Stantec

EXE ESTUARY
Coastal Modelling Assessment

April 2022

Prepared for:
South West Water

Prepared by:
[redacted]

Report Number: [redacted]

Revision	Description	Author	Date	Quality Check	Date	Independent Review	Date
V1	Initial Report	[redacted]	02/22	[redacted]	02/22	[redacted]	02/22
V2	Updated Report with Budleigh Salterton impacts	[redacted]	13/04	[redacted]	05/22	[redacted]	05/22

Prepared by: [redacted]

Reviewed by: [redacted]

Approved by: [redacted]

Table of Contents

1 Background

South West Water have asked Stantec to undertake a full MIKE21 model build of the Exe Estuary and surrounding coastline in order to evidence the benefits and potential deterioration arising from capital improvement schemes at Phear Park Combined Sewer Overflow (CSO), Maer Road CSO and Maer Lane (Exmouth) Sewage Treatment Works (STW).

The scheme, driven by requirements to improve the Exe Estuary Shellfish Water, would result in more flow being passed forward from Phear Park and Maer Road CSOs which currently discharge directly to the Shellfish Water, towards Maer Lane STW which discharges to the coast via Straight Point Short Sea Outfall (SSO). This is shown schematically in Figure 1. The scheme would have the impact of reducing CSO discharges from Phear Park and Maer Road to less than 10 spills per annum in compliance with Shellfish Water standards. Hydraulic improvements at Maer Lane STW would also mean despite an increase in spill volumes from the SSO as a result of the scheme, annual spill frequencies and spill durations would decrease when compared to the current operational performance.

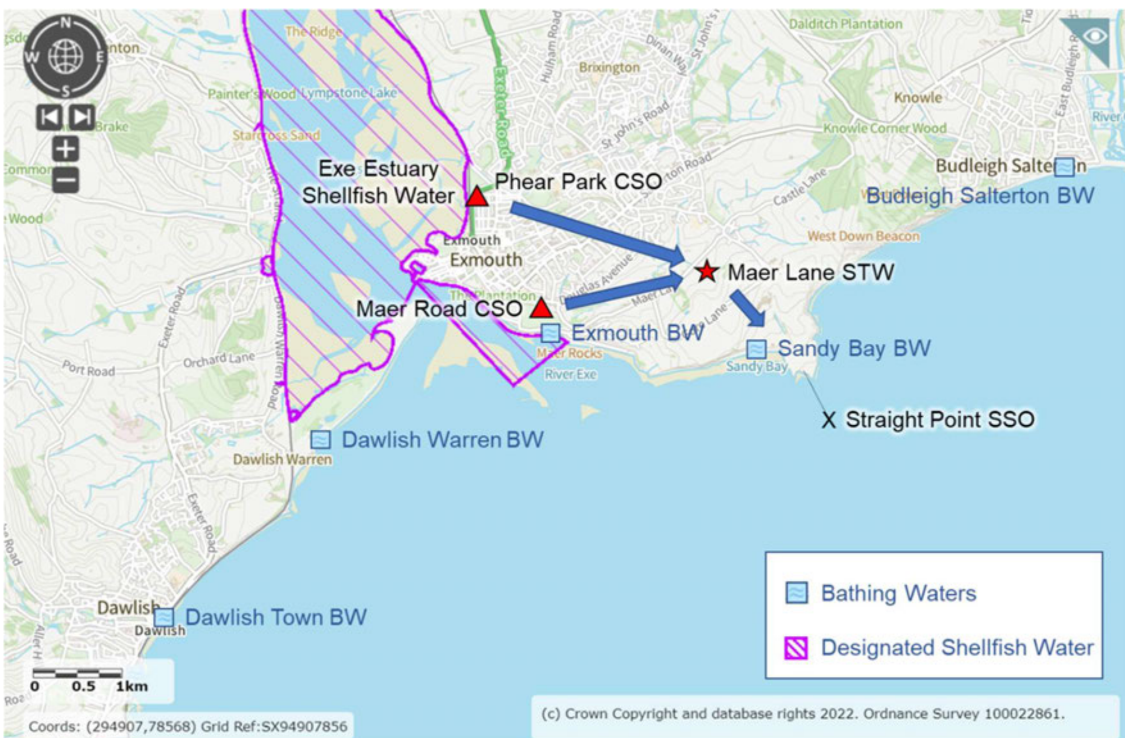


Figure 1 – Schematic of Solution to Achieve Compliance with Exe Estuary Shellfish Waters

Table 1 – Change in Spill Frequencies and Volumes Arising from the Scheme[1]

	Baseline Annual Spill Frequency	Baseline Annual Spill Volume (m^3)	Proposed Annual Spill Frequency	Proposed Annual Spill Volume (m^3)
Phear Park CSO	26.1	80,977	6.7	15,803
Maer Road CSO	39.0	201,071	8.5	8.5
Maer Lane STW	43.2	50,289	36.5	294,248

1.1 Objectives

The stated objectives of the study are as follows:

1. Confirm there is no deterioration arising from the increase in storm discharge volumes from Maer Lane STW via the Straight Point SSO to both the existing Exe Estuary Shellfish Water and Sandy Bay Bathing Water. The scope was increased to confirm no deterioration at other notable sensitive receptors including Budleigh Salterton, Exmouth and Dawlish Warren Bathing Waters and the classified shellfish water beds at Sandy Bay.

2. Considering the discharges from Straight Point outfall only, can South West Water achieve compliance, defined as a 5 cfu/100ml geomean at the boundary of the Sandy Bay Classified Shellfish Water, without the need for storm disinfection or an outfall extension. If not, what length of extension is required?

The work must also be cogniscient of the timescales of the wider project as compliance with the shellfish water at the Exe Estuary is required by September 2022.

1.2 Sensitive Receptors

It is important to note the regulatory differences associated with the key environmental receptors:

- Dawlish Town, Dawlish Warren, Sandy Bay, Exmouth and Budleigh Salterton are designated coastal bathing water locations as defined by the revised Bathing Water Directive (rBWD).

- The Exe Estuary Shellfish Water is a designated location as defined by the Shellfish Water Directive.

- These are funded regulatory requirements outlined in the WINEP programme to ensure no deterioration, compliance and improve water quality at designated Bathing and Shellfish Waters. These statutory designations are shown in Figure 1.

- Classified Shellfish Water Production or Harvesting Areas, such as the site off Sandy Bay are classified and managed by the Food Standards Agency. They are not covered by the Shellfish Water Directive have no associated water company funding or regulatory protection. If these go on to become designated sites as defined by the Shellfish Water Directive in the future this will change. Currently there are no plans to seek official designation at the Sandy Bay Classified Shellfish Water. There are currently four sites in and around the estuary and another two a

[1] Based on an average from 10 year time series network model outputs (A2009-2019).

distance off the coast from Budleigh Salterton. The sites near the estuary are shown in Figure 2.

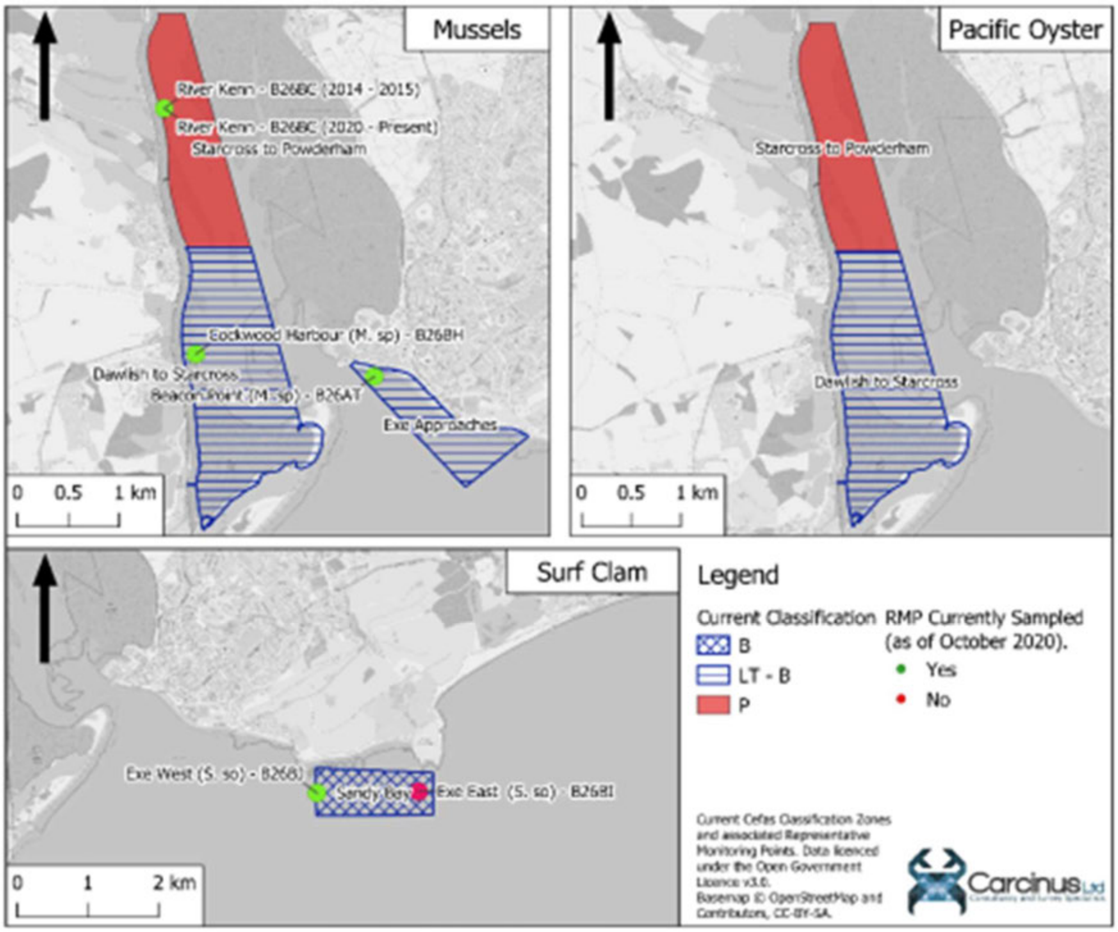


Figure 2 – Current Non-Statutory Shellfish Classification Zones taken from the Food Standards Agency Sanitary Report of the Exe Estuary 2021[2] (P = Prohibited Area, LT = Long Term ‘B’ Classification, RMP = Representative Monitoring Point, ‘B’ = Short Duration ‘B’ Classification)[3]

Whilst regulation of shellfish waters within the UK is somewhat confusing it is important at this point to note the distinction from a water company perspective.

[2] https://www.carcinus.co.uk/wp-content/uploads/2021/03/J0591_20_07_16_Exe_Estuary_Sanitary_Survey_Review_v4.0_FINAL.pdf
[3] Shellfish production and relay areas are classified according to the levels of E. coli detected in shellfish flesh (https://www.food.gov.uk/business-guidance/shellfish-classification)

2 Model Build

A full model build and validation report is attached in Appendix A.

3 No Deterioration Checks

No deterioration checks have been carried out on the existing designated Exe Estuary Shellfish Water and Exmouth, Sandy Bay, Dawlish Warren and Budleigh Salterton bathing waters.

3.1 Modelling Parameters

3.1.1 APPROACH

All modelling undertaken for this study has been undertaken in the MIKE FM Particle Tracking (PT) module. Default horizontal and vertical dispersion coefficients have been applied.

All simulations commenced on 12th September 2021, allowing sufficient time for dynamic equilibrium to be achieved before output commenced on 16th September for a complete Neap-Spring-Neap cycle. Water levels through the output time frame are shown in Figure 3.

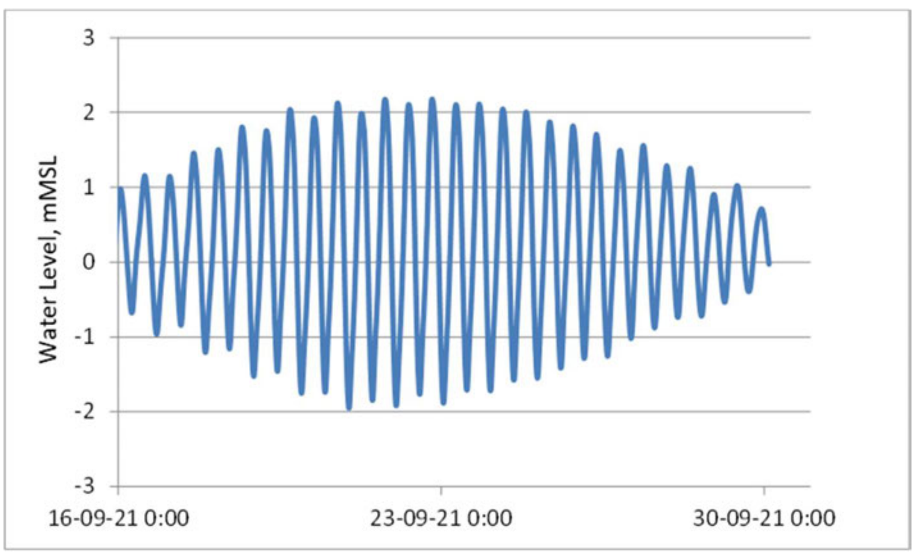


Figure 3 – Water Levels at Straight Point for the model output timeframe

All discharges entered into the model were at arbitrary flow rates and cfu concentrations of 1,000 l/s and 1E6 cfu/100ml respectively. Predicted concentrations were then factored in post-processing as required. Bacterial mortality was included in all model simulations and was set to 20 hours (E.coli) and 40 hours (intestinal enterococci (IE)).

3.1.2 WIND

Statistical wind data for Exmouth was purchased from MeteoBlue for the 10 year period 1 Jan 2012 to 31 Dec 2021. The data is summarised in the wind rose shown in Figure 4.

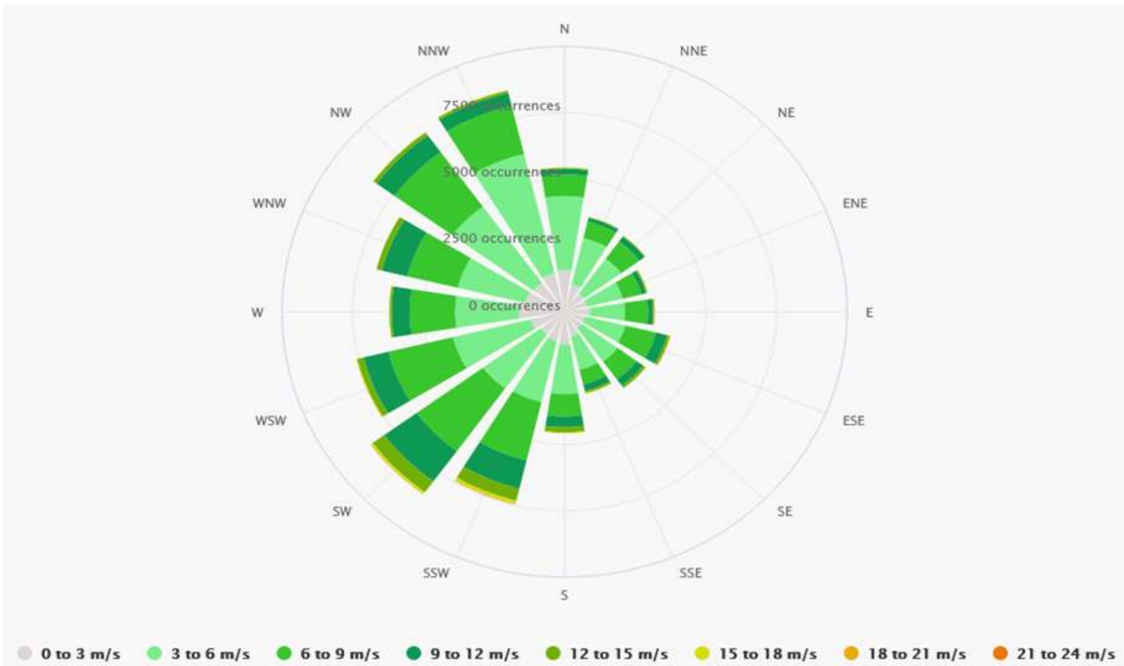


Figure 4 – Exmouth Wind Rose

From the above data, 3 wind conditions were selected for consideration in the modelling, as defined in Table 2. Offshore winds were not modelled, as they would lead to reduced impacts.

Table 2 – Modelled Winds.

Wind Direction	Median Wind Speed Band (m/s)	Modelled Wind Speed (m/s)
SW	6 to 9	7.5
S	3 to 6	4.5
SE	3 to 6	4.5

Where wind has been applied to the model this has been applied both to the PT simulation in question, and to the underlying decoupled hydrodynamic simulation.

In addition to the wind conditions described, “No Wind” conditions were also modelled.

3.2 Designated Shellfish Waters

Due to the diversion of Phaer Park and Maer Road storm effluents (inside the Shellfish Water boundary) to the Maer Road STW and from there to the Straight Point SSO (outside the Shellfish Water boundary), the impacts on the Exe Estuary Shellfish Waters are by definition reduced. No model simulations were therefore required to confirm SFW No Deterioration.

3.3 Bathing Waters

3.3.1 EXMOUTH & SANDY BAY BATHING WATERS

Model predictions indicated no impact (i.e. timeseries of cfu concentrations remain at 0) at the Dawlish Warren, Exmouth or Sandy Bay BWs associated with effluent from the Straight Point SSO, under any of the modelled wind conditions (including No Wind) under continuous discharge conditions.

These predictions are illustrated in Figure 5 to Figure 8 below, showing the plume extents for the No Wind Spring tide. Note these outputs are NOT factored, so represent 1,000 litres / second, 1E6 E.coli cfu/ 100 ml.

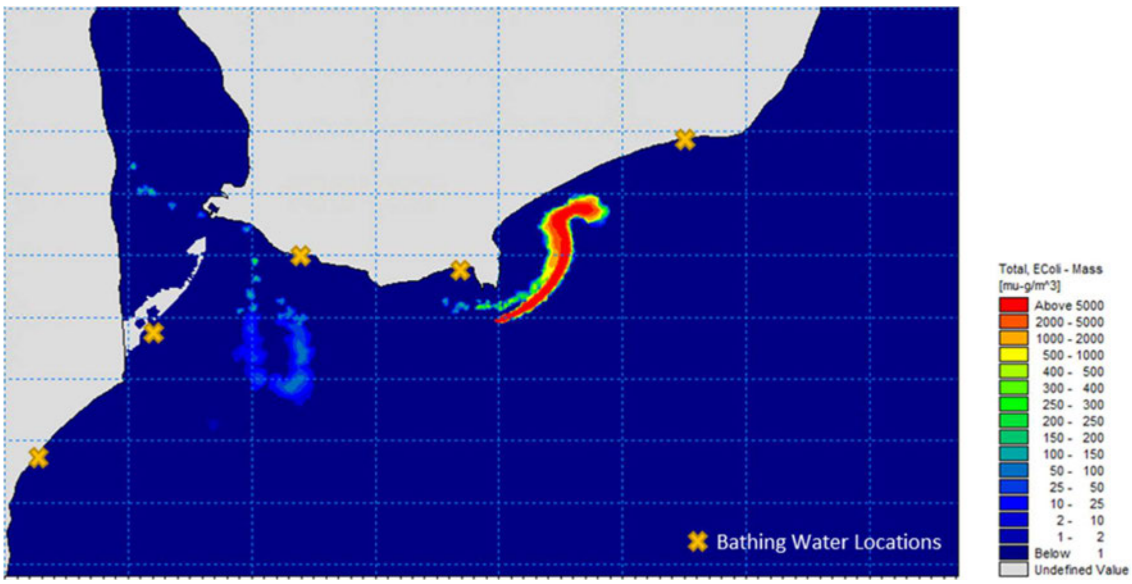


Figure 5 – Predicted E.coli concentrations, HW

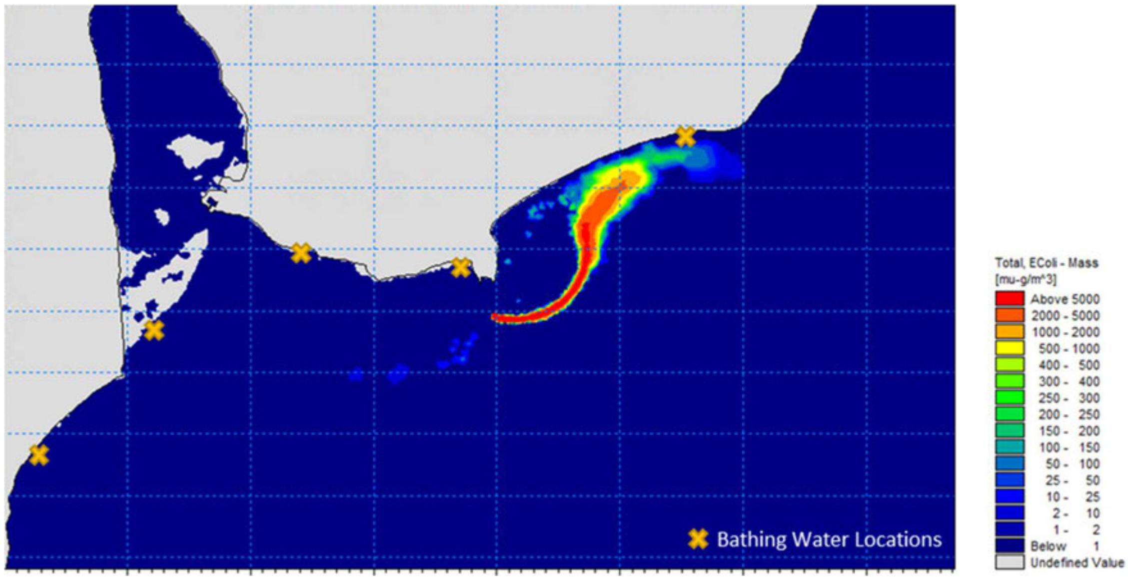


Figure 6 – Predicted E.coli concentrations, HW+3h

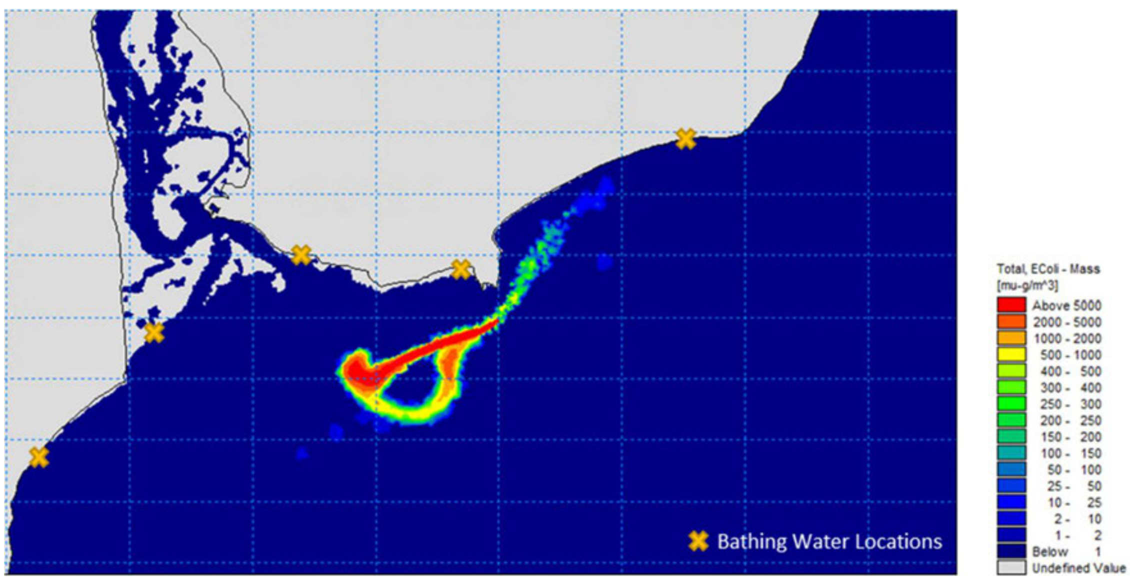


Figure 7 – Predicted E.coli concentrations, LW

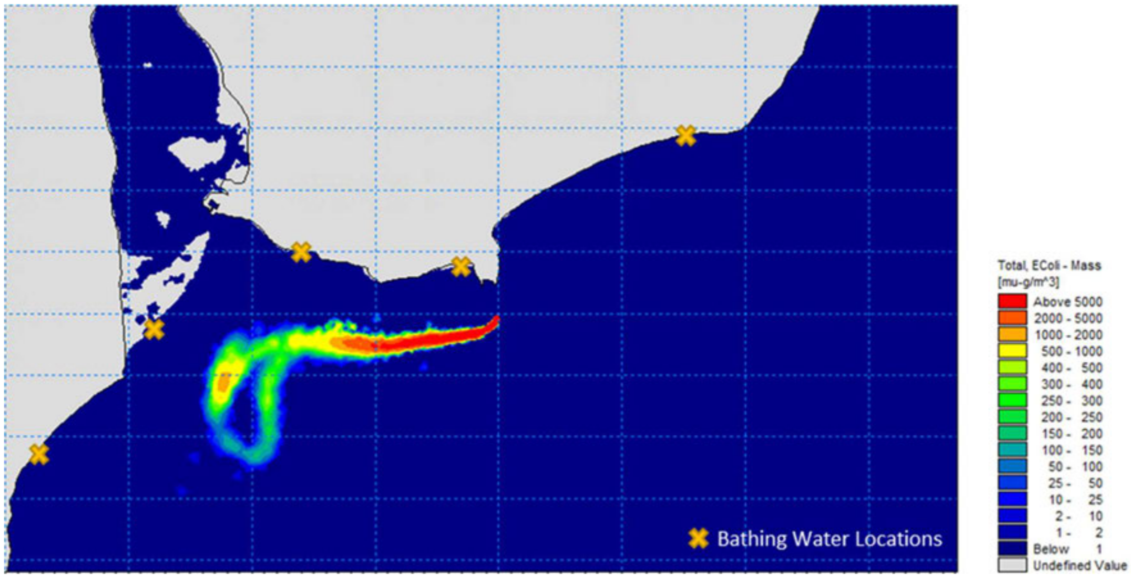


Figure 8 – Predicted E.coli concentrations, HW-3h

Note that Figure 7 above shows the plume being advected away to the west-south-west, but Figure 8 shows a more westerly advection. It was highlighted in the Calibration report that this westerly flow is not consistent with the measured data, which at HW-3 shows the flow direction backing to the south-west. Model predictions are therefore likely to be conservative at this time in terms of impacts at Dawlish Warren, Exmouth and Sandy Bay BWs.

3.3.2 DAWLISH TOWN & DAWLISH WARREN BATHING WATERS

A simulation with easterly wind conditions, to check for impact from the Straight Point outfall on Dawlish Warren and Dawlish Town bathing waters was also undertaken. No impact reported by the model.

3.3.3 BUDLEIGH SALTERTON BATHING WATER

Despite the decrease in storm spill frequencies and spill durations at Straight Point SSO it was felt that a statistically check was required to evidence no deterioration at Budleigh Salterton given the increase in storm volumes and the fact the modelled plume was shown to impact the bathing water under certain conditions.

All model outputs relating to the Budleigh Salterton Bathing Water assessment have been factored to account for either:

1. Flow to Full Treatment (FFT) of 273 l/s continuous discharge of the following concentrations:
    - E.coli – 200,000 cfu/100ml
    - IE – 80,000 cfu/100ml

    or

2. Spill of 1 hour duration, spill volume adjusted in post-processing interrogation, and the following “diluted storm” concentrations:
   - E.coli – 5,000,000 cfu/100ml
   - IE – 2,000,000 cfu/100ml

FFT was considered initially, in order to develop an understanding of the statistical impact of a continuous discharge from Straight Point on the Budleigh Salterton BW. It was then possible to move on to consideration of spill events and their statistical impacts.

Wind Sensitivity

At Budleigh Salterton BW, model predictions indicate that the impact of the plume from Straight Point SSO is wind dependent. To illustrate this, Table 3 shows maximum predicted E.coli concentrations at Budleigh Salterton BW for FFT under the range of wind conditions.

Table 3 – Max. Predicted E.coli cfu/100ml at Budleigh Salterton

Wind	**Max. predicted E.coli cfu/100ml**
No Wind	3.2
SE	1.7
S	5.1
SW	19.0

It is clear from the above that south westerly wind conditions have the largest impact. There is no predicted impact during offshore or shore parallel (westerly) wind conditions.

In order to determine the impact of a Straight Point discharge when averaged over time, it is necessary to include a consideration of wind frequencies for those directions which are predicted to lead to impact at Budleigh Salterton, so that wind conditions which do not lead to impact at Budleigh Salterton are not included in the analysis. See Table 4.

Table 4 – Frequencies of Winds which lead to impact

Direction	**% of the time**
SSE to S	8.9
SSW to WSW	26.9
Total SSE to WSW	*35.8*

The effect of including wind frequency in the calculations is shown in Figure 9 and Figure 10. In order to ensure the analysis is conservative, these figures are for the “worst case” (SW) wind conditions.

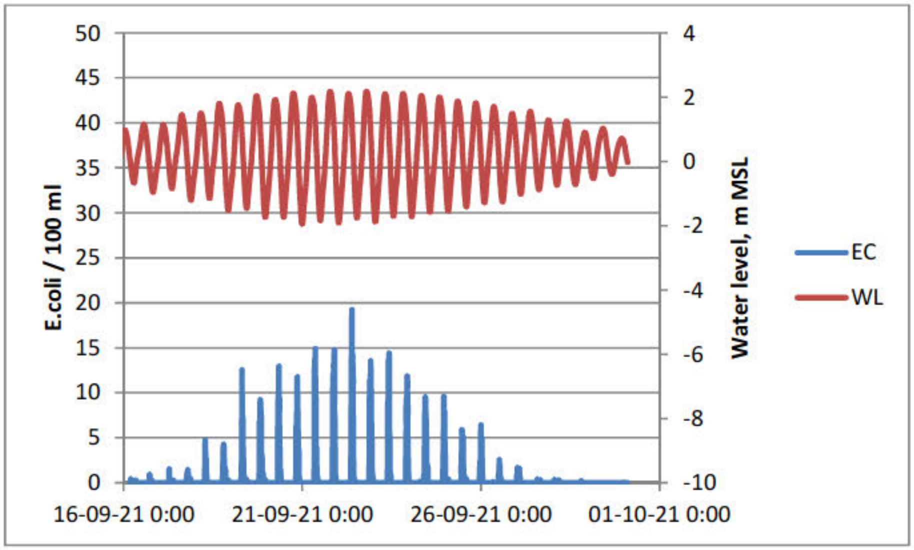


Figure 9 – Predicted E.coli concentrations at Budleigh Salterton, no wind factoring

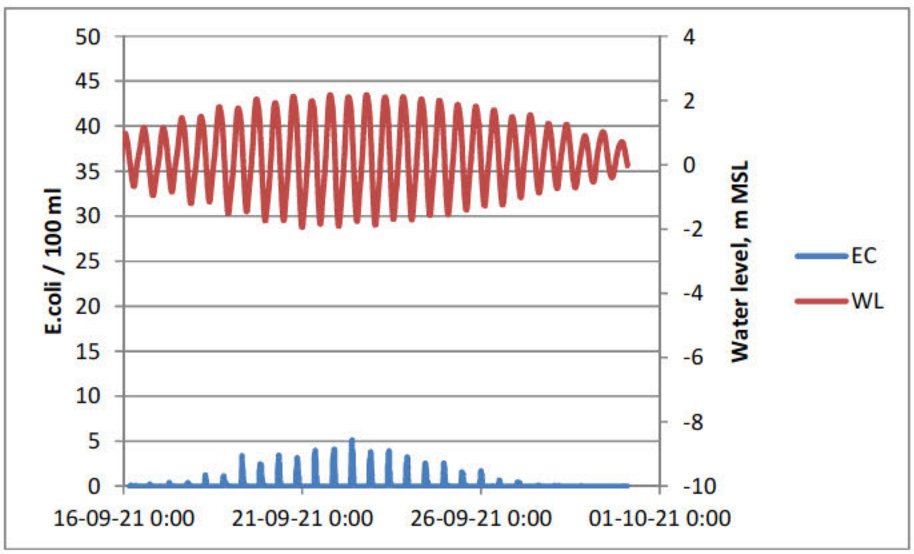


Figure 10 - Predicted E.coli concentrations at Budleigh Salterton, with wind factoring

Spring-Neap sensitivity

Figure 10 shows predicted E.coli for FFT at Budleigh Salterton over the neap-spring-neap cycle (south westerly wind conditions).

In order to account for the statistical impact of a storm discharge from Straight Point SSO, the peak concentrations in Figure 10 were averaged, and the average divided by the maximum concentration, giving a Tidal Factor of 0.38 to be applied to consideration of intermittent discharges.

Intermittent discharges

In order to test the sensitivity of the Budleigh Salterton BW to the timing (relative to HW) of releases from the Straight Point SSO, 13 x 1-hour releases were modelled for HW-6h, HW-5h … HW=6h. Peak predicted concentrations at Budleigh Salterton associated with each of those releases (under SW wind conditions) were normalised and are presented in Figure 11.

The releases were simulated on a spring tide, there being no impact on a neap tide.

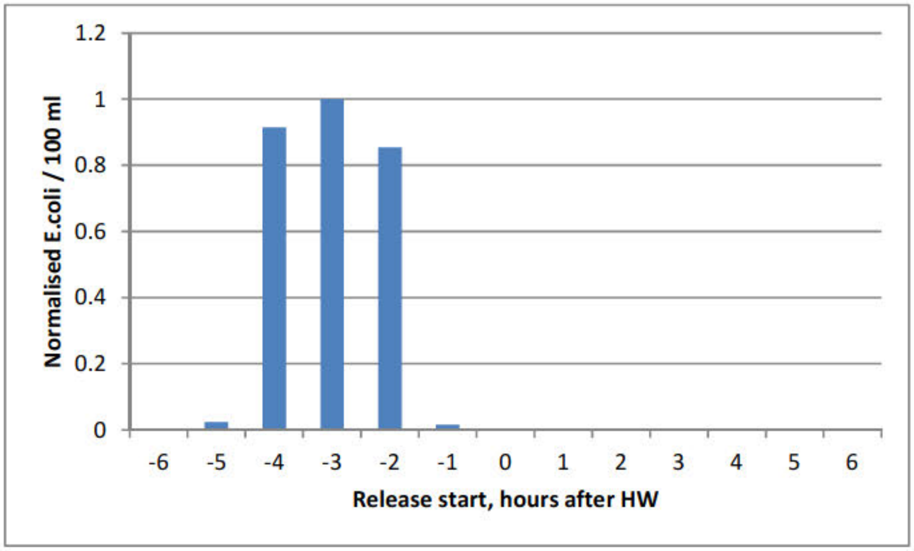


Figure 11 – Normalised impact of 1 hour releases at Budleigh Salterton

From Figure 11 it is clear that a 1-hour release at Straight Point SSO only impacts at Budleigh when it occurs at HW-4, -3 and -2, i.e. 3 occurrences out of 13 (23%).

Impact of a spill

To consider the impact of a statistical spill from Straight Point SSO, the following factors are therefore applied to the raw model output, which was generated from a "worst case" simulation of spring tide, HW-3, SW wind:

- Wind factor 0.358
- Tidal factor 0.38
- Timing factor 0.23

The resultant "impact curve" at Budleigh Salterton was then iterated (in terms of volume discharged) so that the maximum E.coli and IE concentrations predicted for Budleigh Salterton BW were 10% of the Excellent compliance values of 250 E.coli cfu/100ml and 100 IE cfu/100ml respectively, i.e. 25 E.coli cfu/100ml and 10 IE cfu/100ml.

The resulting impact curves for a representative spill event are shown below in Figure 12 and Figure 13.

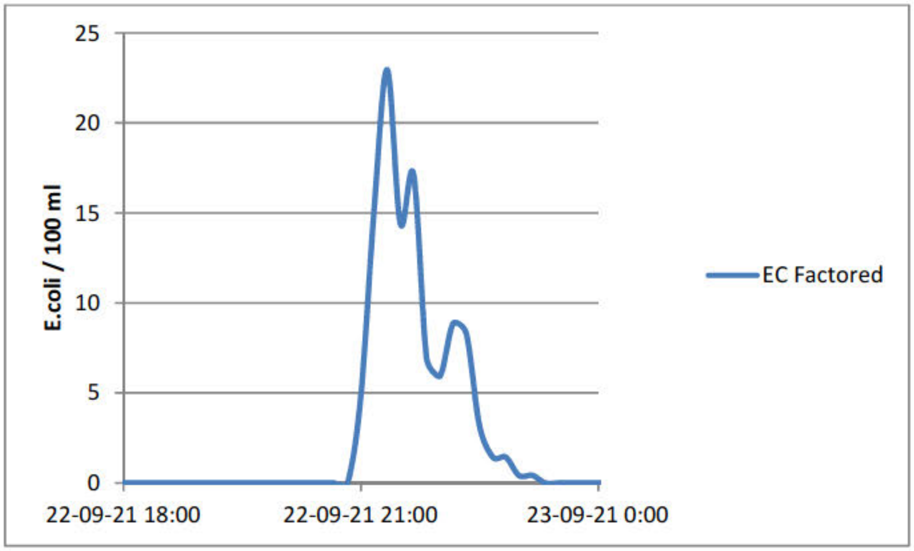


Figure 12 – EC Impact Curve

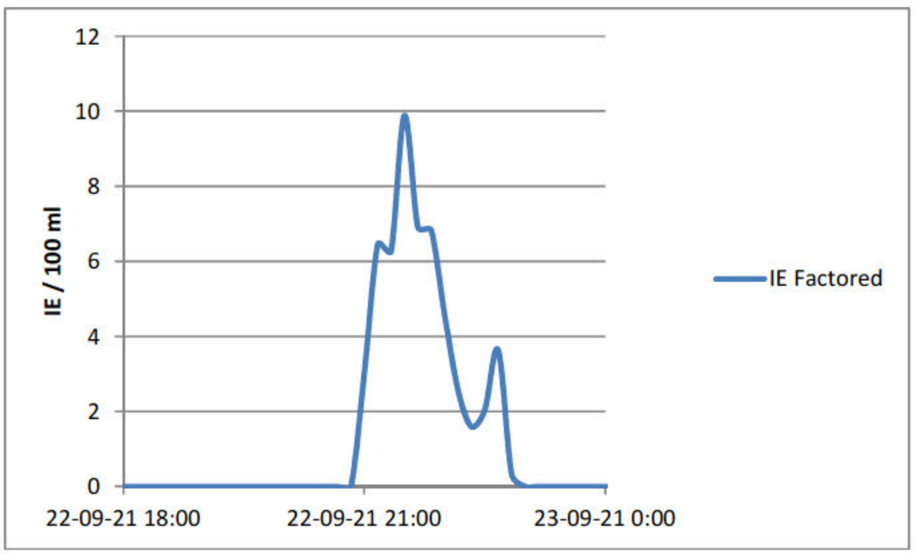


Figure 13 – IE Impact Curve

The spill volume required to achieve both <25 E.coli cfu/100 ml and <10 IE cfu/100 ml predicted impact at Budleigh Salterton was 2592 m^3.

By ranking all of the modelled spills from the 10 year time series hydraulic sewerage model outputs and breaking these into 1 hour unit spills we can determine the number of unit spill events which would have caused a detriment of 25 EC cfu/100ml or 10 IE cfu/100ml.

This exercise was repeated with further reduced target E.coli concentrations. The results are presented in Table 5. From Figure 12 and Figure 13 above, very similar results are generated when the IE target concentrations are reduced instead and therefore are not shown here for clarity.

Table 5 – Number of spills which would cause given deteriorations

Deterioration When Defined as E.coli (cfu/100ml)	Deterioration When Defined as Percentage of Classification	One hour unit spill volume required to cause Deterioration (m^3)	Number of Modelled One Hour Unit Spills Within the 10 Year Dataset
25	10%	2592	0
10	4%	1116	17
5	2%	558	46

Table 5 shows that statistically there were no modelled unit impact spills within the entire 10 year modelled period which would have caused a deterioration of >25 EC cfu/100ml and on average <5 spills a year which would cause a deterioration of >5 EC cfu/100ml.

It can therefore be concluded that statistically the increase in storm volumes coming from Straight Point SSO will have a negligible impact on bathing water quality at Budleigh Salterton BW.

4 Classified Shellfish Waters & Shellfish Water Production Areas

As a reminder there is no funding or regulatory commitment to protecting, maintaining or enhancing Classified Shellfish Waters or Shellfish Water Production Areas.

However, for completeness the Exe PT model has also been applied to consider no deterioration and how the FFT discharge from Straight Point SSO would be predicted to impact upon compliance, should Sandy Bay Classified Shellfish Water get a future designation under the Shellfish Water Directive.

4.1 No Deterioration

Literature is unclear on whether prolonged exposure (ie spill frequency and duration) or short term exposure to high concentrations (ie storm volume) has the greater impact on shellfish within estuary and coastal environments and as such it is not possible to define ‘deterioration’ with regards to Sandy Bay Classified Shellfish Water. It should be noted however that spill frequencies and spill durations from Straight Point SSO associated with the proposed solution decrease when compared to the modelled baseline.

A simulation with west-north-westerly wind conditions was also undertaken, to check for impact from the Straight Point outfall on a Shellfish Water Production Area located 2.5 nautical miles south east of Otterton Point. No impact predicted by the model.

4.2 Compliance with Shellfish Water Directive Standards

The model was run for the neap-spring-neap timeframe, for the No Wind condition, with timeseries of predicted E.coli concentrations extracted at points along the eastern and western boundaries of the Sandy Bay Classified Shellfish Water as shown in Figure 14. The location of the outfall is also marked.

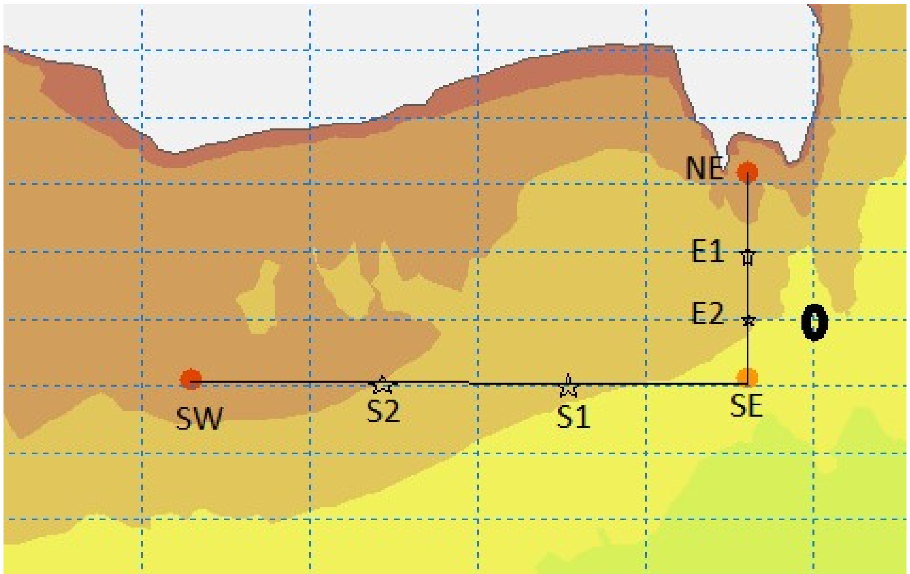


Figure 14 – Proposed SFW boundaries and model monitoring points

Geomean E.coli concentrations have been calculated and are presented in Table 6. In calculating the geomeans, all 0 values in the model output were replaced by 1. For reference, a compliant designated Shellfish Water is required to achieve less than 5 EC cfu/100ml at any given point.

Table 6 – Modelled Geomeans at Sandy Bay Classified Shellfish Water

Monitoring Point	Geomean E.coli cfu/100ml
NE	<2
E1	<2
E2	2.1
SE	32
S1	2.7
S2	2.1
SW	<2

From Table 6 it can be seen that predicted geomeans exceed 5 E.coli / 100 ml at the SE monitoring location. This means that just based on the existing FFT from Straight Point SSO should the classified shellfish water get designated in the future under the directive it would be 'Uncompliant'.

4.2.1 OUTFALL EXTENSION

The model simulation was then repeated with the outfall extended 250m due south. Geomean E.coli concentrations have again been calculated and are presented in Table 7.

.

Table 7 – Proposed SFW geomeans, 250m outfall extension

Monitoring Point	Geomean E.coli / 100ml
NE	<2
E1	<2
E2	<2
SE	2.2
S1	<2
S2	<2
SW	<2

From Table 7 it can be seen that predicted geomeans do not exceed 5 E.coli cfu/100 ml at any of the monitoring locations and as such a 250m outfall extension would allow compliance with the Shellfish Water Directive when considering FFT. A full compliance assessment factoring in wind conditions and storm discharges would be needed to fully evidence this conclusion.

As there are currently no plans to seek designation of this site under the Shellfish Water Directive and there is no funding or regulatory requirement upon SWW to look to improve this receptor any outfall extension as part of the current proposed is not recommended.

Appendix A Model Build Report

River Exe Numerical Modelling

Calibration Report

Satellite data downloaded from Copernicus Open Access Hub (https://scihub.copernicus.eu/dhus/#/home) and processed using ACOLITE.

09 May 2022

T1.02

River Exe Numerical Modelling

	Name	Signature
Author	[redacted]	[redacted]
Checked by	[redacted]	
Reviewed by	[redacted]	

Revision record:

Issue	Date	Status	Comment	Author	Checker	Reviewer
1	13/12/2021					

Report Reference: This is the reference

Report Status: This is the status

Contents

FIGURES

ILLUSTRATIONS

No table of figures entries found.

TABLES

APPENDICES

1 Introduction

Stantec UK Ltd (Stantec) was instructed by South West Water (SWW) to develop numerical modelling tools to be applied for assessing dispersion from existing outfall locations in the Entrance of the Exe and offshore of Straight Point. The study area lies on the south coast of the UK within Lyme Bay in the English Channel (see Figure 1-1).

This report details the build of the numerical model developed for the study and documents its performance against available calibration data to demonstrate its suitability as a tool for assessing the required discharges.

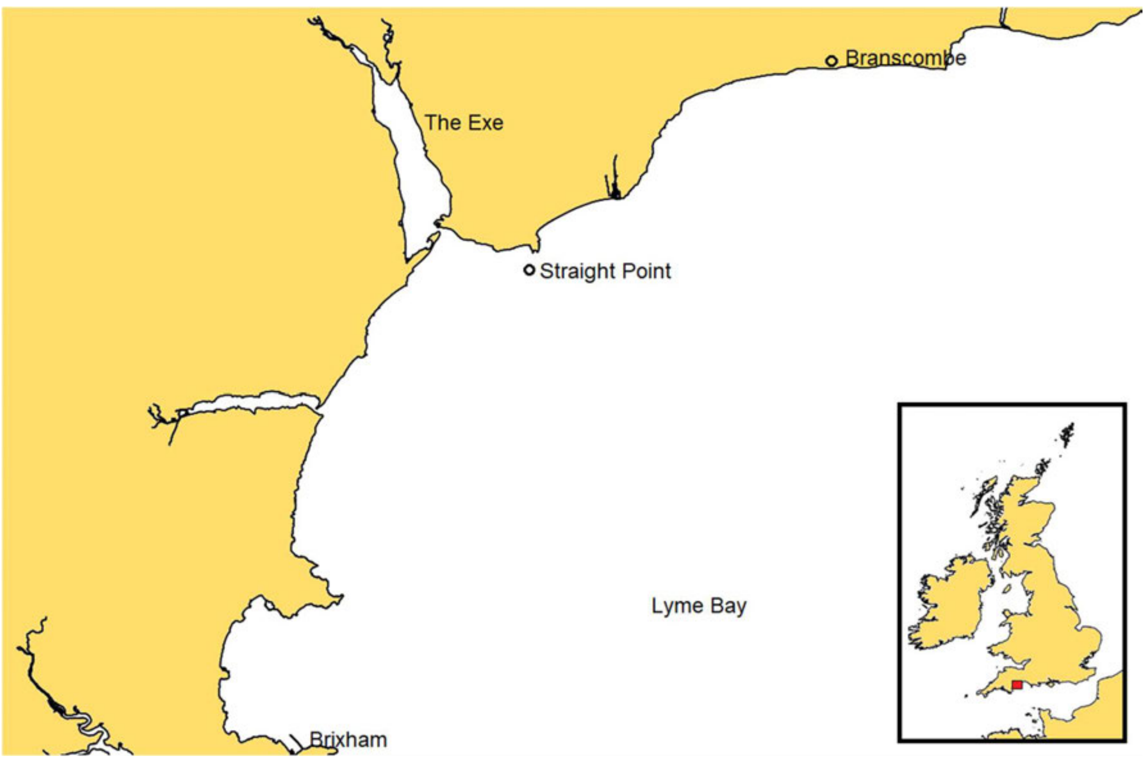


Figure 1-1 Study Area

The report is structured as follows:

- Details on the model setup are provided in Section 2;
- Details on the model calibration are provided in Section 3; and
- A short summary is provided in Section 4.

2 Model Setup

A hydrodynamic model of the western half of Lyme Bay has been configured in the MIKE software which is developed by the Danish Hydraulics Institute (DHI). The MIKE suite of software is internationally recognised state of the art software which has previously been adopted in the UK and internationally for similar projects.

Details of the hydrodynamic (HD) model setup (including the mesh, bathymetry, boundary conditions and bed roughness) are provided in the following sections.

2.1 Mesh

The flexible mesh (FM) approach, which allows the spatial resolution of the model mesh to be varied throughout the model domain, has been adopted in this study. This ensures that the model accuracy and efficiency can be balanced, with a higher mesh resolution in areas of interest or where small scale features play a critical role in the hydrodynamics (for example though the entrance of the Exe), while a lower mesh resolution can be adopted in offshore areas and away from any areas of interest.

The model mesh extends approximately 23 km to the south of Exmouth and approximately 40 km in an east-west direction from Brixham to the west and to offshore of Branscombe to the east (Figure 2-1). The mesh has a variable resolution of approximately 30 to 50 m at the proposed outfall locations and through the entrance channel into the Exe Estuary, reducing to around 1 km in the deeper offshore regions.

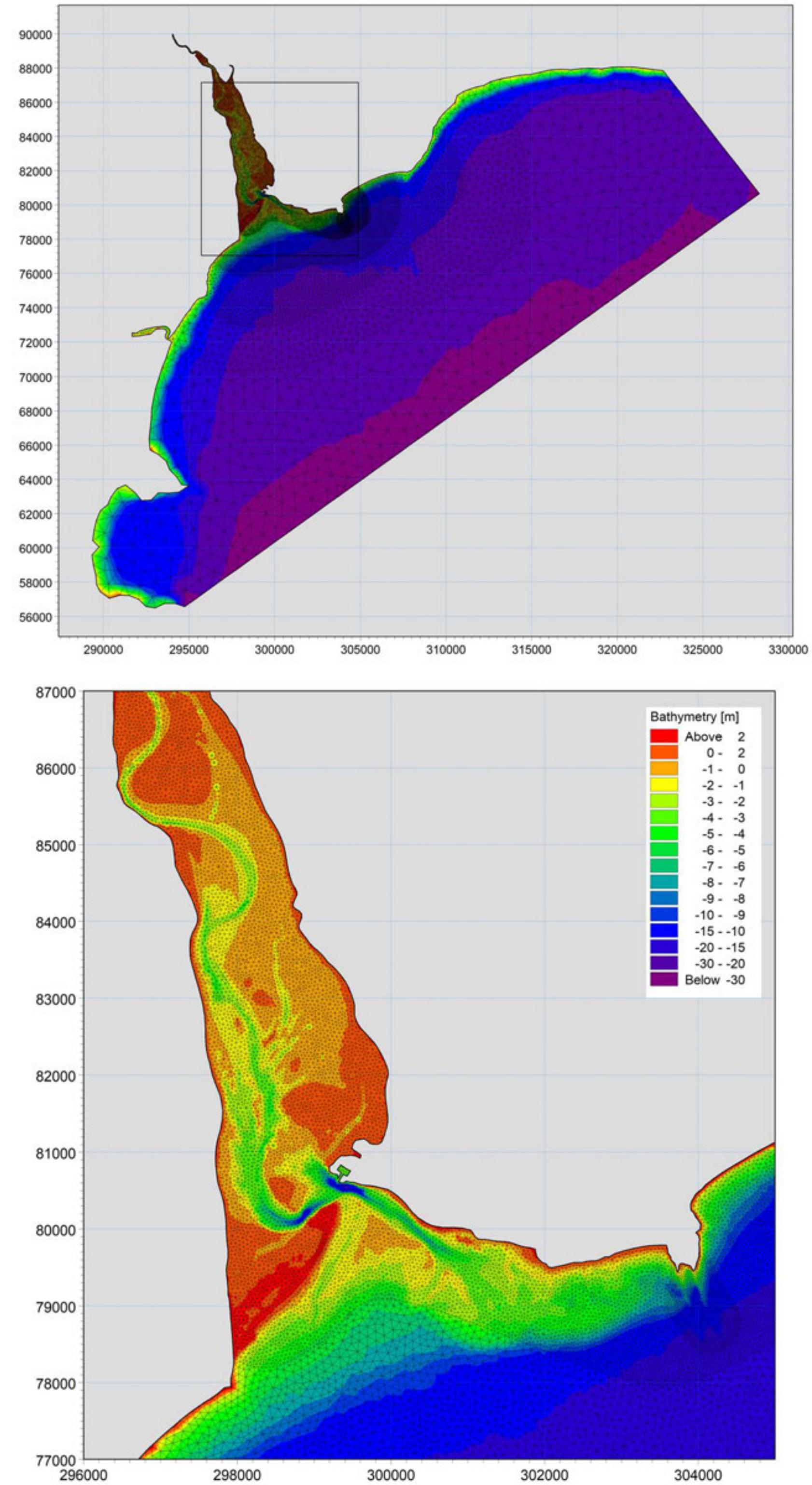


Figure 2-1 Mike FM model mesh

2.2 Model Bathymetry

The model bathymetry is derived from the following sources:

- Swath bathymetry survey of Straight Point from September 2021, with 0.2 m resolution (Titan, 2021);
- Swath bathymetry survey 117609 Exmouth Harbour Channel survey from March 2020, with 1 m resolution (accessed from the Admiralty datahub);
- LiDAR data of the lower Exe from September 2020, with 1 m resolution (accessed from Channel Coastal Observatory (CCO));
- Swath bathymetry data survey HI 1671 Teignmouth to Exmouth from November 2019 to February 2020, with 2 m resolution (accessed from the CCO);
- LiDAR data of the upper Exe from October 2018, with 1 m resolution (CCO);
- Swath bathymetry data survey HI 1242 Portland Bill to Petit Tor Point from May 2008 to May 2009 with 2 m resolution (accessed from the Admiralty datahub); and
- EMODnet Digital Terrain Model (DTM) which has a 1/16th arc minute resolution (approximately 75 m by 115 m) to fill any gaps in the offshore region (EMODnet, 2020).

The coverage of the various datasets is shown in Figure 2-2. The data were all corrected to a single vertical datum (Ordnance Datum Newlyn (ODN)) and interpolated onto the model mesh. The resultant model bathymetry is shown in Figure 2-3.

During the process of merging the bathymetric datasets it was noted that within the Exe and at the entrance to the Exe there had been changes in the locations of the channels between surveys. Priority was given to the newest bathymetric data, although it should be noted that the most recent intertidal data is from September 2020 while the most recent subtidal data within the Exe was from February 2020. Some changes in bathymetry are likely to have occurred since this time, particularly in the region at the end of the Warren and across Pole Sand, where rates of ongoing morphological change in response to storm events can be significant. This is likely to affect the flow regime in this area and this should be taken into consideration during the calibration period (discussed in more detail in Section 3.4).

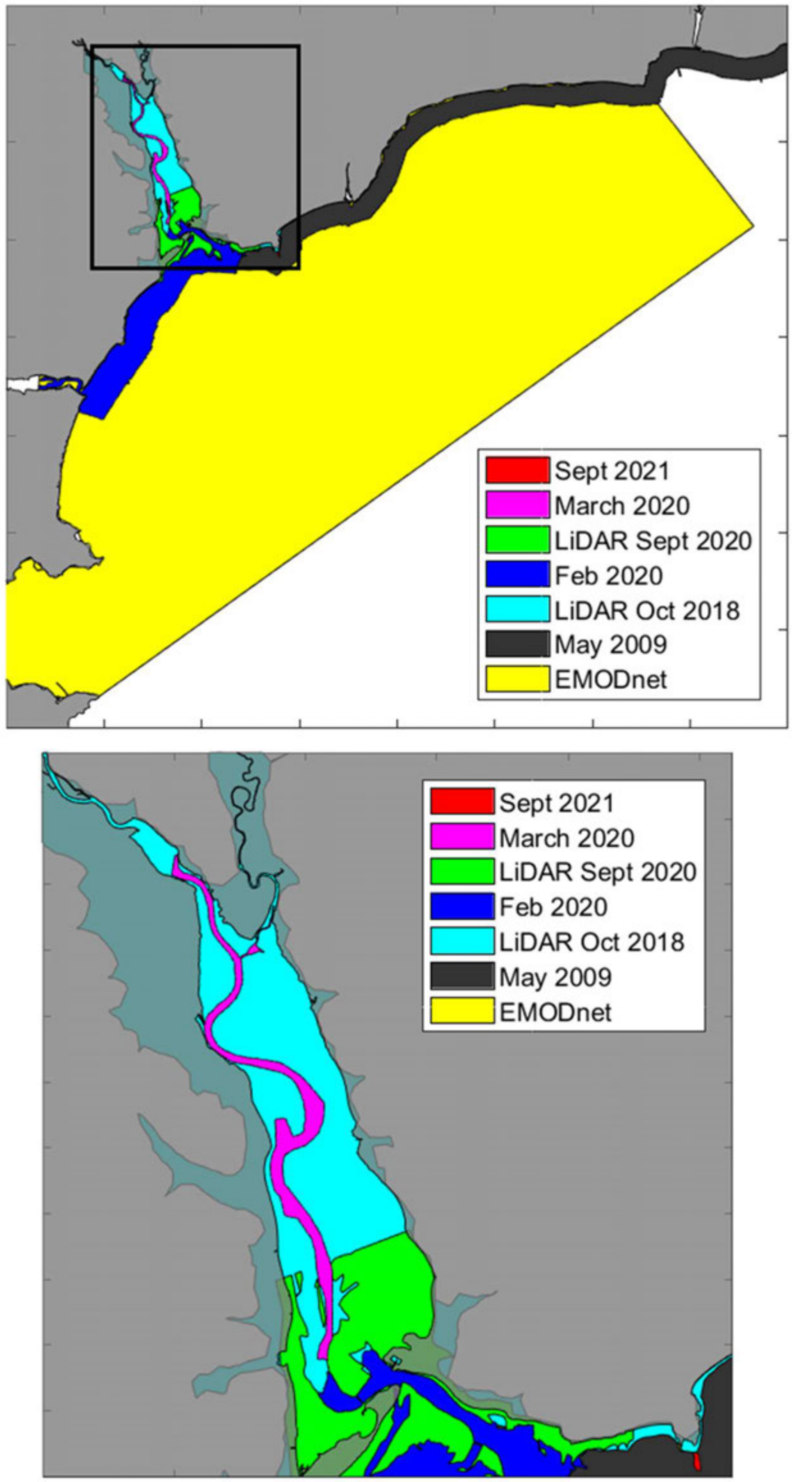


Figure 2-2. Bathymetry data sources

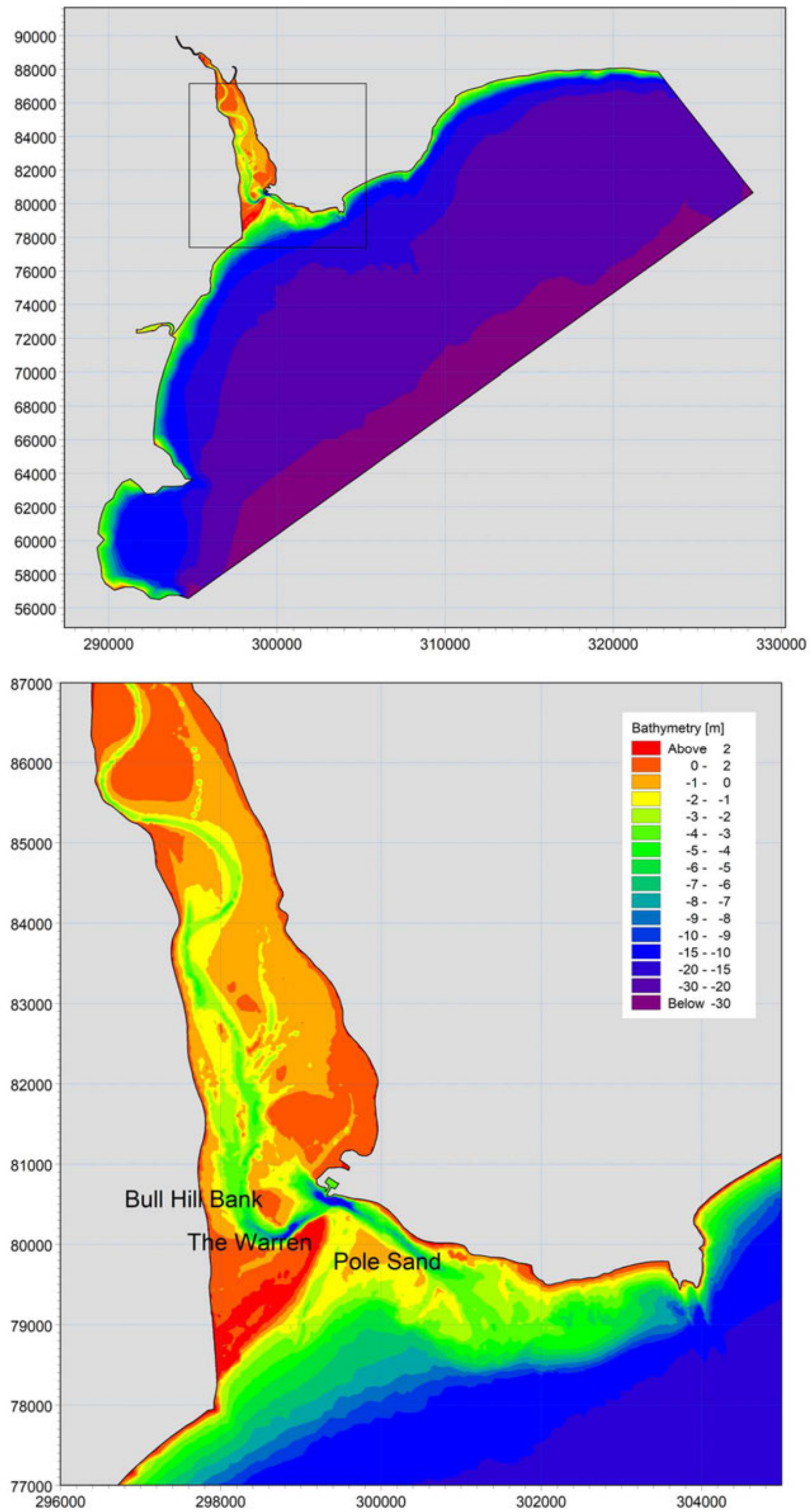


Figure 2-3. Model bathymetry

2.3 Model Boundaries

The location of the model boundaries within the English Channel mean that Global Tidal products such as KMS, DTU10 and TPO 8.0 are unlikely to enable the model to replicate measured tidal levels to an acceptable degree since they do not fully resolve the shallow water constituents which account for a large amount of the tidal variability in the study region. Tidal boundaries have therefore been obtained by simulating the propagation of the tide from the shelf edge using a tidal model of the northwest European shelf (the 'UK Tide Model' (UKTM) developed by Port and Coastal Solutions (PCS)).

The sensitivity of the modelled hydrodynamics to the inclusion of freshwater discharges from rivers and to wind forcing was undertaken. Results from the sensitivity testing showed that flows during the calibration period were largely insensitive to the inclusion of freshwater and wind forcing.

2.4 Bed roughness

During the model calibration a number of bed roughness values and maps were tested. Overall, the best model performance was achieved using a constant bed roughness Manning M value of 40 $m^{1/3}/s$ and so this bed roughness was adopted.

3 Model Calibration

Model calibration is the process of specifying model parameters so that the model reproduces observed data to a suitable level of accuracy. Model validation is used to confirm that the calibrated model continues to consistently represent the observed conditions to the required level of accuracy, in periods other than the calibration period, without any additional adjustment to the model parameters. The calibration and validation processes provide confidence in the model results and are essential to ensure the accurate representation of the hydrodynamics.

3.1 Calibration Metrics

The Foundation for Water Research guidelines (FWR, 1993) form the basis of the assessment criteria of model performance. Different metrics have been developed for estuarine and coastal sites in recognition of the varying levels of complexity in these different environments. The following performance criteria are applicable for water levels:

- modelled water levels (WL) should be within ± 0.1 m or to within 10% of the tidal range over a spring tide and 15% of the tidal range over a neap tide. In estuaries this is relaxed to 15% and 20% on spring and neap tides, respectively; and
- timing of high water (HW) and low water (LW) should be within 15 minutes.

A parameter is considered to be acceptable if either the absolute or relative criterion is met. These metrics only consider the agreement at the peaks, additional statistics have been considered to further quantify the model performance taking account of the water levels throughout the tide. These include:

- Root Mean Square (RMS) difference should be within ± 0.1 m, this is relaxed to ± 0.3 m at the head; and
- Phasing difference should be within 15 minutes.

The following performance criteria are applicable for flows:

- modelled peak current speeds at the time of Peak Flood (PF) and Peak Ebb (PE) should be within ± 0.1 m/s (relaxed to ± 0.2 m/s in estuaries) or in relative terms to within 10 – 20%; and
- modelled peak flow directions at PE and PF should be within 10º (relaxed to 20º in estuaries) of measured directions over a spring neap tidal cycle.

These metrics only consider the agreement at the peaks, additional statistics have been considered to further quantify the model performance taking account of the flows throughout the tide. These include:

- Root Mean Square (RMS) difference in flow speed should be within ± 0.2 m/s; and
- Phasing difference should be within 15 minutes.

These standards provide a good basis for assessing model performance, but experience has shown that sometimes they can be too prescriptive and it is also necessary for visual checks to be undertaken. Under certain conditions, models can meet statistical calibration standards but appear to perform poorly. Conversely, seemingly accurate models can fall short of the guidelines. Consequently, a combination of both statistical calibration standards and visual checks has been used to ensure that the model can accurately simulate the hydrodynamics.

In addition, the quality and representativeness of the available data to the simulated model parameters should be taken into account during the model calibration process.

3.2 Calibration Data

The following data were available for model calibration:

- water level data from a gauge at Exmouth (obtained from CCO); and
- current data from three 13 hour boat surveys in September 2021 (Titan survey, 2021). Two of the surveys were in the entrance of the Exe (see Figure 3-1) and were undertaken on a spring and a neap tide, while the third was located offshore of Straight Point and was undertaken on a spring tide.

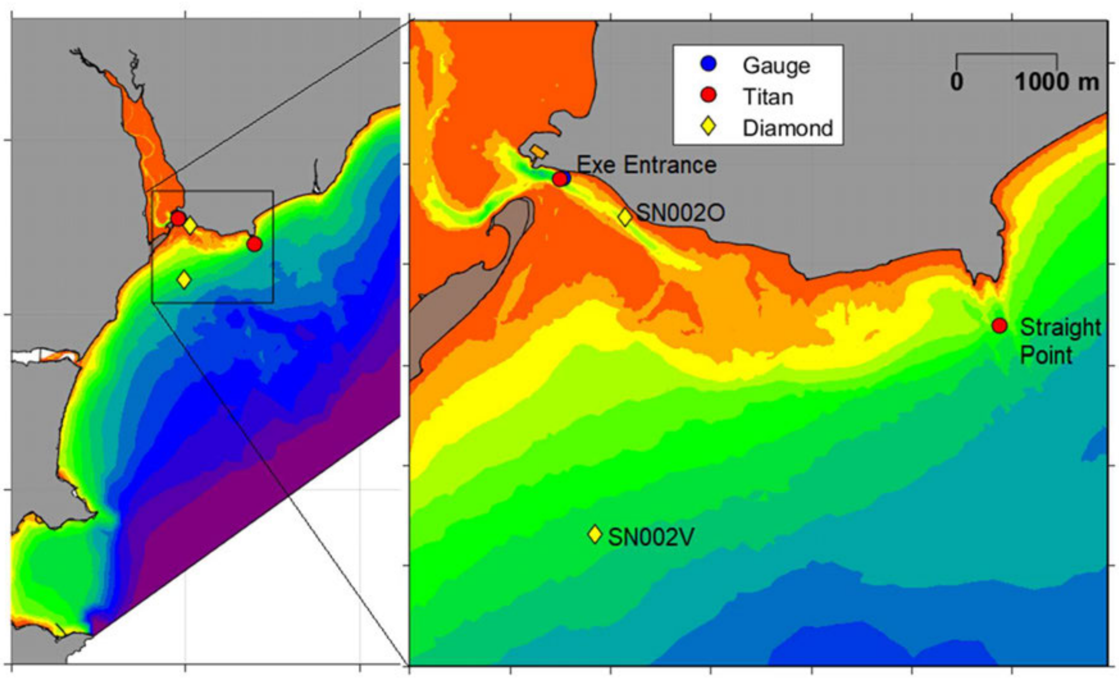


Figure 3-1 Model calibration data locations

For the purposes of model validation, water levels from a separate 15 day spring-neap cycle in March 2019 were compared against modelled water levels at Exmouth. In addition, flows were validated against flows from two tidal diamonds located within the model domain (SN002O in the entrance to the Exe and SN002V approximately 2 km south of Pole Sand).

3.3 Modelled Water Levels

Modelled water levels are compared against measured and predicted water levels at Exmouth in Figure 3-2. Ahead of undertaking any comparison it is important to note any differences between what is represented by the modelled and observed water levels. The model only includes the contribution of the tide to the water level, while the measured water level also includes the influence of meteorological conditions (i.e. the effect of air pressure and wind). The predicted water level also only includes variations in water level from the tide, however Exmouth is not a primary port location and as such it's predicted tide is based on an interpolation of tidal levels from other nearby sites, which may affect the accuracy. In view of this it is considered most appropriate to compare the modelled water levels against the measured water levels. Sensitivity testing to wind conditions found the model to be insensitive to the wind conditions during the model calibration period. The comparison between modelled and measured water levels at Exmouth show that the model is able to accurately replicate the amplitude and phasing of water level variations throughout a spring-neap tidal cycle.

To further quantify the level of agreement between the modelled and measured water levels a statistical analysis has been undertaken and the results are provided in Table 3-1.

The model achieves the more stringent calibration standards for coastal waters except for the RMS error, which lies just outside (0.15 m compared to the standard of 0.10 m). The RMS standard is only defined in absolute terms and so does not take account of tidal range, therefore in macrotidal settings such as the Exe this standard is much harder to achieve than in areas with smaller tides. A value of 0.15 m is equivalent to 10% of a mean neap tidal range and less than 4% of a mean spring tidal range (well within the defined equivalent relative standards) and as such it is considered that the model replicates the water levels at the Exe to an acceptable level of accuracy.

Table 3-1. Statistical comparison of modelled and measured water levels.

Site	**WL difference (m)**			**WL difference (%)**		**Phase difference (minutes)**		
	HW	***LW***	***RMS***	***HW***	***LW***	***HW***	***LW***	***All***
Exmouth	0.04	-0.06	0.15	1	-2	-9	-4	-3

Notes: Differences are modelled minus predicted/measured so that positive values indicate that the model value is high/late relative to predicted/measured

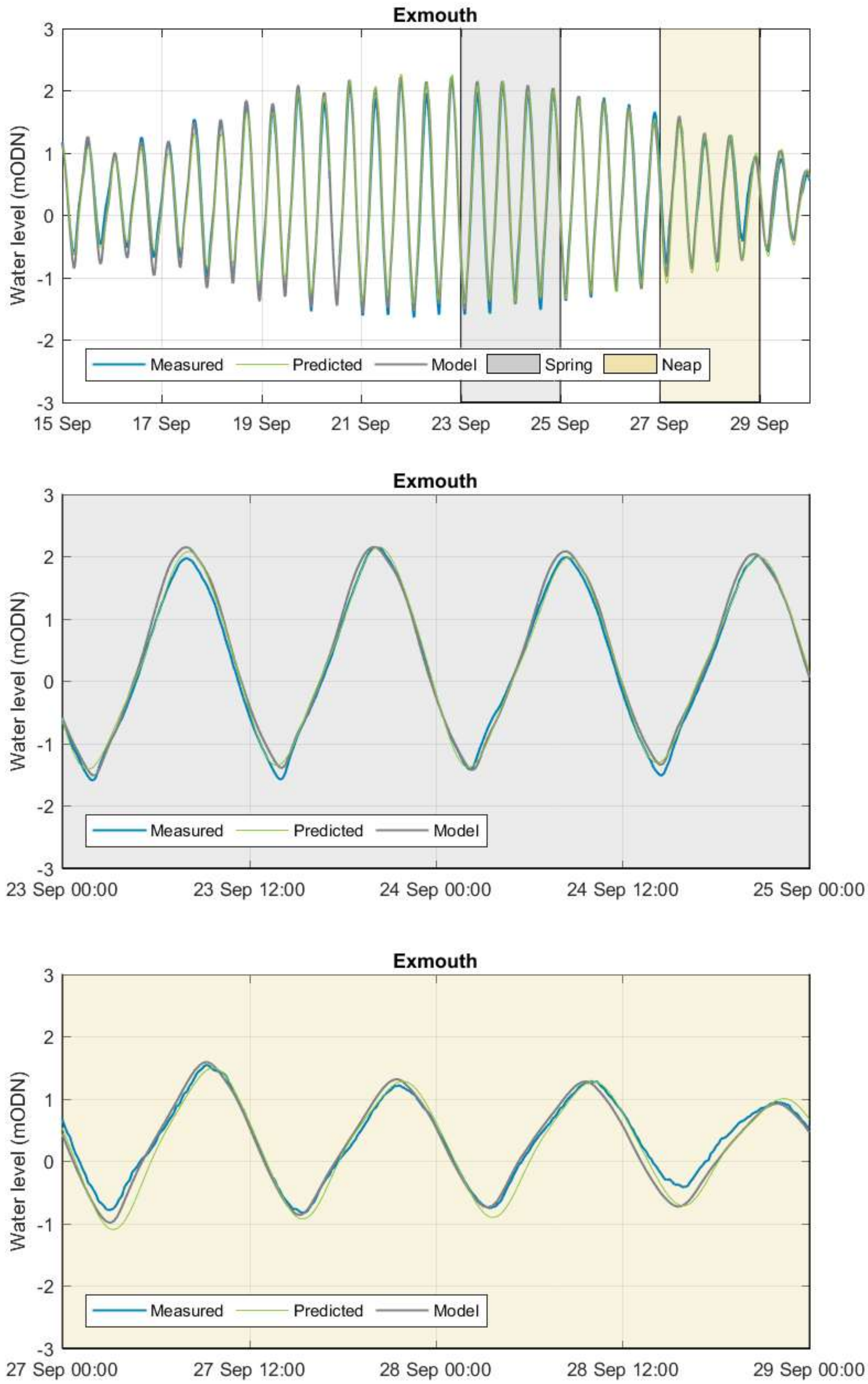


Figure 3-2. Modelled water levels at Exmouth plotted against measured and predicted data (CCO).

3.4 Modelled Flows

Before comparing modelled and measured currents at a single site, it is useful to provide an overview of the flows in the model domain to show how the flows at the measurement sites relate to the wider flow regime and to identify where the modelled and measured flows could be expected to diverge. For example, if the observation point is located within an eddy the local flows may differ significantly from those nearby and the modelled flows at a single point may not show a good comparison against measured flows. Streamline plots of the flow field have been created at the time of peak ebb and the time of peak flood (where the time of the peak is defined as the model timestep with the fastest ebb and flood flows). Plots are shown at three spatial scales, regional scale (across the model domain, Figure 3-3), local scale 1 (at the entrance to the Exe, Figure 3-4) and local scale 2 (off Straight Point, Figure 3-5). The timesteps shown for the local plots differ to those for the regional scale plots to show the peak flows locally and to enable comparison with the measured data.

The plots show the following:

- in the offshore area of Lyme Bay the peak flows occur shortly after the times of HW (when flows are westward) and LW (when flows are eastward);
- in the offshore area of Lyme Bay flows on the flood tide are slightly faster than those on the ebb;
- the fastest flows in the region occur in the entrance to the Exe;
- in the entrance to the Exe peak ebb and peak flood flows occur approximately midway between the time of high and low water;
- flood and ebb flows through the entrance to the Exe are broadly comparable, however the location where the highest flow speed occurs differs between the flooding and ebbing tide. This is because the water level is different at the time of peak ebb and peak flood (being slightly higher on the flood);
- flows are deflected around the headland at Straight Point; and
- there is a small acceleration in flows off Straight Point as a result of shallower bathymetry.

The fast flows within the entrance to the Exe drive sediment transport both into and out of the Exe Estuary as evidenced by the presence of both a flood tide delta (Bull Hill Bank) and an ebb tide delta (Pole Sand). These deltas, the spit across the entrance to the Exe ('The Warren') and the entrance channel are all areas subject to ongoing change. Since the completion of the most recent subtidal survey of the Entrance Channel area (February 2020), a notice to mariners issued on the 16 July 2021 identified an increase in area and spreading to the west of the Bull Hill Bank while a notice issued on the 20 April 2021 identified a repositioning of the buoys at the southern end of Pole Sand.

Satellite imagery captured on the 6th September 2021 around the time of low tide (when the water level was -1.26 mODN) is shown in Figure 3-6. Due to the low water level and relatively low turbidity at the time of image capture, it is possible to identify the shapes of the delta and spit. Comparison between the satellite imagery and the model bathymetry indicates that some changes have occurred at the northern end of the Warren with the seaward beach receding. It also appears that some erosion at the northern edge of Pole Sand could have occurred. In December 2020 a large wave event (with significant wave height of 5.25 m and a peak direction of 169 degrees) resulted in damage of the seawall adjacent to the entrance to Exmouth Dock. Marine sediment was noted to have been transported onto the esplanade at this time and this wave event is likely to have contributed to some of the changes observed. These changes are likely to have affected the flows within the entrance and may result in some differences between modelled and observed flows.

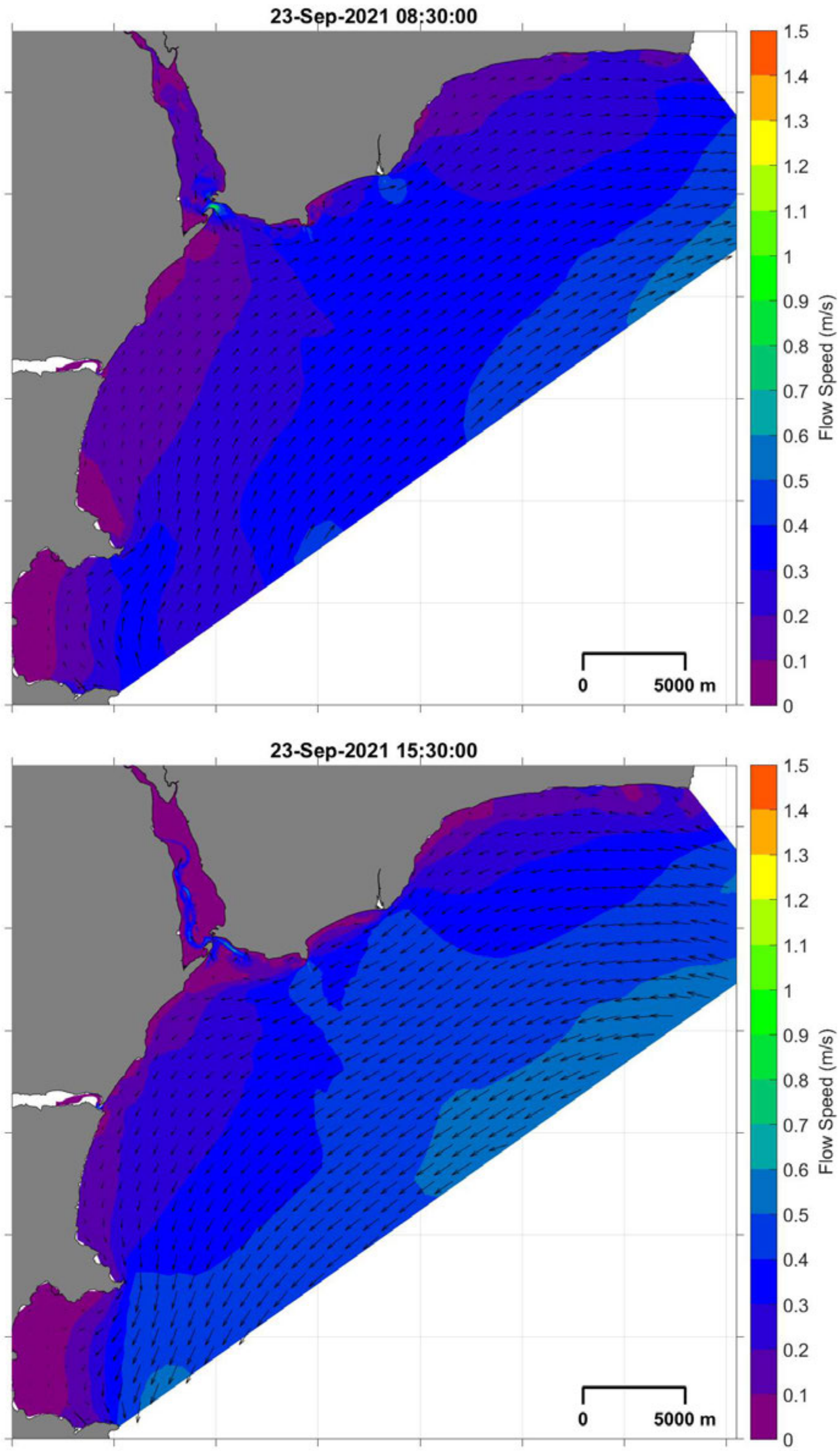


Figure 3-3. Modelled current vectors across the model domain at the time of peak ebb and peak flood on a spring tide

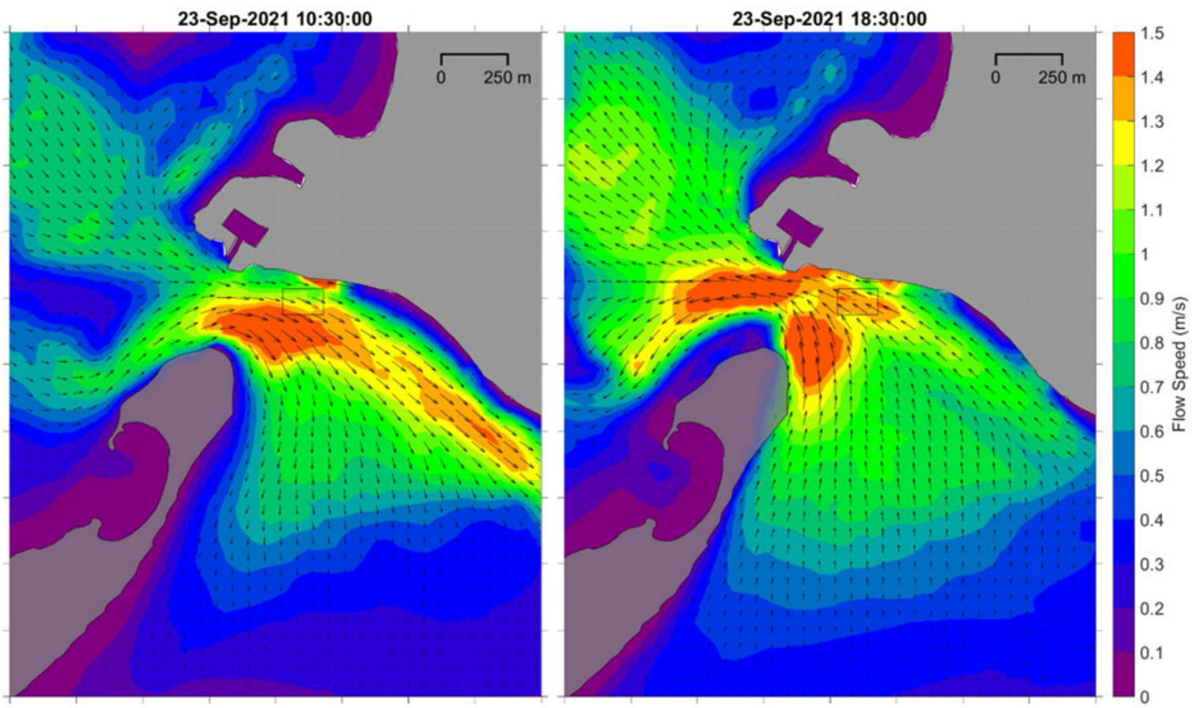


Figure 3-4. Modelled current vectors at the entrance to the Exe at the time of peak ebb and peak flood on a spring tide

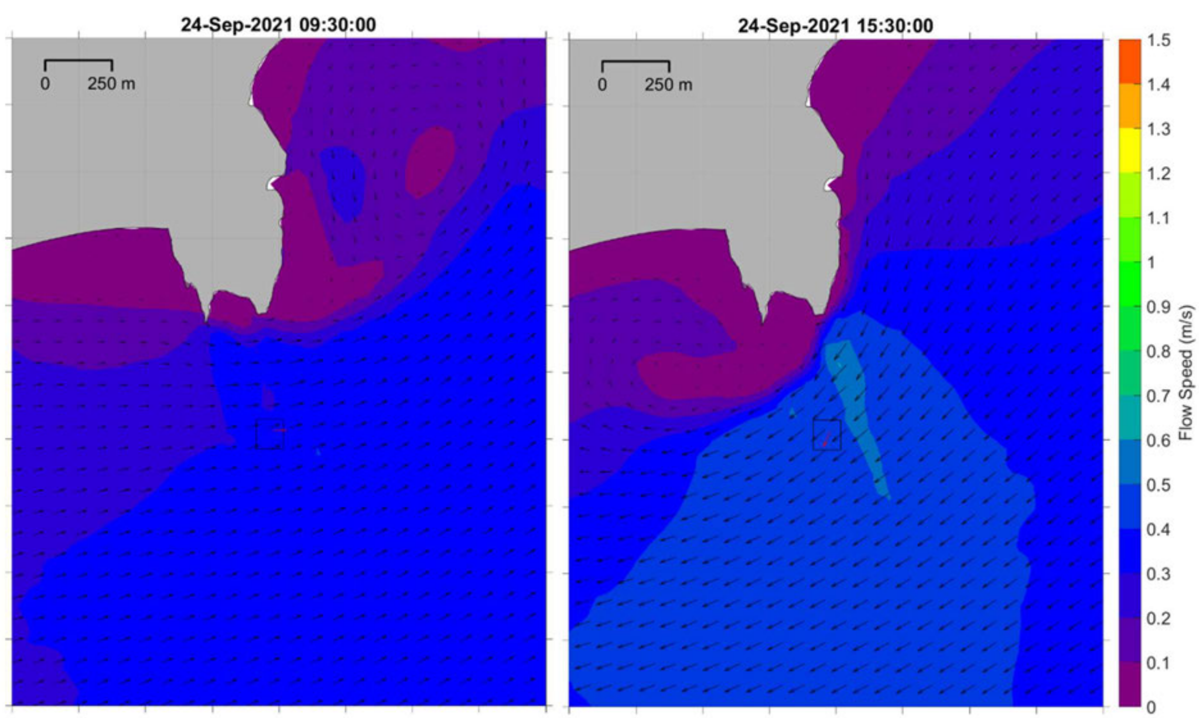
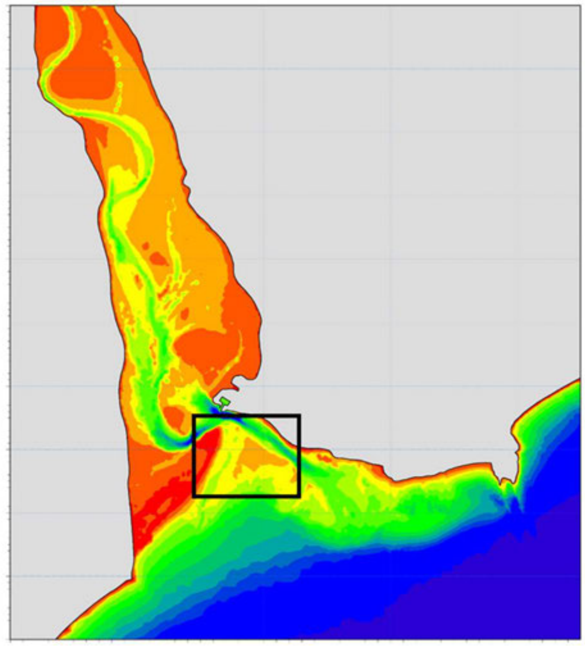


Figure 3-5. Modelled current vectors off Straight Point at the time of peak ebb and peak flood on a spring tide



Satellite data downloaded from Copernicus Open Access Hub (https://scihub.copernicus.eu/dhus/#/home) and processed using ACOLITE (Vanhellemont and Ruddick, 2016).

Figure 3-6. Sentinel 2 true colour image from 6th September 2021

Comparison between modelled and measured flows at the entrance to the Exe are shown for a spring tide and a neap tide as a timeseries in Figure 3-7 and Figure 3-8, respectively. The plots show that the model replicates the timing of the flows and general shape of the flow curves but has a tendency to slightly underestimate the peak flow speeds. Results from the statistical analysis (Table 3-2) indicates that this difference is of the order of 15% on the spring ebb tide and 17% of the neap flood tide, which is within the 10-20% relative defined standard. This difference is likely to be partially a result of changes in the bathymetry at the entrance to the Exe which occurred between the time of the bathymetric survey and the hydrodynamic measurements.

The modelled and measured flow directions show a good agreement on the ebb tide, however on the flood tide the measured flows are to the west while the modelled flows are orientated west northwest, aligned with the channel. This could be a result of changes in bathymetry (for example a deepening off the end of the Warren to the north of Pole Sand facilitating a more westward flow direction). The direction difference is outside of the standard for coastal waters but within the standard for estuarine waters and as such is considered acceptable for this study.

Comparison between modelled and measured flows off Straight Point are shown for a spring tide in Figure 3-9. The model replicates the timing and magnitude of the flows very well, but does not replicate the asymmetry in the flow directions which was observed to occur with ebb flows directed to the east and flood flows directed south southwest so that the flood and ebb directions are only 110 degrees different rather than 180 degrees as more typically occurs. The asymmetry suggests that an eddy off the headland (in the lee of the flow direction) may be influencing the flows on the food and ebb tide. While the model indicates the formation of such an eddy in the lee of the headland on both the flood and ebb tide it may be that the size of the eddy is slightly underpredicted or the location is slightly offset accounting for the differences in flow direction. As a result, the flow directions fail to meet the defined standards (being 29 degrees out on the flood and 17 degrees out on the ebb). Despite this, it is considered that the model is likely to be replicating the large scale net flow residuals (with good comparisons in modelled flows against Admiralty streamline plots). In addition, simulations with the model will provide a conservative assessment with respect to bathing water quality as it has a greater tendency to drive flows off the headland into the adjacent beaches.

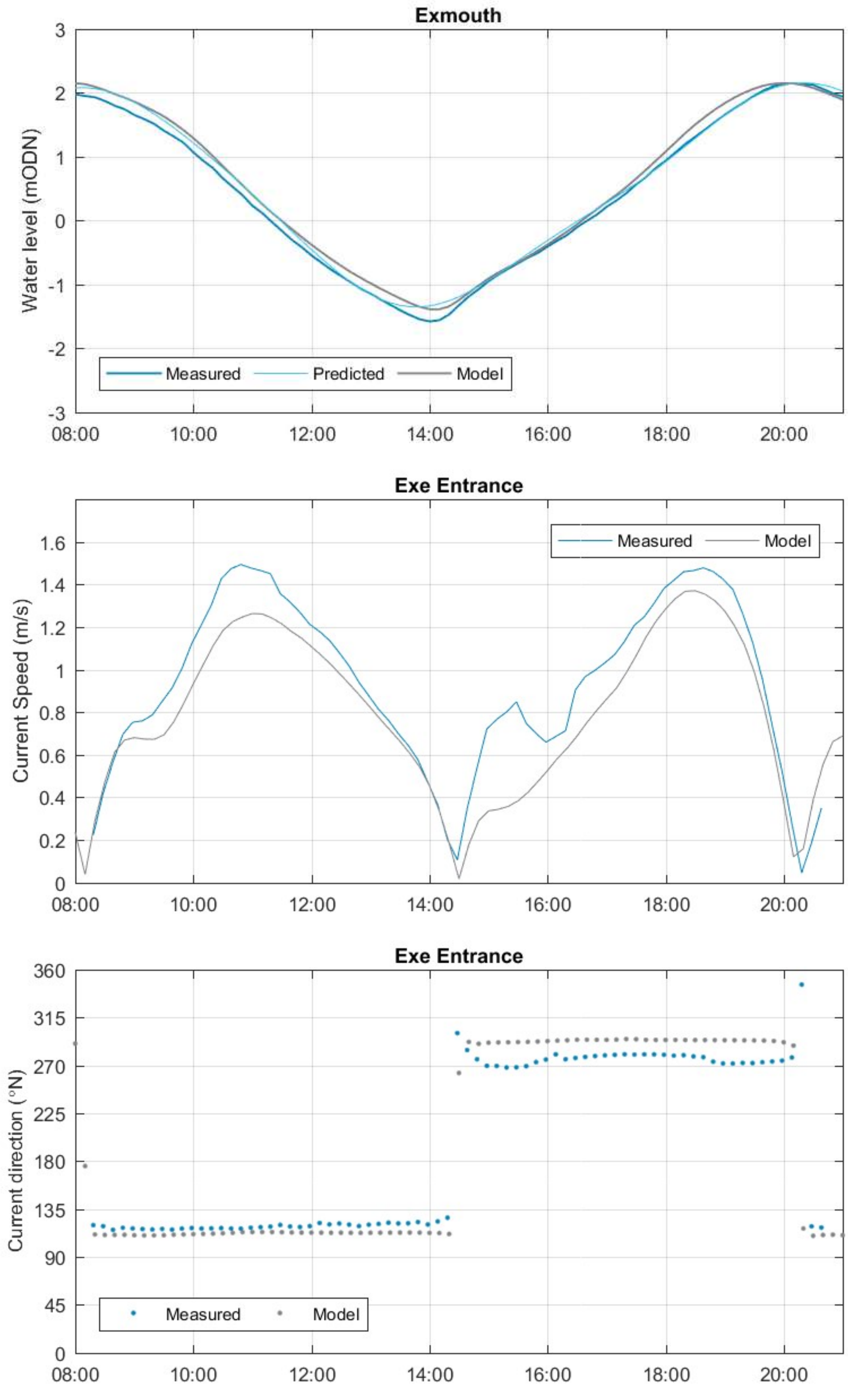


Figure 3-7. Time series of currents at the entrance to the Exe on a spring tide

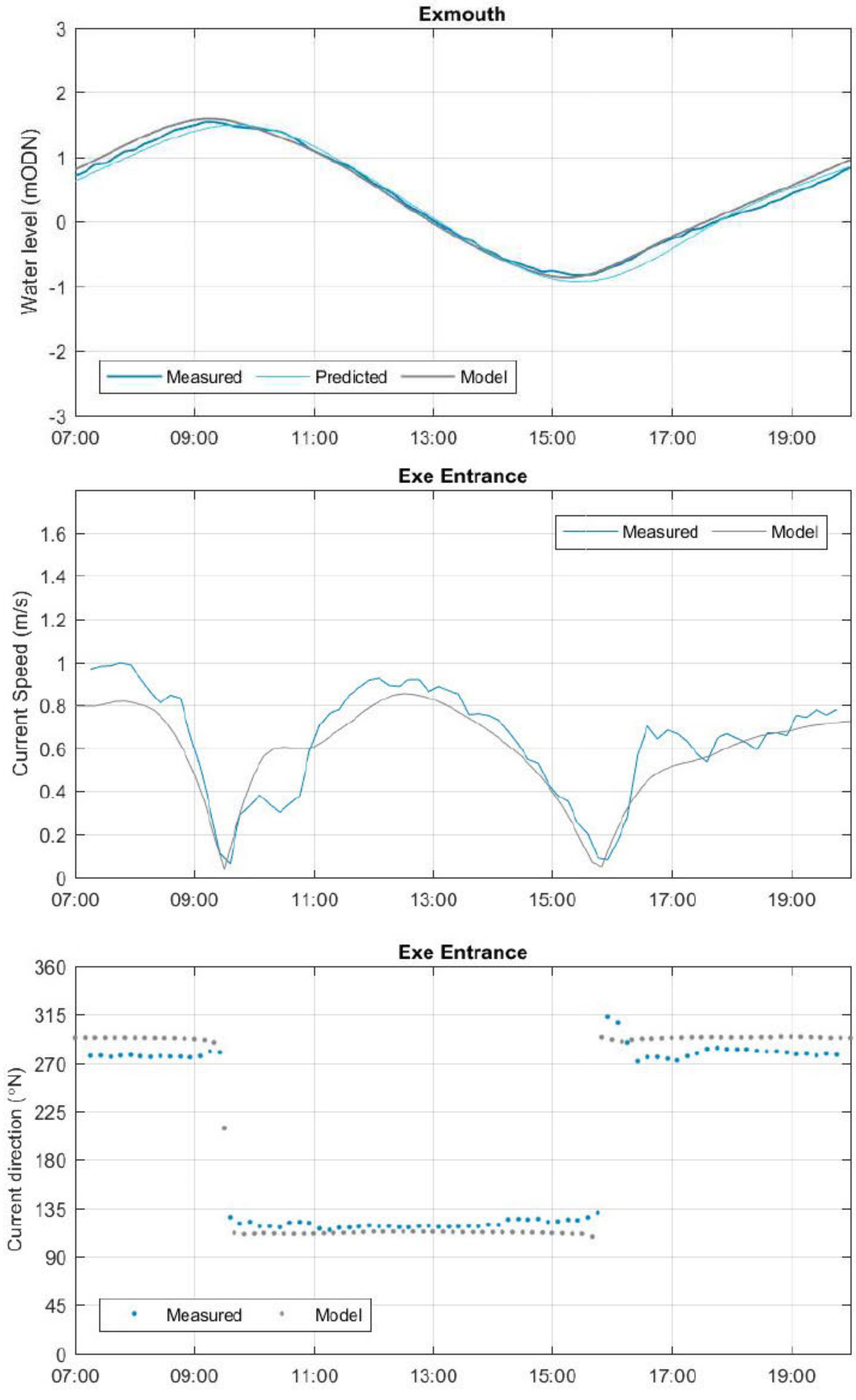


Figure 3-8. Time series of currents at the entrance to the Exe on a neap tide

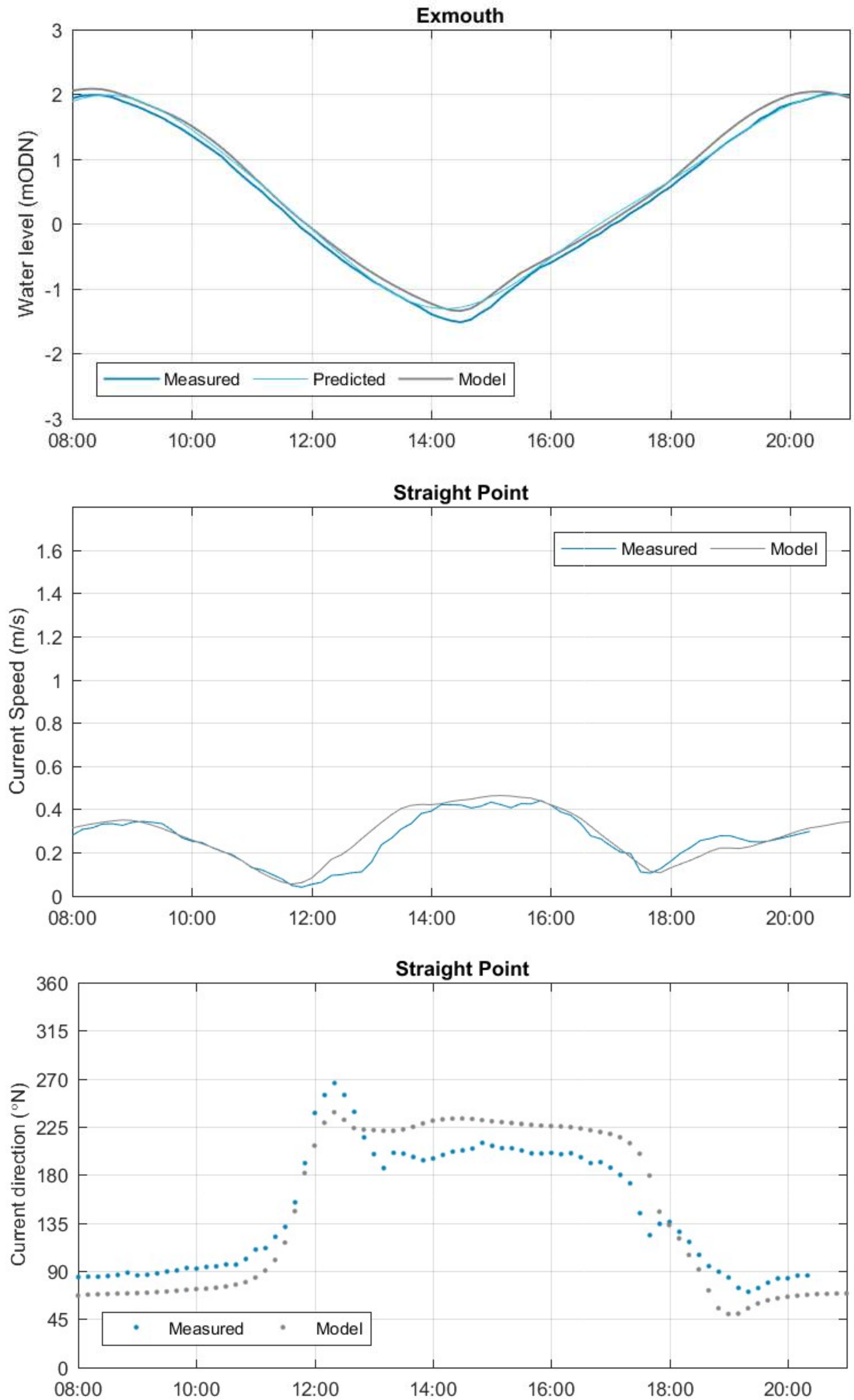


Figure 3-9. Time series of currents at Straight Point on a spring tide

Table 3-2 Statistical comparison of modelled and observed currents

Site	Speed difference (m/s)			Speed difference (%)		Direction difference (°)		Phase difference (minutes)
	PF	*PE*	*RMS*	*PF*	*PE*	*PF*	*PE*	*All*
Exe Entrance, Spring	-0.10	-0.23	0.18	-7	-15	17	-3	2
Exe Entrance, Neap	-0.17	-0.06	0.11	-17	-7	16	-5	-5
Straight Point	0.02	0.01	0.04	5	3	29	-17	-9

Notes: Differences are modelled minus predicted/measured so that positive values indicate that the model value is high/late relative to predicted/measured

3.5 Model Validation

Comparison between modelled and measured water levels at the Exmouth gauge during the March 2019 validation period are shown in Figure 3-10. The comparison shows that the model generally does a good job replicating both the magnitude and timing of the variations in tidal level. This is confirmed by the statistics (Table 3-3), which are similar to those from the calibration period and which, with the exception of the RMS error, meet the guideline calibration standards. The water levels on some days during the validation period show that the gauged levels were notably higher than the modelled water levels, particularly on the 6^{th} to 8^{th} and the 12^{th} March 2019. The predicted levels are much closer to those from the model (with an RMS error of 0.13 m) and it is likely that high river discharge and/or low pressure increased the measured water levels. The daily river discharge was above the 50% Exceedance (Q50) flow for the whole validation period and close to or above 10% Exceedance (Q10) for more than half of the validation period (NRA, 2021) including on the days noted above when gauged levels were higher than the modelled levels. This indicates that water levels at Exmouth are sensitive to river discharge during periods of high flow (and flows are also likely to be affected).

Table 3-3. Statistical comparison of modelled and predicted water levels during the model validation period.

Site	WL difference (m)			WL difference (%)		Phase difference (minutes)		
	HW	*LW*	*RMS*	*HW*	*LW*	*HW*	*LW*	*All*
Exmouth	-0.02	-0.09	0.23	-1	-3	-2	8	-2

Notes: Differences are modelled minus predicted/measured so that positive values indicate that the model value is high/late relative to predicted/measured

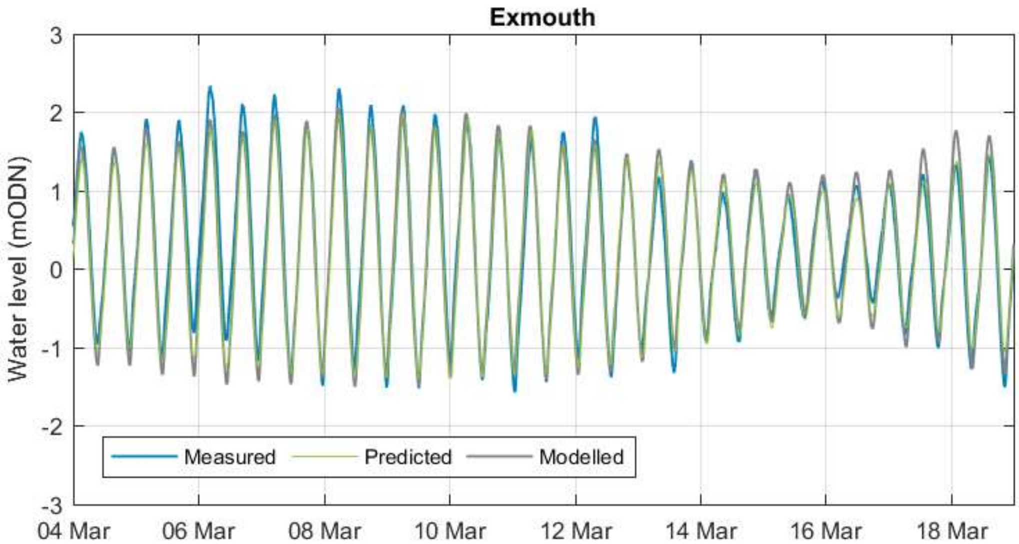


Figure 3-10. Modelled water levels at Exmouth plotted against measured and predicted data (CCO) during the model validation period

There are no measured flow data available during the validation period and modelled flows have therefore been compared against tidal diamond data. Prior to this comparison, it should be noted that the provenance of data (including data, acquisition method and weather conditions) used for tidal diamonds is unknown. Often the data is of 19th Century origin and were collected using simplistic log-and-line methods on a spring tide (range not published, but not necessarily mean spring), with simple factoring applied to provide predictions for other tidal conditions. In addition, tidal diamonds represent surface flows while the model simulates depth averaged flows. These limitations with the tidal diamond data should be considered when comparing flows against those from the model.

Time series of predicted flows from the tidal diamonds near the entrance to the Exe (SN002O) and to the south of the Warren (SN002V) are compared to modelled flows in Figure 3-11 and Figure 3-12, respectively. The plots show that there is a tidal asymmetry in flows at SN002O (with ebb flows of more than 1.5 m/s, compared to flood flows of 1.2 m/s, while at SN002V flows are very low throughout the tide (less than 0.2 m/s). The model replicates both these features and simulates the directions and timing of the tidal flows. The tidal diamond data suggest that the ebb and flood flows have a similar magnitude at SN002V while the modelled ebb flows are about half of those of the flood flows. Given the noted caveat with tidal diamond data and the fact that the flows are so slow, this discrepancy is not considered to be a cause for concern. Statistics for the comparison of modelled flows against flows from tidal diamond SN002O are provided in Table 3-4 and confirm that the model performs to within the defined metrics.

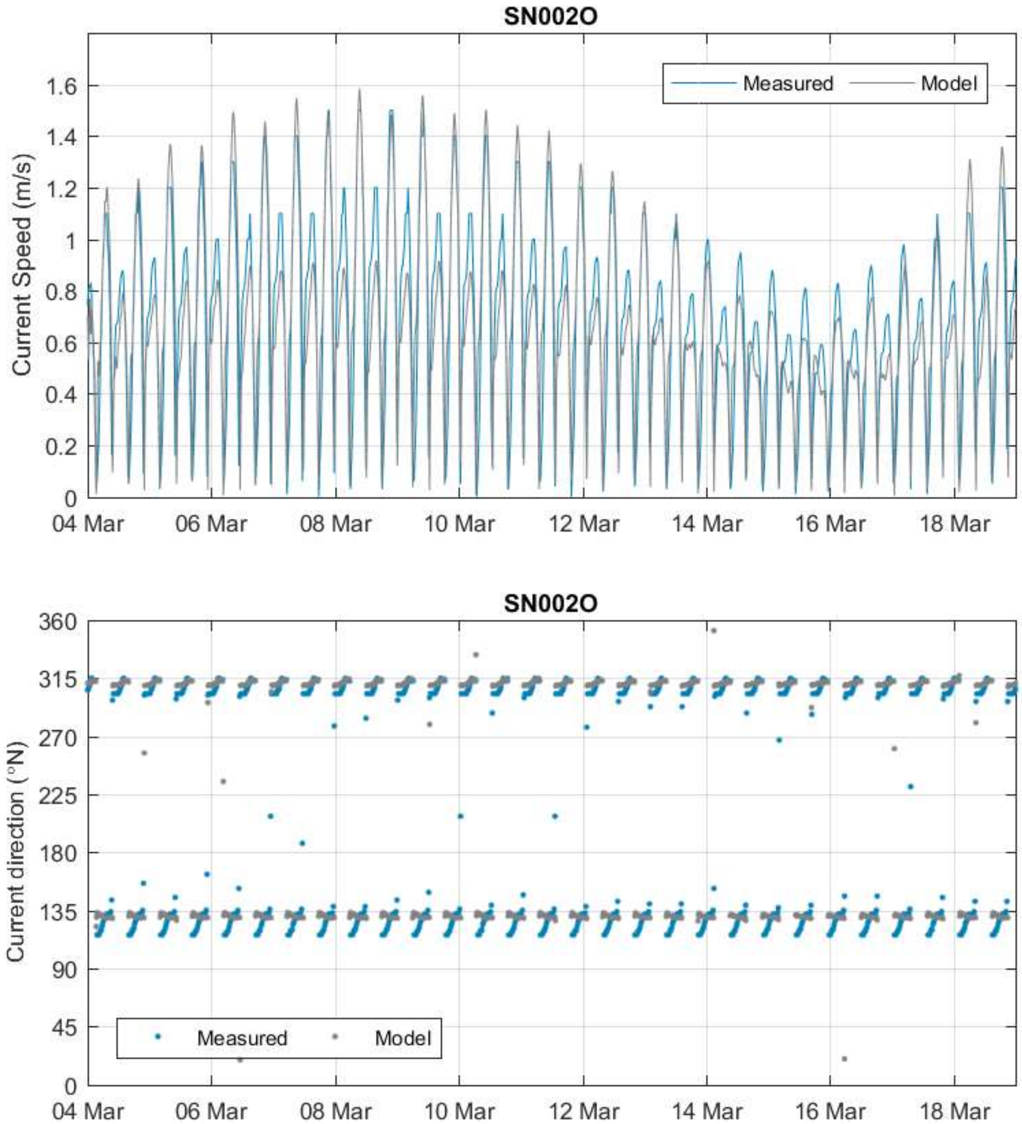


Figure 3-11. Time series of currents at SN002O for a spring-neap cycle

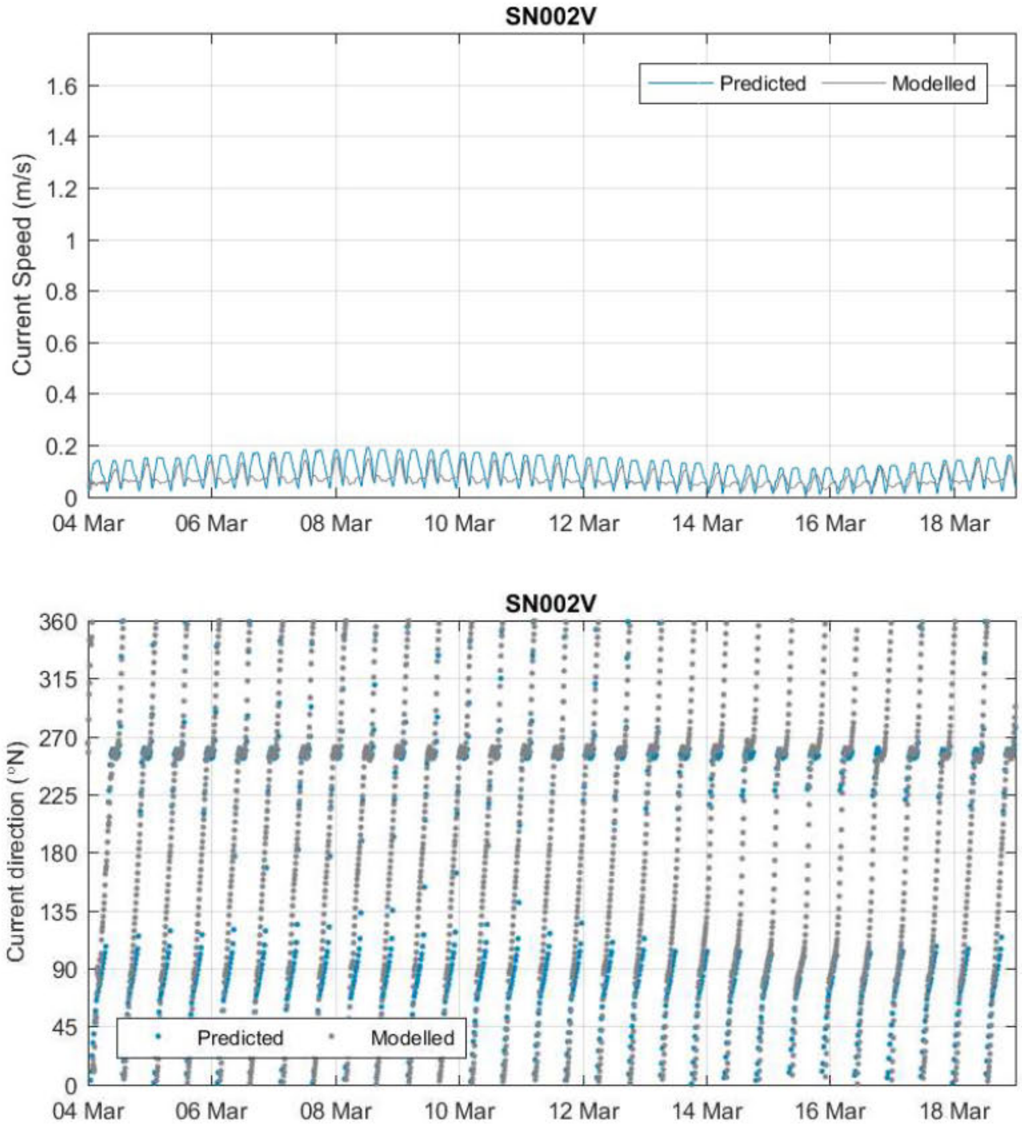


Figure 3-12. Time series of currents at SN002V for a spring-neap cycle

Table 3-4 Statistical comparison of modelled flows against Tidal Diamonds

Site	Speed difference (m/s)			Speed difference (%)		Direction difference (°)		Phase difference (minutes)
	PF	*PE*	*RMS*	*PF*	*PE*	*PF*	*PE*	*All*
SN002O	-0.15	0.03	0.16	-12	2	1	-1	3
SN002V	-0.03	-0.08	0.05	-16	-44	-3	3	13

Notes: Differences are modelled minus predicted/measured so that positive values indicate that the model value is high/late relative to predicted/measured

4 Summary

A hydrodynamic model of the Exe and western region of Lyme Bay has been configured in the MIKE21 software suite using a Flexible Mesh approach. The build has utilised numerous high resolution bathymetric datasets, with surveys over the study area being less than two years old. The model performance has been calibrated using measured data collected at the outfall locations and validated against predicted tidal diamond data. Overall, the model was found to perform well and to achieve the FRA modelling standards. The main points of note when applying the model for assessing discharges from the outfalls are:

- the water levels (and potentially currents) at the entrance to the Exe are sensitive to freshwater flows during periods of high freshwater flow (greater than Q50);
- the ebb and flood tidal delta and the Warren are areas of ongoing morphological change and changes to these features will affect flows through the entrance of the Exe. Changes to the channel have also been noted to have occurred over recent years; and
- flows off Straight Point are complex with eddies forming in the lee of the headland. While the model simulates these eddies, comparison of modelled flow directions against measured data suggest that the modelled eddies may be smaller than those which occur. As a result, the model has a tendency to drive both flood and ebb flows further inshore than observed. Despite this the model replicates the large scale flow patterns and is considered to provide a conservative tool for the assessment on bathing waters.

5 References

EMODnet Bathymetry Consortium (2020): EMODnet Digital Bathymetry (DTM). https://doi.org/10.12770/bb6a87dd-e579-4036-abe1-e649cea9881a.

FWR (1993): Framework for marine and estuarine model specification in the UK; The Foundation for Water Research (FWR).

NRA (2021): Flow data from Trews Weir (station 45007) from the National River Archive (2021). https://nrfa.ceh.ac.uk/data/station/meanflow/45007

Titan (2021): River Exe and Straight Point VMADCP, Operations Report. Titan Environmental Services Ltd, CS0608.

Vanhellemont, Q., & Ruddick, K. (2016). Acolite for Sentinel-2 : Aquatic Applications of Msi Imagery. 2016 ESA Living Planet Symposium, (May), 9–13.