evidence can be provided to confirm that this effect is included appropriately.

Note: The writer understands that Southern Water will be carrying out sensitivity analyses of the impact of the Coriolis slope effect on the northern and western boundaries of the re-constructed MIKE 21/3 model.

Recommendation: 3 - ST and MT

It is recommended that at the earliest opportunity a field monitoring programme is undertaken to measure the key hydrodynamic parameters, continuously and synchronously, at several (ca. 6) key sites across the domain. This should first be done to re-calibrate and validate the coarse grid model and, at a later stage, undertaking a further field study using ADCPs to validate the finer grid models in the shallower bathing waters, which is crucial. In the writer's experience there is scope for improving the accuracy of the model predictions to meet the FWR criteria, particularly regarding tidal phasing, and thereby leading to more confidence in the model predictions.

Note: The writer understands that Southern Water will review existing hydrometric survey data and where necessary commission further hydrometric surveys to provide a complete set of calibration and validation data for the re-constructed MIKE 21/3.

Recommendation: 4 - ST and MT

It is recommended that for improved accuracy in the coastal bathing waters, in addition to switching to an unstructured grid model (as advised in ***Recommendation 1****), the minimum grid resolution should be reduced in the nearshore zones to typically 50 m, and a maximum of 75 m, subject to grid dependency tests and run-times.*

Note: The writer understands that Southern Water now has a licence for the unstructured MIKE 21/3 model and is about to implement its use. This model will have a refined grid cell structure in nearshore areas.

Recommendation: 5 - ST

It is recommended that if Southern Water decide to continue using their existing nested models over the long term for predicting hydrodynamic and solute transport processes in the nearfield zones, then for improved accuracy the intermediate and fine grids should be nested down in ratios of 1:3 or 1:5, thereby ensuring that the predicted data coincide at the centre of the coarse and central fine grids, enabling direct comparisons to be made between the predicted data in both grid sets and grid dependency inherently tested.

Note: The writer understands that Southern Water now has a licence for the unstructured MIKE 21/3 model and is about to implement its use. The implementation of this model will obviate the need for nesting.

Recommendation: 6 - ST

It is recommended that Southern Water undertake observational assessments of the bed characteristics along their bathing waters to estimate the approximate k_s *equivalent sand grain roughness heights in the nearshore region. This will ensure that the roughness shear stress included in the shallower waters is not higher than the bed characteristics which, in turn, would lead to increased energy dissipation of the tidal currents in the model, particularly in the critical bathing water areas.*

Note: The writer understands that Southern Water now has a licence for the unstructured MIKE 21/3 model and is about to implement its use. Model calibration and validation will be carried out and bed characteristics will be used to estimate the approximate bed roughness. The writer recommends that these data are first converted to an equivalent sand grain roughness height and then used to estimate an equivalent Manning coefficient or Manning number.

Recommendation: 7 - ST and MT

In the writer's experience the wind can have a significant impact on coastal bathing water hydrodynamic and solute transport processes. It is therefore recommended that the representation of the wind stress effects on the variation in the trajectory and physical characteristics of the discharge plumes are investigated in more detail, particularly regarding the impact of larger winds (ca. 10-20 m/s) on the surface velocities. This can be done through documentation of the treatment of the wind stress representation, including its impact on the assumed vertical *velocity profile, and how the vertical diffusion and dispersion coefficients are refined to account for increasing wind velocities. The writer questions the implication that wind velocities exceeding 5 m/s in the data relating to Beachbuoy do not lead to increased concerns about bathing water quality risk, and clarification on the wind representation could lead to more confidence in the assumption that a wind speed of 5 m/s is the peak critical wind velocity.*

Note: The writer understands that simulations have already been undertaken with higher wind speeds and the results of these simulations will be included in Beachbuoy in the short-term. In addition, the writer understands that Southern Water now has a licence for the unstructured MIKE 21/3 model and is about to implement its use. It is understood that additional runs will be undertaken to evaluate the impact of higher wind speeds on wind dispersion and diffusion in the updated model.

Recommendation: 8 - MT

In the writer's experience and based on the summary of turbulence modelling cited in Section 2, it would appear that in the nearshore coastal waters an eddy viscosity value of 1 m^2/s may be relatively large and that a value of typically 10% of that currently used would be more realistic. A lower eddy viscosity will reduce turbulent diffusion in the bathing water zone and could lead to maintaining a higher concentration of FIOs within the advected plume. It is therefore recommended that in the future at least a one-equation turbulence model be used to estimate the turbulent diffusion process, particularly across the fine grid domain.

Note: The writer understands that Southern Water now has a licence for the unstructured MIKE 21/3 model and is about to implement its use. The implementation of the eddy viscosity in this model will be considered carefully including use of the Smagorinsky formulation.

Recommendation: 9 - MT

In the writer's experience, and for the typical values included in equation 10, in the nearshore bathing waters the range of dispersion-diffusion coefficients of 0.1-0.25 m^2/s is relatively small and that a value of typically at least an order of magnitude greater would be more realistic. Furthermore, the dispersion-diffusion coefficients in analytical and idealised flume laboratory studies are strongly dependent on the product of the local velocity and depth, and it is recommended that the solute transport model should be refined to include velocity and depth effects and the gradient of the dispersion-diffusion coefficients should also be included in any future modelling studies.

It should also be noted that wind stress effects can be significant in dispersion-diffusion process representation (i.e., D_w in equation 10) and these parameters will increase with wind stress effects, and particularly for high winds. These additional stress effects should also be included in future model studies, ideally based on velocity profile parameterisations reported in the literature.

Note: The writer understands that Southern Water now has a licence for the unstructured MIKE 21/3 model and is about to implement its use. This model will be validated against buoyant dye tracing data and depth and velocity effects will be carefully considered. It is also understood that additional runs will be undertaken to evaluate the impact of higher wind speeds on wind dispersion and diffusion.

Recommendation: 10 - MT

In the writer's experience the prediction of FIO concentrations along bathing waters is highly dependent on the values included in the model for the decay rate. This process is highly complex and dependent on a range of variables, requiring intensive field data for several parameters for accurate and robust predictions. However, whilst much of these data are expensive and labour intensive to collect and analyse, it is nevertheless advised that the key variations in day- and night-time decay rates are included in model studies, and simulations are undertaken for both day- and night-time outfall releases. Whilst the values currently used for T_{90} *decay rates are deemed to be conservative, nevertheless experience has shown that key stakeholders, including the public, are more reassured when different decay rates are included in any real-time model-based water quality signage.*

Note: The writer notes that current decay rates used are conservative when compared to values measured for the River Ribble and Fylde Coast and understands that in the revised model the use of day- and night-time varying decay rates will be considered.

Recommendation: 11 - MT and LT

In the writer's experience for any coastal modelling predictions of FIO concentrations etc. to be used in a real-time "Predict and Protect" tool, such as Beachbuoy, it is desirable that the coastal model uses the latest developments widely used within the industry, such as an unstructured grid, a finer grid resolution, improved representation of turbulence and dispersion processes and parameters, and a more realistic representation of wind driven effects. Any Predict and Protect tool should use state-of-the-art modelling tools for assessing health risk impacts.

Note: The writer understands that Southern Water now has a licence for the unstructured MIKE 21/3 model and is about to implement its use. This model will have a refined grid structure, an improved representation of turbulence and dispersion-diffusion processes and presumably a more realistic representation of wind driven effects.

Recommendation: 12 - ST and MT

It is recommended that sampling studies be commissioned for all key source inputs to enable all CSO, riverine and harbour entrance inputs to be included in the coastal models, with the revised model predicted data then being filtered and included in Beachbuoy. This would allow Southern Water to be able to confirm their net inputs to the system, e.g., by inputting riverine E. coli and Intestinal Enterococci fluxes into the models at the boundaries, and thereby quantifying the impact of their discharges relative to other source inputs on bathing water compliance. By decoupling the inputs in the models and comparing the relative impacts would allow Southern Water to prioritise any future capital investments relative to the corresponding impacts.

Note: The writer understands that Southern Water will investigate including third party water quality inputs into the models in the future.

Recommendation: 13 - ST and MT

In order to provide more confidence in the model predicted accuracy of faecal bacteria levels along Southern Water's bathing beaches, it is recommended that an extensive sampling *programme is undertaken for a preferred beach of the nearshore hydrodynamic parameters and E. coli and Intestinal Enterococci concentrations. In particular, concentrations should be measured along transects normal to the beach, providing evidence-based data for model calibration and validation. This would lead to more confidence in the model predictions and any extended bathing water quality information provided through Beachbuoy.*

Note: The writer now understands that Southern Water have undertaken some bathing beach monitoring and are looking to do more detailed monitoring for a priority beach in the future.

Recommendation: 14 - LT

It is recommended that Southern Water investigate further the Copenhagen real time coastal models and their link to real-time bathing water quality signage. However, rather than integrate a fully deterministic computational coastal model within a signage system, which would be expensive in terms of modelling and data management costs, it is recommended that Southern Water move towards embedding the coastal modelling data within a hydroinformatics tool to provide real-time input data to Beachbuoy. This would enable more accurate real-time data on bathing water quality to be presented through Beachbuoy.

Recommendation: 15 - ST

It is recommended that in the short term some simulations of the effluent release from a typical outfall (such as Portobello) be undertaken around MWL, i.e., with peak currents, and the plume trajectory and concentrations be compared with releases at high and low water. If found to provide marked differences in the data currently linked to Beachbuoy, then it is recommended that MWL release data should also be included in Beachbuoy in the future.

Recommendation: 16 - ST and MT

For accurate predictions of the hydrodynamic and FIO transport processes in the region around the Solent and the Isle of Wight it is recommended that this coastal model is refined as soon as possible. In the writer's opinion, the grid for this complex water body is too coarse to pick up some of the main complex hydrodynamic processes likely to occur in the region. Furthermore, the bed topography is also highly variable in the region and the use of depth and velocity varying turbulent, dispersion and diffusion processes is particularly appropriate in view of the boundary constraint features of the Solent. The use of an unstructured model would be particularly suitable for this region and with the finest grid being 50 m, or less.

Table of Contents

List of Figures

List of Tables

Beachbuoy Independent Assessment: Oceanographic Modelling Review

1. Introduction

In July 2023 the reviewer was invited by Atkins, on behalf of Southern Water (SW), to undertake a review of the Southern Water Beachbuoy system, with a particular remit to review the oceanographic and coastal zone modelling, as one of four independent experts. The 'Oceanographic Modelling Expert' review included: "producing an expert's report, responding to questions in relation to the report, participating in discussions with Southern Water and other interested parties regarding the report's contents. This document constitutes the report.

The Beachbuoy system is a web-based tool, developed by Southern Water, with the objective of providing near real-time information about storm release activity near the water company's bathing beaches along their coastline. The tool is available on the Southern Water website and historically if any of Southern Water's outfalls associated with a bathing water released effluent during storm conditions, then this would have triggered a status change of the bathing water icon. The status of the Beachbuoy icon can change regardless of whether there would have been any impact on the bathing water quality, and any possible health risk associated with the release from the outfall.

In September 2022, Southern Water upgraded the map within Beachbuoy to predict the impact on any of their bathing waters of an outfall release under storm conditions, based on the location of the outfall, the duration of the release, and the tidal conditions at the time. In predicting the impact of such a release on the bathing water quality, predictions were obtained through interpolation of data from a range of datasets obtained from the hydro-environmental coastal models for the region, run for a range of conditions and primarily driven by tide and duration effects. The hydro-environmental model included a linked hydrodynamic model, which predicted the tidal elevations and currents, and a solute mass transport model for predicting Faecal Indicator Organisms (FIOs) concentrations, and particularly *E. coli*. The solute mass transport model included the key processes of: advection, diffusion and dispersion, and kinetic decay. The linked model was run for 84 bathing waters in Southern Water's region, and for each outfall 1-, 3- and 12-hour duration discharge releases were considered for: high water neap and spring, and low water neap and spring. This range of simulations has provided approximately 2,000 model datasets.

The results from the 12 modelled tidal states have been consolidated into a table, which summarises whether the outfall release is likely to have any impact on the associated bathing waters, with '1' indicating a potential impact and '0' no likely impact. Tables for every outfall have been uploaded into Beachbuoy, which uses the tidal (but excludes wind) conditions at the time of an outfall discharge, and its duration, to predict whether there is any non-compliant impact on the bathing beaches.

This review focuses primarily on the oceanographic and coastal numerical modelling, of both the hydrodynamic and solute transport processes modelled, and the implementation of these model predictions into Beachbuoy. Confidence in the deterministic hydro-environmental modelling results obtained for a wide range of scenarios should lead to improved confidence in Beachbuoy being able to provide relatively accurate nearshore real-time predictions of the regional bathing water quality. Furthermore, with reliable and robust hydro-environmental coastal modelling tools being available, then future scenario changes can also be predicted, such as: assessing the impact of sea level rise, changes in enhanced water treatment processes or reduced CSO discharges etc.

2. Modelling Approach

(i) General

Southern Water Services commissioned Southern Science Ltd. to construct and calibrate a numerical model of the region around the Southern Water's coastal area. In undertaking these numerical model developments, Southern Science Ltd. have used an original version of MIKE 21, with this industry standard model developed in the 1990s by the Danish Hydraulics Institute (DHI). This version of the model is based on an Alternating Direction Implicit (ADI) finite difference algorithm, with the model solving the two-dimensional Reynolds Average Navier-Stokes equations to predict the key hydrodynamic parameters, namely the tidal elevations and currents, and the solute transport equation to predict the depth integrated concentration fluxes across a regular space staggered grid. The approach adopted has been to use nested models with the grid size being from 2,000 m for the coarsest grid domain, and then down to finer grids, such as: 500 m, 250 m and 125 m, as for the Portobello Long Sea Outfall study. The main driving model is the 2,000 m coarse grid model, consisting of two open boundaries. These boundaries include: (i) an approximate 200 km long boundary from Plymouth Sound to the North and Roscoff, along the French coast, to the South, and (ii) an approximate 300 km long boundary from a point between Skegness and Spurn Point on the English coast to the West and across the North Sea to Terschelling along the Dutch coast to the East.

This modelling suite being used for the Southern Water coastal modelling studies, and the overall structure of the setup of three nested models within the main driving model is now dated, with some key aspects of the fluid mechanics and dispersion-diffusion processes included in the modelling suite being basic for improved bathing water quality predictions. Based on the current modelling suite using a structured and nested finite difference grid, it is recommended that at the earliest opportunity Southern Water should use an improved modelling suite for predicting the tidal and wind driven currents and solute transport concentration levels along Southern Water's coastal zone and bathing waters.

Recommendation: 1

Southern Water consider replacing their existing oceanographic and coastal zone modelling suite with a more refined model, based on an unstructured grid finite volume or finite element structure, and with improved representations of the physical and biological processes in the governing hydrodynamic and solute transport equations, particularly in the shallower near-shore bathing waters. The current unstructured grid finite volume or finite element models widely used include (in alphabetical order): Delft3D Flexible Mesh Suite (Deltares, 2021)*, MIKE 21/3 Flow Model* (Danish Hydraulic Institute, 2017)*, and TELEMAC-MASCARET* (Electricite de France, 2022). *The models Delft3D and TELEMAC-MASCARET are available as Open Source, but at the time of writing this report MIKE 21/3 is not available in open-source form.*

Note: The writer understands that Southern Water now has a licence for the unstructured MIKE 21/3 model and is about to implement its use.

The above cited models (used widely internationally by the water industry, consultants etc.) are all based on using an unstructured grid structure and with the governing equations solved using either the finite volume or finite element method. An unstructured grid model has the advantage of not needing nested models and thereby avoiding momentum conservation challenges at the boundaries between different grid size sub-models. These models also offer the opportunity of focusing the finest grid resolution in regions of particular interest, such as bathing water beaches and in the proximity of outfalls etc.

In outlining the need for improved representation of a range of physical and biological processes in Southern Water's hydro-environmental coastal modelling suite, the writer is mindful of the need to predict the tidal and wind driven currents, and the diffusion and dispersion processes, as accurately as possible to acquire defensible and robust deterministic predictions for assessing the impact of outfall discharges on the associated bathing water quality. The relevant key physical and biological process refinements for consideration in any future modelling studies to be linked to Beachbuoy are outlined in the following sections.

(ii) Coarse Grid Model Boundary Representation

As outlined in the previous section the open boundaries for the coarse grid model were based on specifying tidal harmonic constituents along both open boundaries, i.e., with the northern boundary located due west-east across the North Sea from the English to Dutch coasts, and with the western boundary located due north-south across the English Channel from the English to French coasts.

In the modelling report by Southern Science Ltd. (Southern Water Services Ltd, 1995) on the treatment of the open boundary conditions for the 2 km grid, it is stated that water elevations were obtained at each grid cell along the boundaries using the IOS (now NOC – National Oceanographic Centre) method of predicting tidal elevations from a harmonic analysis. However, it is not clear if the open boundary conditions along the northern and western boundaries include changes in the tidal harmonic components that match the Coriolis slope for geostrophic currents, assumed to be normal to these long open boundaries. Without measured data of any tangential currents along these open boundaries then it is recommended that the tidal currents are assumed to be normal across the open boundaries and thereby match the Coriolis slope, given for the northern boundary (Kreitmair, 2021) as:

$$\frac{\partial \eta}{\partial y} = -\frac{fU}{g} \tag{1}$$

where η = water surface elevation relative to datum, y = tangential co-ordinate axis along the northern boundary, $f = 2\omega Sin\varphi$ = the Coriolis parameter arising from the earth's rotation, where ω is the angular frequency of rotation of the earth and φ is the angle of latitude, U = depth mean velocity component normal to the open boundary axis, and g = gravitational acceleration. In the writer's experience then if the Coriolis slope is not included along long open oceanic boundaries, or the harmonic constituents are not adjusted to account for this slope, then the Coriolis slope should be included either directly in the open boundary water elevations along the boundary, or the tidal harmonics should be checked and refined accordingly. Otherwise, circulation can be engendered along the boundaries (particularly at slack water), affecting the key boundary hydrodynamic processes, and generating unrealistic vorticity.

Recommendation: 2

It is not clear if the Coriolis slope effect is included in the coarse grid model, either directly or indirectly, along the northern and western open boundaries and the inclusion of this effect should be checked to ensure that if any questions are raised about its inclusion in the model, then evidence can be provided to confirm that this effect is included appropriately.

Note: The writer understands that Southern Water will be carrying out sensitivity analyses of the impact of the Coriolis slope effect on the northern and western boundaries of the re-constructed MIKE 21/3 model.

(iii) Grid Resolution and Nesting

The original coarse grid model was set-up with a grid resolution of 6,750 m. However, this was rightly reduced to 2,000 m and with nested finer grid sub-models at 500 m, 250 m and 125 m, for the Portobello study, and with similar nesting for the other studies. With the simplified and revised criteria for compliance of FIO levels, associated with the 2006 Bathing Water Directive, it is essential to ensure that the most accurate open boundary conditions are used to drive the local area models from the coarse grid model. Since the key process of FIO transport is generally likely to be governed by advection, or transport by the tidal and wind driven currents, then it is essential to ensure that the hydrodynamics are predicted as accurately as possible in the regions of interest, i.e., in the region of bathing and/or shellfish water sites.

For the coarse grid model, and the domain covered by this model, the grid resolution of 2 km and the bathymetry obtained from published depths on the admiralty charts was deemed appropriate for the Regional Model. The model was calibrated and verified against 10 Admiralty chart diamond sites and 12 standard port sites in the North Sea and English Channel and for a further 3 to 6 field monitoring sites located near to the coast for each fine grid model region. Calibration was undertaken for each data site at neap tides and with validation then being undertaken at the same sites using the corresponding spring tide data. It is critical that this model predicts the hydrodynamics reasonably accurately as this model forms the basis of the driving boundary conditions for the nested models. To assess the accuracy of such coarse grid coastal models for predicting tidal elevations and currents (both speed and direction) it has been conventional for water companies and regulatory authorities etc. to assess the accuracy of the model predicted relative to field measured data parameters using the Foundation for Water Research (FWR) criteria, as used extensively for coastal and estuarine model studies (Foundation for Water Research, 1993). The guidelines for required performance at the validation stage are summarised from the report as follows:

- Levels to within +/-0.1 m;
- Speeds to within +/-0.1 m/s;
- Directions to within +/-10^{o};
- Timing of high water to within +/-15 minutes.

Alternatively, some of these criteria can be considered in percentage terms, although these criteria are less commonly used in the writer’s experience (particularly for water levels):

- Speeds to within +/-10-20%
- Levels to within 10% of spring tidal ranges or 15% of neap tidal ranges.

In general, the writer would question the accuracy of the model predictions of the key hydrodynamic parameters against these FWR criteria, and for the reasons that follow in this sub-section. In the writer's experience more accurate model predictions could be obtained for water elevations and tidal currents if more refined representations of the key physical parameters in the governing equations were included and as outlined in the following sub-sections.

To highlight some examples of the level of accuracy of the model predictions relative to calibration data, typical examples (randomly chosen) are given for the Portobello Long Sea Outfall study: for high tide water level differences and timings respectively: (i) Figure II.C.40, at Selsey ≈ 0.33 m (> 0.1 m) and ≈ 58 mins (> 15 mins), (ii) Figure II.C.38, at Hastings ≈ 0.3 m (> ≈0.1 m) and ≈ 40 mins (> 15 mins), (iii) Figure II.C.33, at Brighton ≈ 0.16 m (> 0.1 m) and ≈ 50 mins (> 15 mins); likewise for current speeds: (iv) Figure II.C.15, at E 536 ≈ 0.22 m/s (> 0.1 m/s), (v) Figure II.C.16, at D 536 ≈ 0.22 m/s (> 0.1 m/s), (vi) Figure II.C.18, at V 2045 ≈ 0.33 m/s (> 0.1 m/s). These are some arbitrary random points chosen using neap tide predicted and measured data used to compare the water levels, time differences at high tide and tidal current speeds, with none of these examples being within the FWR framework for peak comparative differences. In the writer's experience of extensively overseeing model applications for a range of coastal studies, it is common to see compliance with the FWR framework particularly for water elevations and times of high tide, but often there can be non-compliance for current speeds and especially in shallow water.

Part of the reason for a lack of compliance with the FWR framework is that the comparisons have been primarily made against current meter, tide gauge and Admiralty chart data, which are generally not used alone these days for model calibration and validation. More often field data are gathered synchronously across the domain using a suite of ADCPs (Acoustic Doppler Current Profilers) to provide continuous data at key sites across the domain, including at least one profiler located along one of the open boundaries.

Recommendation: 3

It is recommended that at the earliest opportunity a field monitoring programme is undertaken to measure the key hydrodynamic parameters, continuously and synchronously, at several (ca. 6) key sites across the domain. This should first be done to re-calibrate and validate the coarse grid model and, at a later stage, undertaking a further field study using ADCPs to validate the finer grid models in the shallower bathing waters, which is crucial. In the writer's experience there is scope for improving the accuracy of the model predictions to meet the FWR criteria, particularly regarding tidal phasing, and thereby leading to more confidence in the model predictions.

Note: The writer understands that Southern Water will review existing hydrometric survey data and where necessary commission further hydrometric surveys to provide a complete set of calibration and validation data for the re-constructed MIKE 21/3.

For the finer grid models these were typically nested at 500 m, 250 m and 125 m in regions of particular interest, such as in predicting the beach bathing water FIO levels arising from a storm water overflow or long sea-outfall. In terms of the nested models the writer has three key concerns, including: (i) the grid resolution of the finest grid, (ii) the patching between the grids, i.e., from the coarse to the finer grid models, and (iii) the transfer of boundary data from the larger to smaller grid and vice versa, and particularly where the grid orientations differ.

In considering first the grid resolution, in the writer's experience the finest realistic grid resolution should, in the first instance, be used to address the main objective of the modelling studies. In this case the main objective of the study was to assess the impact of existing long sea outfalls on the water quality of nearby bathing waters and to identify whether or not, for a given set of conditions from an outfall discharge, and with an assumed concentration level of *E. coli* and/or Intestinal Enterococci (IE) which exceeds the Bathing Water standards as specified in the EU Water Framework Directive, as summarised in Table 1 (EU Water Framework Directive, 2013). For the case of the Portobello study, the location of the southern boundary is just over 6 km from the outfall location and with Beachy Head being just over 2 km from the headland. The writer would have moved the eastern and western boundaries of the finest grid model to the locations of the boundaries of the 250 m grid, and the southern boundary to the nearby 090000N Ordnance Datum location. By moving both the eastern and western boundaries further out would have more accurately conserved mass and momentum transfer at the coarse to fine grid interface boundaries. This would have reduced any possibility of the outfall plume reaching close to the boundary and where the hydrodynamic parameters are often not predicted with the same degree of accuracy as compared to the rest of the model.

The writer now understands that Southern Water now has a licence for the unstructured MIKE 21/3 model and is about to implement its use. The boundaries of this model will contain the model plume from all locations in the Southern Water area.

In particular, the writer's experience of participating in numerous similar studies (undertaken in the UK and internationally) has indicated that the 125 m finest grid resolution sub-model was too coarse, especially in being able to predict the occurrence of nearshore complex flow structures, such as tidal eddies, which can significantly affect the nearshore bathing water hydrodynamic and water quality process predictions. It is appreciated that in the 1990s computing power was much more limited than the resources available with current day powerful workstations and even laptops, nevertheless grid resolution can be critical along nearshore bathing waters in predicting complex hydrodynamic processes.

Table 1. Bathing water standards EU Directive 2006.

Classification	Enterococci (cfu/100 ml)	*E. coli* (cfu/100 ml)	Percentile Evaluation
Inland Waters			
Excellent	200	500	95
Good	400	1000	95
Sufficient	330	900	90
Coastal and Transitional Waters			
Excellent	100	250	95
Good	200	500	95
Sufficient	185	500	90

An example of the need to ensure fine grid resolution in the nearfield coastal zone was illustrated in a bathing water compliance study undertaken by the writer in supporting a consulting company in 1991, and as illustrated in Figure 1. Here it can be seen that for the 333 m grid resolution, in the figure to the left, the current is generally parallel to the coast and illustrates the plume from the design of a 900 m long outfall advecting away from the bathing water and in a north westerly direction. However, when the resolution was reduced to 75 m and grid dependency checked, the model predicted strong tidal eddies along the bathing waters and the predicted faecal coliform concentrations along the North Beach at Whitby were predicted to continue to result in non-compliance with the 1976 EU Bathing Water Directive (BWD). To overcome this predicted continuing non-compliance with the BWD the outfall length was extended to 1,600 m, beyond the recirculating zones along the coast, and thereby leading to predicted compliance at the norther beach and as shown in Figure 2.

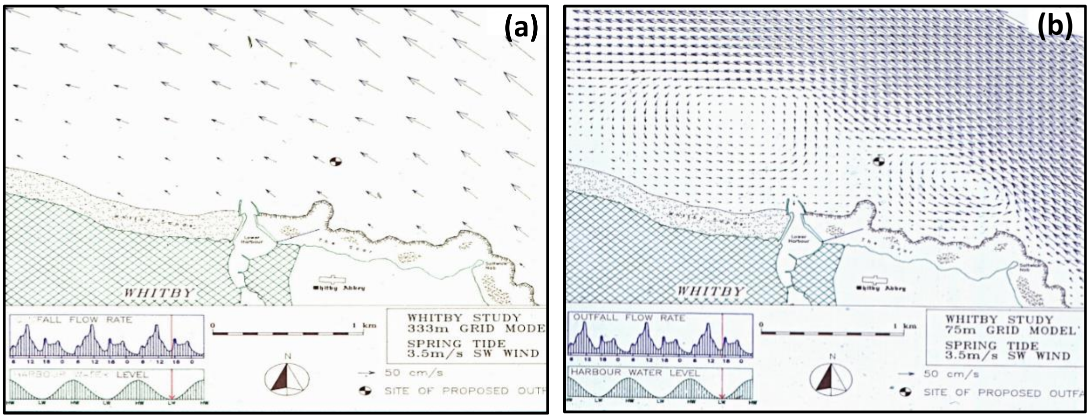


Figure 1. Predicted tidal currents at Whitby using a grid resolution of: (a) 333 m, and (b) 75 m. Note the significant difference in the predicted nearshore currents.

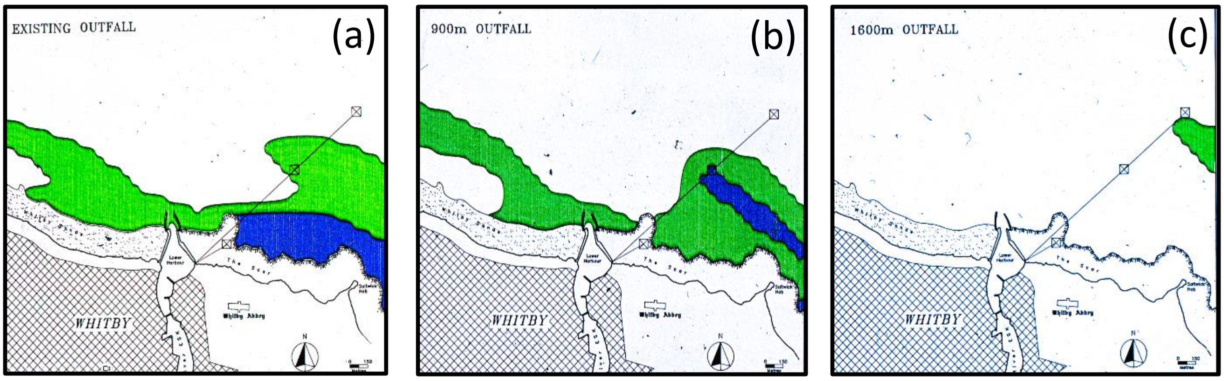


Figure 2. Predicted faecal coliform levels along Whitby bathing waters at low spring tide for: (a) existing outfall, (b) 900 m long outfall, and (c) 1,600 m outfall (Green > 100 cfu/100ml and Blue > 2,000 cfu/100ml).

Recommendation: 4

*It is recommended that for improved accuracy in the coastal bathing waters, in addition to switching to an unstructured grid model (as advised in **Recommendation 1**), the minimum grid resolution should be reduced in the nearshore zones to typically 50 m, and a maximum of 75 m, subject to grid dependency tests and run-times.*

Note: The writer understands that Southern Water now has a licence for the unstructured MIKE 21/3 model and is about to implement its use. This model will have a refined grid cell structure in nearshore areas.

In the modelling report by Southern Science Ltd. (Southern Water Services Ltd, 1995) the grid nesting has been undertaken at resolutions of 500 m, 250 m and 125 m from the coarse grid 2 km model. Studies undertaken in the early 1990's by a PhD student at the University of Bradford, and supervised by the writer (Alstead, 1994), showed that it was desirable to nest (or patch) at ratios of 1:3 (i.e., coarse to fine) or 1:5. In doing so the water levels at the centre of the coarse grid match the centre of the middle grid square in the fine grid domain and the bathymetry and velocity components in the coarse grid can be compared directly with the corresponding values around the fine grid squares adjacent to the coarse grid square. This refinement to nesting is important in predicting nearshore complex hydrodynamic processes, such as recirculating eddies in bathing waters etc., and has been extended further through subsequent studies by various authors, including Nash et al. (Nash & Hartnett, 2010).

Nash and Hartnett went on to show that to conserve momentum fully, particularly along the tangential direction at the boundary, then 'ghost cells' were needed to ensure that the velocity and momentum flux along the boundary were also fully conserved. This is illustrated in their paper on boundary error reduction and illustrated in Figure 5 (Nash & Hartnett, 2014).

Recommendation: 5

It is recommended that if Southern Water decide to continue using their existing nested models over the long term for predicting hydrodynamic and solute transport processes in the nearfield zones, then for improved accuracy the intermediate and fine grids should be nested down in ratios of 1:3 or 1:5, thereby ensuring that the predicted data coincide at the centre of the coarse and central fine grids, enabling direct comparisons to be made between the predicted data in both grid sets and grid dependency inherently tested.

Note: The writer understands that Southern Water now has a licence for the unstructured MIKE 21/3 model and is about to implement its use. The implementation of this model will obviate the need for nesting.

(iv) Bottom Roughness Representation

For the bed roughness the conventional representation has been to use the Manning roughness coefficient in open channel flow as given by the following equation for steady flows, in SI units (Chow, 1959):

$$U = \frac{1}{n} R^{2/3} S_f^{1/2} \tag{2}$$

where U = depth mean free stream current, n = Manning roughness coefficient (s/m$^{1/3}$), R = hydraulic radius, which for a wide channel (and coastal modelling) is approximated to the local depth, and S_f = friction slope. In representing the Manning's coefficient, it is important to appreciate that the term is not dimensionless and therefore corrections need to be made to the coefficient if using a different notation to SI units).

In the DHI MIKE 21 suite the Manning coefficient is represented in a less traditional form, wherein the Manning Number (N) is expressed as the reciprocal of the traditional representation, i.e., $N = {}^{1}/_{n}$, where N has units of m$^{1/3}$/s. This representation has been used in the Southern Science modelling studies, using coefficients generally varying from 30 to 40 m$^{1/3}$/s, which would equate to traditional Manning coefficient values of 0.033 to 0.025 s/m$^{1/3}$, with larger rougher values being used in the nearshore coastal waters.

Although this approach is appropriate for rivers, and where it is still widely used, it is less appropriate for coastal and oceanic waters where it is difficult to quantify the choice of the Manning number, or roughness coefficient, relative to some physical parameters of the bed morphology etc. (unlike rivers where extensive historical field data exists). Furthermore, the Manning representation assumes that the flow is rough, turbulent flow and that the local head loss is dependent only on the size and characteristics of the bed roughness, i.e., where form drag dominates (such as wakes in the lee of ripples and dunes). However, for low tidal velocity flows occurring typically along bathing water beaches etc., Reynolds number effects can be more pronounced, reflecting the increased influence and impact of skin friction, i.e., for flow over sand grains. This complex hydrodynamic phenomenon is increasingly used in computational coastal models and can be represented using the more comprehensive friction formulae as given, for example, by the Colebrook-White equation (Henderson, 1966) and used in the writer’s models (Falconer, Lin, & Kashefipour, 2005):

$$C = \frac{H^{1/6}}{n} = -17.715 \ log_{10}\left[\frac{k_s}{12H} + \frac{0.282C}{R_e}\right] \tag{3}$$

where C = de Chezy roughness coefficient, H = local (time-varying) depth, n = Manning roughness coefficient, k_s = Nikuradse equivalent sand grain roughness, and R_e= local Reynolds number, representing the relative mean turbulent characteristics of the flow. The other advantage in using the Colebrook-White formulation to represent the bed roughness, rather than the Manning formulation, is that the physical roughness parameter k_s can be directly related to the height of the bed features, such as ripples or dunes on the beach bed, rather than based on a descriptive representation of the bed features as for the Manning coefficient.

For the range of Manning (n) values cited above, and included in the Portobello LSO report, then the k_s values corresponding to the Manning coefficients range of 0.033 to 0.025 s/m$^{1/3}$ (or 30 to 40 m$^{1/3}$/s using DHI’s definition of a Manning number) would equate to equivalent sand grain roughness heights of 0.288 to 0.070 m (or 28.8 to 7.0 cm) respectively in a depth of 2 m, and roughness heights of 0.365 to 0.046 (or 36.5 to 4.6 cm) respectively in a depth of 20 m. However, it is not clear to the writer as to why the values of the bed roughness are not significantly higher in the deeper water relative to the much shallower coastal bathing waters. This could have a marked impact on plume advection in the shallower bathing waters.

Note: The writer understands that the Manning’s number will be calibrated for the new updated models against any additional calibration data, taking into account bed forms and agreement with hydrometric data. However, the writer suggests that the bed forms are first defined in terms of an equivalent sand grain roughness height and then converted to an equivalent Manning coefficient or Manning number.

Recommendation: 6

It is recommended that Southern Water undertake observational assessments of the bed characteristics along their bathing waters to estimate the approximate k_s *equivalent sand grain roughness heights in the nearshore region. This will ensure that the roughness shear stress included in the shallower waters is not higher than the bed characteristics which, in turn, would lead to increased energy dissipation of the tidal currents in the model, particularly in the critical bathing water areas.*

Note: The writer understands that Southern Water now has a licence for the unstructured MIKE 21/3 model and is about to implement its use. Model calibration and validation will be carried out with the BGS superficial sediment maps being used in future to inform the choice of bed roughness where appropriate. The writer recommends that these data are first converted to an equivalent sand grain roughness height and then used to estimate an equivalent Manning coefficient or Manning number.

(v) Wind Stress Representation

In coastal bathing water quality studies, the writer's experience has shown that the representation of wind stress effects can be significant, particularly in shallow coastal basins where improved sensitivity can be obtained in 2D models using refined second order parabolic velocity distributions (Falconer & Chen, 1991). This is best illustrated for modelling 3D velocity patterns in an idealised coastal basin and a lake in Cumbria (Kocyigit & Falconer, 2004a). In the writer's experience in 2D hydrodynamic models applied to coastal waters the impact of the wind stress on the surface generally shows little impact in terms of the transport of effluent plumes unless the velocity distribution is represented in a more realistic manner, as evidenced by field data. Also, the coefficient of surface frictional resistance needs to be refined to take account of changes in the interaction between the surface wind stress and the fluid surface current because of changes in the wave characteristics on the surface.

$$\tau_{xw} = C_s \rho_a W_x W_s \tag{4}$$

where τ_{xw} = wind shear stress in the x-direction, C_s = air-water resistance coefficient, ρ_a = air density, W_x = wind velocity component in the x-direction, and W_s = wind speed. In general, many model studies audited by the writer to-date have assumed a constant value for the air-water resistance coefficient (typically 0.0026). However, the writer has found that the representation of the air resistance coefficients developed from extensive field data by Wu provide a more evidence-based representation of the complex interaction between the wind and surface water in coastal and oceanographic domains (Wu, 1982; Wu, 1969):

$$\begin{aligned} C_s &= 1.25 \div {W_s}^{0.2} \times 10^{-3} \; for \; W_s \leq 1 \, m/s \\ C_s &= 0.5 \times {W_s}^{0.5} \times 10^{-3} \; for \; 1 < W_s \leq 15 \, m/s \\ C_s &= 2.6 \times 10^{-3} \; for \; W_s > 15 \, m/s \end{aligned} \tag{5}$$

In the writer's experience it is difficult to represent the impact of a strong wind on the advection of a discharge plume from an outfall in the region of coastal bathing waters, as the impact of a strong wind (typically over 10 m/s) is to change the velocity distribution away from the traditional assumed logarithmic velocity profile. Nonetheless, the above representation for the air-water resistance coefficient and a refinement of the velocity distribution to a second-order parabolic representation can lead to improved predictions for bathing water impacts. It is also worth noting, and widely accepted, that in open oceanic waters the surface fluid currents can be represented as a function of the wind speed measured at 10 m, with corresponding measured surface currents being highly variable and typically increased by 3% or more of the wind speed, for winds in the range 5-30 m/s (Weber, 1983).

Recommendation: 7

In the writer's experience the wind can have a significant impact on coastal bathing water hydrodynamic and solute transport processes. It is therefore recommended that the representation of the wind stress effects on the variation in the trajectory and physical characteristics of the discharge plumes are investigated in more detail, particularly regarding the impact of larger winds (ca. 10-20 m/s) on the surface velocities. This can be done through documentation of the treatment of the wind stress representation, including its impact on the assumed vertical velocity profile, and how the vertical diffusion and dispersion coefficients are refined to account for increasing wind velocities. The writer questions the implication that wind velocities exceeding 5 m/s in the data relating to Beachbuoy do not lead to increased concerns about bathing water quality risk, and clarification on the wind representation could lead to more confidence in the assumption that a wind speed of 5 m/s is the peak critical wind velocity.

Note: The writer understands that simulations have already been undertaken with higher wind speeds and the results of these simulations will be included in Beachbuoy in the short-term. In addition, the writer understands that Southern Water now has a licence for the unstructured MIKE 21/3 model and is about to implement its use. It is understood that additional runs will be undertaken to evaluate the impact of higher wind speeds on wind dispersion and diffusion in the updated model.

(vi) Eddy Viscosity and Turbulence Representation

In the writer's experience one of the key parameters that can be critical in evaluating the tidal elevations, currents and diffusion-dispersion processes of solute transport fluxes in bathing waters is the eddy viscosity and the representation of complex turbulent flows, particularly in relatively shallow coastal waters. In the current model being used for modelling the turbulent stresses in nearshore bathing waters the simplest constant eddy viscosity approach is adopted. This has two key disadvantages in delivering an accurate model for predicting nearshore processes. Firstly, the approach is basic and a gross over-simplification of a complex hydrodynamic process; even in the simplest case of uniform flow in a straight channel we know that the turbulent eddy viscosity is a function of both the mean velocity and depth, with both parameters changing significantly in the nearshore coastal zone. Secondly, by assuming a constant eddy viscosity then the gradient of the eddy viscosity is not included in the governing equations used in the model, with the simplification being shown for the x-direction below:

$$\frac{\partial}{\partial x}\upsilon_t\left(\frac{\partial U}{\partial x}+\frac{\partial U}{\partial x}\right) \Rightarrow \upsilon_t\left(\frac{\partial^2 U}{\partial x^2}+\frac{\partial^2 U}{\partial x^2}\right) \qquad (6)$$

where υ_t = depth averaged eddy viscosity and U = depth averaged local velocity. Whilst the change in the eddy viscosity in the longitudinal direction (i.e., $\frac{\partial}{\partial x}\upsilon_t$) is often relatively small this is generally not the case for the change in the eddy viscosity in the lateral direction.

In most recently developed models, more refined and accurate turbulence models are included in the model to predict shallow water flows and particularly relating to predicting recirculating flows, such as tidal eddies. Such eddies can advect the trajectory path of an outfall discharge plume towards bathing waters, as shown in Figure 1, and thereby affecting the model predicted bathing water FIO concentrations.

For improved turbulence model predictions most model studies include increasingly refined and improved turbulence models, the simplest of which was included in the DIVAST (Depth Integrated Velocities And Solute Transport) model (as developed by the writer) and used extensively for bathing water studies in the period ca. 1986-2006 (Falconer, 1986). This model is based on the original work of Elder for pipes (Elder, 1959) and refined by Fischer et al. (Fischer, List, Koh, Imberger, & Brooks, 1979) for free surface river flows to give:

$$\upsilon_t = C_e\, U_* H \tag{7}$$

where C_e = eddy viscosity coefficient (typically = 0.15), U_* = shear velocity (= $\frac{\sqrt{g}U_s}{C}$ where g = gravitational acceleration, U_s = free stream current speed, and $C = \frac{H^{1/6}}{n}$ where C = Chezy roughness coefficient, H = local depth and n = Manning roughness coefficient. However, field data by Fischer et al. (1979) showed that for the eddy viscosity coefficient even a typical value of 0.15 is low compared to measured data recorded in rivers and nearshore coastal waters, with values for $\frac{\upsilon_t}{U_* H}$ typically ranging from 0.42 to 1.61. In more recent studies by the writer the coefficient in equation (7) has been increased from 0.15 to typically 1.0, or more.

In the model studies undertaken by Southern Science Ltd. it appears that a constant value was assumed across the domain giving υ_t = 1 m^2/s for all studies. However, for the Portobello Long Sea Outfall study, assuming a local mean depth of 5 m, a typical current at Site 2 (nearest to the outfall) of ≈ 0.5 m/s (peak), and a Manning roughness coefficient ≈ 0.03 (N = 33), then the corresponding value for υ_t would be 0.18 m^2/s. In 50 m of water and using the same values for U_s and n, the eddy viscosity becomes 1.24 m^2/s, i.e., nearly 7 times larger in oceanic waters where the depth is increased 10-fold. Thus, using a conservative and relatively large value for the eddy viscosity coefficient in equation (7) of 1.0 (compared with 0.15), the typical value of the turbulent eddy viscosity is 0.18 m^2/s as compared with 1.0 m^2/s. This would suggest a reduced turbulent eddy dissipation horizontally and thereby a reduced spreading of the plume, as discussed in the next section.

For completeness current modelling studies by specialist CFD companies etc. have often included more sophisticated two-equation turbulence models, such as the widely used k-ε (or k-υ_t) model. More recently finer grid resolution open source models have been developed, such as Open-Foam (OpenFoam, 2023), using more sophisticated Large Eddy Simulation (LES) based turbulence models, such as the Smagorinsky model (Smagorisky, 1963; Avalos-Patino, Neethling, & Piggott, 2023; Rodi, Constantinescu, & Stoesser, 2013). In these models the eddy viscosity is parameterized to the sub-grid scale shear stress by filtering the velocity fields and linking to the local grid size, for example (Wikipedia, 2023):

$$\upsilon_t = C_s \Delta x \Delta y \sqrt{\left(\frac{\partial U}{\partial x}\right)^2 + \left(\frac{\partial V}{\partial y}\right)^2 + \frac{1}{2}\left(\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x}\right)^2} \tag{8}$$

where C_s = dimensionless coefficient, evaluated from model calibration and with typical values of 0.176 (Abbott & Minns, 1998), $\Delta x, \Delta y$ = local grid sizes in the x, y directions, and U, V = depth mean velocity components in the x, y directions respectively.

Recommendation: 8

In the writer's experience and based on the summary of turbulence modelling cited in Section 2, it would appear that in the nearshore coastal waters an eddy viscosity value of 1 m^2/s may be relatively large and that a value of typically 10% of that currently used would be more realistic. A lower eddy viscosity will reduce turbulent diffusion in the bathing water zone and could lead to maintaining a higher concentration of FIOs within the advected plume. It is therefore recommended that in the future at least a one-equation turbulence model be used to estimate the turbulent diffusion process, particularly across the fine grid domain.

Note: The writer understands that Southern Water now has a licence for the unstructured MIKE 21/3 model and is about to implement its use. The implementation of the eddy viscosity in this model will be considered carefully including use of the Smagorinsky formulation.

(vii) Diffusion and Dispersion Representation

Regarding the transport of FIOs from an outfall to nearshore bathing waters, or elsewhere within the domain, the model includes transport by two key processes, namely: (i) advection by the current, and (ii) spreading of the plume by shear dispersion (D_l) and turbulent diffusion (D_t). For the turbulent diffusion of a solute particle in the horizontal flow field then the transport is similar to the diffusion of turbulence in the flow, i.e., the solute particles are transported by the turbulent perturbations. This gives a diffusion coefficient, similar to that for the eddy viscosity in equation (7) (Falconer et al., 2005). Likewise, for the vertical turbulent diffusion of a solute, and in the absence of stratification and field data, it is common to assume a linear shear stress distribution and a logarithmic velocity profile giving (Vieira, 1993):

$$D_{tz} = U_* \kappa z \left(1 - \frac{z}{H}\right) \tag{9}$$

where D_{tz} = vertical turbulent diffusion, U_* = shear velocity, κ = coefficient (= 0.4), and z = vertical co-ordinate relative to the depth H.

For the longitudinal dispersion term represented by the shear velocity distribution, both in the horizonal and vertical planes, this can be expressed in a similar manner as for turbulent diffusion term of equation (7) giving, for two-dimensional coastal flows (Preston, R W, 1985):

$$D_{xx} = \frac{(D_l U^2 + D_t V^2)H\sqrt{g}}{U_s C} + D_w$$
$$D_{yy} = \frac{(D_l V^2 + D_t U^2)H\sqrt{g}}{U_s C} + D_w \tag{10}$$
$$D_{xy} = D_{yx} = \frac{(D_l - D_t)UVH\sqrt{g}}{U_s C} + D_w$$

where $D_{xx}, D_{yy}, D_{xy}, D_{yx}$ = dispersion-diffusion terms in the xx, yy, xy and yx planes respectively, and D_w= wind induced dispersion coefficient, with the other terms being defined previously. For values of D_l and D_t, these dimensionless constants can be obtained from field data, or alternatively minimum values can be obtained by assuming a logarithmic velocity profile, wherein for theoretically based studies D_l = 5.93 (Elder, 1959) and D_t = 0.15 (Fischer, 1973). However, in practical studies these values tend to be rather low (Fischer et al, 1979), with measured values of D_l and D_t ranging from 8.6 to 7,500, and 0.42 to 1.61 respectively. In the absence of field data, undertaken in the form of extensive dye dispersion studies, the writer has found that the most accurate results have generally been obtained in the DIVAST model using typical values of: D_l = 13.0 and D_t = 1.2 (Falconer, 1991).

Using the same values as for the previous section in estimating typical values for D_{xx} for depths of 5 m and 50 m and for U and V velocity components of 0.5 m/s and zero respectively and for a Manning roughness coefficient ≈ 0.03, gives, for depths of 5 and 50 m: D_{xx} = 2.34 m^2/s and 15.90 m^2/s respectively. These values show how the dispersion-diffusion coefficient varies with depth and is significantly larger than the range of 0.1-0.25 m^2/s cited in the Portobello Long Sea Outfall report (Southern Water Services, 1995).

Recommendation: 9

In the writer's experience, and for the typical values included in equation 10, in the nearshore bathing waters the range of dispersion-diffusion coefficients of 0.1-0.25 m^2/s *is relatively small and that a value of typically at least an order of magnitude greater would be more realistic. Furthermore, the dispersion-diffusion coefficients in analytical and idealised flume laboratory studies are strongly dependent on the product of the local velocity and depth, and it is recommended that the solute transport model should be refined to include velocity and depth effects and the gradient of the dispersion-diffusion coefficients should also be included in any future modelling studies.*

It should also be noted that wind stress effects can be significant in dispersion-diffusion process representation (i.e., D_w *in equation 10) and these parameters will increase with wind stress effects, and particularly for high winds. These additional stress effects should also be included in future model studies, ideally based on velocity profile parameterisations reported in the literature.*

Note: The writer understands that Southern Water now has a licence for the unstructured MIKE 21/3 model and is about to implement its use. This model will be validated against buoyant dye tracing data and depth and velocity effects will be carefully considered. It is also understood that additional runs will be undertaken to evaluate the impact of higher wind speeds on wind dispersion and diffusion.

(viii) Decay Rate Representation

The final variable parameter dependent on field and/or laboratory data in the governing hydrodynamic and solute transport equations in predicting the transport of FIOs is the decay rate. This term is expressed generically in the form of a variable k, with units of time^{-1}, where the time can be in seconds, hours or days, depending on the time scale of the project simulations. However, in the most widely used computational deterministic models used for predicting the decay rate of FIOs in bathing waters, the parameter is generally expressed in hours and in the form of a T_{90} value (Guilland, Derrien, Gourmelon, & Pommepuy, 1997). The corresponding relationship between k and T_{90} is given as:

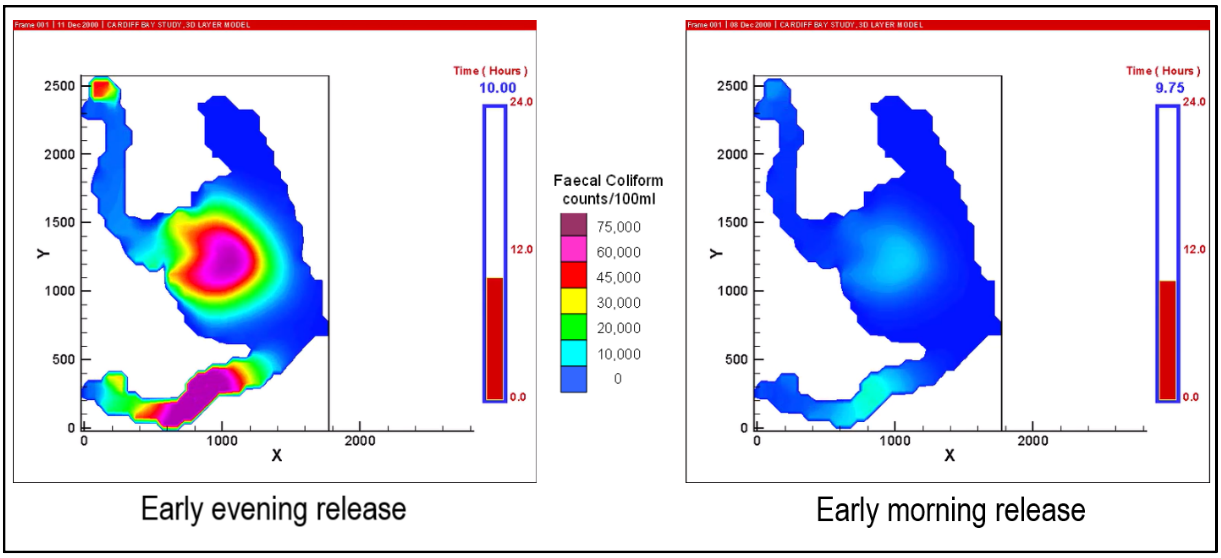
$$T_{90} = \frac{2.303}{k} \tag{11}$$

where T_{90} = time required for the concentration to reduce by 90% and k = kinetic decay rate. In field and/or laboratory measurement studies the value of T_{90} is usually cited in terms of hours and a typical data set of measurements for the River Ribble and Fylde Coast basins is shown below (Kay, Personal Communication, 2015).

Table 2. Measured variation in decay rates for different bacteria and water salinities.

	n	**Mean T_{90} (Hours) Irradiated**	**Mean T_{90} (Hours) Dark**	**Mean Total Irradiation D_{90} (MJ m^{-2})**
E. coli				
Freshwater	68	13.61	**355.51	6.65
Estuarine	32	8.56	*30.64	5.17
Saline	20	2.33	33.77	1.41
Intestinal Enterococci				
Freshwater	68	14.87	65.70	8.99
Estuarine†	32	11.08	84.63	6.70
Saline	20	4.98	57.39	3.01

In the Portobello Long Sea Outfall studies, a dispersion sensitivity analysis was undertaken for a T_{90} decay rate of 10 hrs, which is relatively conservative in comparison to the measured values for saline water in Table 2, but for a different site. However, if effluent is discharged from the long sea outfall at night, then the T_{90} values will be considerably higher and particularly in estuarine waters. This effect on model predictions is illustrated idealistically in Figure 3, which shows two identical releases of an arbitrary concentration at the domain limit for the two rivers flowing into Cardiff Bay. Whilst this screenshot from lecture notes overly highlights the impact of varying decay rates on the receiving water downstream concentration distributions of faecal coliforms, the results also show the significance and importance of considering the impact on bathing waters of night-time, as well as day-time, releases from an outfall.



Early evening release

Early morning release

Figure 3. Model simulations of faecal coliform concentration distributions in Cardiff Bay for different decay rate during night-time and day-time.

In modelling studies being audited and undertaken by the writer since the mid-1990s most bathing water compliance studies have considered decay rates which vary at least between day and night and the time of release has also been considered. More recent model studies have included more complex and refined representations of the kinetic decay of bacteria, such as the Mancini equation (Mancini, 1978), given as:

$$k = \ [0.8 + 0.02S] \times 1.07^{T-20} + \frac{I_A}{k_e H}[1 - e^{k_e H}] \qquad (12)$$

where k =decay rate, S = percentage of seawater, T = temperature, I_A = average daily surface solar radiation, k_e = light extinction coefficient, and H = total mixed depth. More recent studies by King et al. (King, Ahmadian, & Falconer, 2021) have refined the 3D TELEMAC model to include complex representations of the decay rate for faecal bacteria, based on detailed studies for Swansea Bay, undertaken by Stapleton et al. (Stapleton, et al., 2007a; Stapleton, et al., 2007b). These results show significant differences in the depth averaged values predicted in Swansea Bay using the 2D TELEMAC model and the depth integrated 3D TELEMAC model, see King et al., with typical results shown in Figure 4 for the 2D and 3D model predictions.

The results from this study by King et al. (2021) show the increasing need to model FIO concentrations along bathing waters using the following refinements: (i) 3D simulations in the nearshore bathing waters, which show significant concentration differences between the surface and near bed FIO concentrations, with the bed concentrations being higher for this study site and therefore having more impact on shellfish health risks; (ii) fine grid resolutions, down to 50 m grid size in Figure 4; (iii) including all the key CSO and riverine inputs in the simulations; (iv) including time varying decay rates; (v) including more representative turbulence and diffusion-dispersion coefficients (varying at least with velocity and depth); and (vi) including extensive field data of hydrodynamic, *E. coli* and Intestinal Enterococci data along the bathing waters for model calibration and verification.

Recommendation: 10

In the writer's experience the prediction of FIO concentrations along bathing waters is highly dependent on the values included in the model for the decay rate. This process is highly complex and dependent on a range of variables, requiring intensive field data for several parameters for accurate and robust predictions. However, whilst much of these data are expensive and labour intensive to collect and analyse, it is nevertheless advised that the key variations in day- and night-time decay rates are included in model studies, and simulations are undertaken for both day- and night-time outfall releases. Whilst the values currently used for T_{90} *decay rates are deemed to be conservative, nevertheless experience has shown that key stakeholders, including the public, are more reassured when different decay rates are included in any real-time model-based water quality signage.*

Note: The writer notes that current decay rates used are conservative when compared to values measured for the River Ribble and Fylde Coast and understands that in the revised model the use of day- and night-time varying decay rates will be considered.

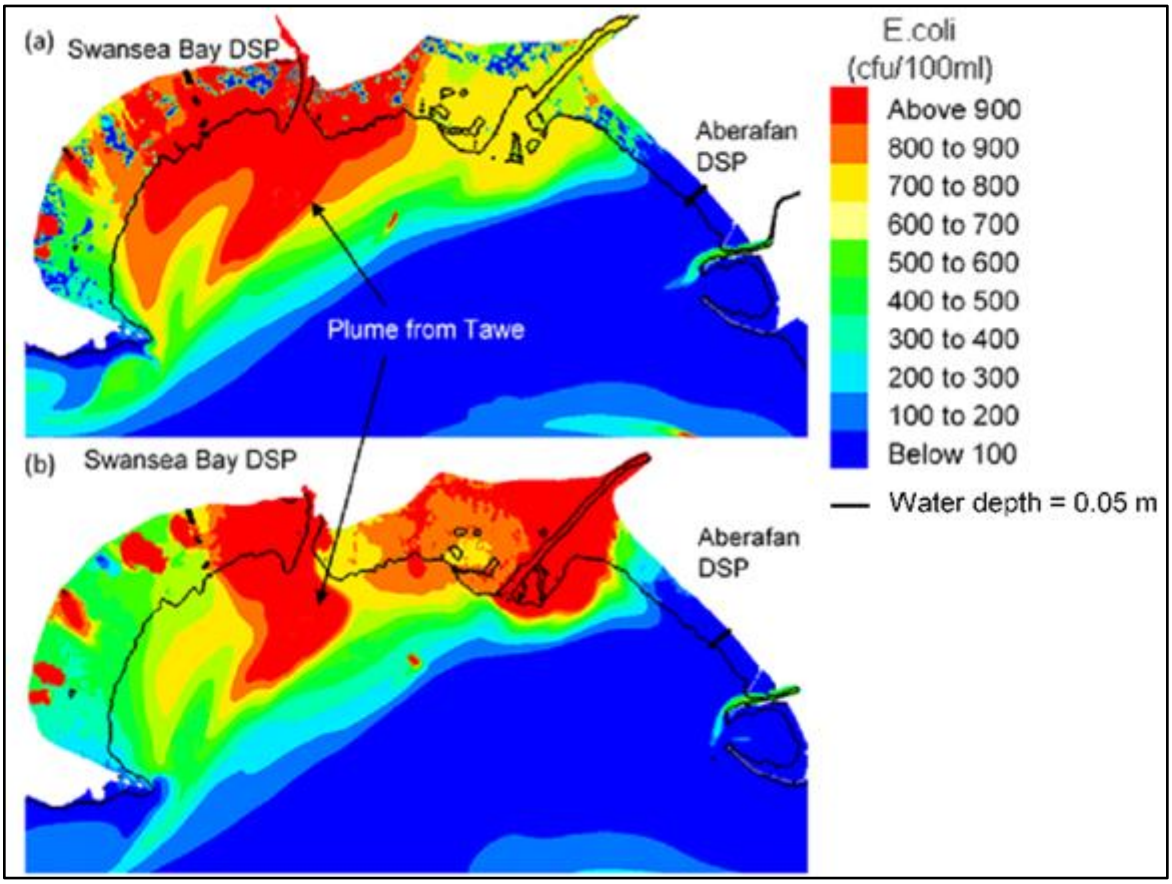


Figure 4. Comparison of *E. coli* concentration distributions in Swansea Bay using the Stapleton et al. decay function in a 2D and 3D model, with 3D predictions averaged over depth.

3. General Model Conclusions

Southern Water are to be acknowledged for providing their stakeholders and public consumers with information about the duration and times of plume discharges from their outfalls and assets. However, in their approach to model the impact of storm overflow releases on their bathing waters, predictions are currently made using a series of coastal models (nested within a coarse grid model) which predict the key hydrodynamic and solute transport processes to inform on the *E. coli* concentration distributions from the company's long sea outfalls and other assets. The confidence in the predictions of *E. coli* concentration distributions in the company's bathing water zones is therefore dependent on the setup of the coastal models, and the corresponding process predictions and coefficient values used. The models are also dependent on the quality of calibration and validation data. This approach is to be commended, but the writer is concerned about a number of issues relating to the coastal models and the calibration and validation data, based on extensive experience on similar projects. In the writer's opinion the model predictions could be significantly improved and/or made more robust in the future, wherein the model predictions would increase stakeholder and public confidence in enabling Beachbuoy to be used as a 'Predict and Protect' bathing water quality indicative tool. A summary of the writer's concerns about the limitations of the coastal models and the data used etc. are given below:

- The coarse 2 km grid model is generally fine, but the nested models raise a number of concerns, including: (i) they are not nested using conventional approaches by nesting down 3:1 (or 5:1), where the central fine grid cell coincides with the central point of the coarse grid cell, thereby allowing direct comparisons of water levels and solute levels at the centre of both cells; (ii) no refence is made to boundary cells and it is therefore difficult to see how tangential momentum is conserved fully across the fine grid boundary – this can be particularly critical in nearshore coastal waters where large changes in depth may occur (such as the Solent); and (iii) some of the fine grid nested domains are not orientated along the same plane as the coarse grid model, thereby introducing further mass and momentum conservation complexities across the fine grid boundaries.
- The fine grid model in the nested models along Southern Water's coastline is typically 125 m minimum. In the experience of the writer for nearshore coastal waters this is too coarse a grid size for predicting complex hydrodynamic processes and FIO concentration levels in nearshore bathing waters. Such a grid size area is more than twice the area of a standard football pitch (105 m x 68 m) and too coarse to pick up sharp changes in the bathymetry and spatial changes in such processes as turbulence, dispersion and diffusion.
- Few details are given in the reports on the calibration and validation data, but velocities and water levels are based on current measurements using a current meter, and Admiralty Chart and port data. There are also limited data acquired in the critical nearshore zones. In the opinion of the writer more sophisticated data are needed using ADCPs and coastal zone *E. coli* and Intestinal Enterococci data, and ideally along transects located normal to a preferred bathing beach. The validation comparisons are generally fair, but the lack of close agreement in water levels, both at peak tides and the disparity in the tidal phase (sometimes of the order of an hour) are concerning. In the writer's experience on other studies water elevations and tidal phasing generally agree very closely with field data at almost all monitored sites. Many of the comparisons between the model predicted and field and Admiralty Chart data do not agree with the Foundation for Water

Research (1993) guidelines, whereas in most model studies recently audited by the writer the level of agreement is generally within these guidelines, particularly in deeper water (ca. > 5 m). In general, and compared to similar studies, the level of agreement between both sets of data is reasonable, with scope for much closer agreement giving more confidence in the model.

- Where the choice of the Manning's number has been changed it is suggested that some site reference evidence needs to be acquired to confirm this change. It is therefore recommended that a site visit is undertaken with the specific objective of looking for reasons as to why the roughness has been changed at various locations, e.g., do the bed characteristics change in the region from sand to rock or gravel etc. It is also understood that in the future Southern Water plan to use the BGS superficial sediment layer maps to justify changing the Manning's number at various sites across the domain.
- One of the writer's main concerns is the representation of the wind stress and the way it changes the surface currents, as well as the vertical dispersion and diffusion processes. In 2D modelling it is desirable to link the wind stress to an assumed vertical velocity distribution as higher winds – particularly cross-winds – can have a significant impact on surface plume trajectories. The wind stress is proportional to the square of the wind speed, and therefore a wind speed of 10 m/s will increase the surface stress by 4-fold compared to a wind speed of 5 m/s, and by 16-fold for a wind speed of 20 m/s.
- Another key concern is the representation of the physical processes of turbulence, diffusion (i.e., the transport of a particle/solute by turbulence in the flow) and dispersion (the differing transport rate of a solute through the water column as a result of the bed and wind shear impacting on the vertical velocity profile; i.e., a particle/solute will move much faster near the surface of the water column vis-à-vis a particle/solute near the bed). These processes have been much over-simplified in the model compared to widely used models, with the writer's models including improved representations as far back as the early 1980s. The current representation of these processes is expressed as a constant (often referred to as a 0D model), but even in the simplest case these processes are known to be functions of at least the local mean velocity and depth. Furthermore, by assuming a constant value for the eddy viscosity, and diffusion and dispersion terms then the spatial gradient of these terms has inherently been assumed to be zero and such gradients could have a significant impact on predicting tidal eddies and plume trajectories in nearshore coastal waters. This is thought to be potentially critical by the writer in the Solent waters and the narrow-entranced harbours of Chichester and Langstone.
- In the reports provided to the writer there seems to be limited information about FIO inputs from the EDM data and riverine discharges. It is difficult to make health risk assessments from just information on time and duration of discharges, particularly CSO data. Furthermore, based on the work of Kay et al. (Kay, et al., 1994; Kay, et al., 2004) and WHO guidelines it appears that some other water companies across the UK are investigating Intestinal Enterococci (IE) impacts on bathing waters and including IE in coastal models as well as *E. coli*. Although not an expert in this field, it is the writer's impression that IE is increasingly becoming a priori for assessing health risk in bathing waters. The Water Quality Expert reviewing these studies is known by the writer (along with many others) to be a leading international figure in this field. It therefore seems appropriate to the writer for Southern Water to commence an in-depth field monitoring programme of

IE as a key FIO, as well as more intensive hydrodynamic field monitoring data using current reliable and accurate monitoring equipment, such as ADCPs.

4. Responses to Southern Water Beachbuoy Questions

(i) General

Further to the appointment of the writer as the ‘Oceanographic Modelling Expert’ to provide “an independent assessment on the current Beachbuoy system’s ability to provide consistent, reliable and credible near real-time warnings of potential water quality impacts from storm overflow releases”, and the generic comments made in Sections 2 and 3 of this report, this section provides the writer’s assessment of Beachbuoy in the context of a series of questions asked on a number of points relating to Beachbuoy. These responses are split into 6 sections, including: (i) Human Health Implications, (ii) Review Process and System, (iii) Automatic Review Process, (iv) General Modelling, (v) User Engagement, and (vi) documentation. Only the questions relevant to the coastal modelling studies were provided to the writer for comment by Southern Water’s consultants, namely Atkins.

(ii) Human Health Implications

1. Beachbuoy (BB) compliance with current Government Health & Safety Legislation

The writer has limited experience in answering this question and particularly in comparison with the expertise of the ‘Water Quality Expert’ (who is internationally renowned for his expertise in this field). However, based on the writer’s experience of working with water quality experts on a number of comparable projects for other water companies and similar studies, the writer would make the following comments:

- It appears from the internal Southern Water report provided to the review group (Southern Water, 2023a) that Beachbuoy is compliant with the Government Health and Safety Legislation in terms of *E. coli,* with a warning being issued if the predicted concentration exceeds 500 cfu/100ml at the bathing water sites. However, it is not clear to the writer if Intestinal Enterococci (IE) is to be predicted in the same way as there is limited reference to IE in the coastal model study reports provided.

  Note: The writer since understands that modelling of intestinal enterococci is currently in progress and will form part of the Beachbuoy analyses in the future.

- Based on the Southern Water (2023a) report cited above, the comment is made that “a time series of FIO concentrations were extracted from the coastal modelling results---“. For the reasons outlined in Section 2 of this report, the writer is concerned about a number of key hydrodynamic and solute transport processes and coefficients being over-simplified in the coastal modelling simulations. Whilst the FIO concentration predictions may not change significantly with improved physical and biological process representations, the representations and parameters currently used in Southern Water’s coastal models are particularly vulnerable to concerns being raised about the reliability of the model predictions.

- More bathing water data are needed to support the assessment of the bathing water quality against Government Health and Safety Legislation. More data are recommended, particularly in the form of nearshore data, for future applications of Beachbuoy, so that more confidence can be acquired in the parameters used in the coastal models. In particular, the models need to be calibrated and validated against hydrodynamic and FIO field data in the regions of most concern, namely the bathing waters.

Recommendation: 11

In the writer's experience for any coastal modelling predictions of FIO concentrations etc. to be used in a real-time "Predict and Protect" tool, such as Beachbuoy, it is desirable that the coastal model uses the latest developments widely used within the industry, such as an unstructured grid, a finer grid resolution, improved representation of turbulence and dispersion processes and parameters, and a more realistic representation of wind driven effects. Any Predict and Protect tool should use state-of-the-art modelling tools for assessing health risk impacts.

Note: The writer understands that Southern Water now has a licence for the unstructured MIKE 21/3 model and is about to implement its use. This model will have a refined grid structure, an improved representation of turbulence and dispersion-diffusion processes and presumably a more realistic representation of wind driven effects.

2. *Identify ALL Circumstances where BB users are not receiving RED warnings when they should be! Is this a problem for BB users?*

The writer is particularly concerned about the representation of wind driven effects and the modelling of wind impact on a discharge plume using a 2D coastal model. The implication in the results is that wind-driven impacts above about 5 m/s have little further impact. A wind analysis report (Port & Coastal Solutions, 2023) provides valuable information about the frequency of winds from various directions, but no details have been provided as to how the wind stress is represented in the 2D model and, in particular, how the surface roughness coefficient and the assumed velocity profile are refined for stronger winds, i.e., over about 5 m/s. In the writer's experience it is difficult to predict wind driven effects on the hydrodynamic and dispersion processes accurately in a 2D model, with wind effects becoming increasingly 3D in nature in nearshore bathing waters and particularly for stronger winds. It is therefore more difficult to model accurately wind driven effects in shallow waters using a 2D model, with field data measured for Esthwaite Water showing velocities being closer to a second order parabolic profile, vis-à-vis a logarithmic profile, following earlier studies by Chen and Falconer (Kocyigit & Falconer, 2004b).

Based on the Technical Note (2023) at almost all sites quoted in the note the most frequent winds are from the Southwest and West. In the writer's experience it would seem possible that the stronger winds from these directions, and an improved representation of wind stress effects in the model, might well lead to RED warnings not being predicted in Beachbuoy when improved representations of the processes in the model may well advect higher concentrations of FIOs to the bathing waters.

3. *Identify ALL Circumstances where BB users are incorrectly receiving RED warnings whilst there is no real threat. Is this a problem for BB users?*

Based on the coastal models currently being used to predict the bathing water FIO concentrations to provide the data for Beachbuoy to interpret, it is difficult to confirm with confidence if the predicted concentrations are conservative or not. For example, in the opinion of the writer typical values using improved representations of the dispersion and diffusion processes would lead to larger (typically x10) values than used in the current models. The effect of using larger values is likely to produce a wider plume, but with a lower peak concentration. However, the disadvantage of receiving RED warnings too frequently when not appropriate, often results in bathers deciding not to pay too much attention to the warnings; this experience has been quite common in flood alerts.

Part of the problem in incorrectly receiving RED warnings is that the sampling consists typically of 1 spot sample on any particular day being taken by the EA, as understood by the writer, whereas the model offers the opportunity of a time series of *E. coli* predictions along the bathing water. It is noted that the coastal model produces time varying *E. coli* predictions at all grid points and the impact in Beachbuoy is identified from consideration of the timeseries data, which covers a 72-hour period. Impacting sites are those which exceed the *E. coli* threshold for one or more model timesteps, but a finer grid model of ca. 50 m grid size along the coast would give more accurate predictions of *E. coli levels* along the bathing beaches.

For any information provided with the Beachbuoy tool it should be made clear that the health risks along the bathing water are predicted only from inputs from Southern Water's assets. Clearly Southern Water cannot be held accountable for inputs from agriculture sources etc.

5. *Identify ALL undocumented threats to bathing waters examples to include:*
    - *Lavant (Chichester Harbour),*
    - *Eastney Long Sea Outfall (several bathing waters in Eastern Solent),*
    - *Budds Farm (Chichester Harbour intermixing with Langstone Harbour),*
    - *CSOs in the tidal River Medina up to Newport impacting Cowes/East Cowes and Gurnard beaches.*

The writer understands that Lavant WwTWs isn't included in the current coastal models. However, whilst the modelling carried out for other outfall impact investigations indicates that the Lavant WwTWs would not have an impact on any bathing waters, it is understood that the WwTWs will be included in a refined unstructured grid coastal model to be set up in the near future. The writer expects that these model studies would then eliminate the Lavant WwTWs as a potential source of non-compliance.

The writer understands that Eastney long sea outfall discharges some 5.7 km offshore, into the fast-moving waters of the Solent. The writer further understands that due to the location of the outfall, i.e., at some considerable distance from Eastney Beach and the entrance to Langstone Harbour, it has not currently been included in Beachbuoy. However, it is suggested that it could be included in future coastal models. This would give some reassurance to all stakeholders that it had been considered in the modelling.

Budds Farm WwTWs and the outfalls have been included in Langstone Harbour. In the writer's opinion the grid resolution in Langstone Harbour is too coarse and it is understood that this basin will be modelled with a finer grid resolution in the future, giving more confidence in the predicted faecal bacteria concentration levels across the harbour and discharging out through the entrance on ebb tides.

For the Medina Estuary, whilst all overflows downstream of Fairlee are in Beachbuoy and have been modelled, overflows upstream of this point have also been modelled and found not to have any impact on the bathing waters using the current model. However, it is recommended that these simulations are redone with improved coastal modelling process representations and appropriate coefficients at some stage in the future and with a finer grid resolution.

6. *Identify cumulative threats from discharges within harbours/rivers/estuaries/etc where ALL Blue Flag beaches are unexpectedly affected e.g., West Wittering (from Chichester Harbour outfalls) and Hayling Beachlands (from Langstone Harbour Outfalls). Are these a problem for BB users?*

In the writer's opinion, and based on similar experience from related projects, it is desirable that all the key point and diffuse source inputs discharging along the bathing beaches (including river inputs and from semi-enclosed embayments, such as Chichester Harbour), should be included in the coastal model, including non-Southern Water inputs where available, such as river inputs (including diffuse sources from agriculture etc.). The writer understands that all Southern Water's key inputs are currently included in the coastal models, although it is noted that these outfalls are not included in Beachbuoy if they are shown not to have an impact on the bathing waters. The reasons for the writer advising that all key point and diffuse source inputs should be included in the model are two-fold: (i) if there is an unpredicted failure along a bathing beach, and not identified in Beachbuoy, then in the experience of the writer key stakeholders (including the public) are more likely to blame the water company, even if the company is not responsible for the input; and (ii) some other water companies are already including all key point and diffuse inputs in their modelling studies, with several now also using 3D models. Such an example is illustrated below and where Dwr Cymru has included all the known outfalls illustrated in Figure 5, along Swansea Bay, see King et al. (2021). The resulting predictions for the *E. coli* levels in Swansea Bay using the 3D coastal model are shown in Figure 4 in Section 2 of this report, with further details being given in King et al. (2021).

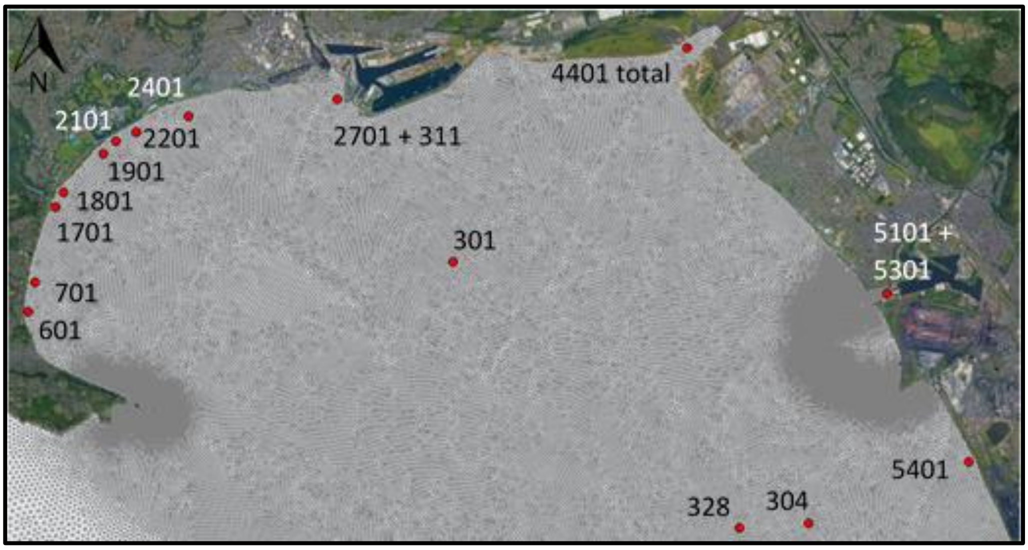


Figure 5. All outfalls shown for the input location of CSOs and outfalls in the 3D model of Swansea Bay (in collaboration with CREH and Dwr Cymru).

Note: From data recently provided to the writer it is clear that cumulative impacts (including Southern Water's assets and other impacts where available) are now being assessed by Southern Water and this approach is deemed to be appropriate and welcomed by the writer.

Recommendation: 12

It is recommended that sampling studies be commissioned for all key source inputs to enable all CSO, riverine and harbour entrance inputs to be included in the coastal models, with the revised model predicted data then being filtered and included in Beachbuoy. This would allow Southern Water to be able to confirm their net inputs to the system, e.g., by inputting riverine E. coli and Intestinal Enterococci fluxes into the models at the boundaries, and thereby quantifying the impact of their discharges relative to other source inputs on bathing water compliance. By decoupling the inputs in the models and comparing the relative impacts would allow Southern Water to prioritise any future capital investments relative to the corresponding impacts.

Note: The writer now understands that Southern Water will investigate including third party water quality inputs in the future.

7. *Identify ALL outfalls, anywhere on the Southern Water patch, that have yet to be linked as a threat to bathing waters. The most recent example is Peel Common affecting Portsmouth (modified in 2021). Peel Common has been operational for decades. Are these problematic for BB users?*

The writer's response to this question is the same as that provided in the response to question 5.

8. *Is the upper limit of 500 cfu/100ml a reasonable for Escherichia coli (EC) when most of the 83 bathing waters show EA testing well under 100 cfu/100ml during the bathing season. Southern Water says "in our area, 80 out of 84 bathing waters are rated excellent or good, with none rated poor". Should the limit be reduced to say 250?*

The writer is not an expert in this field and the advice of the Water Quality Expert (who has an international reputation in this field) should be taken in response to this answer.

9. *Should the pathogen Intestinal enterococci (IE) be modelled in BB given EA sampling routinely shows IE significantly higher than EC (i.e., composite modelling)?*

In the writer's experience the main focus over recent years in assessing bathing water standards in nearshore coastal and transitional waters has been on E. coli concentrations. However, with the growing engagement of citizens involved in 'citizen science projects' through the clean river groups etc., there has also been a growing concern about IE levels in freshwater basins. Therefore, in the writer's experience, it is not surprising that there also appears to be growing concern about IE in coastal and transitional waters. In the opinion of the writer, it would therefore be prudent to plan to include IE in the coastal modelling studies, as well as *E. coli,* with these data then also being included in Beachbuoy.

In the Review Question document, the writer notes that suggestions have been made as to how IE could be included in the existing models, using a simple relationship between IE and *E. coli,* and also using a higher constant T_{90} decay rate of 80 hr. However, such an approach does not include the effects of irradiance in daylight hours and does not take account of whether the CSO discharge occurs during day- or night-time. As for the previous question, the Water Quality Expert is more experienced in being able to comment on this question.

Note: The writer understands that Southern Water are planning to include IE in future modelling. Additionally, day- and night-time decay rates will also be considered for inclusion in future modelling studies.

10. *Propose how BB could distinguish between discharges involving rainfall and discharges of raw undiluted sewage caused by infrastructure failure. Typically, these are "disguised"/"camouflaged" as stormwater discharges, e.g., Event id 638885 (Bexhill). Maybe these should attract black or skull and crossbones icons?*

In the writer's experience there are generally two main sources of effluent discharges of FIOs into coastal waters. These include: (i) storm exceedance of the 1 in 30 designs (or similar) of the WwTWs, resulting in untreated effluent being discharged into the outfall and with this input primarily being caused by excessive rainfall; and (ii) diffuse source inputs, primarily from agriculture sources or similar, added to the river due to high rainfall and then discharged into the estuary. So far as the writer is aware there is no reliable method of distinguishing in an urban drainage model between rainfall and raw undiluted sewage caused by infrastructure failure. However, this distinction could be made by data collection of sewage effluent fluxes into a river or coastline from CSO inputs and then subsequently including this information in the coastal model, post the event. This approach would not be possible to deliver in real time, and therefore diffuse and point source inputs could be difficult to include in Beachbuoy in real time, other than by monitoring riverine flows at the tidal limit. Where undiluted sewage is discharged into an outfall because of an infrastructure failure then in the experience of the writer this is more likely to arise when the rainfall intensity is either zero or relatively low. The writer would therefore suggest that the potential to revise Beachbuoy to include advice on whether the release is the result of rainfall or equipment failure should be investigated and, if possible, included in the next available release of Beachbuoy.

In the 'Interim supporting information ----' in the 'Review question' document, it states that "The modelling undertaken is conservative". However, for the reasons given in Section 2 of this report and in sub-section (v) of this Section, the writer believes that there are sufficient concerns reported about the technicalities and setup of the coastal models (particularly the fine grid models) to question this statement. Alternative terminology is suggested to be used, such as: 'The company has made every attempt to aim to be as conservative as possible in their coastal modelling predictions, such as assuming that the entire wastewater load is discharged at 3 x Dry Weather Flows (DWFs)'. This approach effectively assumes an emergency undiluted release of 3 x DWF.

Several key model numerical features (such as grid size) and physical process parameters also first need to be made to represent the numerical, hydrodynamic and kinetic processes more accurately before it can be said with confidence that the modelling is conservative – many of which the writer notes are planned to be refined when the model is updated to the latest MIKE 21/3 software. Alongside these key refinements, more intensive and accurate hydrodynamic and FIO data needs to be collected, ideally along transects in the horizontal and vertical planes for a preferred beach, and with the resulting model data then being used for further model validation before including in Beachbuoy.

11. *Consider Beachbuoy could be extended to cover all shellfish water and bathing water points from Bracklesham Bay in the east to Totland Bay in the west would therefore provide the level of coverage appropriate to the leisure water users of the Solent.*

In the writer's experience there can be considerable differences between the predicted FIO concentrations near the surface and the bed layers, particularly where turbidity levels are relatively high. The surface waters can have significantly lower concentrations than the near bed levels (primarily due to reduced light penetration and longer decay rates near the bed), with swimmers more likely to ingest near surface waters, whereas shellfish are more vulnerable to near bed FIO concentrations. This disparity in the near-surface and bed concentrations can only be predicted relatively accurately in a coastal model using a fully 3D model. An example of these findings is published for Swansea Bay in King et al. (2021). In the writer's opinion 2D models of FIO predictions can be extended to cover both shellfish and bathing water points of interest, but the extension of a 2D model for shellfish water compliance assessment needs to be treated with caution without extensive 3D hydrodynamic and FIO data.

Note: The writer understands that after the implementation of MIKE 21/3 Southern Water will explore the scope for 3D modelling, which will give more confident predictions of near-bed water quality parameters, and which will be particularly relevant to shellfish waters.

(iii) Review Process and System

5. *Identify all of the data sources used in the manual review process and how the data is used for decision making. Establish if decisions are accurate and timely given the information used.*

The writer is not familiar with the manual process of data collection and transfer on an hourly basis from the coastal models to Beachbuoy. With the current models and data availability this approach seems appropriate, and the writer will defer a response to this point to the Software and Systems Expert.

(iv) Automatic Review Process

1. *Is the use of single "pixel" (just a few square metres on the ground) automatic "sampling" reasonable on a multi-km long beach particularly considering the juxtaposition of the "pixel" with outfall threats. (e.g., Eastney)?*

In the writer's opinion there are two separate issues in response to this question: (i) the validity of assessing bathing water quality taken just at one point on a long bathing beach, and assessing risk based on data from a much larger model grid; and (ii) the validity of assessing the bathing water quality at one point along a bathing beach where the variation in the FIO concentration along the beach could vary considerably from point to point.

In considering the first point, the finest grid resolution in the Southern Water coastal models along the bathing waters is typically 125 m x 125 m (although for one site the grid size is 100 m x 100 m and for some sites much larger). This means that the predicted FIO concentration value in the finest grid point along the beach, covering the compliance point, has a plan surface area of 15,625 m^2. In comparison, this area equates to a larger area than the size of two adjacent full size football pitches (i.e., 105 m x 68 m x 2 = 14,280 m^2). In contrast if the finest grid resolution was 50 m, as a recommended minimum, then the surface area of the finest grid cell would be 50 m x 50 m = 2,500 m^2, i.e., just over 1/3rd of the size of a single football pitch. Hence, reducing the grid resolution in all the fine grid coastal models to 50 m or less, particularly along popular bathing beaches, would improve the representation of several complex hydrodynamic processes (as illustrated in Figure 1, in Section 2) and, in particular, would also improve on the accuracy of predicting the concentrations at the compliance point (i.e., the monitoring site).

In addition to monitoring FIO concentration levels at the compliance point(s) more recent monitoring studies, undertaken by some water companies, have included transect FIO data normal to the beach. Such an example is given in Figure 6 below, for Swansea Bay, as shown in King et al. (2021), with these data monitoring transects being planned and monitored by Prof. David Kay and his team at the Centre for Research into Environment and Health (CREH). Such data allow more evidence-based calibration and verification comparisons to be made for coastal models, particularly in nearshore bathing waters.

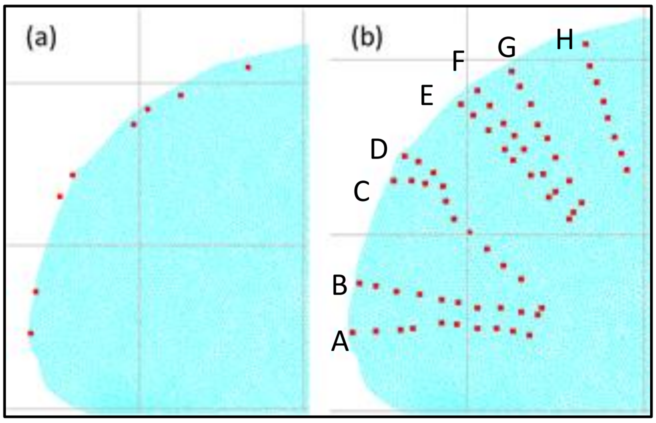


Figure 6. Static source points at outlet locations (a), and source transects along Swansea Bay (b).

Recommendation: 13

In order to provide more confidence in the model predicted accuracy of faecal bacteria levels along Southern Water's bathing beaches, it is recommended that an extensive sampling programme is undertaken for a preferred beach of the nearshore hydrodynamic parameters and E. coli and Intestinal Enterococci concentrations. In particular, concentrations should be measured along transects normal to the beach, providing evidence-based data for model calibration *and validation. This would lead to more confidence in the model predictions and any extended bathing water quality information provided through Beachbuoy.*

Note: The writer now understands that Southern Water have undertaken some bathing beach monitoring and are looking to do more detailed monitoring for a priority beach in the future.

2. *Is the use of 1-, 3- and 12-hour tidal assessments reasonable given so many discharges are well in excess of 12 hours in duration and frequently multiple hundreds of minutes in duration? All in the context of T_{90} = 40 hours (i.e., 3 tidal cycles)*

In the writer's opinion, these tidal assessments seem reasonable and not dissimilar to typical values used by other organisations. However, with some discharges being "well in excess of 12 hours" it would seem prudent to run some simulations of the corresponding coastal models, for popular bathing beaches, for a longer discharge duration and for the maximum discharge time known to occur.

Although a constant T_{90} value of 40 hours would seem conservative, this value does not differentiate between night- and day-time discharges. For late evening or early morning discharges, following a storm event, this value might not be conservative. Likewise, during the daytime, and particularly with high irradiance, then this value of T_{90} would be unduly conservative. It is recommended previously that a time varying T_{90} value based on field data, or a more representative process-based equation (such as Mancini, 1978), be used in the coastal models to give more accurate time varying predictions.

Note: The writer understands that Southern Water are going to consider including day- and night-time varying decay rates in future coastal modelling studies.

3. *Is it reasonable for the "initial" impact/no-impact assessment to stick with the event for its lifetime of tens or even hundreds of hours. Does the impact/no-impact assessment get routinely recalculated?*

In the writer's opinion it is not reasonable to use the outputs from Beachbuoy for say longer than 24 hours without updating. A storm event and a south-westerly wind could change the assessed health risk for swimmers, surfers etc. along a bathing beach, and in a relatively short time scale. In an earlier response the writer advised that the data inputs to Beachbuoy could be automated and if Beachbuoy is to be extended to provide a real-time online tool then in due course data could be updated online and in real-time through informatics tools, such as Artificial Neural Networks (ANNs). However, the current hourly updating is commendable based on the existing data availability.

4. *Low atmospheric pressure storms (the main cause of stormwater discharges) bring huge changes in tidal height (+/-20%), high tide time (+/- 30mins), wind speed (x4), wind direction +/-180 degrees), UV (cloud cover) and other parameters. ALL of these parameters have a significant impact on E-Coli longevity, dispersion and advection in the real-world environment. Are these parameters realistically modelled and used in automatic decision making?*

The writer agrees with the concerns raised in this point about the coastal models and Beachbuoy and, for the reasons outlined in more detail in Section 2 of this report, the writer has some concerns as to why the answer to this question should be: ‘No’. The main reasons of concern by the writer can be summarised as follows: (i) the open boundary conditions driving the coarse grid model, which then provide the hydrodynamic boundary conditions for the finer grid models, are based on the tidal harmonics and do not account for significant low-pressure storms, including surges etc. (so far as the writer can establish the models have not been run for such conditions); and (ii) the wind speed can have a significant impact on the trajectory, vertical velocity distribution and mixing, and dispersion-diffusion processes of an outfall plume. From the information provided to the writer it is not clear that these impacts have been adequately included in the coastal models. The recommendation to address this point is within **Recommendation 7**.

It is also worth noting that as a result of climate change the UK has become more vulnerable to convective storms, thereby leading to significant storms during a day, or part of a day, often followed by calmer and drier conditions soon after. Thus, bathing water quality and health risk can be more vulnerable to storm events on the previous day, or night. Also, the main impact of UV (cloud cover) would be to affect the decay rate for *E. coli* and Intestinal Enterococci, with the T_{90} value likely to be longer (i.e., reduced decay) during a storm event. The coastal model studies undertaken for most bathing water studies for Southern Water have used a generally conservative constant decay rate of typically 40 hours. Whilst this is commendable, and generally deemed to be conservative, it is also worth noting that comparable bathing water quality studies being undertaken by other water companies are increasingly using at least diurnal changes in T_{90} decay rates.

(v) General Modelling

1. *Are pertinent bathymetric aspects properly modelled (e.g., Langstone/Chichester Harbour entrance) for all tidal sequences?*

The writer is satisfied that based on the information provided in the reports the bathymetry is generally pertinent for the coastal models, with the Environment Agency Lidar data and coarse grid boundary conditions being updated annually. It has not been possible for the writer to check on the specific bathymetric representation associated with the entrance conditions to Langstone and Chichester harbours. It is therefore recommended that particular attention is paid to the bathymetry at the entrances to Langstone Harbour and Chichester Harbour during the construction and testing of the new unstructured MIKE 21/3 model. The model should be tested to ensure that fluxes through the harbour entrances are correctly represented.

2. *Are ALL parameter “safety factors” reasonable for accurate modelling (e.g., but not limited to UV, Wind speed, wind direction, DWF)?*

In the writer’s experience there are a number of physical processes that are not well represented in the model and currently use the simplest of representations. These are outlined in more detail in Section 2 of this report, but include, in particular: (i) the finest grid size – which could be finer for bathing water hydrodynamic and solute transport predictions; (ii) nesting and the conservation of tangential momentum at the boundaries; (iii) turbulence – where the simplest 0D equation is used, i.e., where the eddy viscosity is independent of the local velocity and depth; (iv) dispersion and diffusion of FIOs, where again a simple 0D equation is used and independent of local velocity and depth; and (v) the wind representation appears to be over-simplified for a 2D hydro-environmental coastal modelling study.

In the Bathing Water Quality report prepared by Port & Coastal and Atkins (Port & Coastal and Atkins, 2023) refence is made to similar modelling studies undertaken as part of a major hydro-epidemiological monitoring and modelling assessment of *E. coli* concentrations in the River Ribble Basin and along the Fylde Coast (Huang, Falconer, & Lin, 2017). However, in this paper (along with other papers reporting on this study) all the processes cited above were addressed using more accurate hydrodynamic and biologically based process representations, as outlined in Falconer et al. (2005) and previously Falconer (1991).

Regarding the DWFs these values are based on typical data as used conventionally in similar studies and would meet realistic inputs from the outfalls and CSOs.

In summary, it is not possible to confirm that the parameters used in the coastal models provide adequate “safety factors” for bathing water quality predictions. Some parameters, such as the constant T_{90} value of typically 40 hours, are conservative, but the related processes of turbulence, dispersion and diffusion are not well represented, and particularly for high south westerly wind conditions.

3. *Reassess all outfall threats to bathing waters should Automatic Review Process scope #4 (above) should parameter modification that extends the reach of outfall pollution be required. This should include all outfalls irrespective of being 10km distant.*

So far as the writer can establish it appears that the main outfalls and CSO inputs have been included in the model, although there are none of any significance identified along the shoreline from the plume plots. It should also be noted that in the experience of the writer it is generally unlikely that an outfall located some 10 km offshore would significantly affect bathing water faecal bacteria concentrations. In the document ‘Review Question’ and ‘Interim Supporting Information’ reference is made to using the same models for shellfish waters. However, for shellfish waters then FIO concentrations are needed near the bed, and in the experience of the writer these would be different from those values near the surface or depth averaged concentrations, based on the predictions obtained using a 3D model. Hence, any extension of the results of the model studies being reported herein will be considered differently, in that focus will be more on bed rather than surface concentrations, and a different set of standards will be used, namely the EA guidance concentrations for the water column rather than bathing water standards.

4. *Would both volumetric and duration data be more helpful to BB users. Volumetric discharge data is far more informative than time (because of significant outfall diameter variations)? The level of risk is after all directly proportional to the volume of sewage effluent not its duration.*

In the opinion of the writer an estimate of the volumetric and duration data for the outfall discharges would be appropriate to include in Beachbuoy and would be as meaningful as providing the average concentration for a fixed time duration. This information would be appropriate to complement the input data specified in the coastal model. However, the writer understands that volumetric data are not currently measured.

5. *Should the cumulative effects of multiple outfall threats from single and/or multiple bathing waters be modelled? Currently the impact of each discrete discharge from each and every outfall on each bathing waters are considered entirely in isolation. There is significant oversight here causing significant RED flag suppression (e.g., Cowes/Gurnard area).*

In the writer's opinion it would be advisable to include all outfall threats in the coastal models and subsequently into Beachbuoy. It is understood that cumulative potential threats of non-compliance at bathing water sites have not previously been undertaken, but that Southern Water are currently planning to investigate such threats in the future. A method is currently being developed to combine short events from the same outfall and this is to be welcomed.

It is also encouraging to note that Southern Water are planning to acquire 'intelligent buoys' which include sensors for *E. coli* and IE, and which will provide near real-time monitoring. It is understood by the writer that two 'intelligent buoys' have already been deployed and this is to be welcomed.

6. *Could any discharge events, at any time, be masking or camouflaging other discharges irrespective of status?*

It would be advisable for Southern Water to include any known discharge events that might be masking RED flags in Beachbuoy. However, it is acknowledged that it is difficult for any water company to include all discharge events and especially those not related to the operations of a water company. Many of these unknown discharges are related to diffuse source pollution from agricultural run-off, leakage from septic tanks etc.

7. *Is there a problem with modelling discharge inputs into harbour/river/estuary confined bodies of water? E-Coli longevity, dispersion and advection is going to be different in confined water spaces as compared with the open sea. Is this more concentrated material from a confined body of water considered in the modelling from a limits perspective? (e.g. a discharge into Langstone Harbour will come back when the tide turns and affect a bathing water like Eastney in less than 12 hours when initially no impact).*

This is an important point for consideration and particularly where the harbour entrance is narrow and near a bathing water, such as the case for Langstone Harbour. In modelling such a narrow-entranced basin it is critical to ensure that the flow and FIO flux across the entrance is predicted as accurately as possible. For this purpose, it is desirable to use an unstructured grid model, thereby enabling a very fine grid resolution to be set up in the entrance region to reproduce accurately the area of flow (including deep channels) and velocities through the basin entrance. This point is covered in **Recommendations 1 and 4.**

In confined water bodies with a narrow entrance, such as harbours and large marinas, the treatment of many of the processes outlined in Section 2 become even more critical, particularly turbulence, dispersion and diffusion. However, it should also be noted that a conservative decay rate (or T_{90} value) was used in calculating the *E. coli* concentration values. Also, where a tide induced jet flows through a relatively narrow harbour entrance it can lead to the process of ‘tidal pumping’ (Zheng, et al., 2016) wherein effluent/sediment discharges at the head of the harbour can accumulate over time, leading to higher concentrations of bacteria than those discharging from the outfall, particularly at night. The process of tidal pumping is schematically illustrated in Figure 7 below. Although the paper by Zheng et al. (2016) focuses on nitrates, as mentioned in the paper similar processes can occur with bacteria. More recent studies by the writer and others have shown that bacteria adsorption and desorption onto the sediments (on the bed and in suspension) can lead to the decay rate for bacteria being very long, particularly for dark conditions. With sediment brought back into suspension on the subsequent spring tide, particularly under storm conditions, then sediment transport and bacteria desorption can also be a mechanism of FIO transport in a river or coastal basin. This was found to be the case in the River Ribble Basin study and contributed to the flux of *E. coli* from the Ribble catchments to the Fylde Coast (Huang G. , Falconer, Lin, & Xu, 2022). In the past the writer also has experience of studying a range of water quality parameters in Poole Harbour and Holes Bay, where several of the processes referenced above were found to be critical (e.g., Falconer, 1986).

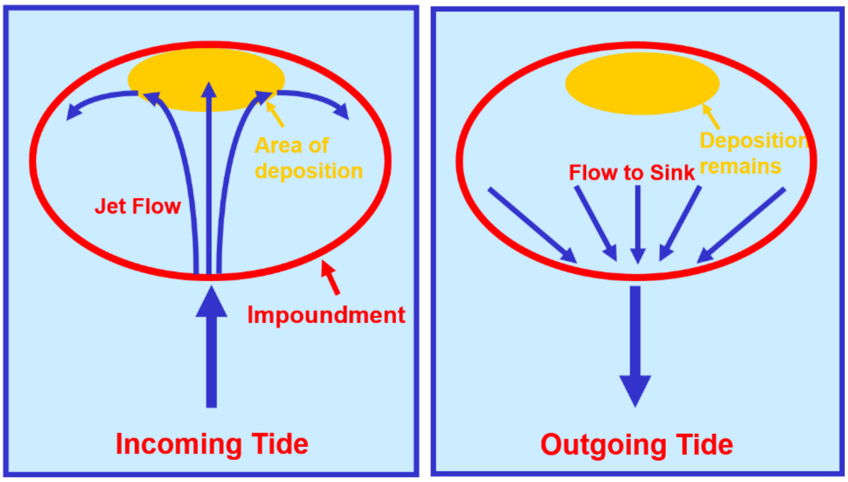


Figure 7. Schematic illustration of tidal pumping impact on sediment sediment transport processes (also applicable to FIO processes).

8. *How would real time satellite tidal/cloud data and other real-time data sources improve BB accuracy and levels of user trust. Copenhagen's well respected and trusted system uses real time data, is this considered best practice?*

The writer is aware of the Copenhagen real-time satellite tidal data etc. system, through being one of three members of the Independent Expert Group reviewing the extreme London floods of 2021. In the opinion of the writer, it would be difficult for a water company to develop such a sophisticated real time modelling system as that for Copenhagen, both in terms of the need for a supercomputer and the continuing expertise and engagement of a specialist organisation, such as DHI (originally the Danish Hydraulic Institute, but now a not-for-profit international company specialising in state-of-the-art applied modelling). Although it would be expensive and difficult to replicate the Copenhagen real-time system directly, in the longer-term Southern Water could investigate the scope for undertaking numerous runs of the latest DHI unstructured grid models and apply these models for a wide range of extreme events. The data from these model runs could then be stored and implemented into a hydroinformatics tool, such as an Artificial Neural Network (ANN) or Genetic Algorithm (GA), with the outputs from the hydroinformatics tool then being included directly into Beachbuoy and generating real-time risk assessment information for the public about bathing water quality. The writer is aware of such approaches currently being investigated for optimising tidal range energy generation in tidal lagoons and barrages (Xue, Ahmadian, Jones, & Falconer, 2021), and more recently for application to coastal bathing water studies (Lam & Ahmadian, 2023). Such a course of action by Southern Water in the longer term, would put the company at the fore-front of bathing water quality risk assessment information for the public.

Recommendation: 14

It is recommended that Southern Water investigate further the Copenhagen real time coastal models and their link to real-time bathing water quality signage. However, rather than integrate a deterministic computational coastal model within a signage system, as currently done in part through Beachbuoy, it is recommended that Southern Water move towards embedding the coastal modelling data within a hydroinformatics tool (such as an Artificial Neural Network model) to provide real-time input data to Beachbuoy. This would enable more accurate real-time data on bathing water quality to be presented through Beachbuoy.

9. Are there any missing BB features from the reviewer's perspective?

In the opinion of the writer the main missing feature of Beachbuoy is that information is not included for releases at MWL (Mean Water Level) in assessing whether flags should be ‘1’ or ‘0’. The releases only seem to be provided at high or low water when, in general, the tidal currents are in the slack water phase and are a minimum. In contrast at MWL, for both flood and ebb tides, the tidal currents would be close to a maximum and the discharge plume would be advected by the largest currents and before the plume had diffused extensively, i.e., the highest concentrations at the centre of the plume would be maintained at a higher level for further into the plume trajectory.

Recommendation: 15

It is recommended that in the short term some simulations of the effluent release from a typical outfall (such as Portobello) be undertaken around MWL, i.e., with peak currents, and the plume trajectory and concentrations be compared with releases at high and low water. If found to provide marked differences in the data currently linked to Beachbuoy, then it is recommended that MWL release data should also be included in Beachbuoy in the future.

Note: The writer notes that some of these runs have since been undertaken and the results will be added to Beachbuoy to give more confidence in the outputs obtained for impact assessment.

10. *Consider how closely the software modelling tools used map to the unique tidal environment of the Solent over a rolling period of at least 14 days, understanding the applicability of the models to the local conditions within the Solent system and capturing the change in effect across the tidal cycle from neaps to springs.*

In the writer's experience the finest grid resolution of 125 m is too coarse to predict accurately the complex hydrodynamic processes in the Solent over a spring-neap cycle. Towards the western end of the Isle of Wight (near Norton), there is a headland from the mainland coast, protruding seawards about 2.25 km (towards the Isle of Wight) and with the minimum flow width in the Solent of about 1.25 km, leading only to about 10 grid squares across the entrance width. With a simple 0D turbulence model, and a relatively coarse fine grid resolution for this region, then the model would be unlikely to predict accurately any tidal eddies generated in the region (see Figure 1 of this report). This is further evidenced by the predicted velocity data comparisons in this region against Admiralty Chart data, as shown in the Figure 3.5 plots in the Southern Science report (Southern Water Services Ltd, 1998). Furthermore, the entrance into the Solent between the headland and the nearest land location on the Isle of Wight is at an angle of approximately 45% to the grid orientation. It is also noted that the southern boundary location of the finest grid is relatively close to the southernmost tip of the Isle of Wight, thereby potentially constraining the velocity structure along the southernmost reach. It is understood by the writer that Southern Water have acquired an unstructured grid version of MIKE 21/3D from DHI, and this model would offer the potential for improved hydrodynamic predictions in the region.

Recommendation: 16

For accurate predictions of the hydrodynamic and FIO transport processes in the region around the Solent and the Isle of Wight it is recommended that this coastal model is refined as soon as possible. In the writer's opinion, the grid for this complex water body is too coarse to pick up some of the main complex hydrodynamic processes likely to occur in the region. Furthermore, the bed topography is also highly variable in the region and the use of depth and velocity varying turbulent, dispersion and diffusion processes is particularly appropriate in view of the boundary constraint features of the Solent. The use of an unstructured model would be particularly suitable for this region and with the finest grid being 50 m, or less.

11. *Focus on the decision process behind the recently adopted category of non-impacting discharges. Given the cyclical movement of water within the Solent over many tidal cycles, it is difficult to understand how a decision that a discharge is 'non-impacting' can be made. It would be helpful if the review could report on the level of confidence that could be applied to the output. MIKE 21 is a long established and respected suite, but it is important to assess the accuracy of its models as used within the unique Solent environment.*

Based on the model setup and results in the Southern Water Services report (1998), in the writer's opinion it is currently difficult to state that a discharge is 'non-impacting' in the Solent and primarily for the reasons outlined in the previous section (i.e., question 10), including the model grid resolution in a highly turbulent region and due to several process modelling simplifications. However, using an unstructured grid model with a higher grid resolution in the Solent (ca. 50-75 m minimum resolution) and with improved turbulence, dispersion and diffusion representations in the model, then more confidence can be obtained in establishing whether a discharge is 'non-impacting', or not, on a bathing beach. The unstructured latest version of MIKE 21/3 provides an improved grid representation, without the need for nesting, as well as a much-improved turbulence model (namely the Smagorinsky model), which is grid-size dependent. These recommendations are covered in **Recommendations 1, 4, 5 and 8**.

Regarding MIKE 21/3, this is a highly refined and widely used model world-wide. In the field of hydro-epidemiological modelling for predicting hydrodynamic processes and bathing water quality standards in coastal waters, there are three internationally leading commercial computational models. In the writer's opinion these models are similar in quality and structure, as outlined in Section 2(i) of this report. The models include: MIKE 21/3D from DHI, Delft 3D from Deltares, and Telemac from HR Wallingford. Whilst all three models are similar in terms of the processes modelled and parameterisation, the only disadvantage of MIKE 21/3D is that the code in not open source. This is a disadvantage in that the code cannot be refined through specialist university research teams etc., where such refinements have been made to Delft 3D and Telemac. However, the argument against open-source software is that refinements can often be made by third parties, where the changes made are not numerically or physically correct, or sufficiently proven, and then passed on to other modellers or commercial organisations for model application to practical studies. The writer has personal experience of such failings being made to his own open-source model DIVAST, which was provided widely to companies in the early 1990s.

12. *The report should assess whether the modelling adequately covers the various tidal flows and back eddies throughout the Solent and through each tidal cycle when assessing the level of impact over 24-hour and 72-hour time frames.*

As outlined in response to questions 10 and 11 above the writer has reservations about the accuracy of the model predictions, particularly regarding the hydrodynamics, for the reasons outlined in Section 2 of this report. For example, in the writer's experience a finer grid resolution and a more accurate turbulence model, at least based on the local velocity and depth, would have been expected to show signs of a pronounced and well-structured tidal eddy around the headland to the west of Pennington and in the narrow Solent entrance. However, in viewing the spring tide currents throughout the tide in this region, there is no evidence of the formation of any well-structured tidal eddies in the region, as illustrated in the model current predictions shown in Figure 3.7 (a-m), in the Southern Water Services report (1998). The prediction of tidal eddies in nearshore coastal waters can be critical in assessing bathing water quality (see Figures 1 and 2), and particularly for shellfish water quality, as the formation of tidal eddies leads to sediment accumulation at the centre of the eddy and pollutant trapping – particularly near the bed – as illustrated for sediments in Figure 8.

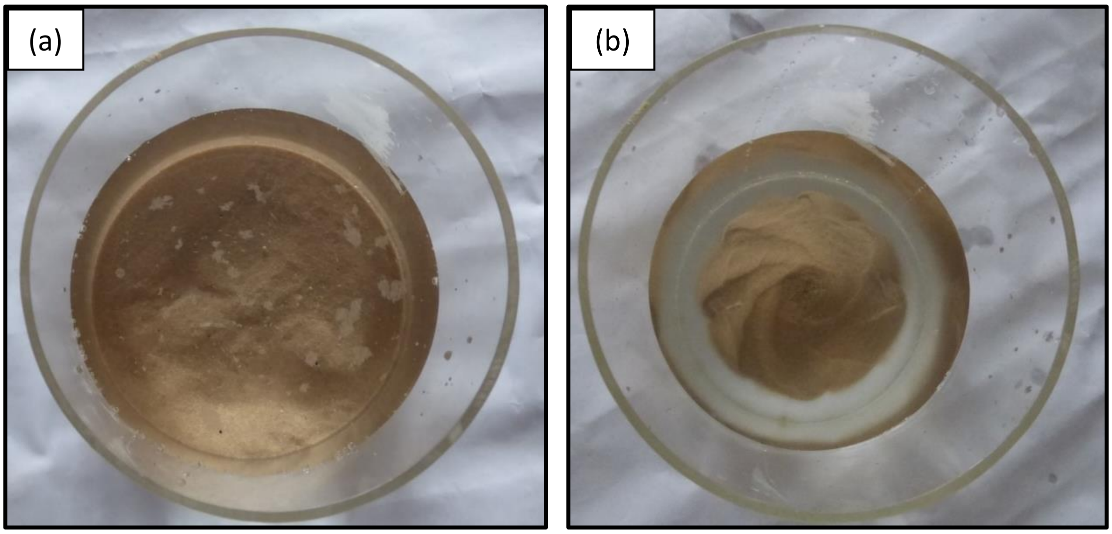


Figure 8. Schematic illustration of eddies causing sediment to accumulate at centre: (a) uniformly distributed initially, and (b) accumulated at centre after stirring.

Furthermore, for several of the current predictions in Figure 3.5 of the Southern Science report, where comparisons are reported against Admiralty Chart data, the comparisons show several predicted peak currents which are noticeably less than the Chart data, particularly as shown in Figure 3.5 (e) where the measured current is ca. 2.0 m/s, whereas the corresponding predicted value is ca. 1.0 m/s, i.e., only 50% of the Admiralty Chart value. This comparison is well out with the FWR criteria, which is widely used within the water industry and adopted with reasonable confidence, particularly in deeper water and as for this region. Further field data collected with ADCPs and a much finer grid resolution model are therefore recommended. These points are included in **Recommendations 3 and 4**.

13. *Review whether the volumetric loadings and conversion from duration applied in the model are appropriate representation.*

In the writer's experience and compared to similar studies being undertaken by other water companies etc., the volumetric loading of 3 x DWFs (Dry Weather Flows) is at least comparable to, and in many cases greater than, that used by other water companies in comparable studies. However, whilst it is acknowledged that the DWF is population dependent, it would have been useful to have had typical DWF rates cited in each report to give the reader an indication of the relative solute flux and dilution extent for each outfall. In some reports a figure has been quoted (typically between 1.0 and 1.5 m^3/s), with these figures appearing to be as expected. It would also have been informative to have included both peak and mean flows for each outfall. The FIO bacteria levels were generally assumed to be 2.0×10^7 cfu/100 ml, with this level being scaled during post processing to give a release concentration of 5.0×10^7 cfu/100 ml. In comparison to similar studies this value would generally be considered to be a conservative value in the experience of the writer, with values often used in some comparable studies being ca. 5×10^5 cfu/100 ml.

As stated in the response to question 4 above, in the writer's opinion it would be useful to provide some mean volumetric flow data, as well as a concentration value and a time of duration of the discharge. Therefore, mass fluxes could be calculated and added into the reporting. This point is included within **Recommendation 3**.

14. *Are the judgements being made about tidal water flows in order to determine 'impact' on a bathing beach reasonable in the context of the Solent?*

In the opinion of the writer there is a particular need to improve the processes represented and the parameters (or coefficients) used in the nested models for the Solent region. The writer has outlined the main refinements that could be made to give improved confidence in the model predictions and these points are outlined in detail in Section 2 of this report, and in response to questions 10, 11 and 12 above.

15. *What is your level of confidence that the MIKE 21 can closely model the actual tidal conditions close into the Solent shoreline, its harbours, estuaries and beaches?*

The writer has full confidence in the model MIKE 21 being capable of closely predicting the actual tidal currents 'close into the Solent shoreline, its harbours, estuaries and beaches'. However, for the reasons outlined in Section 2 of this report and in response to questions 10, 11 and 12 above, the writer would have more confidence in the predictions if a finer grid had been used in the region and if the southernmost boundary had been cited further away from the Isle of Wight. Also, in view of the length of the headland just to the west of Pennington, the writer would suggest that a higher order turbulence model and improved representations of the dispersion and diffusion coefficients would have been more appropriate.

16. *Given the mapping between the GIS coordinates used for the Beachbuoy sites and the EA defined 'Bathing Water' and 'Shellfish Areas', assess the feasibility of extending Beachbuoy coverage to include all Solent and Kent shellfish areas, an upgrade that would provide required coverage for Solent water users and enable Southern Water to meet the shellfish water quality priority set by Defra.*

In the experience of the writer the difference between the near surface and near bed FIO levels can be significantly different in coastal waters, with the concentrations near the bed often being either much higher or lower than the values in the surface layers. For bathers in nearshore coastal waters, it is more likely that any water ingested will be near surface water. In contrast, shellfish sites are generally in deeper water and where the surrounding FIO concentrations may be higher due to the lower level of light penetration and reduced decay through the water column, or lower due to the limited transport of faecal bacteria from the buoyant surface plume to the near bed zone. The near bed concentration can also accumulate with time due to the increased impact of adsorption to, or desorption from, the bed and suspended sediments. It is therefore ideally more appropriate to consider using a 3D model if near bed FIO concentrations are needed for shellfish sites, alternatively data of *E. coli* and/or IE concentrations could be measured through the water column at critical sites and then functionally related to the corresponding depth mean FIO concentrations predicted using a 2D coastal model.

(vi) User and Engagement

2. *Surfers Against Sewage safer seas app is a well trusted app used for many years. It uses just two colours RED and GREEN (Bad/Good) would it be reasonable/helpful for BB to adopt a simpler approach, or whether the current approach is appropriate and there is sufficient confidence in the precision of the data?*

Although not an expert in this field, the writer did think this was appropriate on first reading about Beachbuoy. The concept of a ‘traffic light’ system is increasingly being used in flood risk assessment (but not so much in the UK) and in the writer’s experience this is a simple and understandable way of presenting risk to the public.

3. *Is BB reliable? Does it update metronomically every hour (no, it actually does not!) is this a problem from a user health perspective?*

In the writer’s experience Beachbuoy is an encouraging tool to inform the public in general terms about the potential health risks associated with bathing at a particular beach, on a particular day, and it should continue to be used. However, by improving the grid resolution, process modelling (particularly wind effects) and parameterisation in the coastal models currently being used would lead to more confidence in the predicted data upon which information is used within Beachbuoy. Furthermore, and into the future, a larger range of coastal model runs could be undertaken and, using hydroinformatics tools (such as ANNs and GAs), along with automated data collection etc., then real-time information could be provided to the public of the health risks of bathing in Southern Water’s beaches on any particular day. This information could then be provided during the bathing season to regional TV and radio channels (e.g., BBC), along with regional weather updates.

(vii) Documentation

1. *Is current supplementary BB information in the public domain misleading or inaccurate? This needs to be corrected.*

In the writer’s opinion the Beachbuoy information in the public domain is not intentionally misleading or inaccurate. However, based on the comments made in sections 2 and 4 of this report, it is the writer’s view that there is scope for improving the accuracy in the results obtained in future coastal modelling studies and thereby leading to more confidence in the information being presented to the public and key stakeholders via Beachbuoy. However, in the meantime it is recommended that Beachbuoy continues to be used by Southern Water but advising that the accuracy of Beachbuoy is expected to be improved once refined and improved coastal models are set up and operational. These modelling studies would include higher grid resolution, improved turbulence representation and would have been fully calibrated and validated against ADCP data, along with existing current data.

5. References

Abbott, M. B., & Minns, A. W. (1998). *Computational Hydraulics - Second Edition.* Aldershot: Ashgate Publishing Ltd.

Alstead, R. D. (1994). *Numerical Modelling of Tidal Flow Using Nested ad Patched Grid Schemes.* PhD Thesis: University of Bradford.

Avalos-Patino, J. E., Neethling, S. J., & Piggott, M. D. (2023). A parameter-free LES model for anisotropic mesh adaptivity. *Computer Methods in Applied Mechanics and Engineering*, 416, 116365, 1-25.

Chow, V. T. (1959). *Open-Channel Hydraulics.* Tokyo: McGraw-Hill Kogakusha, Ltd.

Danish Hydraulic Institute. (2017). *MIKE 21 & MIKE 3 Flow Model*. Retrieved from https://manuals.mikepoweredbydhi.help/2017/Coast_and_Sea/MIKE_321_FM_Scientific_Doc.pdf

Deltares. (2021, 08). Retrieved from Delft3D FM Suite 2D3D: https://www.deltares.nl/en/software-and-data/products/delft3d-flexible-mesh-suite

Directive 2006/7/EC of the European Parliament and and of the Council . (2006). *Concerning the management of bathing water quality and repealing Directive 76/160/EEC.* Brussels: Official Journal of the European Union.

Elder, J. W. (1959). The dispersion of marked fluid in a turbulent shear flow. *Journal of Fluid Mechanics*, 5(4), 544-560.

Electricite de France. (2022, 08). *TELEMAC-MACARET*. Retrieved from http://opentelemac.org/index.php/community

Environment Agency. (2022, 01). *Bathing Water Linked Data.* Retrieved from Data.Gov.UK: https://environment.data.gov.uk/data/bathing-water-profile/ukj3100-16500/2022:1.html

EU Water Framework Directive. (2013). *The Bathing Water Regulations 2013: Schedule 5 Classification.* Retrieved from legislation.gov.uk: https://www.legislation.gov.uk/uksi/2013/1675

Falconer, R. A. (1986). Water quality simulation study of a natural harbour. *ASCE Journal of Waterway, Port, Coastal and Ocean Engineering*, 112(1), 15-34.

Falconer, R. A. (1991). Review of modelling flow and pollutant transport in hydraulic basins. *Proceedings of First International Conference on Water Pollution: Modelling, Measuring and Prediction* (pp. 3-23). Southampton: Computational mechanics Publications.

Falconer, R. A., & Chen, Y. (1991). An improved representation of flooding and drying and wind stress effects in a two-dimensional tidal numerical model. *Proceedings of the Institution of Civil Engineers, Part 2*, 12, 659-678.

Falconer, R. A., Lin, B., & Kashefipour, S. M. (2005). Modelling water quality processes in estuaries. In P. D. Bates, S. Lane, & R. Ferguson, *Computational Fluid Mechanics: Applications in Environmental Hydraulics* (pp. 305-328). Chichester: John Wiley and Sons Ltd.

Fischer, H. B. (1973). Longitudinal dispersion and turbulent mixing in open channel flow. *Annual Review of Fluid Mechanics*, 5, 1092-1102.

Fischer, H. B., List, E. J., Koh, R. C., Imberger, J., & Brooks, N. H. (1979). *Mixing in Inland and Coastal Waters.* San Diego: Academic Press Inc.

Foundation for Water Research. (1993). *A Framework for Marine and Estuarine Model Specification in the UK FR0374.* Marlow: Water Research Centre.

Guilland, J. F., Derrien, A., Gourmelon, M., & Pommepuy, M. (1997). T90 as a tool for engineers: interest and limits. *Water Science and Technology*, 35 (11-12), 277-281.

Henderson, F. M. (1966). *Open Channel Flow.* New York: MacMillan Publishing Co., Inc.

Huang, G., Falconer, R. A., & Lin, B. (2017). Intergrated hydro-bacterial modelling for predicting bathing water quality. *Estuarine, Coastal and Shelf Science*, 188, 145-155.

Huang, G., Falconer, R., Lin, B., & Xu, C. (2022). Dynamic tracing of faecal bateria processes from a river basin to an estuary using a 2D/3D model. *River*, 1, 149-161.

Kay, D. (2015). *Personal Communication.* Lampeter: Centre for Research in Environment and Health.

Kay, D., Bartram, J., Pruss, A., Ashbolt, N., Wyer, M. D., Fleisher, J. M., . . . Rees, G. (2004). Derivation of numerical values for the World Health Organization guidelines for recreational waters. *Water Research*, 38, 1296-1304.

Kay, D., Fleisher, J. M., Salmon, R. L., Jones, F., Wyer, M. D., Godfree, A. F., . . . Shore, R. (1994). Predicting likelihood of gastroenteritis from sea bathing: results from randomised exposure. *The Lancet*, 344, 905-909.

King, J., Ahmadian, R., & Falconer, R. A. (2021). Hydro-epidemiological modelling of bacterial transport and decay in nearshore coastal waters. *Water Research*, 196, 117049, 1-14 .

Kocyigit, M. B., & Falconer, R. A. (2004a). Modelling of wind-induced currents in water basins. *Proceedings of the Institution of Civil Engineers, Water Management*, WM4, 197-210.

Kocyigit, M. B., & Falconer, R. A. (2004b). Three-dimensional numerical modelling of wind-driven circulation in a homogeneous lake. *Advances in Water Resources*, 27, 1167-1178.

Kreitmair, M. J. (2021). Derivation of the Shallow Water Equations. In M. J. Kreitmair, *The Effect of Uncertainty on Tidal Stream Energy Resource Estimates* (pp. 17-25). Switzerland: Springer.

Lam, M. Y., & Ahmadian, R. (2023). Predicting fecal-indicator organisms in coastal waters using a complex nonlinear artifical intelligence model. *Journal of Environmental Engineerng*, 149(2), 1-14.

Mancini, N. J. (1978). Numerical estimates of coliform mortality rates under various conditions. *Water Pollution Control Federation*, 50(11), 2477-2484 .

Nash, S., & Hartnett, M. (2010). Nested circulation modelling of inter-tidal zones: details of a nesting approach incorporating moving boundaries. *Ocean Dynamics*, 60, 1479-1495.

Nash, S., & Hartnett, M. (2014). Development of a nested coastal circulation model: Boundary error reduction. *Environmental Modelling & Software*, 53, 65-80.

OpenFoam. (2023, 08 14). *Open Foam*. Retrieved from Open Foam: https://www.openfoam.com/

Port & Coastal and Atkins. (2023). *Bathing Water Quality: Modelling of impacts on bathing waters.* Edinburgh: Atkins.

Port & Coastal Solutions. (2023). *Technical Note: Wind Analysis.* Southampton: Port & Coastal Solutions.

Preston, R W. (1985). *The representation of dispersion in two-dimensional shallow water flow.* Leatherhead : Central Electricity Research Laboratories, TPRD/U278333/N84.

Rodi, W., Constantinescu, G., & Stoesser, T. (2013). *Large-Eddy Simulation in Hydraulics.* London: Taylor and Francis Group.

Saunders, A. (2023). *Personal Communication.* Worthing: Southern Water.

Smagorisky, J. (1963). General circulation experiments with the primitive equations: I The basic experiemtn. *Monthly Weather Review*, 91(3), 99-164.

Southern Water. (2021). *Management of Wastewater in Portsmouth and Havant.* Retrieved from Southern Water: https://www.southernwater.co.uk/Media/Default/images/3060_PortsmouthHavant_WWT_v4.pdf#:~:text=Within%20the%20Portsmouth%20and%20Havant%20system%20there%20are,some%20stormwater%20into%20the%20Solent%20deep%20water%20channel.

Southern Water. (2023a). *Critical conditions to trigger a warning.* Worthing: Southern Water.

Southern Water Services Ltd. (1995). *PORTOBELLO LSO Appendix II Hydrodynamic Model Calibration and Verification.* Crawley: Southern Science Ltd.

Southern Water Services Ltd. (1998). *The Solent and the Isle of Wight Tidal Hydrodynamic Model.* Crawley: Southern Water Services Ltd.

Stapleton, C. M., Wyer, C. D., Kay, D., Bradford, M., Humphrey, N., Wilkinson, J., . . . McDonald, A. T. (2007a). *Fate and Transport of particles in estuaries - Vol. III: laboratory experiments, enterococci decay rates and association with sediments.* Bristol: Environment Agency.

Stapleton, C. M., Wyer, C. D., Kay, D., Bradford, M., Humphrey, N., Wilkinson, J., . . . McDonald, A. T. (2007b). *Fate and transport of particles in estuaries - Vol. IV: numerical modelling for bathing water enterococci estimation in the Severn Estuary.* Bristol: Environment Agency.

Vieira, J. K. (1993). Dispersive processes in two-dimensional models. In M. B. Abbott, & W. A. Price, *Coastal, Estuarial and Harbour Engineers' Reference Book* (pp. 179-190). London: E & F N Spon.

Weber, J. R. (1983). Steady wind- and wave-induced currents in the open ocean . *Journal of Physical Oceanography*, 13, 524-530.

Wikipedia. (2023, 08 14). *Smagorinsky model for the sub-grid scale eddy viscosity*. Retrieved from Turbulence Modelling: https://en.wikipedia.org/wiki/Turbulence_modeling

Wu, J. (1969). Wind stress and surface roughness at air-sea interface. *Jounral of Geophysical Research*, 74(2), 444-455.

Wu, J. (1982). Wind-stress coefficients over sea surface from breeze to hurricane . *Journal of Geophysical Research*, 87, 9704-9706.

Xue, J., Ahmadian, R., Jones, O., & Falconer, R. A. (2021). Design of tidal range energy generation schemes using a Genetic Algorithm model . *Applied Energy*, 286, 116056, 1-15.

Zheng, Y., Hou, L., Liu, M., Liu, Z., Li, X., Lin, X., . . . X, J. (2016). Tidal pumping facilitates dissimilatory nitrate reductions in interdial marshes. *Scientific Reports (Nature)*, 6, 21338, 1-12.