



CITY OF CAPE TOWN MARINE OUTFALLS SEAWATER QUALITY MONITORING Annual Report 01

PREPARED FOR:



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1 INTRODUCTION

In 2017 the City of Cape Town (CCT) appointed the CSIR to conduct an assessment of the effects of the domestic effluent discharged from the marine outfalls located at Hout Bay, Camps Bay and Green Point on human health and the surrounding marine environment (CSIR 2017). The assessment evaluated effects on receiving water quality, sediment properties and levels of contaminants in seafood organisms at sites located adjacent to the outfalls and found there to be minimal effects directly attributable to the discharges. It was however noted that the human health and/or environmental effects of the outfalls may change over time, and so the implementation of a comprehensive monitoring programme was recommended. Following and in accordance with this after a tender process Lwandle Technologies (Pty) Ltd (Lwandle) was contracted by the CCT to conduct seasonal (winter and summer) monitoring of the three marine outfalls, for a period of three years from August 2019 to May 2022.

1.1 SCOPE OF WORK

The required scope of the monitoring as detailed in the tender documents 124S/2018/19 includes:

- weekly seawater quality monitoring (collection and analysis of seawater samples and water column profiling) at 16 prescribed nearshore sites around each of the three outfalls for a period of six weeks during winter (non-upwelling) and summer (upwelling) each year,
- weekly seawater quality monitoring of faecal indicator bacteria (collection and analysis of seawater samples) at three prescribed beach sites adjacent to each of the three outfalls over each six-week sampling season each year,
- seawater toxicity testing at two nearshore sites proximal to each of the three outfalls on alternate days over a 14-day period within each six-week sampling season each year,
- the monitoring of contaminants in the flesh of mussels suspended at 12 prescribed sites in the receiving environment at each outfall over each six-week sampling season each year,
- the deployment of an ADCP and thermistor string at one location at each of the three outfalls over one winter and one summer six-week sampling period (i.e., for one year only) to collect wave, current and temperature data for hydrodynamic model calibration, and
- three-dimensional numerical hydrodynamic modelling of plume dispersion in the receiving environment at each of the three outfalls over two periods representative of winter and summer (for one year only).

Lwandle has completed the first year of monitoring (i.e. the first two seasons). Winter (non-upwelling) sampling was conducted in September/October 2019 and summer (upwelling) sampling was conducted in February/March 2020. All data and findings from each of these monitoring periods were presented to the CCT in respective data reports (LT 839 DTR_01_V2.0 and LT 839 DTR_02_V1.0).

Following the completion of each year of monitoring, the submission of an annual report presenting and comparing all data for both seasons sampled at each of the three outfalls is required. This report fulfils this requirement and presents and compares the seasonal data collected during the first year of monitoring. Results are presented for each outfall separately in the appendices:

- APPENDIX A: Hout Bay
- APPENDIX B: Camps Bay
- APPENDIX C: Green Point

Note that an interim report was submitted in June 2020. Due to delays experienced during the COVID-19 pandemic, some laboratory results from the summer sampling season were outstanding and so were not presented in that report. The laboratory results have since been received, this report presents an update to the initial interim report and includes results for total suspended solids, total organic carbon, orthophosphate and ammonia in water samples and the concentrations of trace metals in mussel flesh.

1.2 REPORT OBJECTIVES

The objectives of the first annual report are:

- to present and compare the data collected in the winter September/October 2019 monitoring period to those collected in the summer February/March 2020 monitoring period,
- to check compliance of these data with relevant national water quality guidelines and highlight any outliers,
- to provide an assessment of the effects of the outfalls on the local marine ecology in the receiving environment outside of the presumed zone of initial dilution (ZID),
- to provide an assessment of the effects of the outfalls on human health,
- to use the data collected in this monitoring period along with results of the dispersion modelling, to determine the zones of initial dilution at each outfall and to identify instances of discharge plumes reaching the respective shorelines. If necessary, the obtained results will enable refinement of sampling site locations for the second and third year's of sampling.

2 APPROACH

The approach and sampling procedures are detailed in the PEP submitted to the CCT (LT-839 PEP V1.0) as well as in the two respective data reports (LT 839 DTR_01_V2.0 and LT 839 DTR_02_V1.0). A summary is provided in Table 2.1.

Table 2.1: Summary of the sampling approach and analyses conducted during the first year of monitoring at the Hout Bay, Camps Bay and Green Point marine outfalls on behalf of the City of Cape Town.

Work scope component	Location	Frequency	Duration of monitoring	Sampling equipment	Parameters measured	Analytical practitioner
Seawater quality	16 prescribed sites in the nearshore surrounding each of the three outfalls.	Weekly	Six weeks in winter (non-upwelling) and four ¹ weeks in summer (upwelling).	3.5 L Niskin bottle	Enterococci, total suspended solids, total organic carbon, phosphorus (measured as orthophosphate) ² , nitrogen (measured as ammonia) ²	Lwandle with analyses conducted by the CSIR
Seawater quality		Weekly	Six weeks in winter (non-upwelling) and four ¹ weeks in summer (upwelling).	Multi-parameter YSI EXO2 CTD (measuring at a frequency of 4 Hz)	Temperature, conductivity, turbidity ³ , pH, dissolved oxygen	Lwandle
Seawater quality	3 prescribed sites at beaches inshore and adjacent to each of the three outfalls.	Weekly	Six weeks in winter (non-upwelling) and four ¹ weeks in summer (upwelling).	5 L bucket or sampling bottle	Enterococci ⁴	Lwandle with analyses conducted by the CSIR
Seawater toxicity	Two sites in the nearshore surrounding each of the three outfalls	Alternate days	Two ⁵ weeks that align with the winter (non-upwelling) and summer (upwelling) monitoring periods.	Sampling bottle	Toxicity of water samples to sea urchins.	Lwandle with analyses conducted by the CSIR
Trace metal contaminants in bivalve flesh ⁶	12 prescribed nearshore sites in the receiving environment surrounding each of the outfalls.	NA	Mussels suspended at sites for duration of six-week sampling period in winter (non-upwelling) and summer (upwelling).	20 <i>Mytilus galloprovincialis</i> in a mesh bag suspended on moorings at each site	Mussel growth Trace metal (Zn, Cu, Ni) concentration in flesh	Anchor Environmental Consultants with analyses conducted by the CSIR
ADCP and thermistor string deployment for model calibration	One nearshore site at each of the three outfalls.	NA	Mooring deployed for duration of six-week ⁷ sampling period in winter (non-upwelling) and summer (upwelling) for one year only.	Upward facing TRDI 600 kHz ADCP, thermistor string consisting of five Tidbit temperature loggers secured at defined depths.	Currents, waves, temperature	Lwandle
Numerical hydrodynamic modelling ⁸	In the vicinity of the discharge point at each of the three outfalls.	NA	Plume dispersion simulated over two periods, representative of winter and summer. Modelling study to be conducted in first year of monitoring only.	NA	Model outputs: <i>E. coli</i> , enterococci, TSS and a conservative tracer in each horizontal and vertical element of the computational mesh at 1-hour intervals throughout the simulation period.	PRDW
Notes: 1. Summer sampling was stopped two weeks earlier than anticipated due to the implementation of the country-wide lockdown as a result of the COVID-19 pandemic. 2. Analyses for phosphorous and nitrogen were not completed during the winter sampling period due to difficulties at the contracted laboratory. 3. Erroneous turbidity data was obtained during the summer survey, and so while turbidity profiles are presented in the respective data reports, they are not reported on here. 4. Enterococci are the preferred bacterial indicator for coastal waters as they are more persistent than other indicators such as <i>E. coli</i> (Jin et al. 2004). 5. Summer toxicity sampling was only conducted over a period of four days due to the COVID-19 outbreak. 6. The ecological monitoring of mussel flesh was conducted by a third-party subcontractor. The results are referred to, and their detailed presentation is included in APPENDIX D. 7. During the summer sampling period mooring retrieval could not take place due to the COVID-19 outbreak and so deployment and measurement periods at all three outfalls were longer than six weeks. 8. The numerical modelling was conducted by a third-party subcontractor. The results of the modelling studies are referred to, with an in-depth description of the models run at each of the three outfalls presented in APPENDICES E, F and G.						

3 WATER QUALITY GUIDELINES

The water quality guidelines applied in this monitoring programme are summarised in Table 3.1. They are derived from the South African Water Quality Guidelines for Coastal Waters Volume 1: Natural Environment (Department of Water Affairs and Forestry (DWAF) 1995) and Volume 2: Recreational Use (Department of Environmental Affairs (DEA) 2012)

An update to the 1995 guidelines has been recommended to ensure alignment with current international practices (Department of Environmental Affairs (DEA) 2018). It was recommended that guideline values should be derived from a site-specific reference system (i.e., obtained from a reference site) which should be determined as the range defined by the 20th and 80th percentiles of the seasonal distribution of a given parameter. These guidelines have not yet been gazetted, but are applied here to salinity, pH, dissolved oxygen, total suspended solids and phosphorus.

Table 3.1: South African Water Quality Guidelines applicable to the receiving marine environment surrounding the three City of Cape Town marine outfalls at Hout Bay, Camps Bay and Green Point.

Constituent	Recommended Guideline	Reference
Salinity	Median salinity should range between the 20 th and 80 th percentiles of a site and season specific reference dataset.	DEA (2018)
pH	Median pH should range between the 20 th and 80 th percentiles of a site and season specific reference dataset.	DEA (2018)
Dissolved oxygen	Median dissolved oxygen should not fall below the 20 th percentile of a site and season specific reference dataset.	DEA (2018)
Enterococci	90 th percentile $\leq$ 185 cfu/100 mL	DEA (2012)
Total suspended solids	Median concentration should not exceed the 80 th percentile of a site and season specific reference dataset.	DEA (2018)
Phosphorus (as orthophosphate)	Median concentration should not exceed the 80 th percentile of a site and season specific reference dataset.	DEA (2018)
Nitrogen (as ammonium)	$\leq$ 600 μ g/L	DWAF (1995)

For the application of the DEA (2018) guidelines, one reference site at each outfall was selected according to their locations offshore of each of the outfalls and predominant current directions. To increase the number of sample points, reference sites were grouped and the obtained guideline statistics (the 20th and 80th percentiles) were applied at all three outfalls. The justification for this is that oceanographic processes on the south west coast of South Africa generally occur at the mesoscale (10-100 km) and thus similar salinity, pH and dissolved oxygen ranges are expected to occur at Hout Bay, Camps Bay and Green Point. With continued monitoring, and increased sample numbers at each site, the grouping of reference sites will be re-examined.

Percentile values were calculated over six sampling weeks in winter and four sampling weeks in summer. Salinity, pH and dissolved oxygen data were collected from water column profiles. For the analyses of compliance of these variables to water quality guidelines, profile data were grouped

into surface (0 – 5 m), mid (5 – 15 m) and bottom (>15 m) depths. For the analyses of compliance of total suspended solids and phosphorus to water quality guidelines, laboratory results for reference sites were also grouped into surface, mid and bottom depths.

The guideline values applied are detailed in Table 3.2 below.

Table 3.2: 20th and 80th percentiles of water quality constituents obtained from three reference sites offshore the Hout Bay, Camps Bay and Green Point outfalls. Percentile ranges are applied as guidelines to the relevant constituents as described in DEA (2018).

Constituent	Percentile	Depth		
		Surface (0-5 m)	Mid-depth (5-15 m)	Bottom (>15 m)
Winter				
n (profiles)		170	353	297
Salinity (psu)	20 th	34.94	34.89	34.79
	80 th	35.19	35.14	35.06
pH	20 th	8.17	8.15	8.11
	80 th	8.43	8.39	8.36
Dissolved oxygen (mg/L)	20 th	7.99	7.35	6.08
n (laboratory analyses)		18	18	18
Total suspended solids (mg/L)	80 th	6	8	9
Orthophosphate (µg/L)	80 th	-	-	-
Summer				
n (profiles)		116	234	210
Salinity (psu)	20 th	34.82	34.82	34.82
	80 th	34.90	34.88	34.86
pH	20 th	7.98	7.93	7.88
	80 th	8.25	8.10	7.98
Dissolved oxygen (mg/L)	20 th	5.92	5.05	2.84
n (laboratory analyses)		12	12	12
Total suspended solids (mg/L)	80 th	6	4	5
Orthophosphate (µg/L)	80 th	63	69	71

4 APPENDIX A: HOUT BAY

4.1 DESCRIPTION OF THE OUTFALL

The Hout Bay outfall was commissioned in 1993 and is located on the western side of Hout Bay. The pump station is located approximately 260 m to the south of Hout Bay harbour. The outfall extends in an easterly direction from the shoreline and then doglegs to the southwest. Effluent is discharged approximately 800 m from the rocky headlands on the western side of the bay and 2.5 km from the main swimming beach (Figure 4.1 and Figure 4.2). The diffuser is located at a depth of 37 m.

4.2 SAMPLING LOCATIONS

Figure 4.1 and Figure 4.2 shows the Hout Bay outfall, and locations of the respective sampling and measurement sites during each week of sampling in the winter (August-September 2019) and summer (February-March 2020) monitoring periods. For the purposes of the initial survey design, the CCT estimated the zone of initial dilution (ZID) at the Hout Bay outfall to be within a 272 m radius from the diffusers. This is included on the plots below.

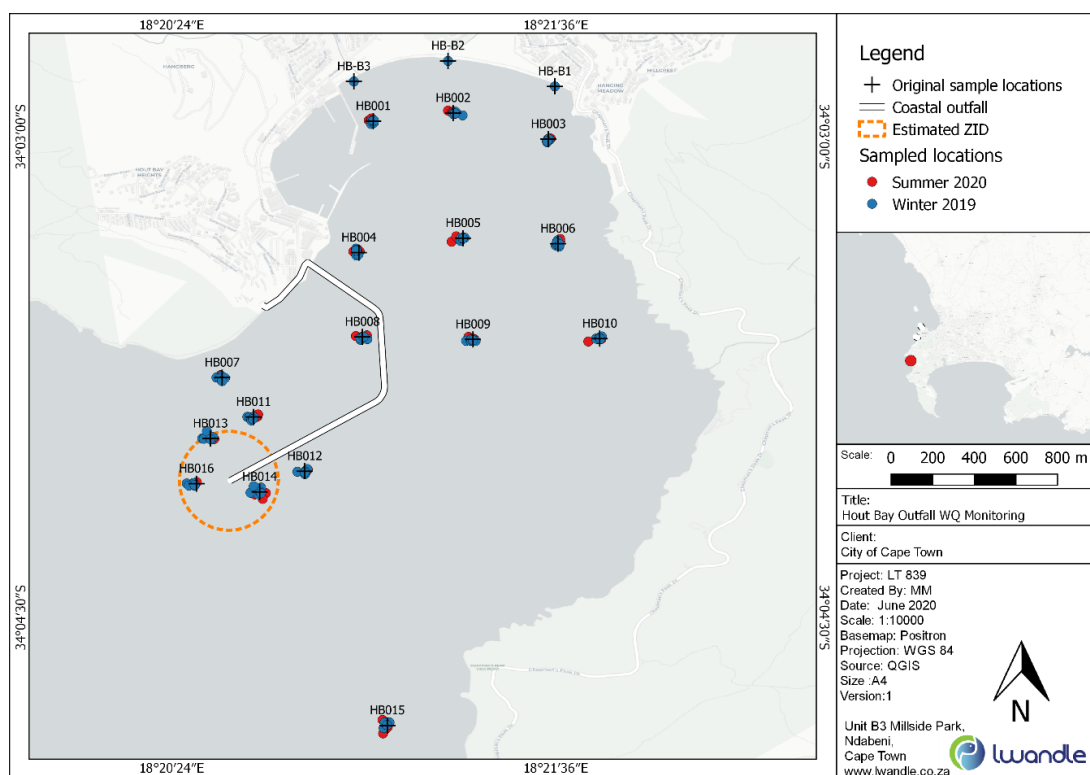


Figure 4.1: Map showing the Hout Bay outfall and the locations of nearshore and beach (HB-B1, HB-B2 and HB-B3) sites sampled during the winter (August-October 2019) and the summer (February-March 2020) monitoring periods.

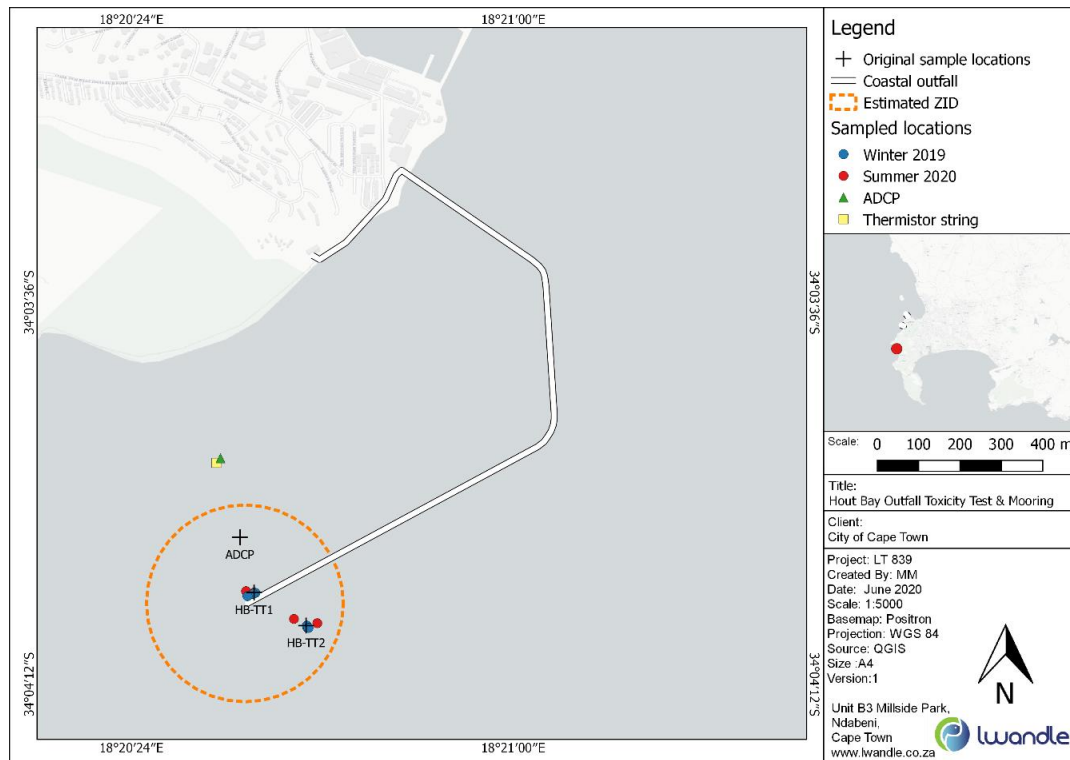


Figure 4.2: Map showing the Hout Bay outfall and the locations of the sites sampled for toxicity testing during the winter (August-October 2019) and the summer (February-March 2020) monitoring periods. The locations of the ADCP and thermistor strings are also shown.

4.3 CURRENTS AND WAVES

The currents at all depths at the ADCP mooring site in Hout Bay primarily flowed in an east-north-easterly direction for the winter deployment period (Figure 4.3). Less frequent west-south-westerly currents were also recorded at all depths. Current speeds generally ranged between 0-0.4 m/s with increasing speed and variation in direction towards the surface. During the summer deployment period, surface currents flowed in a north-easterly and west-south-westerly direction, the former being slightly dominant in frequency (Figure 4.4). The variation in the direction decreased with depth and primarily east-north-easterly and easterly currents were recorded deeper in the water column. Similar to winter, current speeds generally ranged between 0-4 m/s with decreasing speed and variation with depth. There were no indications in either of the current measurement periods of significant flows in the north-east to north direction sector which would be into the bay. However, surface layer flows in summer shows that such can occur (Figure 4.4).

Hout Bay outfall received waves primarily from the south-west during the winter and summer deployment (Figure 4.5 and Figure 4.6). The average peak period mainly ranged between 11-14 seconds during winter and summer.

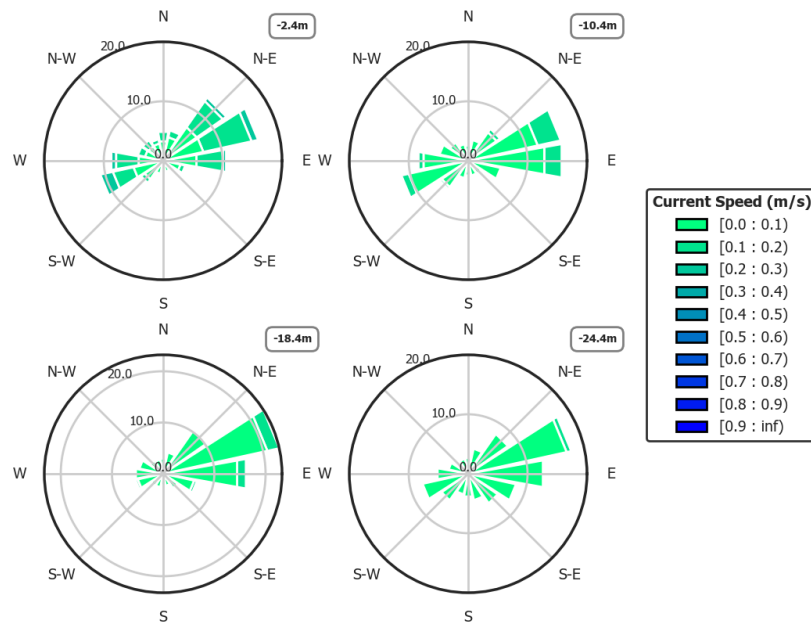


Figure 4.3: Current roses showing average observed speeds and directions throughout the water column from the ADCP moored at the Hout Bay outfall from 22nd August 2019 to 2nd October 2019 (winter).

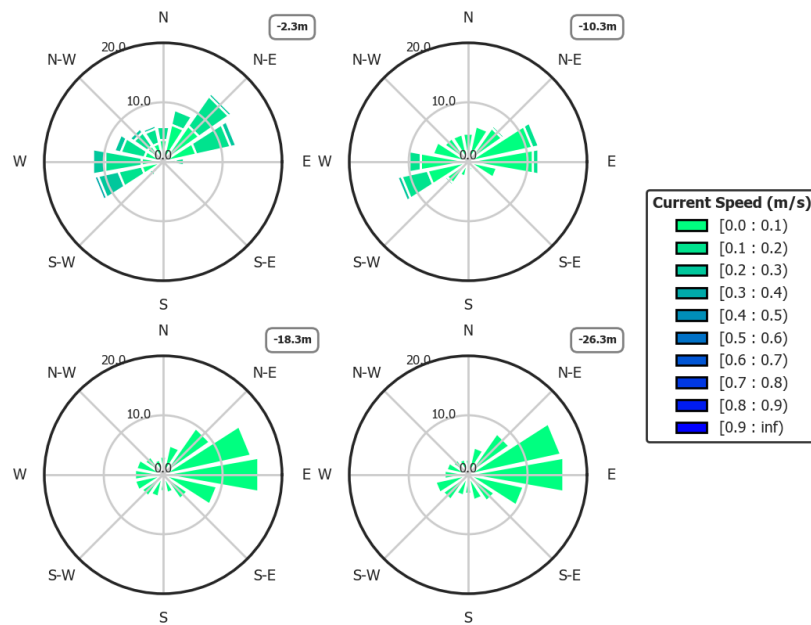


Figure 4.4: Current roses showing average observed speeds and directions throughout the water column from the ADCP moored at the Hout Bay outfall from 13th February 2020 to 27th April 2020 (summer).

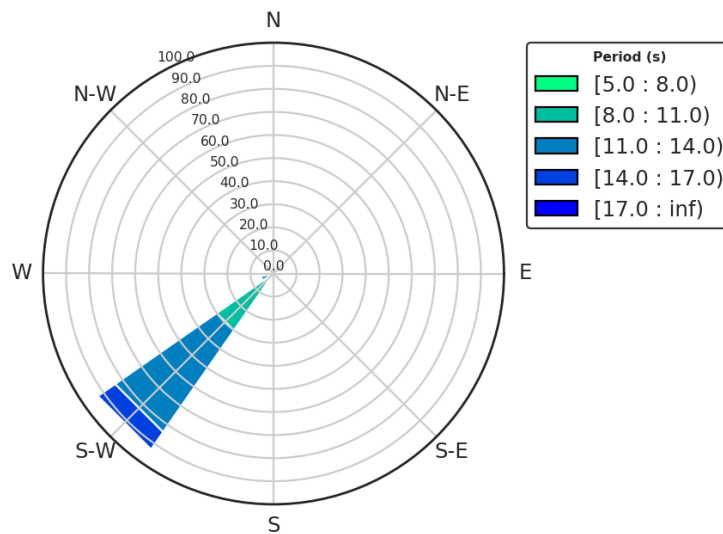


Figure 4.5: Wave rose showing average observed periods and directions from the ADCP moored at the Hout Bay outfall from 22nd August 2019 to 2nd October 2019 (winter).

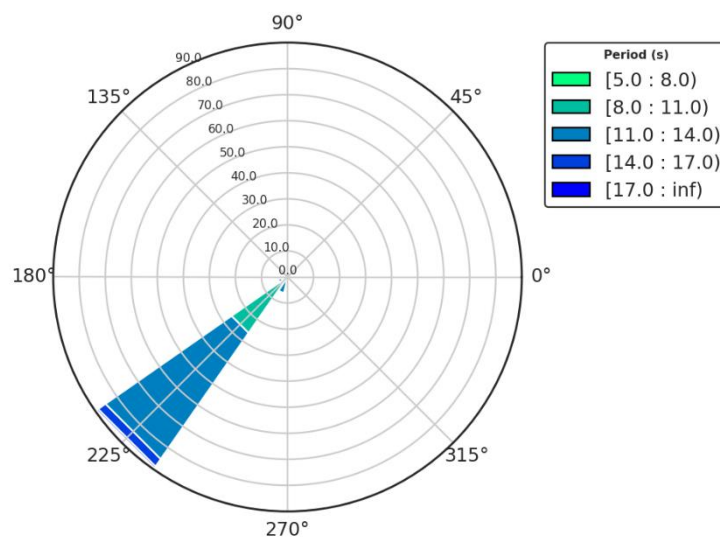


Figure 4.6: Wave rose showing average observed periods and directions from the ADCP moored at the Hout Bay outfall from 13th February 2020 to 27th April 2020 (summer).

4.4 NEARSHORE WATER COLUMN CHARACTERISTICS

The surface, middle and bottom depth values recorded seasonally at the Hout Bay outfall sampling sites for each measured water quality constituent (extracted from CTD data) are presented in the plots below. Parameters are also compared to relevant guidelines where appropriate.

4.4.1 Temperature

The water column temperatures recorded during the summer survey were generally cooler than those measured during winter (Figure 4.7). This is characteristic of the seasonal upwelling in the region. Water column temperatures ranged between 9.31 and 16.61°C in the winter survey and were between 9.47 and 13.31°C during summer, which are within the expected range for the region. The winter survey had a greater range of temperatures measured at all depths and higher inter-week variation in comparison to the summer survey.

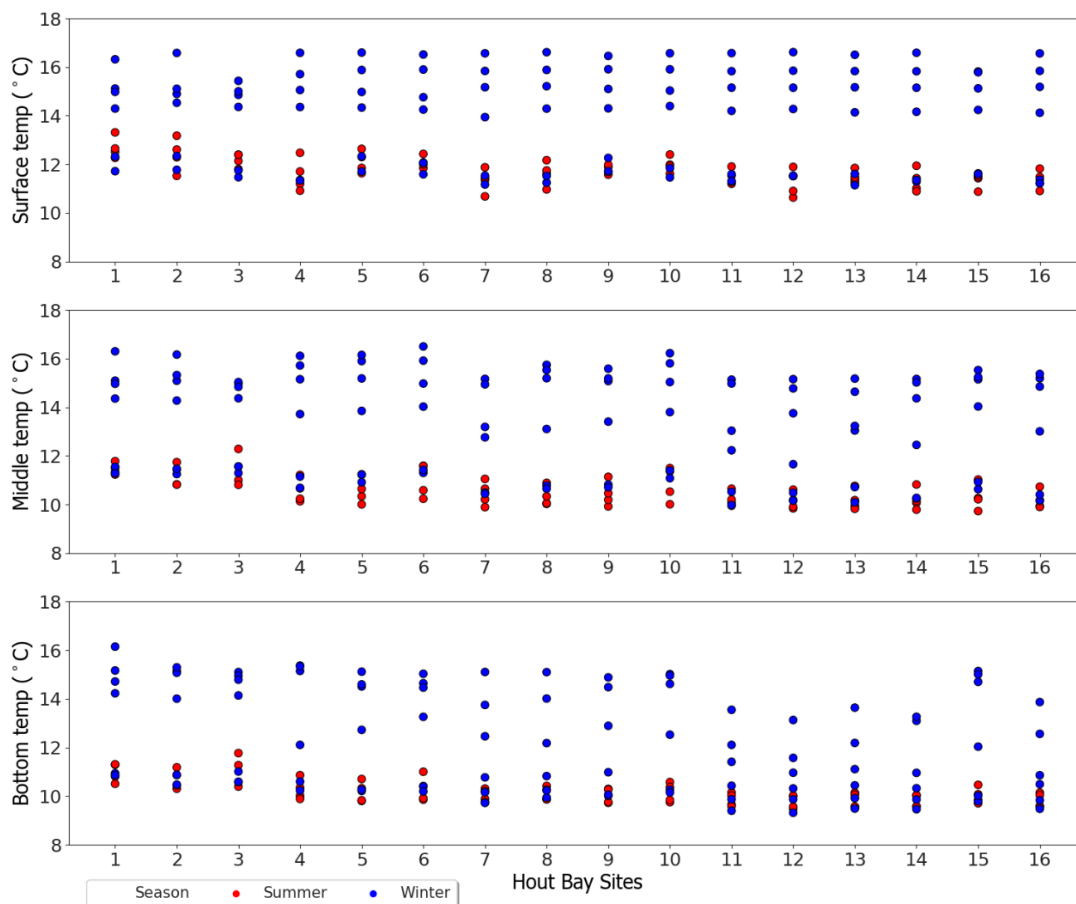


Figure 4.7: Seasonal distribution of temperature (°C) measured at the Hout Bay outfall sites during the 2019 winter and 2020 summer surveys.

4.4.2 Salinity

The recorded salinities had a similar seasonal pattern to temperature with lower salinities generally recorded in the summer, although there were periods where salinities in the winter were lower than those measured in summer (Figure 4.8). Salinities ranged between 34.37 and 35.42 PSU and 34.54 and 34.98 PSU in the winter and summer respectively. The winter survey also had a greater range of salinities measured at all depths and higher inter-week variation in comparison to the summer survey.

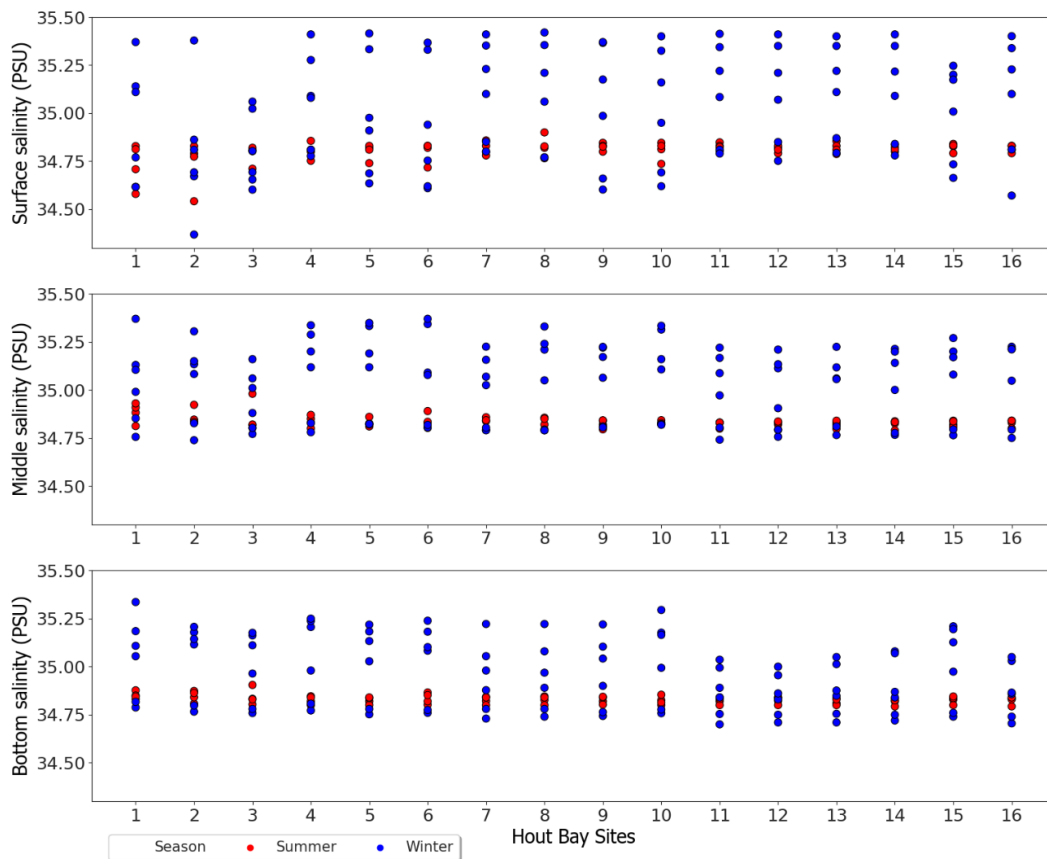


Figure 4.8: Seasonal distribution of salinity (PSU) measured at the Hout Bay outfall sites during the 2019 winter and 2020 summer surveys.

Measured salinity values were compliant with the DWAF (1995) stipulated guideline range (33-36 PSU) during the winter and summer monitoring periods. In the nearfield of the discharge, represented by measurements from stations HB7, HB8, HB9, HB11, HB12, HB13, HB14 and HB16, compliance was also met with the median values in each of the surface (0 – 5 m), mid (5 – 15 m) and bottom (>15 m) depth zones falling into the ranges defined in Table 3.2 (Table 4.1). For this determination nearfield sites were grouped to increase replication but with further monitoring and sample collection, this approach will be re-examined and where possible, site-specific comparisons to guidelines will be made.

Table 4.1: Median salinity values (PSU) in surface (0-5 m), mid (5 – 15 m) and bottom (>15 m) waters measured at nearfield sites surrounding the Hout Bay outfall.

	Depth		
	Surface	Mid	Bottom
Winter			
n	457	937	891
Median	35.11	35.10	34.89
Summer			
n	313	629	627
Median	34.83	34.83	34.83

4.4.3 Turbidity

Turbidity values measured during the 2020 summer survey were considered to be erroneous due to sensor malfunction and so are not included in this report. Profiles were presented in the 2020 summer data report (LT-839 DTR_02_V3) to understand relative patterns and showed that the turbidity profiles at most sites were uniform with depth. This is similar to the winter survey (LT-839 DTR_01_V2) with the exception of a few sites, mainly those closer to shore. The turbidity values recorded during the winter survey ranged between 0.42 and 7.75 FNU. Turbidity was generally increased at bottom depths, presumably due to the suspension of sediment.

4.4.4 pH

Similar to temperature and salinity, pH levels measured during the summer survey were notably lower than those measured during the winter survey (Figure 4.9). pH ranged between 8.00 and 8.39 in the winter and between 7.84 and 8.10 in the summer with higher inter-week variation at all sites observed in the winter. These seasonal patterns observed are consistent with temperature as cooler waters generally have a lower pH due to capacity to hold higher pCO₂ levels.

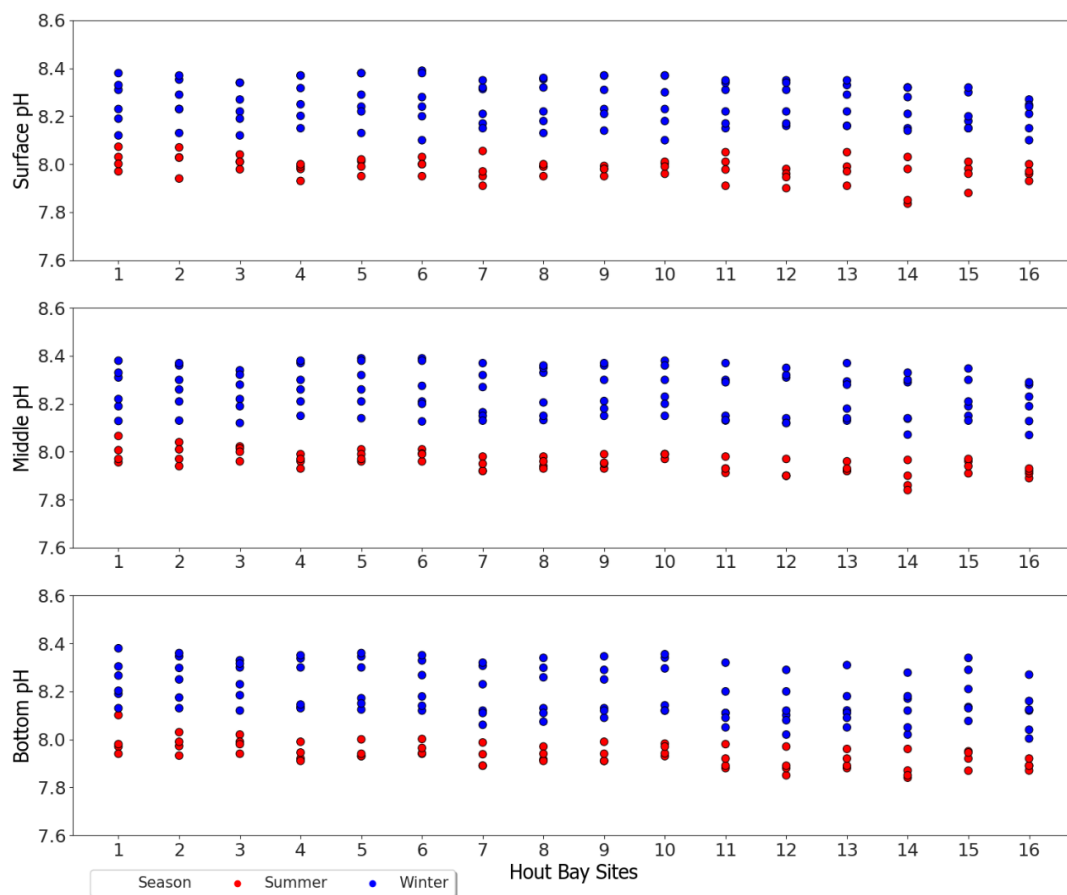


Figure 4.9: Seasonal distribution of pH measured at the Hout Bay outfall sites during the 2019 winter and 2020 summer surveys.

pH values at all depths in the nearfield water body, represented by measurements from stations HB7, HB8, HB9, HB11, HB12, HB13, HB14 and HB16, were compliant with the stipulated guidelines during the winter monitoring period with the median values in each of the surface (0 – 5 m), mid (5 – 15 m) and bottom (>15 m) depth zones falling into the ranges defined in Table 3.2 (Table 4.2). However, during summer the surface pH at sites in the nearfield water body was slightly lower than the guideline range but was compliant with the DWAF (1995) stipulated guideline range (7.30 – 8.20). For this determination nearfield sites were grouped to increase replication but with further monitoring and sample collection, this approach will be re-examined and where possible, site-specific comparisons to guidelines will be made.

It must be noted that the pH values recorded at all Hout Bay sites, particularly during winter are high, and many occur outside the range (7.6 – 8.1) previously recorded for the area (DEA 2015). Because high values occurred at all sites and all depths, the high pH values may be a result of instrument error, even though standard calibration procedures are conducted prior to each survey. Continued measurement of pH in future surveys will assist in establishing whether this is the case. pH measurements during the first year of monitoring should thus be considered relative. Nevertheless, relatively elevated pH (>8) indicates the presence of a mainly oxic water column

which suggests minimal remineralisation of organically rich sediments and probably no build-up of sewage effluent particulate matter in area of measurement.

Table 4.2: Median pH values in surface (0-5 m), mid (5 – 15 m) and bottom (>15 m) waters measured at nearfield sites surrounding the Hout Bay outfall. Median values outside of the guideline range defined in Table 3.2 are highlighted in bold.

	Depth		
	Surface	Mid	Bottom
Winter			
n	457	937	891
Median	8.23	8.23	8.13
Summer			
n	313	629	627
Median	7.96	7.94	7.90

4.4.5 Dissolved Oxygen

Dissolved oxygen concentrations measured at the Hout Bay outfall were generally lower in summer compared to winter and ranged between 6.03 and 9.76 mg/L and 3.41 and 9.06 mg/L in the winter and summer respectively (Figure 4.10). The lowest concentrations were recorded the bottom during the summer survey specifically at sites HB11 to HB14 and HB16. The recorded temperatures at some of these sites during summer were low (<10°C), indicating that the dissolved oxygen concentrations recorded may be as a result of upwelling processes in the area drawing water from deeper intermediate waters.

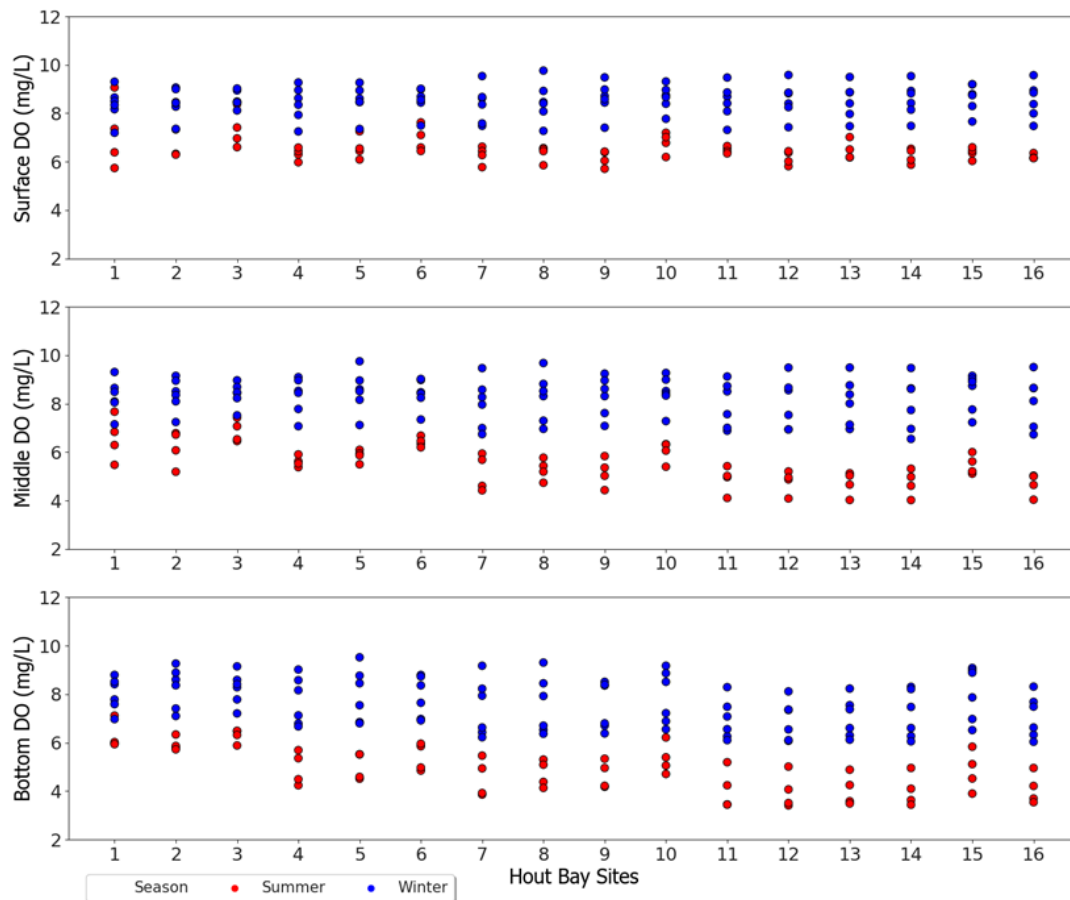


Figure 4.10: Seasonal distribution of dissolved oxygen (mg/L) measured at the Hout Bay outfall sites during the 2019 winter and 2020 summer surveys.

Dissolved oxygen concentrations at all depths in the nearfield water body, represented by measurements from stations HB7, HB8, HB9, HB11, HB12, HB13, HB14 and HB16, were compliant with the stipulated guidelines during both the winter and summer monitoring periods. During both monitoring periods, median values in each of the surface (0 – 5 m), mid (5 – 15 m) and bottom (>15 m) depth zones fell into the ranges defined in Table 3.2 (Table 4.3) and indicate an oxic water body at all depths in the immediate vicinity surrounding the outfall. For this determination nearfield sites were grouped to increase replication but with further monitoring and sample collection, this approach will be re-examined and where possible, site-specific comparisons to guidelines will be made.

Table 4.3: Median dissolved oxygen concentrations (mg/L) in surface (0-5 m), mid (5 – 15 m) and bottom (>15 m) waters measured at nearfield sites surrounding the Hout Bay outfall.

	Depth		
	Surface	Mid	Bottom
Winter			
n	457	937	891
Median	8.47	8.47	7.06
Summer			
n	313	629	627
Median	6.09	5.25	4.37

4.5 NEARSHORE AND BEACH SEAWATER QUALITY

The laboratory analysis results of enterococci, total suspended solids, total organic carbon, orthophosphate and ammonia measured seasonally in water samples obtained from surface, middle and bottom depths at sites in the vicinity of the Hout Bay outfall are presented in the sections below. The results of the analyses of seawater toxicity, from two sites near the outfall, to sea urchins are included.

4.5.1 Enterococci

No clear seasonal pattern was seen in enterococci counts at sites sampled in Hout Bay (Figure 4.11). Individual measurements in surface and bottom waters were mostly below 100 cfu/100 mL during winter and summer. In the mid-depth zone, during both seasons, individual enterococci counts were generally higher than in surface and bottom waters, with many measurements exceeding 100 cfu/100 mL. This is consistent with buoyant plume mixing.

During both winter and summer survey periods, the 90th percentiles in the surface and bottom waters at all nearshore sites sampled in Hout Bay were compliant with the recommended DEA (2012) guideline (≤ 185 cfu/100 mL, Table 3.1). At mid-water depths, 90th percentile enterococci values exceeded the recommended guideline at site HB12 during winter and summer and at sites HB4 and HB9 during summer (Figure 4.12 and Figure 4.13).

Beach sites HB-B1 and HB-B3 mostly had enterococci counts below 100 cfu/100mL in winter and summer and the 90th percentile values were in compliance with the recommended guidelines during both seasons (Figure 4.12 and Figure 4.13). At site HB-B2, however, several measurements exceeded 200 cfu/100 mL in winter and the 90th percentile values during both sampling seasons were greater than the DEA (2012) recommended guideline. Site HB-B2 is located in the middle of Hout Bay swimming beach and is near the Disa River estuary mouth. Water quality monitoring of the estuary has been undertaken by the CCT's Scientific Services Laboratory since 1991. Sporadically elevated enterococci levels have been found in the lower reaches of the estuary and at the outlet, with declining water quality being recorded in some recent years (Anchor Environmental Consultants 2016). The Disa River originates on Table Mountain and flows through

residential areas before entering the sea. It is likely influenced by runoff from the Imizamo Yethu settlement, which is not fully serviced. Elevated enterococci counts were not recorded at any of the nearshore sites in the vicinity of site HB-B2 and so the poorer water quality measured at this site is likely attributable to the river outflow.

It must be noted that percentile values calculated for each site for each season are based on 6 samples in winter and 4 samples in summer. High enterococci values thus affect the percentile values more than what could be the case if there were larger sample sizes. These patterns of non-compliance may therefore change as the monitoring plan continues.

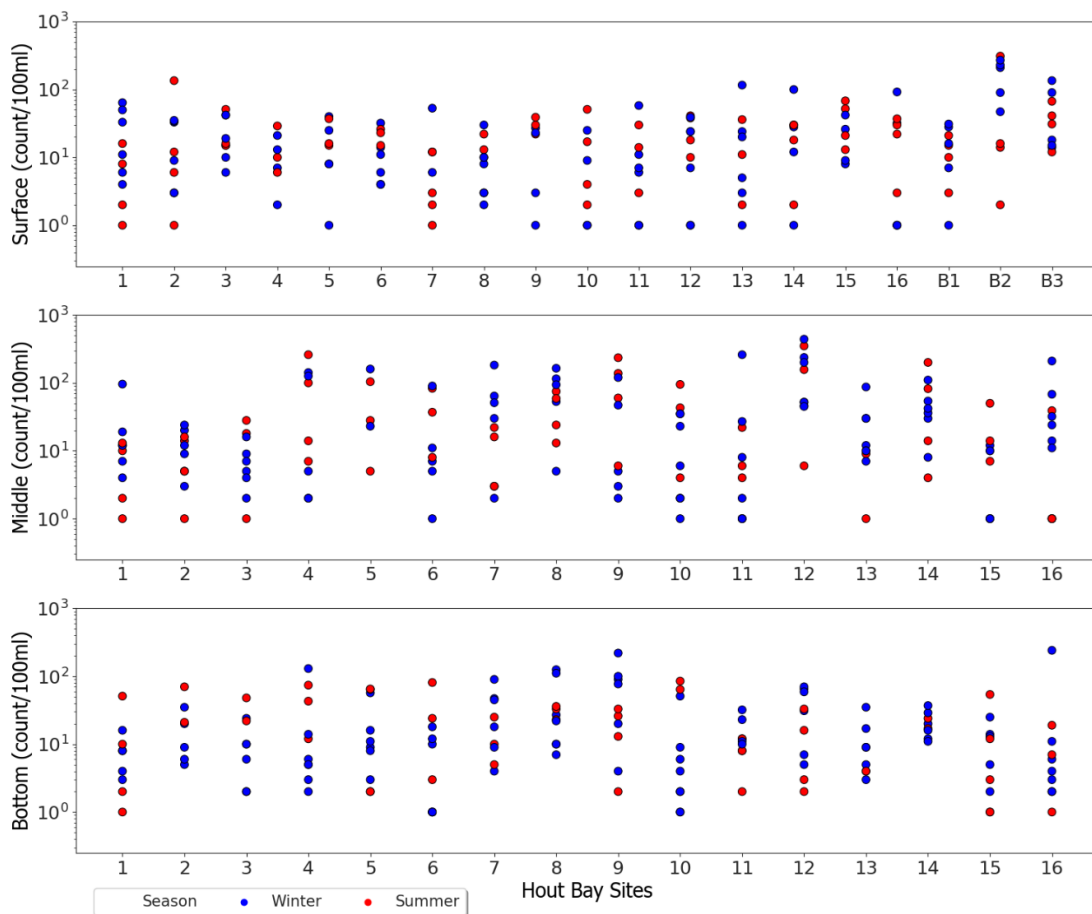


Figure 4.11: Seasonal distribution of enterococci (cfu count/100 mL) measured at surface, mid- and bottom depths at the Hout Bay outfall sites during the 2019 winter and 2020 summer surveys. The enterococci counts measured at beach sites are included in the surface plot (B1, B2 and B3).

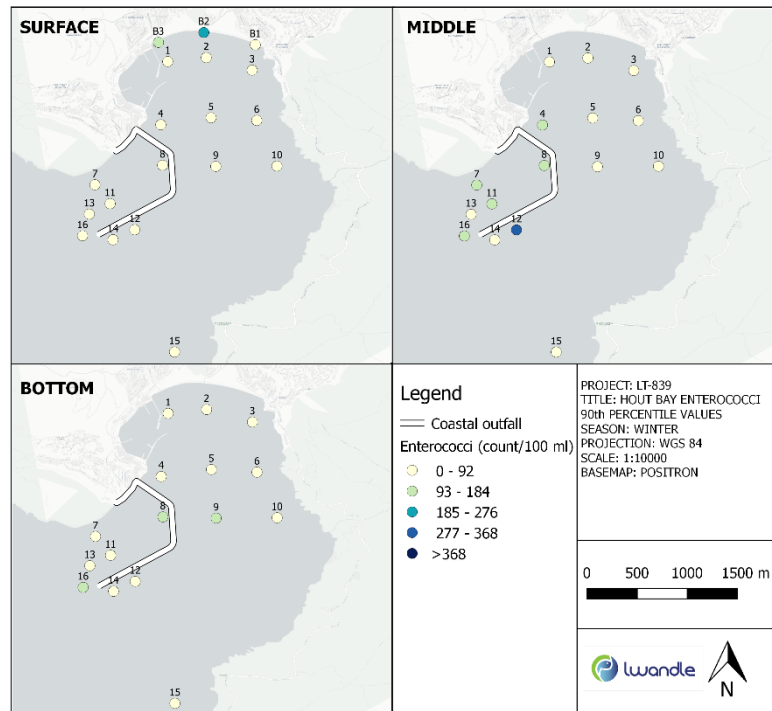


Figure 4.12: Map showing the 90th percentile values of enterococci (cfu count/100 mL) at the surface, middle and bottom at the Hout Bay outfall sites during the 2019 winter survey. The beach sites are included in the surface plot (B1, B2 and B3).

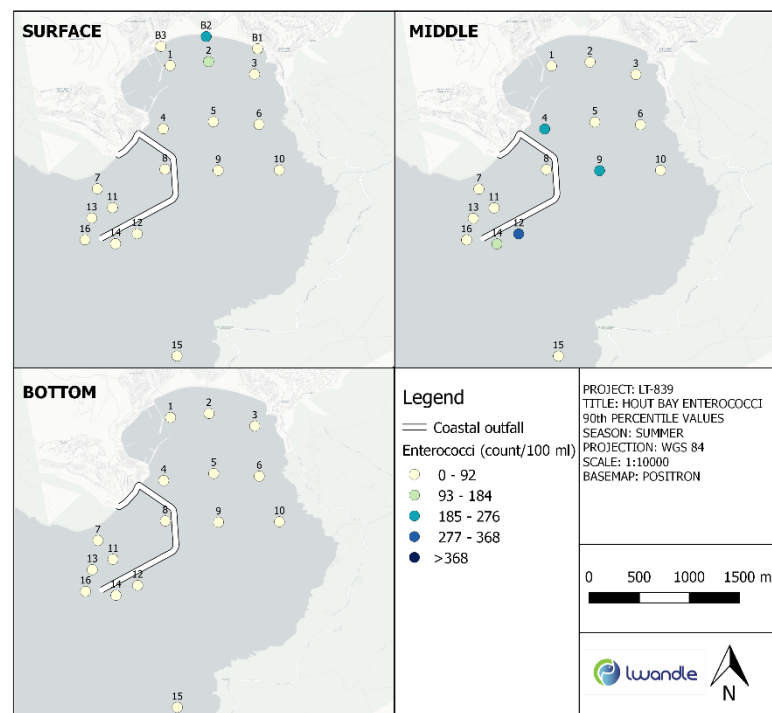


Figure 4.13: Map showing the 90th percentile values of enterococci (cfu count/100 mL) at the surface, middle and bottom at the Hout Bay outfall sites during the 2020 summer survey. The beach sites are included in the surface plot (B1, B2 and B3).

4.5.2 Total Suspended Solids

Total suspended solids (TSS) concentrations were generally higher during the winter survey period than the summer survey period at all depths (Figure 4.14, Figure 4.15 and Figure 4.16). Outliers were recorded in winter at sites HB12 (90 mg/L) during week 2 and HB15 (59 mg/L) during week 3. In the summer survey there was a single outlier at site HB6 (51 mg/L) during week 1 (Figure 4.14).

Median TSS concentrations were relatively higher (most sites were >5 mg/L) in mid and bottom waters compared to surface waters during the winter survey period (Figure 4.15). The highest median concentration was recorded at HB12 (10 mg/L) in bottom waters during winter. In the summer survey, median concentrations were all below 4 mg/L except sites HB5 (5 mg/L), HB6 (5 mg/L) and HB10 (6mg/L) in bottom waters (Figure 4.16).

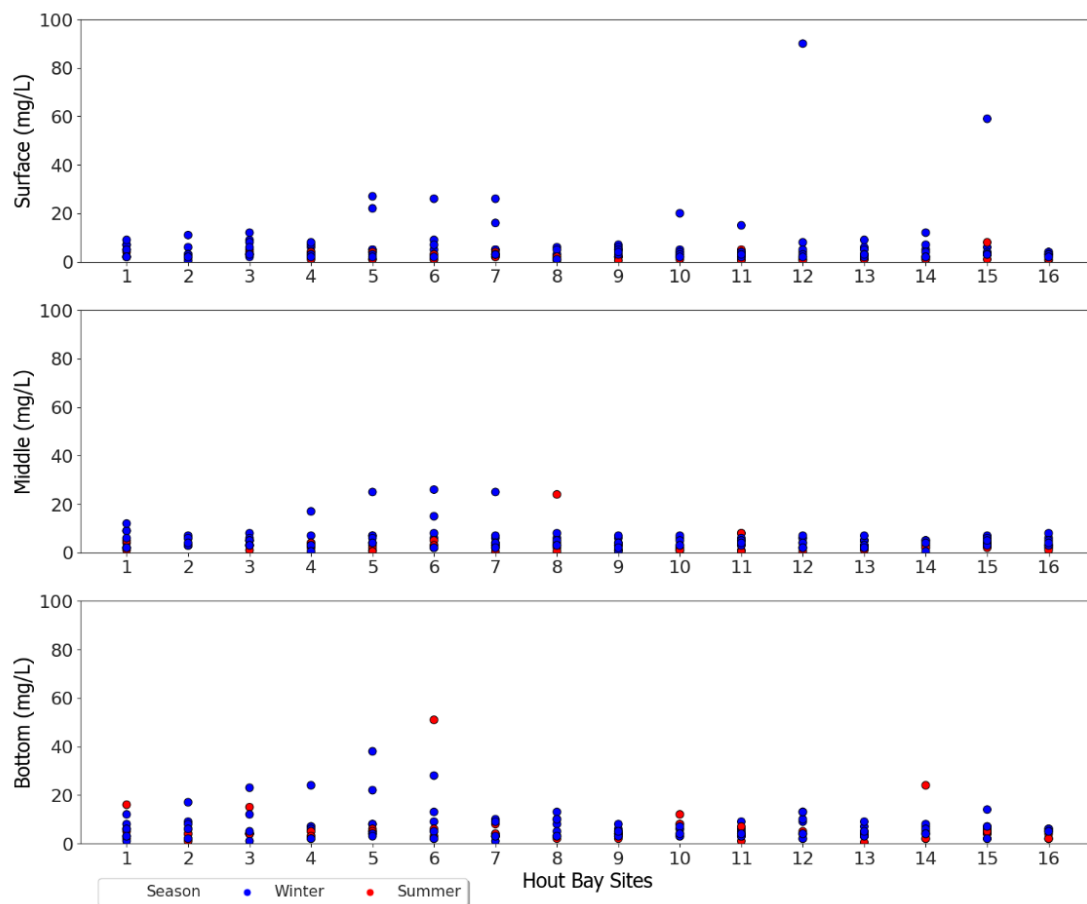


Figure 4.14: Seasonal distribution of suspended solids (mg/L) measured at surface, mid- and bottom depths at the Hout Bay outfall sites during the 2019 winter and 2020 summer surveys. Note: values below the minimum detection limit (MDL, <1) are presented as MDL/2.

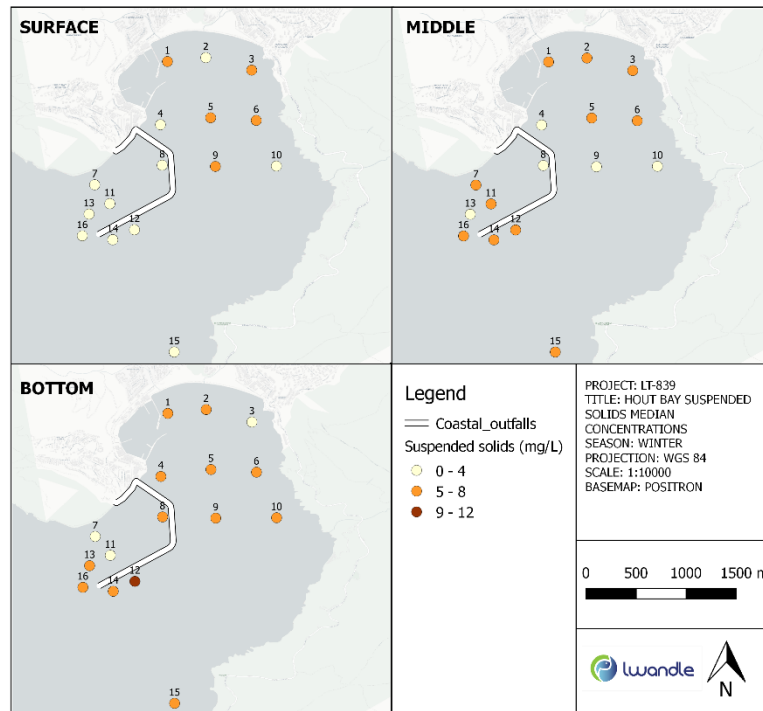


Figure 4.15: Map showing the median concentration of total suspended solids (mg/L) at the surface, middle and bottom at the Hout Bay outfall sites during the 2019 winter survey.

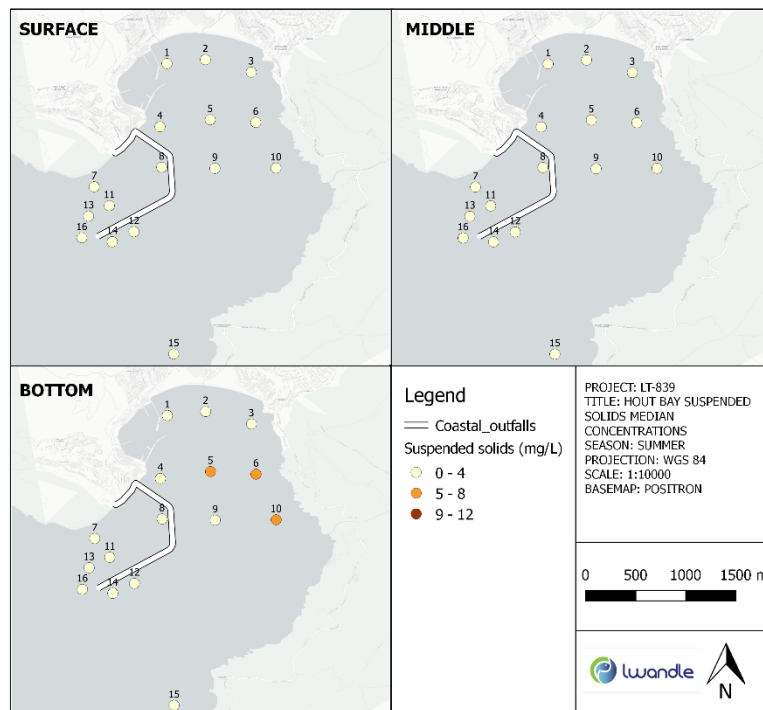


Figure 4.16: Map showing the median concentration of total suspended solids (mg/L) at the surface, middle and bottom at the Hout Bay outfall sites during the 2020 summer survey.

TSS values at all depths in the nearfield water body, represented by measurements from stations HB7, HB8, HB9, HB11, HB12, HB13, HB14 and HB16, were compliant with the stipulated guidelines during both the winter and summer monitoring periods. During both monitoring periods, median values in surface, mid and bottom waters fell into the ranges defined in Table 3.2 (Table 4.4). For this determination nearfield sites were grouped to increase replication but with further monitoring and sample collection, this approach will be re-examined and where possible, site-specific comparisons to guidelines will be made.

Table 4.4: Median total suspended solids values (mg/L) in surface, mid and bottom waters measured at nearfield sites surrounding the Hout Bay outfall.

	Depth		
	Surface	Mid	Bottom
Winter			
n	48	48	48
Median	4	5	5
Summer			
n	32	32	32
Median	2	2	3

4.5.3 Total Organic Carbon

No clear seasonal pattern was seen in total organic carbon (TOC) concentrations at the Hout Bay sites (Figure 4.17, Figure 4.18 and Figure 4.19). TOC concentrations in surface, middle and bottom waters were generally low and ranged between 0.3 and 2.6 mg/L during the winter survey and 0.4 and 3.2 mg/L during the summer survey (Figure 4.17). Both the winter and summer survey had high inter-week variation.

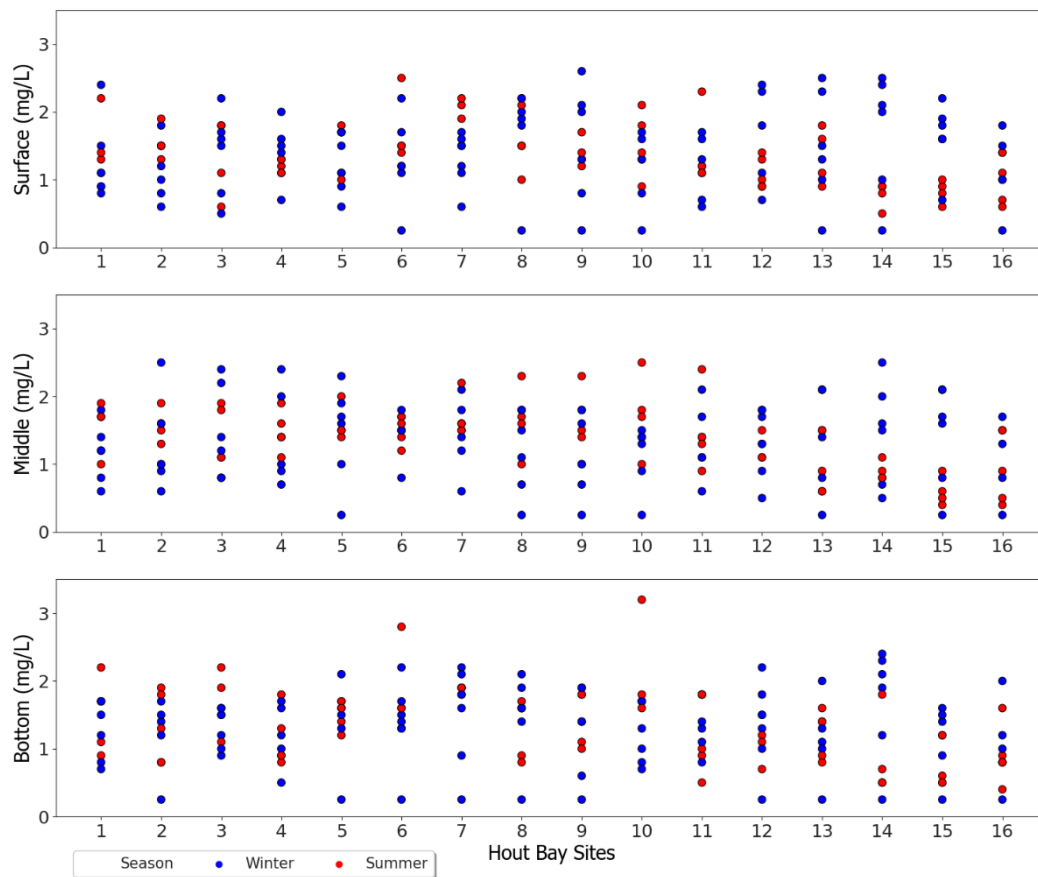


Figure 4.17: Seasonal distribution of total organic carbon (mg/L) measured at surface, mid- and bottom depths at the Hout Bay outfall sites during the 2019 winter and 2020 summer surveys. Note: values below the minimum detection limit (MDL, <0.5 mg/L) are presented as MDL/2.

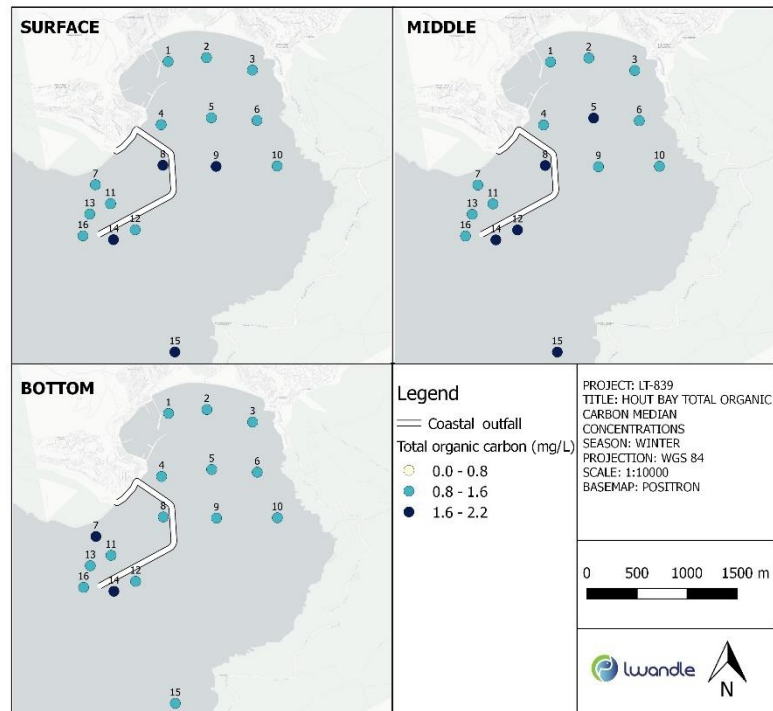


Figure 4.18: Map showing the median concentration of total organic carbon (mg/L) at the surface, middle and bottom at the Hout Bay outfall sites during the 2019 winter survey.

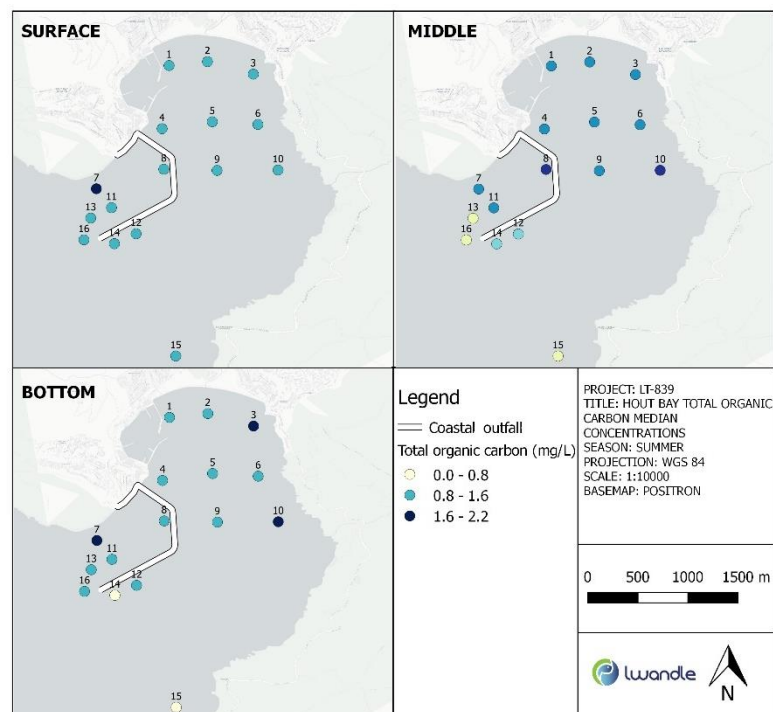


Figure 4.19: Map showing the median concentration of total organic carbon (mg/L) at the surface, middle and bottom at the Hout Bay outfall sites during the 2020 summer survey.

4.5.4 Orthophosphate

Orthophosphate results for the 2019 winter survey are not available due to operational problems experienced in the analysis of samples at the laboratory. The orthophosphate concentrations at sites surrounding the Hout Bay outfall sampled during the 2020 summer survey are presented in the summer data report (LT-839 DTR_02_V3). Concentrations ranged from 46 to 74 $\mu\text{g/L}$. Median orthophosphate concentrations ranged from 61 to 68 $\mu\text{g/L}$ (Figure 4.20) with no clear spatial distribution patterns across depths and/or sample sites.

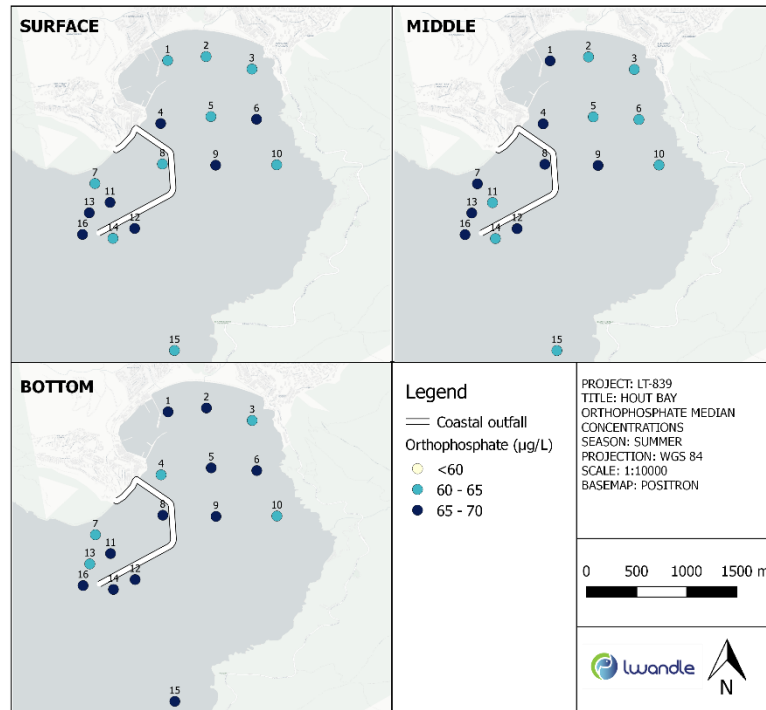


Figure 4.20: Map showing the median concentration of orthophosphate ($\mu\text{g/L}$) at the surface, middle and bottom at the Hout Bay outfall sites during the 2020 summer survey.

Orthophosphate values at mid and bottom depths in the nearfield water body, represented by measurements from stations HB7, HB8, HB9, HB11, HB12, HB13, HB14 and HB16, were compliant with the stipulated guidelines during the summer monitoring period with the median values in surface, mid and bottom waters falling into the ranges defined in Table 3.2 (Table 4.5). However, the median value in surface waters at the nearfield sites were slightly higher than the guideline. For this determination nearfield sites were grouped to increase replication but with further monitoring and sample collection, this approach will be re-examined and where possible, site-specific comparisons to guidelines will be made.

Table 4.5: Median orthophosphate values ($\mu\text{g/L}$) in surface, mid and bottom waters measured at nearfield sites surrounding the Hout Bay outfall. Median values that exceed the guideline are highlighted in bold.

	Depth		
	Surface	Mid	Bottom
Summer			
n	32	32	32
Median	65	65	67

4.5.5 Ammonia

Ammonia results for the 2019 winter survey are not available due to operational problems experienced in the analysis of samples at the laboratory. The ammonia concentrations at sites sampled in Hout Bay during the 2020 summer survey are presented in the summer data report (LT-839 DTR_02_V3). Concentrations were low, ranging from <5 to $40 \mu\text{g/L}$. Most of the measurements (76.6%) were below the MDL and no exceedances of the recommended guideline ($600 \mu\text{g/L}$) were recorded (Figure 4.21).

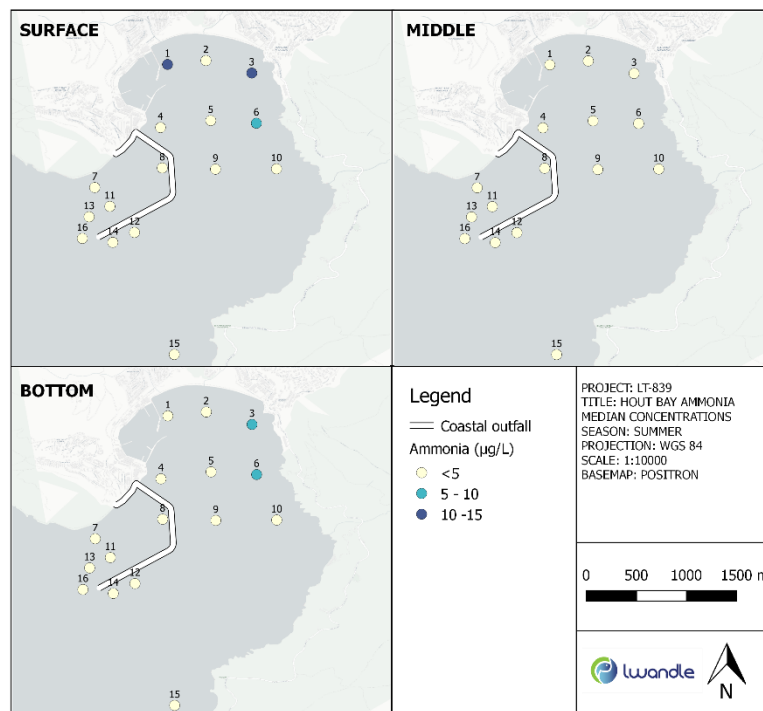


Figure 4.21: Map showing the median concentration of ammonia ($\mu\text{g/L}$) at the surface, middle and bottom at the Hout Bay outfall sites during the 2020 summer survey.

4.5.6 Toxicity

The two nearshore sites sampled during the first year of monitoring showed no toxicity effects of seawater obtained from near the discharge on sea urchins (*Tripneutes gratilla* and *Echinometra mathaei*) fertilisation rates in either of the winter or summer sampling periods (Table 4.6).

Table 4.6: Sea urchin seawater toxicity test results. Samples were obtained from two nearshore sites in the vicinity of the Hout Bay outfall on alternate days during the winter (August-September 2019) and summer (February-March 2020) sampling periods in the first year of monitoring. Toxicity classification is based on mean (n=4) fertilisation success rates.

Date	Season	Site	Species	Mean Fertilisation Success (%)	Std Dev	Toxicity Classification
26/09/2019	Winter	HB-TT1	<i>T. gratilla</i>	97.50	1.29	Not toxic
		HB-TT2	<i>T. gratilla</i>	98.50	0.58	Not toxic
30/09/2019		HB-TT1	<i>T. gratilla</i>	98.25	0.96	Not toxic
		HB-TT2	<i>T. gratilla</i>	98.50	0.58	Not toxic
2/10/2019		HB-TT1	<i>T. gratilla</i>	97.00	0.82	Not toxic
		HB-TT2	<i>T. gratilla</i>	97.75	0.50	Not toxic
5/10/2019		HB-TT1	<i>T. gratilla</i>	98.50	0.58	Not toxic
		HB-TT2	<i>T. gratilla</i>	98.50	0.58	Not toxic
6/10/2019		HB-TT1	<i>T. gratilla</i>	98.50	0.58	Not toxic
		HB-TT2	<i>T. gratilla</i>	98.50	0.58	Not toxic
8/10/2019		HB-TT1	No sample due to bad weather			
		HB-TT2	No sample due to bad weather			
20/03/2020	Summer	HB-TT1	<i>E. mathaei</i>	97.00	0.82	Not toxic
		HB-TT2	<i>E. mathaei</i>	97.50	0.58	Not toxic
23/03/2020		HB-TT1	<i>E. mathaei</i>	96.50	0.58	Not toxic
		HB-TT2	<i>E. mathaei</i>	97.50	0.58	Not toxic

4.6 EFFECTS ON LOCAL MARINE ECOLOGY

Growth rates and trace metal accumulation in mussels (*Mytilus galloprovincialis*) at fixed monitoring stations surrounding the Hout Bay outfall and two control stations were compared across the winter 2019 and summer 2020 surveys. Results (detailed in APPENDIX D: BIOMONITORING PROGRAMME, ANNUAL REPORT) indicated that mussel growth rates at the Hout Bay outfall were significantly greater during winter than in summer. Growth rates also appeared to be slightly higher at the stations located in close proximity to the outfall than those further afield which was more evident during the summer period.

Trace metal concentrations in mussels were higher during winter than in summer at stations surrounding the Hout Bay outfall, with low levels relative to the baseline levels measured during summer, particularly for zinc (baseline: 33.6 mg/kg, outfall sites: 23.94-29.88 mg/kg) and nickel (baseline: 557.48, outfall sites: 129.28-166.79 µg/kg) total wet weights. There was no evidence to

suggest that metal bioaccumulation was higher at stations in close proximity to the outfall than those further afield.

4.7 HYDRODYNAMIC MODELLING, PLUME BEHAVIOUR AND EFFECTS ON HUMAN HEALTH

Results of the hydrodynamic modelling conducted by PRDW (detailed in Appendix E) suggest that for TSS a mixing zone distance of 450 m from the discharge is required to meet the required dilution of 2 587 (as determined by the CCT, detailed in APPENDIX E) in winter/spring, whereas in summer/autumn a mixing zone distance of 360 m is predicted. For *E. coli*, distances of 1 620 m and 1 700 m are predicted to be required in winter/spring and summer/autumn respectively to meet the 90th percentile water quality guideline of 500 cfu/100 mL (as defined in DEA 2012 and referred to in APPENDIX E). For enterococci, distances of 700 m and 600 m are predicted to be required in winter/spring and summer/autumn to meet the 90th percentile water quality guideline of 185 cfu/100 mL. The modelling thus suggests that non-compliance to recommended TSS, enterococci and *E. coli* guidelines extends beyond the initially 272 m estimated ZID radius, nor is it limited to the 300 m mixing zone which is considered appropriate for an offshore discharge in an open coast system (Anchor, 2015).

During typical conditions, modelling showed that the plume from the Hout Bay outfall is advected in a south-westerly or north-easterly direction by prevailing currents. The plume was advected into Hout Bay by currents driven by wave breaking at the southern or northern entrance of the bay however, due to dispersion and decay, bacteria concentrations in the vicinity of the harbour and beach remained low. This is reflected in the laboratory results for enterococci, where most sites at which there was exceedance of the water quality guidelines were located outside of the harbour and swimming areas. Thus, modelling and the field measurement data reported here indicate low risks to human health in swimming and recreational areas within Hout Bay that emanate from the outfall. That being said, during winter and summer consistently high enterococci values were recorded at the beach site HB-B2, resulting in the 90th percentile for both monitoring periods exceeding the guideline value at this site. Elevated enterococci counts were not recorded at any of the nearshore sites and as mentioned, the modelling showed a reduction in the bacterial load in the plume by the time it reached the beach. The poor water quality at site HB-B2 is thus likely to be linked to runoff into the Disa River. Although not arising from the Hout Bay outfall, the high enterococci concentrations at this site indicates risk to bathers which requires management and mitigation.

Outside of Hout Bay, alongshore to the north-west of the outfall, at the Dungeons surf spot, the hydrodynamic modelling showed peaks in *E. coli* concentrations which exceeded 500 cfu/100 mL on occasion. Although the duration of these events was predicted to be short resulting in compliance with the 90th percentile guideline of 500 cfu/100 mL, it still indicates some risk to surfers in this area. Recommendations are provided in the PRDW report in APPENDIX E.

5 APPENDIX B: CAMPS BAY

5.1 DESCRIPTION OF OUTFALL

The Camps Bay outfall serves the Clifton, Camps Bay and Bakoven areas. It was commissioned in 1977 and extends seawards in a north-westerly direction to approximately 1.4 km from Camps Bay beach. It discharges effluent 600 m to the west of Maidens Cove and 800 m to the south-west of Clifton (Figure 5.1 and Figure 5.2). The diffusers are located at 23 m depth.

5.2 SAMPLING LOCATIONS

Figure 5.1 and Figure 5.2 show the Camps Bay outfall, as well as the location of the respective sampling and instrument mooring sites during each week of sampling in the winter (August-September 2019) and summer (February-March 2020) monitoring periods. For the purposes of the initial survey design, the CCT estimated the zone of initial dilution (ZID) at the Camps Bay outfall to be within a 274 m radius from the diffuser. This is included on the plots below.

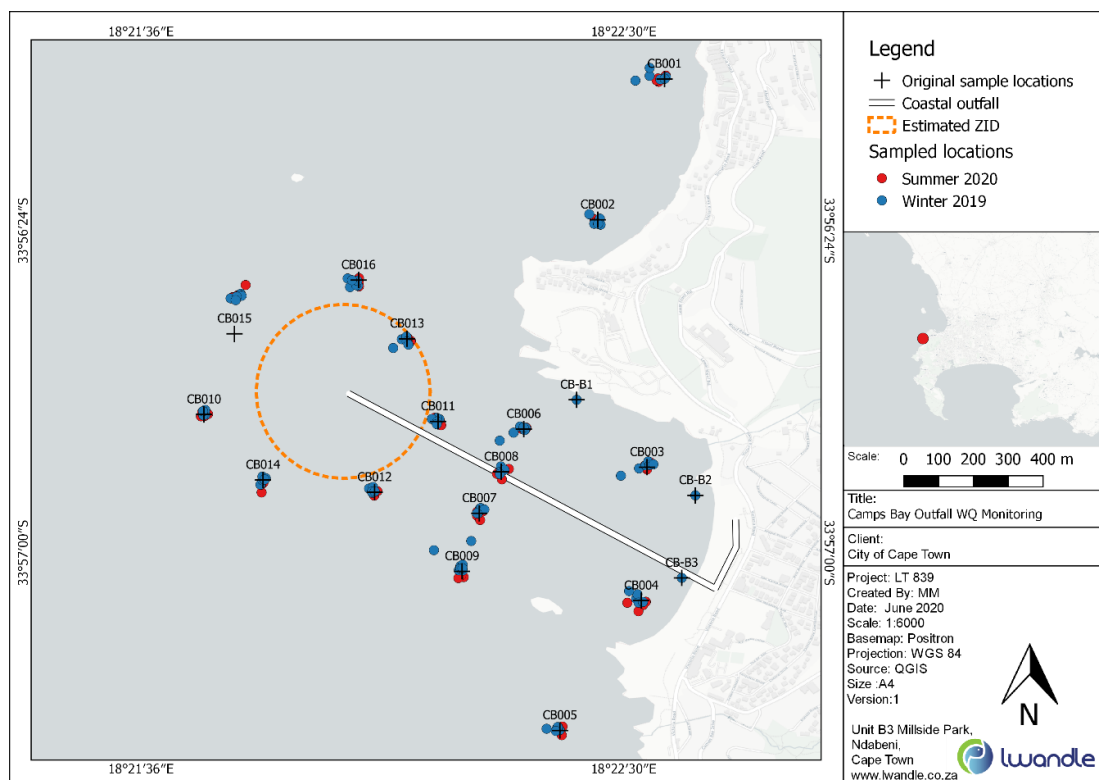


Figure 5.1: Map showing the Camps Bay outfall and the locations of nearshore and beach (CB-B1, CB-B2 and CB-B3) sites sampled during the winter (August-October 2019) and the summer (February-March 2020) monitoring periods.

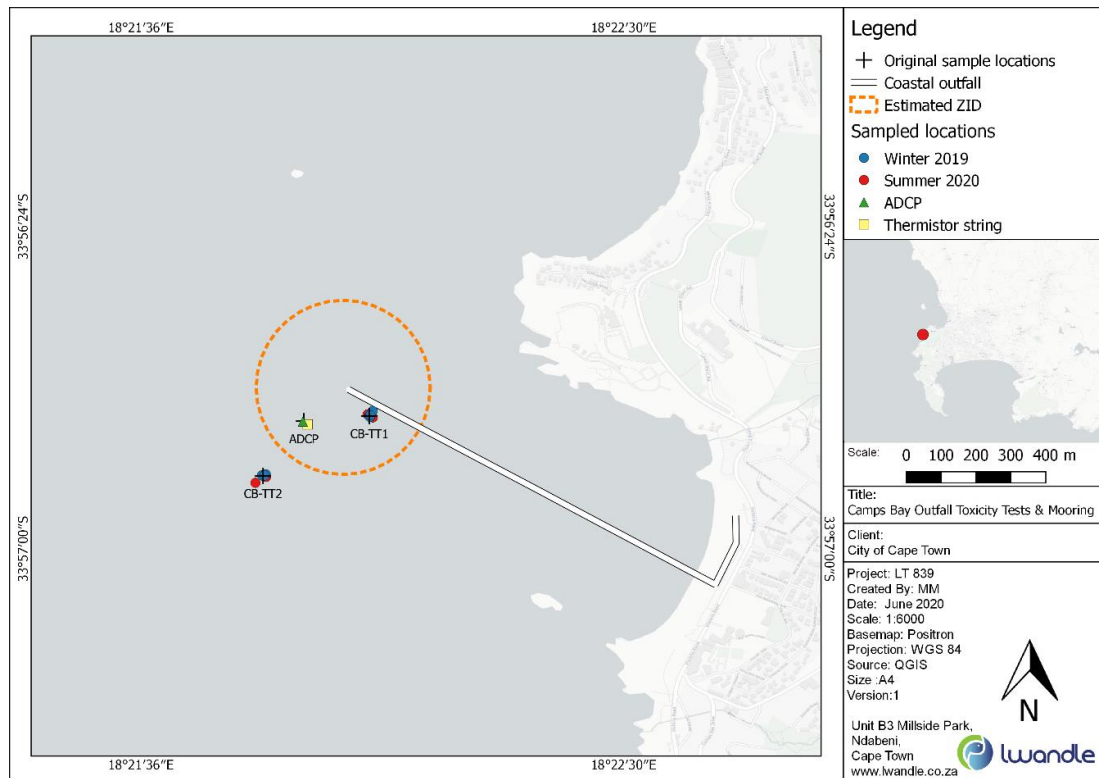


Figure 5.2: Map showing the Camps Bay outfall and the locations of the toxicity test sites sampled during the winter (August-October 2019) and the summer (February-March 2020) monitoring periods. The locations of the ADCP and thermistor strings are also shown.

5.3 CURRENTS AND WAVES

Currents recorded at the ADCP mooring site in Camps Bay during the winter deployment flowed predominantly in a north-westerly direction at all depths but with south and south-easterly currents also recorded at the deeper depths (Figure 5.3). Current speeds ranged between 0-0.3 m/s with the lower velocities being more frequent at depth. During the summer deployment, surface currents primarily flowed in a north-north-easterly and north-easterly direction and currents mid-depth in the water column (8.2 and 15.2 m) had increased north-westerly and south-easterly components (Figure 5.4) compared to the winter measurement period. Northerly to east-south-easterly currents were dominant at the bottom of the water column. Similar to the winter deployment, current speeds ranged between 0-0.3 m/s. Variation in current direction was observed at all depths during both seasons.

Camps Bay outfall received waves primarily from the west-south-west during the winter and summer deployment (Figure 5.5 and Figure 5.6). The average peak period mainly ranged between 10.5-13.5 seconds during winter and summer.

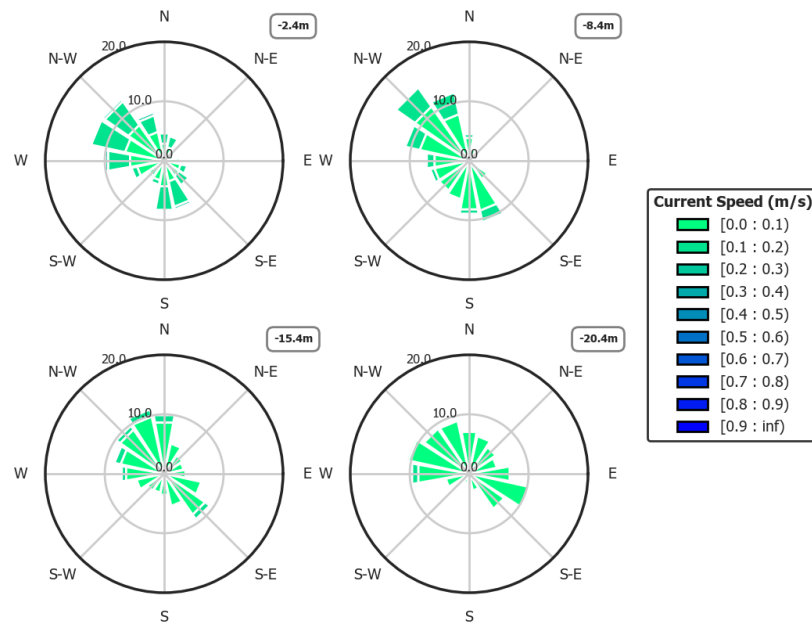


Figure 5.3: Current roses showing average observed speeds and directions throughout the water column measured by the ADCP moored at the Camps Bay outfall from 21st August 2019 to 2nd October 2019 (winter).

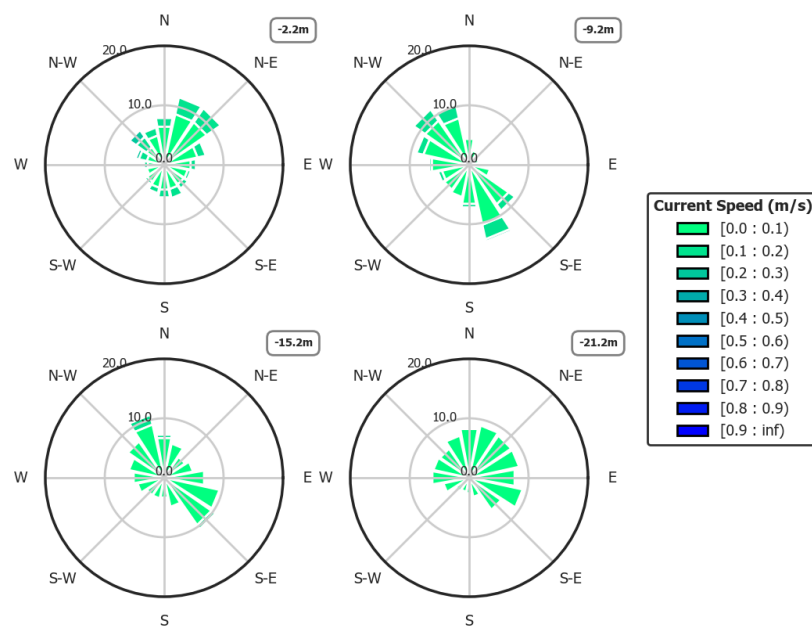


Figure 5.4: Current roses showing average observed speeds and directions throughout the water column measured by the ADCP moored at the Camps Bay outfall from 12th February 2020 to 20th April 2020 (summer).

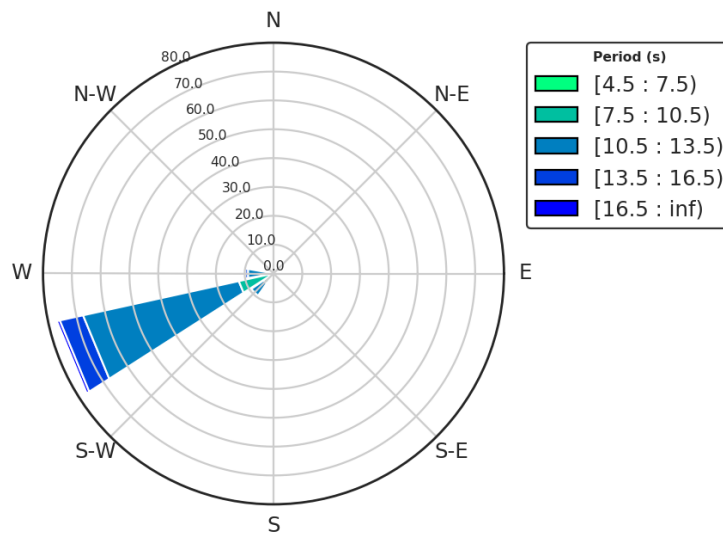


Figure 5.5: Wave rose showing average observed periods and directions from the ADCP moored at the Camps Bay outfall from 22nd August 2019 to 2nd October 2019 (winter).

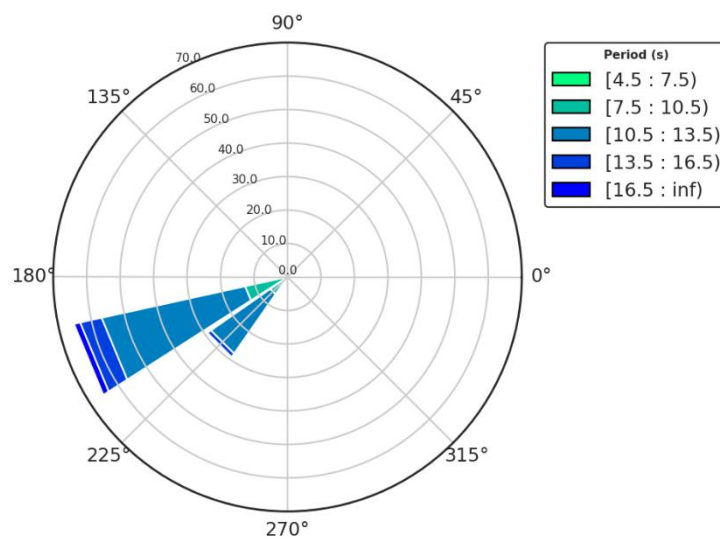


Figure 5.6: Wave rose showing average observed periods and directions from the ADCP moored at the Camps Bay outfall from 13th February 2020 to 27th April 2020 (summer).

5.4 NEARSHORE WATER COLUMN CHARACTERISTICS

The surface, middle and bottom depth values recorded seasonally at the Camps Bay outfall sampling sites for each measured water quality constituent (extracted from CTD data) are presented in the plots below. Parameters are also compared to relevant guidelines where appropriate.

5.4.1 Temperature

The water column temperatures recorded during the summer survey at Camps Bay outfall were slightly cooler than those measured during the winter survey, characteristic of the seasonal upwelling in the region (Figure 5.7). Water column temperatures during the winter survey ranged between 9.79 and 14.90°C and were between 9.76 and 15.31°C during the summer survey. These fall within the expected range for the region. Both the winter and summer survey had high inter-week variation.

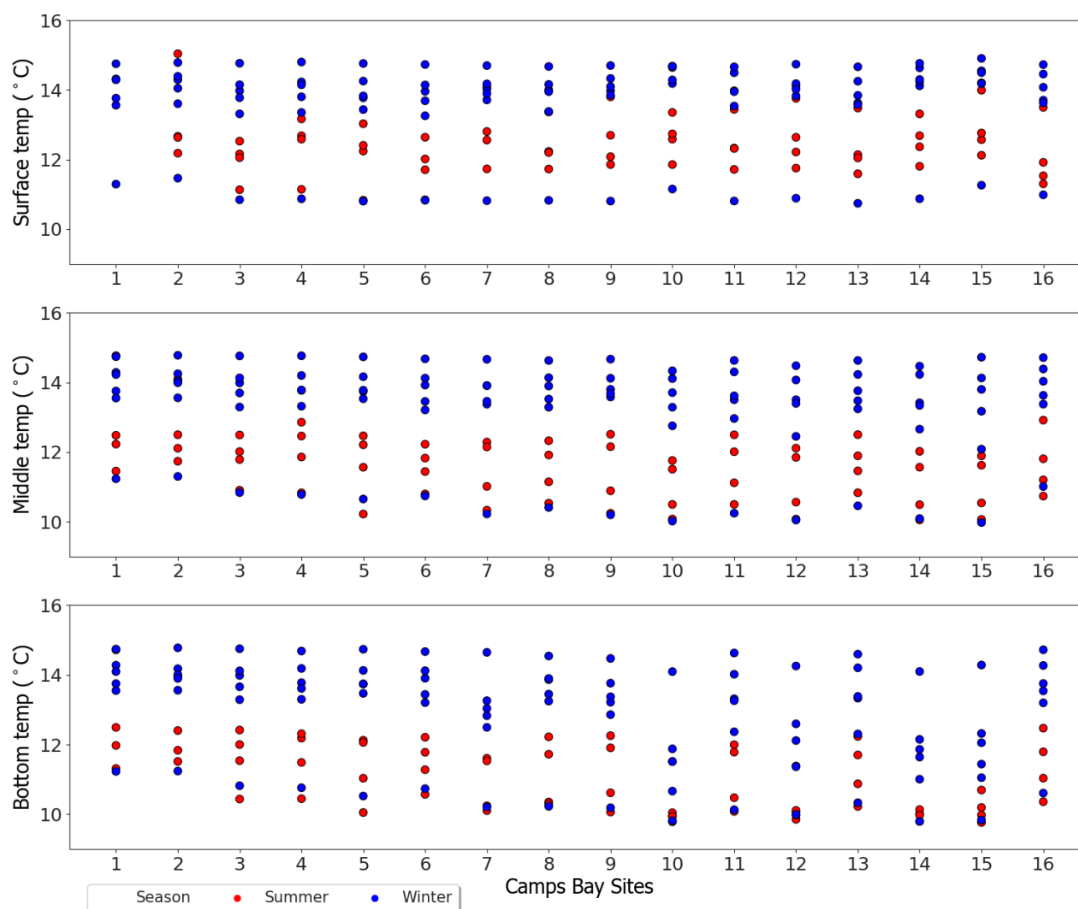


Figure 5.7: Seasonal distribution of temperature (°C) measured at the Camps Bay outfall sites during the 2019 winter and 2020 summer surveys.

5.4.2 Salinity

The recorded salinities had a similar seasonal pattern to temperature with lower salinities generally recorded in the summer, although there were periods where salinities in the winter were notably lower than those measured in summer especially at the surface (Figure 5.8). Salinities ranged from 34.72 to 35.18 PSU and from 34.70 to 35.00 PSU in the winter and summer respectively. The winter survey also had a greater range of salinities measured at all depths and higher inter-week variation in comparison to the summer survey.

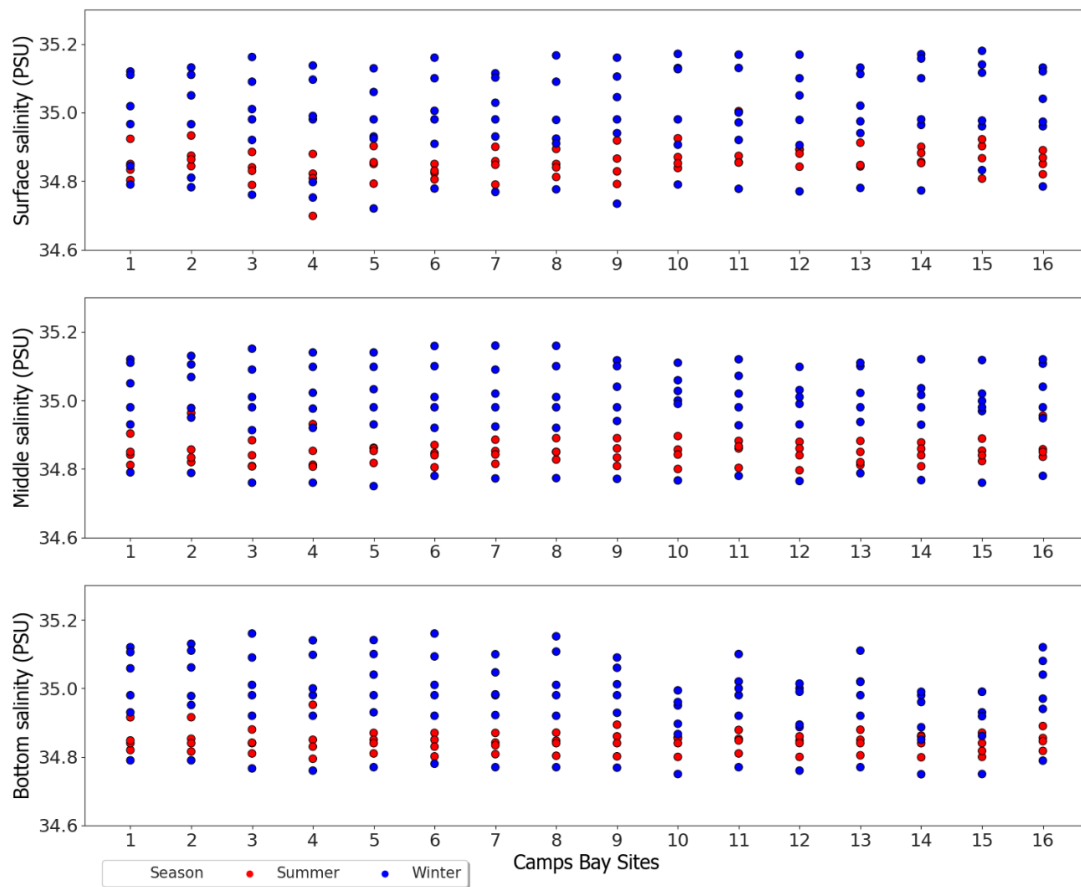


Figure 5.8: Seasonal distribution of salinity (PSU) measured at the Camps Bay outfall sites during the 2019 winter and 2020 summer surveys.

Measured salinity values were compliant with the DWAF (1995) stipulated guideline range (33-36 PSU) during the winter and summer monitoring periods. In the nearfield of the discharge, represented by measurements from stations CB3, CB4, CB6, CB7, CB8, CB9, CB11, CB12, CB13 and CB14, compliance was also met with the median values in each of the surface (0 – 5 m), mid (5 – 15 m) and bottom (>15 m) depth zones falling into the ranges defined in Table 3.2 (Table 5.1). For this determination nearfield sites were grouped to increase replication but with further monitoring and sample collection, this approach will be re-examined and where possible, site-specific comparisons to guidelines will be made.

Table 5.1: Median salinity values (PSU) in surface (0-5 m), mid (5 – 15 m) and bottom (>15 m) waters measured at nearfield sites surrounding the Camps Bay outfall.

	Depth		
	Surface	Mid	Bottom
Winter			
n	545	746	245
Median	34.99	34.99	34.98
Summer			
n	368	505	162
Median	34.85	34.85	34.84

5.4.3 Turbidity

Turbidity values measured during the 2020 summer survey were considered to be erroneous due to sensor malfunction and so are not included in this report. Profiles were presented in the 2020 summer data report (LT-839 DTR_02_V3) to understand relative patterns and showed that the turbidity profiles at most sites were uniform with depth. This is similar to the winter survey (LT-839 DTR_01_V2) with the exception of a few sites, mainly those closer to shore. The turbidity values recorded during the winter survey ranged between 0.46 and 20.49 FNU. Turbidity was generally increased at bottom depths, presumably due to the suspension of sediment.

5.4.4 pH

Similar to temperature and salinity, pH measured during the summer survey were generally lower than those measured during the winter survey (Figure 5.9). pH ranged between 7.98 and 8.47 in the winter and between 7.78 and 8.31 in the summer with higher inter-week variation at all sites observed in winter compared to summer. These seasonal patterns observed are consistent with temperature as cooler waters generally have a lower pH due to capacity to hold higher pCO₂ levels.

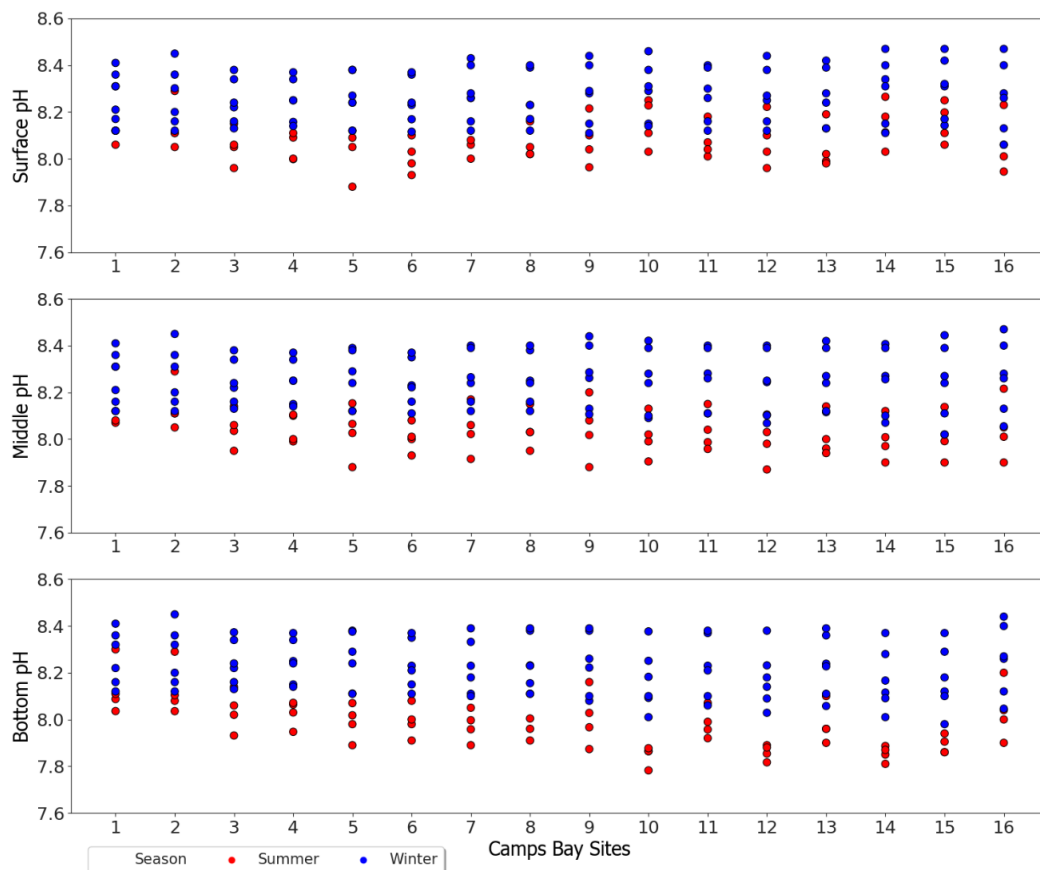


Figure 5.9: Seasonal distribution of pH measured at the Camps Bay outfall sites during the 2019 winter and 2020 summer surveys.

pH values at all depths in the nearfield water body, represented by measurements from stations CB3, CB4, CB6, CB7, CB8, CB9, CB11, CB12, CB13 and CB14, were compliant with the stipulated guidelines during the winter monitoring period with the median values in each of the surface (0 – 5 m), mid (5 – 15 m) and bottom (>15 m) depth zones falling into the ranges defined in Table 3.2 (Table 5.2). During winter, the surface and mid-water column pH at sites in the nearfield water body were slightly higher than the DWAF (1995) stipulated guideline range (7.30 – 8.20). For this determination nearfield sites were grouped to increase replication but with further monitoring and sample collection, this approach will be re-examined and where possible, site-specific comparisons to guidelines will be made

It must be noted that the pH values recorded at all Camps Bay sites, particularly during winter are high, and many occur outside the range (7.6 – 8.1) previously recorded for the area (DEA 2015). Because high values occurred at all sites and all depths, the high pH values may be a result of instrument error, even though standard calibration procedures are conducted prior to each survey. Continued measurement of pH in future surveys will assist in establishing whether this is the case. pH measurements during the first year of monitoring should thus be considered relative. Nevertheless, relatively elevated pH (>8) indicates the presence of a mainly oxic water column

which suggests minimal remineralisation of organically rich sediments and probably no build-up of sewage effluent particulate matter in area of measurement. This is not surprising given the wave climate in the vicinity of Camps Bay.

Table 5.2: Median pH values in surface (0-5 m), mid (5 – 15 m) and bottom (>15 m) waters measured at nearfield sites surrounding the Camps Bay outfall.

	Depth		
	Surface	Mid	Bottom
Winter			
n	545	746	245
Median	8.26	8.25	8.20
Summer			
n	368	505	162
Median	8.04	8.01	7.92

5.4.5 Dissolved Oxygen

Dissolved oxygen concentrations measured at the Camps Bay outfall were generally lower in summer compared to winter and ranged between 5.48 and 11.31 mg/L and 2.19 and 9.10 mg/L respectively (Figure 5.10). The lowest concentrations were recorded the bottom of the water column during the summer survey specifically at sites CB10, CB12, CB14 and CB15. The recorded temperatures at these sites during both winter and summer were low (<10°C) and salinity values were lower during winter. This indicates that different water masses may be present during winter and summer which may influence the low dissolved oxygen seen in summer. This however needs further investigation with continued monitoring.

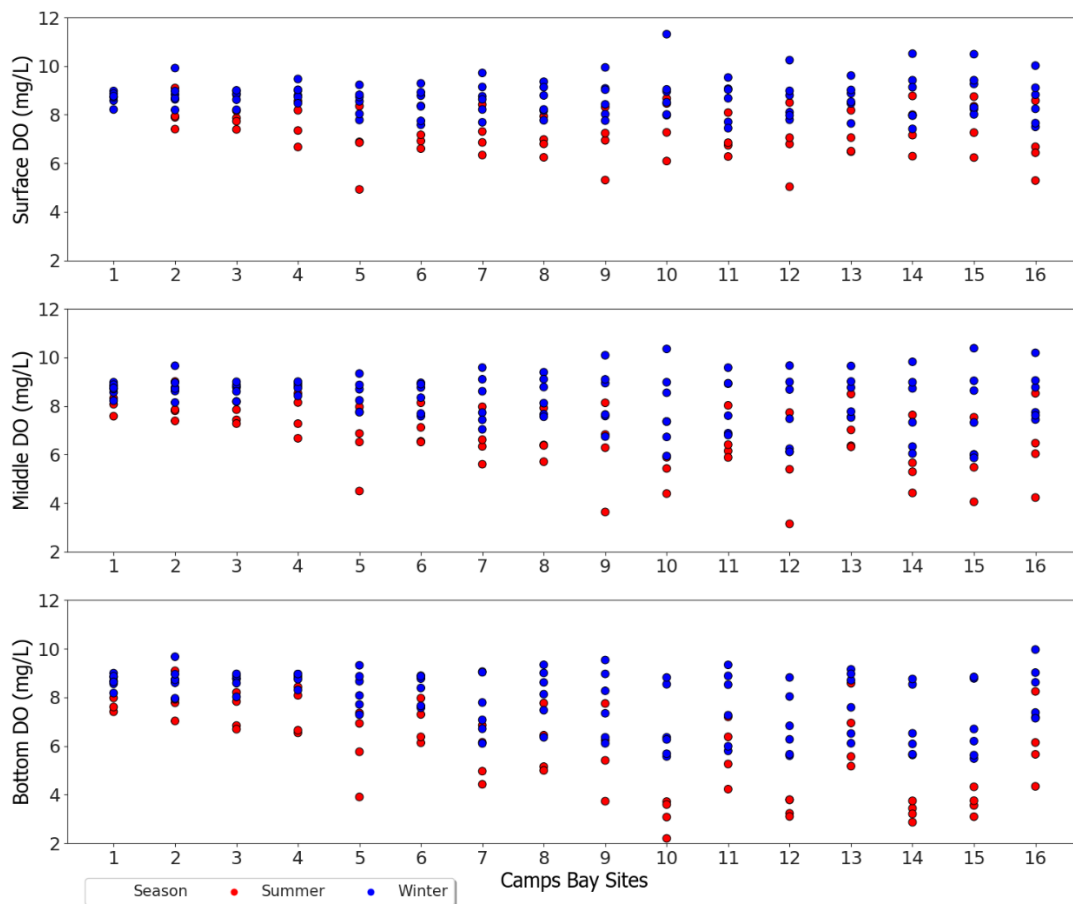


Figure 5.10: Seasonal distribution of dissolved oxygen (mg/L) measured at the Camps Bay outfall sites during the 2019 winter and 2020 summer surveys.

Dissolved oxygen concentrations at all depths in the nearfield water body, represented by measurements from stations CB3, CB4, CB6, CB7, CB8, CB9, CB11, CB12, CB13 and CB14, were compliant with the stipulated guidelines during both the winter and summer monitoring periods. During both monitoring periods, median values in each of the surface (0 – 5 m), mid (5 – 15 m) and bottom (>15 m) depth zones fell into the ranges defined in Table 3.2 (Table 5.3) and indicate an oxic water body at all depths in the immediate vicinity surrounding the outfall. For this determination nearfield sites were grouped to increase replication but with further monitoring and sample collection, this approach will be re-examined and where possible, site-specific comparisons to guidelines will be made.

Table 5.3: Median dissolved oxygen concentrations (mg/L) in surface (0-5 m), mid (5 – 15 m) and bottom (>15 m) waters measured at nearfield sites surrounding the Camps Bay outfall.

	Depth		
	Surface	Mid	Bottom
Winter			
n	545	746	245
Median	8.76	8.28	7.01
Summer			
n	368	505	162
Median	6.92	6.34	4.48

5.5 NEARSHORE AND BEACH SEAWATER QUALITY

The laboratory analysis results of enterococci, total suspended solids, total organic carbon, orthophosphate and ammonia measured seasonally in water samples obtained from surface, middle and bottom depths at sites in the vicinity of the Camps Bay outfall are presented in the sections below. The results of the analyses of seawater toxicity, from two sites near the outfall, to sea urchins are included.

5.5.1 Enterococci

No clear seasonal pattern was seen in enterococci counts at sites sampled in Camps Bay. Individual measurements were generally below 100 cfu/100mL at all depths at all nearshore sites during both seasons (Figure 5.11) and the 90th percentile values for the winter and summer survey periods were mostly below 30 cfu/100mL (Figure 5.12 and Figure 5.13). No exceedances of the recommended DEA (2012) guideline (≤ 185 cfu/100 mL, Table 3.1) were observed.

Individual enterococci counts at the three beach sites were mostly below 20 cfu/100mL during both seasons (Figure 5.11) and the 90th percentile values at all three beach sites for the winter and summer survey periods were in compliance with the recommended guideline.

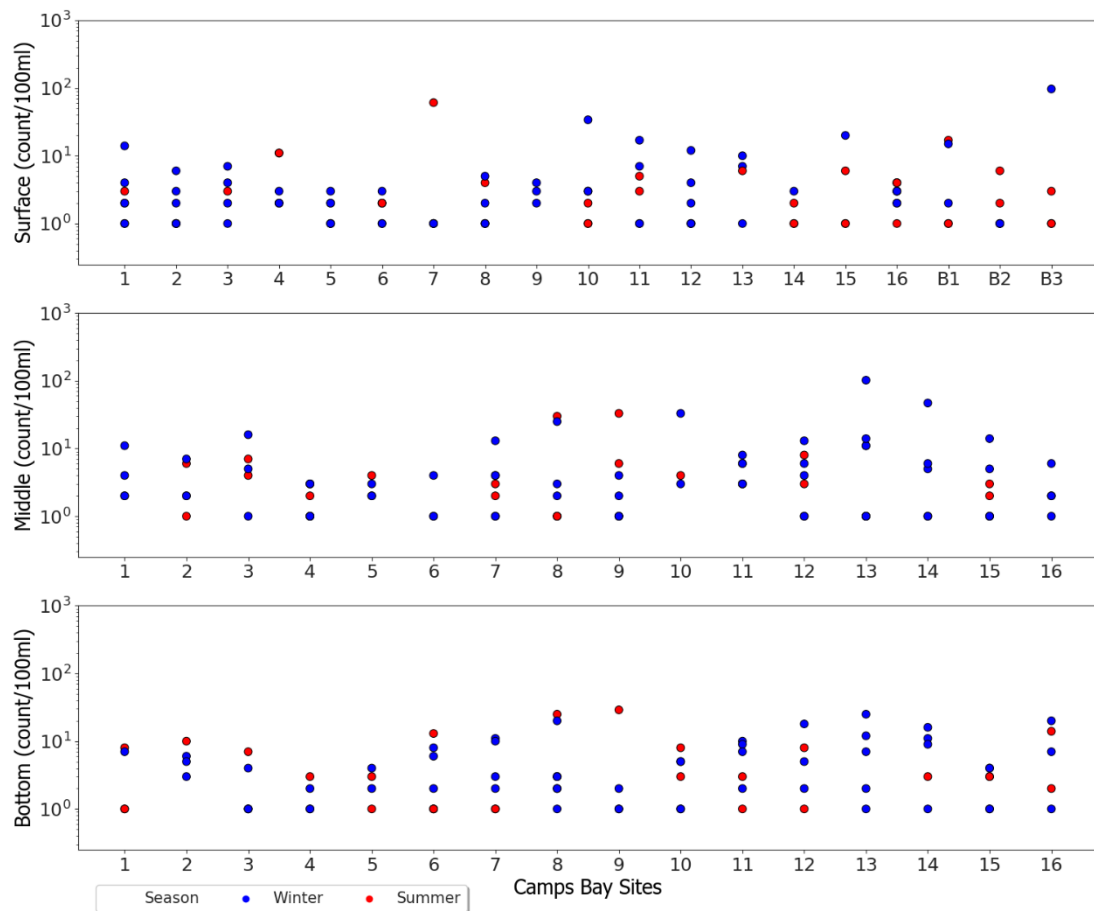


Figure 5.11: Seasonal distribution of enterococci (count/100 mL) measured at surface, mid- and bottom depths at the Camps Bay outfall sites during the 2019 winter and 2020 summer surveys. The enterococci counts measured at beach sites are included in the surface plot (B1, B2 and B3).

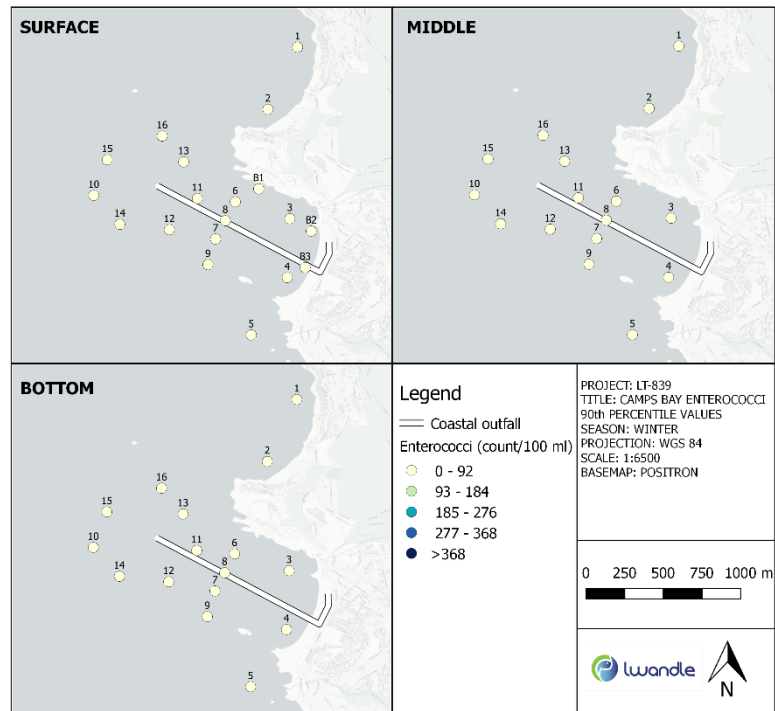


Figure 5.12: Map showing the 90th percentile values of enterococci (count/100 mL) at the surface, middle and bottom at the Camps Bay outfall sites during the 2019 winter survey. The beach sites are included in the surface plot (B1, B2 and B3).

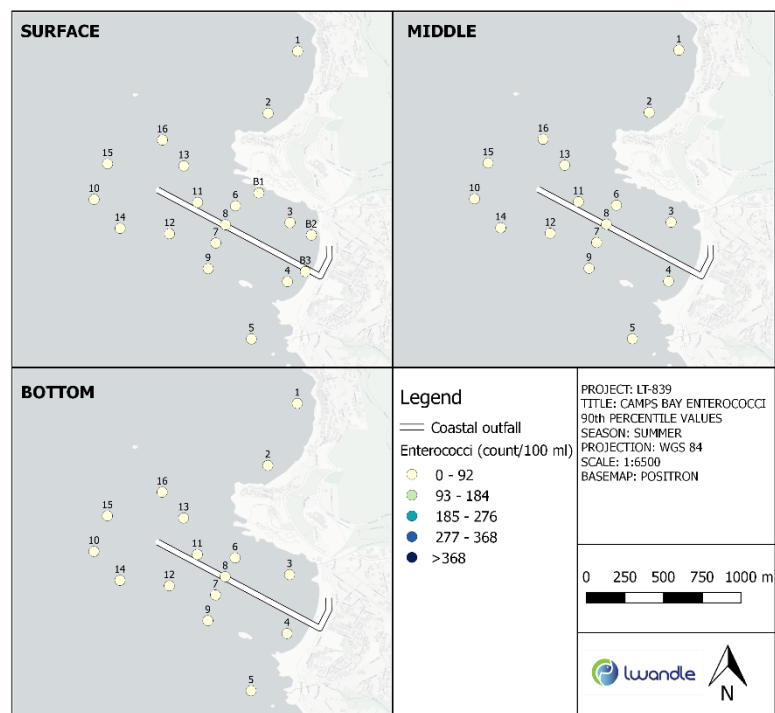


Figure 5.13: Map showing the 90th percentile values of enterococci (count/100 mL) at the surface, middle and bottom at the Camps Bay outfall sites during the 2020 summer survey. The beach sites are included in the surface plot (B1, B2 and B3).

5.5.2 Total Suspended Solids

Total suspended solids (TSS) concentrations were generally higher during the winter survey than the summer survey in surface, middle and bottom waters surrounding the Camps Bay outfall (Figure 5.14, Figure 5.15 and Figure 5.16). Outliers were recorded during the winter at a number of sites at all depths. The largest outlier was recorded at site CB16 with a concentration of 40 mg/L in surface waters during week 3 (Figure 5.14).

Median TSS concentrations were relatively higher (most sites were >5 mg/L) in mid and bottom waters compared to surface waters during the winter survey period (Figure 5.15). The highest median concentration was recorded at CB12 (10 mg/L) in bottom waters during winter. In the summer survey, median concentrations were also relatively higher at mid and bottom waters compared to the surface and the highest concentration was recorded at CB15 (7 mg/L) in bottom waters (Figure 5.16).

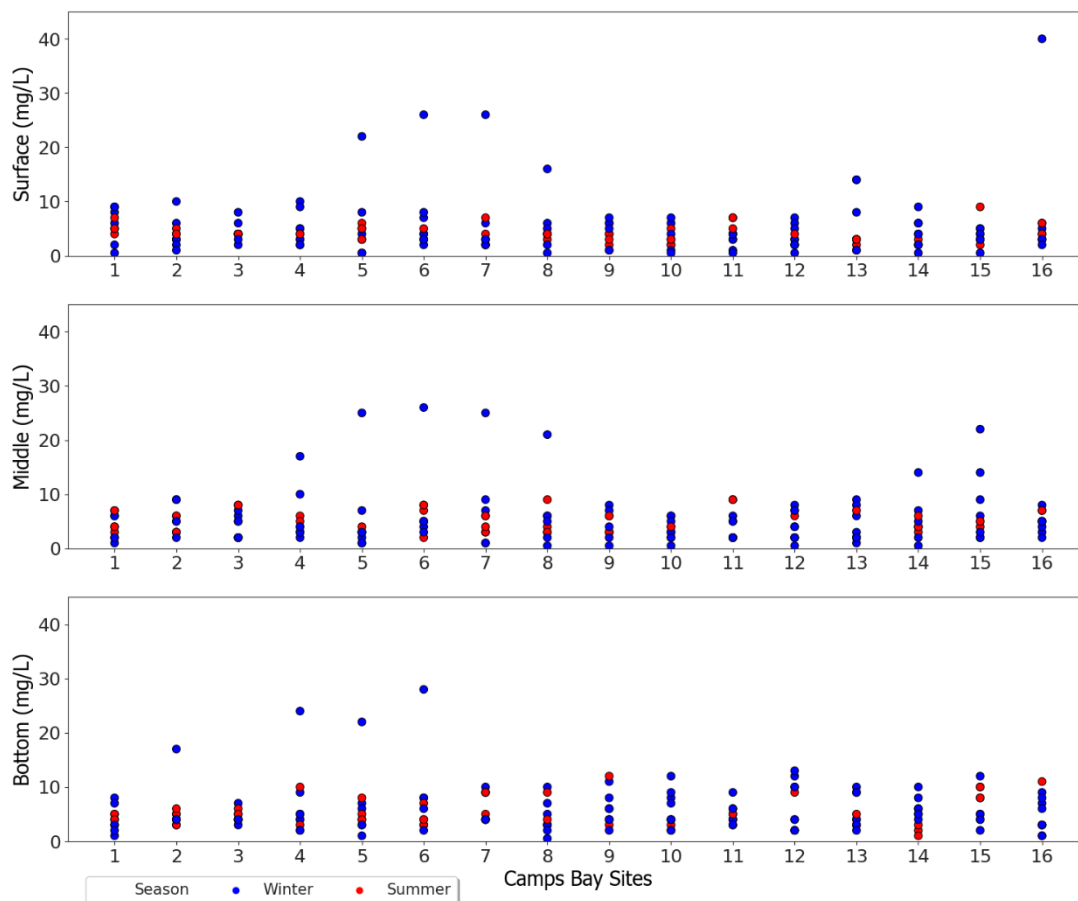


Figure 5.14: Seasonal distribution of suspended solids (mg/L) measured at surface, mid- and bottom depths at the Camps Bay outfall sites during the 2019 winter and 2020 summer surveys. Note: values below the minimum detection limit (MDL, <1) are presented as MDL/2.

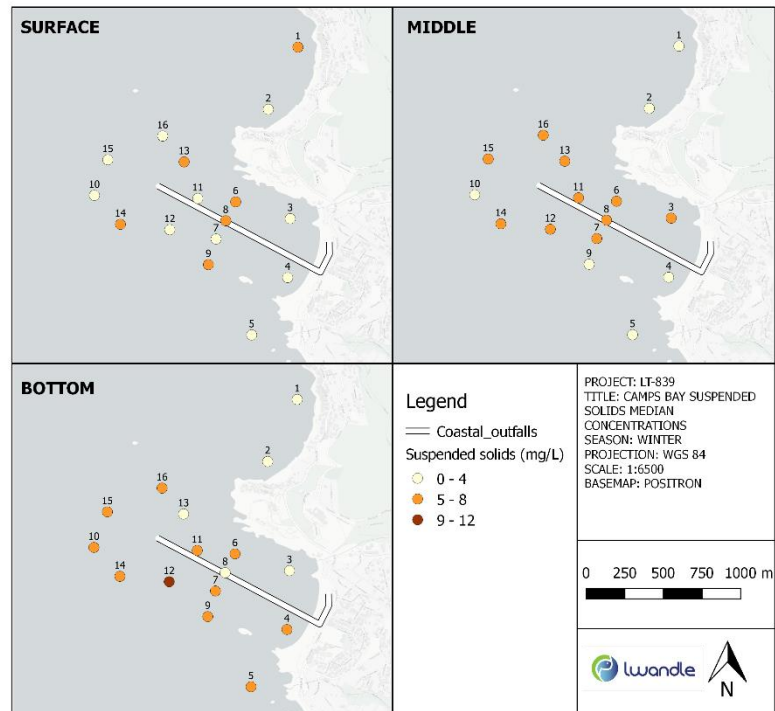


Figure 5.15: Map showing the median concentration of total suspended solids (mg/L) at the surface, middle and bottom at the Camps Bay outfall sites during the 2019 winter survey.

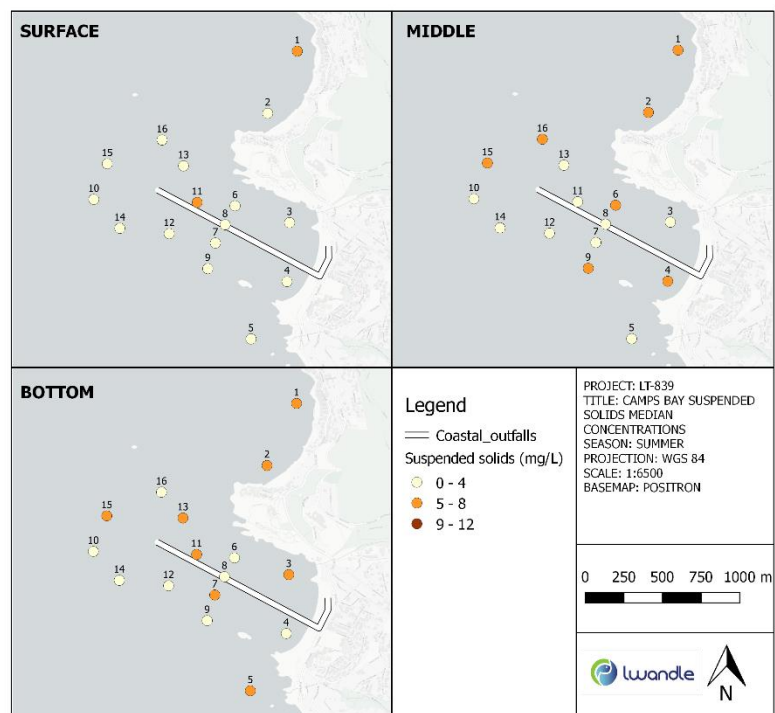


Figure 5.16: Map showing the median concentration of total suspended solids (mg/L) at the surface, middle and bottom at the Camps Bay outfall sites during the 2020 summer survey.

TSS values at all depths in the nearfield water body, represented by measurements from stations CB3, CB4, CB6, CB7, CB8, CB9, CB11, CB12, CB13 and CB14, were compliant with the stipulated guidelines during both the winter and summer monitoring periods. During both monitoring periods, median values in surface, mid and bottom waters fell into the ranges defined in Table 3.2 (Table 5.4). For this determination nearfield sites were grouped to increase replication but with further monitoring and sample collection, this approach will be re-examined and where possible, site-specific comparisons to guidelines will be made

Table 5.4: Median total suspended solids values (mg/L) in surface, mid and bottom waters measured at nearfield sites surrounding the Camps Bay outfall.

	Depth		
	Surface	Mid	Bottom
Winter			
n	60	60	60
Median	4	5	5
Summer			
n	40	40	40
Median	4	4	4

5.5.3 Total Organic Carbon

No clear seasonal pattern was seen in total organic carbon (TOC) concentrations at the Camps Bay sites (Figure 5.17, Figure 5.18 and Figure 5.19). In bottom waters during the winter survey, an outlier was recorded at site CB11 where the TOC concentration was 11 mg/L during week 4. With the exception of the outlier, TOC concentrations in surface, middle and bottom waters at Camps Bay were low and ranged between 0.3 and 2.6 mg/L during the winter survey and 0.5 and 2.8 mg/L during the summer survey (Figure 5.17). Both the winter and summer surveys had high inter-week variation.

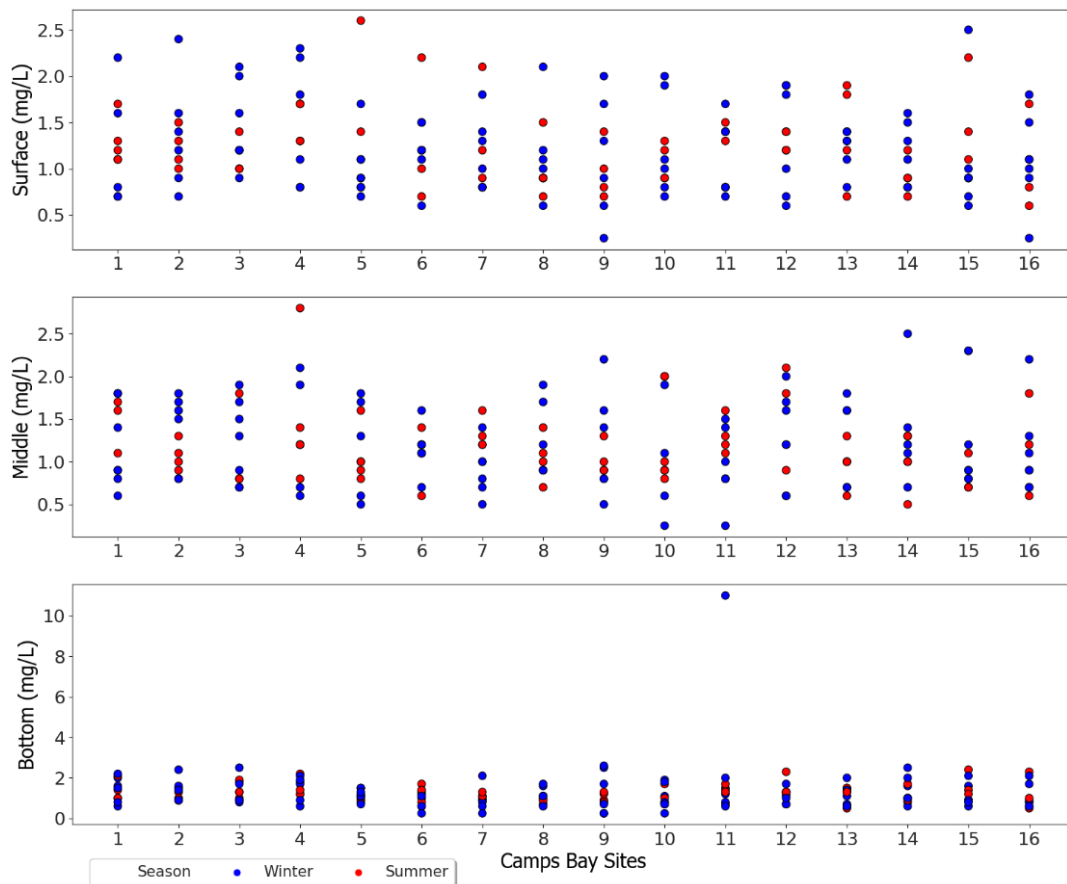


Figure 5.17: Seasonal distribution of total organic carbon (mg/L) measured at surface, mid- and bottom depths at the Camps Bay outfall sites during the 2019 winter and 2020 summer surveys. Note: values below the minimum detection limit (MDL, <0.5 mg/L) are presented as MDL/2. Note that the bottom depth plot has a different scale on the y-axis to aid presentation.

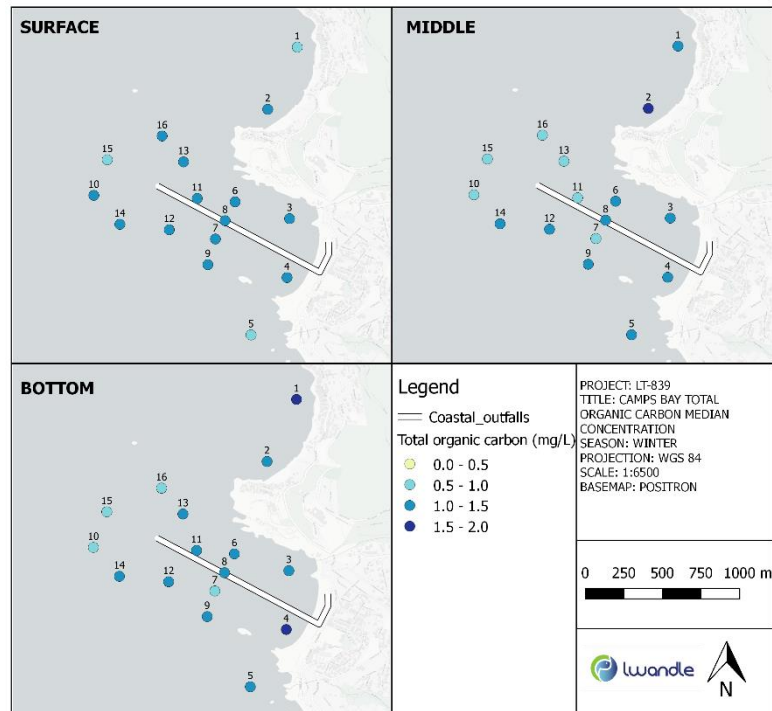


Figure 5.18: Map showing the median concentration of total organic carbon (mg/L) at the surface, middle and bottom at the Camps Bay outfall sites during the 2019 winter survey.

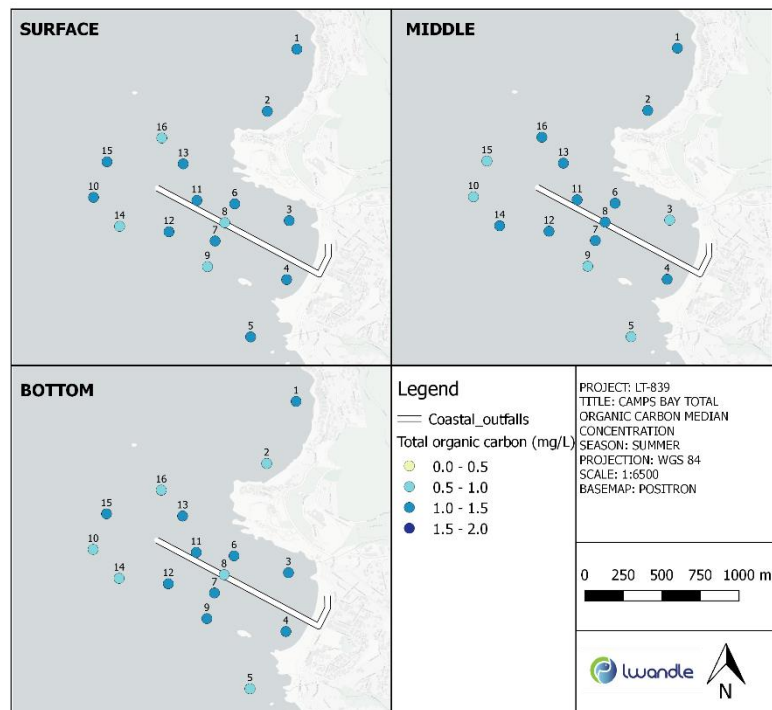


Figure 5.19: Map showing the median concentration of total organic carbon (mg/L) at the surface, middle and bottom at the Camps Bay outfall sites during the 2020 summer survey.

5.5.4 Orthophosphate

Orthophosphate results for the 2019 winter survey are not available due to operational problems experienced in the analysis of samples at the laboratory. The orthophosphate concentrations at sites surrounding the Camps Bay outfall sampled during the 2020 summer survey are presented in the summer data report (LT-839 DTR_02_V3). Concentrations ranged from 9 to 82 $\mu\text{g/L}$. Median orthophosphate concentrations ranged from 30 to 75 $\mu\text{g/L}$ (Figure 5.20). The lowest concentrations were measured in surface waters at sites CB10 (37 $\mu\text{g/L}$), CB14 (30 $\mu\text{g/L}$) and CB15 (30 $\mu\text{g/L}$) whilst higher concentrations (>60 $\mu\text{g/L}$) were mostly recorded in bottom waters.

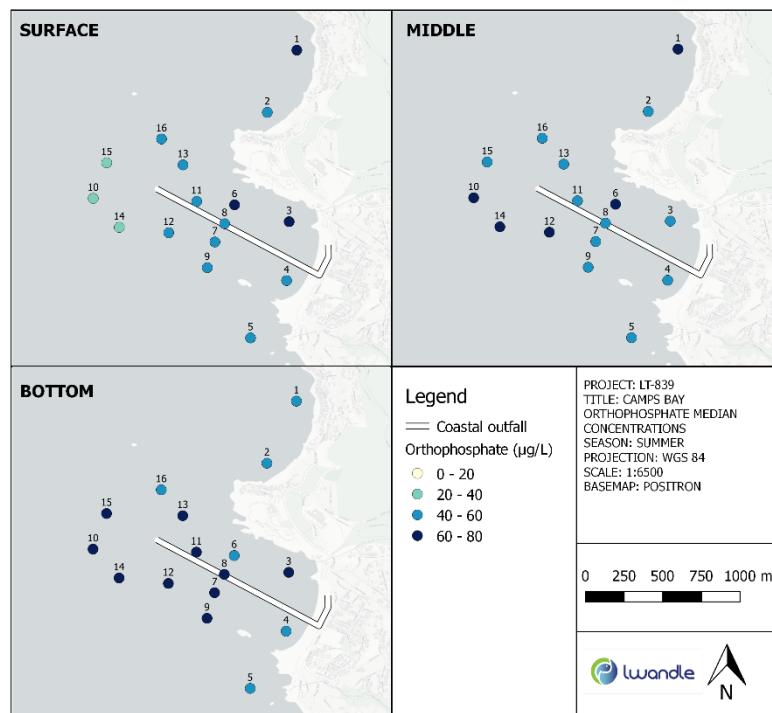


Figure 5.20: Map showing the median concentration of orthophosphate ($\mu\text{g/L}$) at the surface, middle and bottom at the Camps Bay outfall during the 2020 summer survey.

Orthophosphate values at mid and bottom depths in the nearfield water body, represented by measurements from stations CB3, CB4, CB6, CB7, CB8, CB9, CB11, CB12, CB13 and CB14, were compliant with the stipulated guidelines during the summer monitoring period with the median values in surface, mid and bottom waters falling into the ranges defined in Table 3.2 (Table 5.5). For this determination nearfield sites were grouped to increase replication but with further monitoring and sample collection, this approach will be re-examined and where possible, site-specific comparisons to guidelines will be made.

Table 5.5: Median orthophosphate values ($\mu\text{g/L}$) in surface, mid and bottom waters measured at nearfield sites surrounding the Camps Bay outfall.

	Depth		
	Surface	Mid	Bottom
Summer			
n	40	40	40
Median	54	57	65

5.5.5 Ammonia

Ammonia results for the 2019 winter survey are not available due to operational problems experienced in the analysis of samples at the laboratory. The ammonia concentrations at sites sampled in Camps Bay during the 2020 summer survey are presented in the summer data report (LT-839 DTR_02_V3). Concentrations were low, ranging from <5 to $36 \mu\text{g/L}$. Most of the measurements (65% of all measurements) were below the MDL and no exceedances of the recommended guideline ($600 \mu\text{g/L}$) were recorded (Figure 5.21).

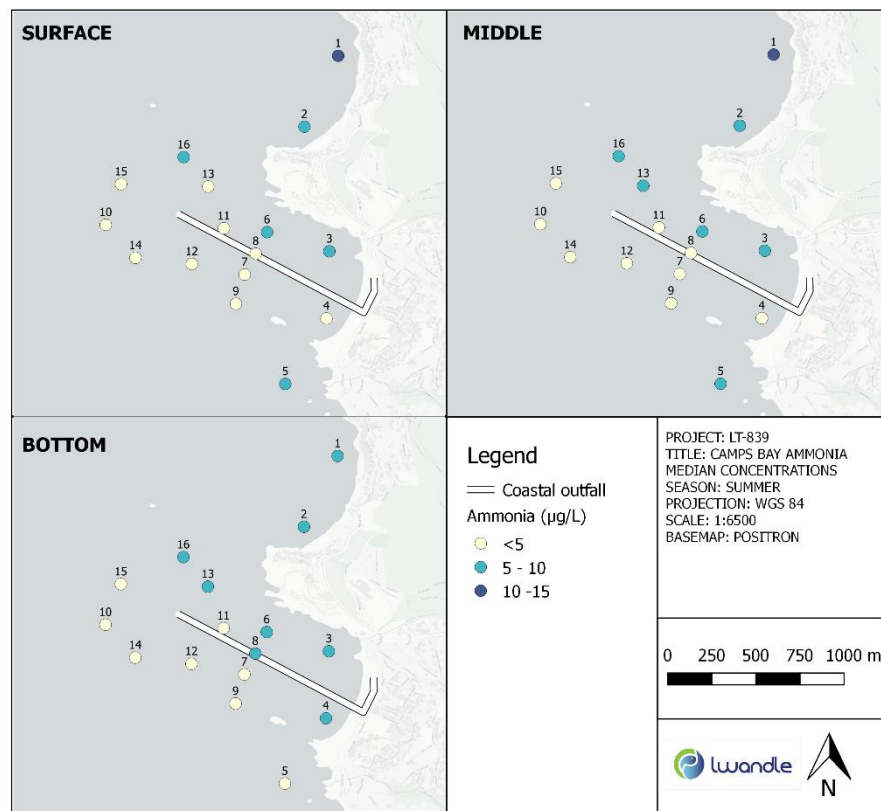


Figure 5.21: Map showing the median concentration of ammonia ($\mu\text{g/L}$) at the surface, middle and bottom at the Camps Bay outfall sites during the 2020 summer survey.

5.5.6 Toxicity

The two nearshore sites sampled during the first year of monitoring showed no toxicity effects of seawater obtained from near the discharge on sea urchins (*Tripneutes gratilla* and *Echinometra mathaei*) in terms of fertilisation rates in either of the winter or summer sampling periods (Table 5.6).

Table 5.6: Sea urchin seawater toxicity test results. Samples were obtained from two nearshore sites in the vicinity of the Camps Bay outfall on alternate days during the winter (August-September 2019) and summer (February-March 2020) sampling periods in the first year of monitoring. Toxicity classification is based on mean (n=4) fertilisation success rates.

Date	Season	Site	Species	Mean % Fertilisation Success	Std Dev	Toxicity Categorisation
26/09/2019	Winter	CB-TT1	<i>T. gratilla</i>	98.50	0.58	Not toxic
		CB-TT2	<i>T. gratilla</i>	98.50	0.58	Not toxic
30/09/2019		CB-TT1	<i>T. gratilla</i>	98.75	0.50	Not toxic
		CB-TT2	<i>T. gratilla</i>	98.50	0.58	Not toxic
2/10/2019		CB-TT1	<i>T. gratilla</i>	97.50	0.58	Not toxic
		CB-TT2	<i>T. gratilla</i>	97.50	0.58	Not toxic
5/10/2019		CB-TT1	<i>T. gratilla</i>	98.75	0.50	Not toxic
		CB-TT2	<i>T. gratilla</i>	98.75	0.50	Not toxic
6/10/2019		CB-TT1	<i>T. gratilla</i>	98.50	0.58	Not toxic
		CB-TT2	<i>T. gratilla</i>	98.75	0.50	Not toxic
8/10/2019		CB-TT1	<i>E. mathaei</i>	98.50	0.58	Not toxic
		CB-TT2	<i>E. mathaei</i>	98.50	0.58	Not toxic
20/03/2020	Summer	CB-TT1	<i>E. mathaei</i>	97.00	0.82	Not toxic
		CB-TT2	<i>E. mathaei</i>	97.50	0.58	Not toxic
23/03/2020		CB-TT1	<i>E. mathaei</i>	97.50	0.58	Not toxic
		CB-TT2	<i>E. mathaei</i>	97.25	0.96	Not toxic

5.6 EFFECTS ON LOCAL MARINE ECOLOGY

Growth rates and trace metal accumulation in mussels (*Mytilus galloprovincialis*) at fixed monitoring stations surrounding the Camps Bay outfall and two control stations were compared across the winter 2019 and summer 2020 surveys. Results (detailed in APPENDIX D: BIOMONITORING PROGRAMME, ANNUAL REPORT) indicated that mussel growth rates at the Camps Bay outfall were greater during winter than in summer. Growth rates also appeared to be slightly higher at the stations located in close proximity to the outfall than those further afield.

Trace metal concentrations in mussels were higher during winter than in summer at stations surrounding the Camps Bay outfall, with generally low levels relative to the baseline levels measured during summer, particularly for zinc (baseline: 33.6 mg/kg, outfall sites: 24.15-

33.22 mg/kg excluding CB8: 34.04 mg/kg) and nickel (baseline: 557.48, outfall sites: 157.51-198.15 µg/kg) total wet weights. There was no evidence to suggest that metal bioaccumulation was higher at stations in close proximity to the outfall than those further afield.

5.7 HYDRODYNAMIC MODELLING, PLUME BEHAVIOUR AND EFFECTS ON HUMAN HEALTH

Results of the hydrodynamic modelling conducted by PRDW (detailed in Appendix F) suggest that for TSS a mixing zone distance of 115 m from the discharge is required to meet the required dilution of 1 550 (as determined by the CCT, detailed in APPENDIX F) in winter/spring, whereas in summer/autumn a mixing zone distance of 160 m is predicted. For *E. coli*, distances of 800 m and 600 m are required in winter/spring and summer/autumn respectively to meet the 90th percentile water quality guideline of 500 cfu/100 mL (as defined in DEA 2012 and referred to in APPENDIX F). For enterococci, distances of 260 m and 250 m are required in winter/spring and summer/autumn to meet the 90th percentile water quality guideline of 185 cfu/100 mL. This indicates that the extent of the mixing zone required for *E. coli* count compliance is larger than that of the initially estimated ZID. The modelling suggests that the extent of the mixing zone surrounding the Camps Bay outfall aligns with what was originally estimated by CCT, with the required dilution and guidelines being met within 274 m from the outfall for TSS and enterococci. Non-compliance to the recommended *E. coli* guideline is not limited to being within the estimated ZID (274 m) nor is it limited to the 300 m mixing zone which is generally considered to be appropriate for an offshore discharge in an open coast system (Anchor, 2015).

During typical metocean conditions, hydrodynamic modelling showed that the plume from the Camps Bay outfall is advected in a northerly direction, alongshore. However, during upwelling events that occur predominantly in summer, the seabed plume is forced onshore at Camps Bay Beach. On occasion, this resulted in enterococci and *E. coli* concentrations at Camps Bay Beach that exceeded 185 and 500 cfu/100 mL respectively. Periodic exceedances of these concentrations were also observed at Maidens Cove and at Clifton 1st and 4th Beaches, mainly during summer, although *E. coli* concentrations greater than 500 cfu/100 mL did occur at these sites in winter as well. Thus, modelling and the field measurement data reported here indicate some risk to bathers and surfers in these areas however, the duration of these peaks was short (<10% of daylight time) resulting in overall adherence to the 90th percentile guidelines of 185 and 500 cfu/100 mL for enterococci and *E. coli* at recreational sites surrounding the Camps Bay outfall. This is reflected in the laboratory results in which no exceedances of the enterococci guidelines were observed at any site. Recommendations are provided in the PRDW report in APPENDIX F.

6 APPENDIX C: GREEN POINT

6.1 DESCRIPTION OF OUTFALL

The Green Point outfall extends approximately 1.6 km offshore of Mouille Point in a north-westerly direction and discharges effluent into Table Bay, to the west of the Port of Cape Town (Figure 6.1 and Figure 6.2). It was commissioned in 1993 and serves the area from Woodstock to Bantry Bay. The diffusers are located at a depth of 26 m.

6.2 SAMPLING LOCATIONS

Figure 6.1 and Figure 6.2 shows the Green Point outfall, as well as the location of the respective sampling and instrument mooring sites during each week of sampling in the winter (August-September 2019) and summer (February-March 2020) monitoring periods. For the purposes of the initial survey design, the CCT estimated the zone of initial dilution at the Green Point outfall to be within a 256 m radius from the diffuser. This is included on the plots below.

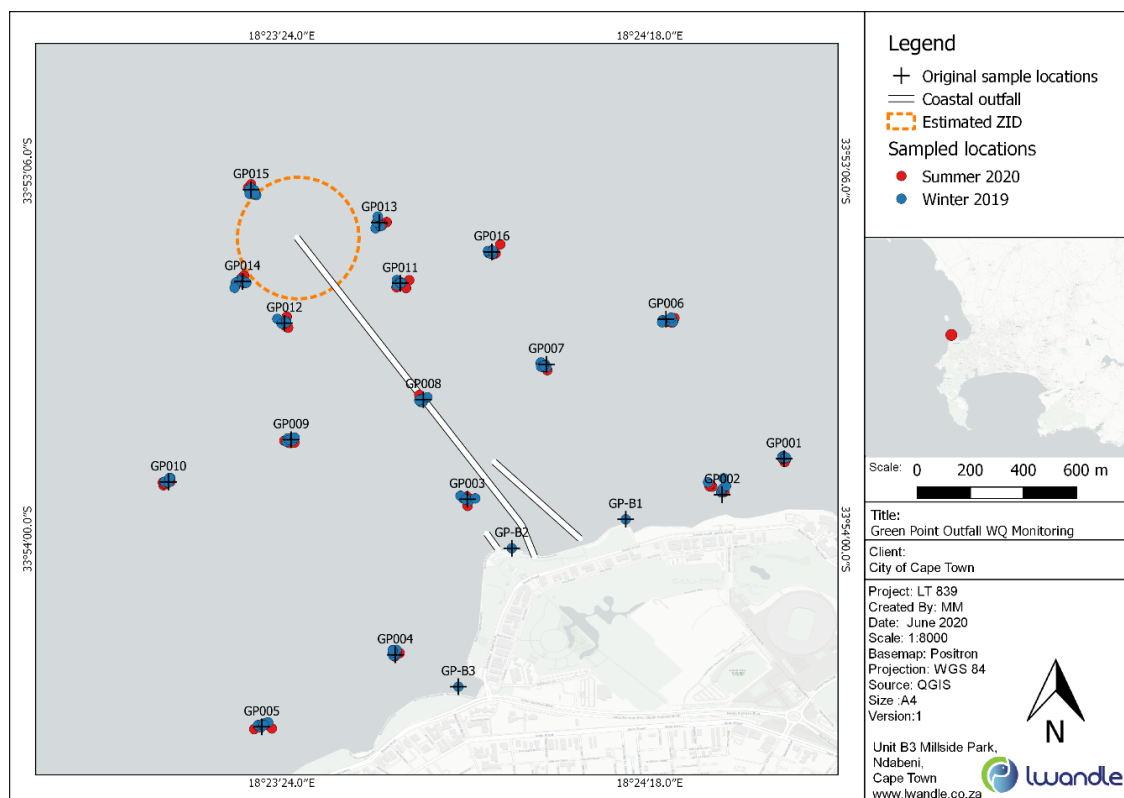


Figure 6.1: Map showing the Green Point outfall and the locations of nearshore and beach (GP-B1, GP-B2 and GP-B3) sites sampled during the winter (August-October 2019) and the summer (February-March 2020) monitoring periods.

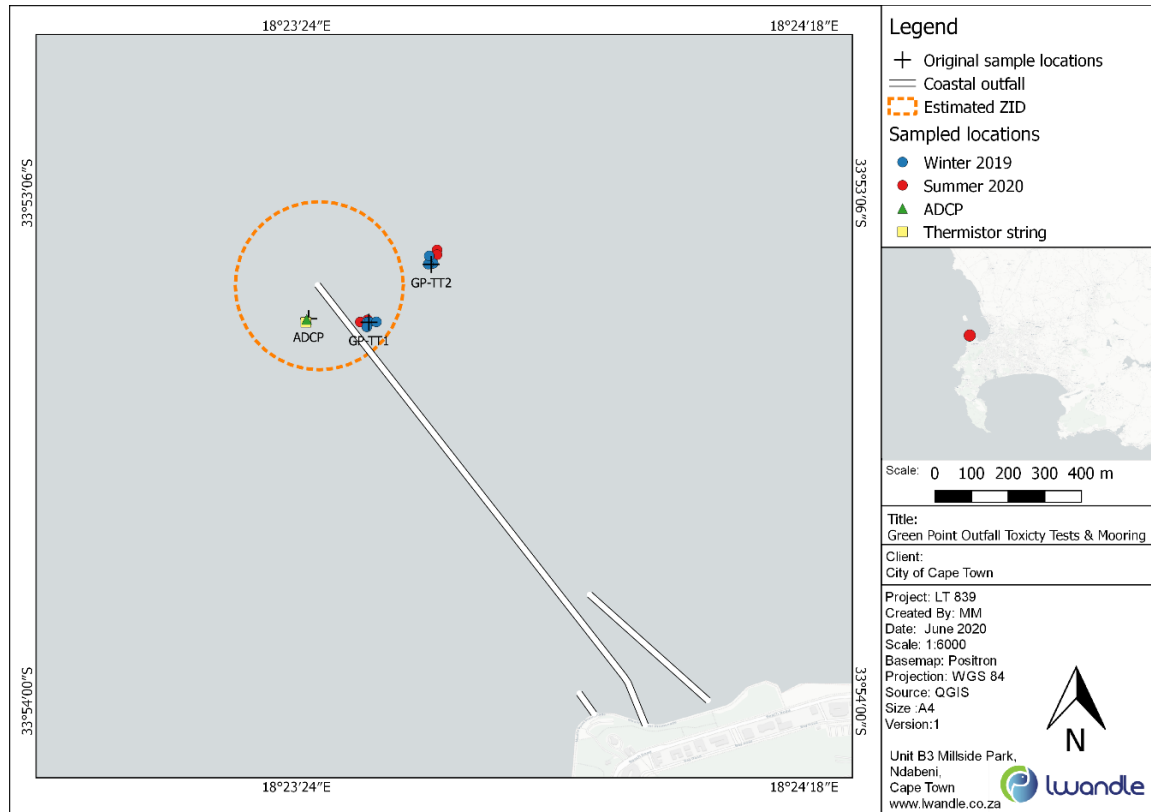


Figure 6.2: Map showing the Green Point outfall and the locations of the toxicity sites sampled during the winter (August-October 2019) and the summer (February-March 2020) monitoring periods. The locations of the ADCP and thermistor strings are also shown.

6.3 CURRENTS AND WAVES

The currents at all depths recorded at the ADCP mooring site in Green Point flowed predominantly parallel to the shoreline to the north east and south west during the winter and summer deployment period (Figure 6.3 and Figure 6.4). North-easterly flows occurred for a higher percentage of time during summer than winter although this flow direction was dominant in both seasons. Current speeds generally ranged between 0-0.4 m/s during winter and summer.

Green Point outfall received waves primarily from the west-south-west during the winter and summer deployment (Figure 6.5 and Figure 6.6). The average peak period mainly ranged between 11-14 seconds during winter and summer.

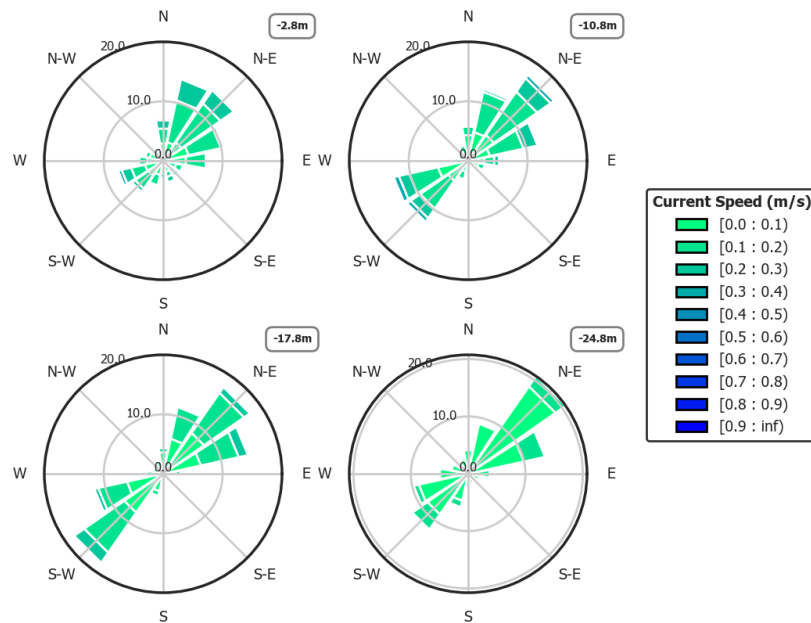


Figure 6.3: Roses showing average observed current speed and direction throughout the water column from the ADCP moored at the Green Point outfall from 21st August 2019 to 2nd October 2019 (winter).

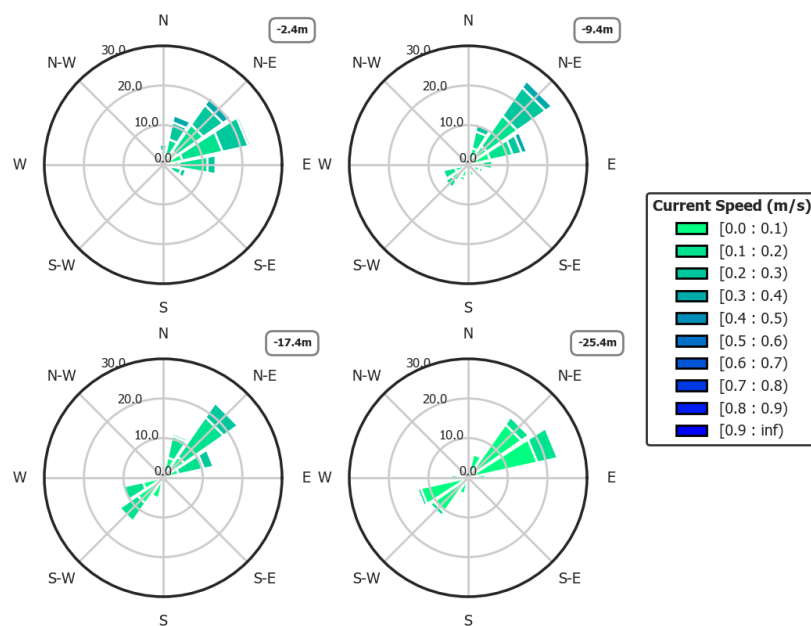


Figure 6.4: Roses showing average observed current speed and direction throughout the water column from the ADCP moored at the Green Point outfall from 12th February 2020 to 20th April 2020 (summer).

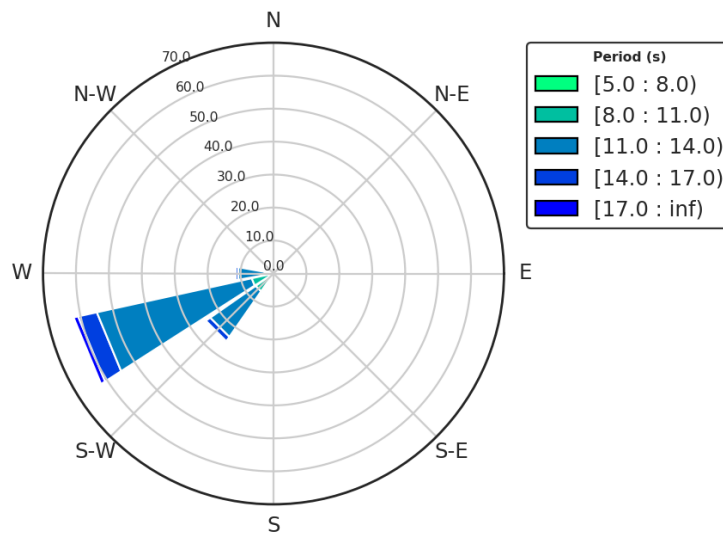


Figure 6.5: Rose showing average observed wave period and direction from the ADCP moored at the Green Point outfall from 22nd August 2019 to 2nd October 2019 (winter).

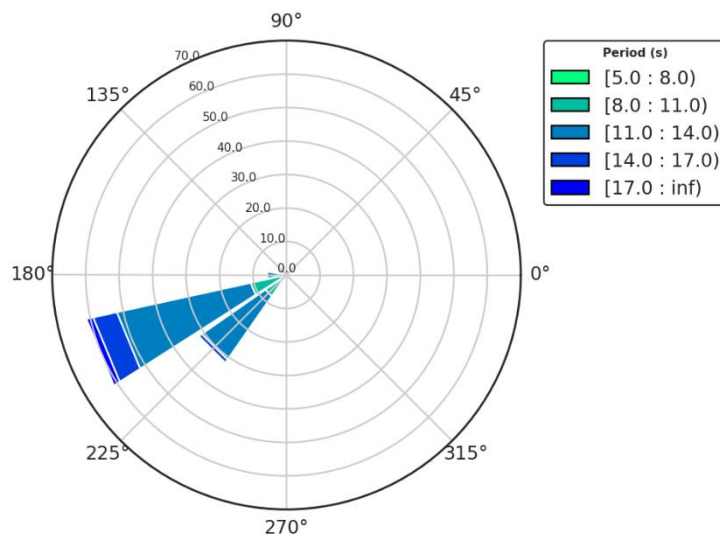


Figure 6.6: Rose showing average observed wave period and direction from the ADCP moored at the Green Point outfall from 13th February 2020 to 27th April 2020 (summer).

6.4 NEARSHORE WATER COLUMN CHARACTERISTICS

The surface, middle and bottom depth values recorded seasonally at the Green Point outfall sampling sites for each measured water quality constituent (extracted from CTD data) are presented in the plots below. Parameters are also compared to relevant guidelines where appropriate.

6.4.1 Temperature

The water column temperatures recorded during the summer survey at Green Point outfall were slightly cooler than those measured during the winter survey, characteristic of the seasonal upwelling in the region (Figure 6.7). Water column temperatures during the winter survey ranged between 9.57 and 16.15°C and between 9.82 and 14.44°C during the summer survey which are within the expected range for the region. Winter temperatures showed a greater range and a higher inter-week variation near the seabed.

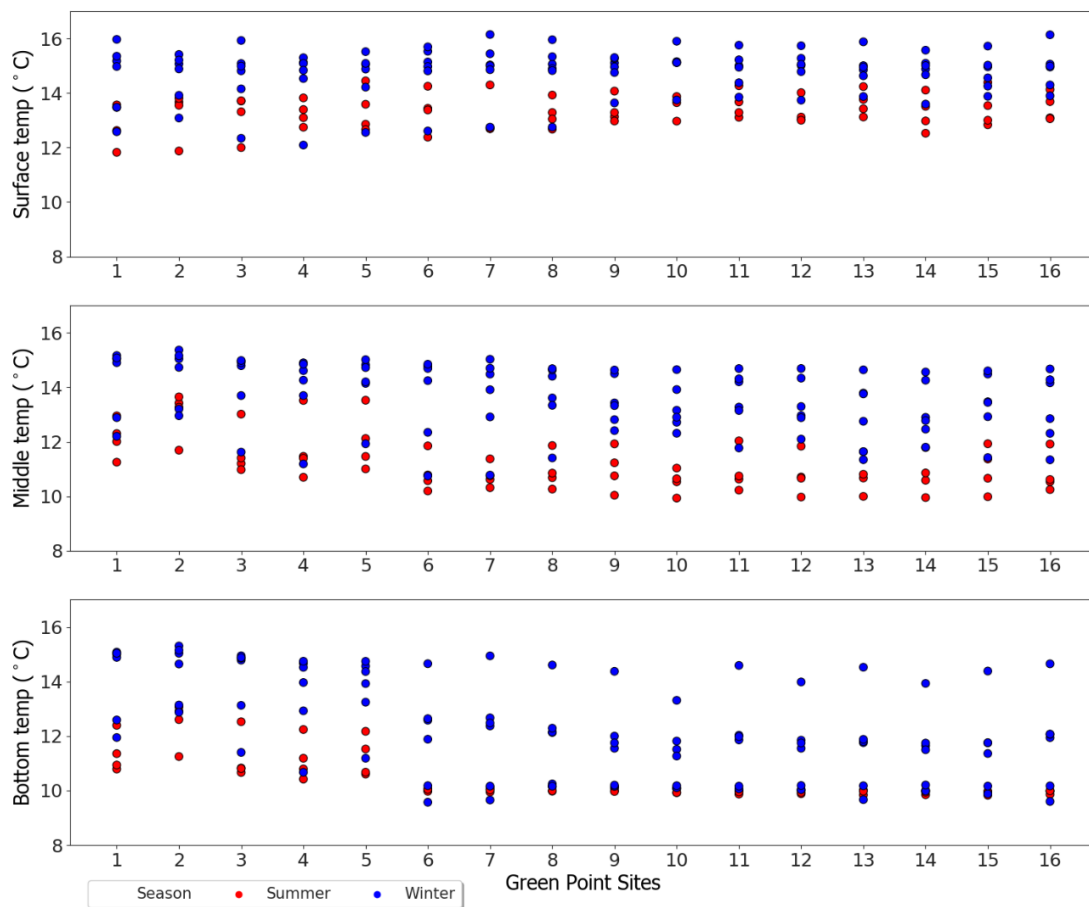


Figure 6.7: Seasonal distribution of temperature (°C) measured at the Green Point outfall sites during the 2019 winter and 2020 summer surveys.

6.4.2 Salinity

Lower salinities were generally recorded in the summer, although there were periods where salinities in the winter were lower than those measured in summer notably near the seabed (Figure 6.8). Salinities ranged between 34.73 and 35.21 PSU and 34.70 and 34.96 PSU in the winter and summer respectively. A greater range of salinities measured at all depths and higher inter-week variation was observed in winter compared to summer.

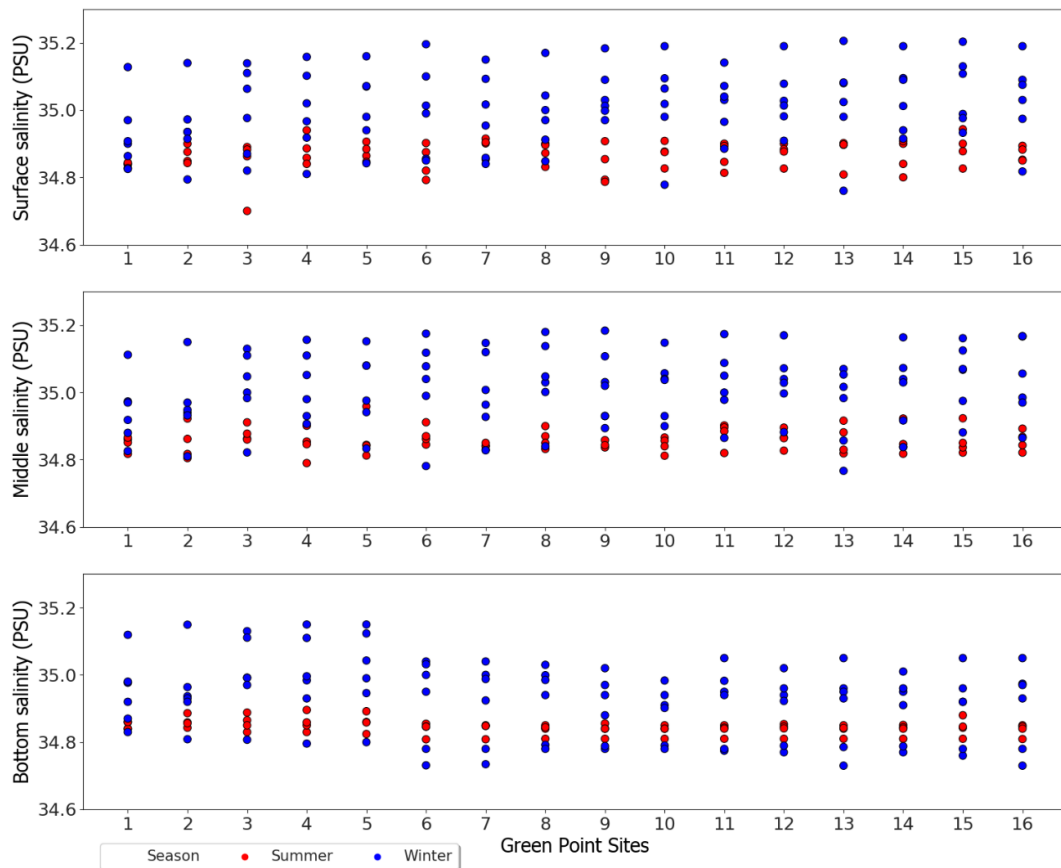


Figure 6.8: Seasonal distribution of salinity (PSU) measured at the Green Point outfall sites during the 2019 winter and 2020 summer surveys.

Measured salinity values were compliant with the DWAF (1995) stipulated guideline range (33-36 PSU) during the winter and summer monitoring periods. In the nearfield of the discharge, represented by measurements from stations GP2, GP3, GP4, GP7, GP8, GP9, GP11, GP12, GP13, GP14 and GP16, compliance was also met with the median values in each of the surface (0 – 5 m), mid (5 – 15 m) and bottom (>15 m) depth zones falling into the ranges defined in Table 3.2 (Table 6.1). For this determination nearfield sites were grouped to increase replication but with further monitoring and sample collection, this approach will be re-examined and where possible, site-specific comparisons to guidelines will be made

Table 6.1 Median salinity values (PSU) in surface (0-5 m), mid (5 – 15 m) and bottom (>15 m) waters measured at nearfield sites surrounding the Green Point outfall.

	Depth		
	Surface	Mid	Bottom
Winter			
n	614	998	871
Median	35.03	35.04	34.95
Summer			
n	407	679	598
Median	34.87	34.86	34.85

6.4.3 Turbidity

Turbidity values measured during the 2020 summer survey were considered to be erroneous due to sensor malfunction and so are not included in this report. Profiles were presented in the 2020 summer data report (LT-839 DTR_02_V3) to understand relative patterns and showed that the turbidity profiles at most sites were uniform with depth. This is similar to the winter survey (LT-839 DTR_01_V2) with the exception of a few sites, mainly those closer to shore. The turbidity values recorded during the winter survey ranged between 0.45 and 48.63 FNU. Turbidity was generally increased at bottom depths, presumably due to the suspension of sediment.

6.4.4 pH

Similar to temperature and salinity, pH measured during the summer survey were generally lower than those measured during the winter survey (Figure 6.9). pH ranged between 7.99 and 8.54 in the winter and between 7.76 and 8.35 in the summer. These seasonal patterns observed are consistent with temperature as cooler waters generally have a lower pH due to capacity to hold higher pCO₂ levels.

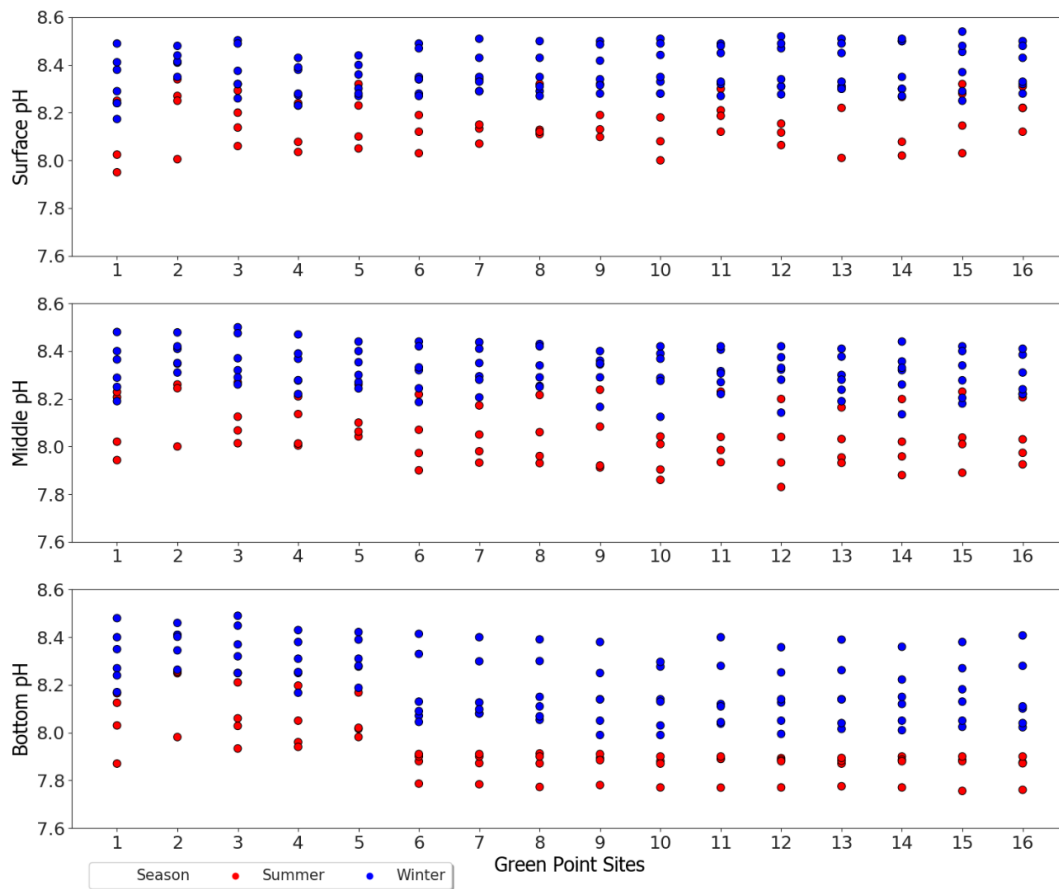


Figure 6.9: Seasonal distribution of pH measured at the Green Point outfall sites during the 2019 winter and 2020 summer surveys.

pH values at all depths in the nearfield water body, represented by measurements from stations GP2, GP3, GP4, GP7, GP8, GP9, GP11, GP12, GP13, GP14 and GP16, were compliant with the stipulated guidelines during the winter monitoring period with the median values in each of the surface (0 – 5 m), mid (5 – 15 m) and bottom (>15 m) depth zones falling into the ranges defined in Table 3.2 (Table 6.2). However, during summer the surface pH at sites in the nearfield water body was slightly lower than the guideline range but was compliant with the DWAF (1995) stipulated guideline range (7.30 – 8.20). For this determination nearfield sites were grouped to increase replication but with further monitoring and sample collection, this approach will be re-examined and where possible, site-specific comparisons to guidelines will be made

It must be noted that the pH values recorded at all Green Point sites, particularly during winter are high, and many occur outside the range (7.6 – 8.1) previously recorded for the area (DEA 2015). Because high values occurred at all sites and all depths, the high pH values may be a result of instrument error, even though standard calibration procedures are conducted prior to each survey. Continued measurement of pH in future surveys will assist in establishing whether this is the case. pH measurements during the first year of monitoring should thus be considered relative. Nevertheless, relatively elevated pH (>8) indicates the presence of a mainly oxic water column

which suggests minimal remineralisation of organically rich sediments and probably no build-up of sewage effluent particulate matter in area of measurement.

Table 6.2: Median pH values in surface (0-5 m), mid (5 – 15 m) and bottom (>15 m) waters measured at nearfield sites surrounding the Green Point outfall.

	Depth		
	Surface	Mid	Bottom
Winter			
n	614	998	871
Median	8.36	8.33	8.18
Summer			
n	407	679	598
Median	8.15	8.05	7.91

6.4.5 Dissolved Oxygen

Dissolved oxygen concentrations measured at the Green Point outfall were generally lower in summer compared to winter and ranged between 4.95 and 13.14 mg/L and 1.11 and 9.93 mg/L in the winter and summer respectively (Figure 6.10). The lowest concentrations were recorded the bottom during the summer the survey specifically at sites GP6 to GP16. The recorded temperatures at these sites during both winter and summer were low (<10°C) and salinity values were lower during winter. This indicates that different water masses may be present during winter and summer which may influence the low dissolved oxygen seen in summer. This however needs further investigation with continued monitoring.

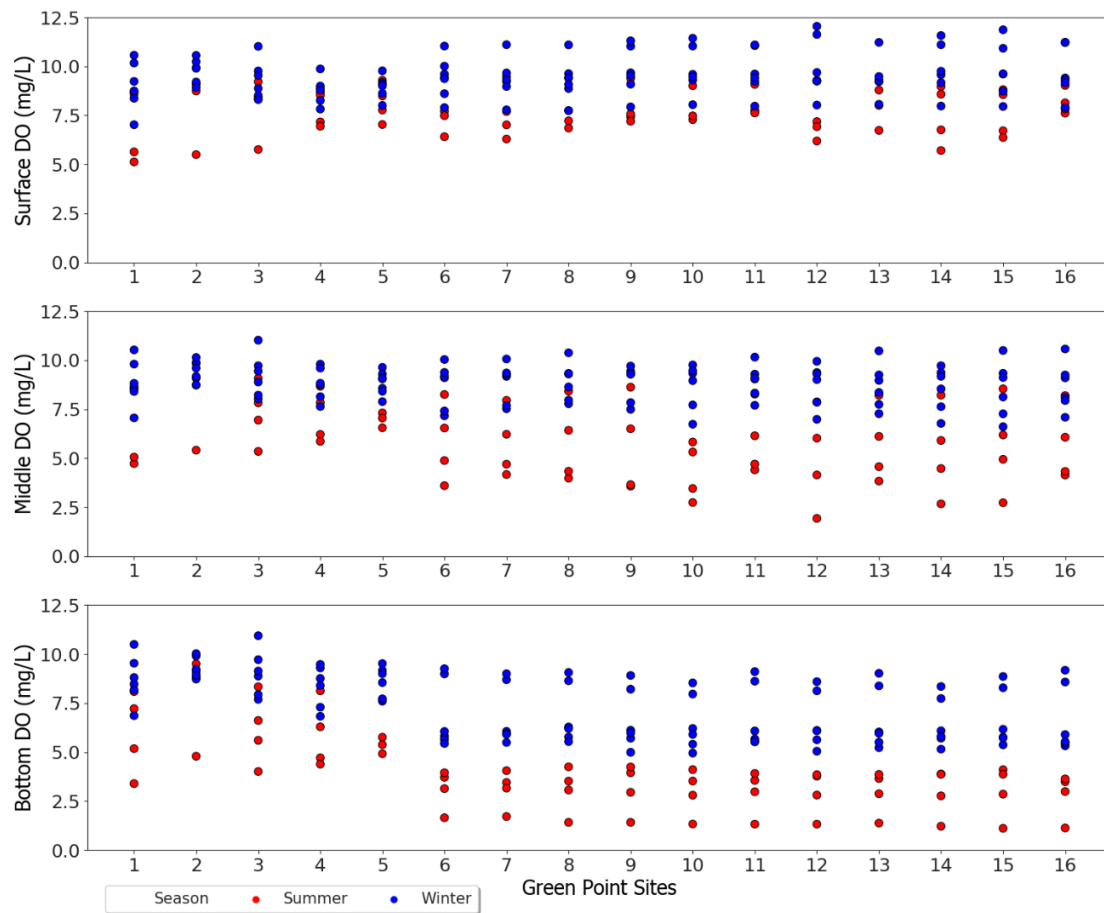


Figure 6.10: Seasonal distribution of dissolved oxygen (mg/L) measured at the Green Point outfall sites during the 2019 winter and 2020 summer surveys.

Dissolved oxygen concentrations at all depths in the nearfield water body, represented by measurements from stations GP2, GP3, GP4, GP7, GP8, GP9, GP11, GP12, GP13, GP14 and GP16, were compliant with the stipulated guidelines during both the winter and summer monitoring periods. During both monitoring periods, median values in each of the surface (0 – 5 m), mid (5 – 15 m) and bottom (>15 m) depth zones fell into the ranges defined in Table 3.2 (Table 6.3) and indicate an oxic water body at all depths in the immediate vicinity surrounding the outfall. For this determination nearfield sites were grouped to increase replication but with further monitoring and sample collection, this approach will be re-examined and where possible, site-specific comparisons to guidelines will be made.

Table 6.3: Median dissolved oxygen concentrations (mg/L) in surface (0-5 m), mid (5 – 15 m) and bottom (>15 m) waters measured at nearfield sites surrounding the Green Point outfall.

	Depth		
	Surface	Mid	Bottom
Winter			
n	614	998	871
Median	9.39	9.23	7.10
Summer			
n	407	679	598
Median	7.60	6.24	3.71

6.5 NEARSHORE AND BEACH SEAWATER QUALITY

The laboratory analysis results of enterococci, total suspended solids, total organic carbon, orthophosphate and ammonia measured seasonally in water samples obtained from surface, middle and bottom depths at sites in the vicinity of the Green Point outfall are presented in the sections below. The results of the analyses of seawater toxicity, from two sites near the outfall, to sea urchins are also included.

6.5.1 Enterococci

No clear seasonal pattern was seen in enterococci counts at sites sampled at Green Point. Individual measurements in surface and bottom waters at all sites during both seasons were mostly below 50 cfu/100mL. Similarly, in the mid-water column at most sites, individual enterococci counts in winter and summer were below 50 cfu/100 mL, however, at some sites, counts were extremely elevated compared to the other depths sampled (Figure 6.11). This is consistent with buoyant plume mixing.

During both winter and summer survey periods, the 90th percentiles in surface and bottom waters at all nearshore sites sampled at Green Point were below 110 cfu/100mL and no exceedances of the recommended DEA 2012 guideline (185 cfu/100mL, Table 3.1) were evident. At mid-water depths, repeated high enterococci counts, greater than 300 cfu/100 mL, were recorded at sites GP13 and GP14 during the winter survey and at sites GP7, GP13, GP14 and GP15 during the summer survey. The 90th percentile enterococci values at these sites during winter and summer respectively therefore exceeded the recommended guideline (Figure 6.12 and Figure 6.13). Sites GP13, GP14 and GP15 are located around the outfall diffusers and site GP7 is west and slightly inshore of these. The high values recorded at these sites may be indicative of incomplete mixing in this zone at midwater depths.

Enterococci counts at beach sites GP-B1 and GP-B2 were mostly below 50 cfu/100mL in winter and summer, however, occasionally extremely high measurements, greater than 500 cfu/100 mL were recorded at both sites. At beach site GP-B3 high enterococci counts of greater than 300 cfu/100mL were recorded during most weeks (Figure 6.11). The 90th percentile value at site GP-B1 exceeded

the guideline value during winter and those at site GP-B2 and GP-B3 exceeded the guideline value during both winter and summer (Figure 6.12 and Figure 6.13). At site GP-B3, the 90th percentile values for both seasons were particularly high: 1 040 and 1 665 cfu/100mL in winter and summer respectively. Site GP-B3 occurs at Three Anchor Bay. Monitoring at this site, conducted by the CCT, has indicated persistent and regular exceedance of the recommended guideline, which is attributed to three large stormwater drains which discharge significant volumes of contaminated water into the area (City of Cape Town 2019; Lwandle 2019).

It must be noted that percentile values calculated for each site for each season are based on 6 samples in winter and 4 samples in summer. High enterococci values thus affect the percentile values more than what could be the case if there were larger sample sizes. These patterns of non-compliance may therefore change as the monitoring plan continues.

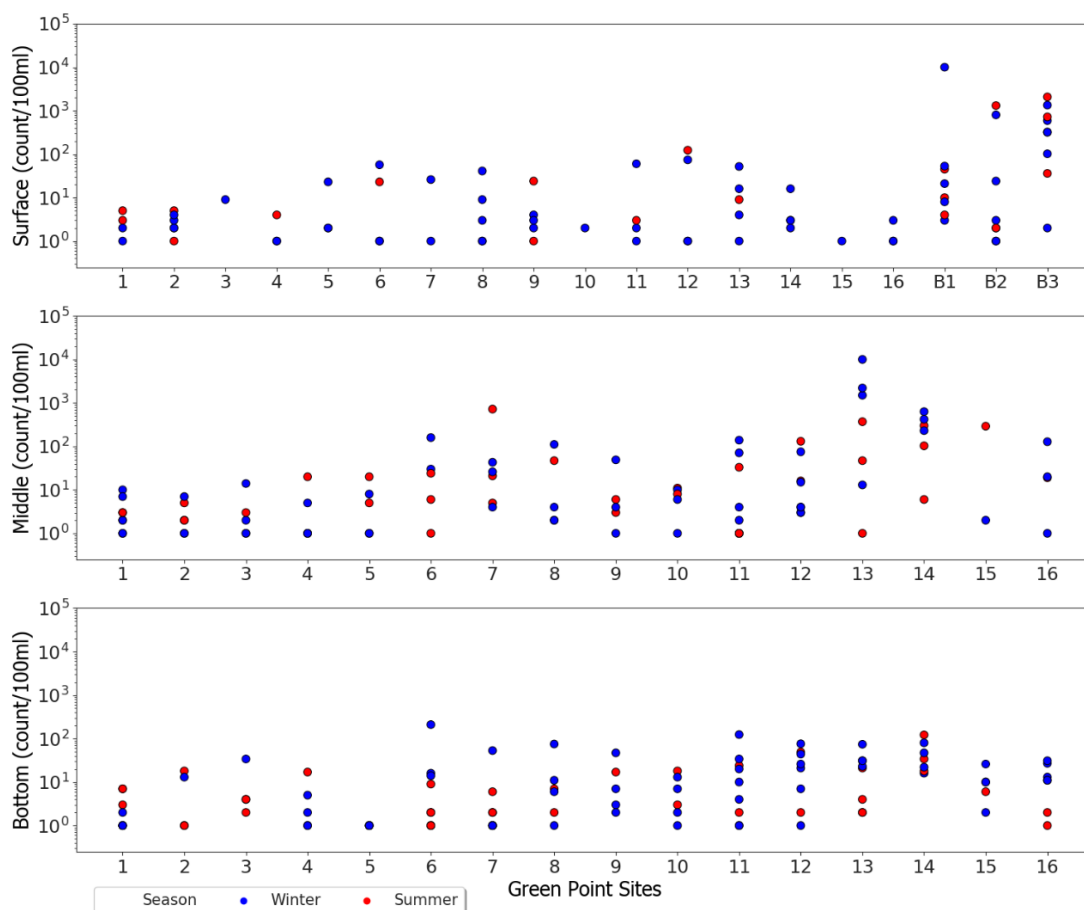


Figure 6.11: Seasonal distribution of enterococci (count/100 mL) measured at surface, mid- and bottom depths at the Green Point outfall sites during the 2019 winter and 2020 summer surveys. The enterococci counts measured at beach sites are included in the surface plot (B1, B2 and B3).

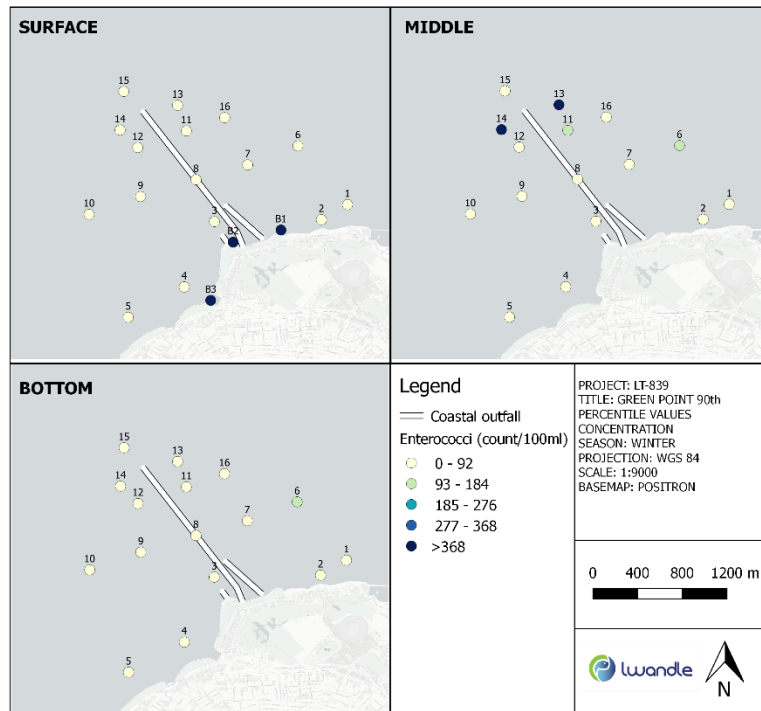


Figure 6.12: Map showing the 90th percentile values of enterococci (count/100 mL) at the surface, middle and bottom at the Green Point outfall sites during the 2019 winter survey. The beach sites are included in the surface plot (B1, B2 and B3).

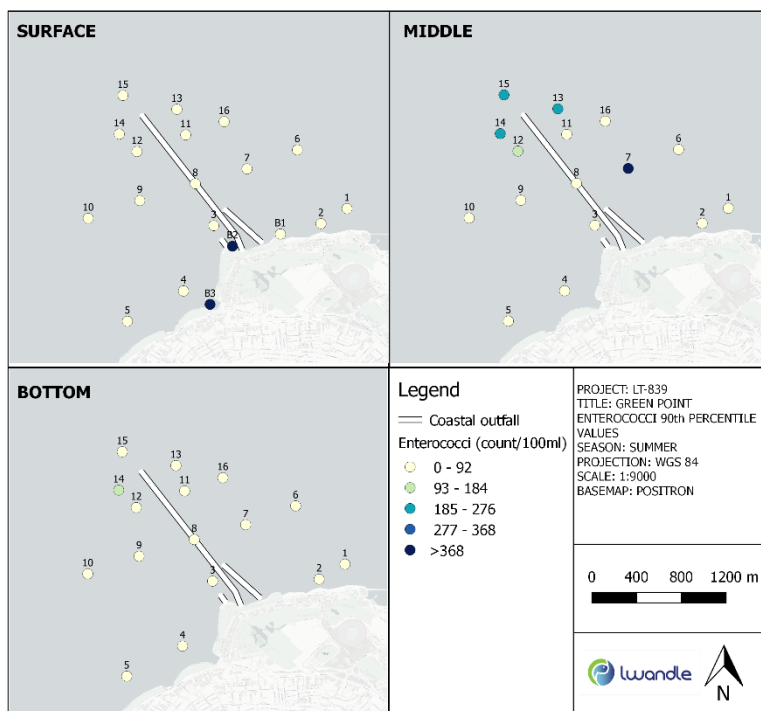


Figure 6.13: Map showing the 90th percentile values of enterococci (count/100 mL) at the surface, middle and bottom at the Green Point outfall sites during the 2019 summer survey. The beach sites are included in the surface plot (B1, B2 and B3).

6.5.2 Total Suspended Solids

Total suspended solids (TSS) concentrations were generally higher during the winter survey than during the summer survey in surface, middle and bottom waters surrounding the Green Point outfall (Figure 6.14, Figure 6.15 and Figure 6.16). Outliers were recorded at a number of sites at all depths. The largest outlier was recorded at site GP8 with a concentration of 140 mg/L in bottom waters during week 4 (Figure 6.14).

Median TSS concentrations were relatively higher (all sites were >5 mg/L) in bottom waters compared to surface and mid waters during the winter survey period (Figure 6.15). The highest median concentration was recorded at GP2 (16 mg/L) in bottom waters during winter. In the summer survey, median concentrations were mostly below 5 mg/L with the exceptions of sites GP13 (surface), GP8, GP12 and GP14 (mid) and GP2, GP7 and GP13 (bottom) which ranged between 5-8 mg/L (Figure 6.16).

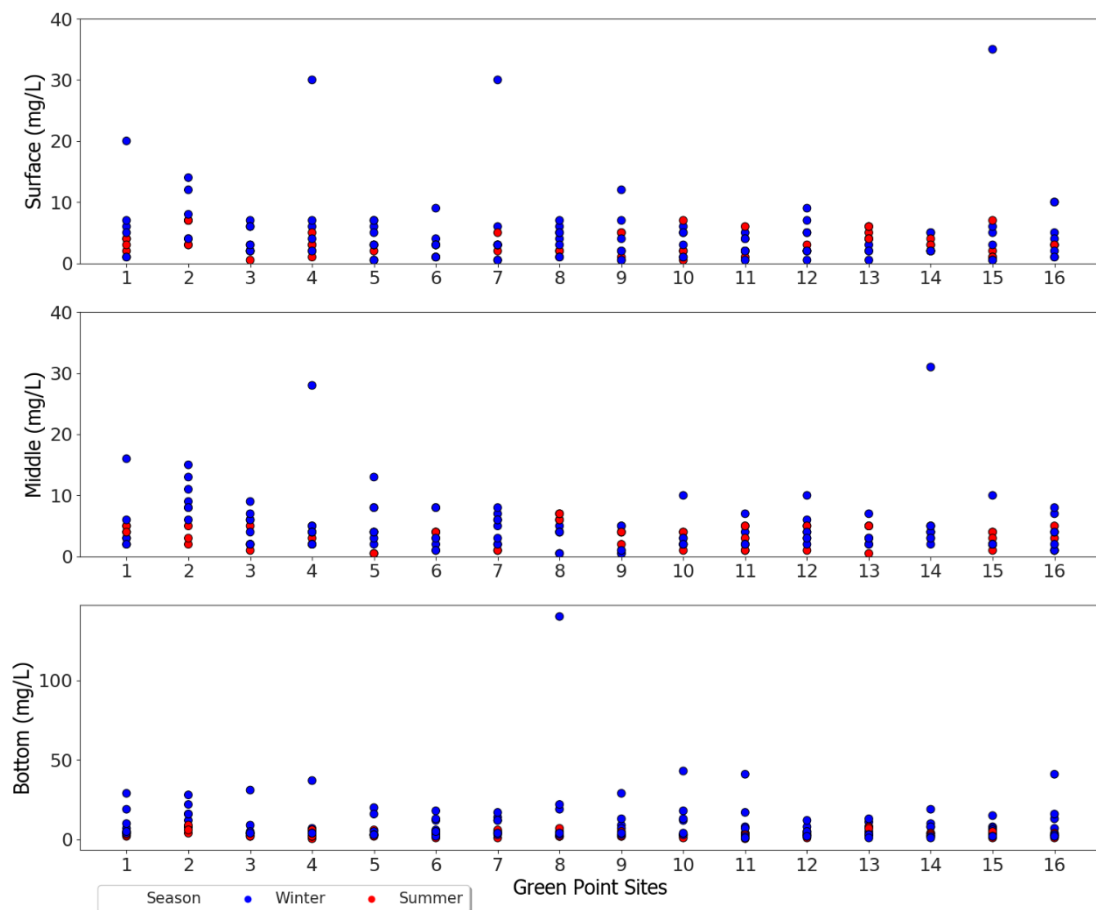


Figure 6.14: Seasonal distribution of suspended solids (mg/L) measured at surface, mid- and bottom depths at the Green Point outfall sites during the 2019 winter (blue circles) and 2020 summer (red circles) surveys. Note: values below the minimum detection limit (MDL, <1) are presented as MDL/2. Note that the bottom depth plot y-axis has a different scale to aid presentation.

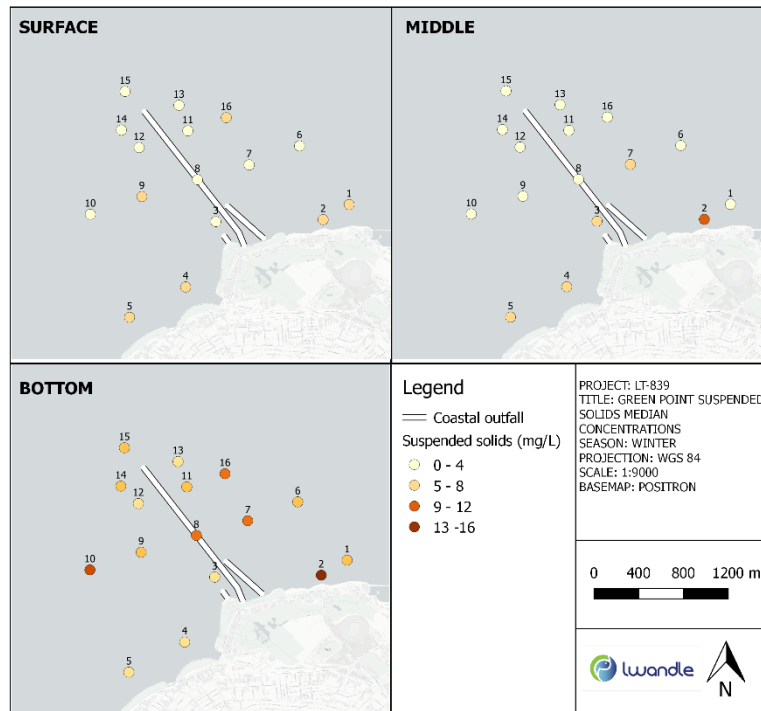


Figure 6.15: Map showing the median concentration of total suspended solids (mg/L) at the surface, middle and bottom at the Green Point outfall sites during the 2019 winter survey.

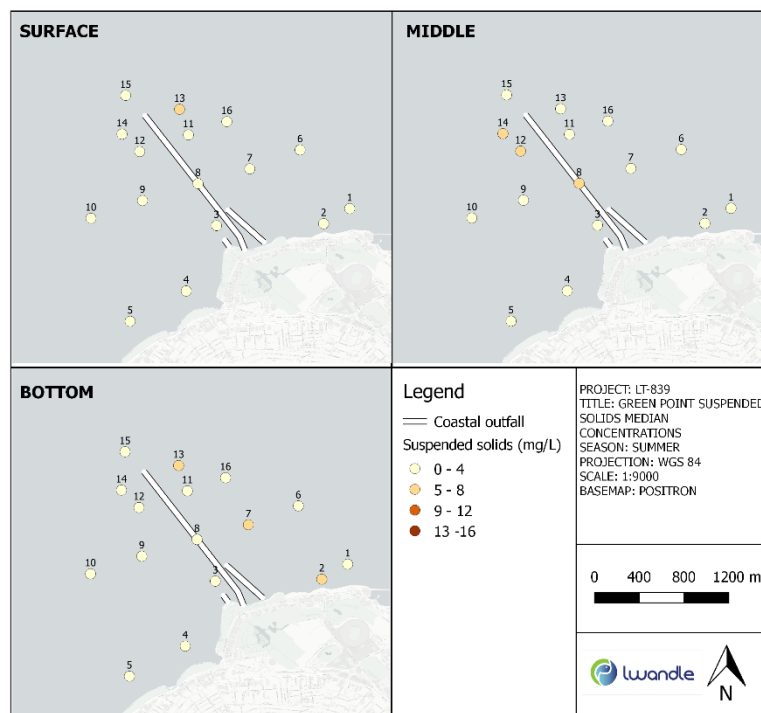


Figure 6.16: Map showing the median concentration of total suspended solids (mg/L) at the surface, middle and bottom at the Green Point outfall sites during the 2020 summer survey.

TSS values at all depths in the nearfield water body, represented by measurements from stations GP2, GP3, GP4, GP7, GP8, GP9, GP11, GP12, GP13, GP14 and GP16, were compliant with the stipulated guidelines during both the winter and summer monitoring periods. During both monitoring periods, median values in surface, mid and bottom waters fell into the ranges defined in Table 3.2 (Table 6.4). For this determination nearfield sites were grouped to increase replication but with further monitoring and sample collection, this approach will be re-examined and where possible, site-specific comparisons to guidelines will be made.

Table 6.4: Median total suspended solids values (mg/L) in surface, mid and bottom waters measured at nearfield sites surrounding the Green Point outfall.

	Depth		
	Surface	Mid	Bottom
Winter			
n	66	66	66
Median	4	4	8
Summer			
n	44	44	44
Median	3	3	3

6.5.3 Total Organic Carbon

No clear seasonal pattern was seen in total organic carbon (TOC) concentration at the Green Point sites (Figure 6.17, Figure 6.18 and Figure 6.19). TOC concentrations in surface, mid- and bottom waters at Green Point were generally low and ranged between 0.5 and 3.7 mg/L during the winter survey and 0.6 and 3.6 mg/L during the summer survey (Figure 6.17). Both the winter and summer survey had high inter-week variation.

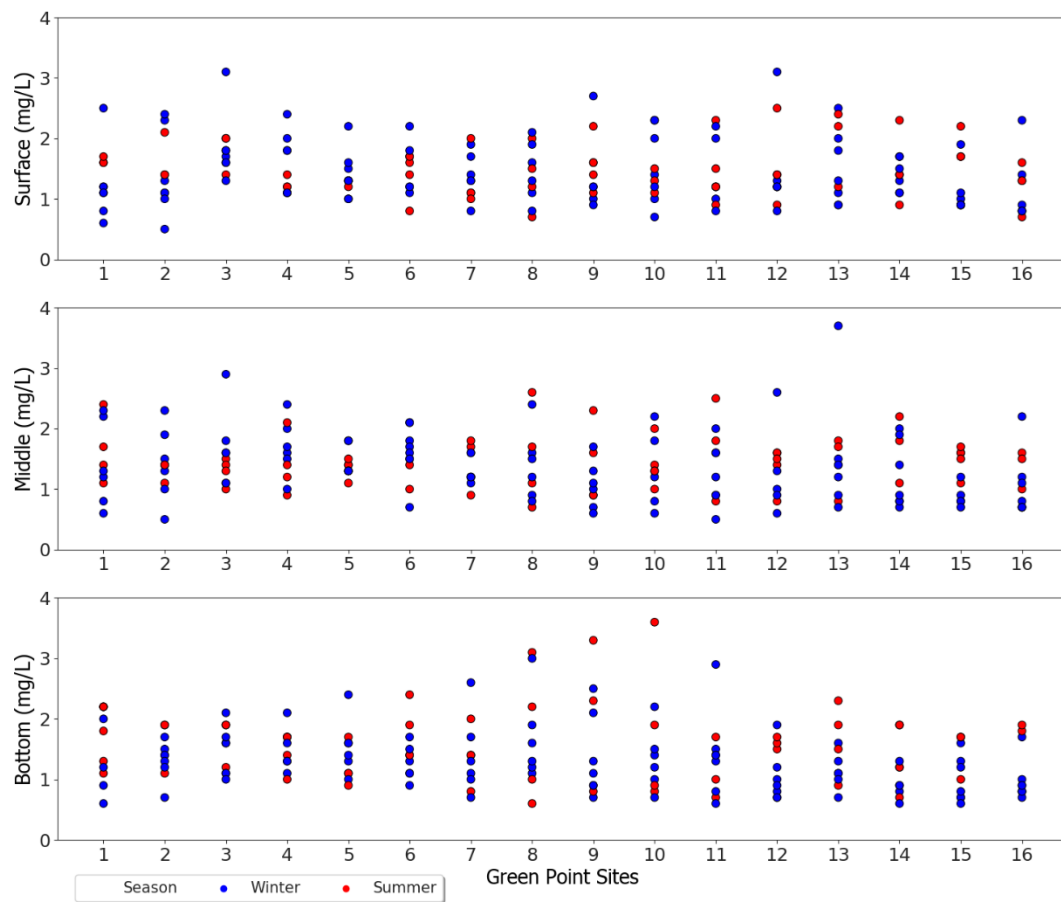


Figure 6.17: Seasonal distribution of total organic carbon (mg/L) measured at surface, mid- and bottom depths at the Green Point outfall sites during the 2019 winter and 2020 summer surveys.

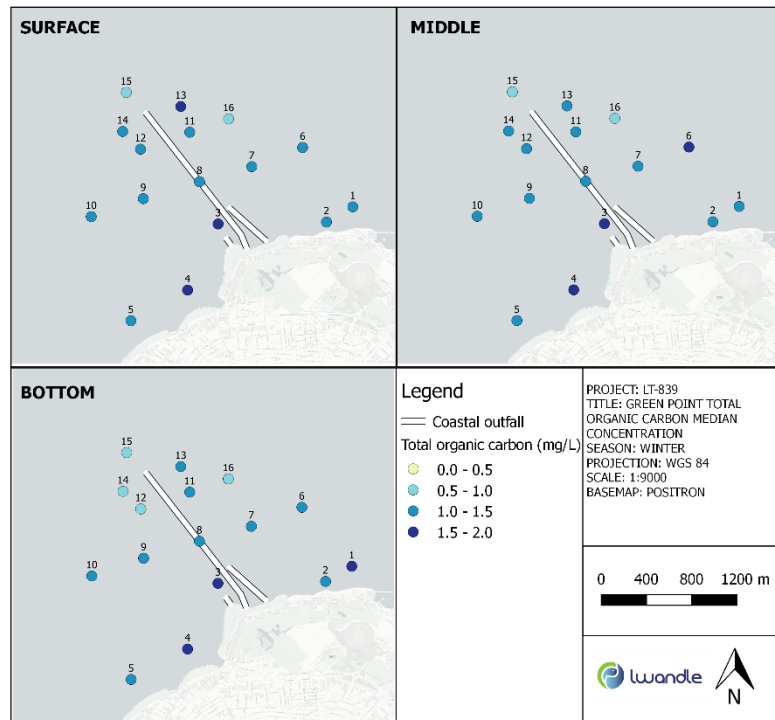


Figure 6.18: Map showing the median concentration of total organic carbon (mg/L) at the surface, middle and bottom at the Green Point outfall sites during the 2019 winter survey.

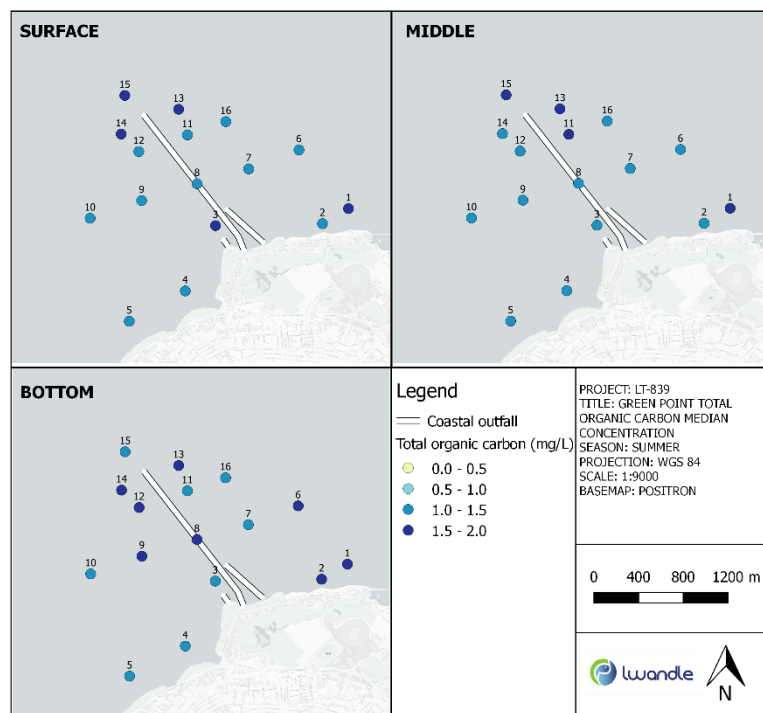


Figure 6.19: Map showing the median concentration of total organic carbon (mg/L) at the surface, middle and bottom at the Green Point outfall sites during the 2020 summer survey.

6.5.4 Orthophosphate

Orthophosphate results for the 2019 winter survey are not available due to operational problems experienced in the analysis of samples at the laboratory. The orthophosphate concentrations at sites surrounding the Green Point outfall sampled during the 2020 summer survey are presented in the summer data report (LT-839 DTR_02_V3). Concentrations ranged from 10 to 85 µg/L. Median orthophosphate concentrations ranged from 35 to 74 µg/L. The lowest concentrations were recorded in surface waters with all sites recording concentrations below 40 µg/L. Higher concentrations (>60 µg/L) were mostly recorded in bottom waters.

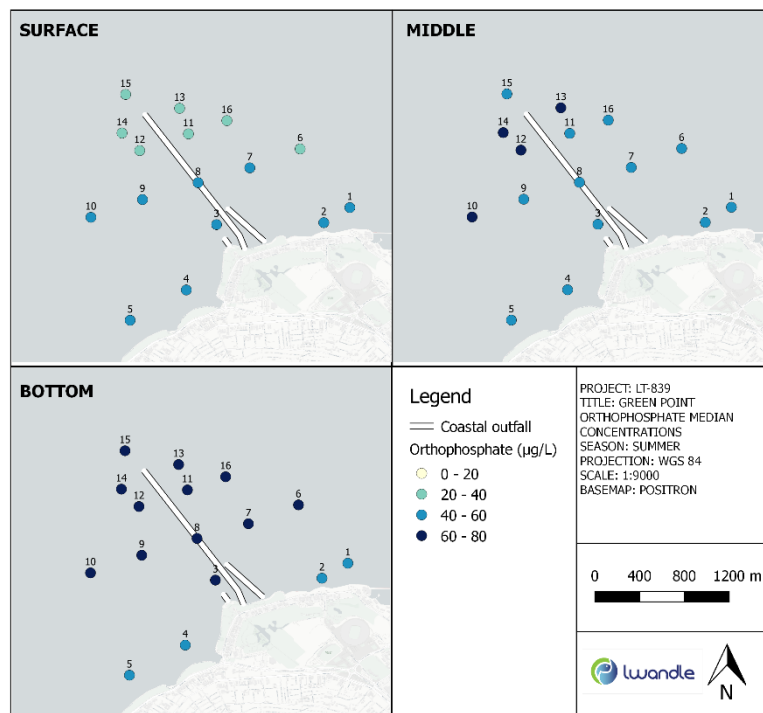


Figure 6.20: Map showing the median concentration of phosphate (µg/L) at the surface, middle and bottom at the Green Point outfall during the 2020 summer survey.

Orthophosphate values at mid and bottom depths in the nearfield water body, represented by measurements from stations GP2, GP3, GP4, GP7, GP8, GP9, GP11, GP12, GP13, GP14 and GP16, were compliant with the stipulated guidelines during the summer monitoring period with the median values in surface, mid and bottom waters falling into the ranges defined in Table 3.2 (

Table 6.5). However, the median value in surface waters at the nearfield sites were slightly higher than the guideline. For this determination nearfield sites were grouped to increase replication but with further monitoring and sample collection, this approach will be re-examined and where possible, site-specific comparisons to guidelines will be made.

Table 6.5: Median orthophosphate values ($\mu\text{g/L}$) in surface, mid and bottom waters measured at nearfield sites surrounding the Green Point outfall.

	Depth		
	Surface	Mid	Bottom
Summer			
n	44	44	44
Median	40	57	70

6.5.5 Ammonia

Ammonia results for the 2019 winter survey are not available due to operational problems experienced in the analysis of samples at the laboratory. The ammonia concentrations at sites sampled in Green Point during the 2020 summer survey are presented in the summer data report (LT-839 DTR_02_V3). Concentrations were low, ranging from <5 to $60 \mu\text{g/L}$. Most of the measurements (77.6%) were below the MDL and no exceedances of the recommended guideline ($600 \mu\text{g/L}$) were recorded (Figure 6.21).

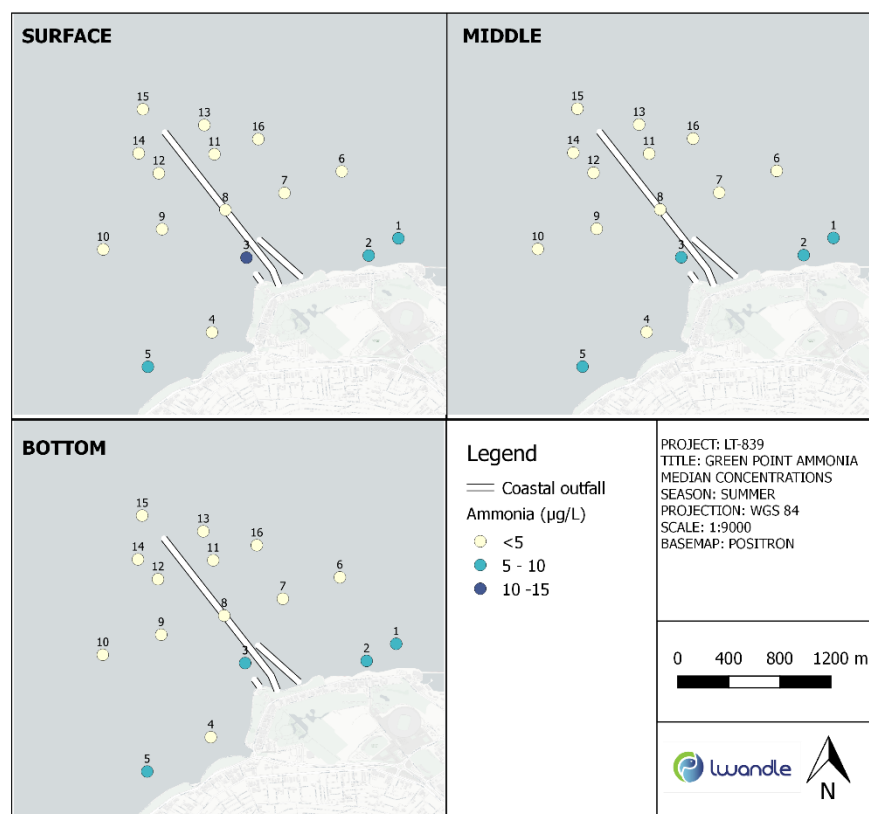


Figure 6.21: Map showing the median concentration of ammonia ($\mu\text{g/L}$) at the surface, middle and bottom at the Green Point outfall sites during the 2020 summer survey.

6.5.6 Toxicity

The two nearshore sites sampled during the first year of monitoring showed no toxicity effects of seawater obtained from near the discharge on sea urchins (*Tripneutes gratilla* and *Echinometra mathaei*) fertilisation rates in either of the winter or summer sampling periods (Table 6.6).

Table 6.6: Sea urchin seawater toxicity test results. Samples were obtained from two nearshore sites in the vicinity of the Green Point outfall on alternate days during the winter (August-September 2019) and summer (February-March 2020) sampling periods in the first year of monitoring. Toxicity classification is based on mean (n=4) fertilisation success rates.

Date	Season	Site	Species	Mean % Fertilisation Success	Std Dev	Toxicity Categorisation
26/09/2019	Winter	GP-TT1	<i>T. gratilla</i>	98.50	0.58	Not toxic
		GP-TT2	<i>T. gratilla</i>	98.50	0.58	Not toxic
30/09/2019		GP-TT1	<i>T. gratilla</i>	98.75	0.50	Not toxic
		GP-TT2	<i>T. gratilla</i>	98.25	0.50	Not toxic
2/10/2019		GP-TT1	<i>T. gratilla</i>	97.75	0.50	Not toxic
		GP-TT2	<i>T. gratilla</i>	97.50	0.58	Not toxic
5/10/2019		GP-TT1	<i>T. gratilla</i>	98.50	0.58	Not toxic
		GP-TT2	<i>T. gratilla</i>	98.25	0.50	Not toxic
6/10/2019		GP-TT1	<i>T. gratilla</i>	98.50	0.58	Not toxic
		GP-TT2	<i>T. gratilla</i>	98.50	0.58	Not toxic
8/10/2019		GP-TT1	<i>E. mathaei</i>	98.50	0.58	Not toxic
		GP-TT2	<i>E. mathaei</i>	98.50	0.58	Not toxic
20/03/2020	Summer	GP-TT1	<i>E. mathaei</i>	97.50	0.58	Not toxic
		GP-TT2	<i>E. mathaei</i>	97.50	0.58	Not toxic
23/03/2020		GP-TT1	<i>E. mathaei</i>	97.75	0.50	Not toxic
		GP-TT2	<i>E. mathaei</i>	97.25	0.96	Not toxic

6.6 EFFECTS ON LOCAL MARINE ECOLOGY

Growth rates and trace metal accumulation of mussels (*Mytilus galloprovincialis*) at fixed monitoring stations surrounding the Green Point outfall and two control stations were compared across the winter 2019 and summer 2020 surveys. Results (detailed in APPENDIX D: BIOMONITORING PROGRAMME, ANNUAL REPORT) indicated that mussel growth rates at the Green Point outfall were greater during winter than in summer. Growth rates also appeared to be slightly higher at the stations located in close proximity to the outfall than those further afield.

Trace metal concentrations in mussels were higher during winter than in summer at stations surrounding the Green Point outfall, with generally low levels relative to the baseline levels measured during summer, particularly for zinc (baseline: 33.6 mg/kg, outfall sites: 21.00-26.78 mg/kg excluding GP3: 59.29 mg/kg) and nickel (baseline: 557.48, outfall sites: 187.87-313.85 µg/kg) total wet weights. There was no evidence to suggest that metal bioaccumulation was higher at stations in close proximity to the outfall than those further afield.

6.7 HYDRODYNAMIC MODELLING, PLUME BEHAVIOUR AND EFFECTS ON HUMAN HEALTH

Results of the hydrodynamic modelling conducted by PRDW (detailed in Appendix G) suggest that for TSS a mixing zone distance of 1 400 m from the discharge is required to meet the required dilution of 1 753 (as determined by the CCT, detailed in APPENDIX G) in winter/spring, whereas in summer/autumn a mixing zone distance of 940 m is required. For *E. coli*, distances of 6 300 m and 6 600 m are required in winter/spring and summer/autumn respectively to meet the 90th percentile water quality guideline of 500 cfu/100 mL. For enterococci, distances of 3 200 m and 2 300 m are required in winter/spring and summer/autumn to meet the 90th percentile water quality guideline of 185 cfu/100 mL. The modelling thus suggests that non-compliance to recommended TSS, enterococci and *E. coli* guidelines is not limited to being within the estimated ZID which has a radius of 256 m, nor is it limited to the 300 m mixing zone which is generally allowed for an offshore discharge in an open coast system (Anchor, 2015).

During typical conditions, modelling showed that the plume from the Green Point outfall is advected alongshore by prevailing currents. South-easterly winds, which mostly occur during summer, advect the plume into Table Bay, but onshore movement of the plume can occur during north-westerly and south-westerly wind conditions. On occasion, this resulted in enterococci and *E. coli* concentrations at Three Anchor Bay and the Sea Point Pool that exceeded 185 and 500 cfu/100 mL respectively (twice in winter/spring and several times in summer/autumn). Periodic exceedances of the guidelines were also observed at the RMS Athens (Thermopylae surf spot) during summer/autumn. This indicates some risk to bathers and surfers in these areas however, the duration of these peaks was short (<10% of daylight time) resulting in overall adherence to the 90th percentile guidelines of 185 and 500 cfu/100 mL for enterococci and *E. coli* at recreational sites surrounding the Green Point outfall.

To an extent, the plume behaviour was reflected in laboratory results for enterococci, where many of the sites at which there was exceedance of the water quality guidelines were located in close proximity to the outfall, outside of recreational areas. Considerable exceedance of the guidelines was observed at beach site GP-B3 at Three Anchor Bay, however, contrary to the modelling results, these exceedances were sustained and occurred in most weeks during winter and summer. Thus, modelling and the field measurement data reported here indicate that in addition to the outfall, the poor water quality at this site may be attributable to other sources such as storm-water runoff. Periodic, extremely high enterococci counts were also observed at beach sites GP-B1 and GP-B2. These may be linked to the outfall but are also likely influenced by other sources of bacterial loads such as storm-water runoff. Irrespective of the source, the high bacterial concentrations at these sites indicate risk to recreational users which requires mitigation and management. Recommendations are provided in the PRDW report in APPENDIX E: FINAL HYDRODYNAMIC MODELLING REPORT FOR HOUT BAY.

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8 APPENDIX D: BIOMONITORING PROGRAMME, ANNUAL REPORT



CITY OF CAPE TOWN

EFFLUENT PIPELINES BIOMONITORING

Annual Report



June 2020



ANCHOR
research & monitoring

CITY OF CAPE TOWN

EFFLUENT PIPELINES BIOMONITORING

Annual Report

June 2020



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EXECUTIVE SUMMARY

A long-term environmental monitoring programme has been implemented for the City's Marine outfall effluent discharge areas based on the City's Outfalls Marine Discharge Monitoring Guidelines. Anchor Research and Monitoring (Pty) Ltd (Anchor) was appointed in conjunction with Lwandle Marine Environment Services (Lwandle) and the CSIR to undertake a monitoring program to assess impacts associated with the discharge of effluent by the City of Cape Town through three outfalls offshore at Hout Bay, Camps Bay and Green Point as required by the Coastal Waters Discharge Permit (CWDP) issued by the Department of Environmental Affairs: Oceans and Coasts for these outfalls.

A seasonal, bi-annual monitoring programme has been implemented to assess the impact of effluents on marine bioindicators. Due to its life history and filter feeding nature, the alien mussel species *Mytilus galloprovincialis* that is abundant on Cape Town rocky shores, was selected for use as an appropriate bioindicator species. This document compares the results of mussel growth and accumulation of trace metals (Zn, Cu, Ni) by mussels between the Winter 2019 and Summer 2020 deployments. During Winter 2019, the mussels were deployed for 46 days while in Summer 2020 the mussels were deployed for a considerably longer period of 72 days due the Covid-19 lockdown preventing the retrieval of the moorings after the scheduled 8 weeks as initially planned

There were clear seasonal differences in the growth rate of mussels used in the two monitoring experiments, with lower average growth rates at all sites recorded during the summer deployment. This is attributed to both lower particulate organic matter and temperature of upwelled water which is more prevalent off the Cape Peninsula during the spring and summer period than winter. Seasonal spawning of mussels in summer and the resultant allocation of energy to reproduction rather than growth is also probably a cause of the observed seasonal growth differences. Growth rates appear to be slightly higher at monitoring stations located in close proximity to the outfalls than those further afield, this was more evident during the summer season. It is expected that the higher growth rates closer to the diffusers and greater average growth rates at the diffusers compared to the controls, are a function of higher levels of organic matter and increased nutrient loading present in the water column in the immediate vicinity of the outfalls.

Trace metal accumulation in mussels also showed clear seasonal trends. Mussels at all locations accumulated all three trace metals (Cu, Ni and Zn) relative to baseline concentration during the 2019 winter deployment, but only accumulated copper at the two controls and at the Green Point and Camps Bay outfalls during the summer 2020 deployment. There is no evidence to suggest that the rate of metal bioaccumulation was higher at stations close to the outfalls relative to those further afield. The seasonal differences in trace metal accumulation are also potentially linked to summer reproductive activity, with trace metals effectively excreted along with gametes during spawning.

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1 BACKGROUND

In 2017 the City of Cape Town (CoCT) conducted a survey that investigated the performance and effects of the domestic effluent outfalls offshore of Hout Bay, Camps Bay and Green Point (Table Bay). The CSIR (2017) found minimal environmental or human health effects specifically attributable to substances discharged through the outfalls (Figure 1.1). Subsequently, a long-term environmental monitoring programme has been implemented for the City's Marine outfall effluent discharge areas based on the City's Outfalls Marine Discharge Monitoring Guidelines. The environmental and/or human health effects of the outfalls may change over time, so the City requires that the effects of the outfalls be carefully monitored and reported on. To ensure the integrity of the marine receiving environment is not unacceptably compromised, the Department of Environmental Affairs issues Coastal Waters Discharge Permits in terms of the Integrated Coastal Management Act, 2008 (Act No. 24 of 2008). The permits stipulate the conditions under which the discharge is legally authorised. The purpose of this report is to demonstrate compliance with the condition of authorisation for effluent discharge in terms of environmental impact monitoring and reporting and to demonstrate and report on the potential impacts of effluent on marine receptors over the next 3 years.



Figure 1.1. Sewage outfall plume at Green Point (Table Bay), Cape Town. Photo taken by Jean Tresfon, 2017.

1.1 Scope of Works

Anchor Research and Monitoring (Pty) Ltd (Anchor) was appointed in conjunction with Lwandle Marine Environment Services (Lwandle) and the CSIR to undertake a monitoring program to assess impacts associated with the discharge of effluent by the City of Cape Town through three outfalls offshore at Hout Bay, Camps Bay and Green Point as required by the Coastal Waters Discharge Permit (CWDP) issued by the Department of Environmental Affairs: Oceans and Coasts for these outfalls. The outfalls are owned and operated by the City of Cape Town and discharge volumes at each pipeline are within the permissible range (Table 1.1)

Table 1.1. The three sea outfalls (pipelines) owned and operated by the City of Cape Town with permissible, current and design discharge volumes (taken directly from CSIR 2017).

Outfall	Distance offshore/Length (m)	Discharge Depth (m)	Number of Diffusers	Design Capacity (ML.day ⁻¹)	Current Discharge (ML.day ⁻¹)	License Discharge (ML.day ⁻¹)
Green Point	1676	28	16	40.0	28.4	27.3
Camps Bay	1497	23	8	5.0	2.4	2.3
Hout Bay	2162	39	14 (5 operable)	9.6	5.7	5.2

A seasonal, bi-annual monitoring programme has been implemented to assess the impact of effluents on marine bioindicators. Due to its life history and filter feeding nature, the alien mussel species *Mytilus galloprovincialis* that is abundant on Cape Town rocky shores, was selected for use as an appropriate bioindicator species. The monitoring programme has three broad objectives, namely:

1. To assess the seasonal growth rate of the Mediterranean mussel, *Mytilus galloprovincialis* at sampling stations surrounding the Green Point, Camps Bay and Hout Bay effluent pipelines over a 6-8 week period and whether or not growth rates are enhanced or suppressed by the increased presence of effluent (proximity to effluent diffuser);
2. To assess if the rate at which trace metal accumulation by *M. galloprovincialis* in Green Point, Camps Bay and Hout Bay is changing over time in relation to proximity to effluent diffusers; and;
3. To assess geographical variation in bioaccumulation rates by mussels in the respective bays and to assess potential links with effluent discharge.

This document compares the results of mussel growth and accumulation of trace metals (Zn, Cu, Ni) by mussels between the Winter 2019 and Summer 2020 deployments. During Winter 2019, the mussels were deployed for 46 days while in Summer 2020 the mussels were deployed for a considerably longer period of 72 days due the Covid-19 lockdown preventing the retrieval of the moorings after the scheduled 8 weeks as initially planned. A schedule of collection, deployment and analysis is listed below (Table 2.1). The report serves the equally important roles of providing managers of the Green Point, Camps Bay and Hout Bay wastewater works with strategic information for managing the discharges and of informing the public on the status (or health) of the marine receiving environments. This report details the annual comparison of the growth rates and trace metal analysis between the first winter and summer sampling periods.

2 APPROACH

2.1 Mooring design setup and deployment

This study forms part of a monitoring programme commissioned by the City of Cape Town (CoCT) to monitor the performance and effects of the domestic effluent outfalls offshore of Hout Bay, Camps Bay and Green Point on the marine environment. At each outfall, twelve fixed monitoring stations were positioned in a cross formation around the diffuser outlet point of each individual pipeline (Figure 2.1). Stations were positioned approximately 100 m, 300 m, 600 m in four directions moving outwards from each effluent outfall. At each station, a mooring comprised of an anchor (20 kg section of railway track), a nylon rope (12 mm) and a subsurface buoy (30 cm diameter) was deployed (Figure 2.2). Mussels (*Mytilus galloprovincialis*) were collected and suspended in a mesh bag on each mooring. The mussel bag was placed at ~4 m (winter) ~5 m (summer) depth below the surface, for 43 and 72 days during the winter and summer periods, respectively. This procedure will be replicated for a further 2 years with ongoing winter and summer deployments (Table 2.1).

The same mooring set up was replicated at the two control sites, but with three mussel bags attached per mooring line for additional replication if required (e.g. if a mussel bag detached). Moorings were designed in such a way that the probability of entanglement by marine mammals was low (no loose or horizontal lines were used) and that the risks of mortality that could result from entanglement were minimised (moorings were light enough such that even small cetaceans could reach the surface to breathe even if they did become entangled).

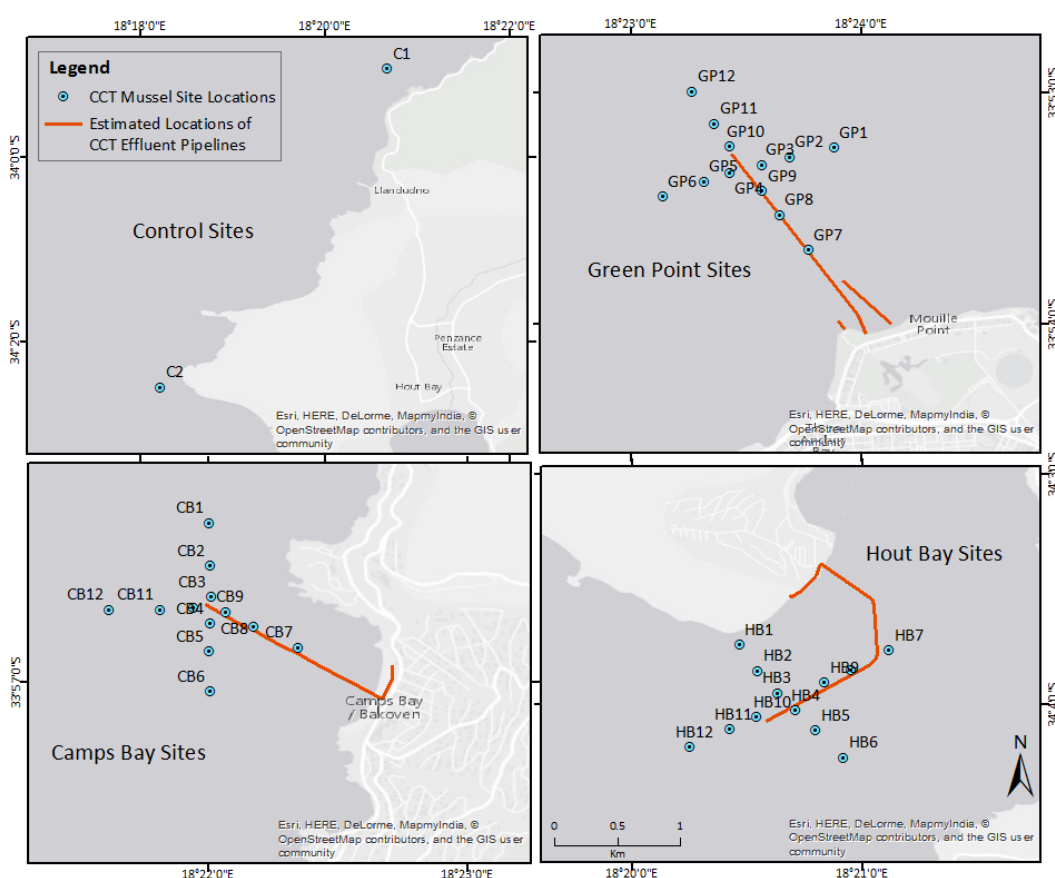


Figure 2.1. Maps of the Cape Town area, showing the positions of the Green Point, Camps Bay and Hout Bay outfalls (approximate outfall locations are denoted by red lines). Locations of ecological biomonitoring stations in Green Point, Camps Bay and Hout Bay are also shown and referred to in the remainder of the report with an E in front of the site name (E_HB1 for example).

Table 2.1. Schedule of collection, deployment and analysis of mussels stocked in mussel bags at strategic points around Green Point, Camps Bay and Hout Bay pipelines, including consecutive seasons for re-stocking mussel bags and associated moorings.

Year	Season	Tasks	No. samples to be analysed
Year 1	Winter 2019 + Summer 2020	- ID, collect, measure and record 900 – 1000 <i>M. galloprovincialis</i> from baseline site - Install 12 bags of 20 mussels each, length 40 – 50 mm, on each mooring at each site location (3) and install 3 bags of 20 mussels each, length 40 – 50 mm, at each control site (2), n = 38 - Submit a sample of oysters (~60 g) from Cohort #1 for baseline trace metal analysis - Retrieve all 38 moorings at end of growth period, ~6weeks - Freeze, measure length for growth rate and send to lab for trace metal (Ni, Zn, Cu) analysis	n = 38per season (completed)
Year 2	Winter 2020 + Summer 2021	- ID, collect, measure and record 900 – 1000 <i>M. galloprovincialis</i> from baseline site - Install 12 bags of 20 mussels each, length 40 – 50 mm, on each mooring at each site location (3) and install 3 bags of 20 mussels each, length 40 – 50 mm, at each control site (2), n = 38 - Retrieve all 38 moorings at end of growth period, ~6weeks - Submit one sample of oysters from Cohort #2 (~60 g) for baseline trace metal analysis - Retrieve all 38 moorings at end of growth period, ~6weeks - Freeze, measure length for growth rate and send to lab for	n = 38 per season
Year 3	Winter 2020 + Summer 2021	- ID, collect, measure and record 900 – 1000 <i>M. galloprovincialis</i> from baseline site - Install 12 bags of 20 mussels each, length 40 – 50 mm, on each mooring at each site location (3) and install 3 bags of 20 mussels each, length 40 – 50 mm, at each control site (2), n = 38 - Retrieve all 38 moorings at end of growth period, ~6weeks - Submit one sample of oysters from Cohort #2 (~60 g) for baseline trace metal analysis - Retrieve all 38 moorings at end of growth period, ~6weeks - Freeze, measure length for growth rate and send to lab for	n = 38 per season

2.2 Mussel collection and analysis

Mussels were collected from the shore at Scarborough on the western coast of the Cape Peninsula which is located in the controlled use zone of the Table Mountain National Park MPA in an area where pollution loading is known to be low (Sparks et al 2018) (Figure 2.3). *Mytilus galloprovincialis* is an alien mussel species and was specifically selected over one of the indigenous mussel species that occur on the Peninsula (*Choromytilus meridionalis*, *Aulacomya ater* or *Perna perna*) for the following reasons:

1. The study will entail temporary translocation but ultimately removal of the test organisms from the Peninsula. Use of an alien species is thus favoured.
2. Numbers of indigenous mussels on the Cape Peninsula are low and are in decline due to invasion by *Mytilus*. Removal of indigenous mussels is therefore not advisable.

3. *M. galloprovincialis* are widely used for biomonitoring elsewhere in South Africa and in other parts of the world and data are thus more directly comparable with data from other studies.



Figure 2.2. Mooring make up, bag attachment and deployment at Green Point, Camps Bay and Hout Bay.

Live mussels with shell lengths in the range 40-50 mm were collected from a rocky shelf area at spring low tide in Scarborough, Cape Town (Figure 2.4). Mussels were positively identified to species level, and the lengths were recorded before they were used to stock the mussel bags (Figure 2.4). Approximately 60 juvenile mussels were randomly selected from the initial batch of 1 000 collected and the tissue was extracted, homogenized and submitted to Stellenbosch CSIR Coastal Laboratory for baseline trace metal analysis for Zn, Cu and Ni. The remaining mussels were then subdivided into 36 mesh bags (20 per bag) and deployed on the moorings for a scheduled 6-week (winter) and 8-week (summer) period. On completion of a seasonal experimental period, the moorings were retrieved, mussels recovered and measured to assess the average growth increment for each sampling site. (Figure 2.5). Tissue was also extracted from each mussel, homogenized and submitted to Stellenbosch CSIR Coastal Laboratory for trace metal analysis.

Shortly after the Summer 2020 deployment, two moorings at the Green Point outfall (GP7 and GP2), and one mooring at the Camps Bay (CB12) were removed by concerned boat operators who mistook the moorings for illegal crayfish traps on an extremely low spring tide. In these instances new 'baseline' mussels were collected, measured and re-deployed at their correct locations on the 21st of February 2020. These baseline mussels were, however, collected from Kometjie instead of Scarborough due to the limited turnaround time that was required for the redeployments. A baseline sample of these mussels was also submitted to the CSIR for trace metal analysis. These mussels will therefore have a shorter 'deployment time' and likely have a different baseline trace metal signature. Furthermore, The Summer 2020 deployment ran longer than scheduled due to the Covid-19 lockdown, with the moorings being at sea for approximately 11 weeks.

During the winter deployment period 6 out of 12 moorings were missing at Green Point, 2 out of 12 moorings at Hout Bay, and 1 out of 2 Control sites were missing, whilst during the summer deployment 7 out of 12 at Green Point and 5 out of 12 moorings were missing at Hout Bay respectively. It is likely that moorings were lost as a result of being ridden over or entangled by vessels that traversed through these sites, or they were pulled up by boat operators suspecting illegal fishing activities during spring low tides. Shipping traffic was noted as being very intensive through the Green Point and Hout Bay sites during the deployment and retrieval periods (several large vessels were observed moving through the mooring arrays each hour during the deployment and retrieval periods) but lower at the Camps Bay and Control sites, and may account for the greater losses experienced at these two sites.

A comprehensive search and recovery procedure was attempted for all missing moorings during both seasonal surveys. Because some of the moorings were lost, we were able to analyse additional baseline samples that had been collected and preserved at the start of the winter experiment without exceeding the available budget, which was a positive outcome since this yielded a more robust baseline measurement. However, the mussels collected for the baseline analysis for the summer experiment were of poor condition with very little tissue being present in each shell, having possibly undergone a spawning event (van Erkom Schurink & Griffiths, 1991, 1993), this meant that only enough tissue for one baseline sample could be submitted for the summer experiment.

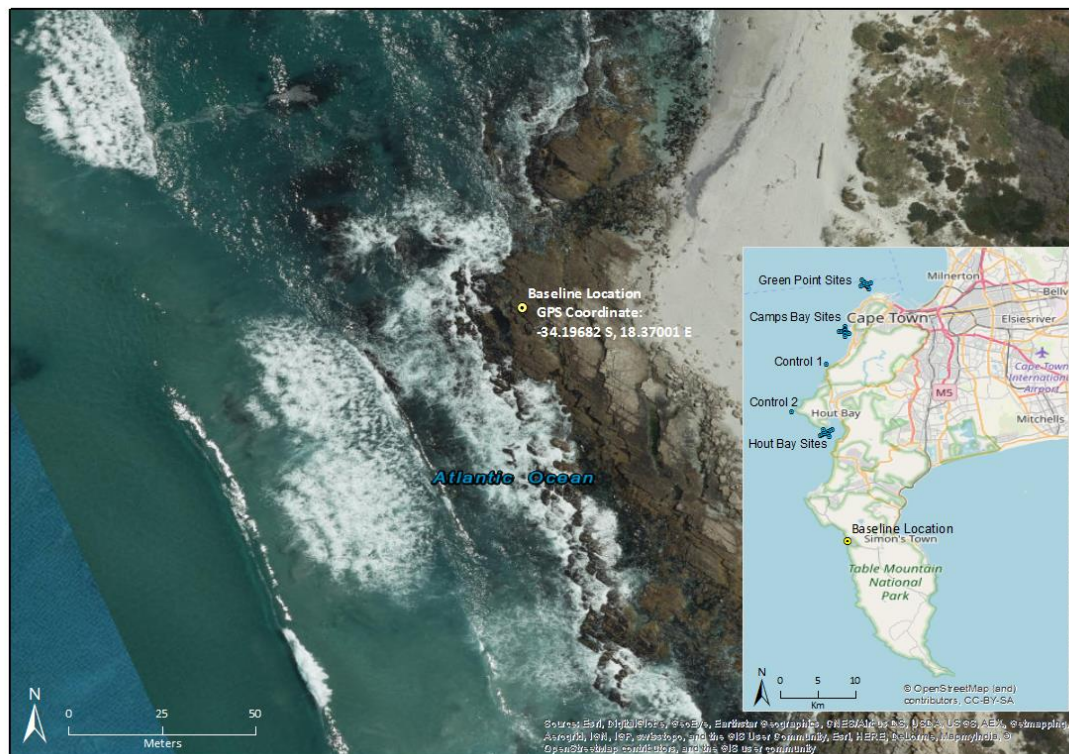


Figure 2.3. Aerial overview of Scarborough intertidal rocky shelf where baseline and biomonitoring mussels were collected with inset of the Cape Town area where the baseline site, three outfall locations and two control site locations are shown.



Figure 2.4. *Mytilus galloprovincialis* collection site at Scarborough, Cape Town rocky shelf on the spring low tide, and species identification, count and measurement process for the mussel bags.



Figure 2.5. Laboratory mussel length measurements for growth rate at the end of the 6-week sampling period and mussel dissection sample preparation for the trace metal analysis.

3 RESULTS

An essential outcome of any outfall biomonitoring programme is to determine if effluent discharge is significantly, negatively impacting on the ecology of the receiving environment and/or is posing a risk to the health of humans that use that environment (CSIR 2017). Biological indicators, in this case mussels *Mytilus galloprovincialis*, were used to measure biological and chemical impacts. Two different metrics, variation in growth rate and variation in trace metal levels in mussel tissue in relation to distance from the outfalls was used to assess the extent of these impacts for the three deep-water sewage outfalls in the Cape Town area. Growth rates and trace metal accumulation were compared across winter and summer seasons as these factors are known to vary seasonally (growth rates e.g. Van Erkom Schurink and Griffiths (1993); trace metals e.g. Bezuidenhout *et al.* 2015, Sparks *et al.* 2018).

3.1 *Mytilus galloprovincialis* growth rates

Data on growth increments of *M. galloprovincialis* deployed at stations surrounding each of the deep-water outfalls (Green Point, Camps Bay, Hout Bay) and at the two control stations (Control 1 and Control 2) are shown on Figure 3.1 below.

Mussel growth averaged across all of the monitoring stations at the Camps Bay, Green Point and Hout Bay outfall was marginally greater than that recorded at the control stations for both the winter and summer seasons (only Control 1 in winter, both Control 1 and Control 2 in summer); with the exception of the average growth rate in summer at Camps Bay which was marginally less than the growth rate at Control 2.

Growth rates were greater in winter compared to summer, this was evident at all three diffusers and at the controls. Growth rates averaged across all of the monitoring stations at each of the outfalls were compared statistically between seasons and to the average growth rates at the controls. The higher growth rates in winter were statistically significant (1-way ANOVA, $P < 0.05$) at both the Hout Bay and Camps Bay outfalls but not the Green Point outfall (1-way ANOVA, $P > 0.05$). Tukey post-hoc tests indicated that the average growth rate at the Camps Bay outfall during Winter was significantly greater than the growth rates recorded at the Camps Bay outfall and both controls during summer, but not Control 1 during winter. At the Hout Bay outfall, Tukey post hoc tests indicated that the average growth rate in winter was significantly greater than those recorded at the Hout Bay outfall and Control 1 outfall during summer, but not Control 1 and Control 2 during winter.

Growth rates appear to be slightly higher at monitoring stations located in close proximity to the outfalls than those further afield, this was more evident during the summer season. It is expected that the higher growth rates closer to the diffusers and greater average growth rates at the diffusers compared to the controls, are a function of higher levels of organic matter and increased nutrient loading present in the water column in the immediate vicinity of the outfalls. Both of which would have had a net positive effect on mussel growth. These findings are in line with those included in the CSIR (2017) and Bustamante and Branch (1996) reports that document increased mussel growth rate in association with high levels of particulate organic matter (POM) which is an important food supply. These and other studies have recorded faster growth rates in *M. galloprovincialis* as well as greater average POM concentrations occurring in moderately exposed sites in comparison to sheltered sites (Bustamante and Branch 1996, Steffani and Branch 2003). Mussel growth rates recorded in the present study do suggest that the mooring stations located at the three outfalls have a greater food supply (POM). Clear seasonal differences were however still evident; whereby average growth rate was greater in winter than summer.

Numerous studies have documented the differential effects of upwelling on mussel growth; where some report that mussels at upwelling sites would have greater growth than those downstream (Xavier et al. 2007); and other authors observed the opposite trend – faster mussel growth associated with sites of weaker upwelling and higher temperatures (Menge et al. 1997a,b; Sanford and Menge 2000; Phillips 2005; Blanchette et al. 2006, 2007). The latter is often characterized by greater onshore concentrations of Chl-*a* (Menge et al. 1997a,b; Sanford and Menge 2000; Wieters et al. 2003). Upwelling centres have colder water; are nutrient rich but poor in Chl-*a* and POM (Graham and Largier 1997; Wieters et al. 2003). Besides food availability, it appears that temperature is an influential factor in driving the observed differential growth rates between the two seasons. A study from Van Erkom Schurink and Griffiths (1993) provided strong evidence that temperature (rather than food availability) was the main variable determining the growth rates of various southern African mussel species, including *M. galloprovincialis*, which yielded faster growth rates in warmer temperatures. In the present study, mussel growth rate was evidently reduced in summer compared to winter, and these findings are in line with the reports previously mentioned, considering upwelling events which result in clear and cold water near the coast, generally occur in spring-summer (Shannon 1985).

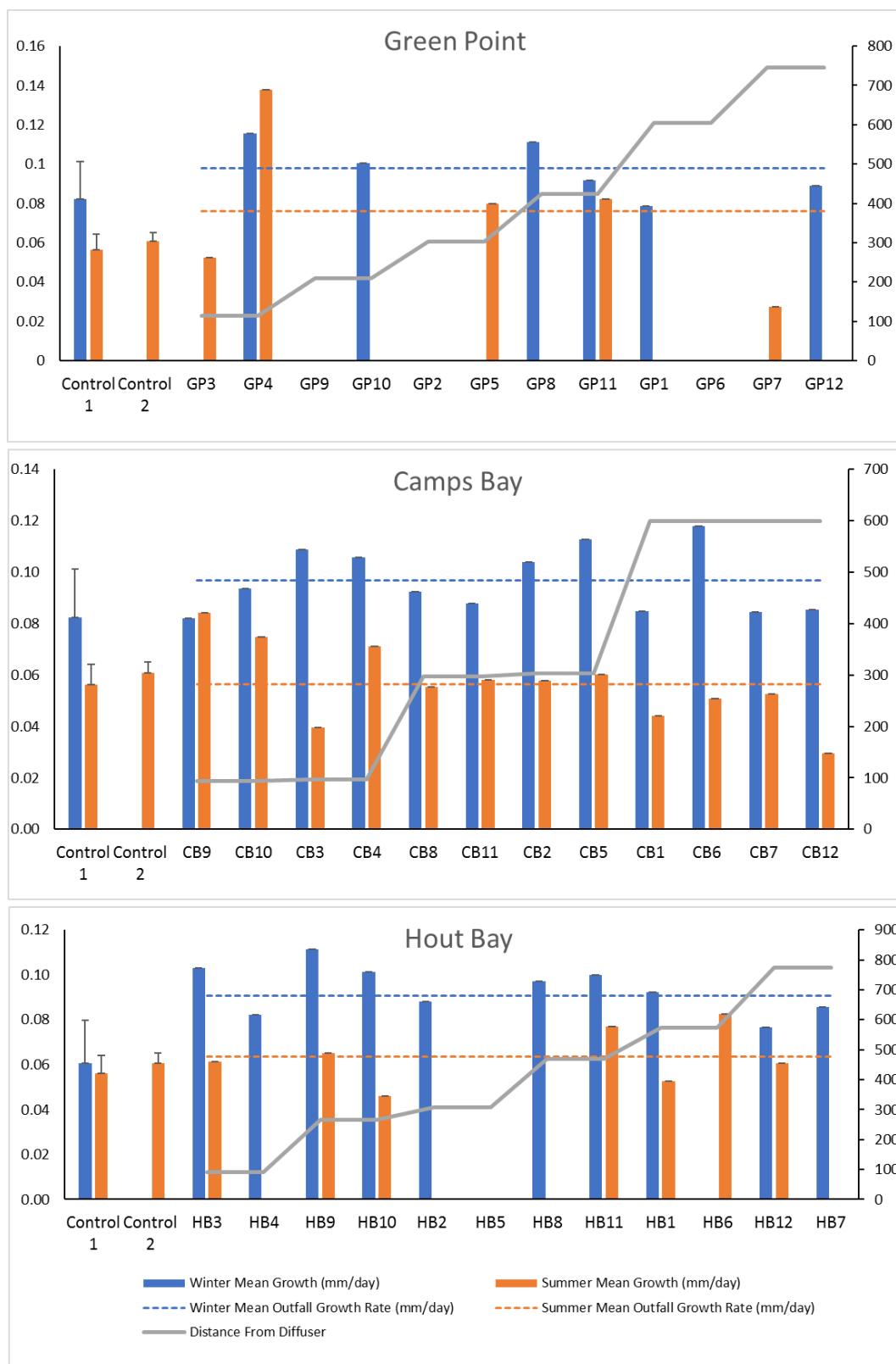


Figure 3.1. *Mytilus galloprovincialis* growth rates (mm/day) on left axis over a 43 day period, September – October 2019 (Winter), and a 72 day period, February to April 2020 (Summer) in relation to distance from effluent diffuser, gray line (m) on right axis for three different deep-water outfall locations, Green Point, Camps Bay, and Hout Bay. The dotted red line indicates the mean growth (mm) for each outfall location.

3.2 Trace metal content

Mussels have the ability to accumulate metals from the marine environment and have been used to assess coastal environmental pollution since the 1970s through Mussel Watch programs and similar studies (Goldberg 1975). Change in trace metal content for mussels deployed at stations surrounding each of the deep-water outfalls and at the control stations relative to baseline (pre-deployment) levels are shown on Figure 3.2 below. This change can be positive (due to a greater rate of intake of trace metals relative to excretion, resulting in accumulation), or negative (due to lower uptake rate, a greater excretion rate or decrease in concentration due to growth of the mussel).

Changes in trace metal concentration between the two seasons is evident for all three metals tested. The 2019 Winter deployment indicates relatively high levels of trace metal content as opposed to the recent 2020 Summer season; whereby very low levels of trace metal was recorded at all of the monitoring stations at the Camps Bay, Green Point and Hout Bay outfall; particularly for Zn and Ni.

Trace metal content averaged across all the monitoring stations at the Camps Bay, Green Point and Hout Bay outfall appeared to be markedly different than that recorded at the control stations for all three metals tested. For both the winter and summer seasons, the average levels of copper across all three outfalls was significantly greater than the controls; with the exception of the summer average at Hout Bay. Average traces of Zn were lower than the control stations at all three outfalls during the winter season. However, this was not evident in the summer season, where average zinc concentrations at all the outfall stations was similar to that of the controls. Ni concentration in mussel tissue was also similar at control and outfall stations during the summer monitoring period. During the 2019 winter monitoring period it was only the stations at the Camps Bay outfall that had a greater average Ni concentration in comparison to the control. There is no evidence to suggest that the rate of metal bioaccumulation was higher at stations close to the outfalls relative to those further afield. Additionally, Zn was observed to have the highest concentration in mussels compared to the other two metals in the winter season. The latter was also reported in Bezuidenhout *et al.* 2015, where Zn had the highest accumulation in mussels (after Fe) compared to the other trace metals tested. Furthermore, Eisler (1981) reports that molluscs preferably accumulate Zn, which probably explains the high concentrations of Zn recorded in mussels in the present study.

Various other monitoring studies have shown notably higher concentrations of trace metals (particularly Cu and Zn) in the mussel *M. galloprovincialis* compared to the present study (Fatoki 2012; Bezuidenhout *et al.* 2015; Sparks *et al.* 2018, Firth 2019). Firth (2019) observed no significant seasonal patterns in the concentration of these trace metals for *M. galloprovincialis*; which contradicts this study in which there were clear seasonal differences. However, Bezuidenhout *et al.* (2015) and Sparks *et al.* (2018) documented distinct seasonal differences, whereby trace metal accumulation in mussels was greater in winter compared to summer, which support the findings of this study. While it was evident that there were clear differences in trace metal concentration measured between the two seasons, it is important to note that new 'baseline' mussels were collected, measured and re-deployed at three mooring positions (GP7, GP2 and CB12) on the 21st of February 2020 (refer to Section 2.2). These baseline mussels were, however, collected from Kommetjie instead of Scarborough due to the limited turnaround time that was required for the redeployments. It was expected that these mussels will have a shorter 'deployment time' and likely have a different baseline trace metal signature. The latter was indeed the case with the decline in Ni from baseline levels been substantially less and the decline in Zn substantially more at the two of these stations than at other stations that had a longer

deployment time. Interestingly, Bezuidenhout *et al.* (2015) reports that several factors (particularly the reproductive cycle) can influence the rate of metal accumulation in mussels. The study suggested that the observed seasonal dynamics of trace metal concentrations could be a result of the spawning that takes place in summer; with the subsequent large release of gametes (Van Erkom Schurink and Griffiths 1991); effectively eliminating any trace metal accumulation in the gametes from the mussel's bodies (Bezuidenhout *et al.* 2015). The latter is supported by the Van Erkom Schurink and Griffiths (1991) study; whereby the reproductive cycle and output in four southern African mussel species were compared; and *M. galloprovincialis* had the greatest gonad material accumulation (weight increase of 3-fold over spawned condition) and release within a single spawn cycle. Summer spawning activity could explain why low levels of trace metal content were recorded at the mussels deployed at the various monitoring stations during the summer season.

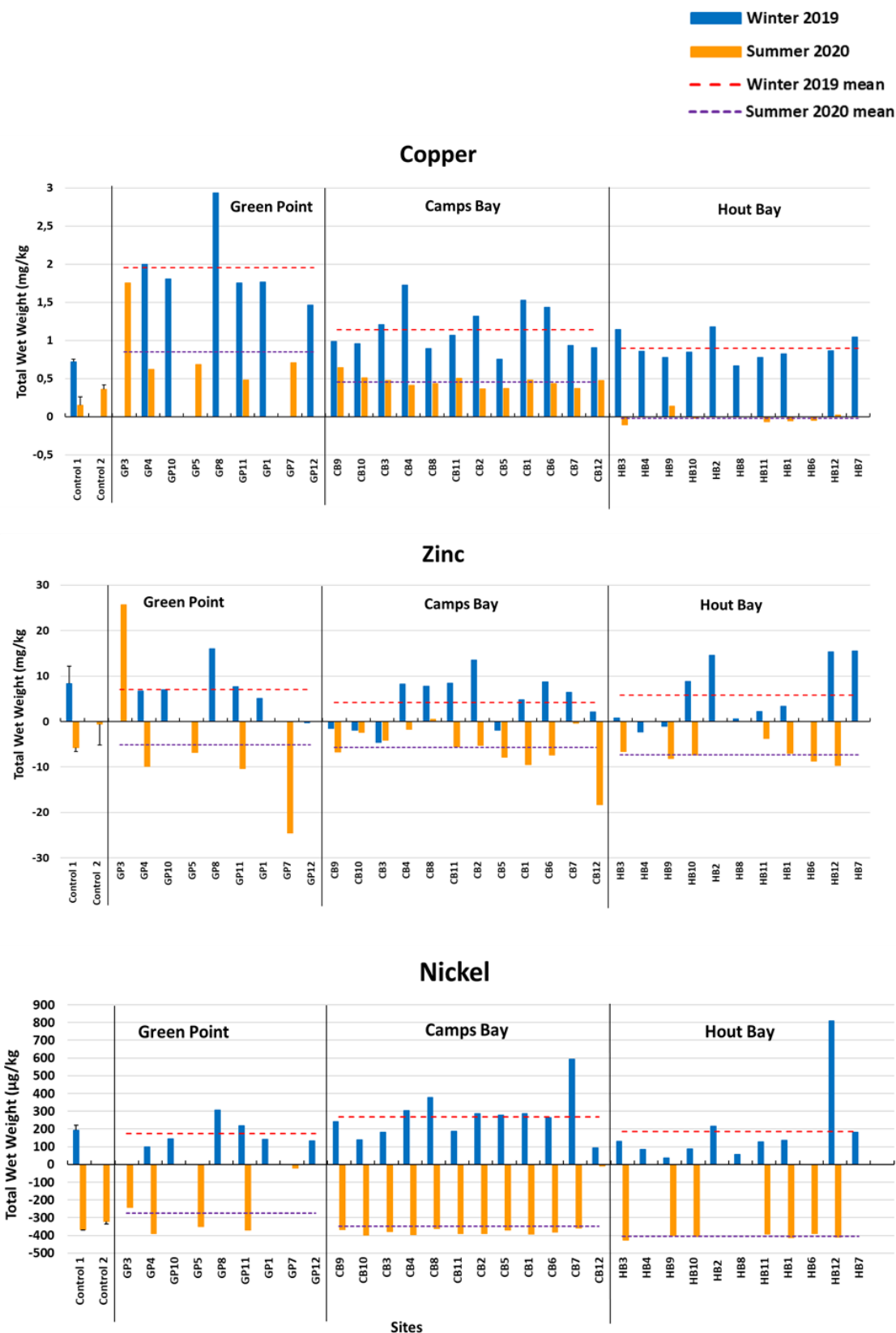


Figure 3.2. Change in levels of trace metal content for mussels deployed in Winter 2019 and Summer 2019 at sites surrounding the deep-water outfalls at Green Point, Camps Bay and Hout Bay, and at the control location at Oudekraal and Kabonkelberg relative to baseline (pre-deployment) levels. Stations are arranged at increasing distances from the outfalls in each case (distance from the outfall increases moving across the page). The dotted red (Winter 2019) and purple (Summer 2020) line indicates the average change across all stations at each site.

4 CONCLUSIONS

There were clear seasonal differences in the growth rate of mussels used in the two monitoring experiments, with lower average growth rates at all sites recorded during the summer deployment. This is attributed to both lower particulate organic matter and temperature of upwelled water which is more prevalent off the Cape Peninsula during the spring and summer period than winter. Seasonal spawning of mussels in summer and the resultant allocation of energy to reproduction rather than growth is also probably a cause of the observed seasonal growth differences. Growth rates appear to be slightly higher at monitoring stations located in close proximity to the outfalls than those further afield, this was more evident during the summer season. It is expected that the higher growth rates closer to the diffusers and greater average growth rates at the diffusers compared to the controls, are a function of higher levels of organic matter and increased nutrient loading present in the water column in the immediate vicinity of the outfalls.

Trace metal accumulation in mussels also showed clear seasonal trends. Mussels at all locations accumulated all three trace metals (Cu, Ni and Zn) relative to baseline concentration during the 2019 winter deployment, but only accumulated copper at the two controls and at the Green Point and Camps Bay outfalls during the summer 2020 deployment. There is no evidence to suggest that the rate of metal bioaccumulation was higher at stations close to the outfalls relative to those further afield. The seasonal differences in trace metal accumulation are also potentially linked to summer reproductive activity, with trace metals effectively excreted along with gametes during spawning.

5 REFERENCES

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6 APPENDICES

Table 6.1 Winter season 1, September to October 2019, *Mytilus galloprovincialis* growth rate raw data. September data is at the start of the 6 week period, pre-deployment, and October data is at the end of the 6 week period, post-deployment.

Date	Sites	Replicates																				Mean Length (mm)	6 Week Growth Rate (mm)
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20		
Sep-19	E_GP1	42	45	44	40	47	48	44	41	45	46	46	42	46	50	44	45	48	45	44	47	44.95	
Sep-19	E_GP2	41	41	40	40	45	47	44	43	50	41	42	40	44	40	49	45	44	46	46	47	43.75	
Sep-19	E_GP3	47	46	45	43	41	46	44	49	45	45	42	47	50	49	49	46	43	44	46	42	45.45	
Sep-19	E_GP4	42	48	40	45	46	42	41	43	46	42	40	45	48	46	42	47	41	41	45	44	43.70	
Sep-19	E_GP5	48	46	44	44	41	40	48	49	42	49	49	40	48	47	41	46	42	43	49	43	44.95	
Sep-19	E_GP6	46	48	40	46	44	47	50	49	47	48	47	40	40	41	41	40	42	49	44	46	44.75	
Sep-19	E_GP7	41	46	47	43	41	41	43	41	49	43	42	50	48	42	50	44	43	44	40	47	44.25	
Sep-19	E_GP8	48	49	44	40	48	42	41	47	49	44	48	45	45	45	44	43	47	41	41	41	44.60	
Sep-19	E_GP9	47	49	40	46	49	42	43	41	42	40	48	42	50	44	48	49	41	41	42	50	44.70	
Sep-19	E_GP10	42	45	49	43	45	43	43	41	45	46	40	43	43	45	40	46	45	44	48	43	43.95	
Sep-19	E_GP11	49	45	48	40	44	49	42	43	41	45	46	46	40	50	41	49	43	43	42	44	44.50	
Sep-19	E_GP12	50	47	43	49	49	40	46	45	49	43	45	44	43	49	44	41	48	41	44	48	45.40	
Sep-19	E_CB1	43	44	45	44	40	41	45	43	44	44	48	40	49	47	42	48	48	42	43	40	44.00	
Sep-19	E_CB2	40	40	43	43	40	45	41	41	44	42	42	41	45	47	48	44	43	45	42	40	42.80	
Sep-19	E_CB3	45	47	42	45	44	49	48.5	40	42	50	42	40	43	41	41	48	46	40	45	44	44.13	
Sep-19	E_CB4	41	41	42	47	48	47	48	48	50	48	44	46	42	44	47	46	43	40	45	46	45.15	
Sep-19	E_CB5	46	47	44	43	47	48	43	46	41.5	40	46	42	43	40	48	48	41	42	42	48	44.28	
Sep-19	E_CB6	50	42	49	40	41	42	40	49	45	44	49	40	48	44	41	42	42	43	44	42	43.85	

Date	Sites	Replicates																				Mean Length (mm)	6 Week Growth Rate (mm)
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20		
Sep-19	E_CB7	43	42	45	44	42	43	43	41	47	41	42	43	47	46	44	49	41	43	41	40	43.53	
Sep-19	E_CB8	47	48	47	44	46	46	40	41	50	42	48	45	44	46	47	42	48	46	43	50	45.50	
Sep-19	E_CB9	45	48	47	42	44	40	43	44	42	41	42	47	42	42	50	42	46	40	40	48	43.75	
Sep-19	E_CB10	41	42	48	45	40	42	40	47	45	47	49	48	44	40	41	42	49	46	43	47	44.30	
Sep-19	E_CB11	47	40	48	47	40	47	42	44	46	46	40	41	41	41	47	44	47	42	47	47	44.20	
Sep-19	E_CB12	43	44	46	46	41	40	48	42	43	48	49	42	48	41	46	41	41	45	45	41	44.00	
Sep-19	E_HB1	50	48	45	50	47	48	46	47	43	42	44	49	45	41	45	42	50	48	41.5	48	45.98	
Sep-19	E_HB2	46	43	49	44	42	40	41	43	47	42	42	47	47	43	42	42	46	50	42	43	44.05	
Sep-19	E_HB3	44	45	40	44	44	45	44	45	40	50	43	40	44	41	42	45	43	45	42	41	43.35	
Sep-19	E_HB4	44	50	43	47	45	43	44	47	46	41	48	47	47	42	45	41	48	40	48	44	45.00	
Sep-19	E_HB5	43	46	44	41	49	41	48	46	47	47	45	42	42	48	50	42	50	43	40	45	44.95	
Sep-19	E_HB6	50	49	42	48	43	45	50	46	43	42	48	43	50	41	44	40	43	49	45	44	45.25	
Sep-19	E_HB7	43	46	45	49	42.5	42.5	40	44	41	43	40	41	41	40	49	47	46	41	42	44	43.35	
Sep-19	E_HB8	49	45	47	47	46	48	41	42	49	45	43	46	43	43	40	47	41.5	40	42	47	44.58	
Sep-19	E_HB9	42	46	43	41	41	41	42	45	50	41	40	45	48	47	44	49	42	40	50	43	44.00	
Sep-19	E_HB10	50	50	49	41	43	49	49	43	43	40	40	40	42	46	46	43	47	41	45	49	44.80	
Sep-19	E_HB11	40	50	42	41	42	46	45	48	42	45	46	47	48	42	46	46	48	50	42	45	45.05	
Sep-19	E_HB12	48	49	46	46	40	49	42	46	41	44	48	49	43	44	45	42	48	45	46	50	45.55	
Sep-19	E_C1a	45	50	46	41	45	48	50	42	48	44	42	47	46	42	45	40	49	43	41	41	44.75	
Sep-19	E_C1b	47	46	46	44	47	49	46	48	41	41	40	41	49	47	45	47	41	46	49	48	45.40	
Sep-19	E_C1c	42	43	40	41	40	45	42	42	45	40	48	42	43	41	41	43	45	42	48	41	42.70	
Sep-19	E_C2a	42	44	46	40	40	48	42	44	48	46	42	40	41	42	45	48	44	42	44	40	43.40	
Sep-19	E_C2b	40	43	44	44	42	42	41	42	48	49	42	41	42	43	40	42	40	41	42	48	42.80	

Date	Sites	Replicates																				Mean Length (mm)	6 Week Growth Rate (mm)
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20		
Sep-19	E_C2c	41	40	42	41	41	45	40	42	45	46	43	40	46	41	43	44	47	41	41	49	42.90	
Oct-19	E_GP1e	52.5	49	51	47	54	45	48.5	45.5	49	46	46	48.5	50	45.5	48	48	52	45	46	50	48.33	3.38
Oct-19	E_GP2e	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Oct-19	E_GP3e	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Oct-19	E_GP4e	46	54	53	51	56	45	48	48.5	51.5	51	49	44.5	47	48	46	46	46	49	47	47	48.68	4.97
Oct-19	E_GP5e	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Oct-19	E_GP6e	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Oct-19	E_GP7e	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Oct-19	E_GP8e	49	47	47	51.5	50	48	47.5	51	48	51	50	50	52	52	54	48.5	51	44	51.5	45	49.38	4.78
Oct-19	E_GP9e	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Oct-19	E_GP10e	44	46	47	48	47.5	48	51	48	45	52	51	49	53.5	48	50	46	48.5	47	47	49	48.28	4.33
Oct-19	E_GP11e	49	49	52	52	48	46	50	46	47	46	47.5	49	46.5	44	53.5	43	51.5	49	54.5	45.5	48.45	3.95
Oct-19	E_GP12e	52	51	51	54	53	49	50	49	48	53	52	46.5	48	52.5	42.5	46	50	46.5	47.5	43	49.23	3.83
Oct-19	E_CB1e	47.5	50	51	51	46	52	50	48.5	41.5	45	48	53	48	45	52	50	44	47	46	48	48.15	3.65
Oct-19	E_CB2e	49.5	51	49	54.5	45	44	45	47.5	46	47	54	44	46	47	48	52.5	42.5	45.5	45	43	47.28	4.48
Oct-19	E_CB3e	50	50	43	51	49	44.5	49	51	44.5	53.5	48	49	48.5	47.5	50	53	48.5	52	46.5	48	48.80	4.68
Oct-19	E_CB4e	51.5	48	48	51	51.5	50.5	47	50	46	50	47	53	47	52	50	52	51	46	52	51	49.70	4.55
Oct-19	E_CB5e	55	54	51	46	50	47	49	47	47	48	49	47	52.5	51.5	46.5	49	51.55	50	46.5	45	49.13	4.85
Oct-19	E_CB6e	52	48	48	52.5	47	49	54	48	48	54	50	49	47	47	45	47	54	48	45	46	48.93	5.08
Oct-19	E_CB7e	46	45	47	49.5	45.5	49	46	43	45	50	46	46	47	49.5	47.5	52.5	44.5	52	45		47.16	3.63
Oct-19	E_CB8e	50	52	51	51	46	54	46	54	47	48	49.5	56	50.5	50	44	50	50	52	44	45	49.48	3.98
Oct-19	E_CB9e	44	46	52	53	51	46.5	44	45	51	50	42	50	49	46	45	49	43.5	42.5	48.5	48	47.28	3.53

Date	Sites	Replicates																				Mean Length (mm)	6 Week Growth Rate (mm)
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20		
Oct-19	E_CB10e	52	49	47	45	50	45.5	53	47	41	49	51.5	44.5	46	45	49	48	53	56	50	45.5	48.33	4.03
Oct-19	E_CB11e	45	52	49	48	50	52	52	51.5	51	45	46	50	47	51	46	50	43.5	44	42	45	47.98	3.78
Oct-19	E_CB12e	45	51	49	46	44	48	47.5	46	45	50	46.5	49	48	46	47	50	50	51	49	46	47.68	3.68
Oct-19	E_HB1e	49	43	55	56.5	45	47	50	54	50	52	54	50	51	45	45	46	49	52.5	52	51	49.85	3.88
Oct-19	E_HB2e	47	41	50	44.5	56	53	47	46.5	43	47.5	45	52	46.5	47	44	51	46	52	50.5	46	47.75	3.70
Oct-19	E_HB3e	49	49	50	46	50	45	51	47	50.5	47	48	48	45.5	52	47	45	50	46	46.5	41.5	47.68	4.33
Oct-19	E_HB4e	49.5	49	52	50	51	53	49	49	48	46	47	50	47	46	49	50	44	45	52	43	48.45	3.45
Oct-19	E_HB5e	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Oct-19	E_HB6e	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Oct-19	E_HB7e	49	49	47	46	52	44	50	44	48	51	42	46	52	43	42	46	45.5	45	45	45	46.58	3.23
Oct-19	E_HB8e	56	55	52	48	54	49	49	50	40.5	43	43	49	53	47	49	52	47	46	48	42.5	48.65	4.08
Oct-19	E_HB9e	47	43	47	47.5	46	50	51.5	48.5	52	49	47	49	48	53	45	42.5	54	52	45	56.5	48.68	4.68
Oct-19	E_HB10e	56.5	53	45	48	48	52	48.5	51.5	52	46	51	45	53	47	47	47.5	44	46	54	46	49.05	4.25
Oct-19	E_HB11e	53	51	49	48	46	52	49	43.5	55	54.5	46.5	52	49	48.5	49.5	46	50	53	42	47.5	49.25	4.20
Oct-19	E_HB12e	49.5	44	53	46.5	45	47.5	48	51	51	53	52.5	49	48.5	54	48	57	45	45	44.5	51	49.15	3.60
Oct-19	E_C1ae	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Oct-19	E_C1be	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Oct-19	E_C1ce	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Oct-19	E_C2ae	41	45	49	43.5	45	46	42	44	46.5	47.5	46	52	49.5	41	48.5	43	42.5	45.5	41	41	44.95	1.55
Oct-19	E_C2be	51	49	48	47	46	44	49	46	45	48	43.5	50	51.5	46	51	49.5	46	46	46	45	47.35	4.55
Oct-19	E_C2ce	43	46	52	49	53	46	45	46	48	47	52	49	48	50	50	47	43	48	44	43	47.43	4.53

Table 6.2 Summer season 2, February to April 2020, *Mytilus galloprovincialis* growth rate raw data. February data is at the start of the 11 week period, pre-deployment, and April data is at the end of the 11 week period, post-deployment.

Date	Sites	Replicates																				Mean Length (mm)	Growth Rate (mm/day)
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20		
Feb-20	E_GP1	45	42	45	40	42	42	43	42	44	47	45	48	43	49	46	47	43	41	41	41	43.80	
Feb-20	E_GP2	45	44	41	43	40	48	43	48	46	49	43	40	43	44	43	48	45	47	48	42	44.50	
Feb-20	E_GP3	41	41	41	43	40	45	45	44	43	47	43	44	41	41	43	49	40	46	48	44	43.45	
Feb-20	E_GP4	45	42	41	42	44	42	48	41	42	45	48	49	45	40	40	44	42	44	41	41	43.30	
Feb-20	E_GP5	46	43	42	49	44	42	41	43	43	41	49	42	42	41	47	43	41	44	46	46	43.75	
Feb-20	E_GP6	41	44	43	43	42	45	40	47	40	41	43	44	41	50	44	41	43	42	46	44	43.20	
Feb-20	E_GP7	42	51	43	45	40	44	47	40	43	47	48	50	41	47	48	42	41	48	45	46	44.90	
Feb-20	E_GP8	40	43	41	44	44	43	43	48	42	45	40	45	43	43	46	42	40	50	40	44	43.30	
Feb-20	E_GP9	41	50	40	48	47	43	42	45	42	46	42	45	41	44	41	40	45	40	40	50	43.60	
Feb-20	E_GP10	41	46	46	46	43	48	43	43	40	46	42	42	43	42	47	50	40	42	42	45	43.85	
Feb-20	E_GP11	50	42	41	43	44	46	43	43	41	43	41	42	46	46	45	43	48	42	46	42	43.85	
Feb-20	E_GP12	43	42	43	48	40	45	40	40	40	43	42	45	43	44	42	41	41	47	41	44	42.70	
Feb-20	E_CB1	43	44	44	43	43	43	49	43	42	44	43	41	45	43	42	44	40	44	42	45	43.35	
Feb-20	E_CB2	44	47	42	46	43	40	42	46	46	43	40	42	44	41	40	46	41	45	47	42	43.35	
Feb-20	E_CB3	49	43	44	46	43	41	42	47	46	42	42	46	40	42	44	47	42	45	47	46	44.20	
Feb-20	E_CB4	46	41	45	45	44	44	43	50	45	41	49	45	40	42	40	48	50	48	49	43	44.90	
Feb-20	E_CB5	40	46	44	40	47	42	43	42	43	41	46	44	48	45	47	44	44	48	41	48	44.15	
Feb-20	E_CB6	49	42	42	45	49	45	43	48	43	47	44	46	46	50	45	42	44	42	43	44	44.95	
Feb-20	E_CB7	43	41	49	48	43	48	43	43	40	45	42	41	43	47	48	42	46	43	43	41	43.95	
Feb-20	E_CB8	42	42	43	41	40	42	43	47	42	40	42	49	46	41	44	46	41	40	44	49	43.20	
Feb-20	E_CB9	49	43	40	42	44	46	41	45	43	48	45	42	41	46	47	45	44	43	43	48	44.25	

Date	Sites	Replicates																				Mean Length (mm)	Growth Rate (mm/day)
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20		
April-20	E_GP2e	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
April-20	E_GP3e	51	49	44	48	52	45	47	45	51	47	45	54	45	46	48	44	43	46	46	50	47.29	0.05
April-20	E_GP4e	57	59	49	52	53	55	49	55	59	58	46	50	54	50	52						53.23	0.14
April-20	E_GP5e	51	52	52	52	49	47	48	52	51	50	51	50	50	49	46	48	49	46	51	49	49.51	0.08
April-20	E_GP6e	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
April-20	E_GP7e	46	49	43	49	52	51	40	46	47	52	43	44	47	44	47	48	45	44	45		46.37	0.03
April-20	E_GP8e	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
April-20	E_GP9e	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
April-20	E_GP10e	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
April-20	E_GP11e	51	47	50	56	47	53	48	55	49	48	49	57	55	50	51	38	49	42	51	52	49.77	0.08
April-20	E_GP12e	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	Nd	nd
April-20	E_CB1e	51	47	53	48	44	47	48	41	45	46	54	43	49	50	49	47	47	45	46	45	47.03	0.04
April-20	E_CB2e	51	45	49	48	51	53	41	46	50	51	46	44	46	45	47	50	44	49	48		47.52	0.06
April-20	E_CB3e	48	47	46	43	45	53	47	50	42	50	50	44	47	49	51	46	44	50	47	44	47.06	0.04
April-20	E_CB4e	53	50	53	45	52	46	47	51	50	52	51	54	52	44	53	49	46	56	43	54	50.03	0.07
April-20	E_CB5e	53	52	49	47	48	46	55	46	47	54	50	47	47	46	44	49	43	50	50		48.49	0.06
April-20	E_CB6e	50	49	50	54	55	51	48	47	47	47	48	52	43	47	52	44	46	46			48.61	0.05
April-20	E_CB7e	49	51	48	45	46	47	47	50	50	49	48	49	48	51	49	44	44	47	46		47.74	0.05
April-20	E_CB8e	45	51	45	50	51	50	50	50	45	42	45	46	44	47	50	55	45	46	44	44	47.19	0.06
April-20	E_CB9e	51	54	46	50	52	57	46	49	47	51	50	49	50	54	50	50	51	51	51		50.31	0.08
April-20	E_CB10e	52	57	52	49	44	46	52	45	52	44	52	52	45	49	50	52	47	42			48.94	0.07
April-20	E_CB11e	48	48	49	46	50	45	52	48	58	43	48	52	47	49	45	43	45	44	49	47	47.59	0.06
April-20	E_CB12e	42	49	49	51	46	44	46	47	44	52	49	48	51	51	44	51	50	26	44	46	46.37	0.03

Date	Sites	Replicates																				Mean Length (mm)	Growth Rate (mm/day)
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20		
April-20	E_HB1e	53	51	53	47	50	50	47	50	46	48	53	45	45	51	53	48	53	49	49	49	49.54	0.05
April-20	E_HB2e	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
April-20	E_HB3e	50	49	54	54	52	46	50	49	47	49	52	47	50	50	47	49	44	47	45		48.93	0.06
April-20	E_HB4e	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
April-20	E_HB5e	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
April-20	E_HB6e	57	46	47	51	52	48	47	52	52	53	52	52	51	50	54	56	49	47	47		50.75	0.08
April-20	E_HB7e	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
April-20	E_HB8e	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
April-20	E_HB9e	47	46	50	46	49	51	51	47	45	49	53	52	52	53	50	50	40	50	49	48	48.91	0.07
April-20	E_HB10e	40	46	44	45	51	50	48	46	50	45	51	46	47	46	45	48	49	52	53	46	47.42	0.05
April-20	E_HB11e	57	50	51	57	52	52	52	52	51	51	49	50	50	49	42	44	47	48	44	48	49.84	0.08
April-20	E_HB12e	48	51	53	49	54	52	45	47	54	50	50	46	43	51	52	49	50	52	51	51	49.91	0.06
April-20	E_C1ae	49	49	50	49	49	47	50	46	49	50	47	49	50	49	44	48					48.44	0.08
April-20	E_C1be	46	47	47	49	50	47	45	50	50	52	50	49	50	46	47	48	47	49	43	42	47.69	0.05
April-20	E_C1ce	50	44	50	48	45	45	52	47	47	50	49	48	48	45	43	49	48	46	47		47.43	0.04
April-20	E_C2ae	48	50	56	53	53	48	47	43	47	44	47	46	49	45	49	52	46	44	42	45	47.70	0.07
April-20	E_C2be	49	47	49	48	48	46	48	42	49	52	45	44	53	44	53	45	47	48	43	49	47.48	0.06
April-20	E_C2ce	51	29	52	52	45	56	52	53	50	49	50	49	47	51	50	47	42	52	53	49	48.90	0.05

Table 6.3 *Mytilus galloprovincialis* trace metal test results for Cu, Ni, and Zn at Camp's Bay, Hout Bay, and Green Point (Table Bay). Results from Winter 1, September 2019 to October 2019 are presented below. Three baseline samples were included in lieu of lost samples and in order to capture a more robust, mean baseline value for each trace metal. (GP = Green Point, CB = Camps Bay, HB = Hout Bay, C = Control).

	Zn Total Wet Weight (mg/kg)	Cu Total Wet Weight (mg/kg)	Ni Total Wet Weight (µg/kg)
South African Standard	No SA Standard	No SA Standard	No SA Standard
International Standard	150-1000	70	50 (mg/kg)
Baseline 1	28.50	0.38	163.80
Baseline 2	24.23	0.38	128.53
Baseline 3	25.44	0.36	131.21
E_GP1	31.10	2.14	282.11
E_GP4	32.73	2.37	239.87
E_GP8	42.07	3.31	447.73
E_GP10	33.00	2.18	286.85
E_GP11	33.68	2.13	360.59
E_GP12	25.74	1.84	275.06
E_CB1	30.84	1.90	426.84
E_CB2	39.56	1.69	427.28
E_CB3	21.40	1.58	323.27
E_CB4	34.25	2.10	445.00
E_CB5	24.13	1.13	419.55
E_CB6	34.78	1.81	403.87
E_CB7	32.43	1.31	733.54
E_CB8	33.85	1.27	517.33
E_CB9	24.55	1.36	383.20
E_CB10	24.15	1.33	280.83
E_CB11	34.44	1.44	327.39
E_CB12	28.19	1.28	233.45
E_HB1	29.43	1.20	277.57
E_HB2	40.58	1.55	356.11
E_HB3	26.83	1.52	271.61
E_HB4	23.77	1.23	225.81
E_HB7	41.54	1.42	321.18
E_HB8	26.65	1.04	198.00
E_HB9	24.99	1.15	176.08
E_HB10	34.82	1.22	229.22
E_HB11	28.21	1.15	267.68
E_HB12	41.40	1.24	950.33
E_C2a	31.19	1.12	312.09
E_C2b	41.99	1.13	388.48
E_C2c	29.93	1.03	303.17

Table 6.4 *Mytilus galloprovincialis* trace metal test results for Cu, Ni, and Zn at Camp's Bay, Hout Bay, and Green Point (Table Bay). Results from Summer 2, February 2020 to April 2020 are presented below. Two baseline samples were included in lieu of lost samples and in order to capture a more robust, mean baseline value for each trace metal. (GP = Green Point, CB = Camps Bay, HB = Hout Bay, C = Control).

	Zn Total Wet Weight (mg/kg)	Cu Total Wet Weight (mg/kg)	Ni Total Wet Weight (µg/kg)
South African Standard	No SA Standard	No SA Standard	No SA Standard
International Standard	150-1000	70	50 (mg/kg)
Baseline 1 (GP2, GP7, CB12)	45.50	0.53	298.20
Baseline 2 (rest of sites)	33.60	0.64	557.48
GP3	59.29	2.40	313.85
GP4	23.69	1.27	168.15
GP5	26.78	1.33	207.90
GP7	21.00	1.24	277.60
GP11	23.28	1.13	187.87
CB1	24.15	1.13	163.74
CB2	28.35	1.01	168.34
CB3	29.48	1.12	178.09
CB4	31.90	1.06	160.69
CB5	25.74	1.01	188.35
CB6	26.22	1.08	177.28
CB7	33.22	1.01	198.15
CB8	34.04	1.08	194.49
CB9	26.91	1.29	190.33
CB10	31.20	1.15	157.51
CB11	28.00	1.15	167.23
CB12	27.18	1.01	289.98
Control CB1	29.48	1.01	192.68
Control CB2	26.40	0.73	187.13
Control CB2	27.72	0.65	190.89
HB1	26.60	0.59	145.77
HB3	27.00	0.54	129.28
HB6	24.84	0.59	166.79
HB9	25.40	0.78	156.60
HB10	26.22	0.63	150.99
HB11	29.88	0.58	165.08
HB12	23.94	0.67	148.73
Control HB1	23.96	0.89	207.50
Control HB2	36.42	1.04	242.95
Control HB3	38.79	1.07	254.17



CITY OF CAPE TOWN
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9 APPENDIX E: FINAL HYDRODYNAMIC MODELLING REPORT FOR HOUT BAY

SAMPLING AND ANALYSIS OF THE CITY OF CAPE TOWN'S MARINE OUTFALLS AT GREEN POINT, CAMPS BAY AND HOUT BAY

Final Report on Dispersion Model Calibration and Results for Hout Bay

REV.00

01 October 2020



Lwandle Technologies (Pty) Ltd / City of
Cape Town
Cape Town, South Africa



CITY OF CAPE TOWN
ISIXEKO SASEKAPA
STAD KAAPSTAD

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Cape Town, South Africa



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1. INTRODUCTION

1.1 Background

The City of Cape Town (CoCT) has appointed Lwandle Technologies (Pty) Ltd (Lwandle) to perform sampling and analysis of the CoCT's marine outfalls at Green Point, Camps Bay and Hout Bay for a period of three years (Tender 124s/2018/19). Lwandle has sub-contracted PRDW South Africa (Pty) Ltd (PRDW) to undertake dispersion modelling for the three outfalls.

1.2 Scope and objectives

The scope of the study is to perform three-dimensional (3D) hydrodynamic and dispersion modelling for the Green Point, Camps Bay and Hout Bay marine outfalls operated by the CoCT. The objectives of the study are as follows:

- Provide imagery and animations of the effluent plume suitable for overlaying the sampling and monitoring data.
- Determine the dilutions achieved in the near- and far-field for a conservative tracer representing dissolved constituents in the effluent such as nutrients, etc. This includes a probabilistic description of the Zone of Initial Dilution (ZID) taking into account variations in metocean conditions and variations in effluent flows and/or concentrations.
- Determine the probability of the plume reaching the shoreline and the concentrations of faecal indicator bacteria (enterococci and E.coli) during these events.
- Determine the concentrations of discharged Total Suspended Solids (TSS) in the water column and where these are deposited on the seabed. This is a proxy for the fate of pollutants that adsorb to solid particles, e.g. heavy metals.

The model results can be used by Lwandle and the CoCT for the following:

- To refine the location of sampling stations (for the second year of sampling).
- To assist interpretation of sampling results, e.g. are observed concentrations likely to have had an outfall as a source or rather stormwater or other sources.
- To predict the metocean conditions when plume may impact bathers.
- To define the size of the ZID and the spatial extent of particulate deposition zones for the Coastal Waters Discharge Permit application.
- To determine how many dilutions are achieved by the time that the plume reaches desalination plant intakes.



Future applications of the models (outside the scope of this study) could include:

- Testing the impacts of changes in flow rates, effluent density (e.g. due to the addition of desalination brine) and effluent concentrations on the dispersion.
- Test options to improve the dispersion, e.g. modifications to the diffuser, lengthening of the pipeline, etc.
- The models could also be operationalised to provide forecasts of bathing water quality as is done in Denmark, Sweden and New Zealand, e.g. <http://newkbh.badevand.dk>. The concept is that if the effluent from the outfalls is impacting bathing beaches a limited number of times per year, then a forecast may be the best short- to medium-term approach to mitigate the associated risk.

1.3 Deliverables

PRDW's deliverables comprise the following:

- Deliverable 1: Progress report on model setup (one report for each outfall).
- Deliverable 2: Progress report on model calibration for winter/spring (August – September 2019) and preliminary results (one report for each outfall).
- Deliverable 3: Final report including model calibration for summer/autumn (February – April 2020) and final results (one report for each outfall).

This report is Deliverable 3 for Hout Bay. This report supersedes the Deliverable 1 and Deliverable 2 reports as all the information contained in the previous reports is included and updated here. Similar reports are provided for Green Point and Camps Bay.

1.4 Report structure

Section 2 presents a description of the models, which include a hydrodynamic, water quality, suspended sediment and wave model. Section 3 presents the discharge characterisation which describes the diffuser, effluent and water quality guidelines. Section 4 describes the model setup which includes the mesh, bathymetry, wind, boundary conditions and model settings. The model calibration is presented in Section 5 followed by the model results in Section 6. Conclusions and recommendations are provided in Section 7 and Section 8.



2. DESCRIPTION OF THE MODELS

2.1 Overview

The modelling was undertaken using the MIKE modelling system developed by DHI in Denmark. PRDW has 15 years of experience in applying these models. The MIKE system is widely used by international engineering consultancies and includes a number of features that makes it an appropriate model for this application, including:

- A dynamic coupling of a near-field jet model within the 3D far-field hydrodynamic model;
- the ability to dynamically couple different sub-models to include all the relevant physical and biogeochemical processes; and
- the use of a flexible mesh which allows refinement around the outfalls.

The following four sub-models were used:

- Hydrodynamic model: 3D hydrodynamics including tides, wind, waves, temperature and salinity. Includes an integral jet model for each port with dynamic two-way coupling of near- and far-field dispersion.
- Water quality model: 3D water quality model for modelling the far-field advection-dispersion of:
 - a conservative tracer representing dissolved constituents in the effluent such as nutrients, etc
 - Faecal indicator bacteria (E.coli and enterococci) including die-off.
- Suspended sediment model: 3D model for modelling Total Suspended Solids (TSS) - advection-dispersion-settling-deposition-resuspension based on combined current-wave bed stresses.
- Spectral wave model: wave refraction and breaking to generate wave-driven currents and wave bed stresses.

2.2 Hydrodynamic model

2.2.1 General description

The three-dimensional MIKE 3 Flow Flexible Mesh Model was used for the hydrodynamic modelling. The application of the model is described in the User Manual (DHI, 2020a), while full details of the physical processes being simulated and the numerical solution techniques are described in the Scientific Documentation (DHI, 2020b).

The model is based on the numerical solution of the three-dimensional incompressible Reynolds averaged Navier-Stokes equations invoking the assumptions of Boussinesq and of hydrostatic pressure. The model consists of the continuity, momentum, temperature, salinity and density equations and is closed by a $k-\epsilon$ vertical turbulence closure scheme. Horizontal eddy viscosity is modelled with the Smagorinsky formulation.

The time integration of the shallow water equations and the transport equations is performed using a semi-implicit scheme, where the horizontal terms are treated explicitly and the vertical terms are treated implicitly. In the vertical direction a structured mesh, based on a sigma-coordinate transformation is used, while the geometrical flexibility of the unstructured flexible mesh comprising triangles or quadrangles is utilised in the horizontal plane.



The model includes the following physical phenomena:

- Currents due to tides;
- Currents due to wind stress on the water surface;
- Currents due to density gradients;
- Currents due to waves; the second order stresses due to breaking of short period waves are included using the radiation stresses computed in the Spectral Wave model;
- Coriolis forcing;
- Bottom friction;
- Flooding and drying;
- Sources and sinks including dynamic near and far-field coupling; and
- Heat exchange.

2.2.2 Near and far-field coupling

An important feature of the model is a dynamic coupling of a near-field jet model and the 3D far-field hydrodynamic model. The near-field solution based on the integral jet model equations by Jirka (2004). Entrainment into the jet is using Distributed Entrainment Sink Approach by Choi and Lee (2007). At the end of the near-field the diluted discharge is released into far-field model as a source, as shown in Figure 2-1.

In order to determine, when the jet/plume becomes passive and thus a part of the ambient flow, a number of stop criteria are invoked:

1. If the jet reaches the water surface.
2. If the jet reaches the bottom.
3. If the jet momentum is smaller than or close to the ambient flow induced momentum.
4. If the jet dies out in the stagnant conditions.
5. If the jet experiences buoyancy reversal twice.
6. If the trajectory of the jet exceeds a maximum travel distance as specified by the user.
7. If the jet exhibits strong curvature, such as going into strong opposing ambient flow.
8. If the jet reaches a domain boundary (open or close).
9. If the jet reaches dried cells.

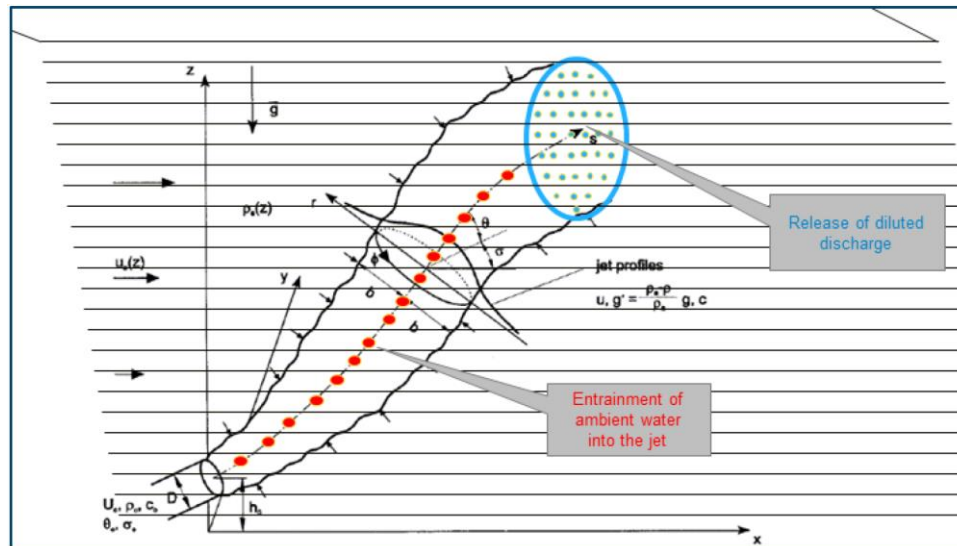


Figure 2-1: Dynamic coupling of near-field and far-field models: entrainment sinks along the plume trajectory and distributed sources at the release location.

2.3 Water quality model

2.3.1 General description

The MIKE 3 ECO Lab Model was used to simulate the far-field dispersion of a conservative tracer and faecal indicator bacteria (E.coli and enterococci). The application of the model is described in the User Manual (DHI, 2020c) while full details of the physical processes being simulated and the numerical solution techniques are described in the Scientific Documentation (DHI, 2020d).

The model simulates the transport and fate of constituents in three dimensions based on advection-dispersion and non-conservative processes. The model can be used to describe chemical, biological, ecological processes and interactions between state variables and also the physical process of sedimentation of components can be described. The hydrodynamics (water levels, currents, temperature, salinity, vertical, dispersion, horizontal dispersion and release location at the end of the near-field) are obtained via an online coupling to the MIKE 3 Flow Flexible Mesh Model and the same three-dimensional grid is used.

An ECO Lab template is used to describe the non-conservative processes relevant for each specific constituent. Since the conservative tracer undergoes advection and dispersion only without any non-conservative processes, no template is required for the conservative tracer. Faecal indicator bacteria (E.coli and enterococci) require an ECO Lab template to simulate die-off, as described below.

2.3.2 Bacteria die-off

In addition to physical dilution, the concentration of faecal indicator bacteria (E.coli and enterococci) reduces due to die-off. The die-off was implemented in the ECO Lab model as described below.



2.3.2.1 ECO Lab model equations

First order decay:

Bacterial decay can be described by the first order decay function for a duration t :

$$C(t) = C_0 e^{-k \cdot t} \quad (1)$$

where

- C = bacteria concentration [CFU.100ml⁻¹]
- C_0 = initial bacteria concentration ($t = 0$) [CFU.100ml⁻¹]
- t = time [hours]
- k = linear decay rate [hours⁻¹]

The decay rate is often expressed as T_{90} : the time needed for the 90% of the bacterial concentration to decay.

Therefore, if $t = T_{90}$, $\frac{C}{C_0} = 0.1$:

$$T_{90} = \frac{\ln(0.1)}{k} \quad (2)$$

where

- T_{90} = time needed for the 90% of the bacterial concentration to decay [hours]

E.coli decay model:

Erichsen, et al. (2006) adopted an E.coli decay model from Jensen (1990). The model describes the decay contributions from dark and light conditions:

$$k_{coli} = k_m + K_l \cdot I_l \quad (3)$$

where

- k_{coli} = E.coli decay rate [days⁻¹]
- k_m = decay coefficient for dark conditions [days⁻¹], see equation 4
- K_l = decay coefficient for light conditions [m².W⁻¹.days⁻¹], see equation 5
- I_l = Solar irradiance [W.m⁻²], see equation 6

The dark decay term is expressed as a function of water temperature:

$$k_m = a_T \cdot T - k_{m0} \quad (4)$$

where

- T = water temperature [°C]
- a_T = temperature dependency constant for dark reaction [h⁻¹.°C⁻¹]
- k_{m0} = initial coliform decay rate for dark reaction [h⁻¹]



The light decay coefficient is expressed as a function of water temperature, and salinity:

$$K_l = S_m \cdot \frac{b_T \cdot T + K_{l0}}{a \cdot S_m - (a-1) \cdot S} \quad (5)$$

where

- S = water salinity [PSU]
- S_m = reference salinity [PSU]
- a = correction for salinity [-]
- b_T = temperature dependency constant for light reaction [$\text{m}^2 \cdot \text{W}^{-1} \cdot \text{h}^{-1} \cdot ^\circ\text{C}^{-1}$]
- K_{l0} = initial coliform decay rate for light reaction [$\text{m}^2 \cdot \text{W}^{-1} \cdot \text{h}^{-1}$]

In a water body, light attenuation can be described as a function of depth using the Lambert-Beer law:

$$I_l = I_0 \cdot e^{-E_{ta} \cdot z} \quad (6)$$

where

- I_l = solar irradiance at depth z below surface [$\text{W} \cdot \text{m}^{-2}$]
- I_0 = surface solar irradiance [$\text{W} \cdot \text{m}^{-2}$]
- z = depth below surface [m]
- E_{ta} = light attenuation coefficient [m^{-1}]

Enterococci decay model:

The enterococci decay rate is expressed relative to the E.coli decay rate:

$$k_{ent} = k_{coli} \cdot r \quad (7)$$

where

- r = decay rate ratio of E.coli to enterococci [-]
- k_{ent} = enterococci decay rate [days^{-1}]

Literature indicates that enterococci decay slower than E.coli: based on 16 samples from 6 studies – e.g. Sinton, et al. (1994) – the median value for r was 0.42 (T_{90} equivalent ratio of 2.39), which has been adopted for this study. It is noted that r ranged from 0.21 to 2.5, indicating the uncertainty level for this value.

2.3.2.2 Validation of die-off model

The ECO Lab model described above was calibrated against measurements to confirm the required constants for this study. The constants are:

- $S_m = 34.5$ PSU
- $a = 1.54$
- $a_T = 2.425 \times 10^{-3} \text{ h}^{-1} \cdot ^\circ\text{C}^{-1}$
- $k_{m0} = 4.167 \times 10^{-3} \text{ h}^{-1}$
- $b_T = 6.25 \times 10^{-5} \text{ m}^2 \cdot \text{W}^{-1} \cdot \text{h}^{-1} \cdot ^\circ\text{C}^{-1}$
- $K_{l0} = 3.13 \times 10^{-4} \text{ m}^2 \cdot \text{W}^{-1} \cdot \text{h}^{-1}$

The measurements were obtained from Bellair, et al. (1977) and included 162 measurement samples of hourly decay rates (T_{90}) of E.coli on the seawater surface at Balmoral Bay near Sydney, Australia. The ECO Lab model assumed a constant water temperature and salinity representative of the measured conditions. Time-

varying solar radiation was obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 global atmospheric model (ECMWF, 2020). Figure 2-2 presents the a comparison of modelled and measured E.coli decay at Balmoral Bay. Also shown are measurements of T_{90} in sewage at Durban from Livingstone et al. (1990).

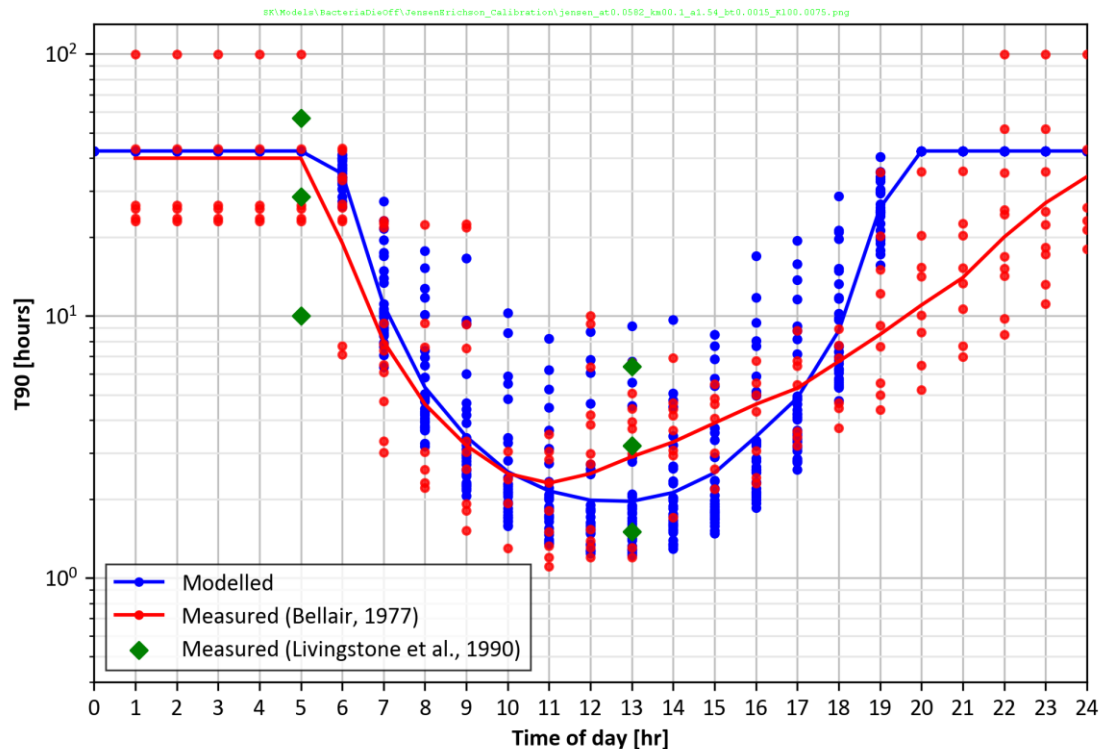


Figure 2-2: Measured and ECO Lab model comparison of E.coli decay at Balmoral Bay. The geometric mean is shown with a solid line. Also shown are measurements at Durban from Livingstone et al. (1990).

The comparison shows that the model is able to reproduce the measurements with satisfactory accuracy. Note the scatter from the model is directly proportional to the solar radiation intensity, whereas the measurements in addition include some variability in the seawater temperature, salinity and statistical randomness.

2.3.3 Model inputs

For the present Cape Town outfall study, a time and space varying surface solar irradiance I_0 was obtained from ECMWF. A constant light attenuation coefficient $E_{ta} = 0.6$ was applied, based on the annual average of Secchi disk measurements in Table Bay provided by Lwandle. Time and space-varying seawater temperature and salinity were obtained from the coupled hydrodynamic model.

2.4 Suspended sediment model

2.4.1 General description

The MIKE 3 Mud Transport Flexible Mesh Model was used to model the concentrations of discharged Total Suspended Solids (TSS) in the water column and where these are deposited on the seabed. This is a proxy for the fate of pollutants that adsorb to solid particles less than $63 \mu\text{m}$, e.g. heavy metals.



The application of the model is described in the User Manual (DHI, 2020e) while full details of the physical processes being simulated and the numerical solution techniques are described in the Scientific Documentation (DHI, 2020f). The hydrodynamics (water levels, currents, temperature, salinity, vertical, dispersion, horizontal dispersion and release location at the end of the near-field) are obtained via an online coupling to the MIKE 3 Flow Flexible Mesh Model and the same three-dimensional grid is used.

The following processes are included in the simulations:

- 3D advection-dispersion of suspended sediment by currents;
- Settling of sediment through water column and deposition onto the seabed, dependent on the critical shear stress for deposition;
- Resuspension of sediment from the seabed, dependent on the critical shear stress for resuspension and the erosion coefficient;
- Bed shear stress due to combined currents and wave orbital velocities, as obtained through direct coupling with the hydrodynamic and spectral wave models.

2.4.2 Model settings

The input parameters used to model the TSS has been obtained from a previous study in Table Bay by PRDW (2017). The study calibrated a suspended sediment model to measured TSS concentrations in the water column and locations of fine sediment depo-centres. The modelled sediment comprises fine cohesive organic and inorganic particles with diameters less than 63 μm . The input parameters are listed in Table 2-1

Table 2-1: Input parameters used in the modelling of TSS.

Parameter	Unit	Value
Settling velocity of suspended sediment	m/s	5×10^{-5}
Critical shear stress for resuspension	N/m ²	0.2
Critical shear stress for deposition	N/m ²	0.1
Resuspension rate	kgDW/m ² /s	1×10^{-4}
Bulk density of dry sediment	kg/m ³ bulk	400

2.5 Wave model

2.5.1 General description

The MIKE 21 Spectral Waves (SW) Flexible Mesh model was used for simulating wave transformation to the nearshore. The application of the model is described in the User Manual (DHI, 2020g), while full details of the physical processes being simulated and the numerical solution techniques are described in the Scientific Documentation (DHI, 2020h). The model simulates the growth, decay and transformation of wind-generated waves and swells in offshore and coastal areas using unstructured meshes. The model used the same mesh as the hydrodynamic model. The model is fully spectral and can be run in either quasi-stationary or instationary mode, depending on the size of the model domain.



The model included the following physical phenomena:

- Dissipation due to bottom friction;
- Dissipation due to depth-induced wave breaking;
- Nonlinear energy transfer amongst the different wave components (quadruplet-wave interactions);
- Refraction and shoaling due to depth variations; and
- Generation of local wind-waves; and
- The effect of time-varying water depth due to the tide - the water depth at each time-step is computed in the hydrodynamic model including tidal and wave-setup.

2.5.2 Model settings

Bottom friction was modelled using a constant Nikuradse roughness of $k_N = 0.5$ m. The modelled water level from the hydrodynamic model was coupled to the wave model. The model was run in the fully spectral, quasi stationary formulation excluding the effect of additional wave generation within the model due to wind.



3. DISCHARGE CHARACTERISATION

3.1 Diffuser configuration

The Hout Bay diffuser is located in a depth of -37.0 m CD as shown in Figure 4-3. Table 3-1 presents the diffuser geometry and individual port configuration. The model assumes that the pipeline and diffusers are operating as described below and that there are no breakages, leaks or blockages.

Table 3-1: Diffuser geometry and flow distribution for Hout Bay.

Diffuser		Ports							
Section no.	Inside diameter [mm] ⁽¹⁾	Port no. ⁽²⁾	Port diameter [mm] ⁽¹⁾	Flow distribution [%] ⁽³⁾	Discharge per port [l/s] ⁽⁶⁾	Port velocity [m/s] ⁽⁶⁾	Spacing [m] ⁽¹⁾	Level above seabed [mm] ⁽¹⁾	Port configuration ⁽¹⁾
1		1	100	11.00%	6.63	0.844	10	1 050	Effluent is discharged horizontally through an elbow bend (illustrated below) with alternating discharge directions  (4)
		2	100	11.10%	6.68	0.851			
		3	100	11.20%	6.79	0.865			
		4	100	11.60%	7.01	0.892			
		5	100	12.20%	7.39	0.941			
2a	364	6	78	8.00%	4.83	1.012			
		7	78	8.30%	5.00	1.046			
		8	78	8.50%	5.16	1.080			
		9	78	8.90%	5.38	1.126			
		10	78	9.30%	5.60	1.171			
2b ⁽⁵⁾		11	78	closed					
		12	78	closed					
		13	78	closed					
		14	78	closed					
		15	78	closed					

Notes:

- (1) Source: PRDW (1989).
- (2) The ports are arranged from offshore (port no.1) to inshore (port no. 15).
- (3) Based on diffuser hydraulics modelling undertaken by the CoCT
- (4) Schematic representation of port configuration
- (5) The first 5 inshore ports are closed
- (6) Calculated using the 50th percentile discharge rates in Table 3-2.

3.2 Discharge rates

Measured flow rates were provided by the CoCT for input to the dispersion model. The measurements comprise daily average flow rates and cover the winter/spring and summer/autumn model simulation periods. Flow rate measurements at 30-minute intervals were only available between 20 February 2020 and 10 April 2020. Measurements available for Green Point at 30-minute intervals were used to scale the Hout Bay dataset for the winter/spring period to ensure that the model results account for diurnal and day to day variations in flows, whilst maintaining the measured daily average flow rates at Hout Bay. The summer/autumn daily dataset were similarly scaled using a typical daily variation obtained from the limited 30-minute dataset from Hout Bay where the high frequency measurements were not available for the simulation period.



Figure 3-1 and Figure 3-2 present time series plots of the Hout Bay effluent discharge rate for the winter/spring and summer/autumn periods respectively. A statistical summary is provided in Table 3-2.

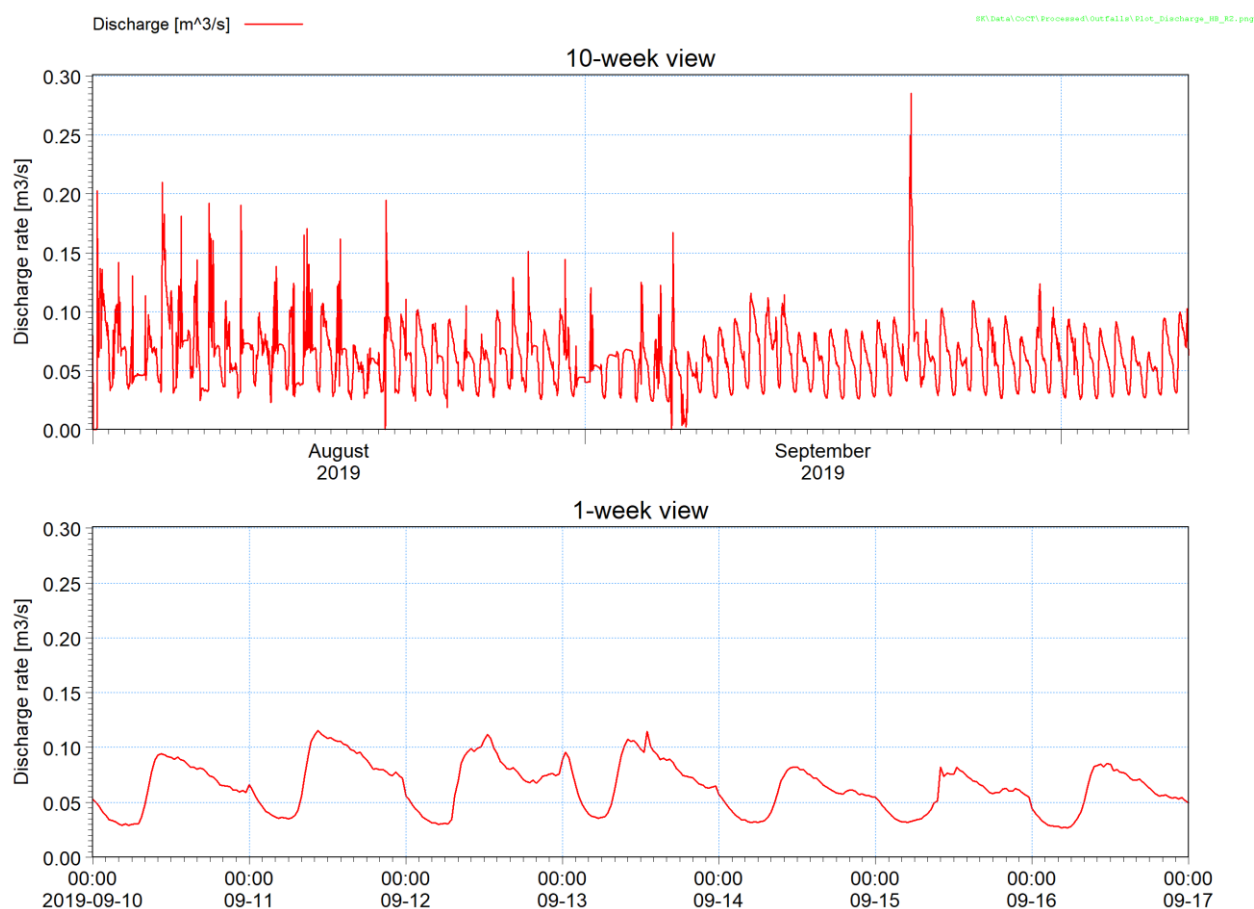


Figure 3-1: Time series of Hout Bay effluent discharge rate for the winter/spring period.

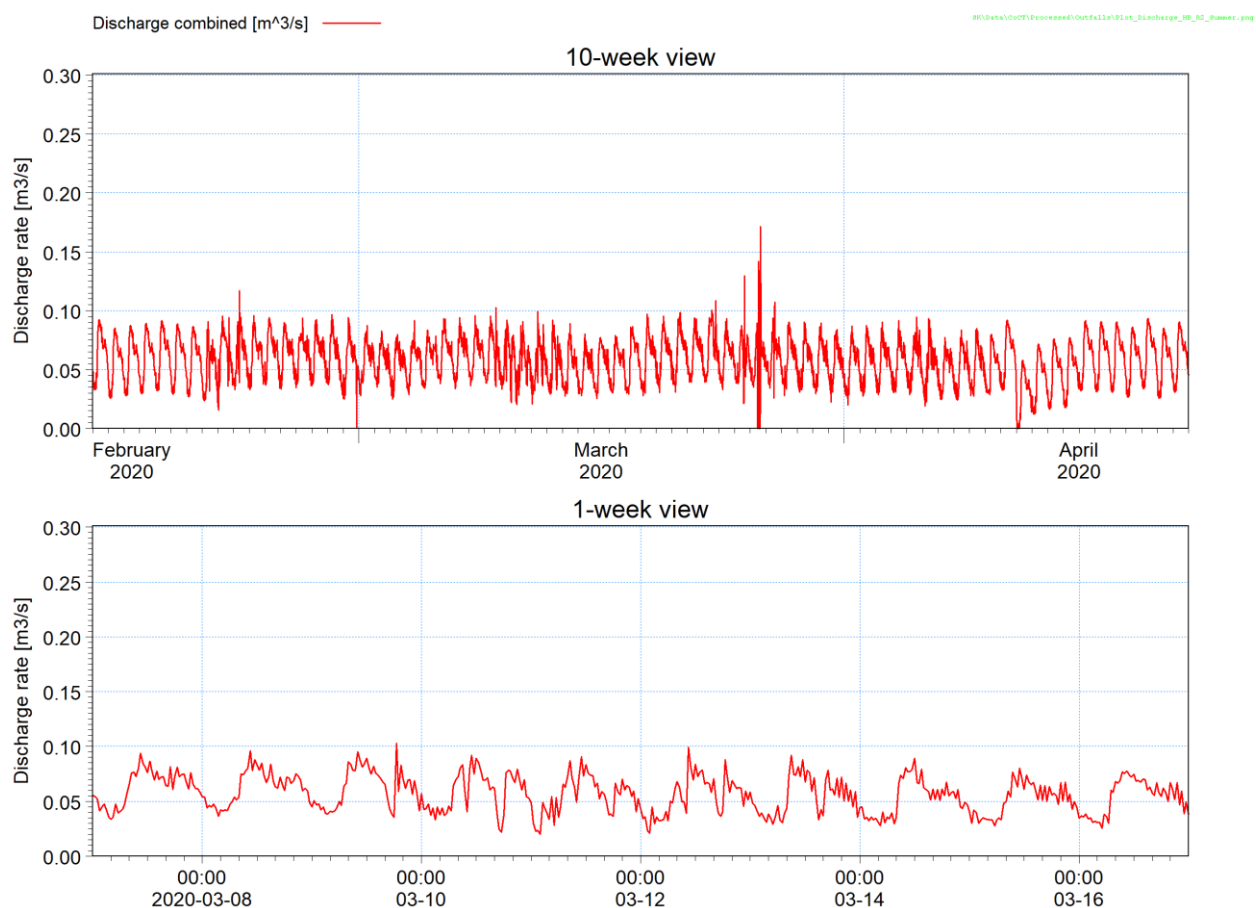


Figure 3-2: Time series of Hout Bay effluent discharge rate for the summer/autumn period.

Table 3-2: Hout Bay effluent discharge rate statistics.

Parameter	Discharge rate	
	Winter/spring	Summer/autumn
Average	5 320 m ³ /d	5 050 m ³ /d
5 th percentile	0.028 m ³ /s	0.031 m ³ /s
50 th percentile	0.060 m ³ /s	0.060 m ³ /s
95 th percentile	0.104 m ³ /s	0.086 m ³ /s



3.3 Effluent concentrations

The effluent concentrations applied in the model are shown in Table 3-1

Table 3-3: Modelled effluent concentrations.

Constituent	Concentration	Comments
E.coli	1 x10 ⁷ CFU/100 ml	Kay et al. (2008), CSIR (2017).
Enterococci	1.3 x10 ⁶ CFU/100 ml	Kay et al. (2008)
TSS	455 mg/l	Provided by CoCT based on the average measured value in the Hout Bay effluent (1 August 2014 – 31 October 2019)
Tracer	100 units	All other constituents will be modelled as a conservative tracer which will have a nominal concentration of 100 units and will be used to model the achieved dilutions.

The effluent temperature was set equal to the seawater temperature at the diffuser and the effluent salinity was set to 0 psu.

3.4 Water quality guidelines

3.4.1 Required dilutions

The analysis of the constituent concentrations in the effluent, the associated water quality guidelines and the required dilutions was undertaken by the CoCT. Based on this analysis the CoCT provided PRDW with three critical constituents as listed in Table 3-4. These required dilutions will be compared to the achieved dilutions obtained from the model.

Table 3-4: Required effluent dilutions.

Constituent	Dilutions
Ammonia	175
Chemical Oxygen Demand (COD)	115
TSS	2 587

The CoCT determined the allowable mixing zone to be within a radius of 272 m from the diffuser.

3.4.2 Bacteria concentrations

The CoCT confirmed that the target values for microbiological indicators for recreational waters in the coastal marine environment should be based on the Department of Environmental Affairs guidelines (DEA, 2012), as shown in Table 3-5.

Table 3-5: Guideline concentrations for enterococci and E.coli to meet the sufficient or fair category for recreational waters in the coastal marine environment.

Constituent	90 th percentile concentration [CFU/100 ml]
Enterococci	≤ 185
E.coli	≤ 500

4. MODEL SETUP

4.1 Model mesh

The WG19 horizontal coordinate system was used for this study. All spatial plots include x and y axes showing the x and y coordinates in metres in the WG19 system. True north is always pointing upwards.

The model mesh comprises triangles with a resolution varying from about 3 km at the offshore boundary to 50 m in the vicinity of the diffuser. Quadrangular elements with a resolution of 25 m were used around the diffuser to resolve the effluent release into the far-field model. The vertical mesh is comprised of twelve sigma layers with equal layer thicknesses.

Figure 4-1 and Figure 4-2 and represent the three-dimensional and horizontal views of the mesh used for the outfall dispersion modelling.

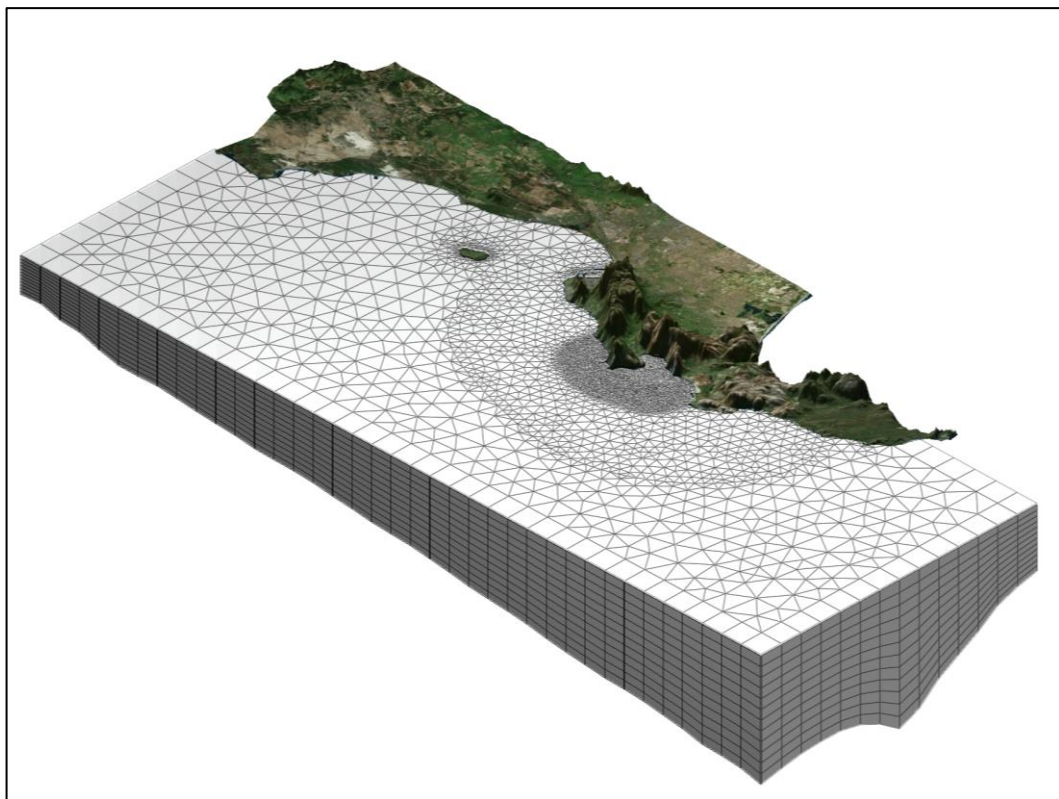


Figure 4-1: Three-dimensional representation of mesh used for the outfall dispersion modelling. Note the vertical axis is not to scale.

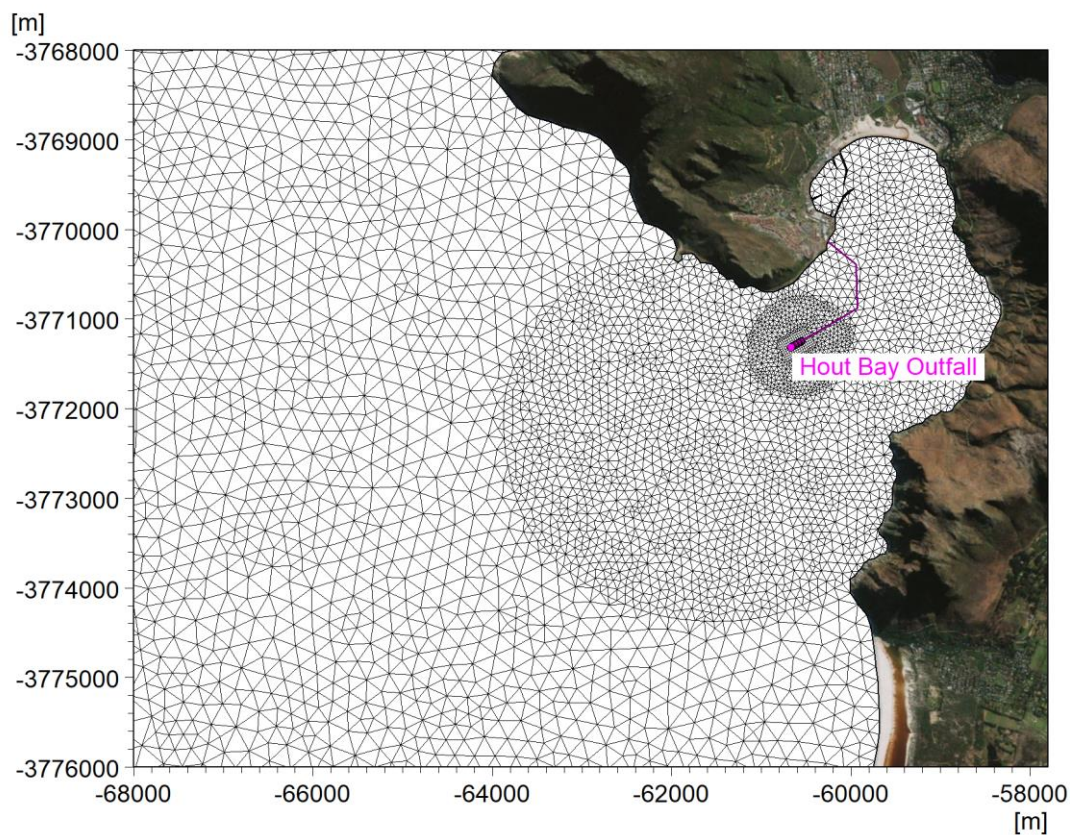
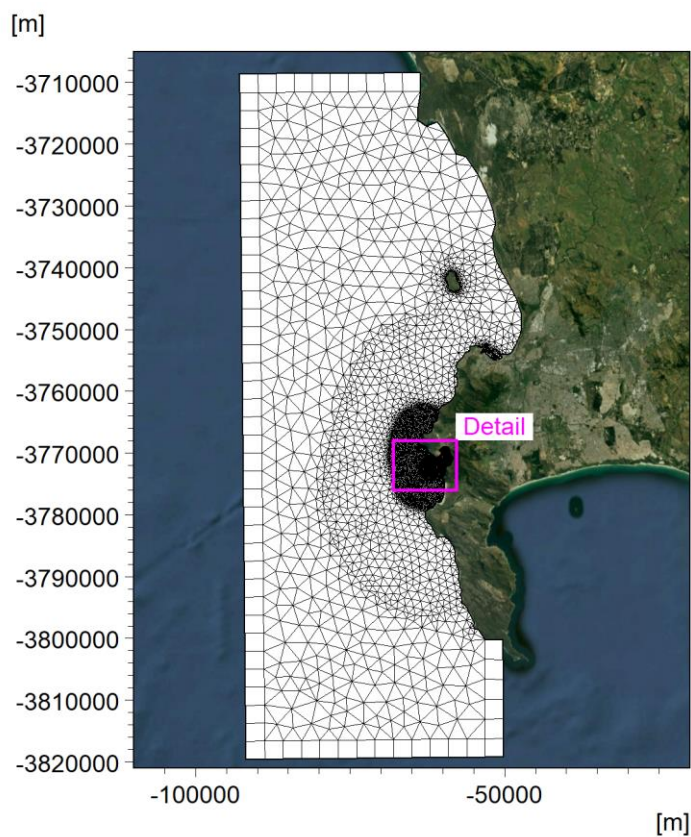


Figure 4-2: Horizontal mesh used for the outfall dispersion modelling.



4.2 Bathymetry

The vertical datum adopted in this study is Chart Datum (CD). CD is 0.825 m below Land Levelling Datum (LLD) which is also known as Mean Sea Level (MSL).

The model bathymetry has been obtained from the following sources:

- CMAP electronic hydrographic charts
- LIDAR topographic surveys landward of the high water mark

Figure 4-3 shows the model bathymetry and the locations of the ADCP and thermistor deployments used for the calibration of the model.

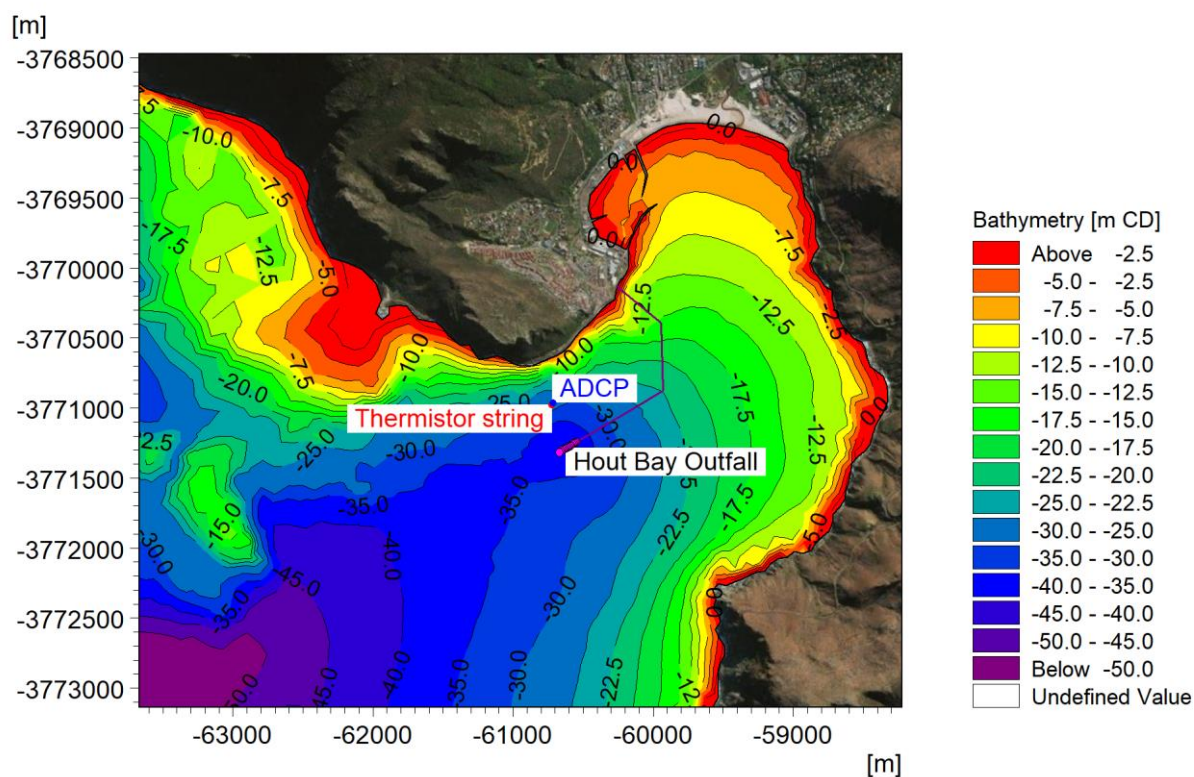
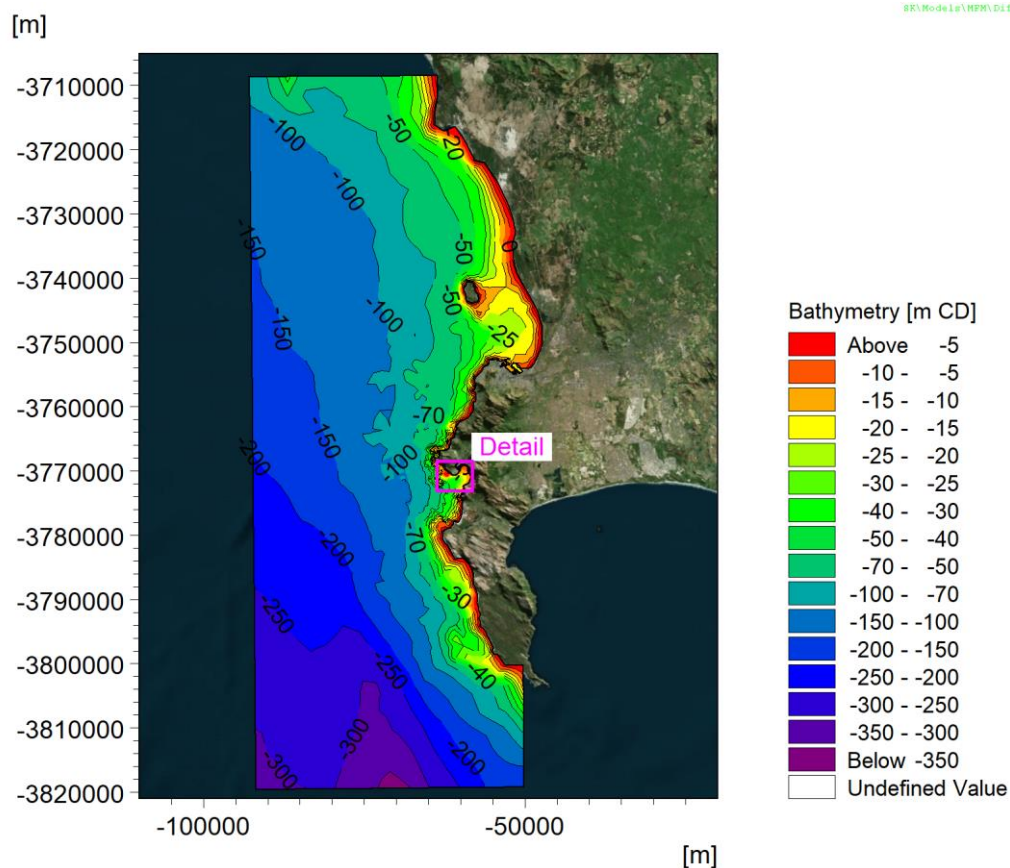


Figure 4-3: Model bathymetry.



4.3 Wind

Wind is an important forcing mechanism for currents, vertical mixing and upwelling – and thus the effluent dispersion. The wind fields near the outfalls are influenced by the surrounding mountains which require a high spatial resolution to resolve.

The Climate System Analysis Group at the University of Cape Town has kindly provided wind data from the Weather Research and Forecasting (WRF) model with a spatial resolution of 4 km and a temporal resolution of 1 hour.

Figure 4-4 shows two snapshots in time illustrating the high spatial variability in the 4 km resolution modelled winds around Cape Town.

Figure 4-5 to Figure 4-8 show comparisons between the modelled winds and measured winds at three locations around Cape Town (Cape Town International Airport, Cape Point and Koeberg) for the winter/spring and summer/autumn modelling periods..

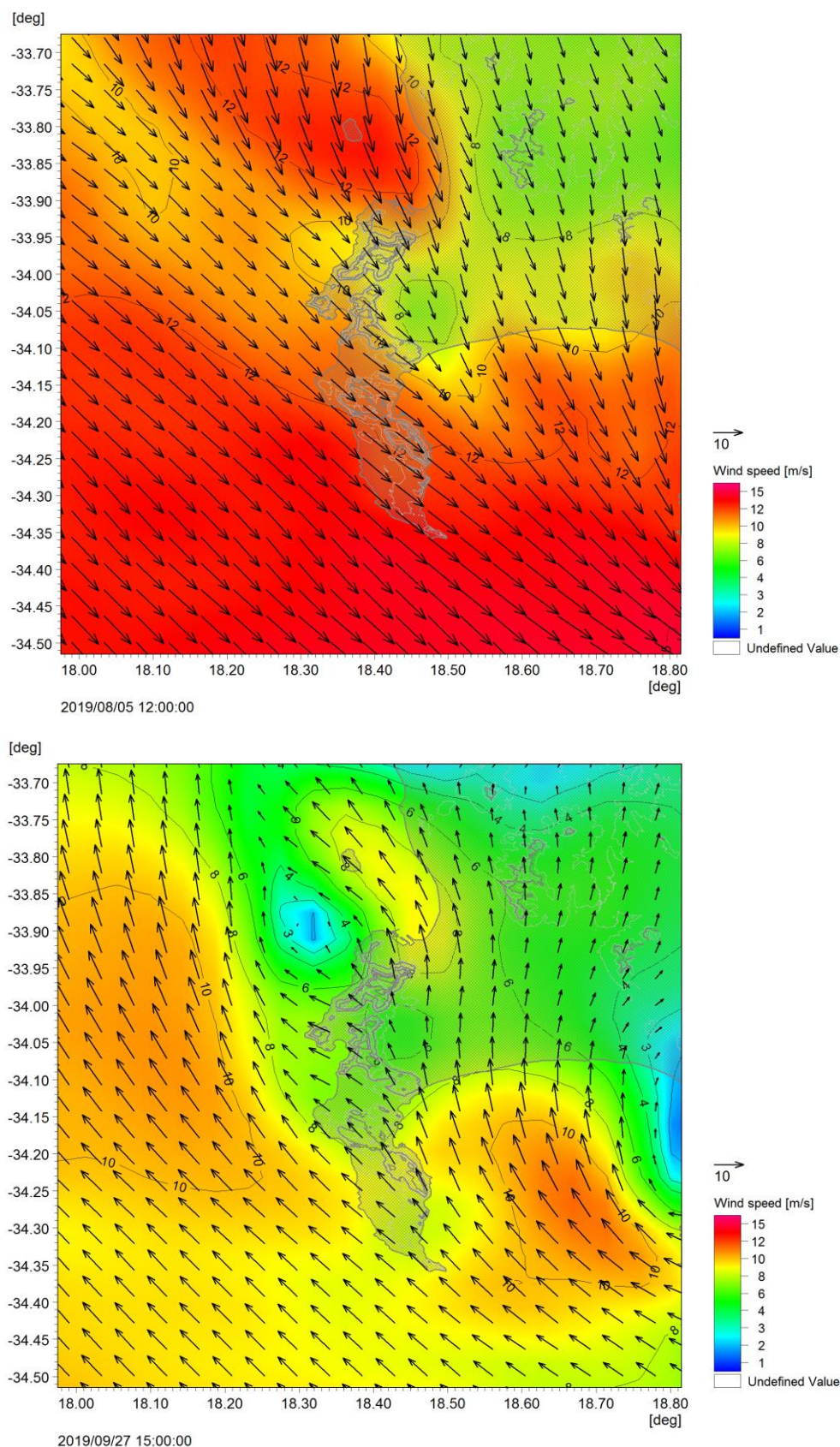


Figure 4-4: Snapshots illustrating the high spatial variability in the 4 km resolution modelled winds around Cape Town (grey lines show topography at 100 m intervals).

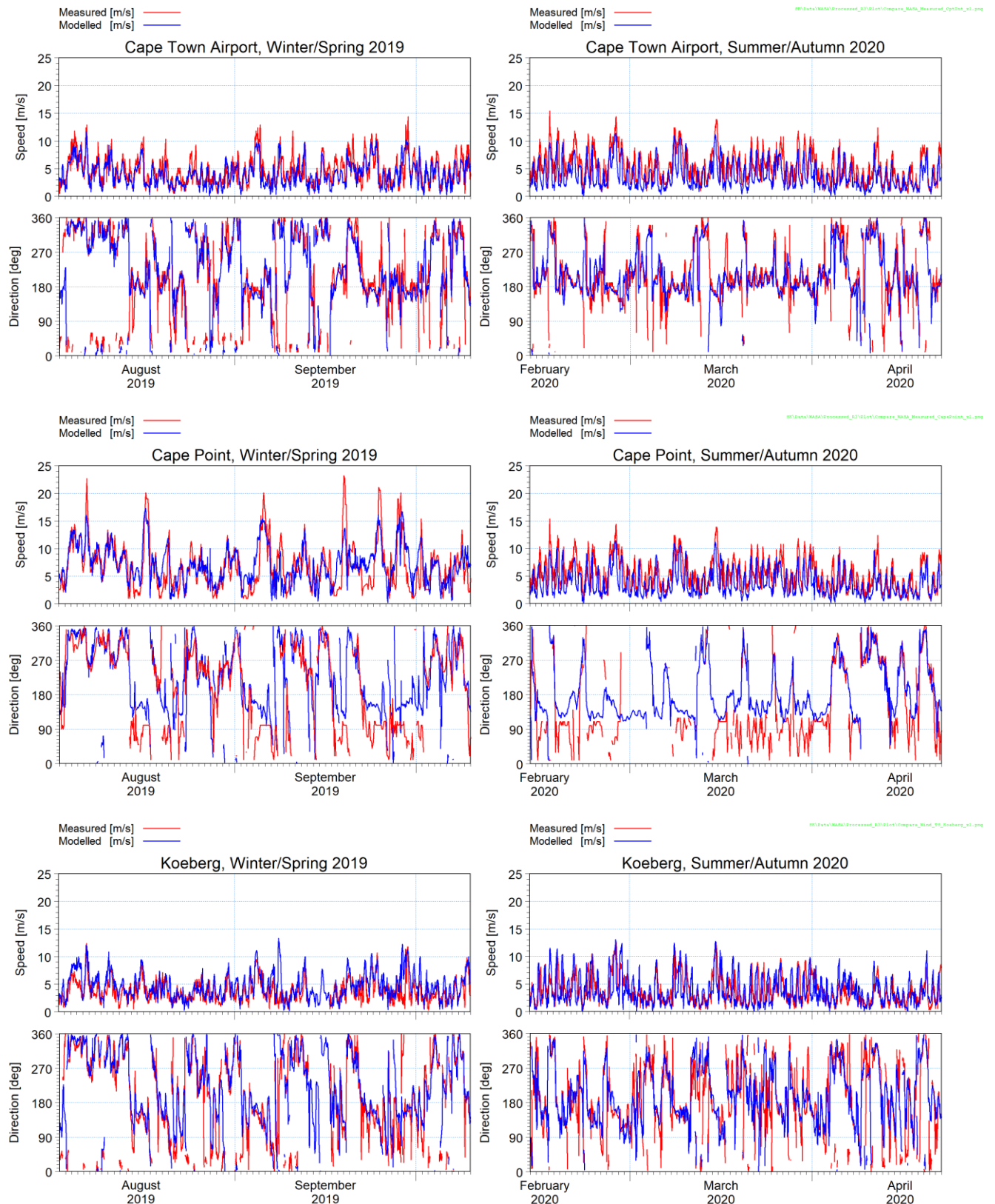


Figure 4-5: Time series of modelled compared to measured winds at Cape Town International, Cape Point and Koeberg.

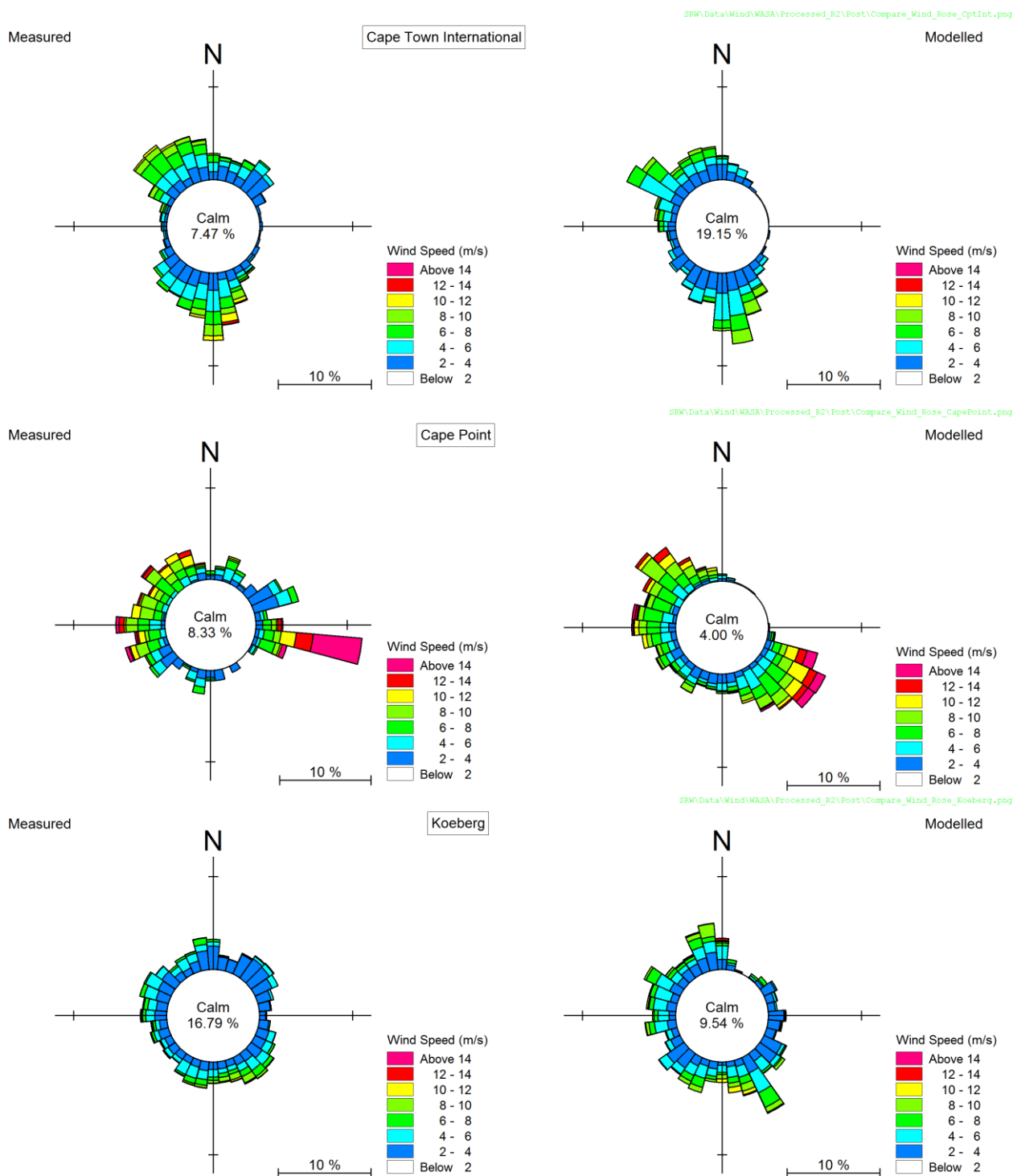


Figure 4-6: Roses of modelled compared to measured winds at Cape Town International, Cape Point and Koeberg for the winter/spring 2019 period.

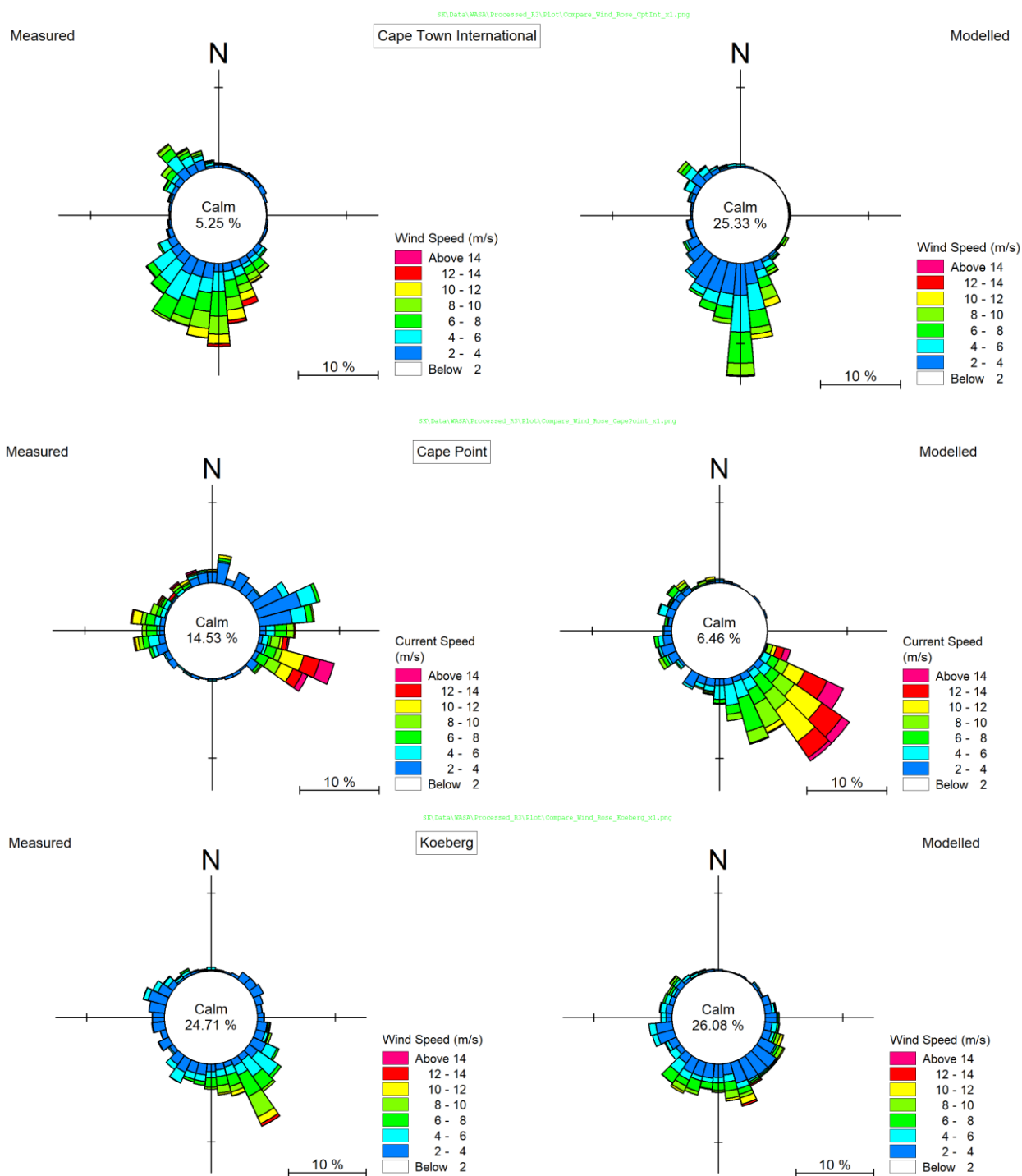


Figure 4-7: Roses of modelled compared to measured winds at Cape Town International, Cape Point and Koeberg for the summer/autumn 2020 period.

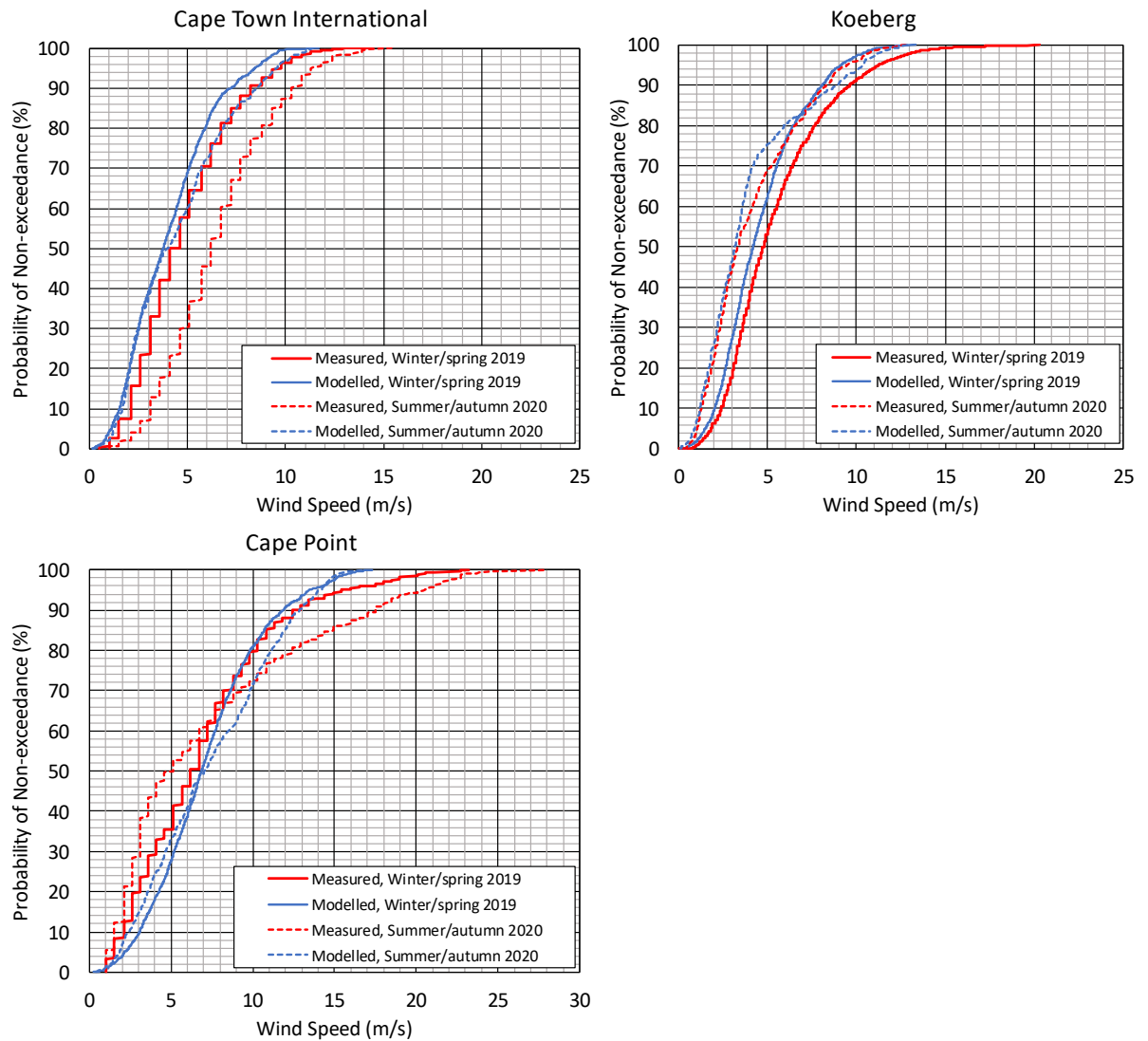


Figure 4-8: Wind speed exceedance of modelled compared to measured winds at Cape Town International, Cape Point and Koeberg.

These results indicate that the WRF modelled winds compare well to the measured winds at three different locations across Cape Town. The main discrepancies are the wind directions at Cape Point which is likely due to the steep cliffs at this location, and the modelled wind speed being approximately 1 m/s to 2 m/s lower than the measurements at Cape Town International.



4.4 Boundary conditions

The model boundary conditions are extracted from global hindcast models as described in Table 4-1:

Table 4-1: Global hindcast models used for the model boundary conditions.

Model	Parameter	Spatial resolution [°]	Temporal resolution [hrs]
HYbrid Coordinate Ocean Model (HYCOM) global ocean circulation model (HYCOM, 2020).	Non-tidal water levels	0.08	3
	Non-tidal ocean currents		
	Seawater temperature		
	Seawater salinity		
DTU10 (Technical University of Denmark) global tidal model (DTU, 2010).	Predicted tides	0.125	Predicted from constituents.
	Predicted tidal currents	0.25	
European Centre for Medium-Range Weather Forecasts (EMCWF) ERA5 global atmospheric model (ECMWF, 2020).	Air temperature	0.25	1
	Humidity		
	Solar radiation		
National Centers for Environmental Prediction (NCEP) global wave forecast model (NCEP, 2020).	Wave spectra	0.5	3

4.5 Model settings

The vertical eddy viscosity was computed using the $k-\epsilon$ vertical turbulence closure scheme, while the vertical eddy dispersion was set to 0.1 times the vertical eddy viscosity. This scaling factor was applied to compensate for additional vertical mixing caused by the use of only 12 vertical layers and the associated smoothing of the vertical density gradients.

The wind friction coefficient and seabed roughness were tuned to physically realistic values which yielded the best agreement between modelled and measured currents at Hout Bay.

5. MODEL CALIBRATION

5.1 Winter/spring

The model was calibrated to metocean data measured by Lwandle during a 6-week period between 21 August 2019 and 3 October 2019. The measurements used for the model calibration comprise:

- ADCP measurements, including:
 - Currents measured across the depth profile in 1 m bins at 10-minute intervals.
 - Fully spectral waves, available at hourly intervals.
- Seawater temperature measured from a thermistor string, available at 5 discrete depth levels between 1.9 m and 24.3 m above the seabed.

The ADCP (X = -60 714 m, Y = -3 770 965 m) and thermistor string (X = -60 724 m, Y = -3 770 978 m) were deployed approximately 100 m northwest of the diffuser at a depth of -29.2 m CD. The locations are shown in Figure 5-1.

5.1.1 Waves

A wave refraction plot for a south-westerly wave event is shown in Figure 5-1.

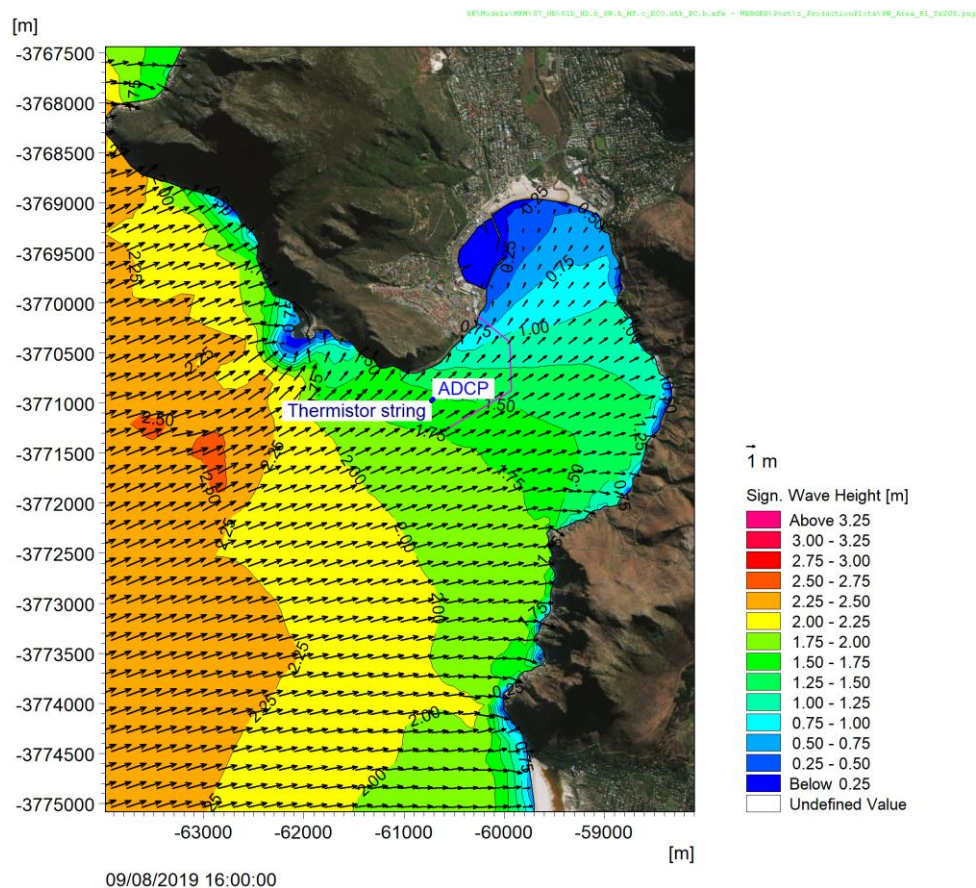


Figure 5-1: Winter/spring: Wave refraction plot for a south-westerly wave event. The modelled wave condition at the ADCP is $H_{m0} = 1.55$ m, $T_P = 9.7$ m, $D_{MP} = 232^\circ$.



Figure 5-2 presents a time series comparison of measured and modelled wave parameters at the ADCP. Measured and modelled wave roses are shown in Figure 5-3. By convention, wave direction is the direction from which the wave is coming, measured clockwise from true north.

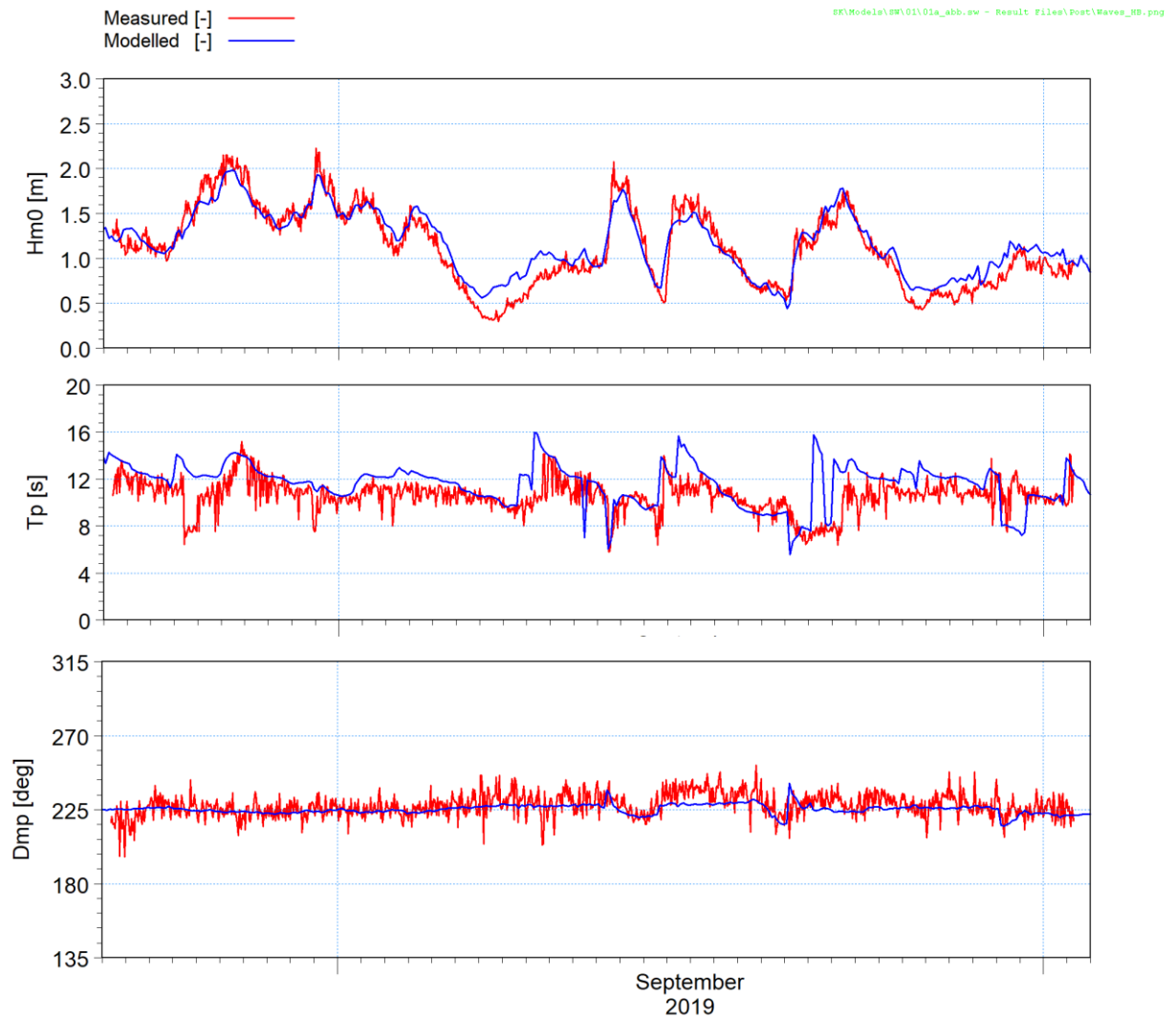


Figure 5-2: Winter/spring: Time series of measured and modelled significant wave height (H_{m0}), peak wave period (T_P) and mean wave direction at T_P (D_{MP}) at the location of the ADCP.

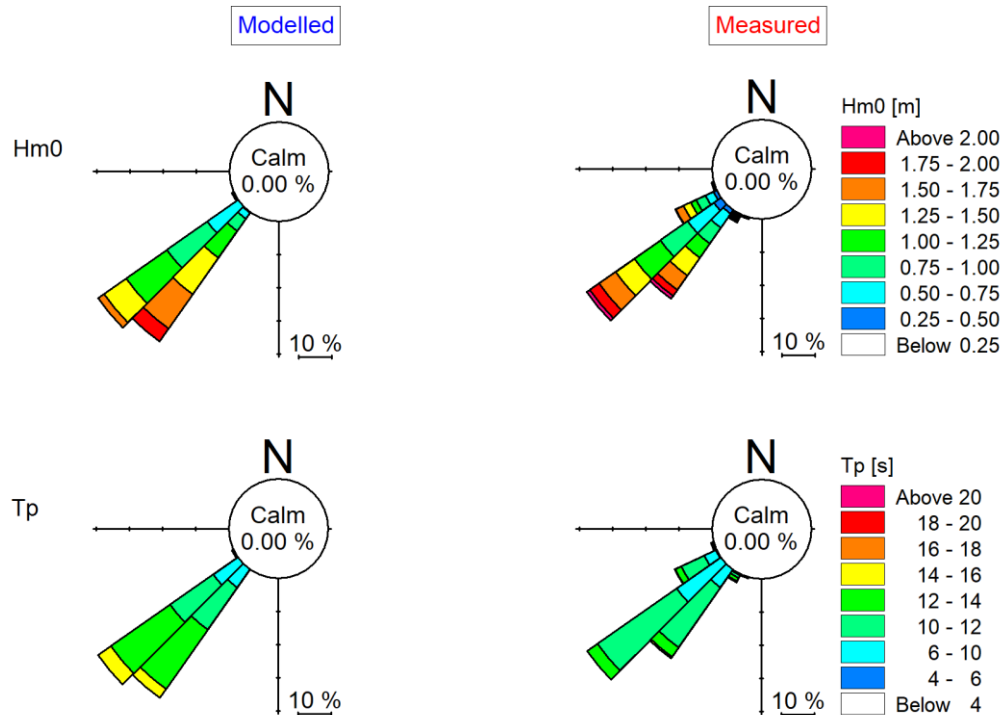


Figure 5-3: Winter/spring: Wave roses of measured and modelled H_{m0} and T_p for the 6-week deployment period at the location of the ADCP.

A good overall comparison could be observed from the time series and wave rose plots. Occasional over- or underprediction of wave heights can be observed, but there is no bias in either direction. The modelled peak wave period and mean wave direction compared well to the measurements. The agreement between the ADCP measurements and the wave model outputs shows the model to be adequately calibrated for the purposes of this study

5.1.2 Water levels

The predicted tidal levels at the Port of Cape Town ($X = -539\,934\text{ m}$, $Y = -3\,752\,769\text{ m}$) were extracted from the MIKE by DHI CMAP Electronic Charts Database (DHI, 2020i). Figure 5-4 presents a time series comparison of modelled water levels to predicted tides at the Port of Cape Town. A water level probability of non-exceedance plot is shown in Figure 5-5 for the Port of Cape Town.

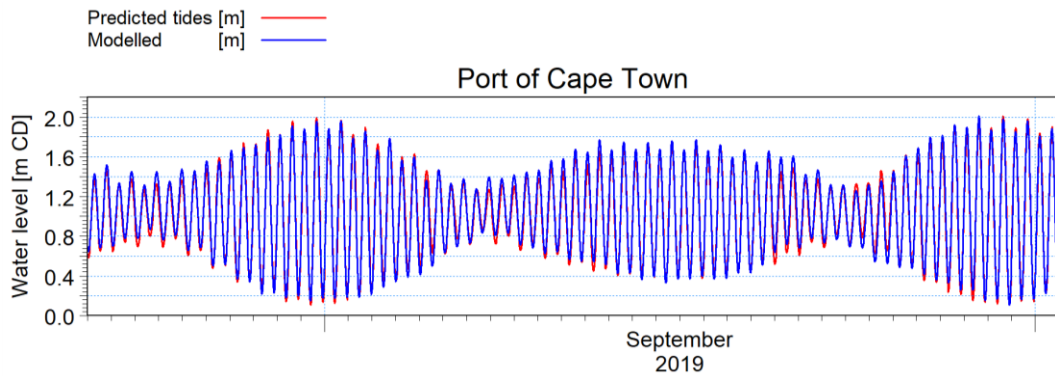


Figure 5-4: Winter/spring: Time series comparison of modelled water levels to predicted tides at the Port of Cape Town.

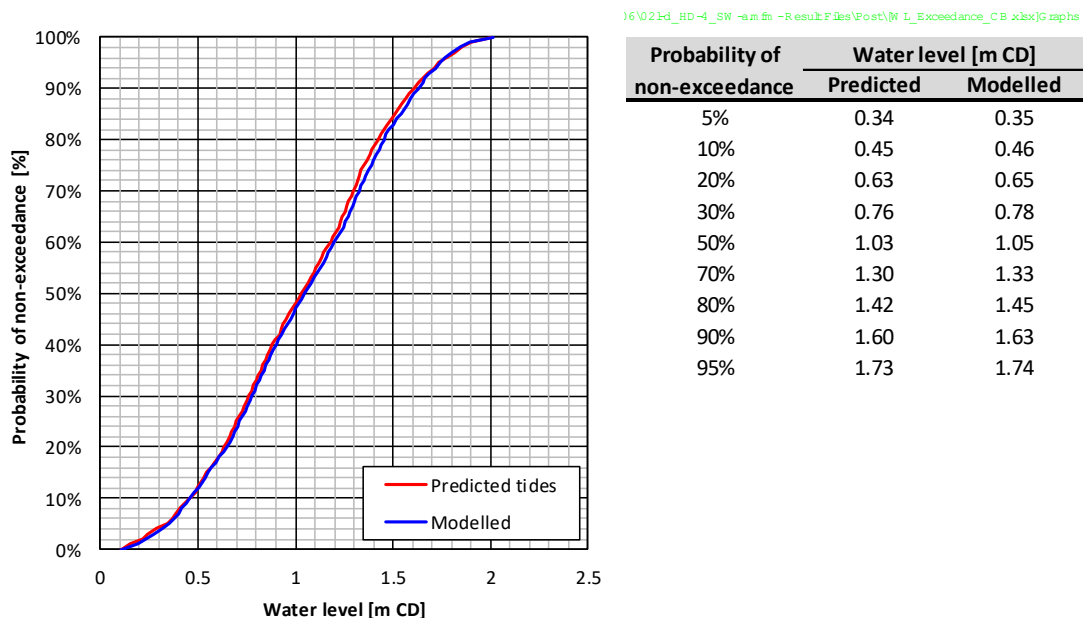


Figure 5-5: Winter/spring: Probability of non-exceedance for predicted tides and modelled water levels for the 6-week deployment period at the Port of Cape Town.

The comparison shows a good overall model prediction in both tidal phase and amplitude.

5.1.3 Currents

A contour plot of instantaneous currents during a north-westerly wind event is shown in Figure 5-6. The modelled currents were compared to the measurements near the seabed (3.4 m above the seabed) and near the surface (24.4 m above the seabed). Figure 5-7 presents a time series comparison of the modelled and measured currents at the ADCP. Non-exceedance curves of current speed for the 6-week period are shown in Figure 5-8. Current rose comparisons of modelled and measured currents are presented in Figure 5-9. Note that current direction is by convention the direction towards which the current is flowing.

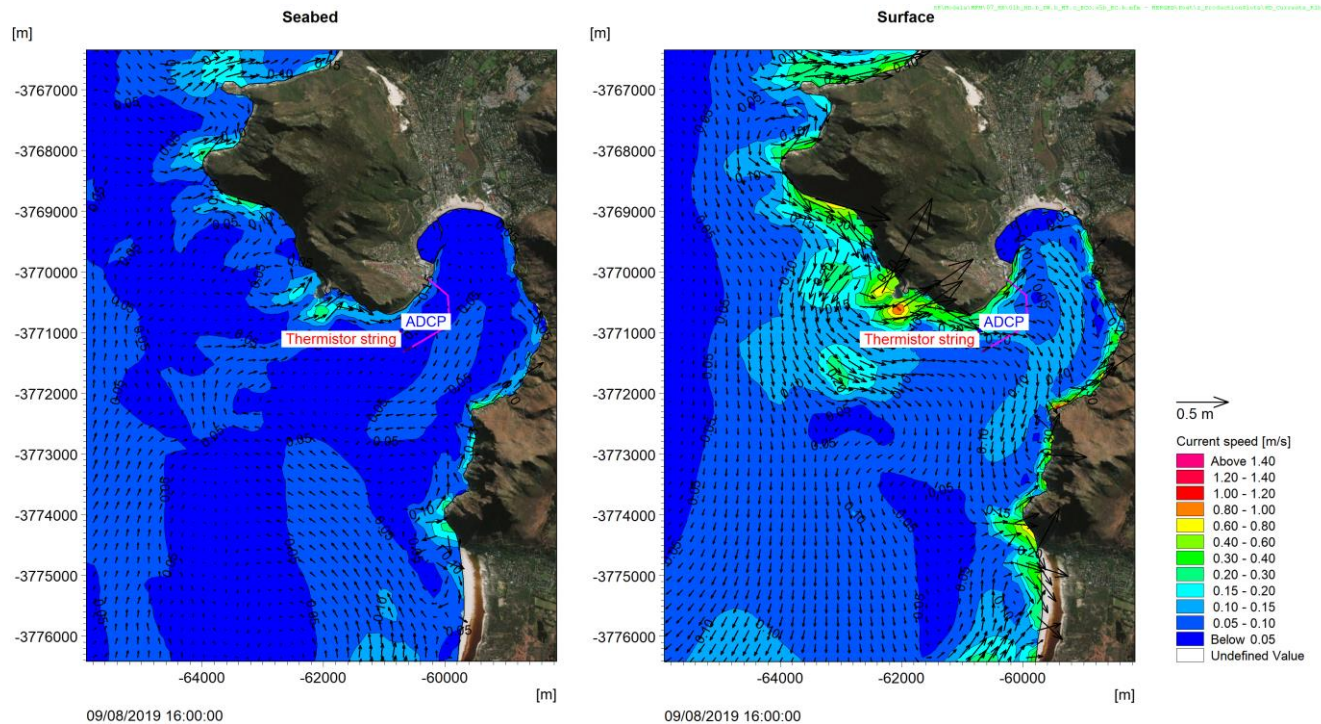


Figure 5-6: Winter/spring: Contour plot of instantaneous seabed (left) and surface (right) currents during a north-westerly wind event (shown in Figure 5-1).

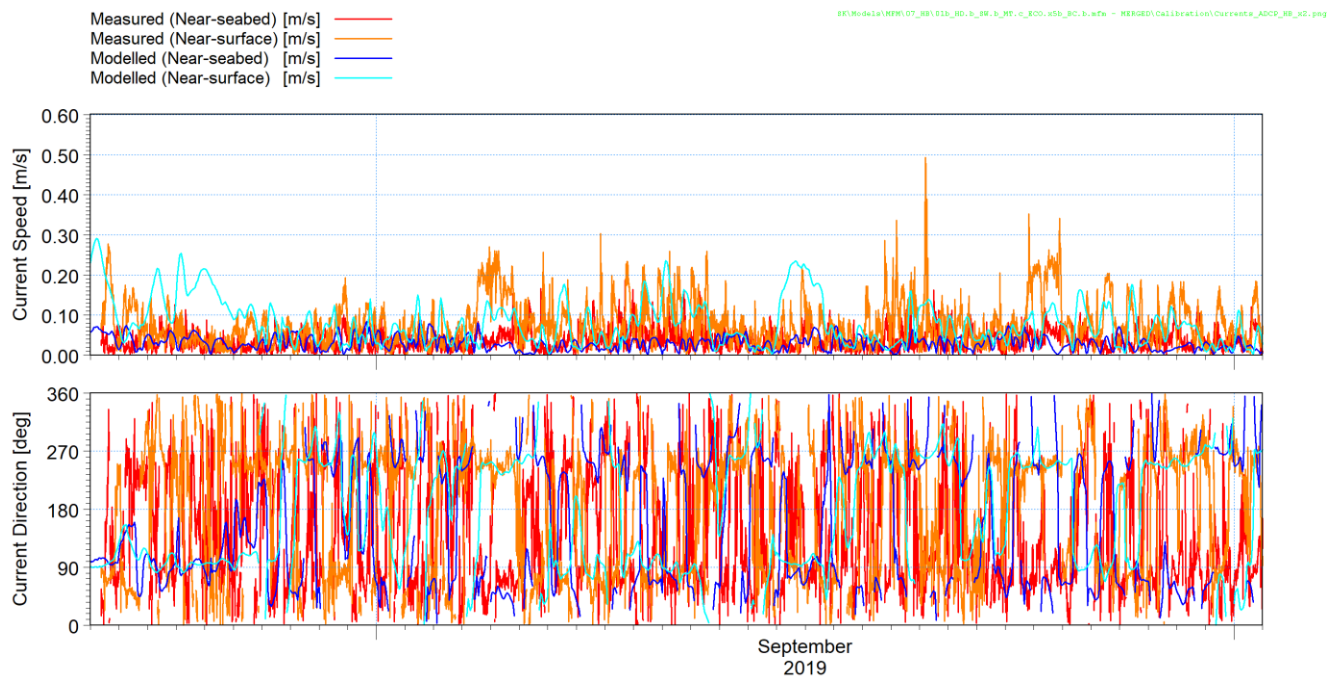
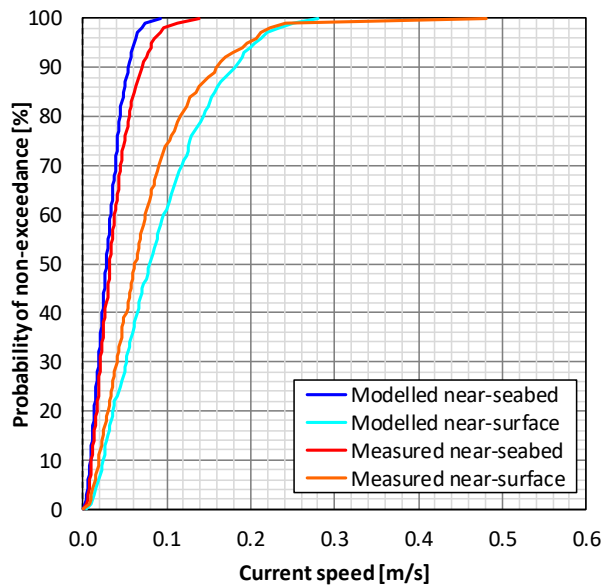


Figure 5-7: Winter/spring: Time series comparison of measured and modelled current speed and direction at the ADCP.



Probability of non-exceedance [%]	Current speed [m/s]			
	Near-seabed		Near-surface	
	Modelled	Measured	Modelled	Measured
10	0.01	0.01	0.02	0.02
20	0.01	0.02	0.04	0.03
30	0.02	0.02	0.05	0.04
40	0.02	0.03	0.06	0.05
50	0.03	0.03	0.08	0.06
60	0.03	0.04	0.10	0.07
70	0.04	0.05	0.12	0.09
80	0.04	0.05	0.14	0.12
90	0.05	0.07	0.18	0.16

Figure 5-8: Winter/spring: Probability of non-exceedance for measured and modelled current speed for the 6-week deployment period at the ADCP.

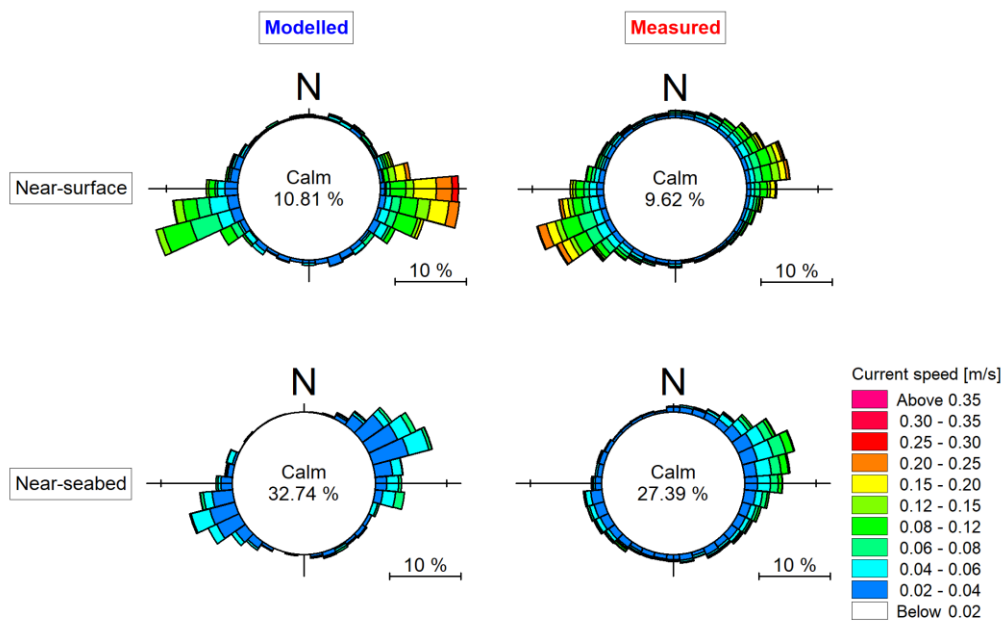


Figure 5-9: Winter/spring: Measured and modelled current roses for the 6-week deployment period at the ADCP.

Near the surface the model shows a tendency to overpredict the operational current speeds and also predicts more frequent easterly currents than observed in the measurements. The operational near-seabed currents are well represented in model in both speed and direction while the stronger currents are slightly underestimated.

Overall the model is able to reproduce the main features of the currents and is considered to be acceptable for the purposes of this study.



5.1.4 Temperature

The modelled seawater temperatures were compared to measurements near the seabed (1.9 m above the seabed) and near the surface (24.3 m above the seabed). Figure 5-10 presents a time series comparison of the modelled and measured seawater temperatures. Non-exceedance curves of seabed and surface temperatures for the 6-week period are shown Figure 5-11. Figure 5-12 presents non-exceedance curves of stratification (seabed to surface) from the measured and modelled temperatures.

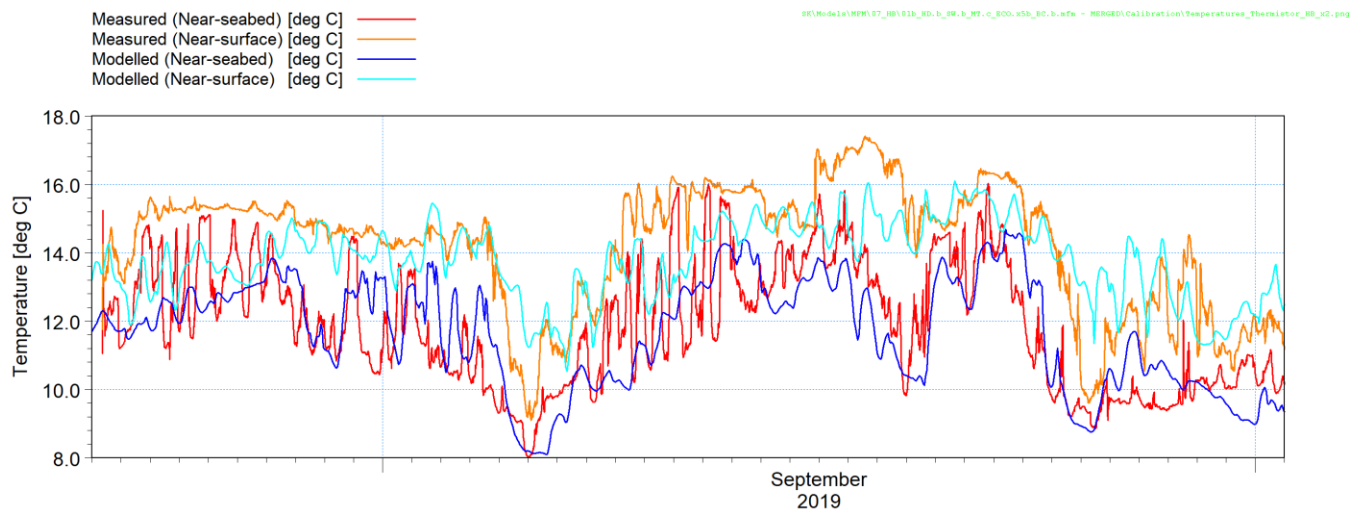


Figure 5-10: Winter/spring: Time series of measured and modelled seawater temperatures at the thermistor string.

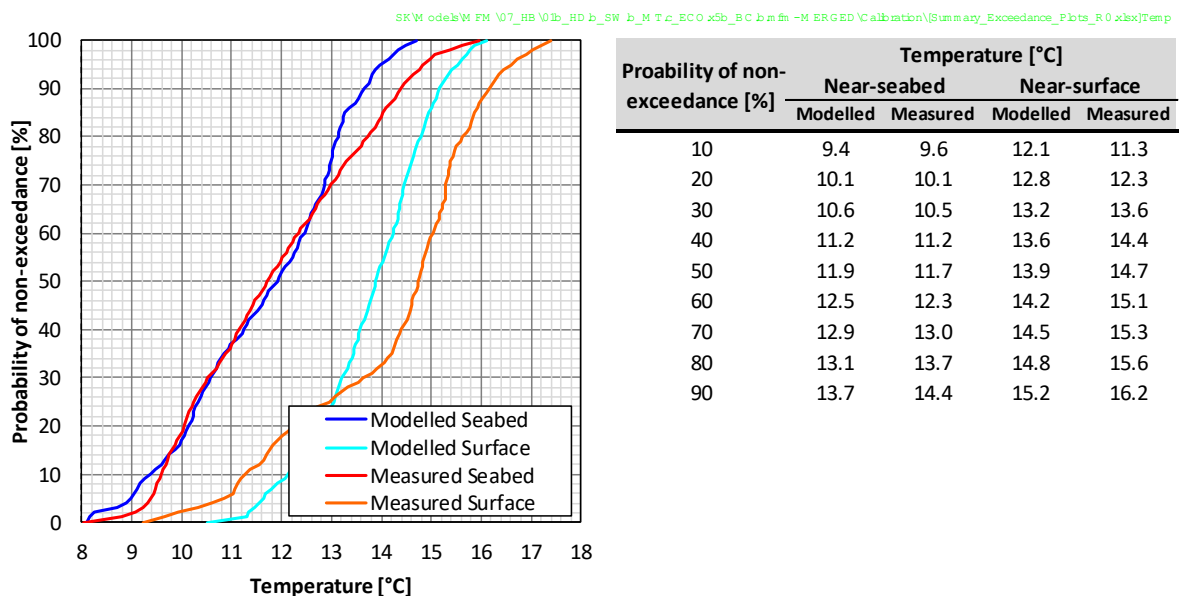


Figure 5-11: Winter/spring: Probability of non-exceedance of measured and modelled seawater temperatures for the 6-week deployment period at the thermistor string.

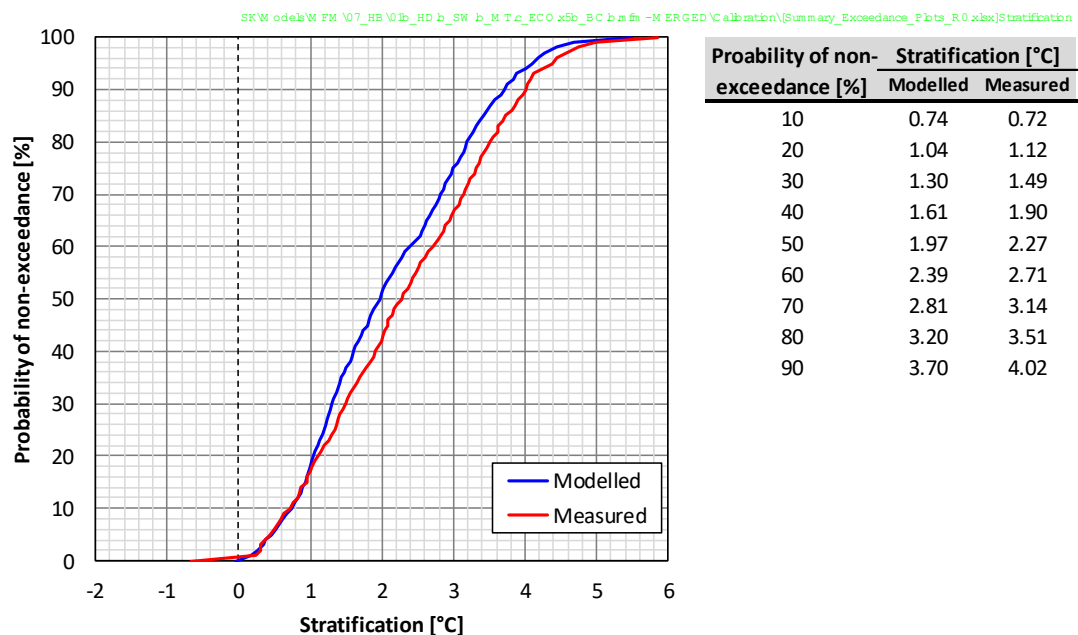


Figure 5-12: Winter/spring: Probability of non-exceedance of measured and modelled seawater temperature stratification (near-seabed to near-surface) for the 6-week deployment period at the thermistor string.

The measured time series shows that the seawater temperatures are complex and vary over a range of time-scales due to upwelling, solar radiation and other dynamic processes. The model is able to predict the mean trend in surface and seabed seawater temperatures including a number of the discrete dynamic events. Periodic over- or underprediction of mid-depth and seabed temperatures can be observed, however the model shows a good statistical distribution of temperatures and the resultant stratification, the latter being an important determinant of the rise height of the plume in the near-field. The model is therefore considered to be adequately calibrated for seawater temperature for the purposes of this study.

5.2 Summer/autumn

The model was calibrated to metocean data measured by Lwandle during a 10-week period between 13 February 2020 and 23 April 2020. The measurements used for the model calibration comprise:

- ADCP measurements, including:
 - Currents measured across the depth profile in 1 m bins at 10-minute intervals.
 - Fully spectral waves, available at hourly intervals.
- Seawater temperature measured from a thermistor string, available at 5 discrete depth levels between 1.9 m and 23.0 m above the seabed.

The ADCP (X = -60 714 m, Y = -3 770 963 m) and thermistor string (X = -60 706 m, Y = -3 770 971 m) were deployed approximately 100 m northwest of the diffuser at a depth of -29.8 m CD. The locations are shown in Figure 5-13.

5.2.1 Waves

A wave refraction plot for a south-westerly wave event is shown in Figure 5-13.

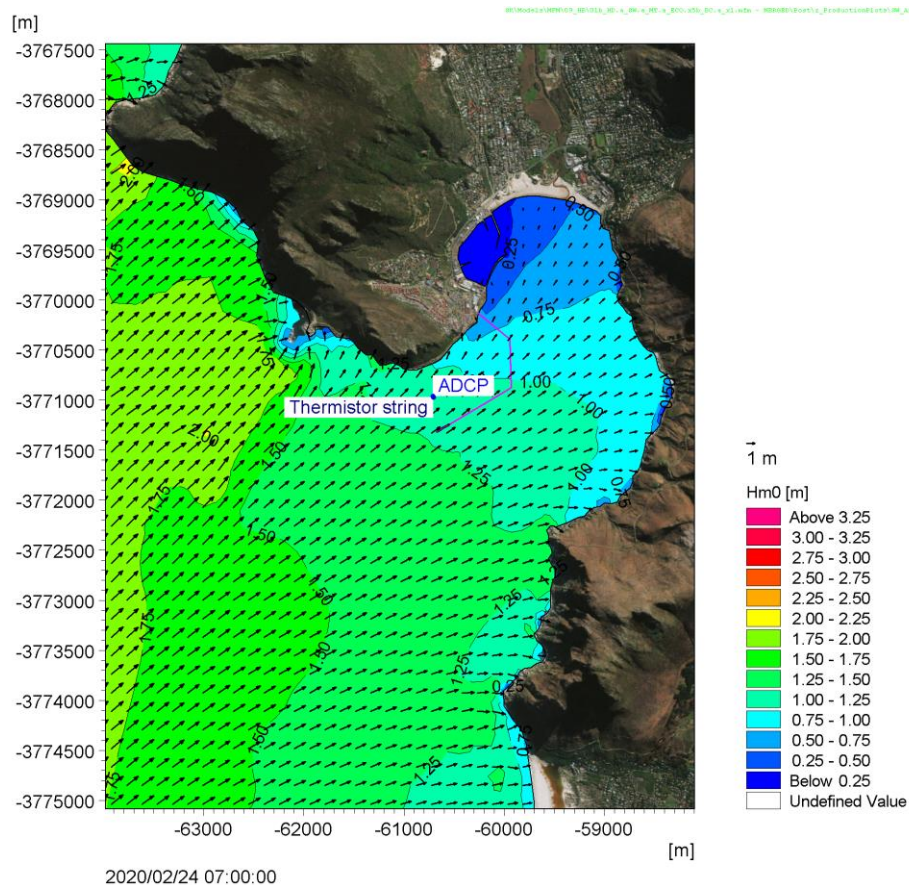


Figure 5-13: Summer/autumn: Wave refraction plot for a south-westerly wave event. The modelled wave condition at the ADCP is $H_{m0} = 1.13$ m, $T_p = 12.2$ m, $D_{MP} = 225^\circ$.

Figure 5-14 presents a time series comparison of measured and modelled wave parameters at the ADCP. Measured and modelled wave roses are shown in Figure 5-15.

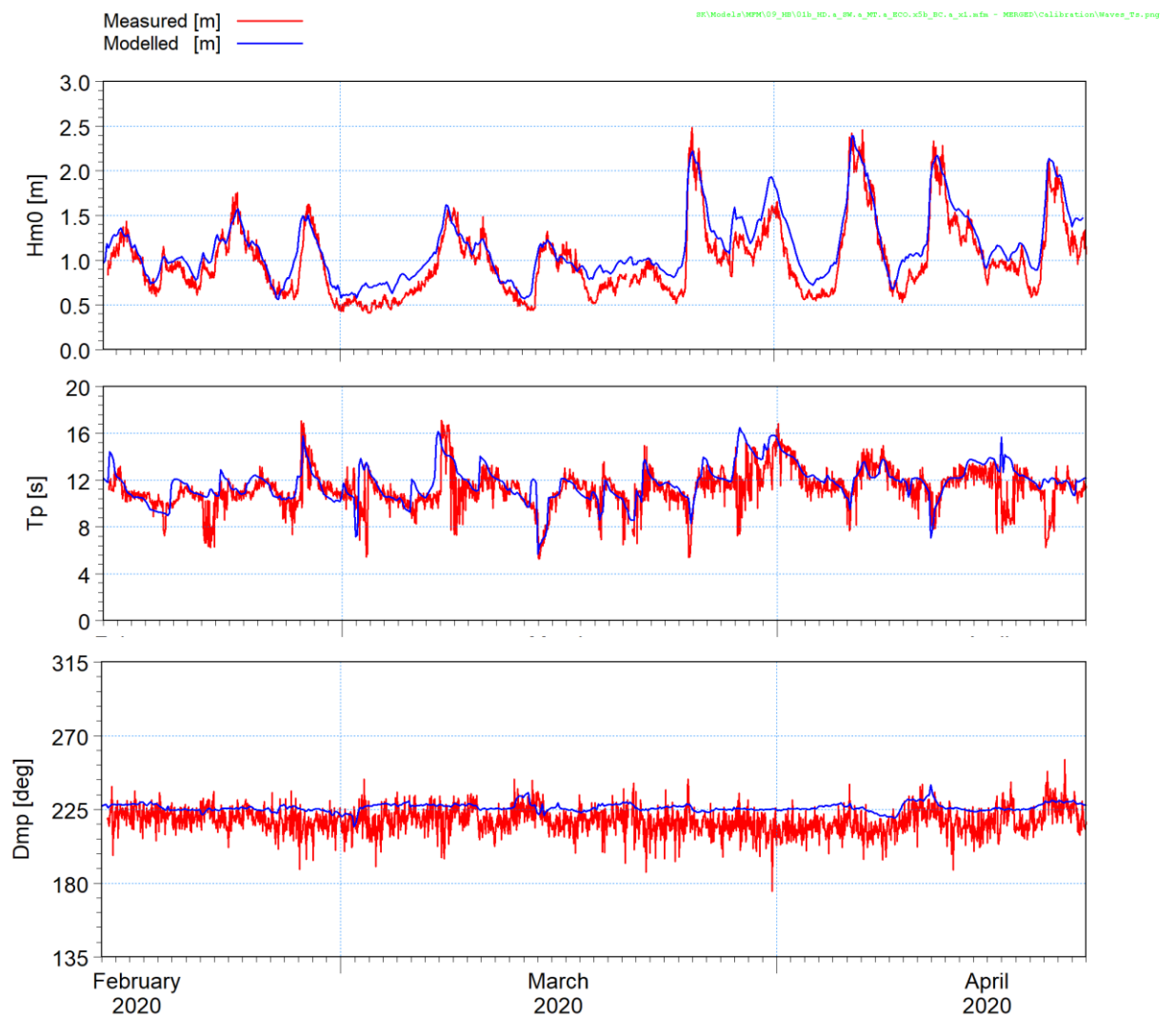
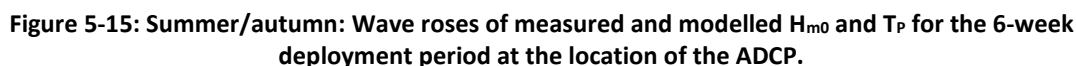
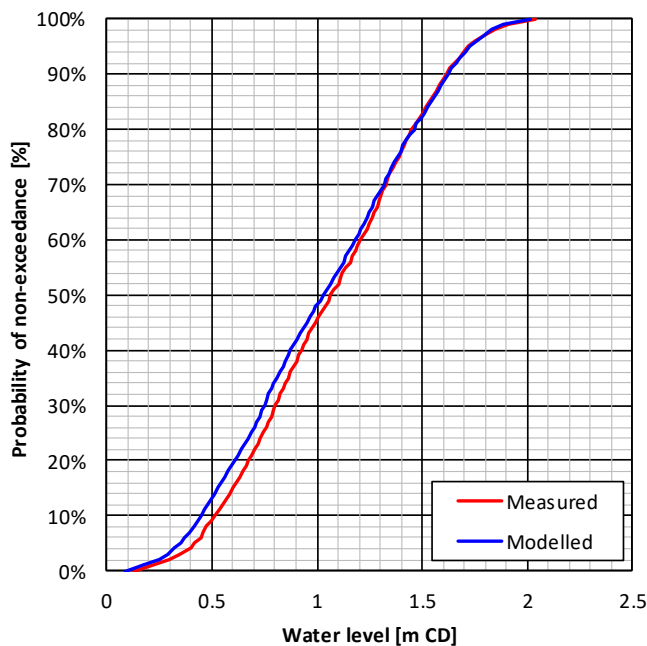


Figure 5-14: Summer/autumn: Time series of measured and modelled significant wave height (H_{m0}), peak wave period (T_p) and mean wave direction at T_p (D_{MP}) at the location of the ADCP.



5.2.2 Water levels

Figure 5-16: Summer/autumn: Time series comparison of modelled water levels to predicted tides at the Port of Cape Town.



\\x3b_B C_a_x2 m fm -M ERGED\\C alibration\\C ompareTs_HD_T ides.xlsx\\G raphs

Probability of non-exceedance	Water level [m CD]	
	Measured	Modelled
5%	0.42	0.35
10%	0.51	0.45
20%	0.67	0.61
30%	0.80	0.75
50%	1.07	1.03
70%	1.32	1.32
80%	1.45	1.46
90%	1.62	1.62
95%	1.72	1.73

Figure 5-17: Summer/autumn: Probability of non-exceedance for predicted tides and modelled water levels for the 6-week deployment period at the Port of Cape Town.

The model shows a good overall model prediction in both tidal phase and amplitude. The slight setdown observed during the first half of the calibration period is likely due to wind effects which are included in the model but not in the predicted tide.

5.2.3 Currents

A contour plot of instantaneous currents during a south-westerly wave/south-easterly wind event is shown in Figure 5-18. The modelled currents were compared to the measurements near the seabed (4.4 m above the seabed) and near the surface (24.4 m above the seabed). Figure 5-19 presents a time series comparison of the modelled and measured currents at the ADCP. Non-exceedance curves of current speed for the 10-week period are shown Figure 5-20. Current rose comparisons of modelled and measured currents are presented in Figure 5-21.

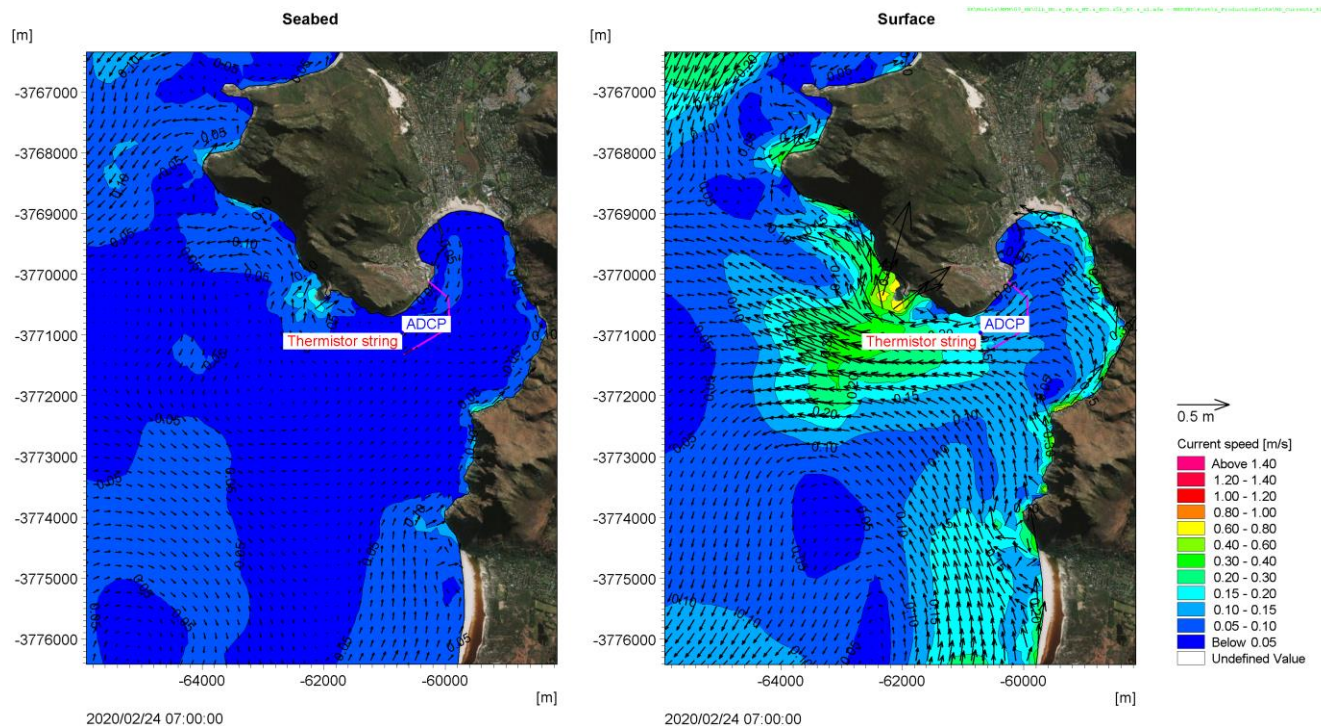


Figure 5-18: Summer/autumn: Contour plot of instantaneous seabed (left) and surface (right) currents during a south-westerly wave/south-easterly wind event (shown in Figure 5-13).

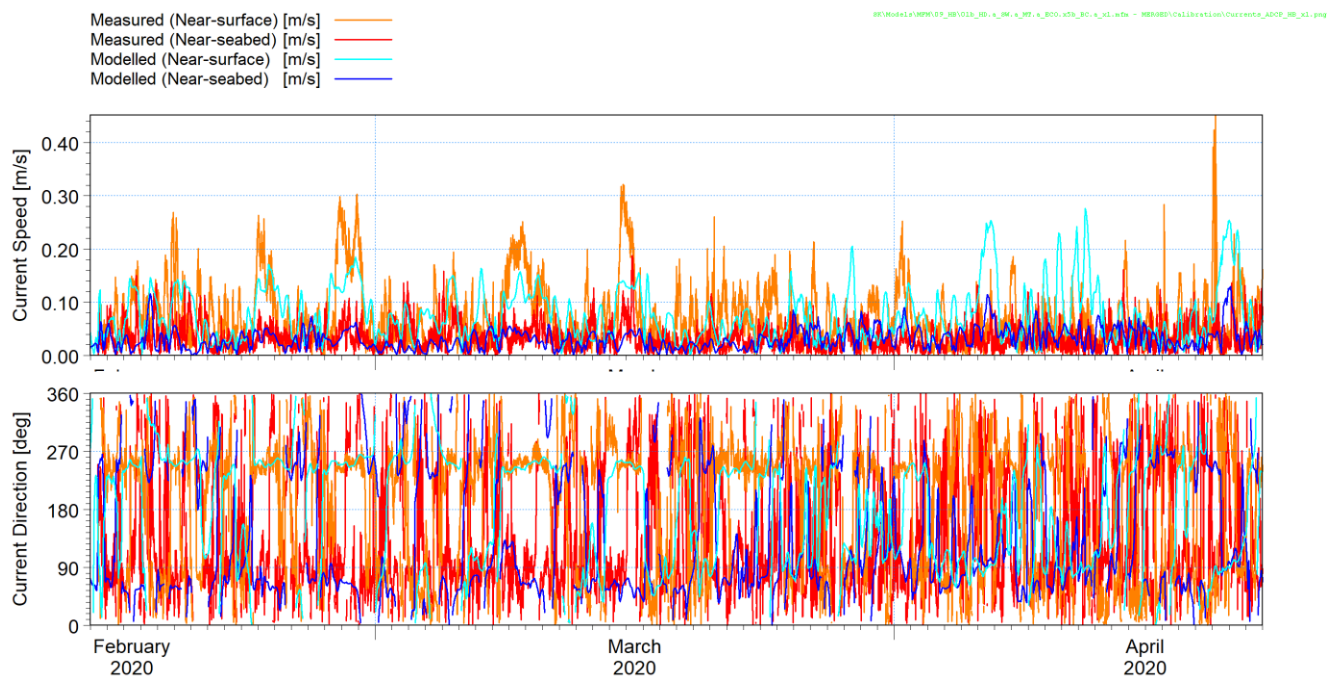


Figure 5-19: Summer/autumn: Time series comparison of measured and modelled current speed and direction at the ADCP.

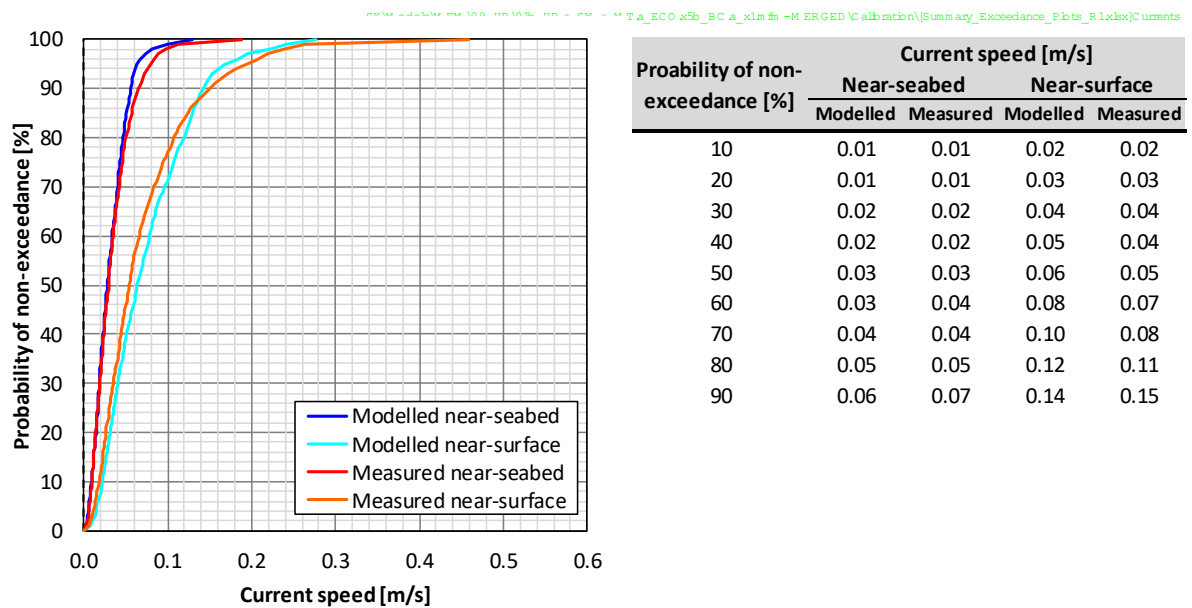


Figure 5-20: Summer/autumn: Probability of non-exceedance for measured and modelled current speed for the 10-week deployment period at the ADCP.

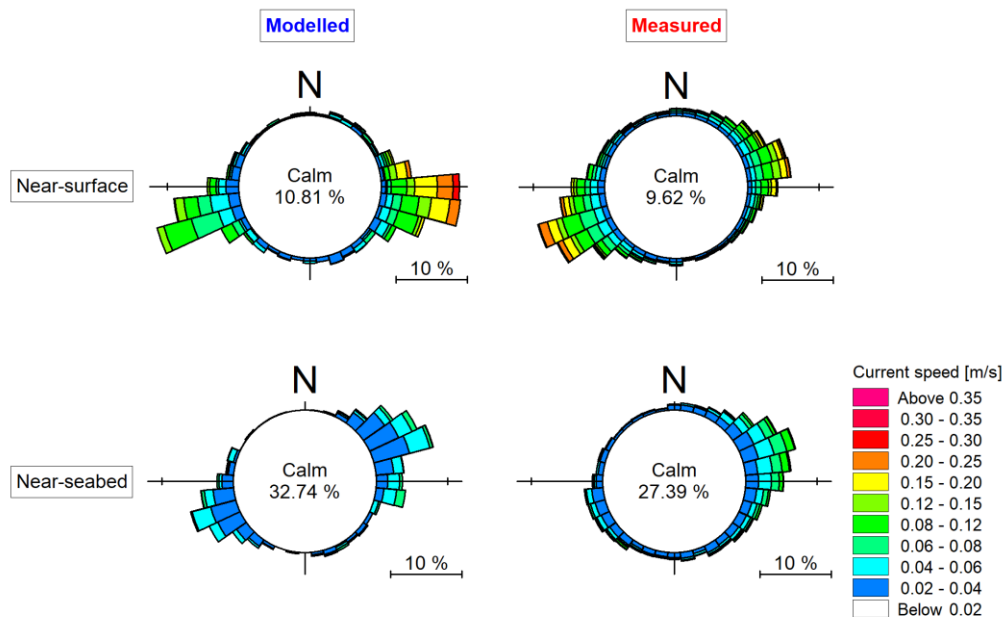


Figure 5-21: Summer/autumn: Measured and modelled current roses for the 10-week deployment period at the ADCP.

The results show a good correlation between the measured and modelled current speed and direction for both depth levels shown. The model showed a tendency to underpredict some of the stronger near-surface events in the first half of the 10-week period, while stronger events in the second half were generally overpredicted. Although there are slight discrepancies in the dominant directions the model is able to reproduce the main features of the currents and is considered to be acceptable for the purposes of this study.



5.2.4 Temperature

The modelled seawater temperatures were compared to measurements near the seabed (7.1 m above the seabed) and near the surface (23.0 m above the seabed). Figure 5-22 presents a time series comparison of the modelled and measured seawater temperatures. Non-exceedance curves of seabed and surface temperatures for the 10-week period are shown Figure 5-23. Figure 5-24 presents non-exceedance curves of stratification (seabed to surface) from the measured and modelled temperatures.

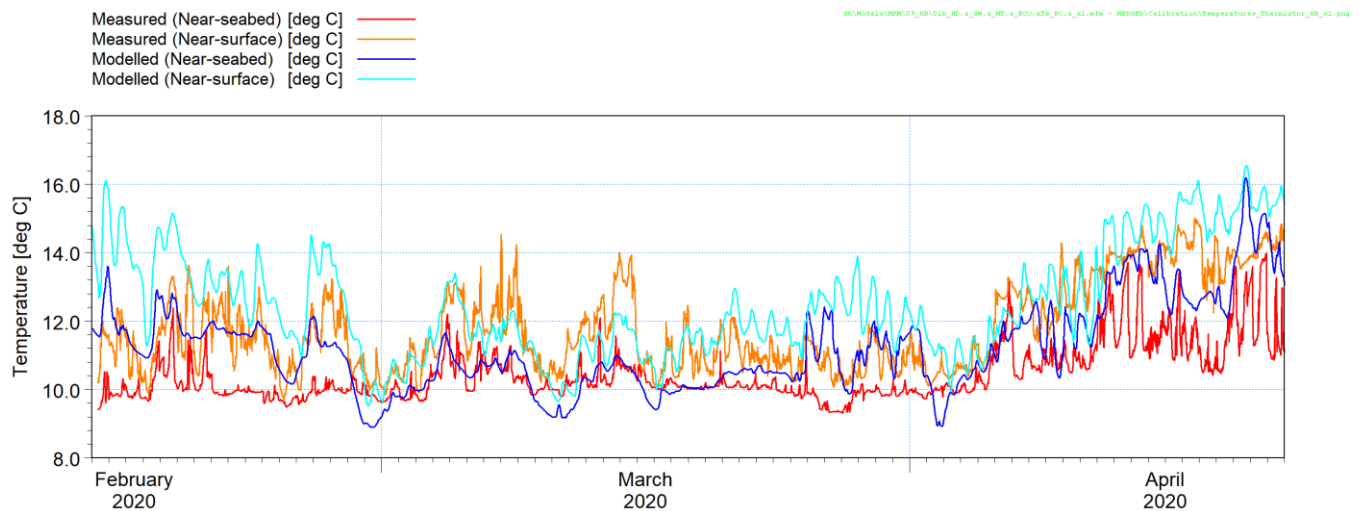


Figure 5-22: Summer/autumn: Time series of measured and modelled seawater temperatures at the thermistor string.

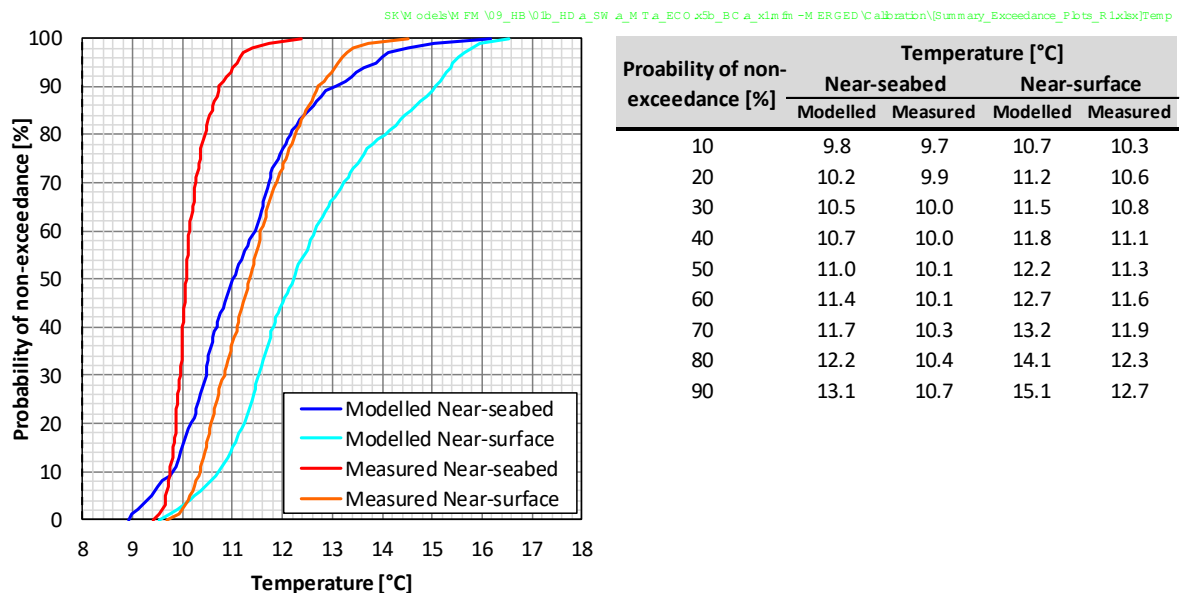


Figure 5-23: Summer/autumn: Probability of non-exceedance of measured and modelled seawater temperatures for the 10-week deployment period at the thermistor string.

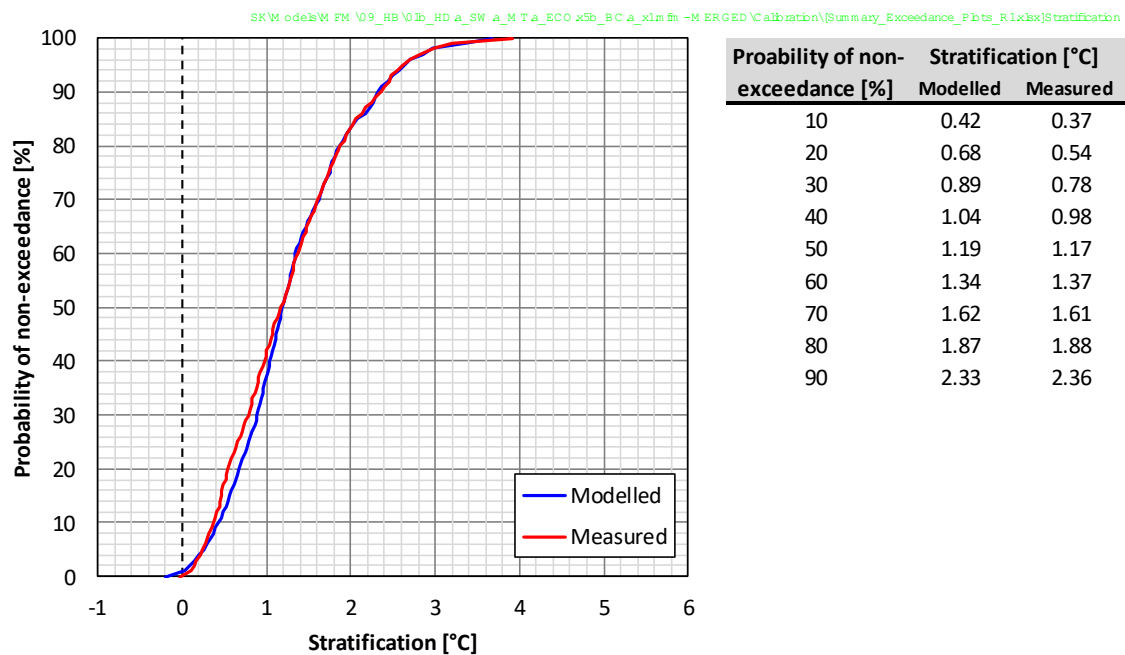


Figure 5-24: Summer/autumn: Probability of non-exceedance of measured and modelled seawater temperature stratification (near-seabed to near-surface) for the 10-week deployment period at the thermistor string.

The measured time series shows that the seawater temperatures are complex and vary over a range of time-scales due to upwelling, solar radiation and other dynamic processes. The model is able to predict the mean trend in surface and seabed seawater temperatures including a number of the discrete dynamic events. The absolute temperatures are generally overpredicted over the profile, but the temperature stratification (near-seabed to near-surface) is well represented. The model is therefore considered to be adequately calibrated for seawater temperature for the purposes of this study.

6. MODEL RESULTS

6.1 Winter/spring

The outfall dispersion model was run for a 10-week period between 1 August 2019 and 9 October 2019 to represent environmental conditions for winter and spring.

The model outputs are the concentrations of E.coli, enterococci, TSS and a conservative tracer in each horizontal and vertical element of the computational mesh at 1-hour intervals throughout the simulation period.

6.1.1 Plume dynamics

Figure 6-1 and Figure 6-2 present examples of the current vectors and E.coli plume at a moment in time for a southerly and north-westerly wind condition. These results show the complex 3D dynamic behaviour of the plume.

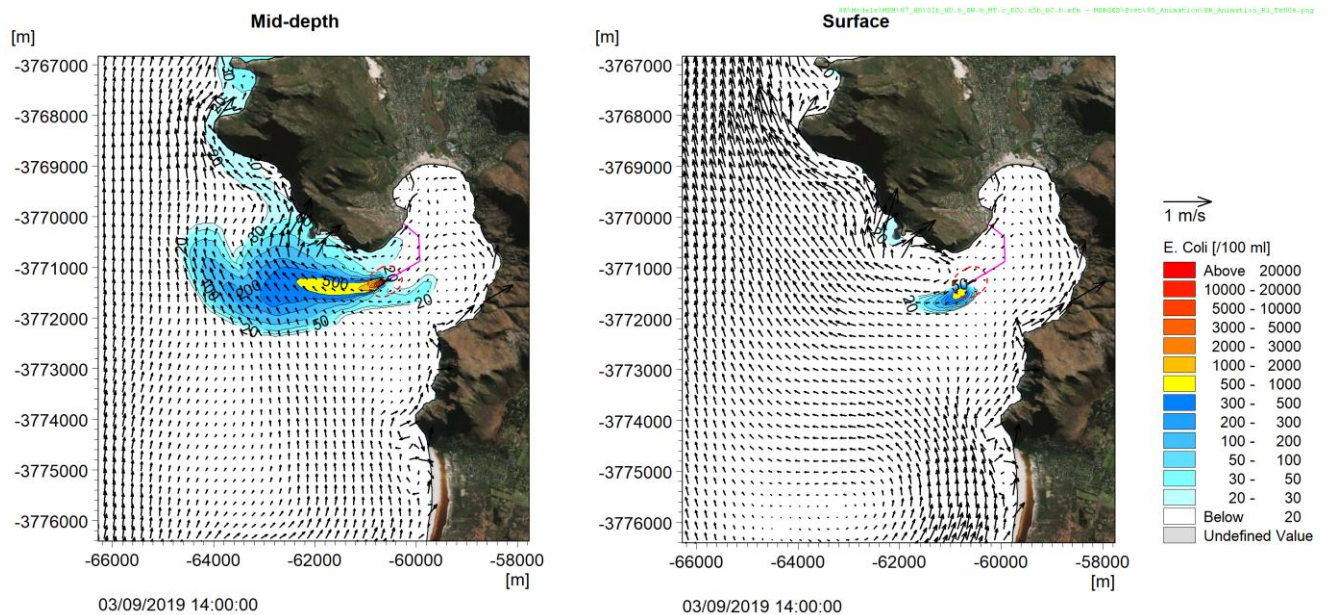


Figure 6-1: Winter/spring: Current vectors and E.coli plume at a moment in time during a southerly wind condition.

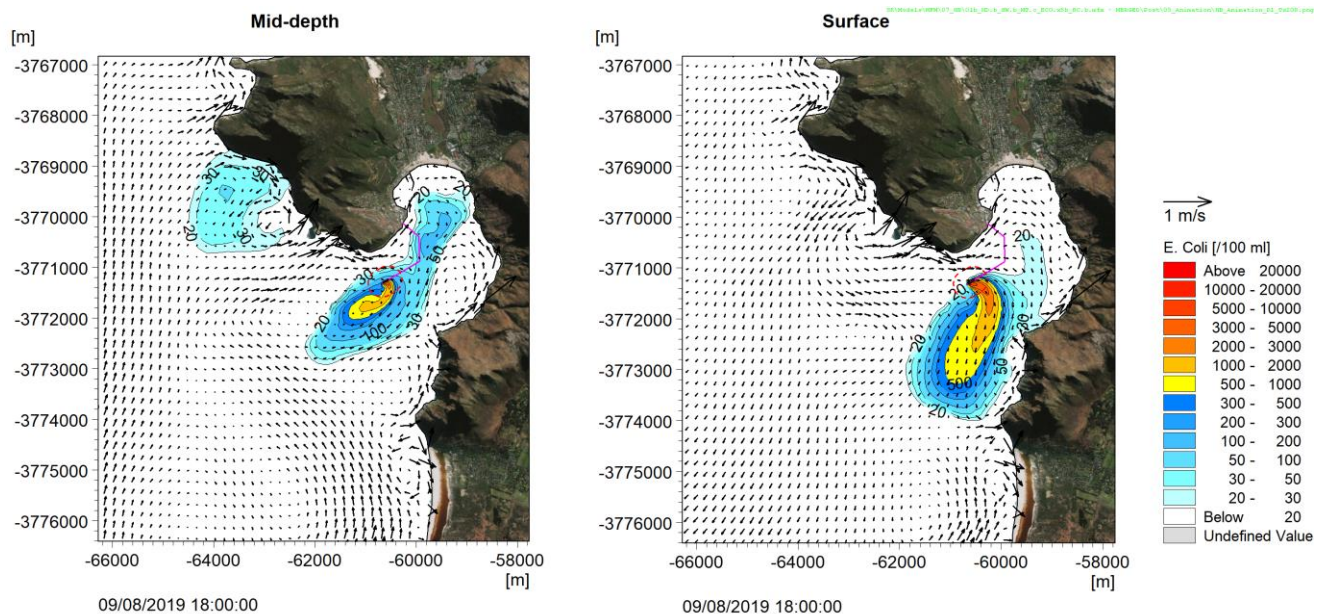


Figure 6-2: Winter/spring: Current vectors and E.coli plume at a moment in time during a north-westerly wind condition.

6.1.2 Dilutions

The concentrations from the conservative tracer were processed to number of dilutions using the equation:

$$\text{Number of dilutions} = \frac{\text{Effluent concentration}}{\text{Dispersed concentration}}$$

The modelled outputs were further processed to extract the 5th percentile number of dilutions in each horizontal and vertical element of the computational mesh. The 5th percentile number of dilutions will be exceeded 95% of the time and are thus close to the expected minimum number of dilutions (i.e. close to the worst case).

Figure 6-3, Figure 6-4 and Figure 6-5 present the 5th percentile dilutions at the seabed, mid-depth) and surface. Mid-depth is the depth below the surface equal to 55% of the local water depth, which was selected as the worst dilutions at Hout Bay occurred at this depth. Figure 6-6 shows a cross section of the 5th percentile number of dilutions extracted along the longest axis of the plume (marked by the dashed green line on the contour plots). Dilutions less than 2 000 are shown in orange as this is close to the dilution required for TSS of 2 587 as discussed in Section 3.4.1. Dilutions greater than 2 000 are shown in shades of blue. Although these exceed the required dilutions for the identified critical constituents, they provide information on the far-field behaviour of the plume.

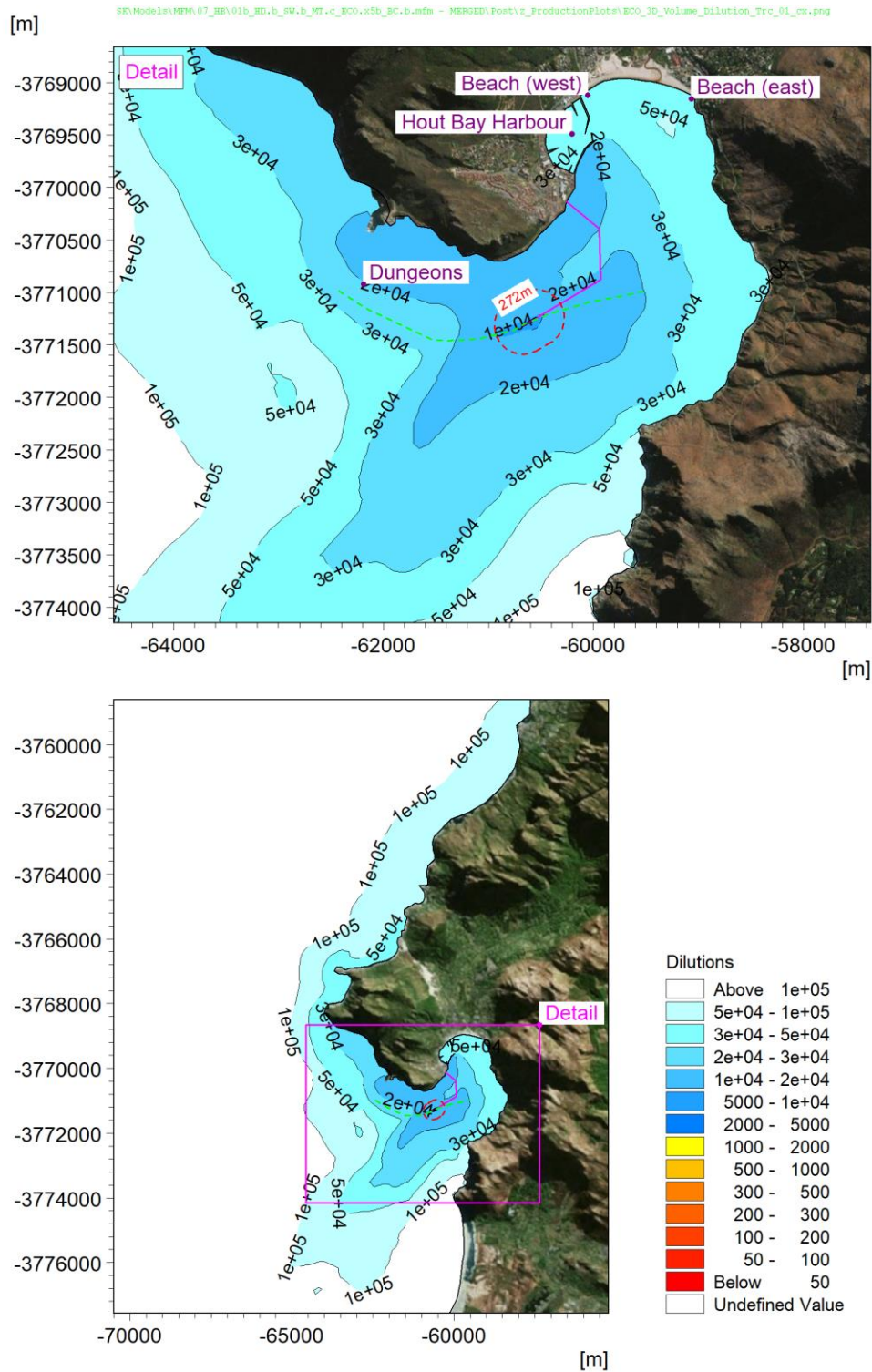


Figure 6-3: Winter/spring: Number of dilutions at the seabed, 5th percentile.

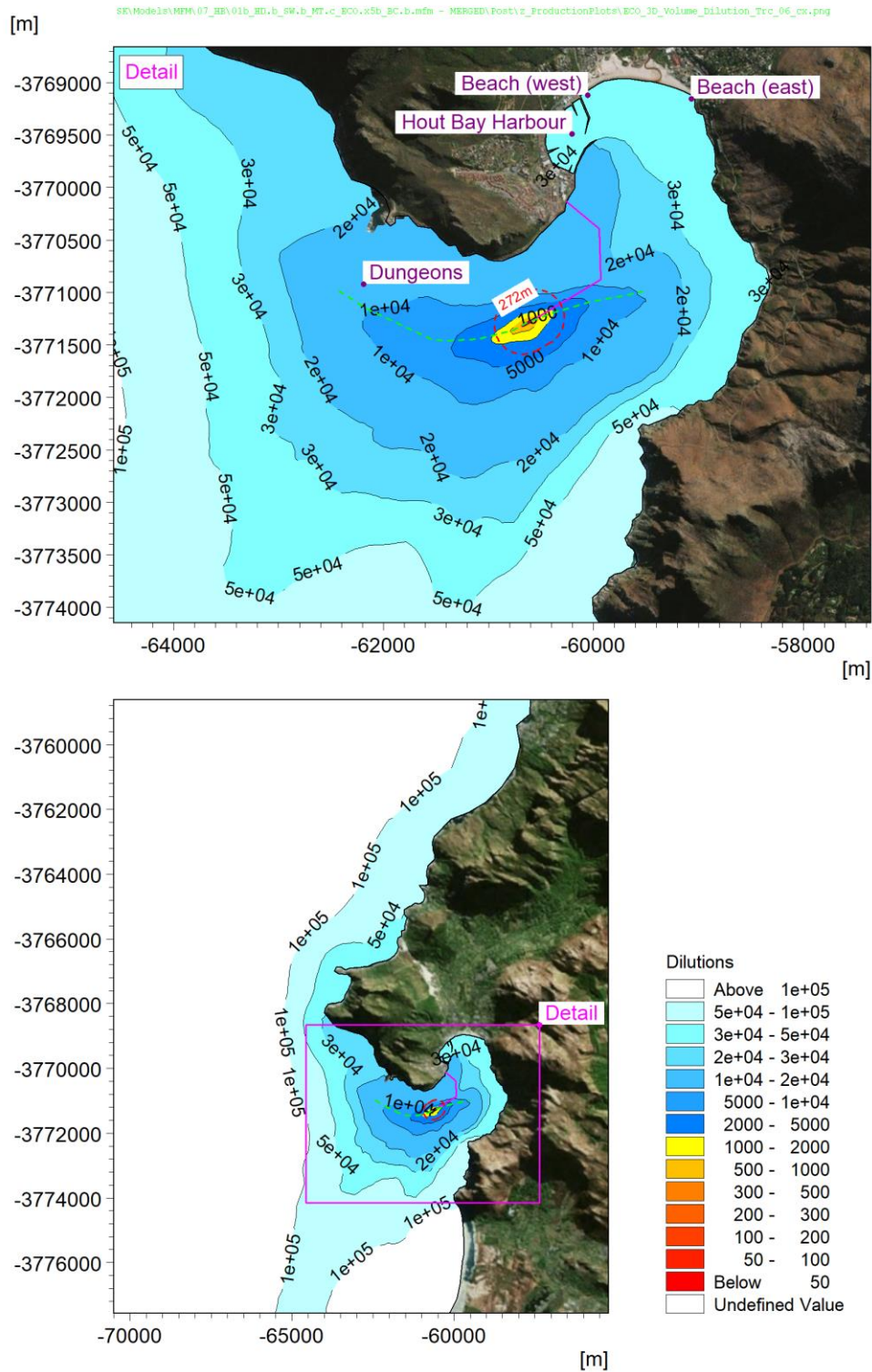


Figure 6-4: Winter/spring: Number of dilutions at mid-depth, 5th percentile.

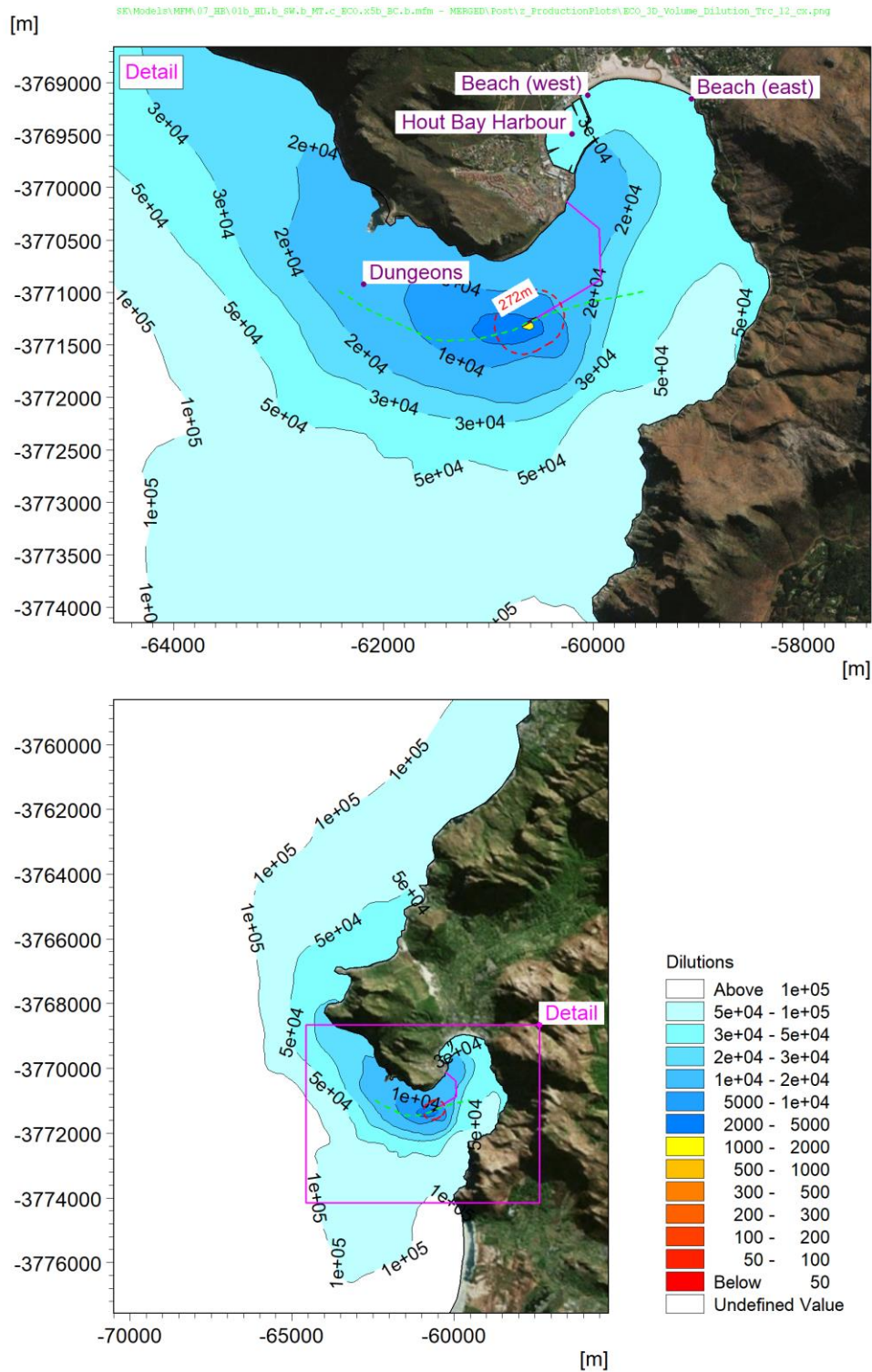


Figure 6-5: Winter/spring: Number of dilutions at the surface, 5th percentile.

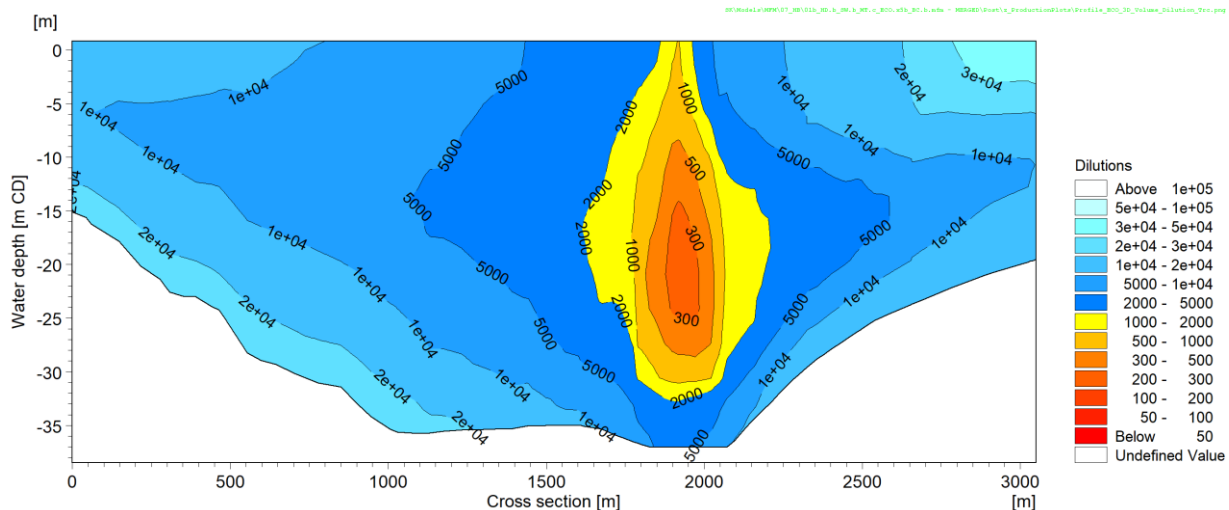


Figure 6-6: Winter/spring: Cross section of 5th percentile number of dilutions along the longest axis of the plume.

The minimum dilutions achieved at the edge of the mixing zone was extracted from the 5th percentile dilutions and is presented Table 6-1.

Table 6-1: Winter/spring: Minimum number of dilutions achieved at the edge of the mixing zone.

Parameter	Value
Minimum number of dilutions achieved at any depth along the edge of the allowable mixing zone (radius = 272 m), 5 th percentile	1 500

The distance from the diffuser to achieve the required dilutions for the three critical constituents (Table 3-4) are presented in Table 6-2.

Table 6-2: Winter/spring: Distance to achieve dilutions, 5th percentile.

Constituent	Dilutions required	Distance
Ammonia	175	< 25 m
COD	115	< 25 m
TSS	2 587	450 m

The mixing zone is spread parallel to the diffuser where it usually becomes entrained in the predominantly northward longshore currents (typically with southerly winds) or spreads offshore to the south-west (typically with northerly winds). During stratified conditions the surface and sub-surface plumes often exhibit different flow directions, e.g. showing offshore advection at the surface and onshore advection at mid-depth. The effluent plume rises due to its buoyancy and usually becomes passive at mid-depth due to mixing with the ambient currents or trapping by stratification. Occasional surfacing of the plume happens during periods of high effluent flows or stagnant hydrodynamic conditions.

The minimum number of dilutions achieved in the allowable mixing zone is 1 500. The constituent requiring the highest dilutions is TSS, which achieved the 2 587 required dilutions 450 m from the diffuser. Ammonia and COD achieved the required dilutions in within 25 m. Note that distances smaller than 25 m could not be measured in the model, due to the mesh resolution.

6.1.3 Bacteria

In addition to dilutions by hydrodynamic processes the bacterial concentrations are further reduced due to bacterial die-off (as described in Section 2.3.2). Figure 6-7 presents the surface and seabed T_{90} values for E.coli and enterococci, extracted in the middle of the Hout Bay diffuser at a depth of -37.0 m CD. Recall from Section 2.3.2.1 the median T_{90} ratio of enterococci to E.coli is 2.39.

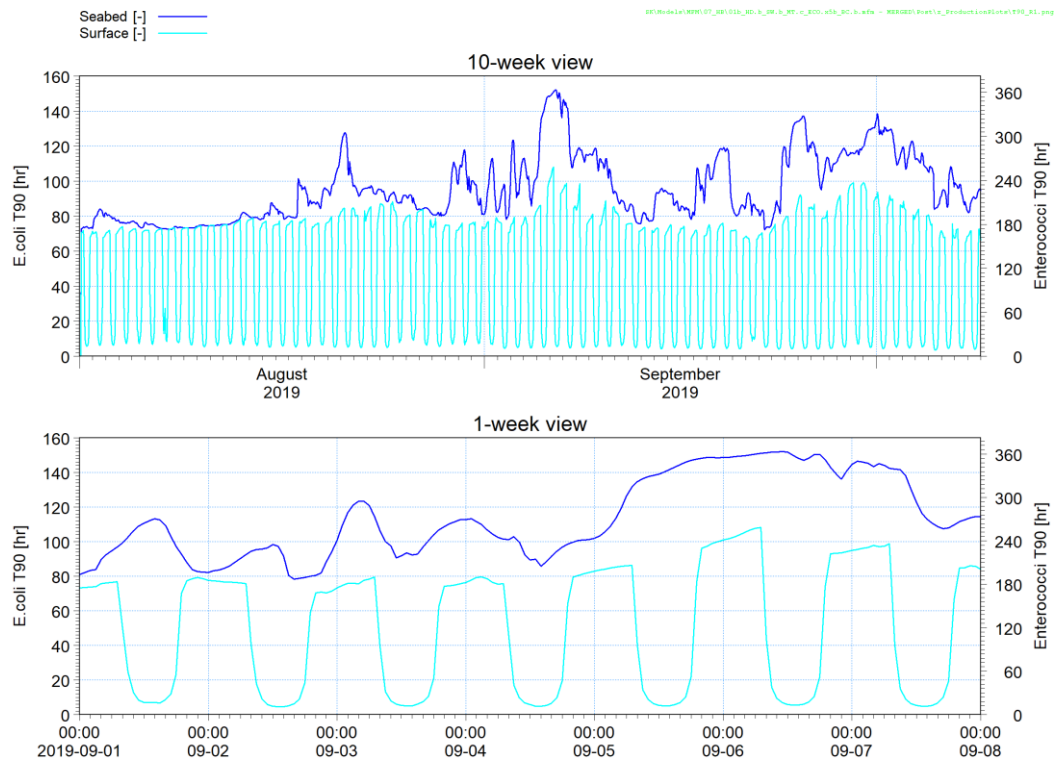


Figure 6-7: Winter/spring: Surface and seabed T_{90} values for E.coli and enterococci.

A significant diurnal variation in die-off rates due to the solar radiation can be observed at the surface, while the seabed remains mostly unaffected due to light attenuation. In the absence of light, the seawater temperature dominates the die-off processes and the stratification determines the gradient between the surface and seabed T_{90} values.

Based on the DEA guidelines (Table 3-5), the model outputs of bacterial concentrations were further processed to extract the 90th percentile concentration at each horizontal and vertical element of the computational mesh for the full simulation period. The 90th percentiles were only sampled during daylight hours (between 07:00 to 18:00) to emulate the recommended microbiological sampling regime in the guidelines.

6.1.3.1 E.coli

Figure 6-8, Figure 6-9 and Figure 6-10 present the 90th percentile E.coli concentrations at the seabed, mid-depth and surface. Concentrations greater than 500 CFU/100 ml are shown in orange as this is the guideline for E.coli as discussed in Section 3.4.2. Concentrations less than 500 CFU/100 ml are shown in shades of blue. Although these are less than the guideline, they provide information on the far-field behaviour of the plume. A time series of highest E.coli concentrations at any depth at four key locations (Hout Bay beach east and

west, Hout Bay harbour and Dungeons surf spot) is shown in Figure 6-11. The locations are shown in the contour plots.

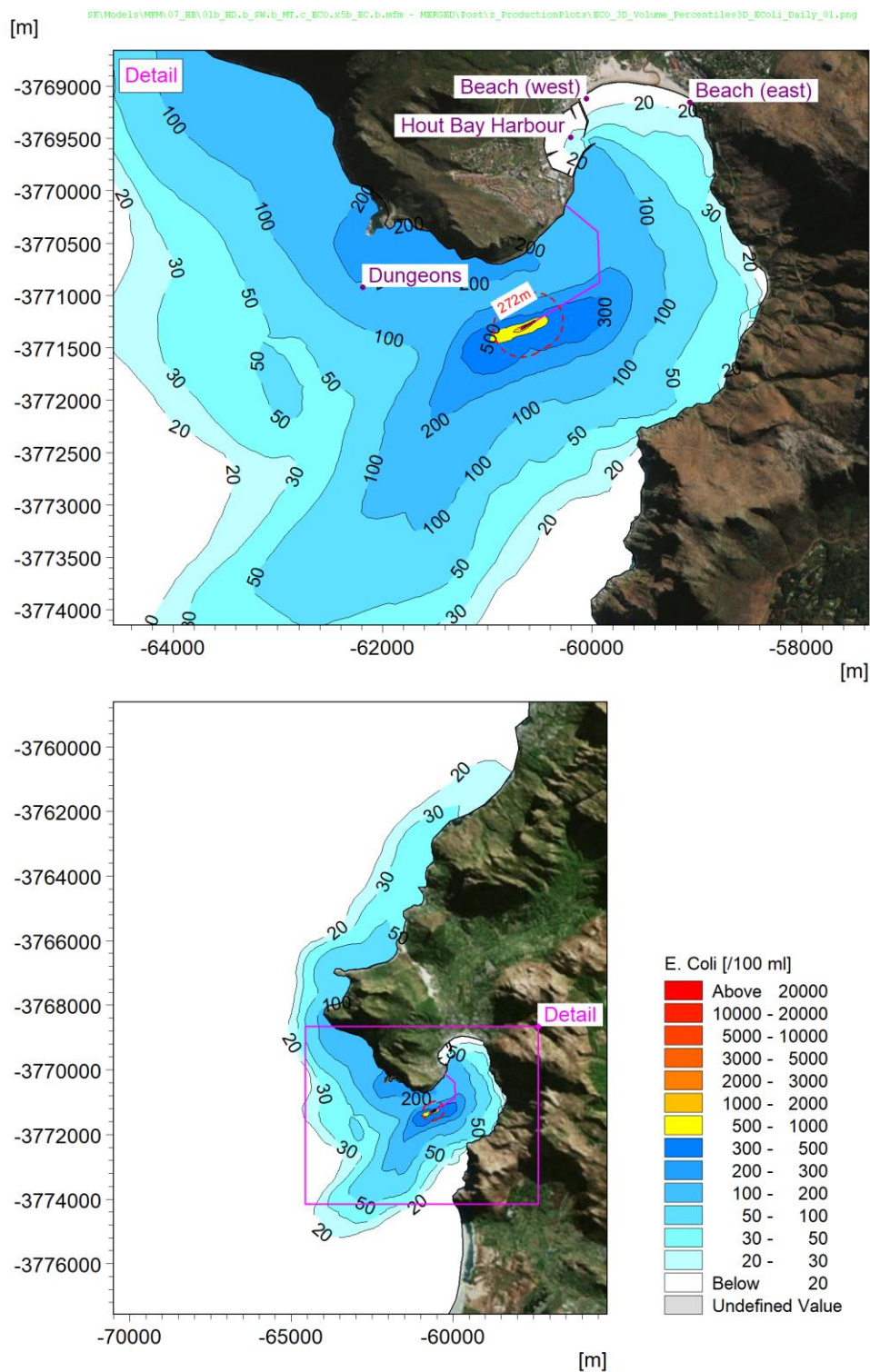


Figure 6-8: Winter/spring: E.coli concentration at the seabed, 90th percentile for daylight hours (07:00 – 18:00).

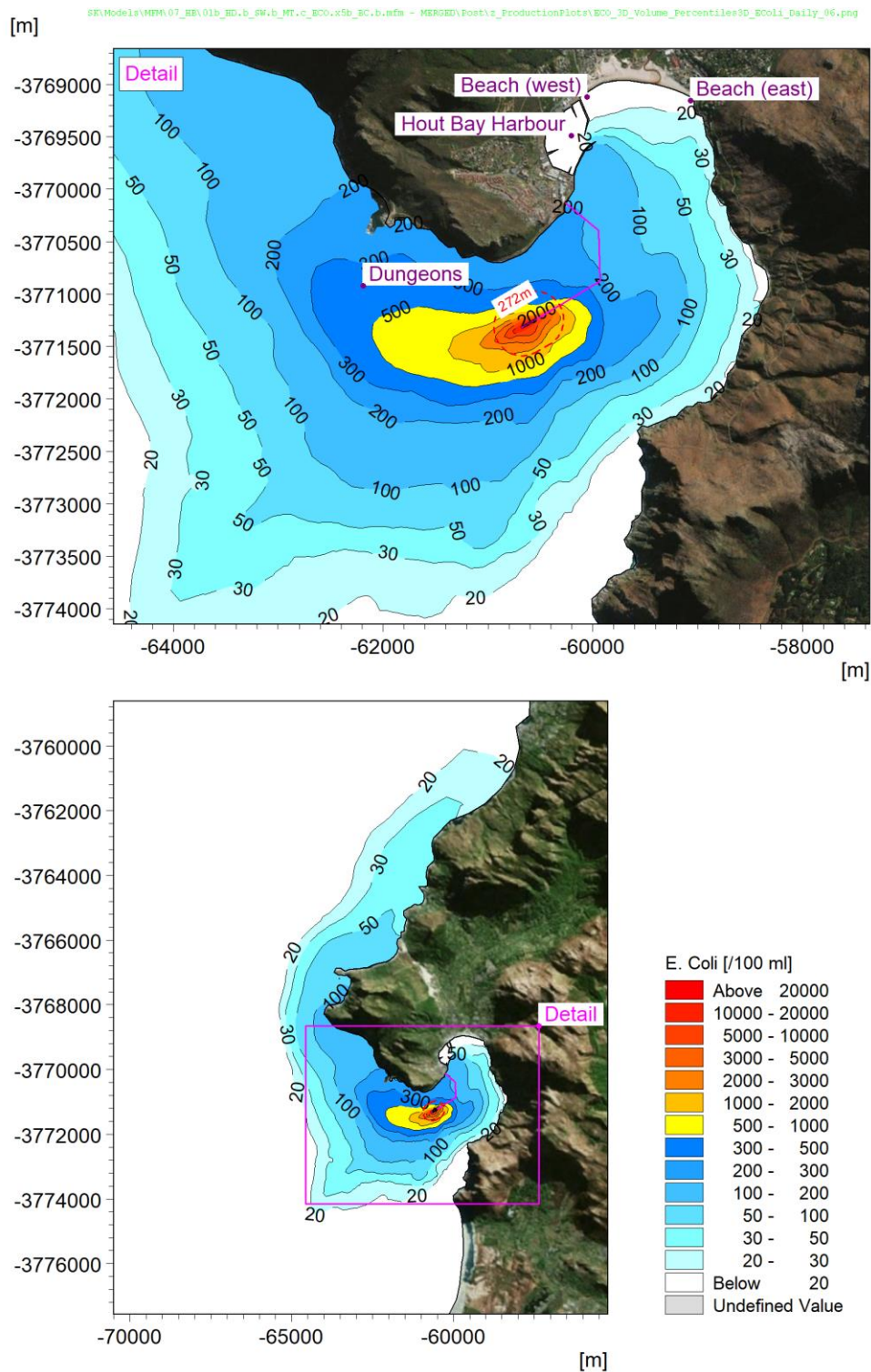


Figure 6-9: Winter/spring: E.coli concentration at mid-depth, 90th percentile for daylight hours (07:00 – 18:00).

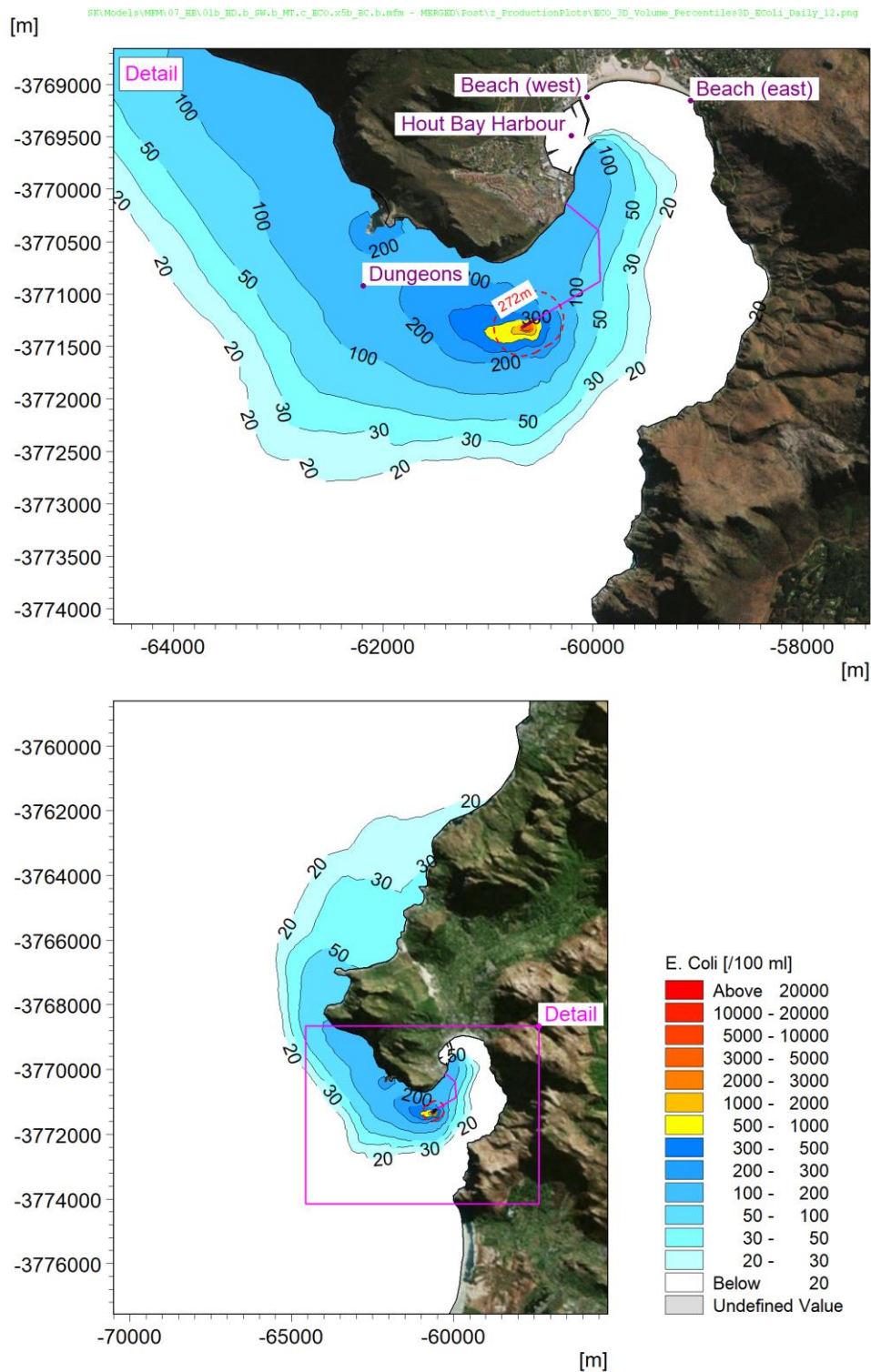


Figure 6-10: Winter/spring: E.coli concentration at the surface, 90th percentile for daylight hours (07:00 – 18:00).

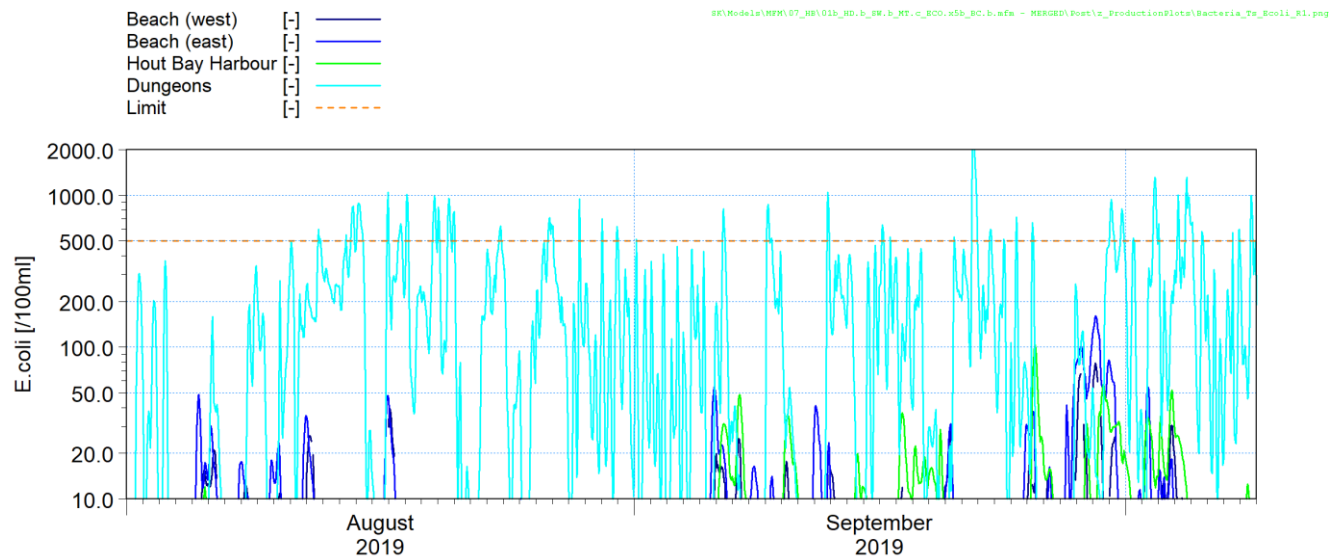


Figure 6-11: Winter/spring: Time series of highest E.coli concentration at any depth at four key locations. The water quality guideline (500 CFU/100 ml 90th percentile in daylight) is also shown in orange.

A mixing zone distance of 1 620 m was required to meet the 90th percentile water quality guideline of 500 CFU/100 ml. The contour plots show that the 90th percentile E.coli concentrations were the highest at mid-depth and concentrations above the 500 CFU/100 ml guideline did not intersect with the shoreline. The E.coli concentrations at the Hout Bay beaches and harbour did not exceed 500 CFU/100 ml. Although Dungeons was exposed to concentrations above 500 CFU/100 ml on many occasions, the duration of these events was just less than 10% of the daylight time and therefore met the water quality guidelines.

6.1.3.2 Enterococci

Figure 6-12, Figure 6-13 and Figure 6-14 present the 90th percentile enterococci concentrations at the seabed, mid-depth and surface. Concentrations greater than 185 CFU/100 ml are shown in orange as this is the guideline for enterococci as discussed in Section 3.4.2. Concentrations less than 185 CFU/100 ml are shown in shades of blue. Although these are less than the guideline, they provide information on the far-field behaviour of the plume. A time series of enterococci concentrations at four key locations is shown in Figure 6-15.

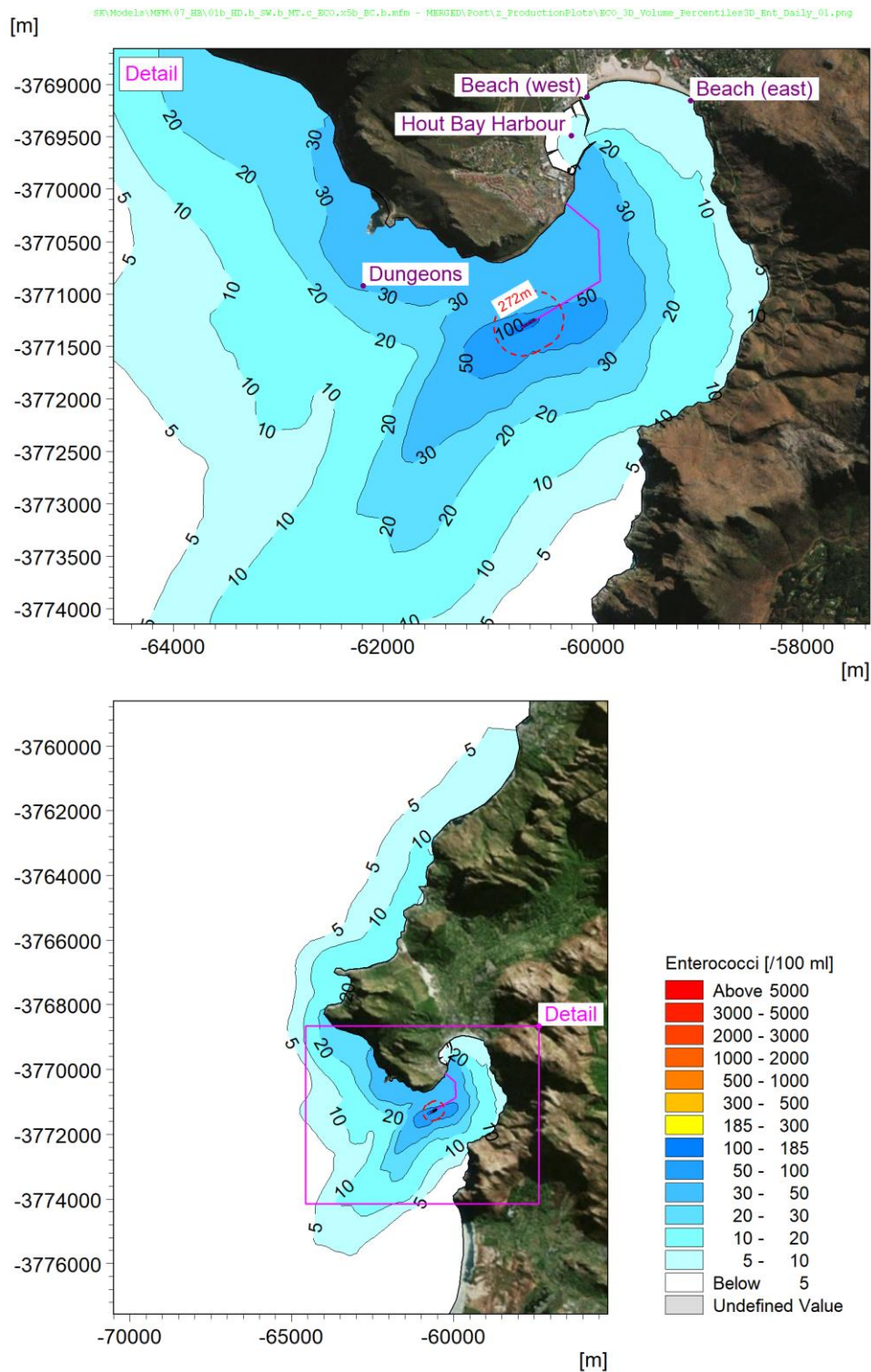


Figure 6-12: Winter/spring: Enterococci concentration at the seabed, 90th percentile for daylight hours (07:00 – 18:00).

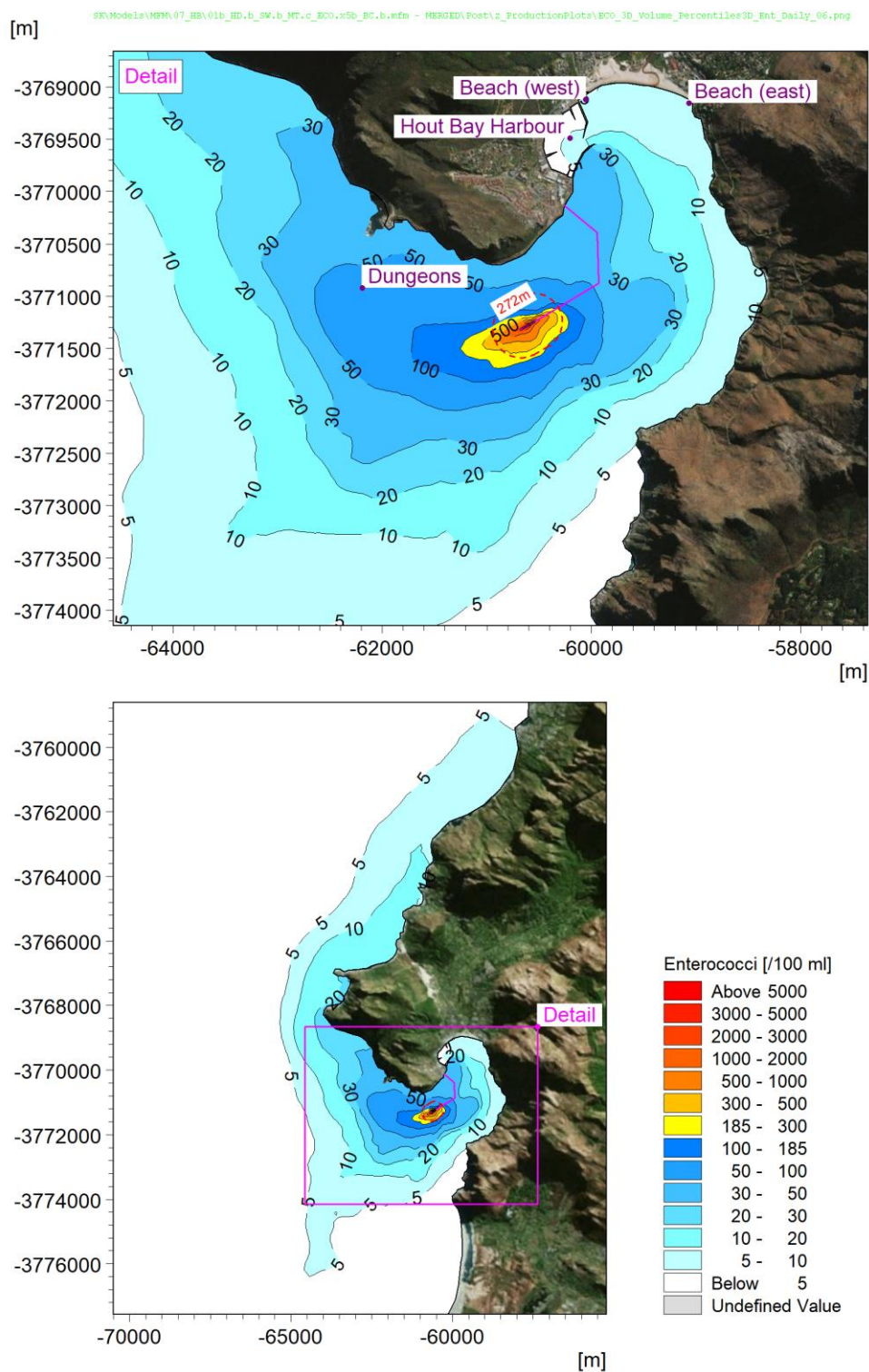


Figure 6-13: Winter/spring: Enterococci concentration at mid-depth, 90th percentile for daylight hours (07:00 – 18:00).

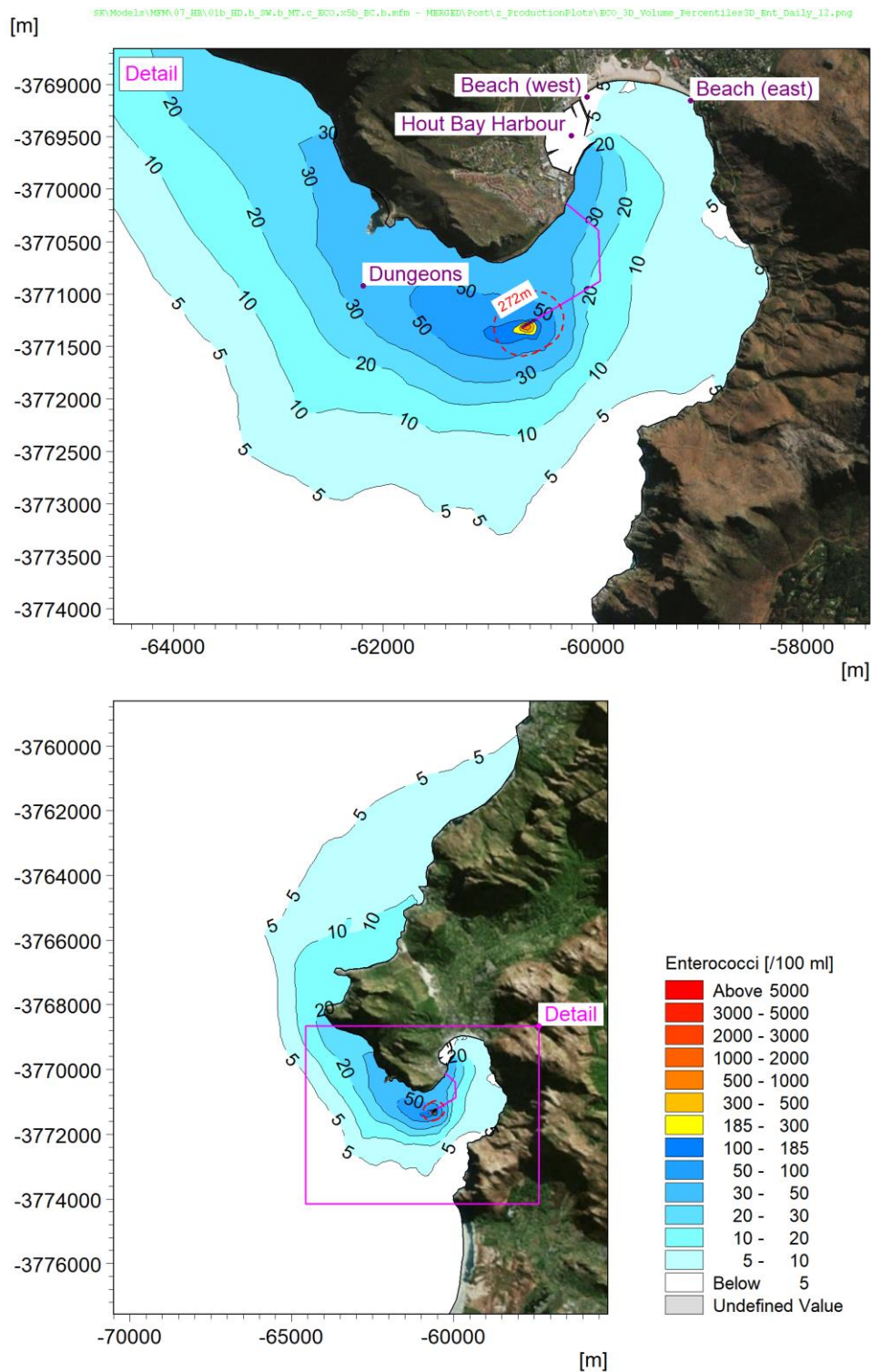


Figure 6-14: Winter/spring: Enterococci concentration at the surface, 90th percentile for daylight hours (07:00 – 18:00).

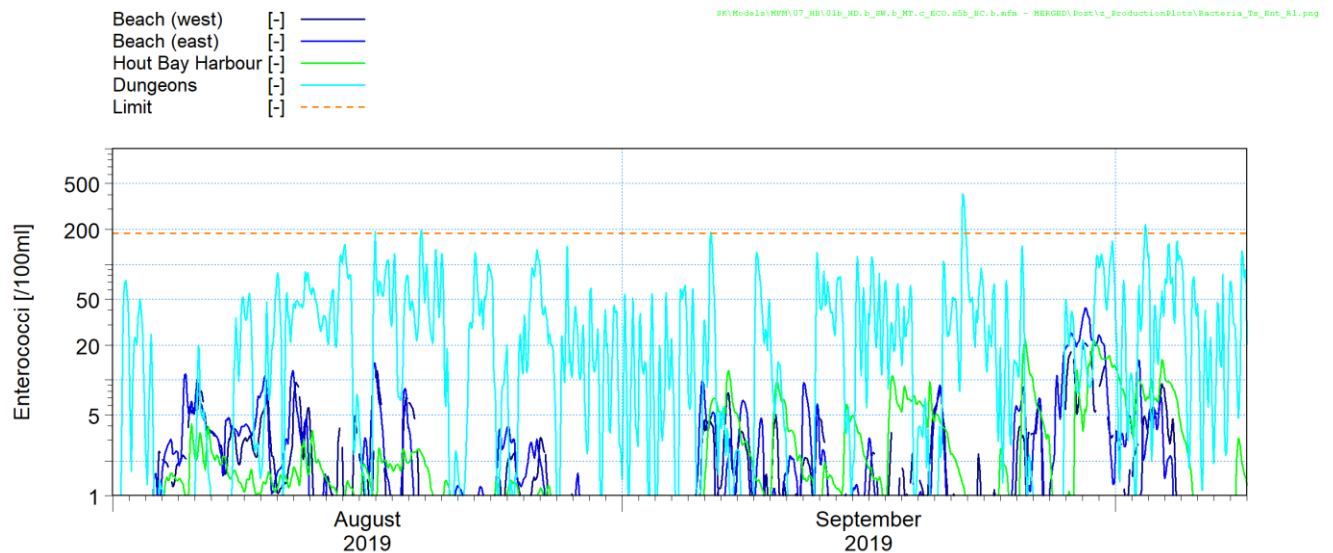


Figure 6-15: Winter/spring: Time series of highest enterococci concentration at any depth at four key locations. The water quality guideline (185 CFU/100 ml 90th percentile in daylight) is also shown in orange.

A mixing zone distance of 700 m was required to meet the 90th percentile water quality guideline of 185 CFU/100 ml. The contour plots show that the 90th percentile enterococci concentrations were the highest at mid-depth and concentrations above the 185 CFU/100 ml guideline did not intersect with the shoreline. The enterococci concentrations at the Hout Bay beaches and harbour did not exceed 185 CFU/100 ml. Although Dungeons was briefly exposed to concentrations above 185 CFU/100 ml, the duration of these events was less than 10% of the daylight time and therefore met the water quality guidelines.

6.1.3.3 Discussion

Based on the applicable water quality guidelines (discussed in Section 3.4.2), E.coli requires a greater mixing zone distance to meet the guidelines compared to enterococci.

The bacteria plumes have the highest concentrations at mid depth (the depth below the surface equal to 55% of the local water depth) where the plume usually becomes trapped. Solar radiation further reduces concentrations closer to the surface (illustrated in Figure 6-7).

During typical conditions the plume is advected in a south-westerly or north-easterly direction by the currents and once outside the bay northward along the coastline by the predominantly northward longshore current or offshore by the less frequent south-westerly currents. Currents driven by wave breaking at the southern or northern entrance of the bay (near the Dungeons surf spot) often advect the plume towards Hout Bay, but due to dispersion and decay the bacteria concentrations are significantly reduced by the time the plume reaches the beach or harbour.

It is noted that the diffuser has a north-east/south-west alignment which is parallel rather than perpendicular to the dominant currents which results in sub-optimal dilutions.

6.1.4 Total suspended solids

The concentrations of TSS were modelled in the water column and specifically where these were deposited on the seabed. This is a proxy for the fate of pollutants that adsorb to solid particles, e.g. heavy metals.

Figure 6-16 presents the bed mass of TSS at the end of the 10-week simulation. The deposited mass in the main depo-centres (demarcated in red) are summarised in Table 6-3. The table also includes the total mass of TSS that were advected outside of the model domain through the boundaries and TSS in suspension at the end of the run.

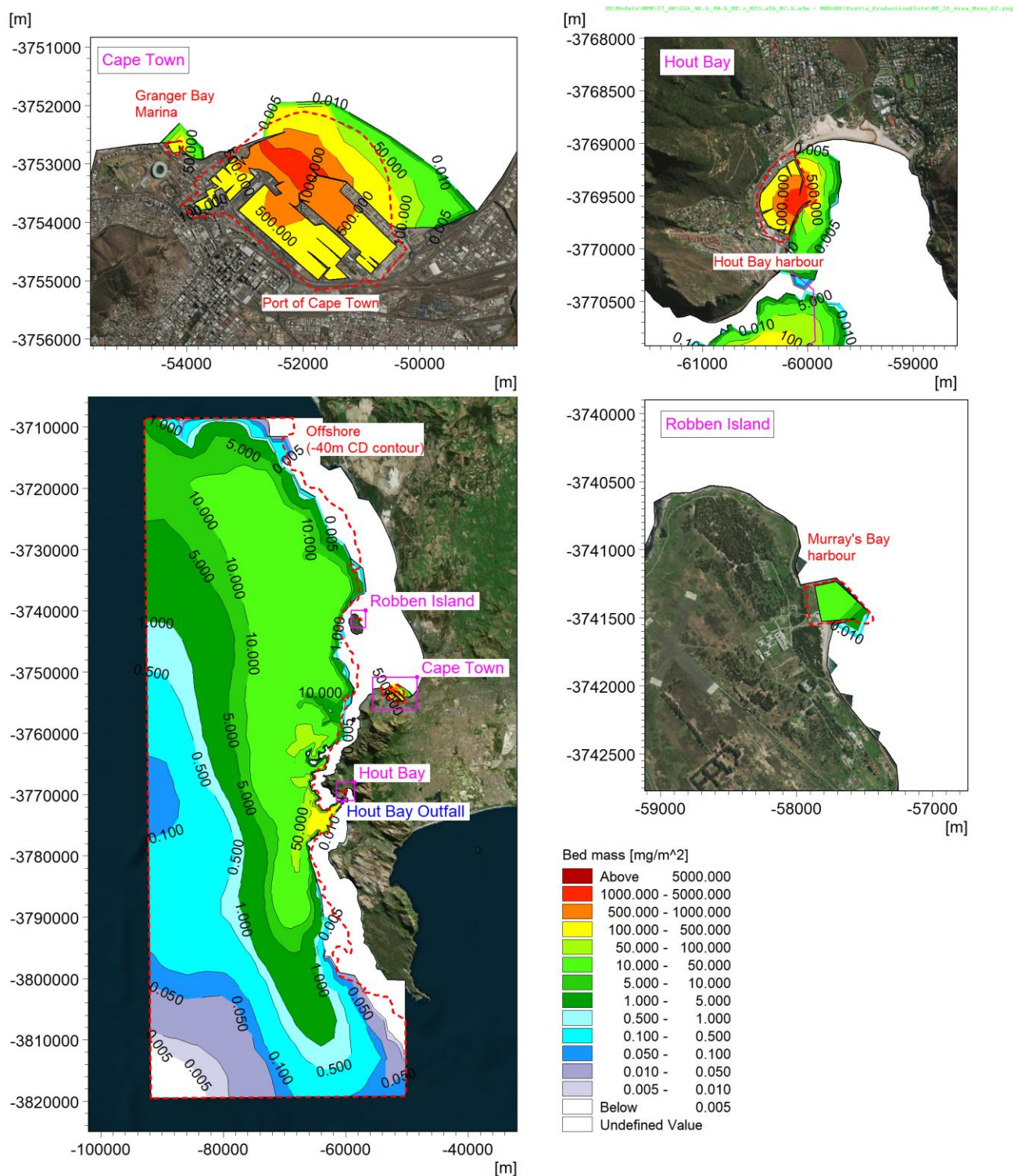


Figure 6-16: Winter/spring: Bed mass of TSS distribution at the end of the 10-week period.

Table 6-3: Winter/spring: Integrated mass at the end of the 10-week simulation period.

Area	Mass [kg]	% released
Port of Cape Town	2 300	1.4%
Murray's Bay Harbour	1.38	< 0.1%
Granger Bay	11	< 0.1%
Hout Bay	145	< 0.1%
Offshore (-40 m CD contour)	28 300	16.9%
Out of domain	91 300	54.5%
Suspended	45 600	27.2%
Total mass released	168 000	100%

The highest concentrations are observed in the sheltered depo-centres, i.e. the Port of Cape Town, Granger Bay marina, Murray's Bay harbour and Hout Bay harbour where the bed shear stress due to waves and currents are sufficiently low to allow deposition. Accumulation also occurs in exposed areas where the water depth is greater than approximately 40 m due to the wave orbital velocities not exerting sufficient stress on the seabed to resuspend the sediment particles.

The largest depo-centre is the Port of Cape Town with approximately 1.4% of the TSS released from the Hout Bay outfall accumulating in the port. These results can be used in the design and interpretation of sediment quality sampling studies.

6.2 Summer/autumn

The outfall dispersion model was run for a 10-week period between 13 February 2020 and 23 April 2020, coinciding with the calibration period, to represent environmental conditions for summer and autumn.

The model outputs are the concentrations of E.coli, enterococci, TSS and a conservative tracer in each horizontal and vertical element of the computational mesh at 1-hour intervals throughout the simulation period.

6.2.1 Plume dynamics

Figure 6-17 and Figure 6-18 present examples of the current vectors and E.coli plume at a moment in time for a south-easterly and north-westerly wind condition. These results show the complex 3D dynamic behaviour of the plume.

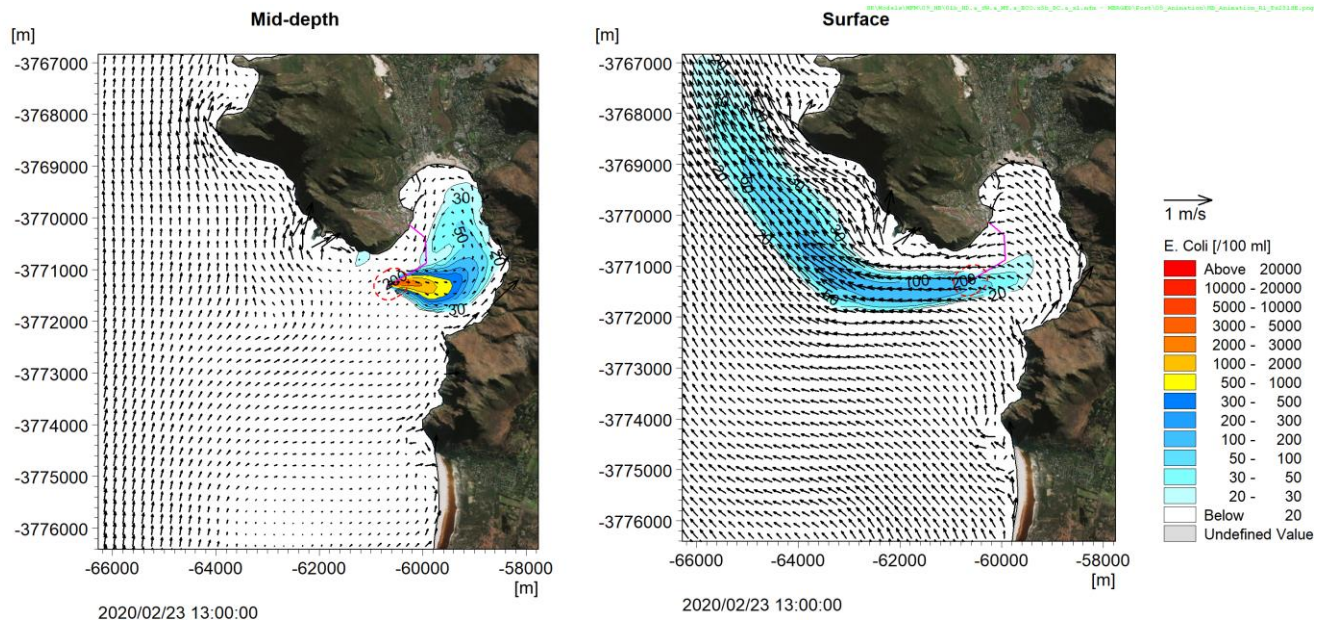


Figure 6-17: Summer/autumn: Current vectors and E.coli plume at a moment in time during a south-easterly wind condition.

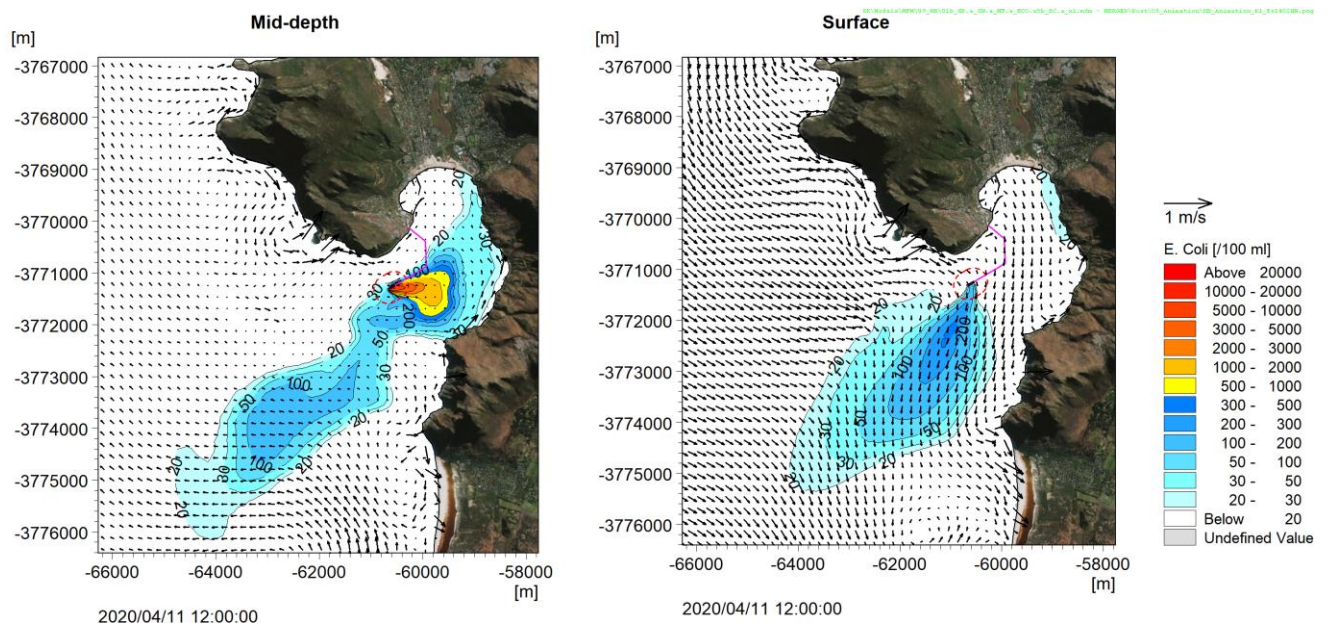


Figure 6-18: Summer/autumn: Current vectors and E.coli plume at a moment in time during a north-westerly wind condition.

6.2.2 Dilutions

The concentrations from the conservative tracer were processed to obtain the 5th percentile number of dilutions in each horizontal and vertical element of the computational mesh as discussed in Section 6.1.2.

Figure 6-19, Figure 6-20 and Figure 6-21 present the 5th percentile dilutions at the seabed, mid-depth and surface. Mid-depth is the depth below the surface equal to 55% of the local water depth, which was selected as the worst dilutions at Hout Bay occurred at this depth. Figure 6-22 shows a cross section of the 5th percentile number of dilutions extracted along the longest axis of the plume (marked by the dashed green



line on the contour plots). Dilutions less than 2 000 are shown in orange as this is close to the dilution required for TSS of 2 587 as discussed in Section 3.4.1. Dilutions greater than 2 000 are shown in shades of blue. Although these exceed the required dilutions for the identified critical constituents, they provide information on the far-field behaviour of the plume.

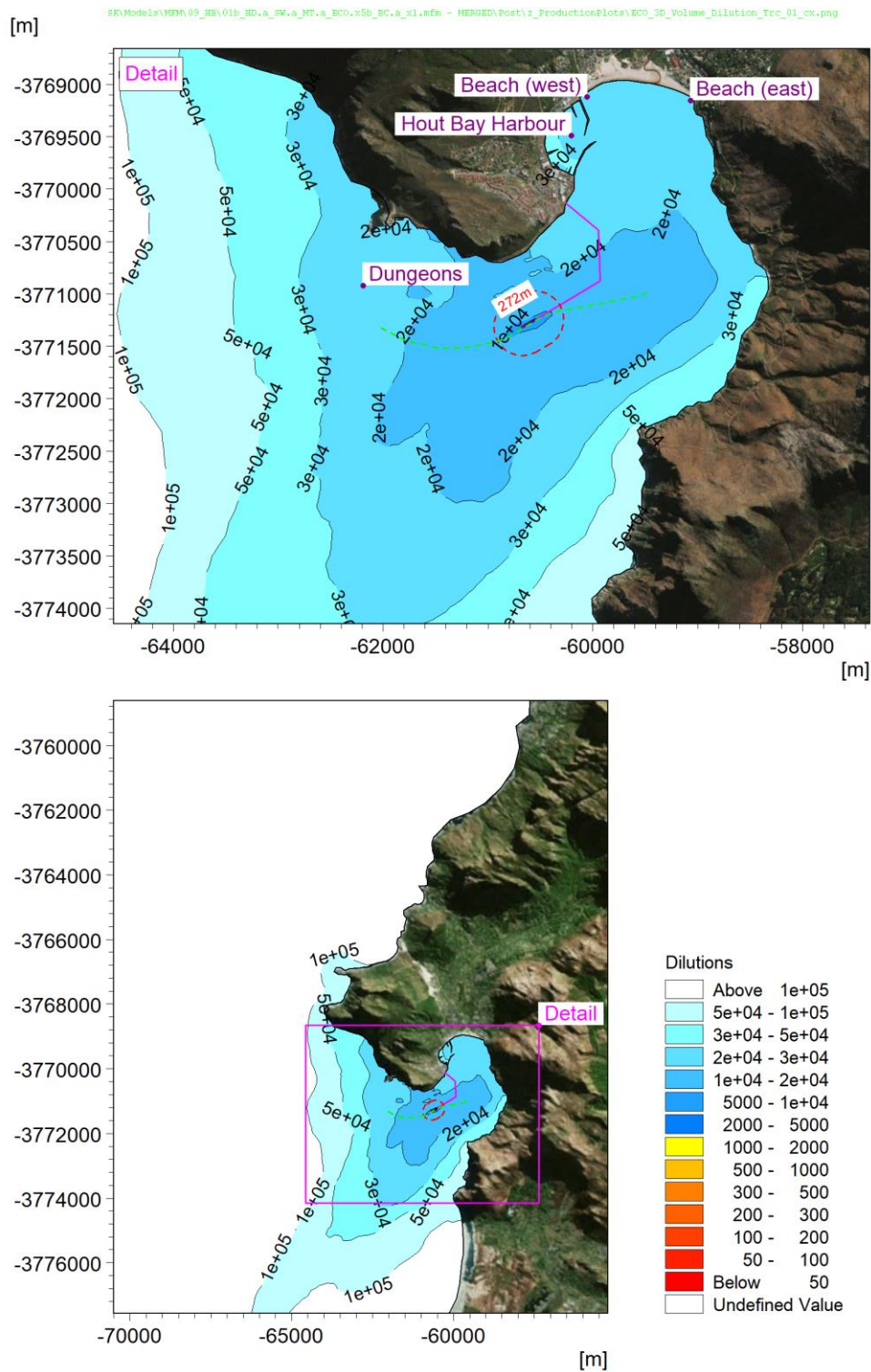


Figure 6-19: Summer/autumn: Number of dilutions at the seabed, 5th percentile.

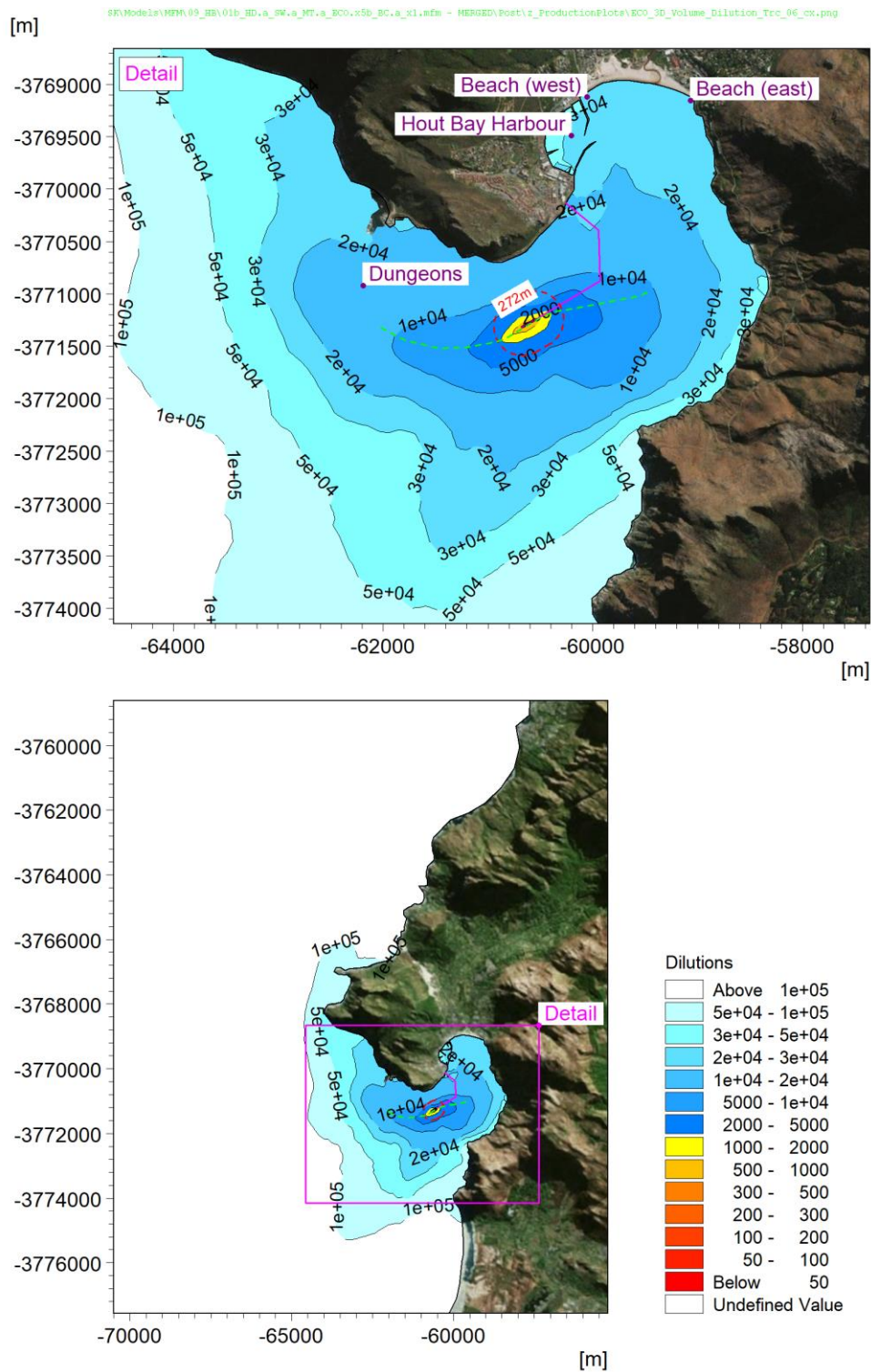


Figure 6-20: Summer/autumn: Number of dilutions at mid-depth, 5th percentile.

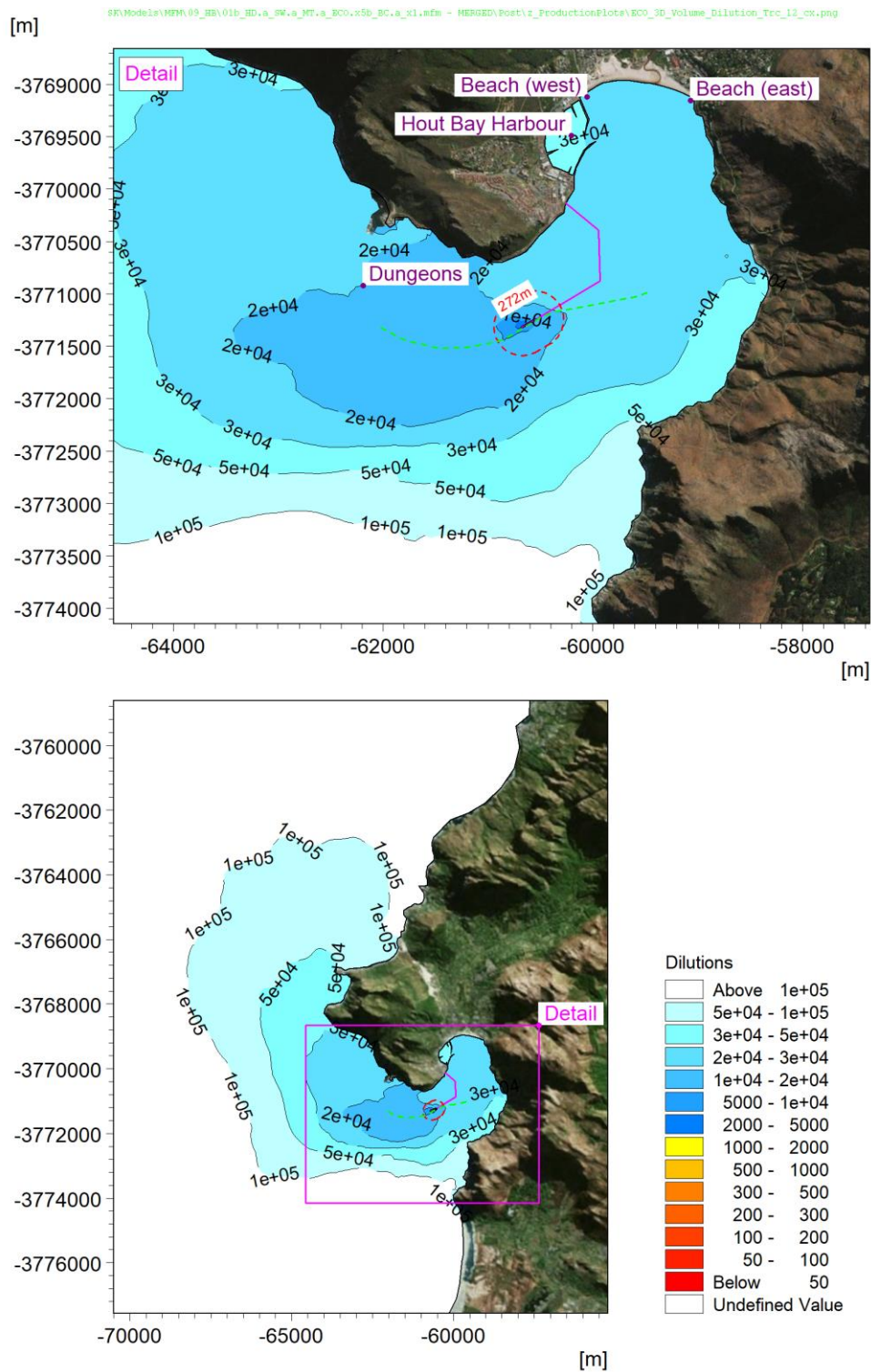


Figure 6-21: Summer/autumn: Number of dilutions at the surface, 5th percentile.

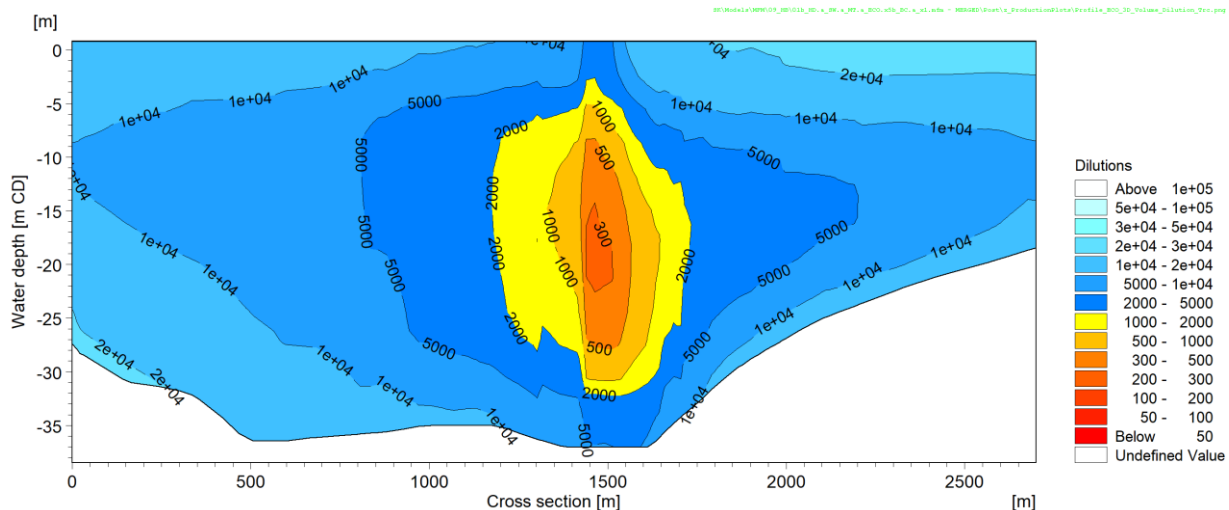


Figure 6-22: Summer/autumn: Cross section of 5th percentile number of dilutions along the longest axis of the plume.

The minimum dilutions achieved at the edge of the mixing zone was extracted from the 5th percentile dilutions and is presented Table 6-4.

Table 6-4: Summer/autumn: Minimum number of dilutions achieved at the edge of the mixing zone.

Parameter	Value
Minimum number of dilutions achieved at any depth along the edge of the allowable mixing zone (radius = 272 m), 5 th percentile	1 950

The distance from the diffuser to achieve the required dilutions for the three critical constituents (Table 3-4) are presented in Table 6-5.

Table 6-5: Summer/autumn: Distance to achieve dilutions, 5th percentile.

Constituent	Dilutions required	Distance
Ammonia	175	< 25 m
COD	115	< 25 m
TSS	2 587	360 m

The plume dynamics show similar trends as observed in the winter/spring period in Section 6.1.2: The plume is spread either by predominantly northward longshore currents (typically with southerly winds) or south-westerly offshore currents (typically with northerly winds). The plume usually becomes passive at mid-depth and occasional surfacing of the plume happens during periods of high effluent flows or stagnant hydrodynamic conditions.

The minimum number of dilutions achieved in the allowable mixing zone is 1 950. The constituent requiring the highest dilutions is TSS, which achieved the 2 587 required dilutions 360 m from the diffuser. Ammonia and COD achieved the required dilutions in within 25 m. Note that distances smaller than 25 m could not be measured in the model, due to the mesh resolution.

6.2.3 Bacteria

In addition to dilutions by hydrodynamic processes the bacterial concentrations are further reduced due to bacterial die-off (as described in Section 2.3.2). Figure 6-23 presents the surface and seabed T_{90} values for E.coli and enterococci, extracted in the middle of the Hout Bay diffuser at a depth of -37.0 m CD. Recall from Section 2.3.2.1 the median T_{90} ratio of enterococci to E.coli is 2.39.

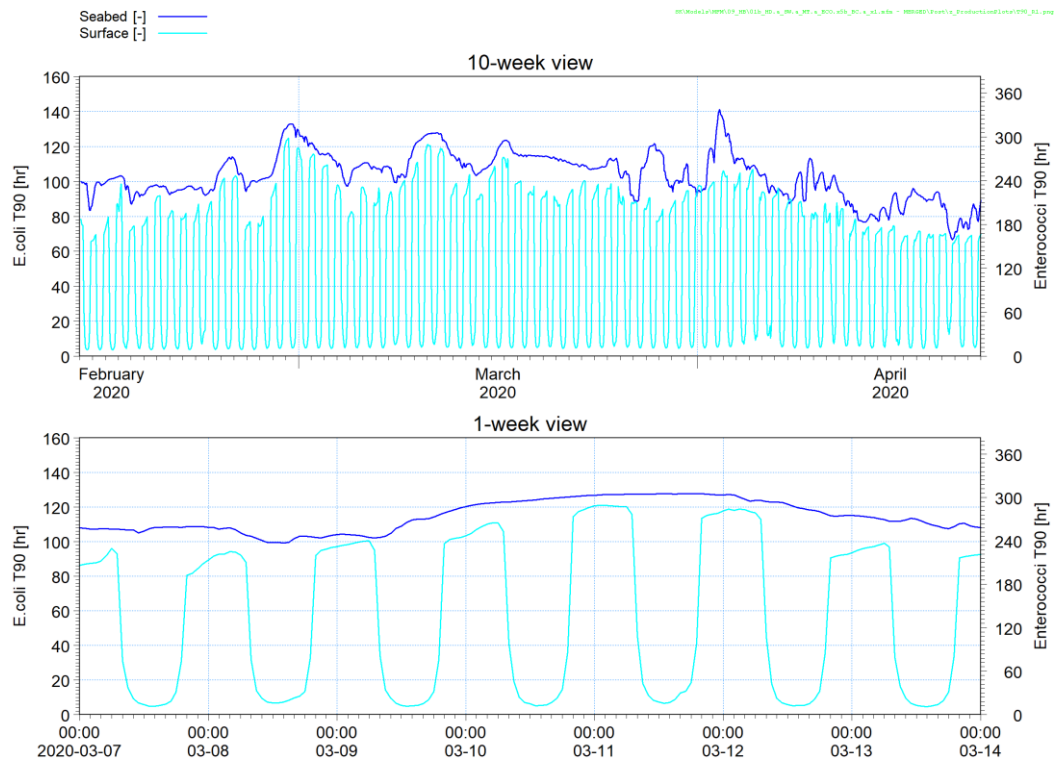


Figure 6-23: Summer/autumn: Surface and seabed T_{90} values for E.coli and enterococci.

A significant diurnal variation in die-off rates due to the solar radiation can be observed at the surface, while the seabed remains mostly unaffected due to light attenuation. In the absence of light, the seawater temperature dominates the die-off processes and the stratification determines the gradient between the surface and seabed T_{90} values.

The model outputs of bacterial concentrations were processed to extract the 90th percentile during daylight hours (between 07:00 to 18:00) to emulate the recommended microbiological sampling regime in the guidelines.

6.2.3.1 E.coli

Figure 6-24, Figure 6-25 and Figure 6-26 present the 90th percentile E.coli concentrations at the seabed, mid-depth and surface. Concentrations greater than 500 CFU/100 ml are shown in orange as this is the guideline for E.coli as discussed in Section 3.4.2. Concentrations less than 500 CFU/100 ml are shown in shades of blue. Although these are less than the guideline, they provide information on the far-field behaviour of the plume. A time series of highest E.coli concentrations at any depth at four key locations (Hout Bay beach east and west, Hout Bay harbour and Dungeons surf spot) is shown in Figure 6-27. The locations are shown in the contour plots.

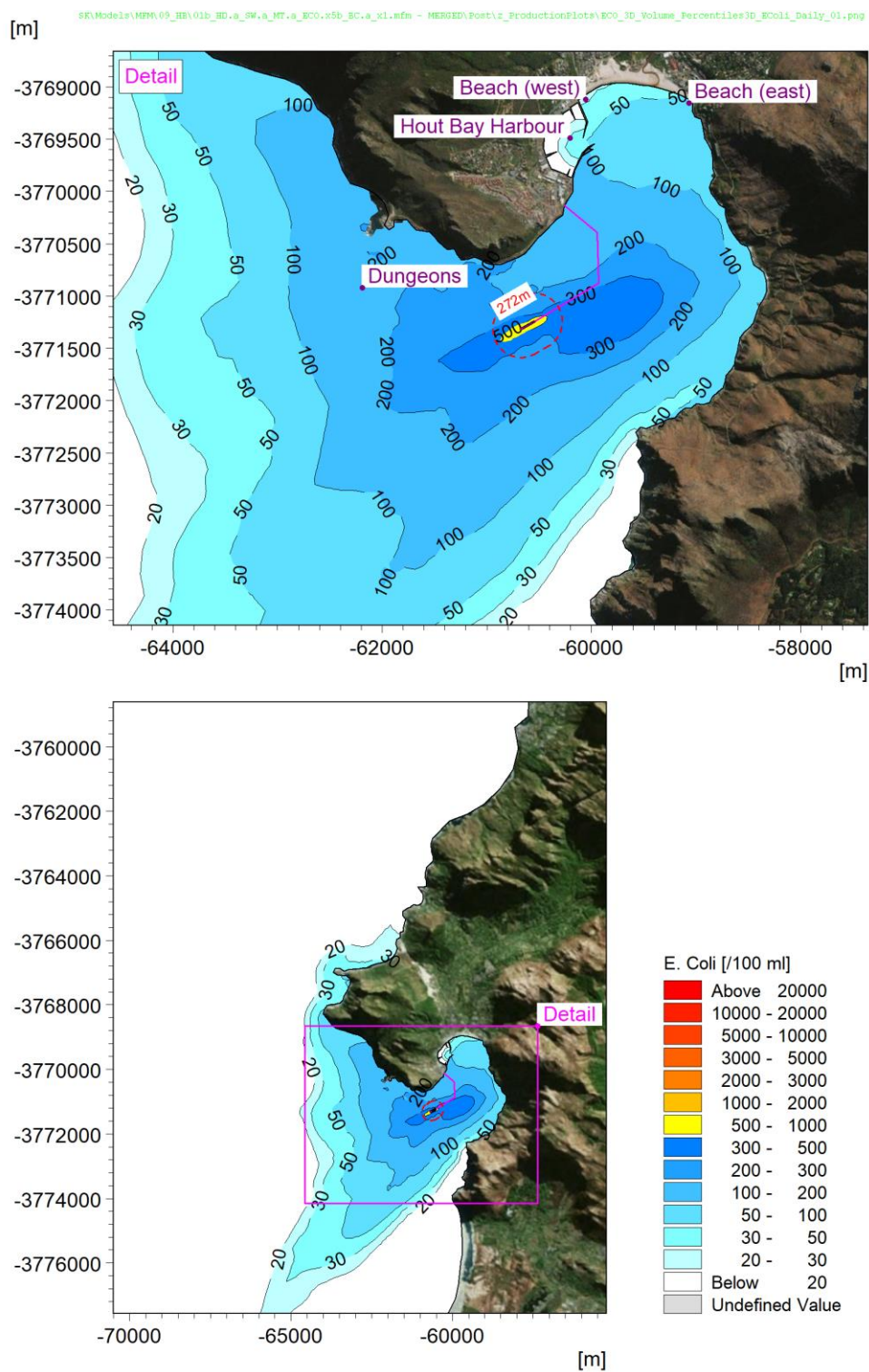


Figure 6-24: Summer/autumn: E.coli concentration at the seabed, 90th percentile for daylight hours (07:00 – 18:00).

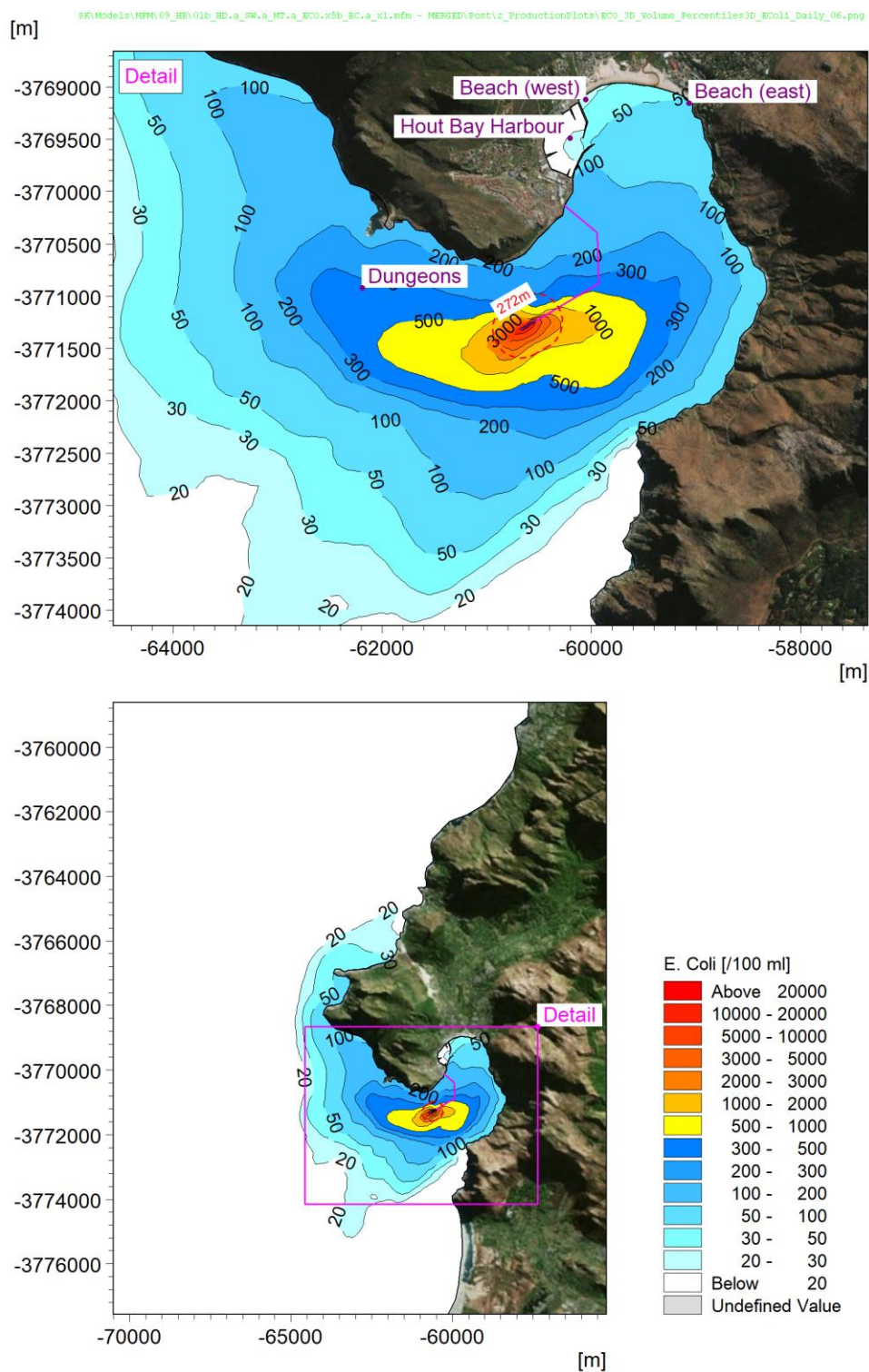


Figure 6-25: Summer/autumn: E.coli concentration at mid-depth, 90th percentile for daylight hours (07:00 – 18:00).

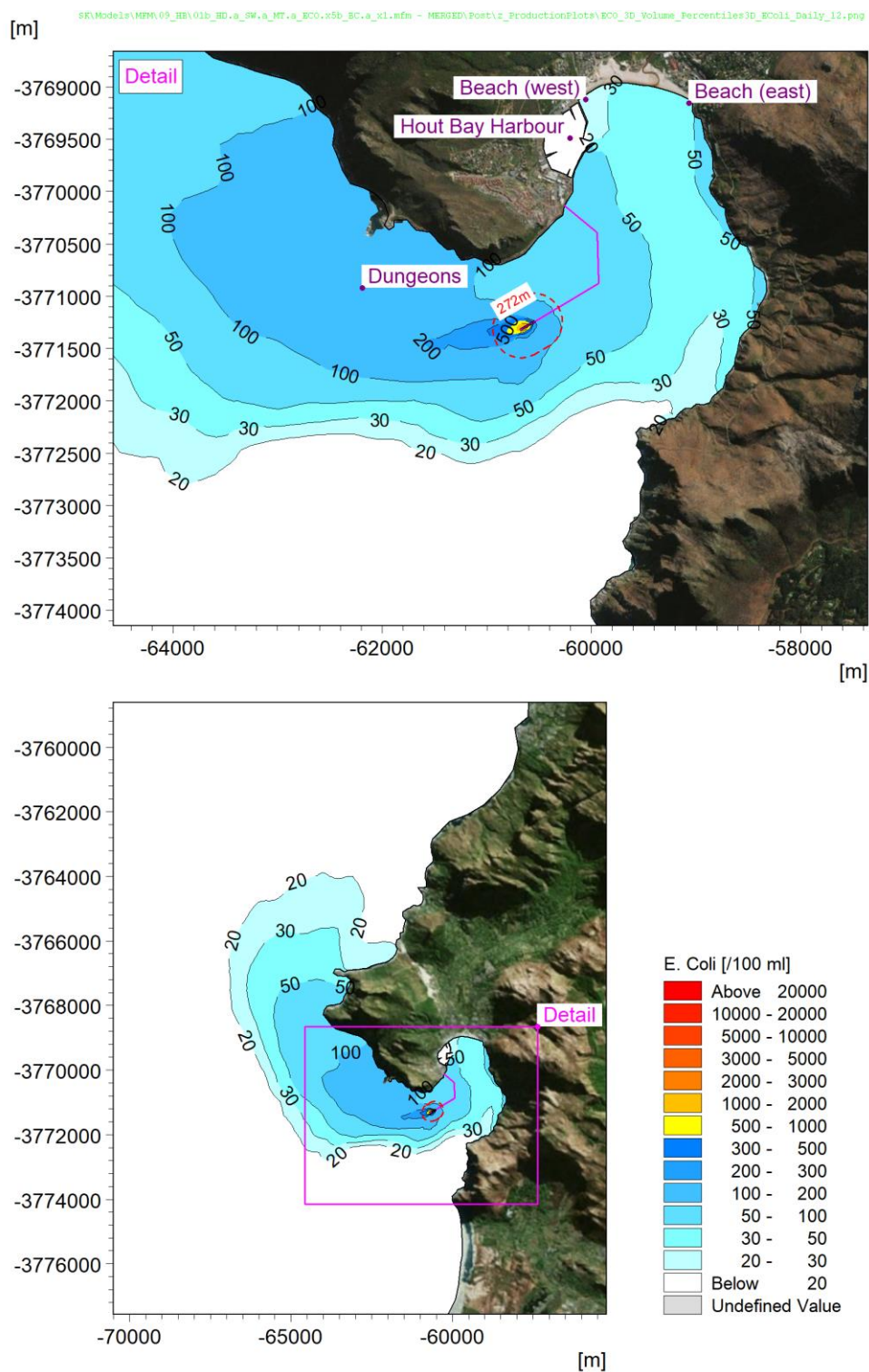


Figure 6-26: Summer/autumn: E.coli concentration at the surface, 90th percentile for daylight hours (07:00 – 18:00).

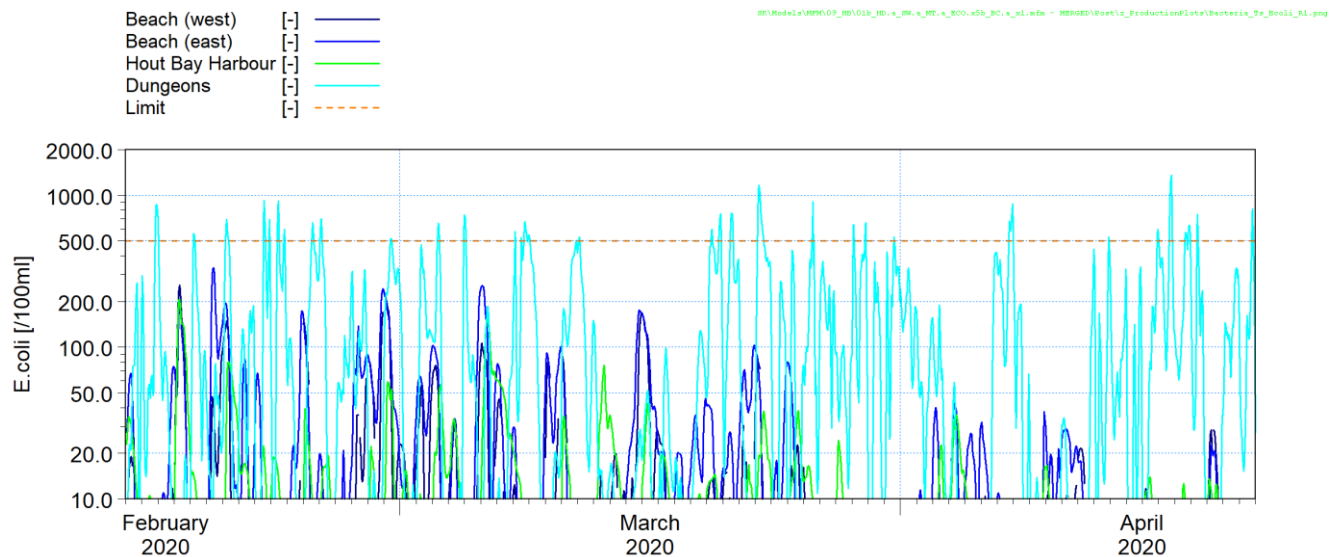


Figure 6-27: Summer/autumn: Time series of highest E.coli concentration at any depth at four key locations. The water quality guideline (500 CFU/100 ml 90th percentile in daylight) is also shown in orange.

A mixing zone distance of 1 700 m was required to meet the 90th percentile water quality guideline of 500 CFU/100 ml. The contour plots show that the 90th percentile E.coli concentrations were the highest at mid-depth and concentrations above the 500 CFU/100 ml guideline did not intersect with the shoreline. The E.coli concentrations at the Hout Bay beaches and harbour are higher than in winter/spring but do not exceed 500 CFU/100 ml. Although Dungeons was exposed to concentrations above 500 CFU/100 ml on many occasions, the duration of these events was just less than 10% of the daylight time and therefore met the water quality guidelines.

6.2.3.2 Enterococci

Figure 6-28, Figure 6-29 and Figure 6-30 present the 90th percentile enterococci concentrations at the seabed, mid-depth and surface. Concentrations greater than 185 CFU/100 ml are shown in orange as this is the guideline for enterococci as discussed in Section 3.4.2. Concentrations less than 185 CFU/100 ml are shown in shades of blue. Although these are less than the guideline, they provide information on the far-field behaviour of the plume. A time series of enterococci concentrations at four key locations is shown in Figure 6-31.

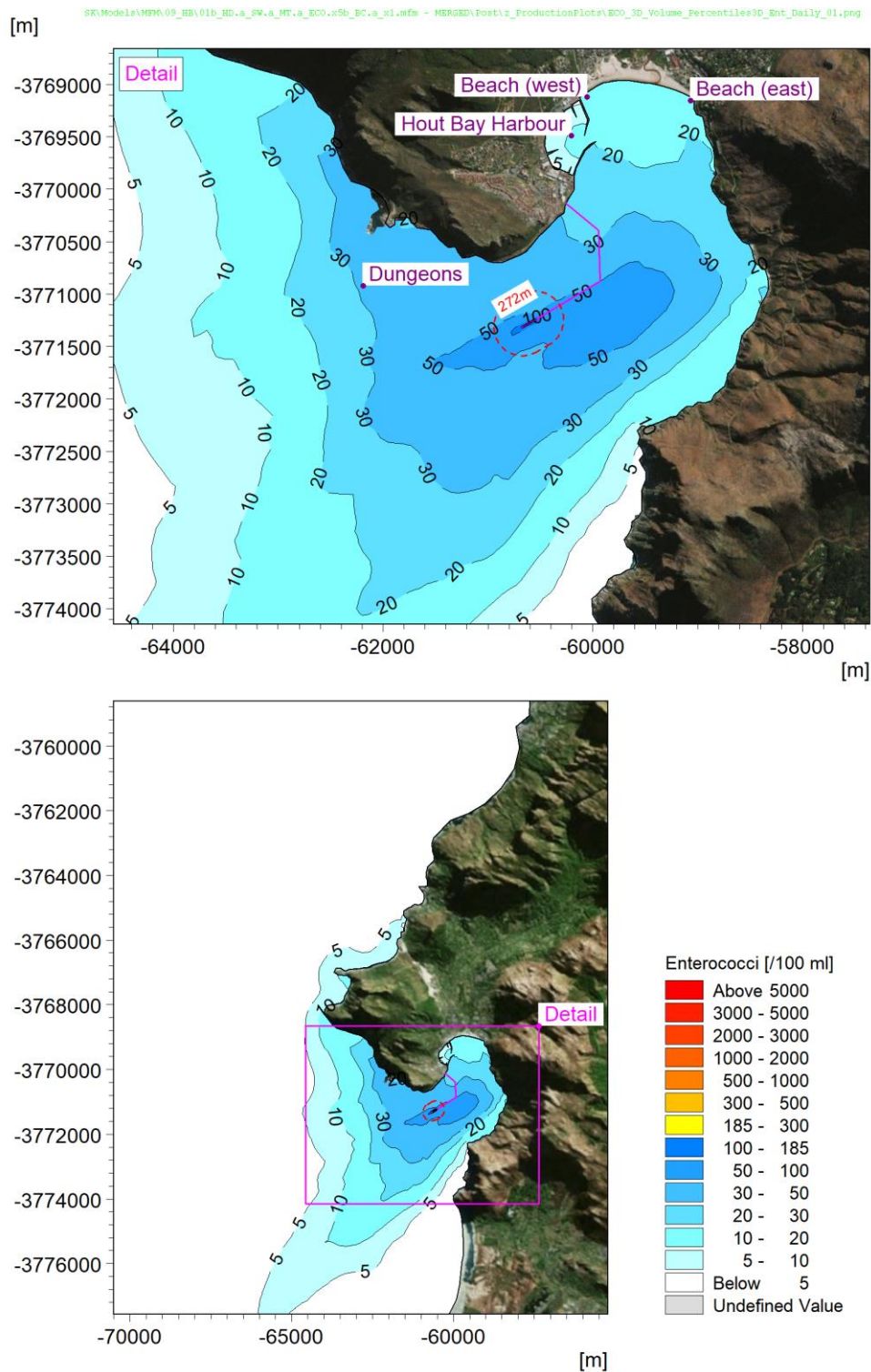


Figure 6-28: Summer/autumn: Enterococci concentration at the seabed, 90th percentile for daylight hours (07:00 – 18:00).

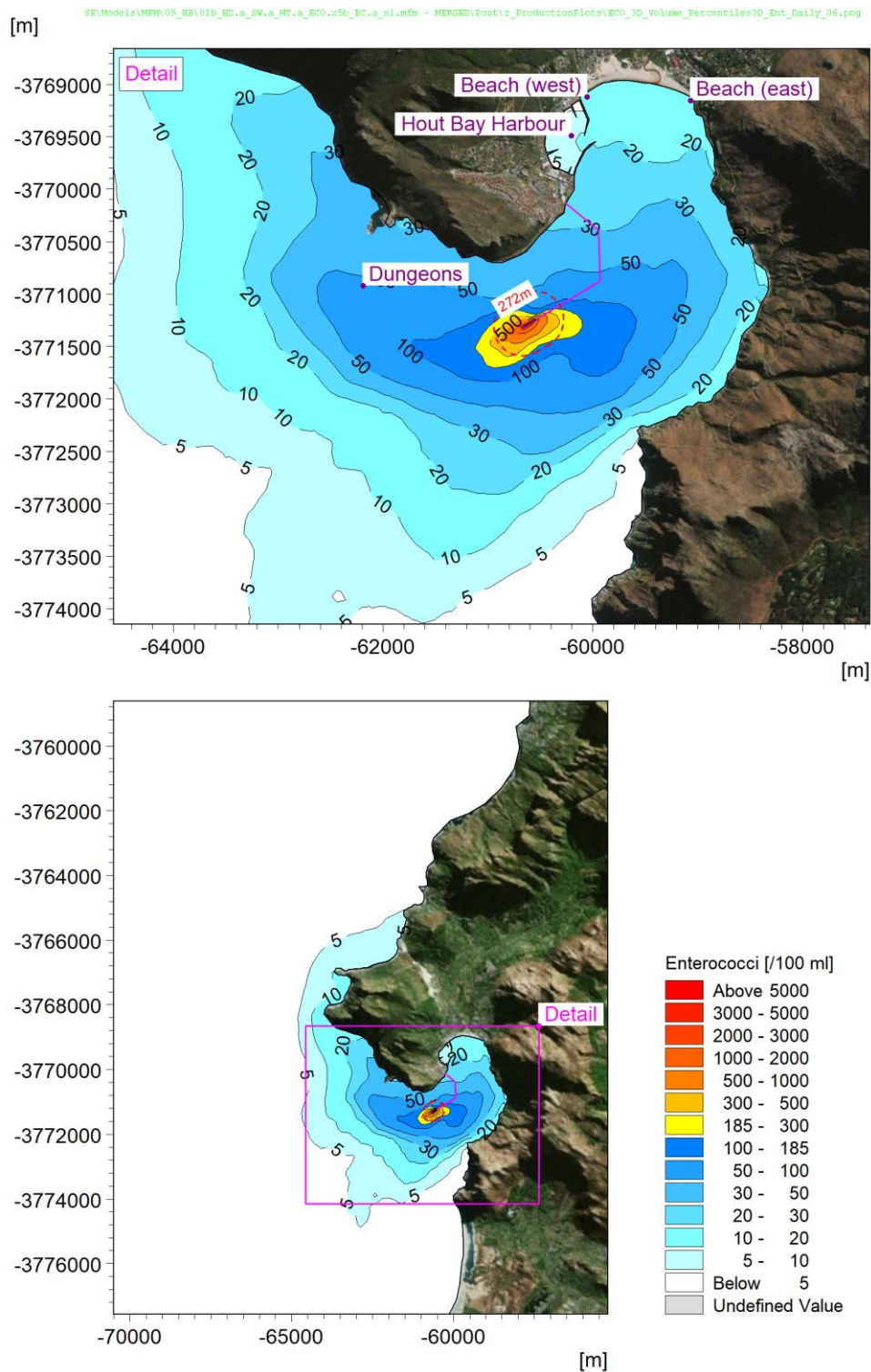


Figure 6-29: Summer/autumn: Enterococci concentration at mid-depth, 90th percentile for daylight hours (07:00 – 18:00).

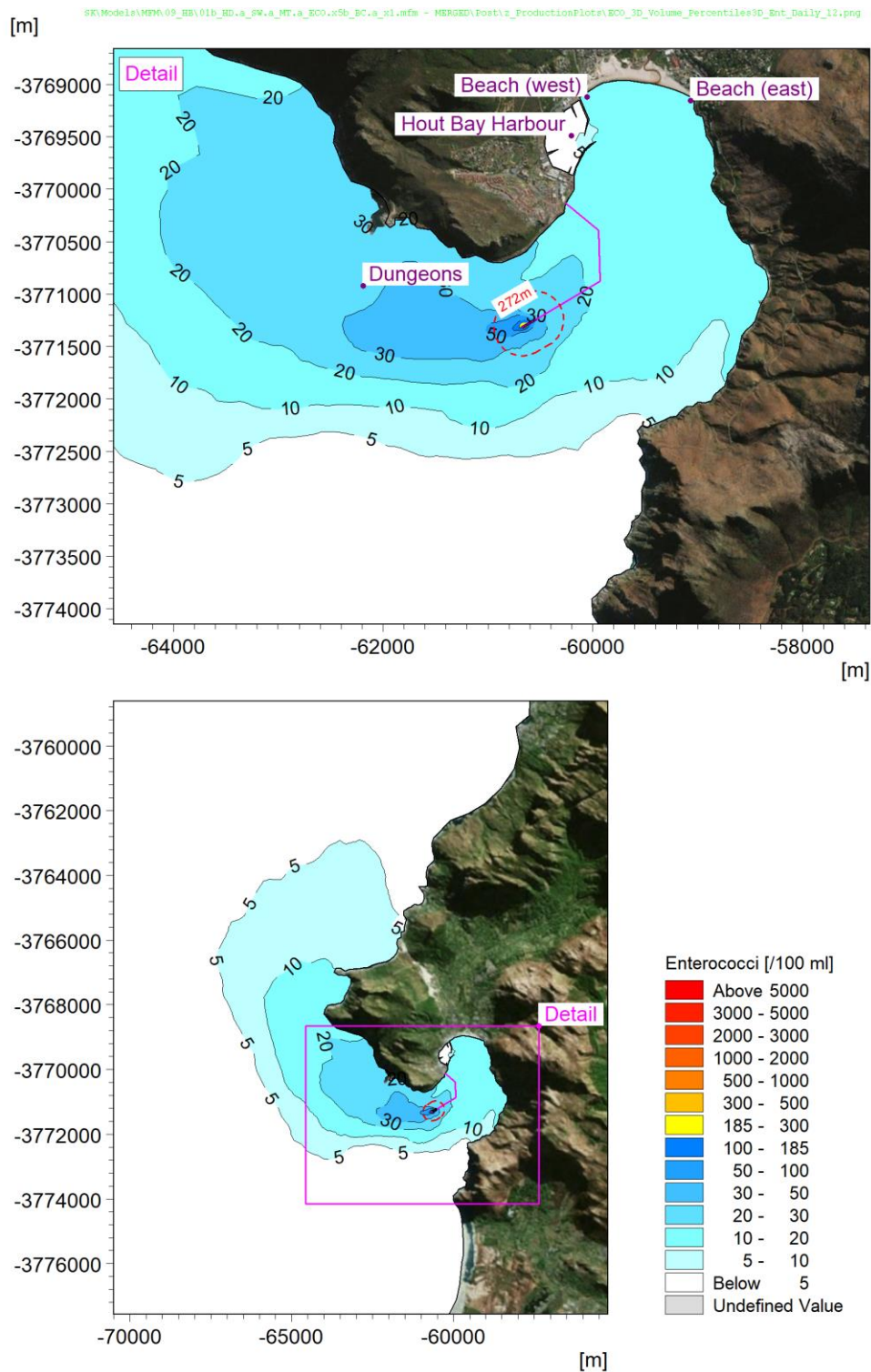


Figure 6-30: Summer/autumn: Enterococci concentration at the surface, 90th percentile for daylight hours (07:00 – 18:00).

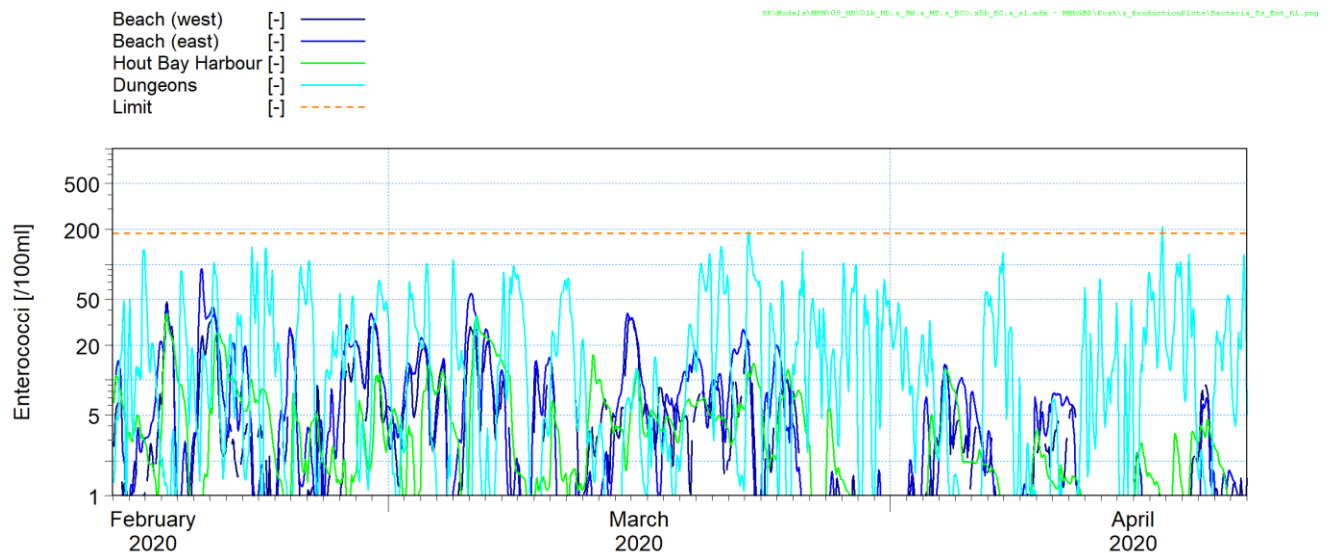


Figure 6-31: Summer/autumn: Time series of highest enterococci concentration at any depth at four key locations. The water quality guideline (185 CFU/100 ml 90th percentile in daylight) is also shown in orange.

A mixing zone distance of 600 m was required to meet the 90th percentile water quality guideline of 185 CFU/100 ml. The contour plots show that the 90th percentile enterococci concentrations were the highest at mid-depth and concentrations above the 185 CFU/100 ml guideline did not intersect with the shoreline. Although Dungeons was briefly exposed to concentrations above 185 CFU/100 ml, the duration of these events was less than 10% of the daylight time and therefore met the water quality guidelines.

6.2.3.3 Discussion

Based on the applicable water quality guidelines (discussed in Section 3.4.2), E.coli requires a greater mixing zone distance to meet the guidelines compared to enterococci.

The bacteria plumes have the highest concentrations at mid depth (the depth below the surface equal to 55% of the local water depth) where the plume usually becomes trapped. Solar radiation further reduces concentrations closer to the surface (illustrated in Figure 6-23).

The plume dynamics show similar trends as observed in the winter/spring period in Section 6.1.3.3: the plume is typically advected in a south-westerly or north-easterly direction by the currents and once outside the bay northward along the coastline by northward longshore currents or offshore by the less frequent south-westerly currents. Wave driven currents advect the plume into Hout Bay, but due to dispersion and decay the bacteria concentrations are significantly reduced by the time the plume reaches the beach or harbour. The Dungeons surf spot was however exposed to concentrations above 500 CFU/100 ml on many occasions.

6.2.4 Total suspended solids

The concentrations of TSS were modelled in the water column and specifically where these were deposited on the seabed. This is a proxy for the fate of pollutants that adsorb to solid particles, e.g. heavy metals.

Figure 6-32 presents the bed mass of TSS at the end of the 10-week simulation. The deposited mass in the main depo-centres (demarcated in red) are summarised in Table 6-6. The table also includes the total mass of TSS that were advected outside of the model domain through the boundaries and TSS in suspension at the end of the run.

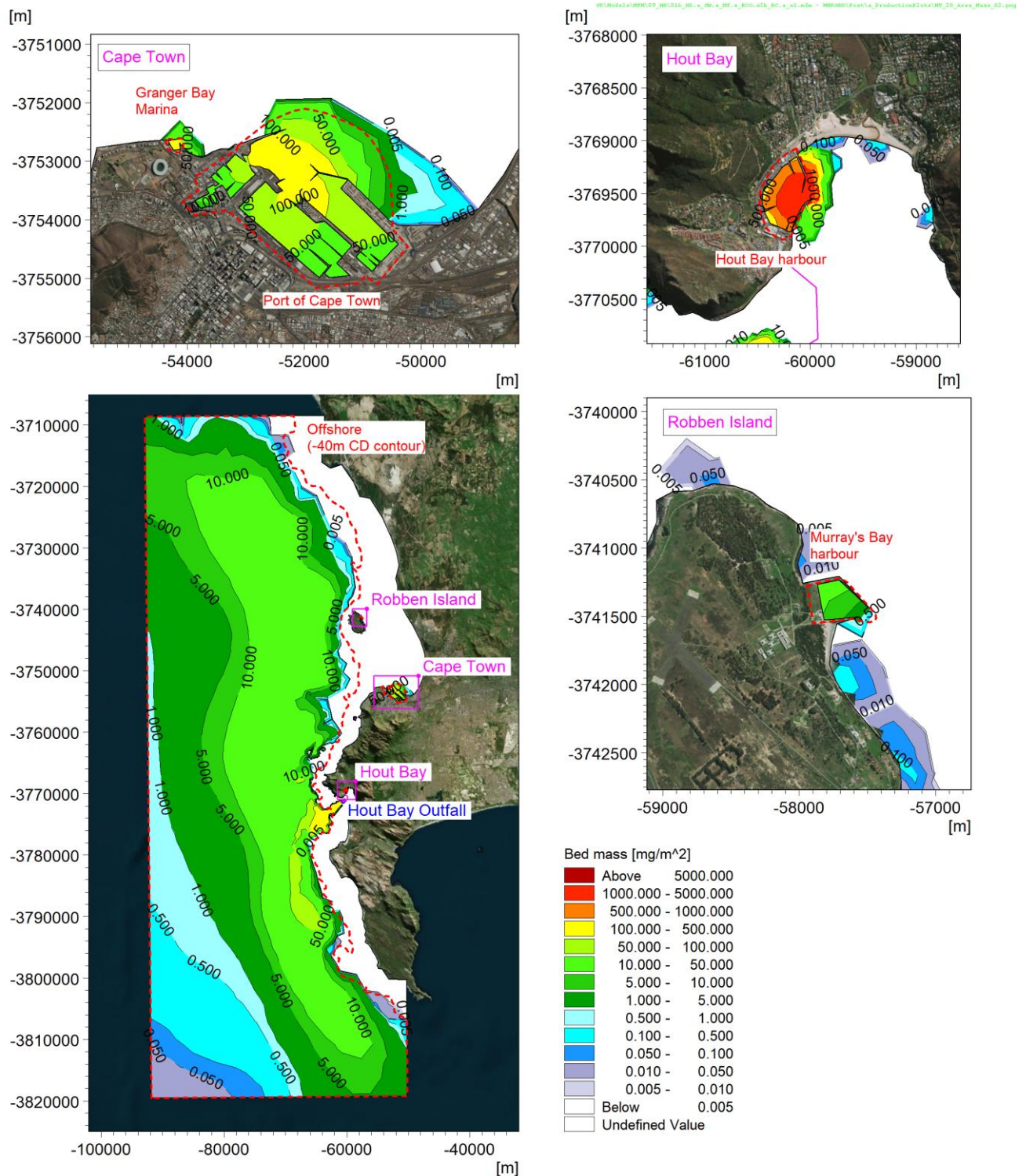


Figure 6-32: Summer/autumn: Bed mass of TSS distribution at the end of the 10-week period.



Table 6-6: Integrated mass at the end of the 10-week simulation period.

Area	Mass [kg]	% released
Port of Cape Town	325	0.2%
Murray's Bay Harbour	0.74	< 0.1%
Granger Bay	3.32	< 0.1%
Hout Bay	256	0.1%
Offshore (-40 m CD contour)	32 700	18.5%
Out of domain	109 000	61.4%
Suspended	35 100	19.8%
Total mass released	177 000	100%

The highest concentrations are observed in the sheltered depo-centres, i.e. the Port of Cape Town, Granger Bay marina, Murray's Bay harbour and Hout Bay harbour where the bed shear stress due to waves and currents are sufficiently low to allow deposition. Accumulation also occurs in exposed areas where the water depth is greater than approximately 40 m due to the wave orbital velocities not exerting sufficient stress on the seabed to resuspend the sediment particles.

The largest depo-centre is the Port of Cape Town with approximately 0.2% of the TSS released from the Hout Bay outfall accumulating in the port. These results can be used in the design and interpretation of sediment quality sampling studies.



7. CONCLUSIONS

A 3D coupled near- and far-field hydrodynamic, water quality, suspended sediment and wave model has been set up for the Hout Bay outfall.

The model has been calibrated against wave, water level, current and seawater temperature measurements for a 6-week winter/spring period and a 10-week summer/autumn period.

The plume dispersion was then simulated for a 10-week winter/spring period and a 10-week summer/autumn period. The model results show the following:

- The plume has the lowest dilutions and highest bacteria concentrations at mid depth (the depth below the surface equal to 55% of the local water depth) where the plume usually becomes trapped.
- During typical conditions the plume is advected in a south-westerly or north-easterly direction by the currents and once outside the bay northward along the coastline by the predominantly northward longshore current or offshore by the less frequent south-westerly current. Wave driven currents advect the plume into Hout Bay, but due to dispersion and decay the bacteria concentrations are significantly reduced by the time the plume reaches the beach or harbour.
- The minimum number of dilutions achieved at the edge of the 272 m radius mixing zone is 1 500 in winter/spring and 1 950 in summer/autumn (5th percentile dilution).
- The required dilution of 2 587 for TSS is met at distance of 450 m from the diffuser in winter/spring and 360 m in summer/autumn (5th percentile dilution).
- E.coli requires a distance 1 620 m to meet the applied guidelines in winter/spring and 1 700 m in summer/autumn (500 CFU/100 ml for the 90th percentile concentration during daylight hours).
- E.coli concentrations at the Hout Bay beaches and harbour do not exceed 500 CFU/100 ml.
- The Dungeons surf spot is exposed to E.coli concentrations above 500 CFU/100 ml on many occasions in both winter/spring and summer/autumn, indicating that there is a risk to surfers at this spot. However, the cumulative duration of these events is slightly less than 10% of the daylight time and the applied water quality guidelines are thus met here and at all locations along the shoreline (500 CFU/100 ml for the 90th percentile concentration during daylight hours).
- The applied guidelines for enterococci result in a smaller zone of impact compared to E.Coli.
- The largest depo-centre is the Port of Cape Town with approximately 1.4% of the Total Suspended Solids released from the Hout Bay outfall accumulating in the port in winter/spring and 0.2% in summer/autumn.



8. RECOMMENDATIONS

Based on the model results the following recommendations are made:

- Modifications to the diffuser should be considered to improve the far-field dispersion of bacteria, e.g. opening the five inshore ports. The effectiveness of these modifications should be tested in the model.
- These results assume that the pipeline and diffusers are operating as designed and that there are no breakages, leaks or blockages. Regular underwater surveys are recommended to ensure that this is the case.
- Consideration should be given to operationalising the model to provide forecasts of bathing water quality, as is done in other countries including Denmark, Sweden and New Zealand, e.g. <http://newkbh.badevand.dk>. The forecast would identify one or two days in advance the occasions when the effluent plume is likely to reach specific bathing beaches or surf spots, which would facilitate mitigation of the associated risks to the public.



9. REFERENCES

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10 APPENDIX F: FINAL HYDRODYNAMIC MODELLING REPORT FOR CAMPS BAY

SAMPLING AND ANALYSIS OF THE CITY OF CAPE TOWN'S MARINE OUTFALLS AT GREEN POINT, CAMPS BAY AND HOUT BAY

Final Report on Dispersion Model Calibration and Results for Camps Bay

REV.00

01 October 2020



Lwandle Technologies (Pty) Ltd / City of
Cape Town
Cape Town, South Africa



**CITY OF CAPE TOWN
ISIXEKO SASEKAPA
STAD KAAPSTAD**

SAMPLING AND ANALYSIS OF THE CITY OF CAPE TOWN'S MARINE OUTFALLS AT GREEN POINT, CAMPS BAY AND HOUT BAY

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1. INTRODUCTION

1.1 Background

The City of Cape Town (CoCT) has appointed Lwandle Technologies (Pty) Ltd (Lwandle) to perform sampling and analysis of the CoCT's marine outfalls at Green Point, Camps Bay and Hout Bay for a period of three years (Tender 124s/2018/19). Lwandle has sub-contracted PRDW South Africa (Pty) Ltd (PRDW) to undertake dispersion modelling for the three outfalls.

1.2 Scope and objectives

The scope of the study is to perform three-dimensional (3D) hydrodynamic and dispersion modelling for the Green Point, Camps Bay and Hout Bay marine outfalls operated by the CoCT. The objectives of the study are as follows:

- Provide imagery and animations of the effluent plume suitable for overlaying the sampling and monitoring data.
- Determine the dilutions achieved in the near- and far-field for a conservative tracer representing dissolved constituents in the effluent such as nutrients, etc. This includes a probabilistic description of the Zone of Initial Dilution (ZID) taking into account variations in metocean conditions and variations in effluent flows and/or concentrations.
- Determine the probability of the plume reaching the shoreline and the concentrations of faecal indicator bacteria (enterococci and E.coli) during these events.
- Determine the concentrations of discharged Total Suspended Solids (TSS) in the water column and where these are deposited on the seabed. This is a proxy for the fate of pollutants that adsorb to solid particles, e.g. heavy metals.

The model results can be used by Lwandle and the CoCT for the following:

- To refine the location of sampling stations (for the second year of sampling).
- To assist interpretation of sampling results, e.g. are observed concentrations likely to have had an outfall as a source or rather stormwater or other sources.
- To predict the metocean conditions when plume may impact bathers.
- To define the size of the ZID and the spatial extent of particulate deposition zones for the Coastal Waters Discharge Permit application.
- To determine how many dilutions are achieved by the time that the plume reaches desalination plant intakes.



Future applications of the models (outside the scope of this study) could include:

- Testing the impacts of changes in flow rates, effluent density (e.g. due to the addition of desalination brine) and effluent concentrations on the dispersion.
- Test options to improve the dispersion, e.g. modifications to the diffuser, lengthening of the pipeline, etc.
- The models could also be operationalised to provide forecasts of bathing water quality as is done in Denmark, Sweden and New Zealand, e.g. <http://newkbh.badevand.dk>. The concept is that if the effluent from the outfalls is impacting bathing beaches a limited number of times per year, then a forecast may be the best short- to medium-term approach to mitigate the associated risk.

1.3 Deliverables

PRDW's deliverables comprise the following:

- Deliverable 1: Progress report on model setup (one report for each outfall).
- Deliverable 2: Progress report on model calibration for winter/spring (August – September 2019) and preliminary results (one report for each outfall).
- Deliverable 3: Final report including model calibration for summer/autumn (February – April 2020) and final results (one report for each outfall).

This report is Deliverable 3 for Camps Bay. This report supersedes the Deliverable 1 and Deliverable 2 reports as all the information contained in the previous reports is included and updated here. Similar reports are provided for Green Point and Hout Bay.

1.4 Report structure

Section 2 presents a description of the models, which include a hydrodynamic, water quality, suspended sediment and wave model. Section 3 presents the discharge characterisation which describes the diffuser, effluent and water quality guidelines. Section 4 describes the model setup which includes the mesh, bathymetry, wind, boundary conditions and model settings. The model calibration is presented in Section 5 followed by the model results in Section 6. Conclusions and recommendations are provided in Section 7 and Section 8.



2. DESCRIPTION OF THE MODELS

2.1 Overview

The modelling was undertaken using the MIKE modelling system developed by DHI in Denmark. PRDW has 15 years of experience in applying these models. The MIKE system is widely used by international engineering consultancies and includes a number of features that makes it an appropriate model for this application, including:

- A dynamic coupling of a near-field jet model within the 3D far-field hydrodynamic model;
- the ability to dynamically couple different sub-models to include all the relevant physical and biogeochemical processes; and
- the use of a flexible mesh which allows refinement around the outfalls.

The following four sub-models were used:

- Hydrodynamic model: 3D hydrodynamics including tides, wind, waves, temperature and salinity. Includes an integral jet model for each port with dynamic two-way coupling of near- and far-field dispersion.
- Water quality model: 3D water quality model for modelling the far-field advection-dispersion of:
 - a conservative tracer representing dissolved constituents in the effluent such as nutrients, etc
 - Faecal indicator bacteria (E.coli and enterococci) including die-off.
- Suspended sediment model: 3D model for modelling Total Suspended Solids (TSS) - advection-dispersion-settling-deposition-resuspension based on combined current-wave bed stresses.
- Spectral wave model: wave refraction and breaking to generate wave-driven currents and wave bed stresses.

2.2 Hydrodynamic model

2.2.1 General description

The three-dimensional MIKE 3 Flow Flexible Mesh Model was used for the hydrodynamic modelling. The application of the model is described in the User Manual (DHI, 2020a), while full details of the physical processes being simulated and the numerical solution techniques are described in the Scientific Documentation (DHI, 2020b).

The model is based on the numerical solution of the three-dimensional incompressible Reynolds averaged Navier-Stokes equations invoking the assumptions of Boussinesq and of hydrostatic pressure. The model consists of the continuity, momentum, temperature, salinity and density equations and is closed by a $k-\epsilon$ vertical turbulence closure scheme. Horizontal eddy viscosity is modelled with the Smagorinsky formulation.

The time integration of the shallow water equations and the transport equations is performed using a semi-implicit scheme, where the horizontal terms are treated explicitly and the vertical terms are treated implicitly. In the vertical direction a structured mesh, based on a sigma-coordinate transformation is used, while the geometrical flexibility of the unstructured flexible mesh comprising triangles or quadrangles is utilised in the horizontal plane.



The model includes the following physical phenomena:

- Currents due to tides;
- Currents due to wind stress on the water surface;
- Currents due to density gradients;
- Currents due to waves; the second order stresses due to breaking of short period waves are included using the radiation stresses computed in the Spectral Wave model;
- Coriolis forcing;
- Bottom friction;
- Flooding and drying;
- Sources and sinks including dynamic near and far-field coupling; and
- Heat exchange.

2.2.2 Near and far-field coupling

An important feature of the model is a dynamic coupling of a near-field jet model and the 3D far-field hydrodynamic model. The near-field solution based on the integral jet model equations by Jirka (2004). Entrainment into the jet is using Distributed Entrainment Sink Approach by Choi and Lee (2007). At the end of the near-field the diluted discharge is released into far-field model as a source, as shown in Figure 2-1.

In order to determine, when the jet/plume becomes passive and thus a part of the ambient flow, a number of stop criteria are invoked:

1. If the jet reaches the water surface.
2. If the jet reaches the bottom.
3. If the jet momentum is smaller than or close to the ambient flow induced momentum.
4. If the jet dies out in the stagnant conditions.
5. If the jet experiences buoyancy reversal twice.
6. If the trajectory of the jet exceeds a maximum travel distance as specified by the user.
7. If the jet exhibits strong curvature, such as going into strong opposing ambient flow.
8. If the jet reaches a domain boundary (open or close).
9. If the jet reaches dried cells.

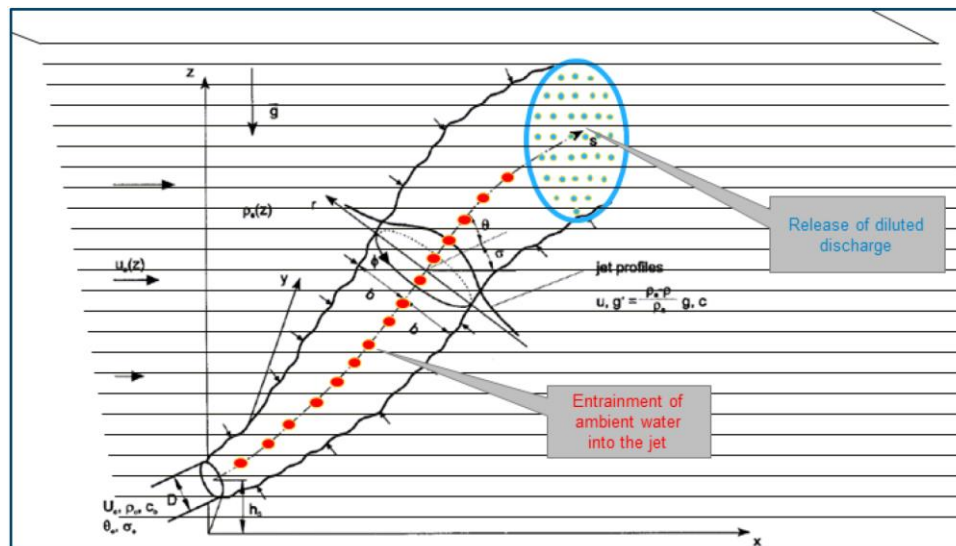


Figure 2-1: Dynamic coupling of near-field and far-field models: entrainment sinks along the plume trajectory and distributed sources at the release location.

2.3 Water quality model

2.3.1 General description

The MIKE 3 ECO Lab Model was used to simulate the far-field dispersion of a conservative tracer and faecal indicator bacteria (E.coli and enterococci). The application of the model is described in the User Manual (DHI, 2020c) while full details of the physical processes being simulated and the numerical solution techniques are described in the Scientific Documentation (DHI, 2020d).

The model simulates the transport and fate of constituents in three dimensions based on advection-dispersion and non-conservative processes. The model can be used to describe chemical, biological, ecological processes and interactions between state variables and also the physical process of sedimentation of components can be described. The hydrodynamics (water levels, currents, temperature, salinity, vertical, dispersion, horizontal dispersion and release location at the end of the near-field) are obtained via an online coupling to the MIKE 3 Flow Flexible Mesh Model and the same three-dimensional grid is used.

An ECO Lab template is used to describe the non-conservative processes relevant for each specific constituent. Since the conservative tracer undergoes advection and dispersion only without any non-conservative processes, no template is required for the conservative tracer. Faecal indicator bacteria (E.coli and enterococci) require an ECO Lab template to simulate die-off, as described below.

2.3.2 Bacteria die-off

In addition to physical dilution, the concentration of faecal indicator bacteria (E.coli and enterococci) reduces due to die-off. The die-off was implemented in the ECO Lab model as described below.

2.3.2.1 ECO Lab model equations

First order decay:

Bacterial decay can be described by the first order decay function for a duration t :

$$C(t) = C_0 e^{-k \cdot t} \quad (1)$$

where

- C = bacteria concentration [CFU.100ml⁻¹]
- C_0 = initial bacteria concentration ($t = 0$) [CFU.100ml⁻¹]
- t = time [hours]
- k = linear decay rate [hours⁻¹]

The decay rate is often expressed as T_{90} : the time needed for the 90% of the bacterial concentration to decay.

Therefore, if $t = T_{90}$, $\frac{C}{C_0} = 0.1$:

$$T_{90} = \frac{\ln(0.1)}{k} \quad (2)$$

where

- T_{90} = time needed for the 90% of the bacterial concentration to decay [hours]

E.coli decay model:

Erichsen, et al. (2006) adopted an E.coli decay model from Jensen (1990). The model describes the decay contributions from dark and light conditions:

$$k_{coli} = k_m + K_l \cdot I_l \quad (3)$$

where

- k_{coli} = E.coli decay rate [days⁻¹]
- k_m = decay coefficient for dark conditions [days⁻¹], see equation 4
- K_l = decay coefficient for light conditions [m².W⁻¹.days⁻¹], see equation 5
- I_l = Solar irradiance [W.m⁻²], see equation 6

The dark decay term is expressed as a function of water temperature:

$$k_m = a_T \cdot T - k_{m0} \quad (4)$$

where

- T = water temperature [°C]
- a_T = temperature dependency constant for dark reaction [h⁻¹.°C⁻¹]
- k_{m0} = initial coliform decay rate for dark reaction [h⁻¹]



The light decay coefficient is expressed as a function of water temperature, and salinity:

$$K_l = S_m \cdot \frac{b_T \cdot T + K_{l0}}{a \cdot S_m - (a-1) \cdot S} \quad (5)$$

where

- S = water salinity [PSU]
- S_m = reference salinity [PSU]
- a = correction for salinity [-]
- b_T = temperature dependency constant for light reaction [$\text{m}^2 \cdot \text{W}^{-1} \cdot \text{h}^{-1} \cdot ^\circ\text{C}^{-1}$]
- K_{l0} = initial coliform decay rate for light reaction [$\text{m}^2 \cdot \text{W}^{-1} \cdot \text{h}^{-1}$]

In a water body, light attenuation can be described as a function of depth using the Lambert-Beer law:

$$I_l = I_0 \cdot e^{-E_{ta} \cdot z} \quad (6)$$

where

- I_l = solar irradiance at depth z below surface [$\text{W} \cdot \text{m}^{-2}$]
- I_0 = surface solar irradiance [$\text{W} \cdot \text{m}^{-2}$]
- z = depth below surface [m]
- E_{ta} = light attenuation coefficient [m^{-1}]

Enterococci decay model:

The enterococci decay rate is expressed relative to the E.coli decay rate:

$$k_{ent} = k_{coli} \cdot r \quad (7)$$

where

- r = decay rate ratio of E.coli to enterococci [-]
- k_{ent} = enterococci decay rate [days^{-1}]

Literature indicates that enterococci decay slower than E.coli: based on 16 samples from 6 studies – e.g. Sinton, et al. (1994) – the median value for r was 0.42 (T_{90} equivalent ratio of 2.39), which has been adopted for this study. It is noted that r ranged from 0.21 to 2.5, indicating the uncertainty level for this value.

2.3.2.2 Validation of die-off model

The ECO Lab model described above was calibrated against measurements to confirm the required constants for this study. The constants are:

- $S_m = 34.5$ PSU
- $a = 1.54$
- $a_T = 2.425 \times 10^{-3} \text{ h}^{-1} \cdot ^\circ\text{C}^{-1}$
- $k_{m0} = 4.167 \times 10^{-3} \text{ h}^{-1}$
- $b_T = 6.25 \times 10^{-5} \text{ m}^2 \cdot \text{W}^{-1} \cdot \text{h}^{-1} \cdot ^\circ\text{C}^{-1}$
- $K_{l0} = 3.13 \times 10^{-4} \text{ m}^2 \cdot \text{W}^{-1} \cdot \text{h}^{-1}$

The measurements were obtained from Bellair, et al. (1977) and included 162 measurement samples of hourly decay rates (T_{90}) of E.coli on the seawater surface at Balmoral Bay near Sydney, Australia. The ECO Lab model assumed a constant water temperature and salinity representative of the measured conditions. Time-

varying solar radiation was obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 global atmospheric model (ECMWF, 2020). Figure 2-2 presents the a comparison of modelled and measured E.coli decay at Balmoral Bay. Also shown are measurements of T_{90} in sewage at Durban from Livingstone et al. (1990).

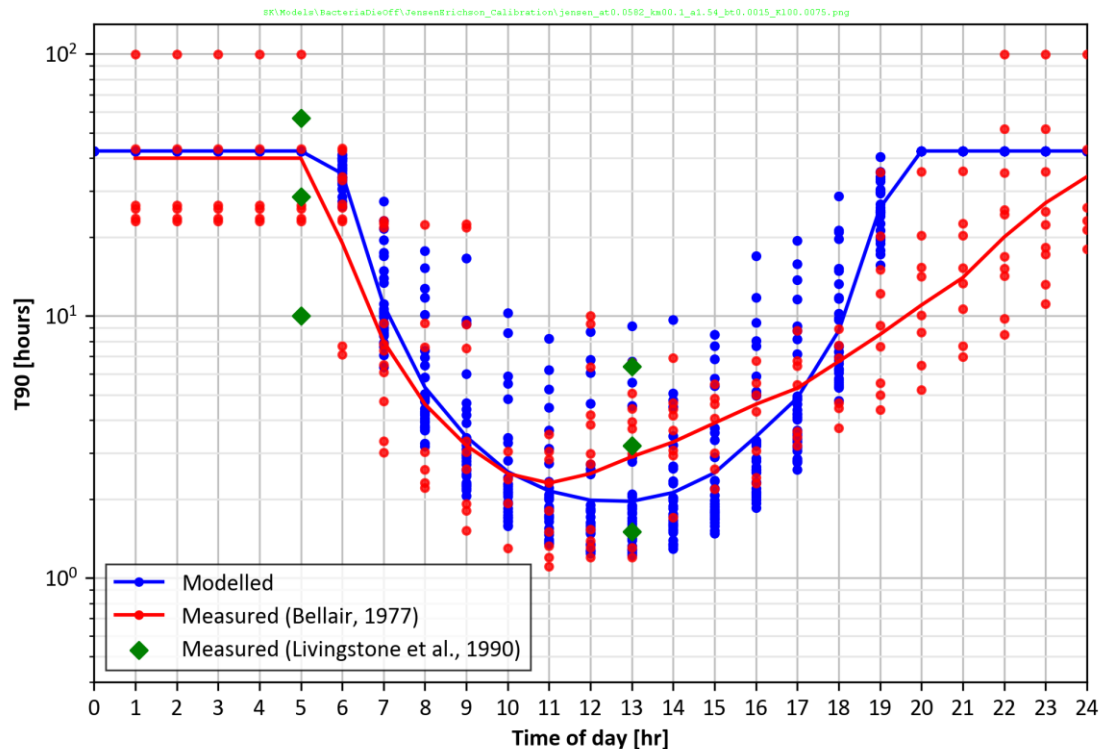


Figure 2-2: Measured and ECO Lab model comparison of E.coli decay at Balmoral Bay. The geometric mean is shown with a solid line. Also shown are measurements at Durban from Livingstone et al. (1990).

The comparison shows that the model is able to reproduce the measurements with satisfactory accuracy. Note the scatter from the model is directly proportional to the solar radiation intensity, whereas the measurements in addition include some variability in the seawater temperature, salinity and statistical randomness.

2.3.3 Model inputs

For the present Cape Town outfall study, a time and space varying surface solar irradiance I_0 was obtained from ECMWF. A constant light attenuation coefficient $E_{ta} = 0.6$ was applied, based on the annual average of Secchi disk measurements in Table Bay provided by Lwandle. Time and space-varying seawater temperature and salinity were obtained from the coupled hydrodynamic model.

2.4 Suspended sediment model

2.4.1 General description

The MIKE 3 Mud Transport Flexible Mesh Model was used to model the concentrations of discharged Total Suspended Solids (TSS) in the water column and where these are deposited on the seabed. This is a proxy for the fate of pollutants that adsorb to solid particles less than $63 \mu\text{m}$, e.g. heavy metals.



The application of the model is described in the User Manual (DHI, 2020e) while full details of the physical processes being simulated and the numerical solution techniques are described in the Scientific Documentation (DHI, 2020f). The hydrodynamics (water levels, currents, temperature, salinity, vertical, dispersion, horizontal dispersion and release location at the end of the near-field) are obtained via an online coupling to the MIKE 3 Flow Flexible Mesh Model and the same three-dimensional grid is used.

The following processes are included in the simulations:

- 3D advection-dispersion of suspended sediment by currents;
- Settling of sediment through water column and deposition onto the seabed, dependent on the critical shear stress for deposition;
- Resuspension of sediment from the seabed, dependent on the critical shear stress for resuspension and the erosion coefficient;
- Bed shear stress due to combined currents and wave orbital velocities, as obtained through direct coupling with the hydrodynamic and spectral wave models.

2.4.2 Model settings

The input parameters used to model the TSS has been obtained from a previous study in Table Bay by PRDW (2017). The study calibrated a suspended sediment model to measured TSS concentrations in the water column and locations of fine sediment depo-centres. The modelled sediment comprises fine cohesive organic and inorganic particles with diameters less than 63 μm . The input parameters are listed in Table 2-1

Table 2-1: Input parameters used in the modelling of TSS.

Parameter	Unit	Value
Settling velocity of suspended sediment	m/s	5×10^{-5}
Critical shear stress for resuspension	N/m ²	0.2
Critical shear stress for deposition	N/m ²	0.1
Resuspension rate	kgDW/m ² /s	1×10^{-4}
Bulk density of dry sediment	kg/m ³ bulk	400

2.5 Wave model

2.5.1 General description

The MIKE 21 Spectral Waves (SW) Flexible Mesh model was used for simulating wave transformation to the nearshore. The application of the model is described in the User Manual (DHI, 2020g), while full details of the physical processes being simulated and the numerical solution techniques are described in the Scientific Documentation (DHI, 2020h). The model simulates the growth, decay and transformation of wind-generated waves and swells in offshore and coastal areas using unstructured meshes. The model used the same mesh as the hydrodynamic model. The model is fully spectral and can be run in either quasi-stationary or instationary mode, depending on the size of the model domain.



The model included the following physical phenomena:

- Dissipation due to bottom friction;
- Dissipation due to depth-induced wave breaking;
- Nonlinear energy transfer amongst the different wave components (quadruplet-wave interactions);
- Refraction and shoaling due to depth variations; and
- Generation of local wind-waves; and
- The effect of time-varying water depth due to the tide - the water depth at each time-step is computed in the hydrodynamic model including tidal and wave-setup.

2.5.2 Model settings

Bottom friction was modelled using a constant Nikuradse roughness of $k_N = 0.5$ m. The modelled water level from the hydrodynamic model was coupled to the wave model. The model was run in the fully spectral, quasi stationary formulation excluding the effect of additional wave generation within the model due to wind.



3. DISCHARGE CHARACTERISATION

3.1 Diffuser configuration

The Camps Bay diffuser is located in a depth of -22.1 m CD as shown in Figure 4-4. Table 3-1 presents the diffuser geometry and individual port configuration. The model assumes that the pipeline and diffusers are operating as described below and that there are no breakages, leaks or blockages.

Table 3-1: Diffuser geometry and flow distribution for Camps Bay.

Diffuser		Ports							
Section no.	Inside diameter [mm] ⁽¹⁾	Port no. ⁽²⁾	Port diameter [mm] ⁽¹⁾	Flow distribution [%] ⁽³⁾	Discharge per port [l/s] ⁽⁵⁾	Port velocity [m/s] ⁽⁵⁾	Spacing [m] ⁽¹⁾	Level above seabed [mm]	Port configuration ⁽¹⁾
1	142	1	115	10.5%	1.84	0.177	12	500	Effluent is discharged horizontally through an elbow bend (illustrated below) with alternating discharge directions
2	222	2	115	13.6%	2.40	0.231		400	
3	295	3	115	14.9%	2.63	0.253		300	
		4	102	12.3%	2.16	0.265			
4	354	5	102	13.3%	2.33	0.285		200	 (4)
		6	92	11.2%	1.98	0.297			
		7	92	11.8%	2.07	0.312			
		8	92	12.5%	2.20	0.330			

Notes:

- (1) Source: CSIR (1992).
- (2) The ports are arranged from offshore (port no. 1) to inshore (port no. 8).
- (3) Based on diffuser hydraulics modelling undertaken by the CoCT
- (4) Schematic representation of port configuration
- (5) Calculated using the 50th percentile discharge rates in Table 3-2.

3.2 Discharge rates

Measured flow rates were provided by the CoCT for input to the dispersion model. The measurements comprise average flow rates at 30-minute intervals and cover the winter/spring and summer/autumn model simulation periods. This will ensure that the model results account for diurnal variations in flows and also the high flows from the episodic discharge of the sewage storage tank at Camps Bay.

Figure 3-1 and Figure 3-2 present time series plots of the Camps Bay effluent discharge rate for the winter/spring and summer/autumn periods respectively. A statistical summary is provided in Table 3-2.

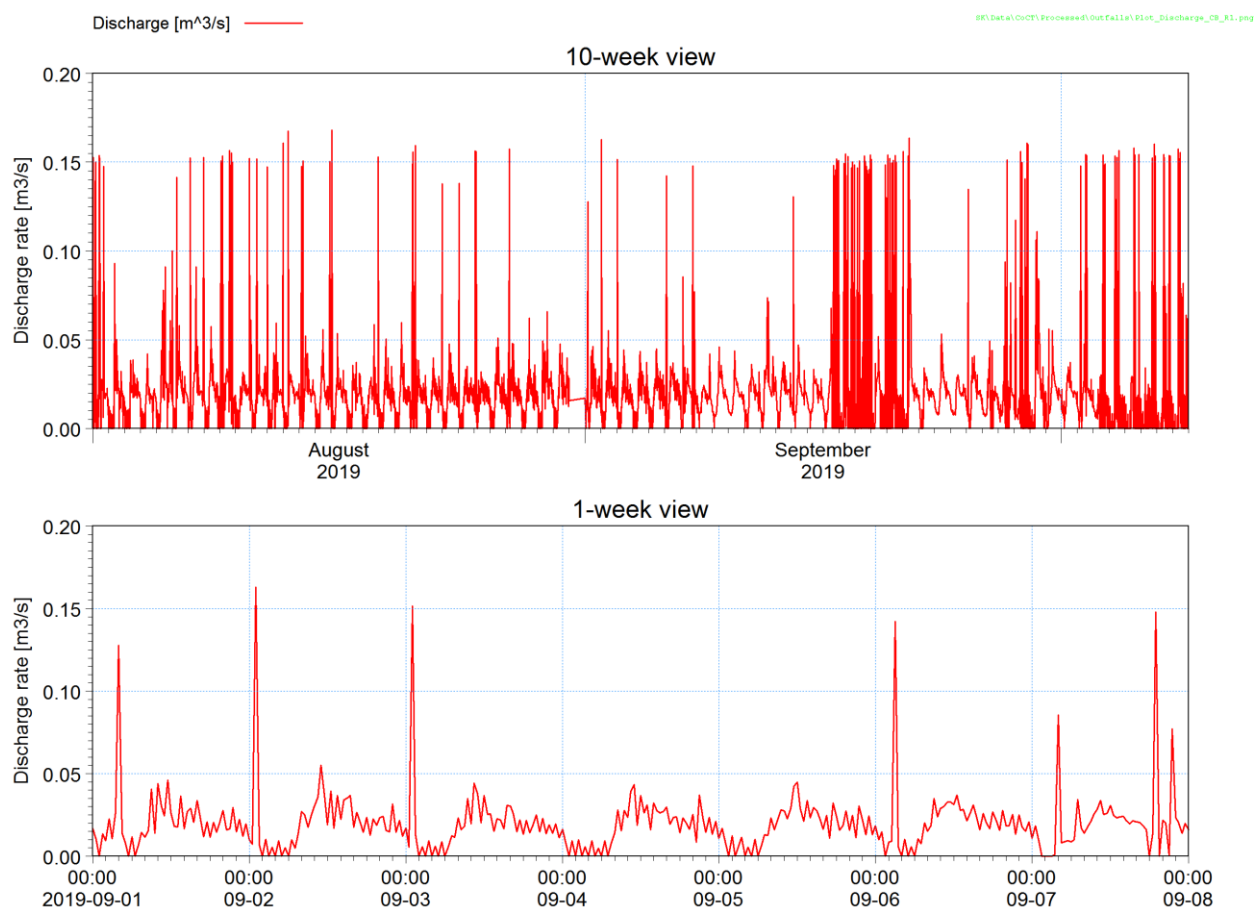


Figure 3-1: Time series of Camps Bay effluent discharge rate for the winter/spring period.

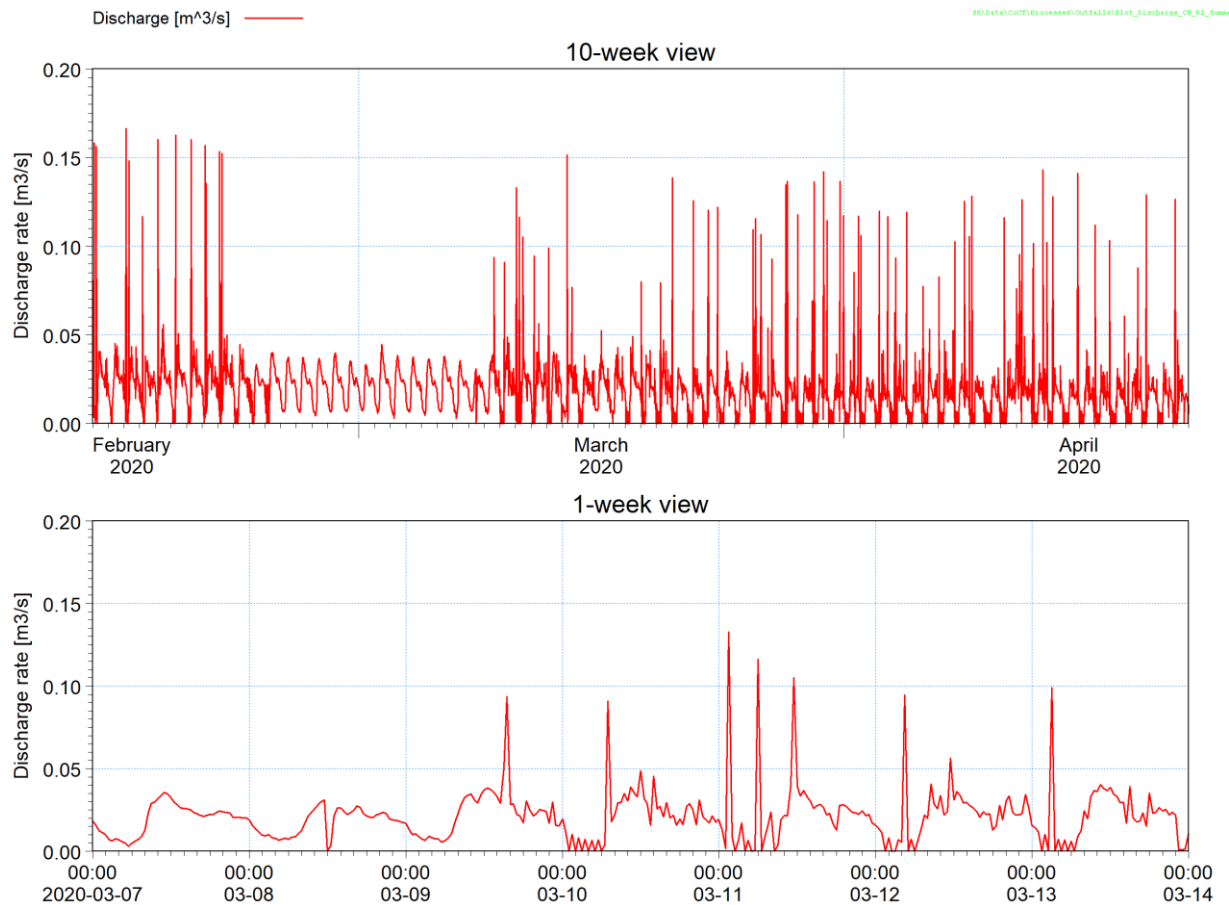


Figure 3-2: Time series of Camps Bay effluent discharge rate for the summer/autumn period.

Table 3-2: Camps Bay effluent discharge rate statistics.

Parameter	Discharge rate	
	Winter/spring	Summer/autumn
Average	1 960 m³/d	1 680 m³/d
5 th percentile	0 m³/s	0 m³/s
50 th percentile	0.018 m³/s	0.018 m³/s
95 th percentile	0.090 m³/s	0.038 m³/s

A slight reduction in effluent discharge rates could be observed from 23 March 2020 due to a national lockdown enforced in response to the COVID-19 pandemic.



3.3 Effluent concentrations

The effluent concentrations applied in the model are shown in Table 3-1

Table 3-3: Modelled effluent concentrations.

Constituent	Concentration	Comments
E.coli	1 x10 ⁷ CFU/100 ml	Kay et al. (2008), CSIR (2017).
Enterococci	1.3 x10 ⁶ CFU/100 ml	Kay et al. (2008)
TSS	314 mg/l	Provided by CoCT based on the average measured value in the Camps Bay effluent (1 August 2014 – 31 October 2019)
Tracer	100 units	All other constituents will be modelled as a conservative tracer which will have a nominal concentration of 100 units and will be used to model the achieved dilutions.

The effluent temperature was set equal to the seawater temperature at the diffuser and the effluent salinity was set to 0 psu.

3.4 Water quality guidelines

3.4.1 Required dilutions

The analysis of the constituent concentrations in the effluent, the associated water quality guidelines and the required dilutions was undertaken by the CoCT. Based on this analysis the CoCT provided PRDW with three critical constituents as listed in Table 3-4. These required dilutions will be compared to the achieved dilutions obtained from the model.

Table 3-4: Required effluent dilutions.

Constituent	Dilutions
Ammonia	154
Chemical Oxygen Demand (COD)	48
TSS	1 550

The CoCT determined the allowable mixing zone to be within a radius of 274 m from the diffuser.

3.4.2 Bacteria concentrations

The CoCT confirmed that the target values for microbiological indicators for recreational waters in the coastal marine environment should be based on the Department of Environmental Affairs guidelines (DEA, 2012), as shown in Table 3-5.

Table 3-5: Guideline concentrations for enterococci and E.coli to meet the sufficient or fair category for recreational waters in the coastal marine environment.

Constituent	90 th percentile concentration [CFU/100 ml]
Enterococci	≤ 185
E.coli	≤ 500

4. MODEL SETUP

4.1 Model mesh

The WG19 horizontal coordinate system was used for this study. All spatial plots include x and y axes showing the x and y coordinates in metres in the WG19 system. True north is always pointing upwards.

The model mesh comprises triangles with a resolution varying from about 3 km at the offshore boundary to 50 m in the vicinity of the diffuser. Quadrangular elements with a resolution of 25 m were used around the diffuser to resolve the effluent release into the far-field model. The vertical mesh is comprised of twelve sigma layers with equal layer thicknesses.

Figure 4-1 and Figure 4-2 and represent the three-dimensional and horizontal views of the mesh used for the outfall dispersion modelling.

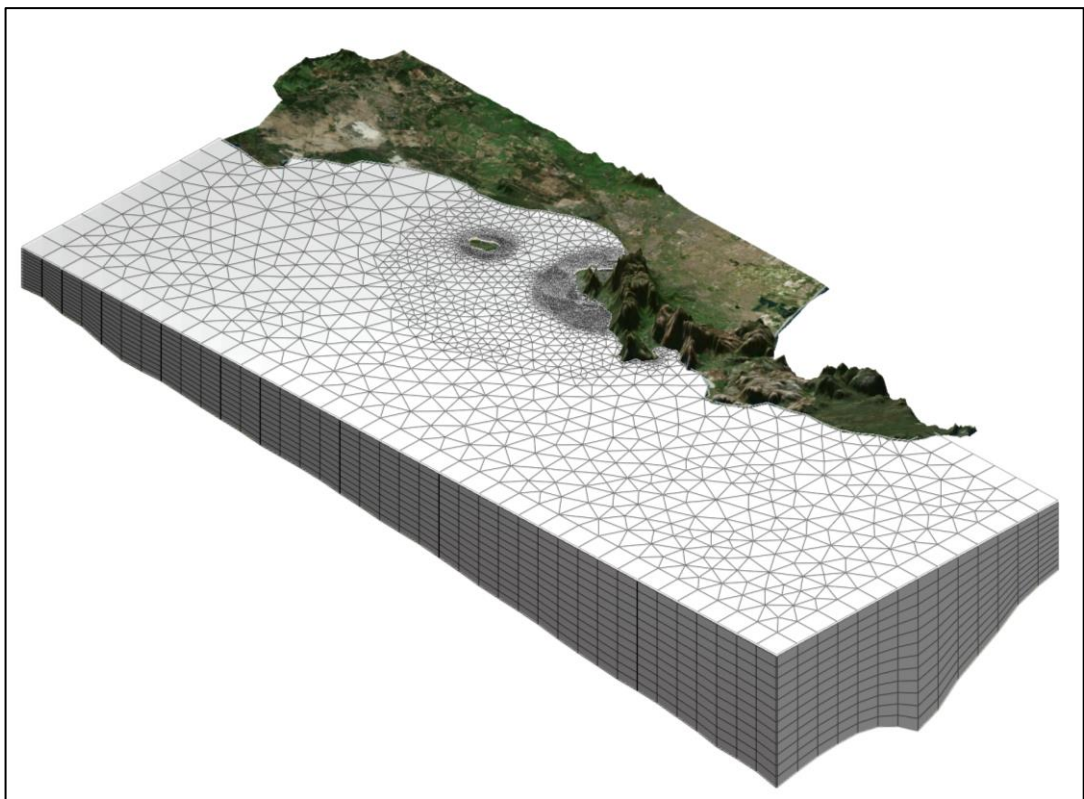


Figure 4-1: Three-dimensional representation of mesh used for the outfall dispersion modelling. Note the vertical axis is not to scale.

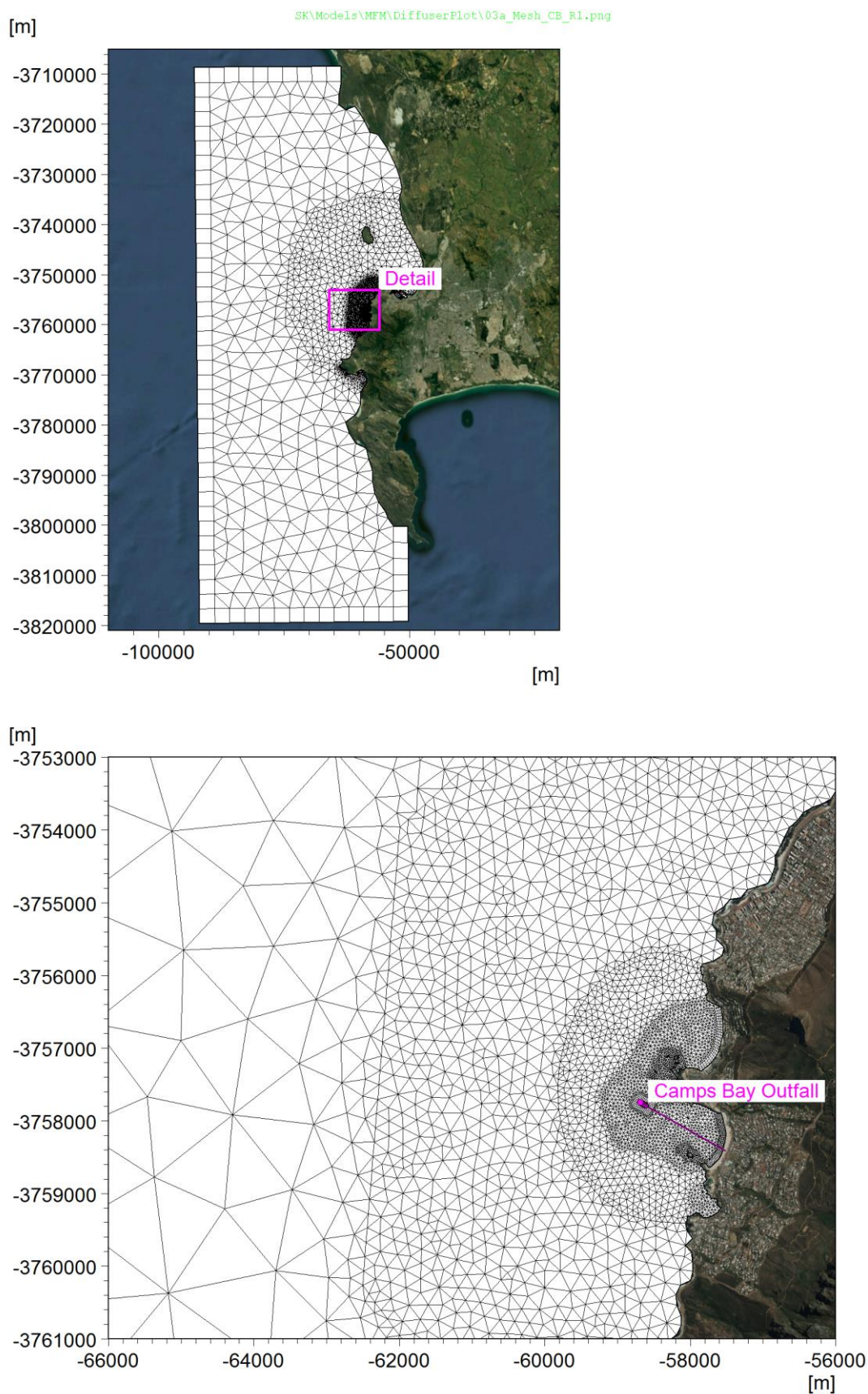


Figure 4-2: Horizontal mesh used for the outfall dispersion modelling.

4.2 Bathymetry

The vertical datum adopted in this study is Chart Datum (CD). CD is 0.825 m below Land Levelling Datum (LLD) which is also known as Mean Sea Level (MSL).

The model bathymetry has been obtained from the following sources:

- CMAP electronic hydrographic charts
- LIDAR topographic surveys landward of the high water mark
- Bathymetric survey of Camps Bay undertaken in 1994 by Underwater Surveys for the Cape Town City Council (see Figure 4-3).
- Qualitative adjustments have been made based on observations from multibeam surveys of the Atlantic Seaboard undertaken between 2012 and 2014 (Van Zyl, 2018).

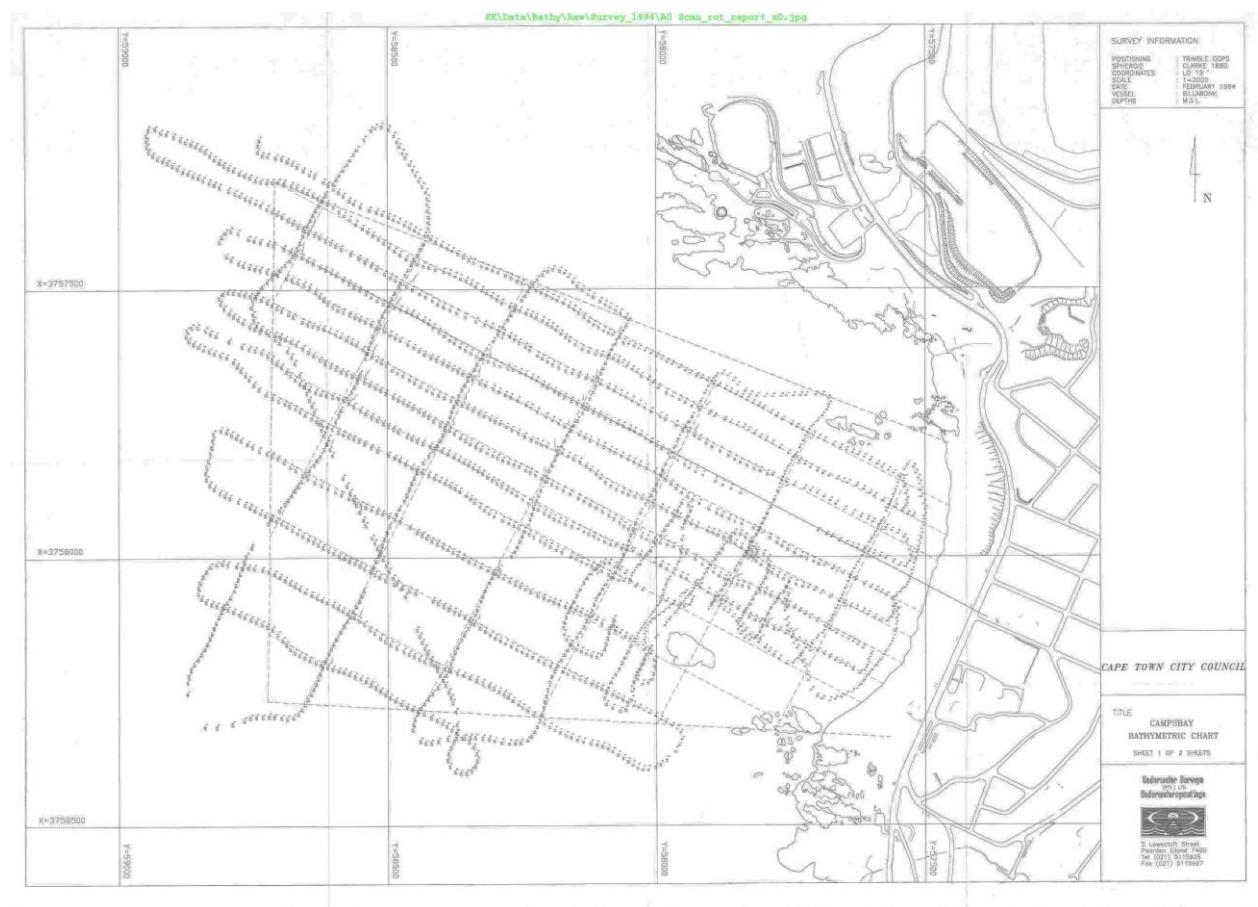


Figure 4-3: Bathymetric survey of Camps Bay undertaken in 1994 by Underwater Surveys for the Cape Town City Council.

Figure 4-4 shows the model bathymetry and the locations of the ADCP and thermistor deployments used for the calibration of the model.

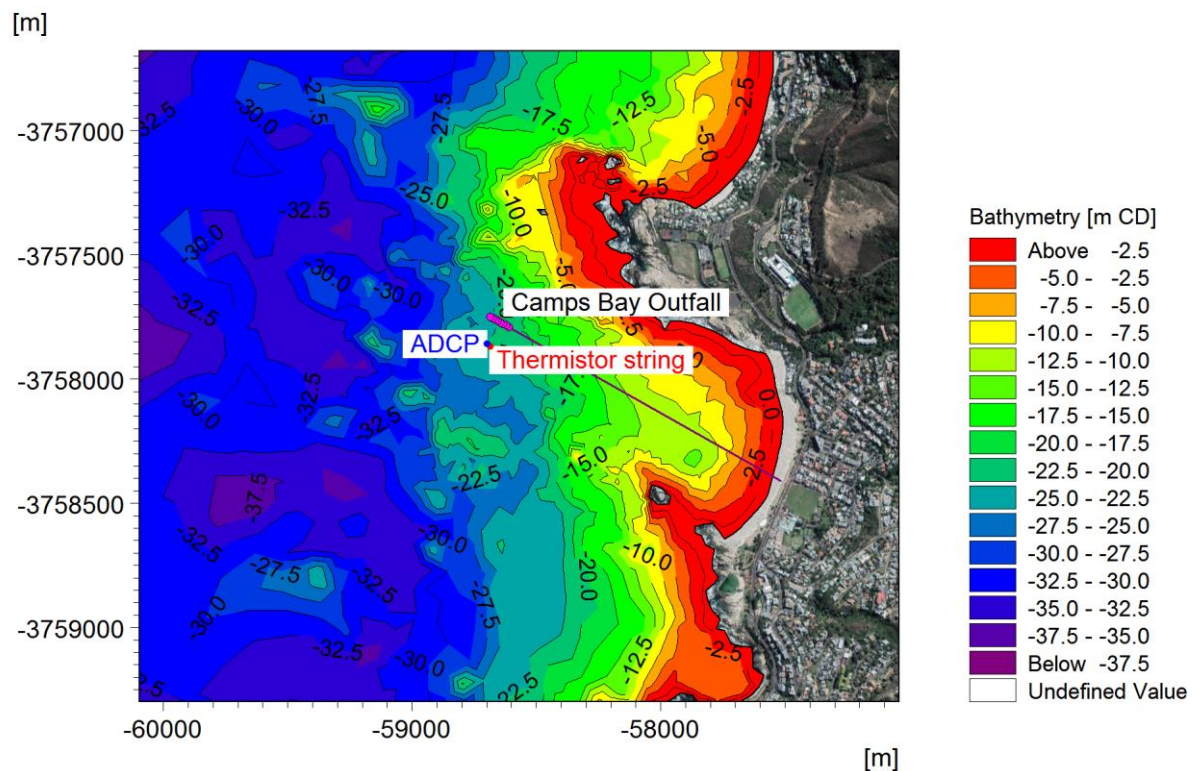
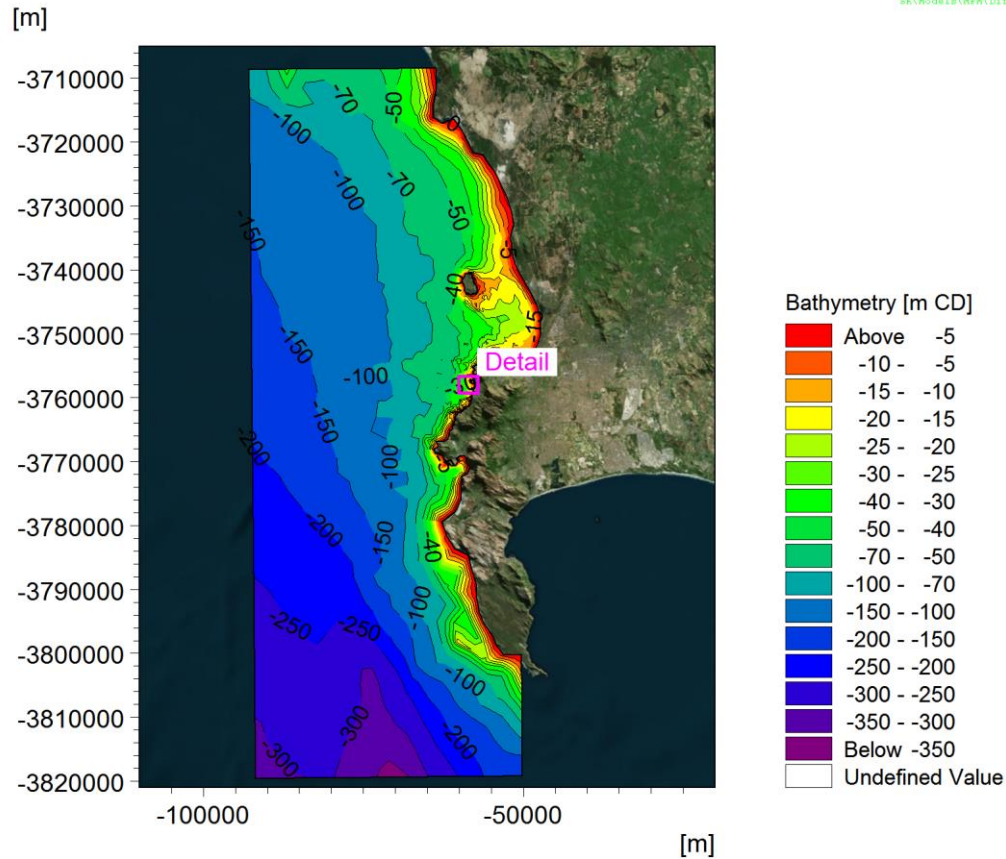


Figure 4-4: Model bathymetry.



4.3 Wind

Wind is an important forcing mechanism for currents, vertical mixing and upwelling – and thus the effluent dispersion. The wind fields near the outfalls are influenced by the surrounding mountains which require a high spatial resolution to resolve.

The Climate System Analysis Group at the University of Cape Town has kindly provided wind data from the Weather Research and Forecasting (WRF) model with a spatial resolution of 4 km and a temporal resolution of 1 hour.

Figure 4-5 shows two snapshots in time illustrating the high spatial variability in the 4 km resolution modelled winds around Cape Town.

Figure 4-6 to Figure 4-9 show comparisons between the modelled winds and measured winds at three locations around Cape Town (Cape Town International Airport, Cape Point and Koeberg) for the winter/spring and summer/autumn modelling periods.

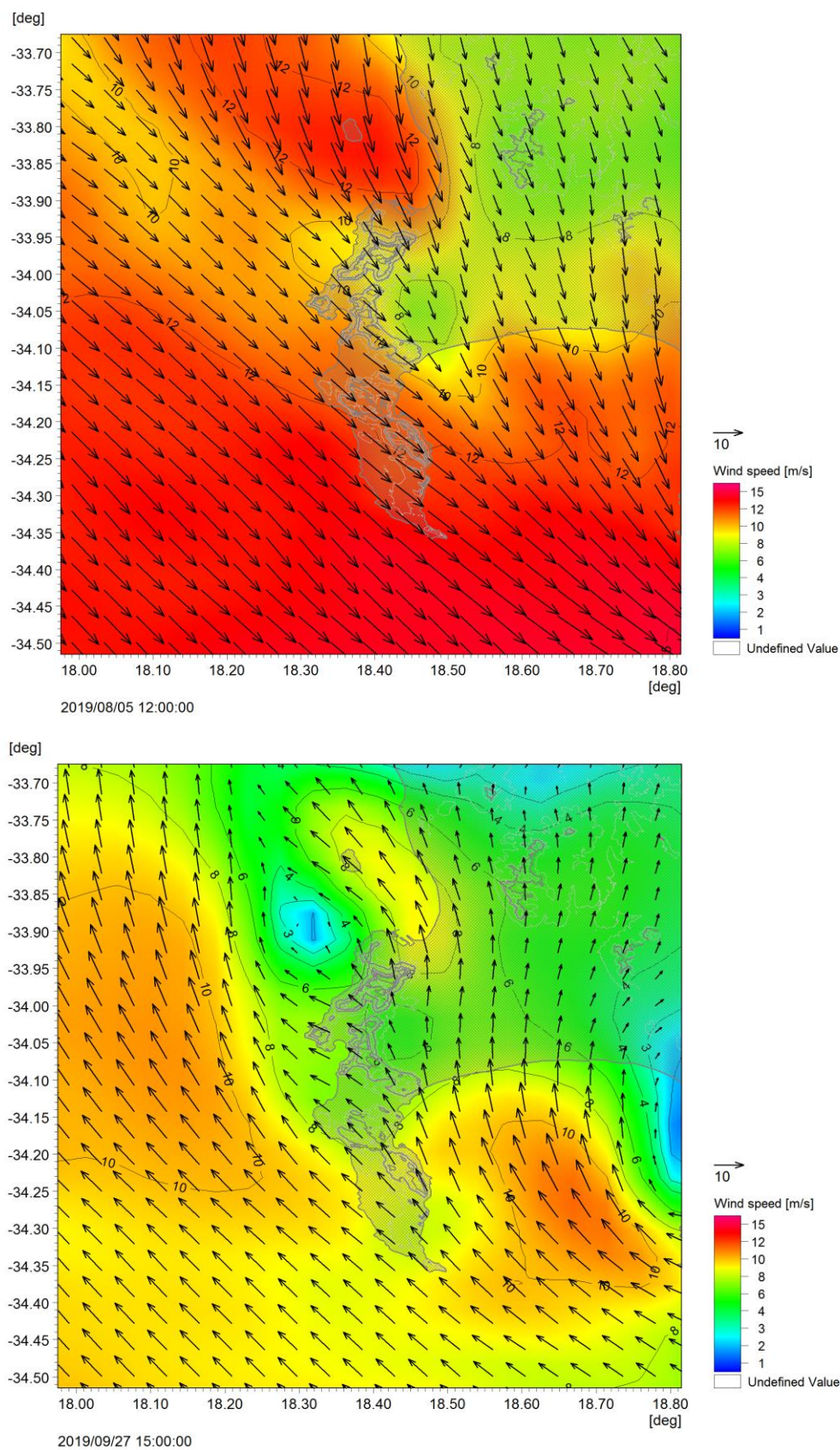


Figure 4-5: Snapshots illustrating the high spatial variability in the 4 km resolution modelled winds around Cape Town (grey lines show topography at 100 m intervals).

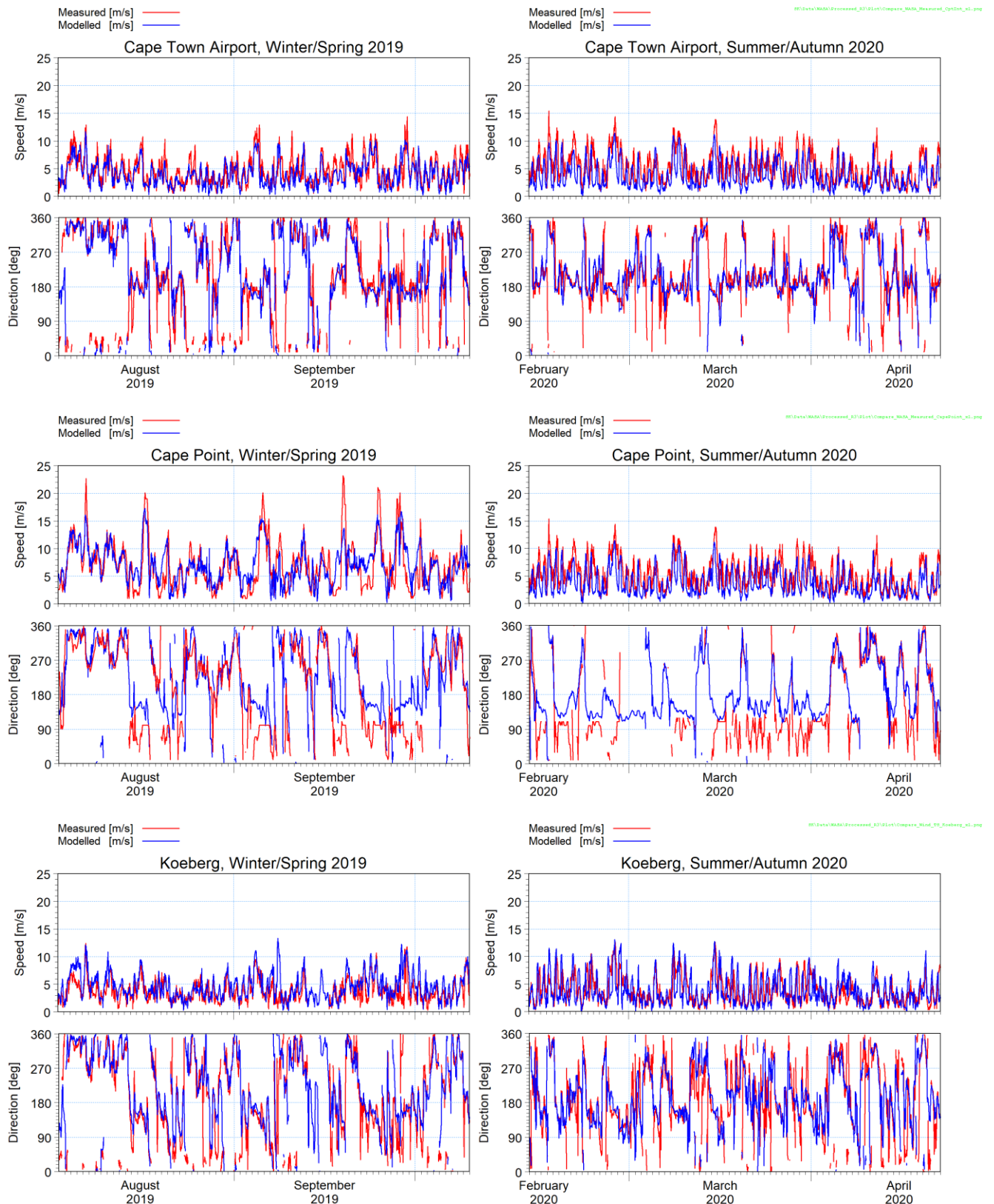


Figure 4-6: Time series of modelled compared to measured winds at Cape Town International, Cape Point and Koeberg.

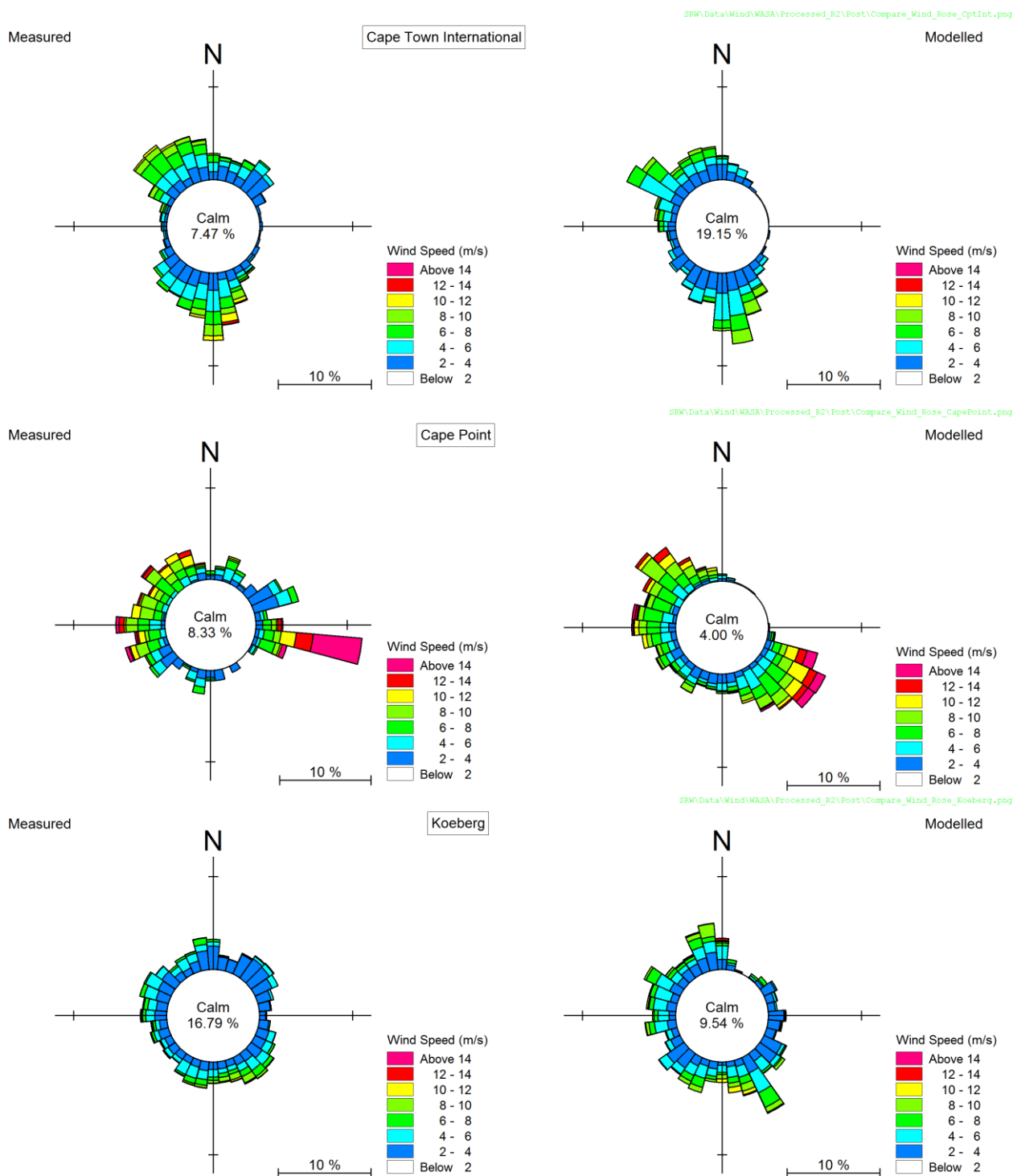


Figure 4-7: Roses of modelled compared to measured winds at Cape Town International, Cape Point and Koeberg for the winter/spring 2019 period.

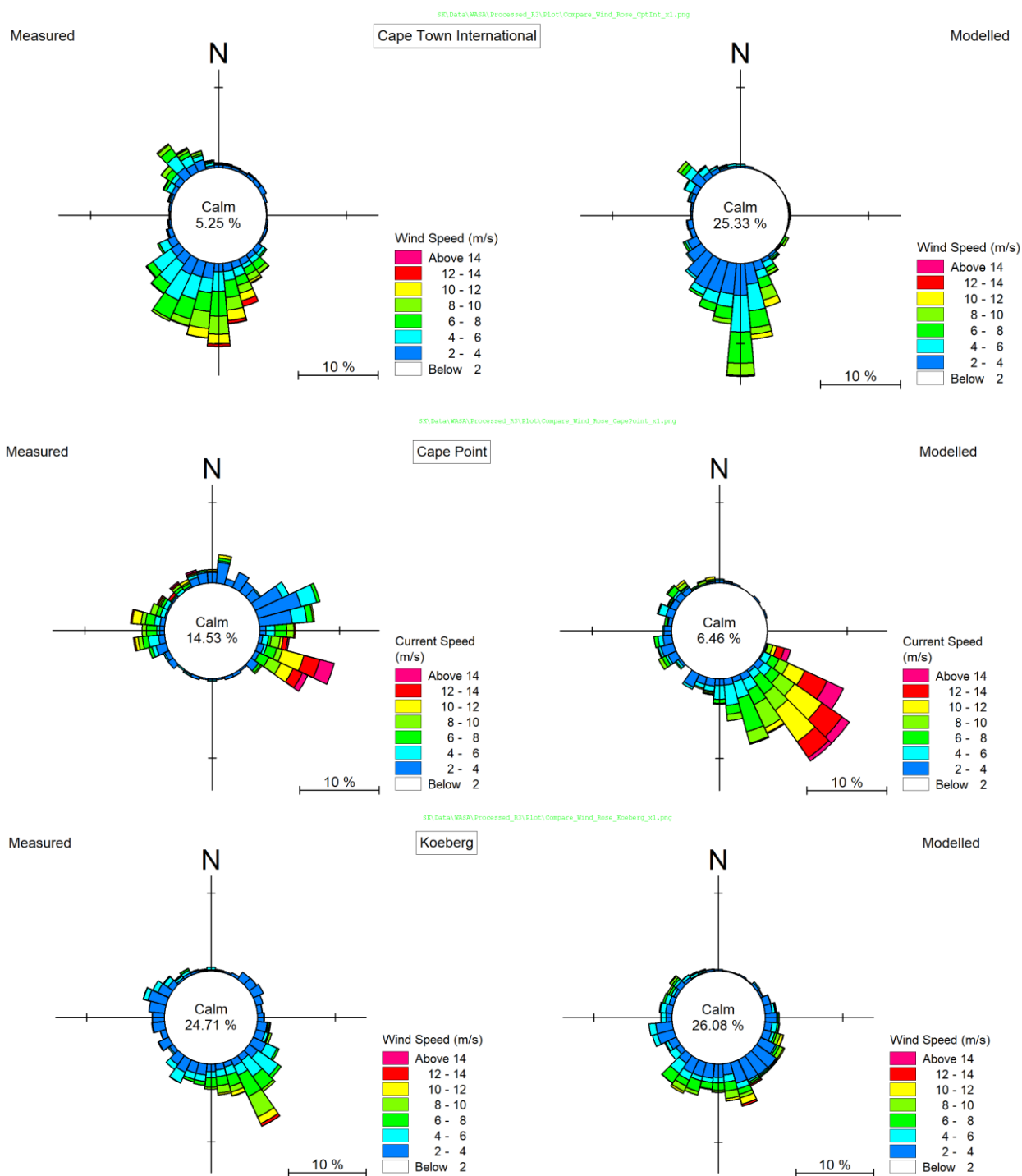


Figure 4-8: Roses of modelled compared to measured winds at Cape Town International, Cape Point and Koeberg for the summer/autumn 2020 period.

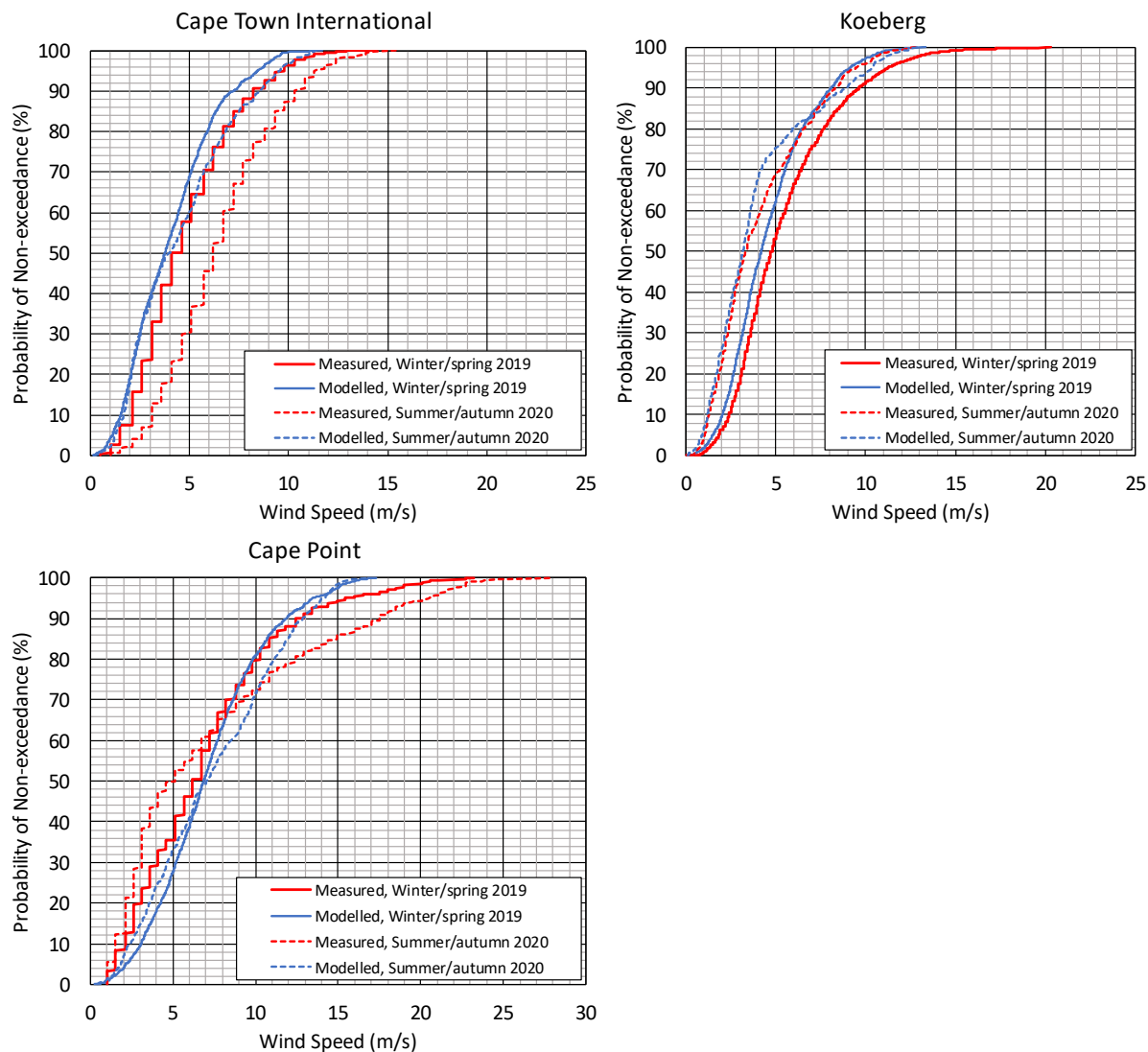


Figure 4-9: Wind speed exceedance of modelled compared to measured winds at Cape Town International, Cape Point and Koeberg.

These results indicate that the WRF modelled winds compare well to the measured winds at three different locations across Cape Town. The main discrepancies are the wind directions at Cape Point which is likely due to the steep cliffs at this location, and the modelled wind speed being approximately 1 m/s to 2 m/s lower than the measurements at Cape Town International.



4.4 Boundary conditions

The model boundary conditions are extracted from global hindcast models as described in Table 4-1:

Table 4-1: Global hindcast models used for the model boundary conditions.

Model	Parameter	Spatial resolution [°]	Temporal resolution [hrs]
HYbrid Coordinate Ocean Model (HYCOM) global ocean circulation model (HYCOM, 2020).	Non-tidal water levels	0.08	3
	Non-tidal ocean currents		
	Seawater temperature		
	Seawater salinity		
DTU10 (Technical University of Denmark) global tidal model (DTU, 2010).	Predicted tides	0.125	Predicted from constituents.
	Predicted tidal currents	0.25	
European Centre for Medium-Range Weather Forecasts (EMCWF) ERA5 global atmospheric model (ECMWF, 2020).	Air temperature	0.25	1
	Humidity		
	Solar radiation		
National Centers for Environmental Prediction (NCEP) global wave forecast model (NCEP, 2020).	Wave spectra	0.5	3

4.5 Model settings

The vertical eddy viscosity was computed using the $k-\epsilon$ vertical turbulence closure scheme, while the vertical eddy dispersion was set to 0.1 times the vertical eddy viscosity. This scaling factor was applied to compensate for additional vertical mixing caused by the use of only 12 vertical layers and the associated smoothing of the vertical density gradients.

The wind friction coefficient and seabed roughness were tuned to physically realistic values which yielded the best agreement between modelled and measured currents at Camps Bay.

The effects of kelp on the currents was accounted for by adding vertical piles as subgrid structures. The dimensions of the piles were adjusted to approximate the results from a physical model study on currents and turbulence within a kelp forest by Rosman, et al. (2010).

5. MODEL CALIBRATION

5.1 Winter/spring

The model was calibrated to metocean data measured by Lwandle during a 6-week period between 21 August 2019 and 3 October 2019. The measurements used for the model calibration comprise:

- ADCP measurements, including:
 - Currents measured across the depth profile in 1 m bins at 10-minute intervals.
 - Fully spectral waves, available at hourly intervals.
- Seawater temperature measured from a thermistor string, available at 5 discrete depth levels between 3 m and 14 m above the seabed.

The ADCP (X = -58 699 m, Y = -3 757 859 m) and thermistor string (X = -58 685 m, Y = -3 757 860 m) were deployed approximately 100 m southwest of the diffuser at a depth of -22.3 m CD. The locations are shown in Figure 5-1.

5.1.1 Waves

A wave refraction plot for a west-south-westerly wave event is shown in Figure 5-1.

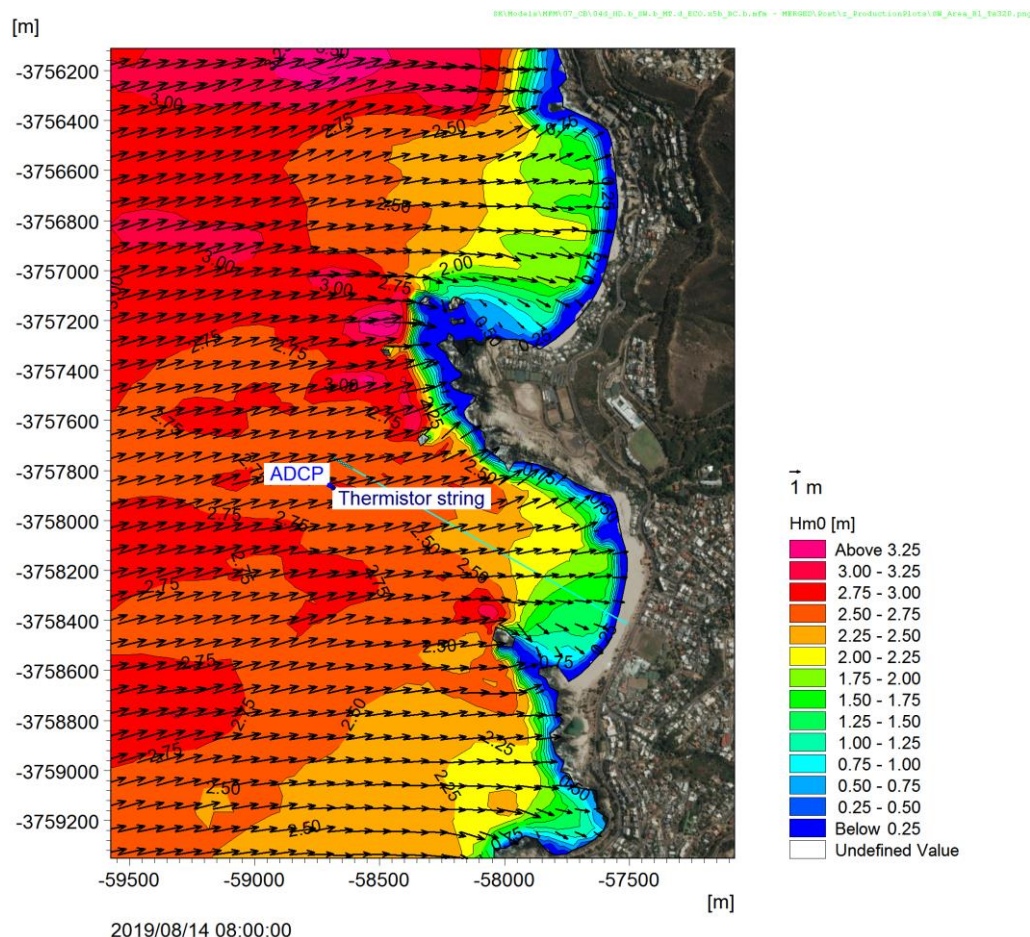


Figure 5-1: Winter/spring: Wave refraction plot for a west-south-westerly wave event. The modelled wave condition at the ADCP is $H_{m0} = 2.74$ m, $T_p = 13.8$ s, $D_{MP} = 256^\circ$.



Figure 5-2 presents a time series comparison of measured and modelled wave parameters at the ADCP. Measured and modelled wave roses are shown in Figure 5-3. By convention, wave direction is the direction from which the wave is coming, measured clockwise from true north.

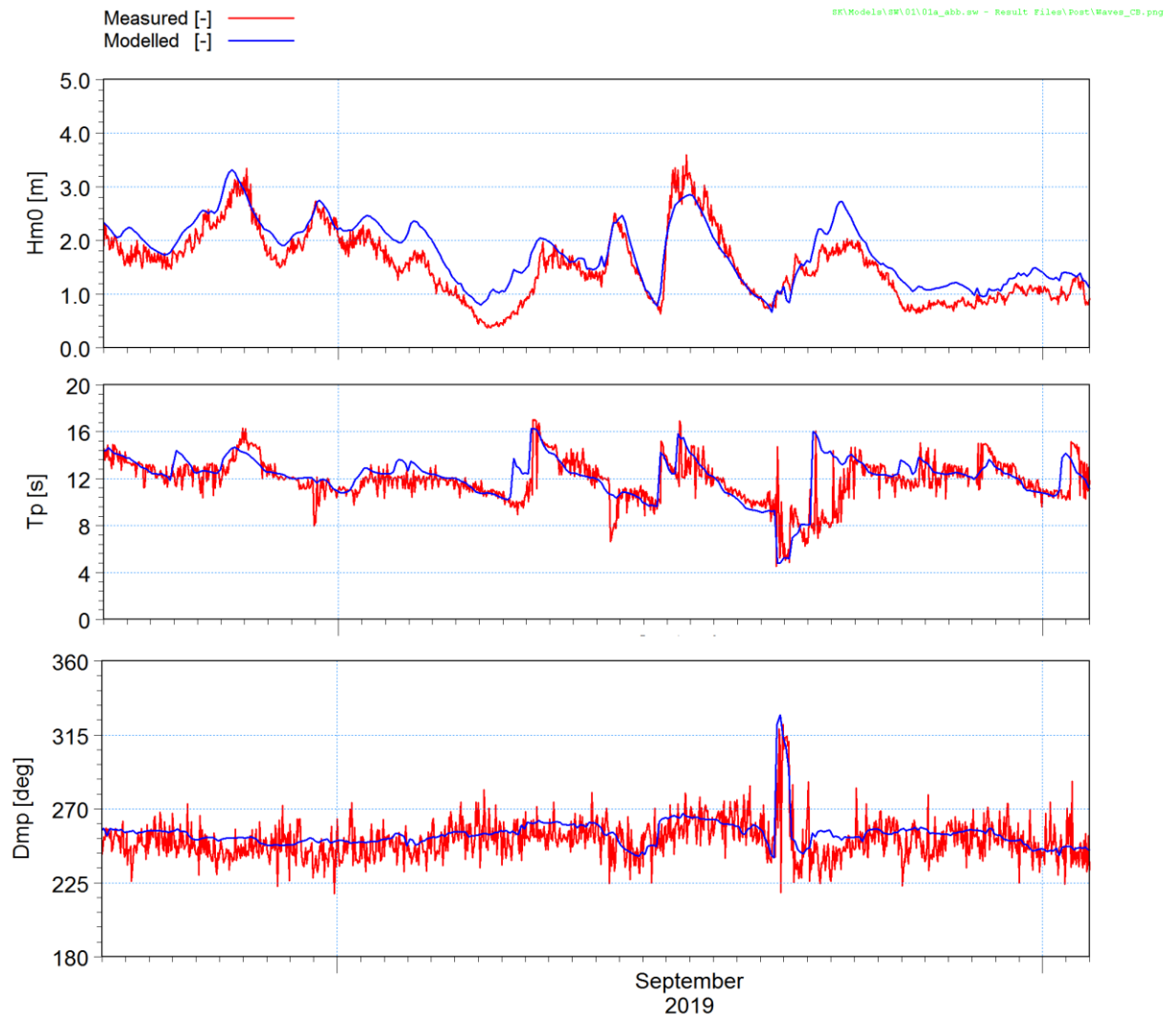


Figure 5-2: Winter/spring: Time series of measured and modelled significant wave height (H_{m0}), peak wave period (T_p) and mean wave direction at T_p (D_{MP}) at the location of the ADCP.

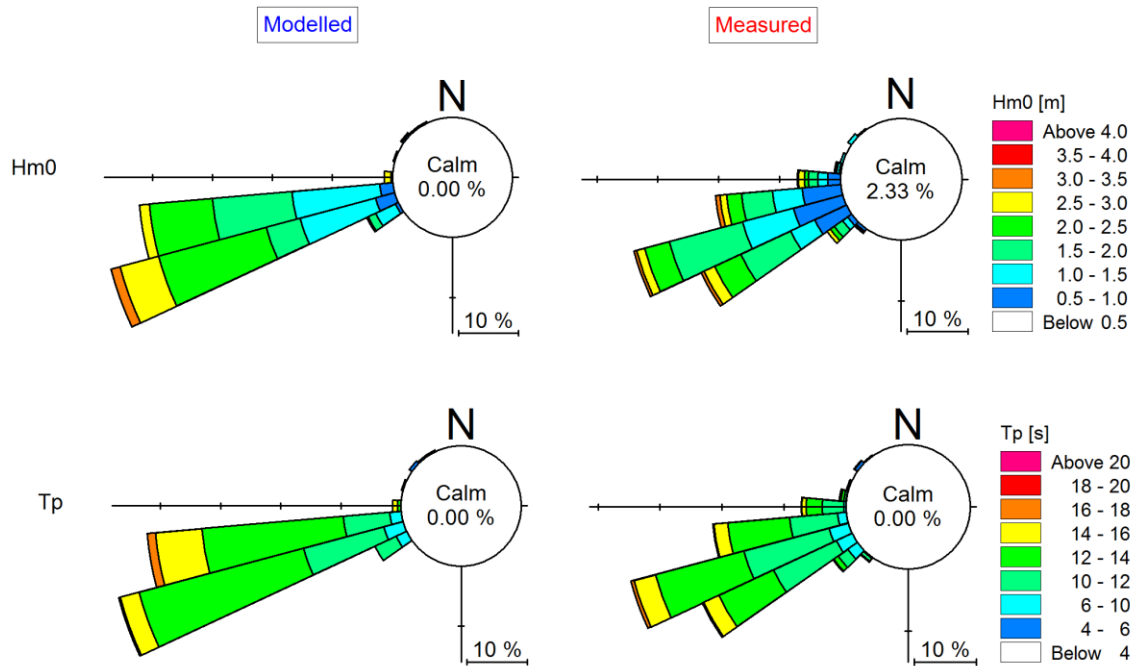


Figure 5-3: Winter/spring: Wave roses of measured and modelled H_{m0} and T_p for the 6-week deployment period at the location of the ADCP.

A good overall comparison could be observed from the time series and wave rose plots. Occasional over- or underprediction of wave heights can be observed, but there is no bias in either direction. The modelled peak wave period and mean wave direction compared well to the measurements. The agreement between the ADCP measurements and the wave model outputs shows the model to be adequately calibrated for the purposes of this study

5.1.2 Water levels

The predicted tidal levels at the Port of Cape Town ($X = -539\,934\text{ m}$, $Y = -3\,752\,769\text{ m}$) were extracted from the MIKE by DHI CMAP Electronic Charts Database (DHI, 2020i). Figure 5-4 presents a time series comparison of modelled water levels to predicted tides at the Port of Cape Town. A water level probability of non-exceedance plot is shown in Figure 5-5.

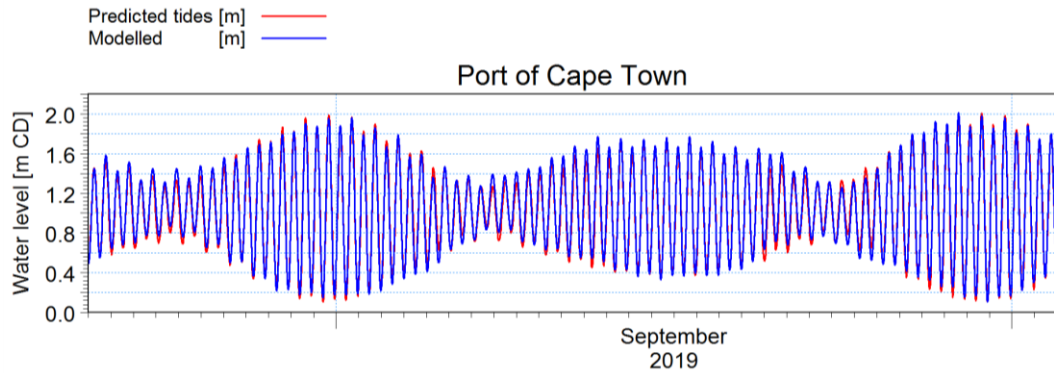


Figure 5-4: Winter/spring: Time series comparison of modelled water levels to measurements at Camps Bay (ADCP) and predicted tides at the Port of Cape Town.

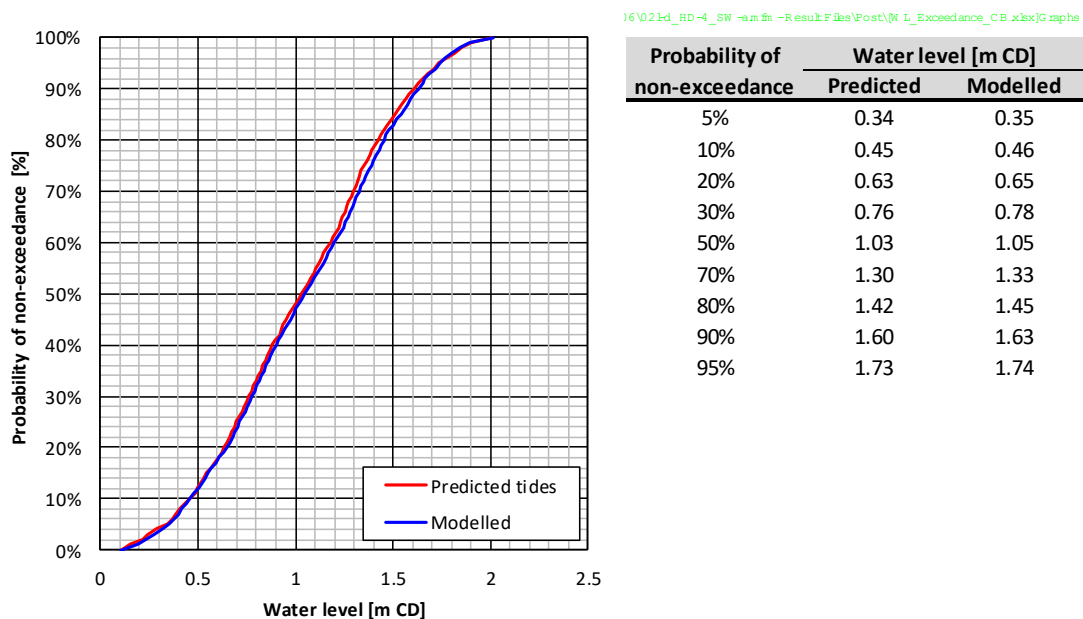


Figure 5-5: Winter/spring: Probability of non-exceedance for predicted tides and modelled water levels for the 6-week deployment period at the Port of Cape Town.

The comparison shows a good overall model prediction in both tidal phase and amplitude.

5.1.3 Currents

A contour plot of instantaneous currents during a west-south-westerly wave/north-westerly wind event is shown in Figure 5-6. The modelled currents were compared to the measurements near the seabed (3.4 m above the seabed) and near the surface (19.4 m above the seabed). Figure 5-7 presents a time series comparison of the modelled and measured currents at the ADCP. Non-exceedance curves of current speed for the 6-week period are shown Figure 5-8. Current rose comparisons of modelled and measured currents are presented in Figure 5-9. Note that current direction is by convention the direction towards which the current is flowing.

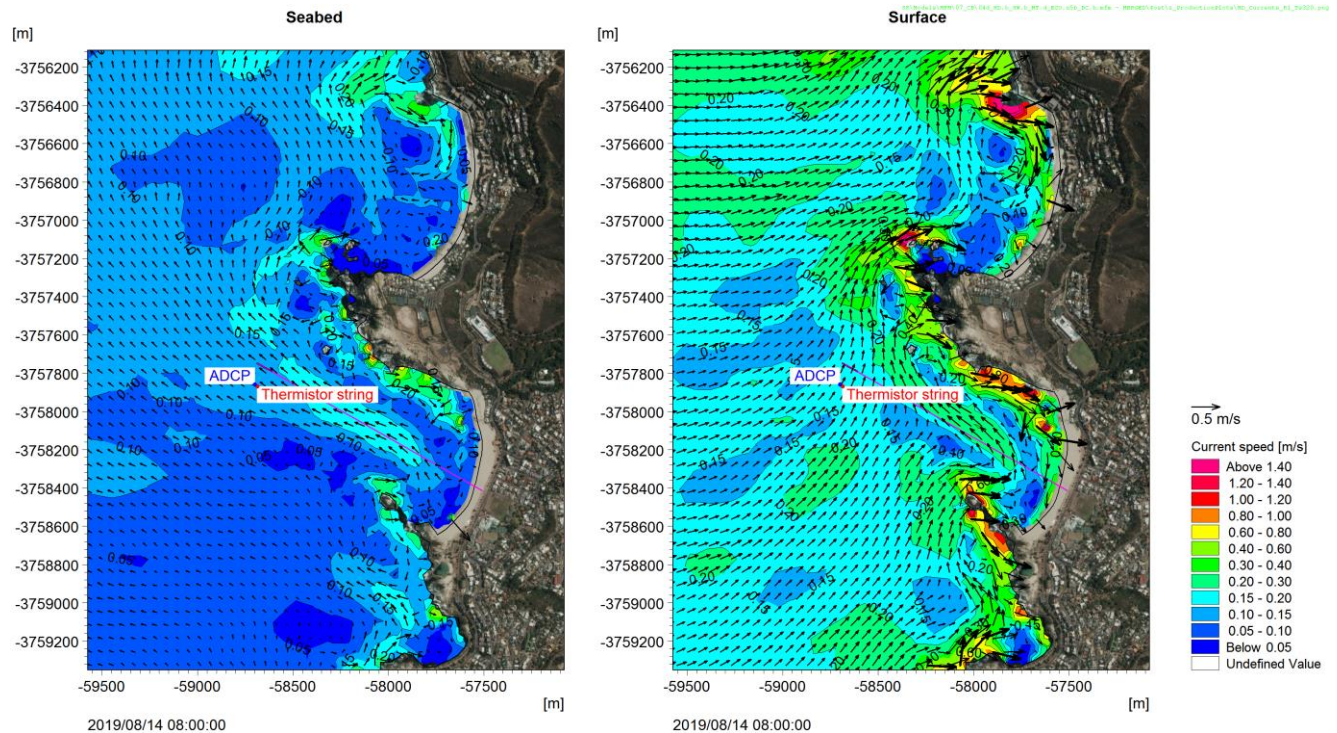


Figure 5-6: Winter/spring: Contour plot of instantaneous seabed (left) and surface (right) currents during a west-south-westerly wave/north-westerly wind event (shown in Figure 5-1).

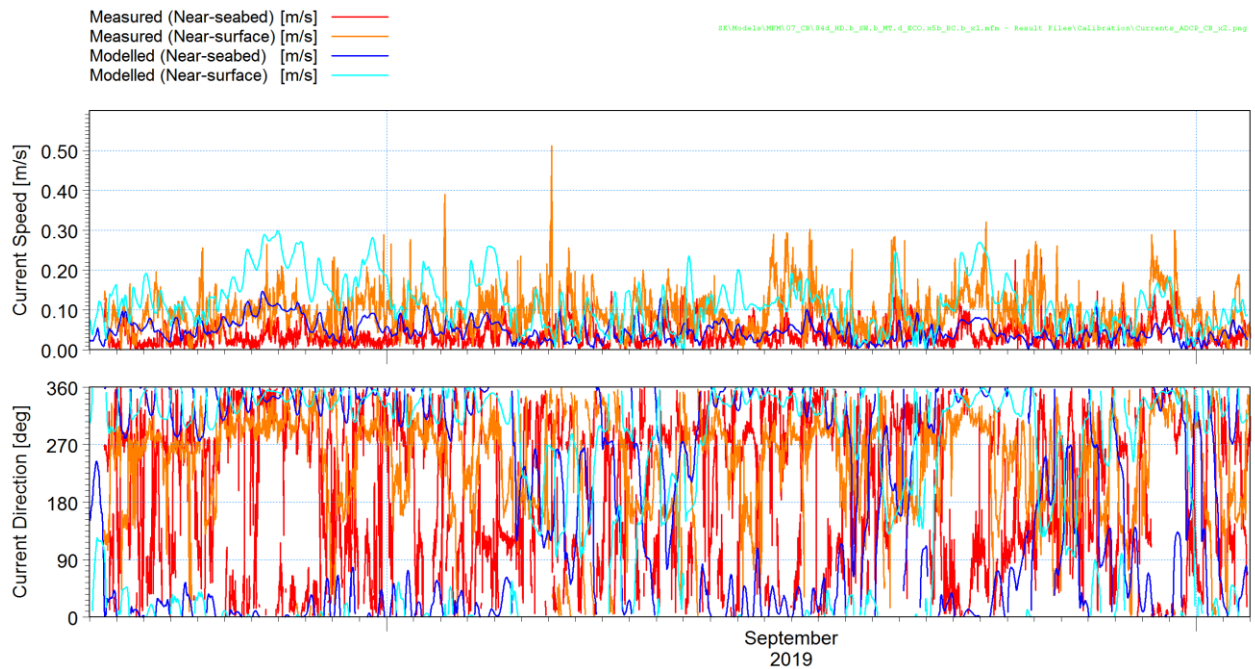
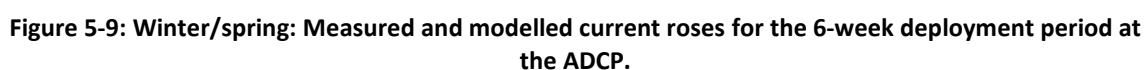


Figure 5-7: Winter/spring: Time series comparison of measured and modelled current speed and direction at the ADCP.



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overpredict the operational current speeds and also predicts more frequent north to north-easterly currents than observed in the measurements.

The complexity and spatial variability (both horizontal and vertical) of currents and eddies can be observed in Figure 5-6. The currents are largely forced by wind and wave breaking on the beaches and rocky outcrops (shown Figure 5-1). Uncertainties arising from variable local wind fields, the presence of kelp and irregular and complex bathymetric features in Camps Bay add up to discrepancies between the measured and the modelled currents.

Overall the model is able to reproduce the main features of the currents and is considered to be acceptable for the purposes of this study.

5.1.4 Temperature

The modelled seawater temperatures were compared to measurements near the seabed (3.0 m above the seabed) and at mid-depth (14.0 m above the seabed). Figure 5-10 presents a time series comparison of the modelled and measured seawater temperatures. Non-exceedance curves of seabed and mid-depth temperatures for the 6-week period are shown Figure 5-11. Figure 5-12 presents non-exceedance curves of stratification (seabed to mid-depth) from the measured and modelled temperatures.

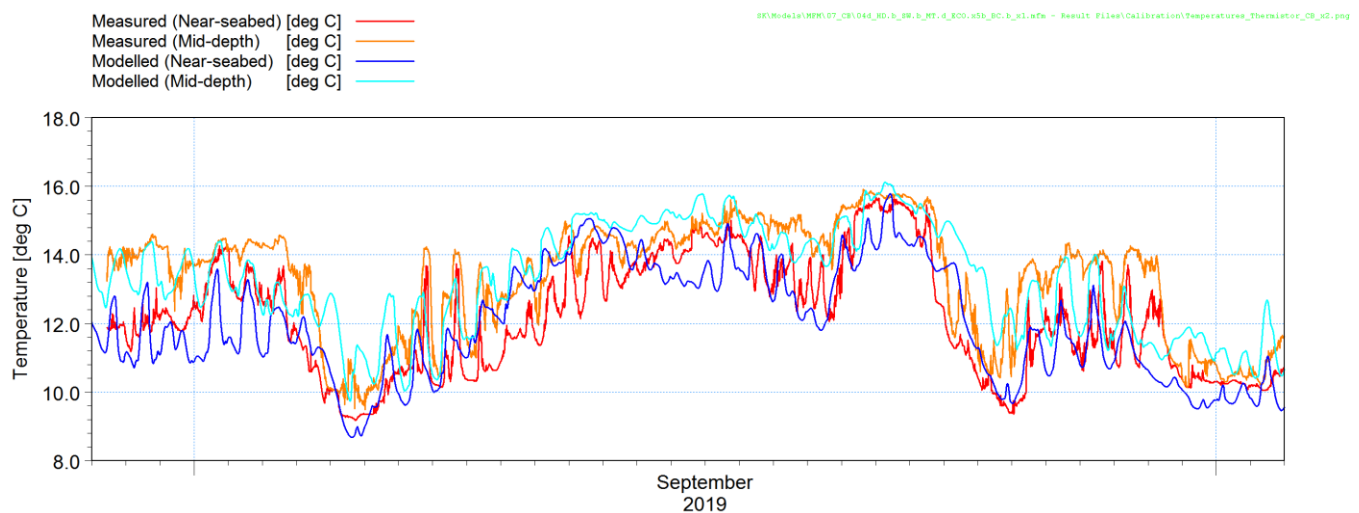


Figure 5-10: Winter/spring: Time series of measured and modelled seawater temperatures at the thermistor string.

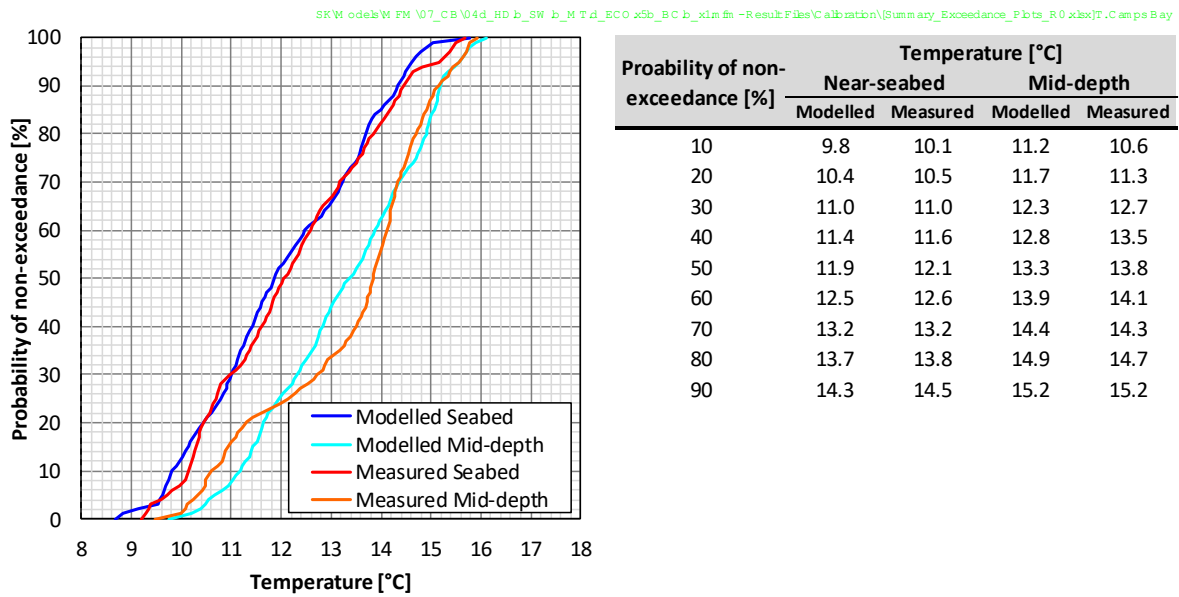


Figure 5-11: Winter/spring: Probability of non-exceedance of measured and modelled seawater temperatures for the 6-week deployment period at the thermistor string.

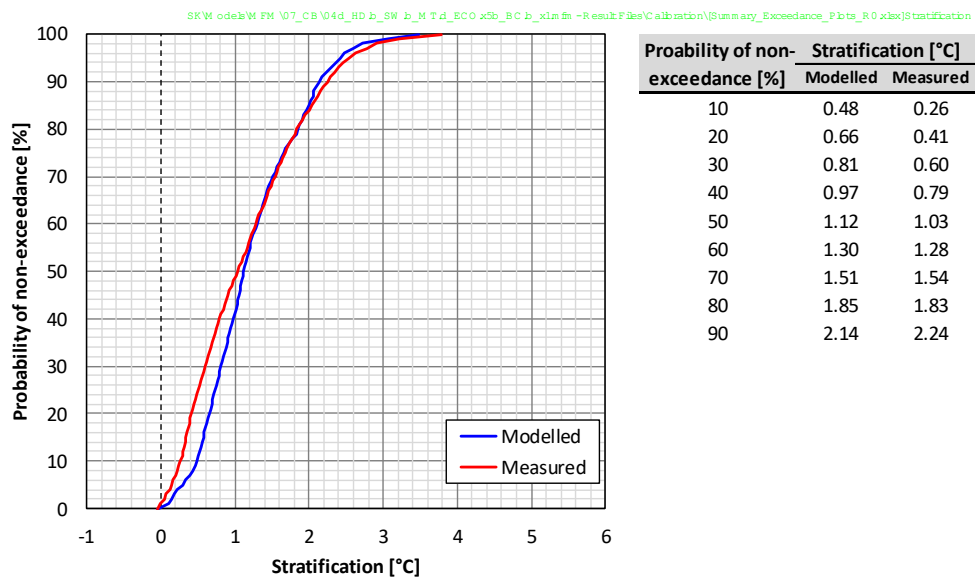


Figure 5-12: Winter/spring: Probability of non-exceedance of measured and modelled seawater temperature stratification (near-seabed to mid-depth) for the 6-week deployment period at the thermistor string.

The measured time series shows that the seawater temperatures are complex and vary over a range of time-scales due to upwelling, solar radiation and other dynamic processes. The model is able to predict the mean trend in mid-depth and seabed seawater temperatures including some of the discrete dynamic events. Periodic over- or underprediction of mid-depth and seabed temperatures can be observed, however the model shows a good statistical distribution of temperatures and the resultant stratification, the latter being an important determinant of the rise height of the plume in the near-field. The model is therefore considered to be adequately calibrated for seawater temperature for the purposes of this study.

5.2 Summer/autumn

The model was calibrated to metocean data measured by Lwandle during a 10-week period between 13 February 2020 and 23 April 2020. The measurements used for the model calibration comprise:

- ADCP measurements, including:
 - Currents measured across the depth profile in 1 m bins at 10-minute intervals.
 - Fully spectral waves, available at hourly intervals.
- Seawater temperature measured from a thermistor string, available at 5 discrete depth levels between 1.9 m and 16.5 m above the seabed.

The ADCP (X = -58 702 m, Y = -3 757 859 m) and thermistor string (X = -58 681 m, Y = -3 757 863 m) were deployed approximately 100 m southwest of the diffuser at a depth of -21.7 m CD. The locations are shown in Figure 5-13.

5.2.1 Waves

A wave refraction plot for a west-south-westerly wave event is shown in Figure 5-13.

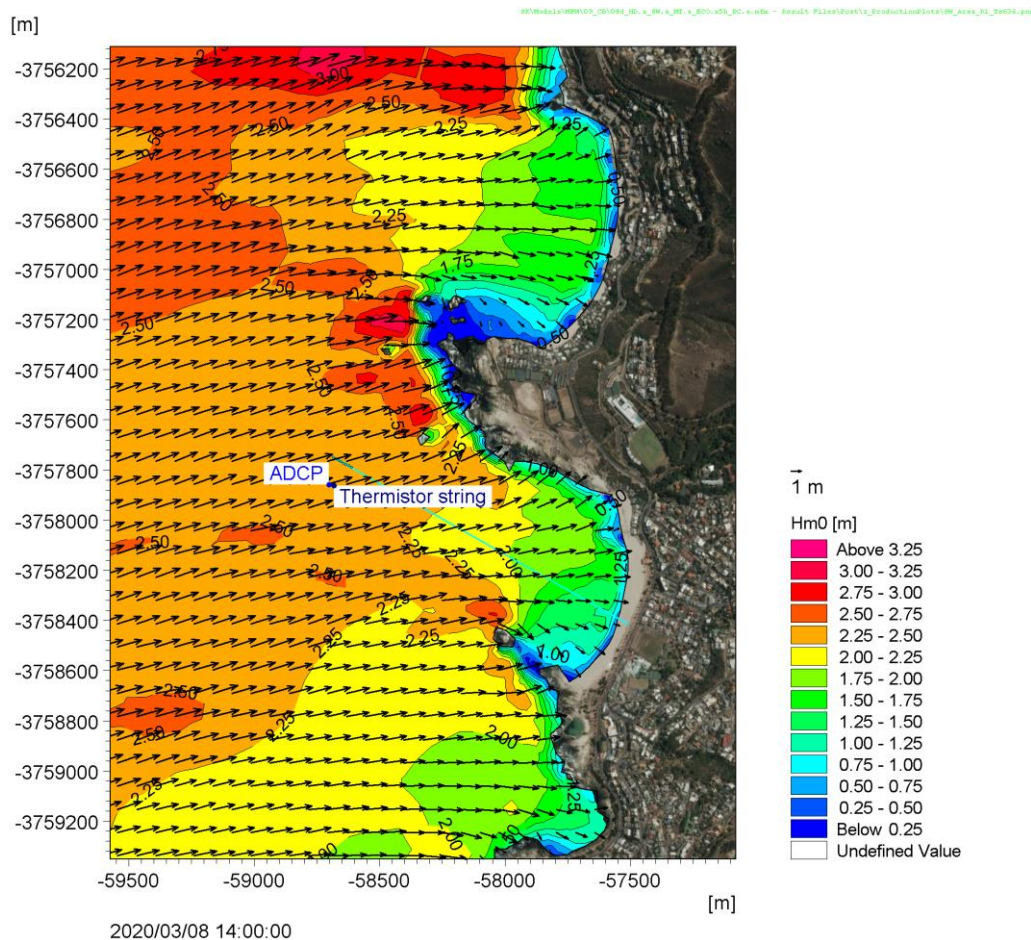


Figure 5-13: Summer/autumn: Wave refraction plot for a west-south-westerly wave event. The modelled wave condition at the ADCP is $H_{m0} = 2.40$ m, $T_p = 14.4$ s, $D_{MP} = 254^\circ$.

Figure 5-14 presents a time series comparison of measured and modelled wave parameters at the ADCP. Measured and modelled wave roses are shown in Figure 5-15.

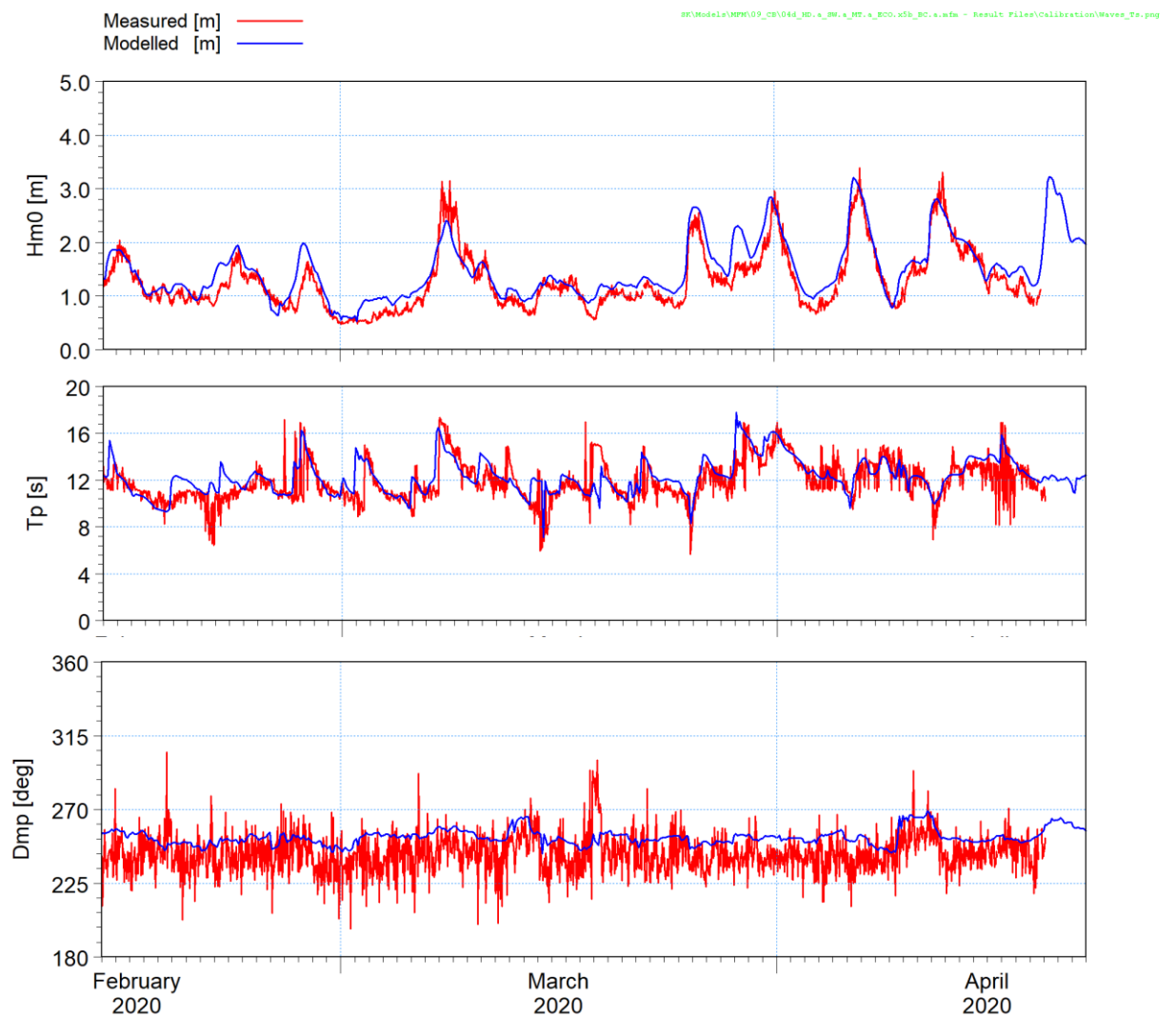


Figure 5-14: Summer/autumn: Time series of measured and modelled significant wave height (H_{m0}), peak wave period (T_p) and mean wave direction at T_p (D_{MP}) at the location of the ADCP.

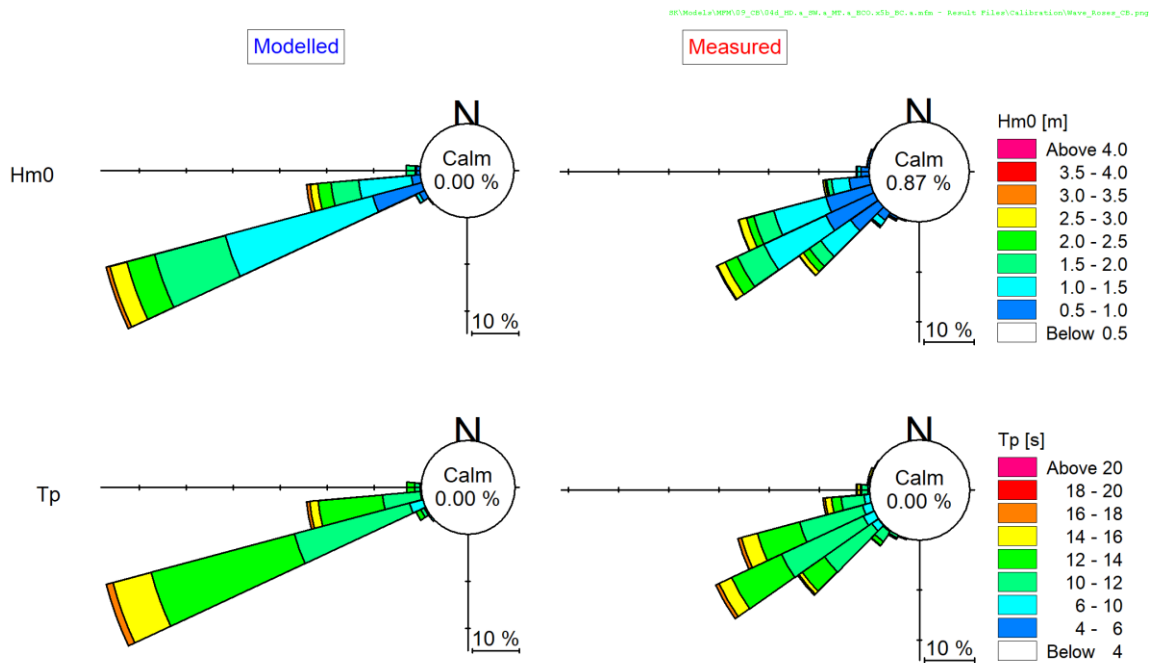


Figure 5-15: Summer/autumn: Wave roses of measured and modelled H_{m0} and T_p for the 10-week deployment period at the location of the ADCP.

The significant wave height is occasionally over- or underpredicted by the model, but there is no systematic bias. There is a good correlation between modelled and measured peak wave period and wave directions, but the latter shows a constant offset of about 10° . Overall the model shows sufficient for the purposes of this study.

5.2.2 Water levels

The predicted tidal levels at the Port of Cape Town (X = -539 934 m, Y = -3 752 769 m) were extracted from the MIKE by DHI CMAP Electronic Charts Database (DHI, 2020i). Figure 5-16 presents a time series comparison of modelled water levels to predicted tides at the Port of Cape Town. A water level probability of non-exceedance plot is shown in Figure 5-17.

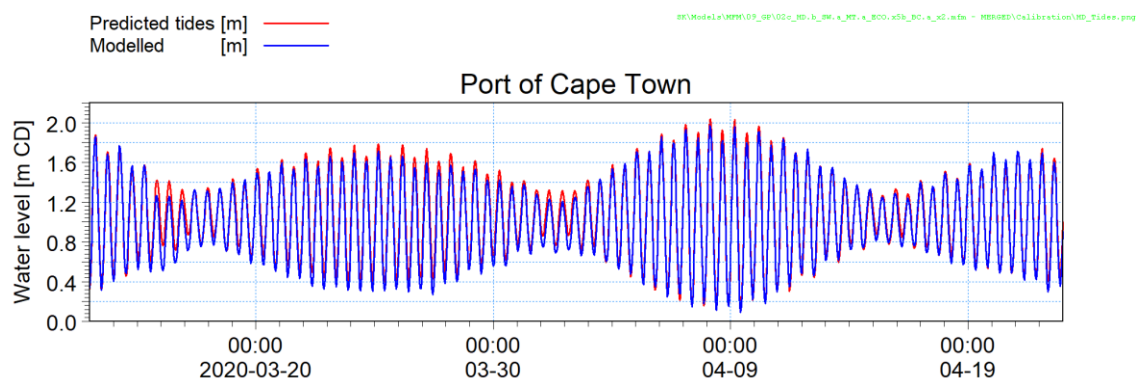
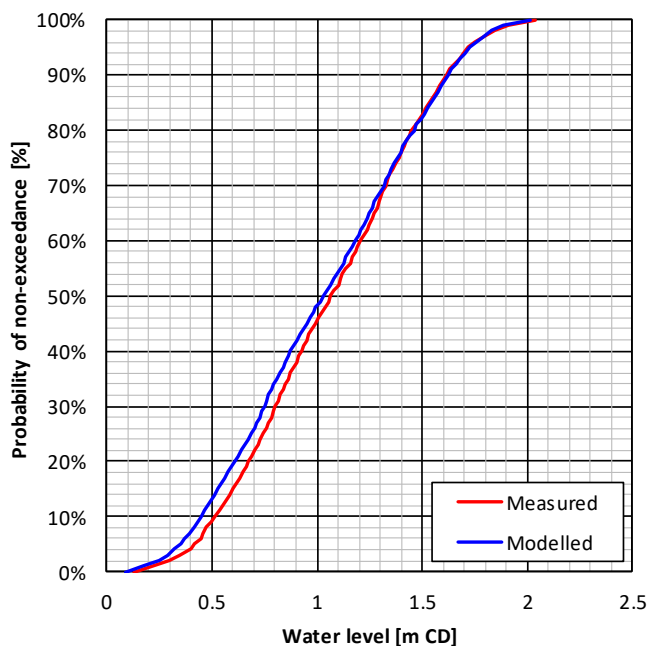


Figure 5-16: Summer/autumn: Time series comparison of modelled water levels to measurements at Camps Bay (ADCP) and predicted tides at the Port of Cape Town.



\\x5b_B C a_x2 m fm -M ERGED\\C alibration\\C ompamTs_HD_T ties.xlsx\\Graphs

Probability of non-exceedance	Water level [m CD]	
	Measured	Modelled
5%	0.42	0.35
10%	0.51	0.45
20%	0.67	0.61
30%	0.80	0.75
50%	1.07	1.03
70%	1.32	1.32
80%	1.45	1.46
90%	1.62	1.62
95%	1.72	1.73

Figure 5-17: Summer/autumn: Probability of non-exceedance for predicted tides and modelled water levels for the 10-week period at the Port of Cape Town.

The model shows a good overall model prediction in both tidal phase and amplitude. The slight setdown observed during the first half of the calibration period is likely due to wind effects which are included in the model but not in the predicted tide.

5.2.3 Currents

A contour plot of instantaneous currents during a west-south-westerly wave/south-easterly wind event is shown in Figure 5-18. The modelled currents were compared to the measurements near the seabed (1.5 m above the seabed) and near the surface (17.5 m above the seabed). Figure 5-19 presents a time series comparison of the modelled and measured currents at the ADCP. Non-exceedance curves of current speed for the 10-week period are shown Figure 5-20. Current rose comparisons of modelled and measured currents are presented in Figure 5-21.

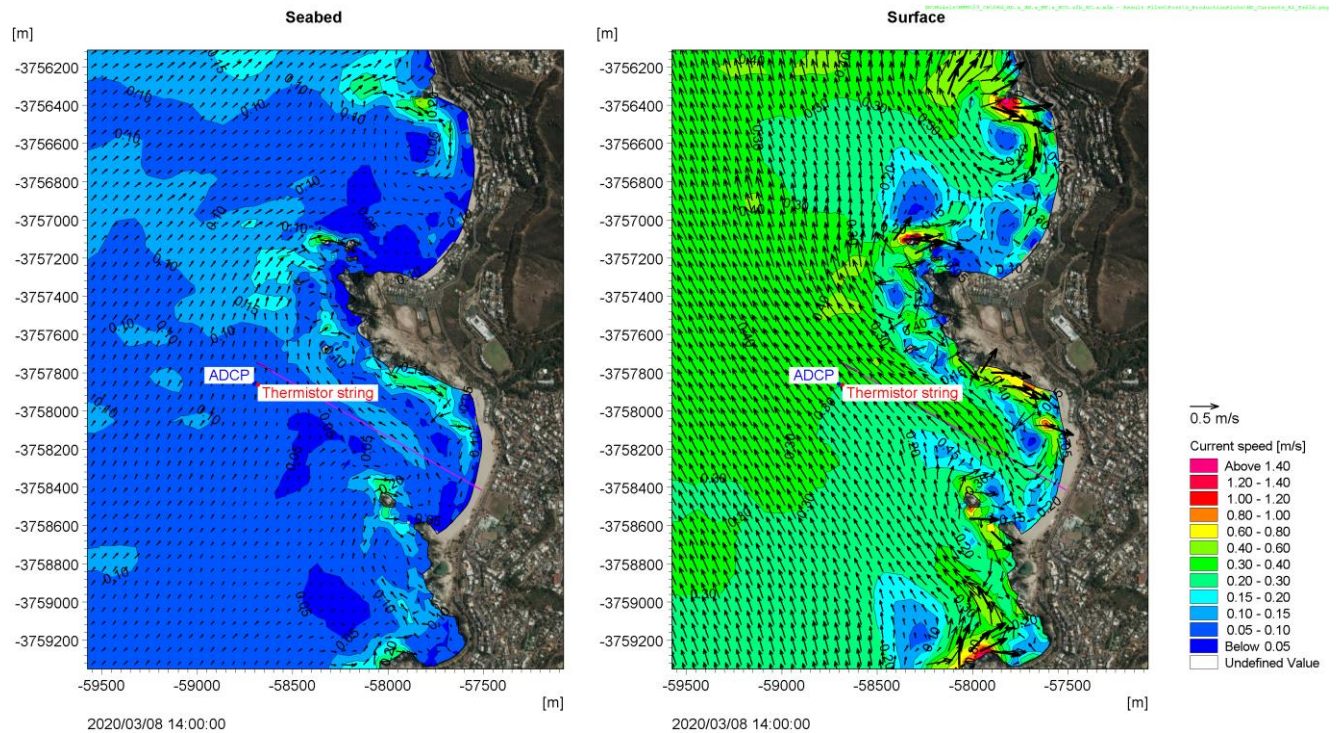


Figure 5-18: Summer/autumn: Contour plot of instantaneous seabed (left) and surface (right) currents during a west-south-westerly wave/south-easterly wind event (shown in Figure 5-1).

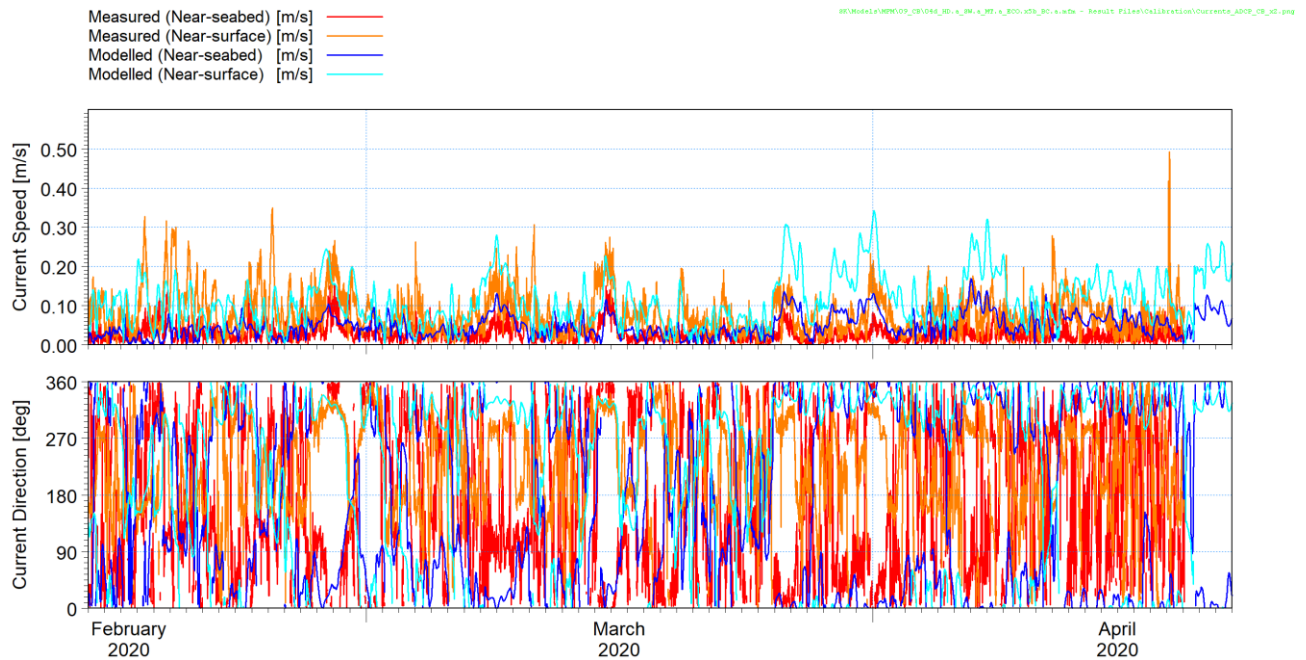


Figure 5-19: Summer/autumn: Time series comparison of measured and modelled current speed and direction at the ADCP.

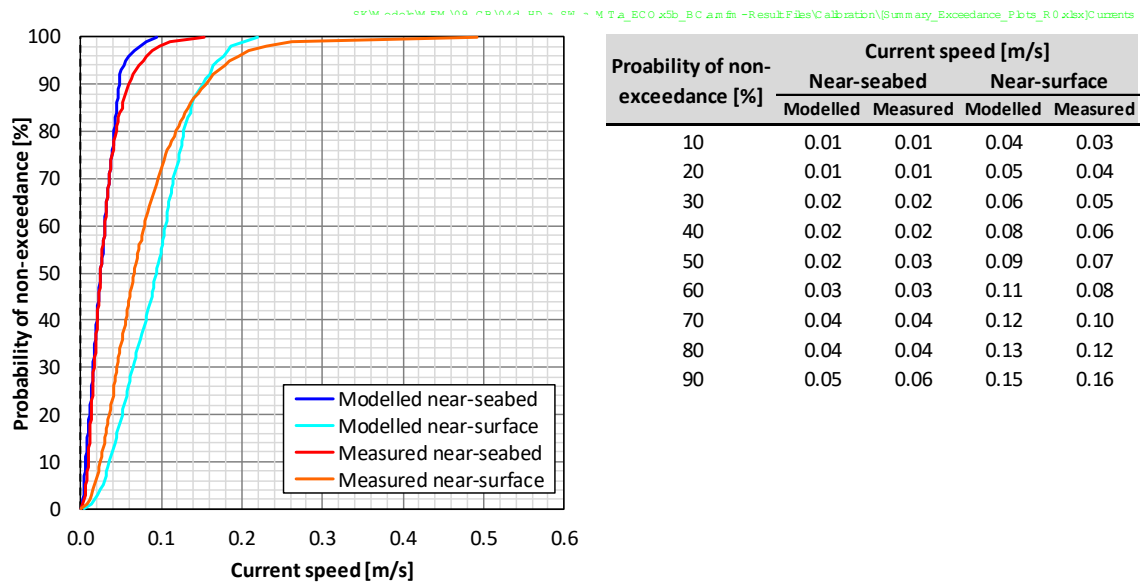


Figure 5-20: Summer/autumn: Probability of non-exceedance for measured and modelled current speed for the 10-week deployment period at the ADCP.

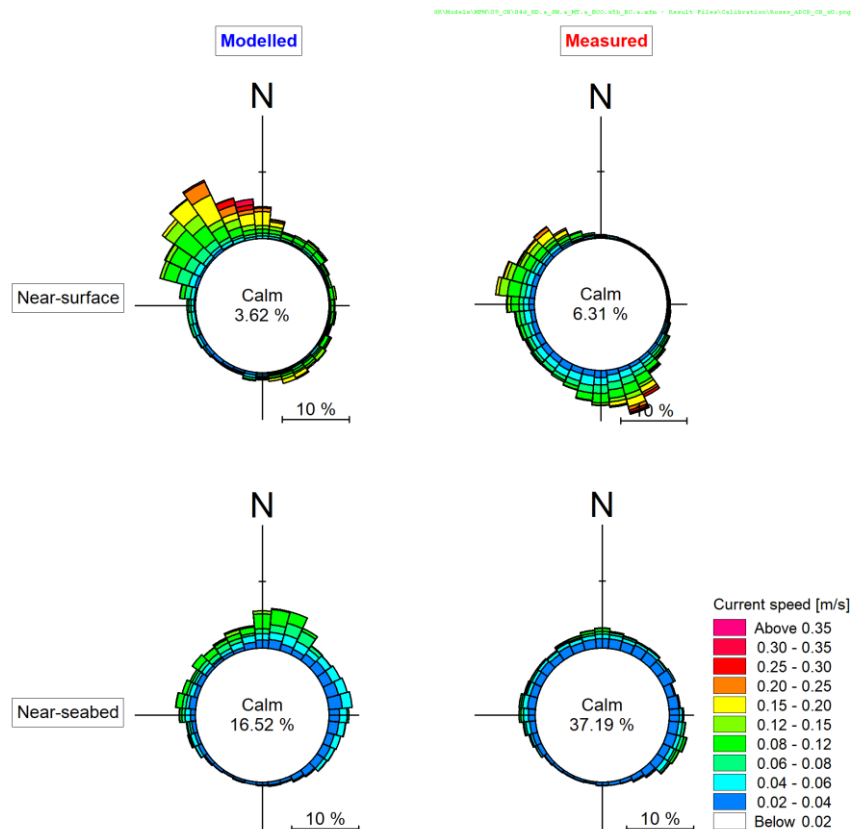


Figure 5-21: Summer/autumn: Measured and modelled current roses for the 10-week deployment period at the ADCP.

Statistically the model shows a good correlation with the measured current speeds, especially near the seabed. The near-surface currents were overestimated for some of the events between end-March and end-

April. Similar to the winter/spring calibration, the model predicts more frequent north to north-easterly currents, while underpredicting the south-easterly to southerly currents observed in the measurements.

The discrepancies between the measured and modelled currents are attributed to the intricacy of the local currents associated with the variable local wind fields, the presence of kelp and the irregular and complex bathymetric features as discussed in Section 5.1.3.

The model is able to reproduce the main features of the currents and is considered to be acceptable for the purposes of this study.

5.2.4 Temperature

The modelled seawater temperatures were compared to measurements near the seabed (5.0 m above the seabed) and near the surface (15.9 m above the seabed). Figure 5-22 presents a time series comparison of the modelled and measured seawater temperatures. Non-exceedance curves of near-seabed and near-surface temperatures for the 10-week period are shown Figure 5-23. Figure 5-24 presents non-exceedance curves of stratification (near-seabed to near-surface) from the measured and modelled temperatures.

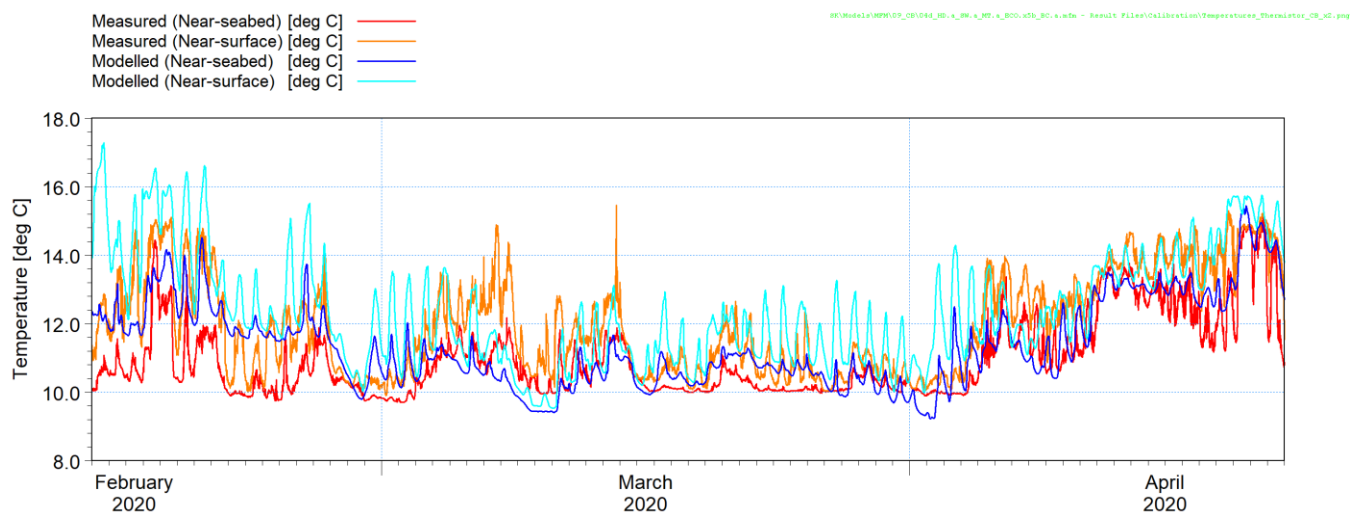


Figure 5-22: Summer/autumn: Time series of measured and modelled seawater temperatures at the thermistor string.

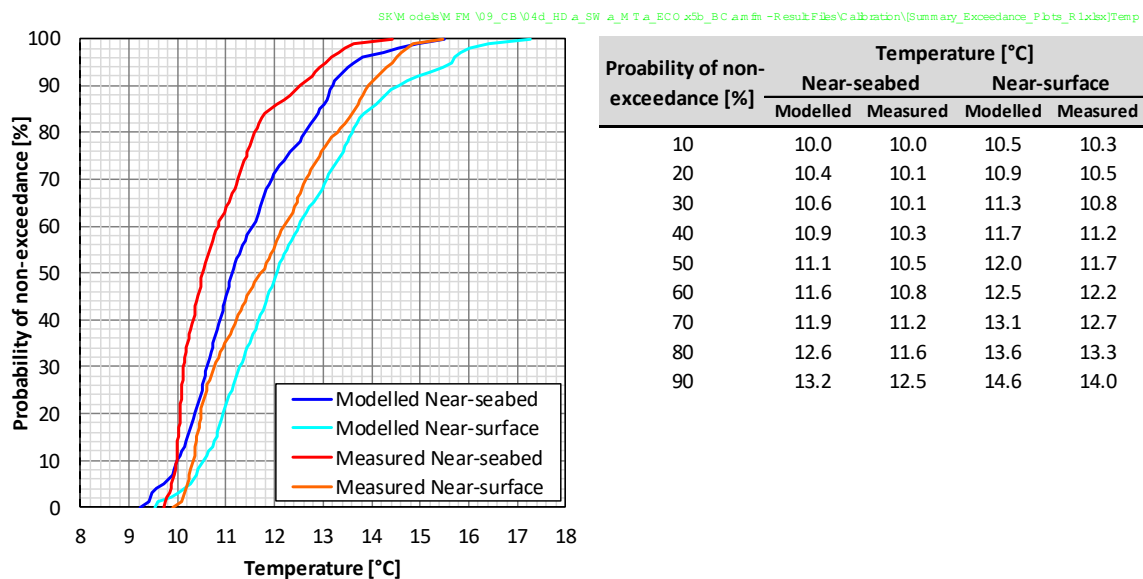


Figure 5-23: Summer/autumn: Probability of non-exceedance of measured and modelled seawater temperatures for the 10-week deployment period at the thermistor string.

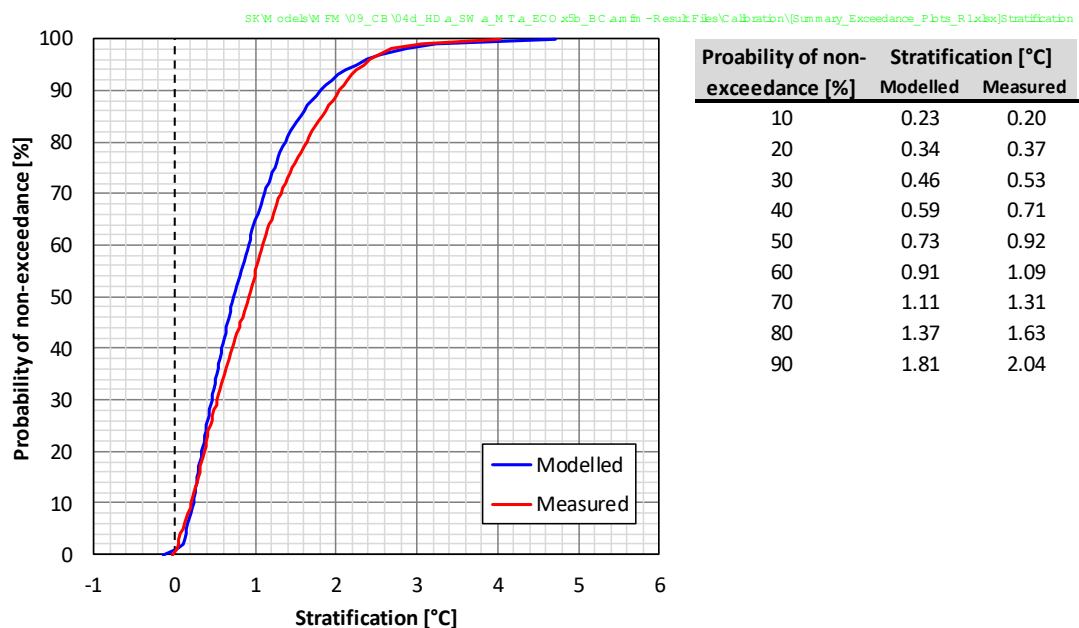


Figure 5-24: Summer/autumn: Probability of non-exceedance of measured and modelled seawater temperature stratification (near-seabed to near-surface) for the 10-week deployment period at the thermistor string.

The model is able to predict the mean trend in near-surface and near-seabed seawater temperatures including some of the discrete dynamic events. On average the model overpredicts the temperatures, however the model shows a fair statistical distribution of temperatures and the resultant stratification, the latter being an important determinant of the rise height of the plume in the near-field. The model is therefore considered to be adequately calibrated for seawater temperature for the purposes of this study.

6. MODEL RESULTS

6.1 Winter/spring

The outfall dispersion model was run for a 10-week period between 1 August 2019 and 9 October 2019 to represent environmental conditions for winter and spring.

The model outputs are the concentrations of E.coli, enterococci, TSS and a conservative tracer in each horizontal and vertical element of the computational mesh at 1-hour intervals throughout the simulation period.

6.1.1 Plume dynamics

Figure 6-1 and Figure 6-2 present examples of the current vectors and E.coli plume at a moment in time for southerly and north-westerly wind conditions. These results show the complex 3D dynamic behaviour of the plume.

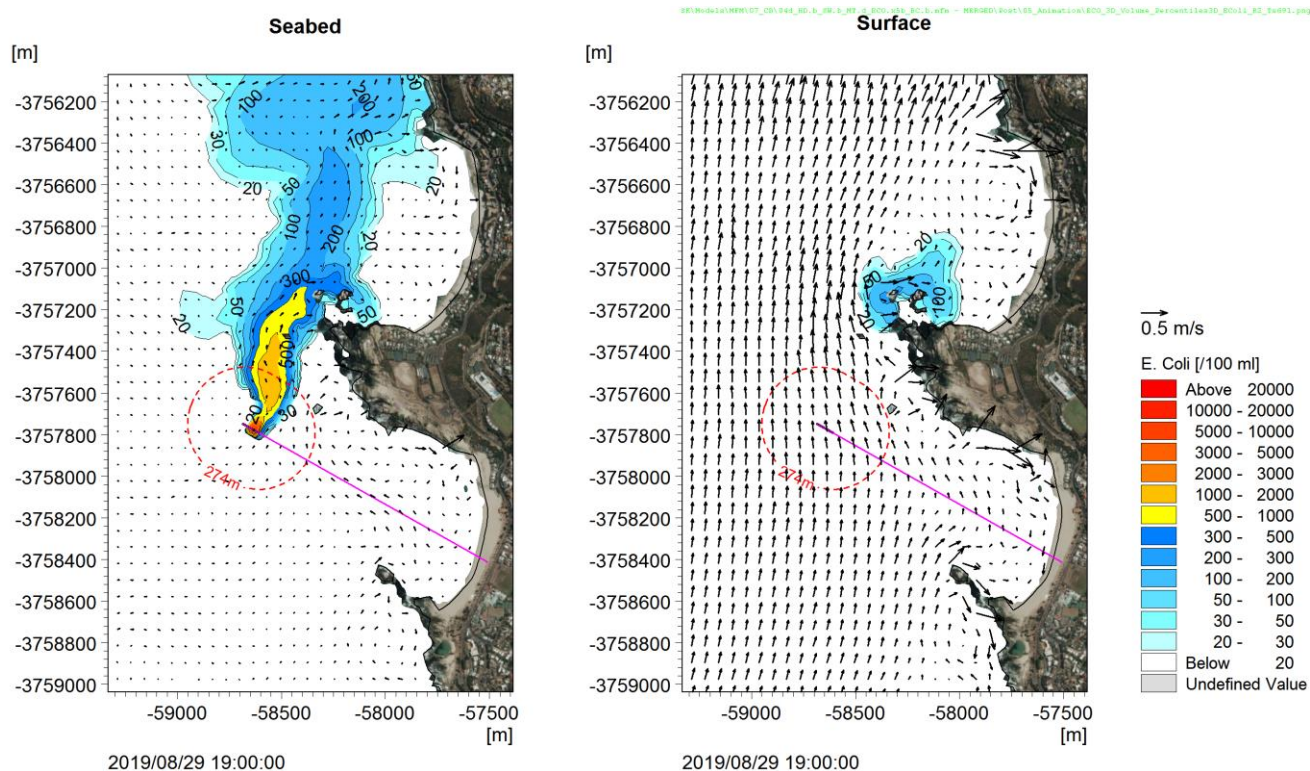


Figure 6-1: Winter/spring: Current vectors and E.coli plume at a moment in time during a southerly wind condition.

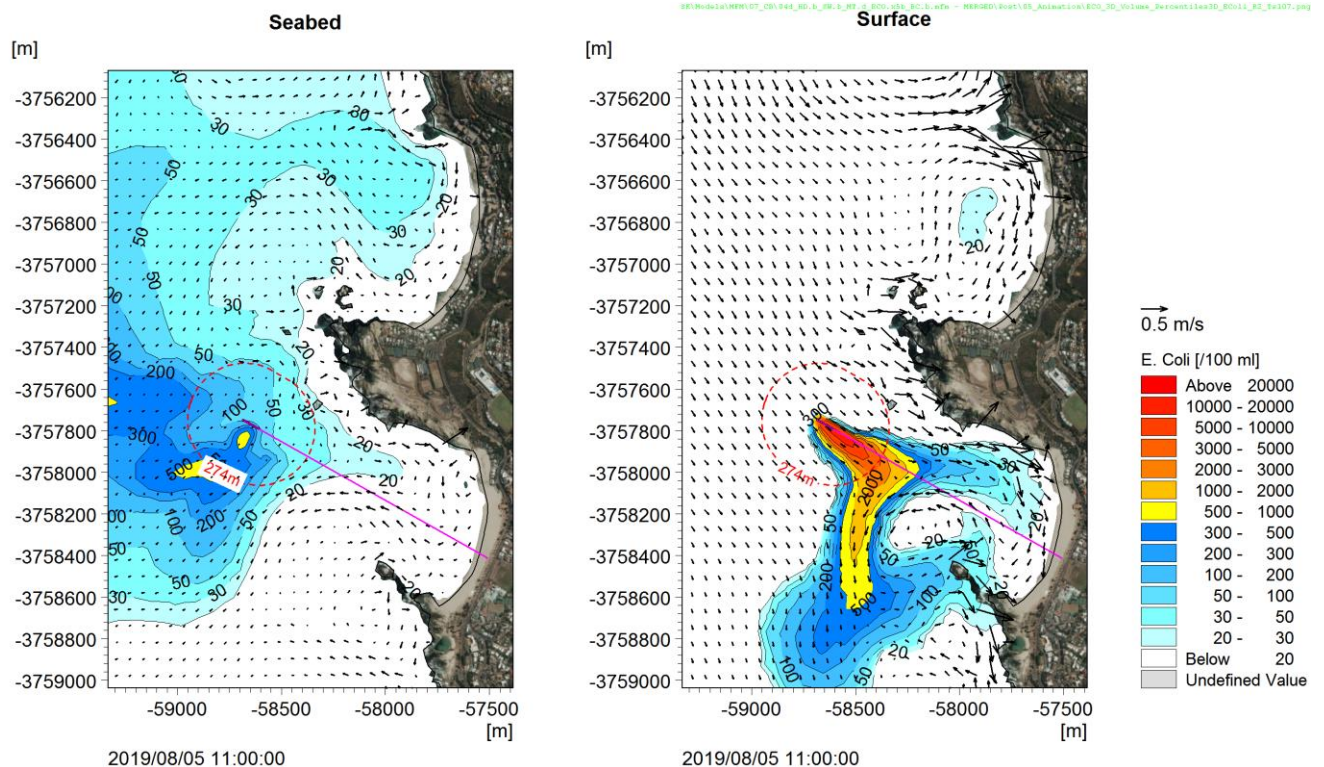


Figure 6-2: Winter/spring: Current vectors and E.coli plume at a moment in time during a north-westerly wind condition.

6.1.2 Dilutions

The concentrations from the conservative tracer were processed to number of dilutions using the equation:

$$\text{Number of dilutions} = \frac{\text{Effluent concentration}}{\text{Dispersed concentration}}$$

The modelled outputs were further processed to extract the 5th percentile number of dilutions in each horizontal and vertical element of the computational mesh. The 5th percentile number of dilutions will be exceeded 95% of the time and are thus close to the expected minimum number of dilutions (i.e. close to the worst case).

Figure 6-3, Figure 6-4 and Figure 6-5 present the 5th percentile dilutions at the seabed, mid-depth (this is the depth below the surface equal to 60% of the local water depth) and surface. Figure 6-6 shows a cross section of the 5th percentile number of dilutions extracted along the longest axis of the plume (marked by the dashed green line on the contour plots). Dilutions less than 2 000 are shown in orange as this is close to the dilution required for TSS of 1 550 as discussed in Section 3.4.1. Dilutions greater than 2 000 are shown in shades of blue. Although these exceed the required dilutions for the identified critical constituents, they provide information on the far-field behaviour of the plume.

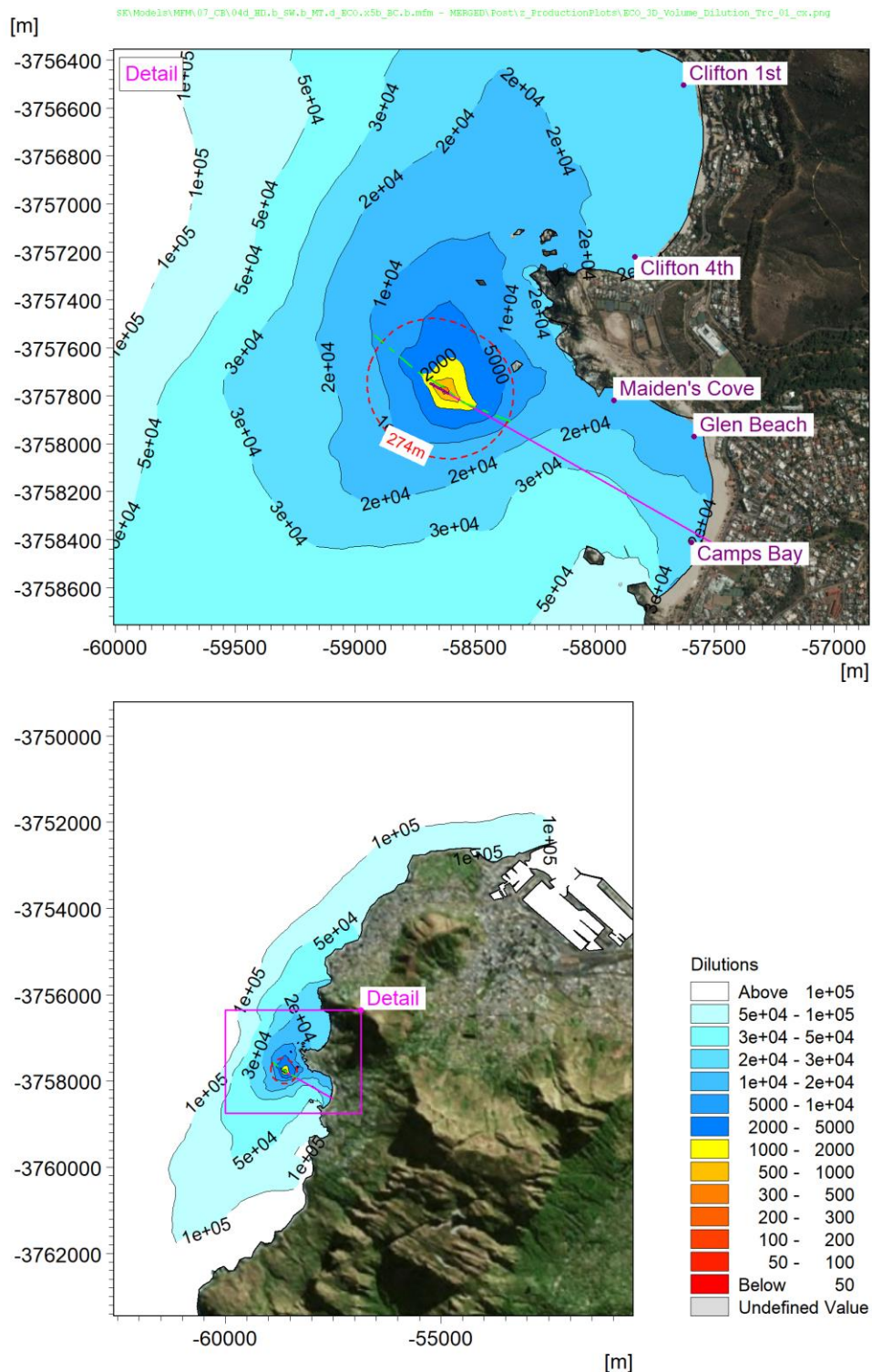


Figure 6-3: Winter/spring: Number of dilutions at the seabed, 5th percentile.

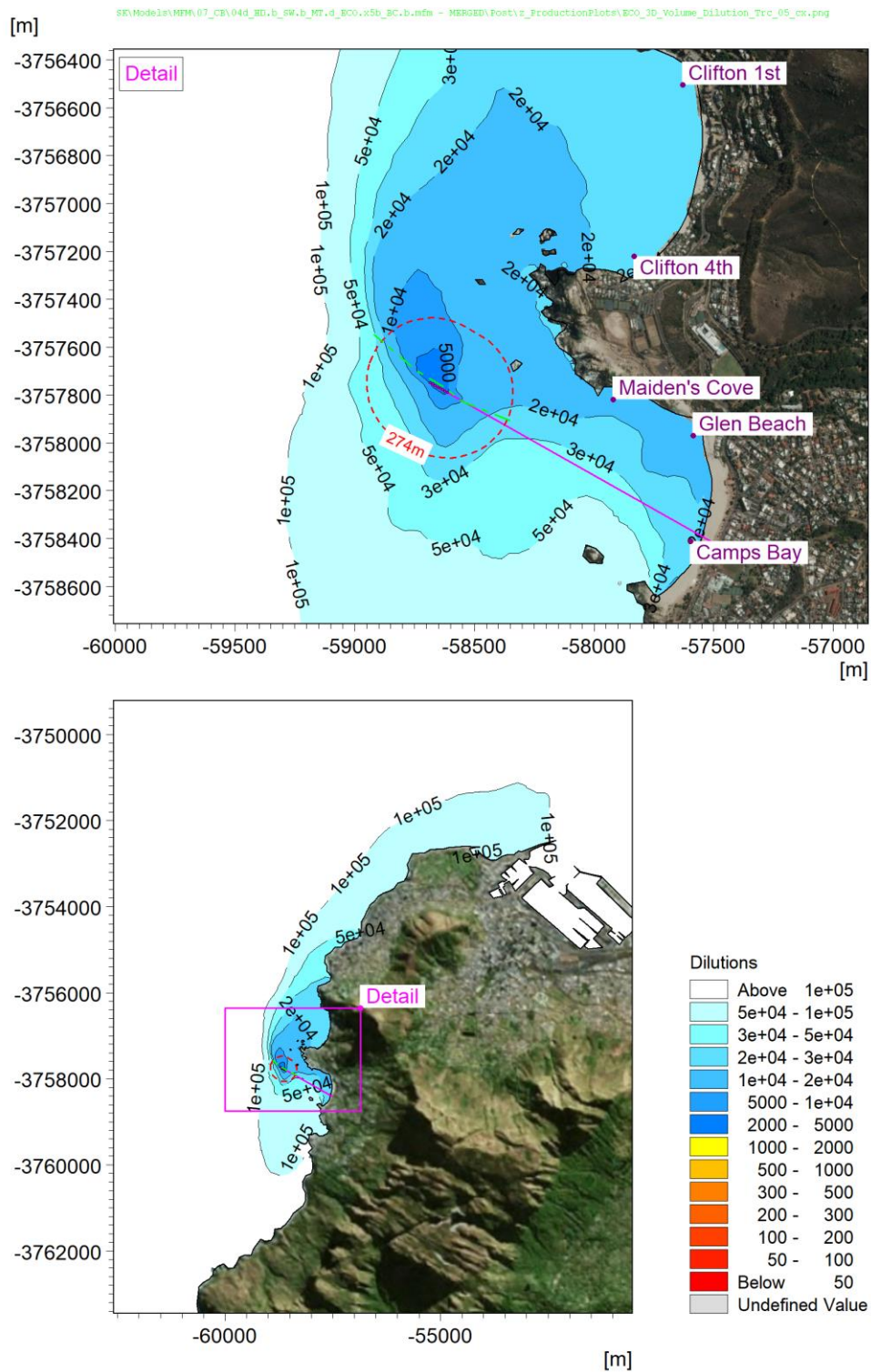


Figure 6-4: Winter/spring: Number of dilutions at mid-depth, 5th percentile.

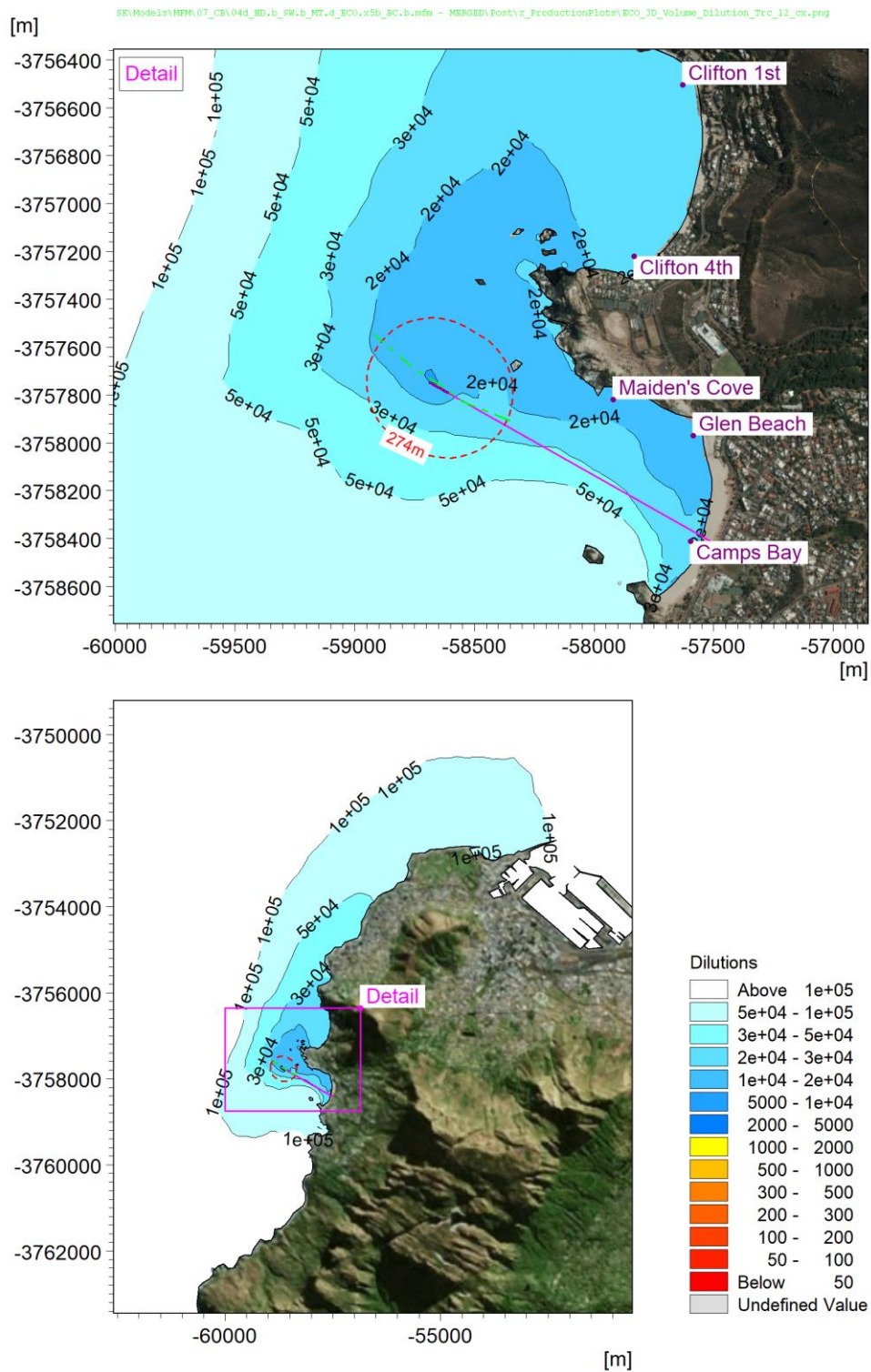


Figure 6-5: Winter/spring: Number of dilutions at the surface, 5th percentile.

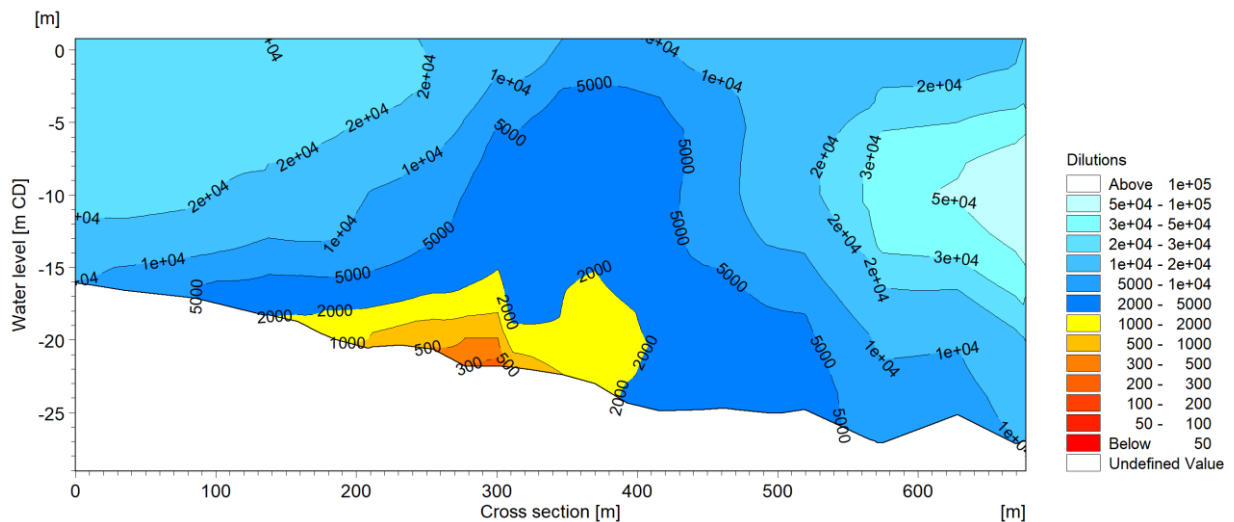


Figure 6-6: Cross section of 5th percentile number of dilutions along the longest axis of the plume.

The minimum dilutions achieved at the edge of the mixing zone was extracted from the 5th percentile dilutions and is presented Table 6-1.

Table 6-1: Winter/spring: Minimum number of dilutions achieved at edge of the mixing zone.

Parameter	Value
Minimum number of dilutions achieved at any depth along the edge of the allowable mixing zone (radius = 274 m), 5 th percentile	3 480

The distance from the diffuser to achieve the required dilutions for the three critical constituents (Table 3-4) are presented in Table 6-2.

Table 6-2: Winter/spring: Distance to achieve dilutions, 5th percentile.

Constituent	Dilutions required	Distance
Ammonia	154	< 25 m
COD	48	< 25 m
TSS	1 550	115 m

The mixing zone spreads the furthest in the longshore direction, due to advection by the predominantly northward currents. Due to the low discharge rates from the diffuser ports the positively buoyant effluent plume usually becomes passive within a short distance from the seabed, resulting in lower dilutions at the seabed. Occasional surfacing of the plume happens during periods of high effluent flows or stagnant hydrodynamic conditions. Upwelling events can also push the effluent to the surface at the shoreline, but the plume is characteristically more diluted in such events.

The minimum number of dilutions achieved in the allowable mixing zone is 3 480. The constituent requiring the highest dilutions is TSS, which achieved the 1 550 required dilutions 115 m from the diffuser. Ammonia and COD achieved the required dilutions in within 25 m. Note that distances smaller than 25 m could not be measured in the model, due to the mesh resolution.

6.1.3 Bacteria

In addition to dilutions by hydrodynamic processes the bacterial concentrations are further reduced due to bacterial die-off (as described in Section 2.3.2). Figure 6-7 presents the surface and seabed T_{90} values for E.coli and enterococci, extracted in the middle of the Camps Bay diffuser at a depth of -22.1 m CD. Recall from Section 2.3.2.1 the median T_{90} ratio of enterococci to E.coli is 2.39.

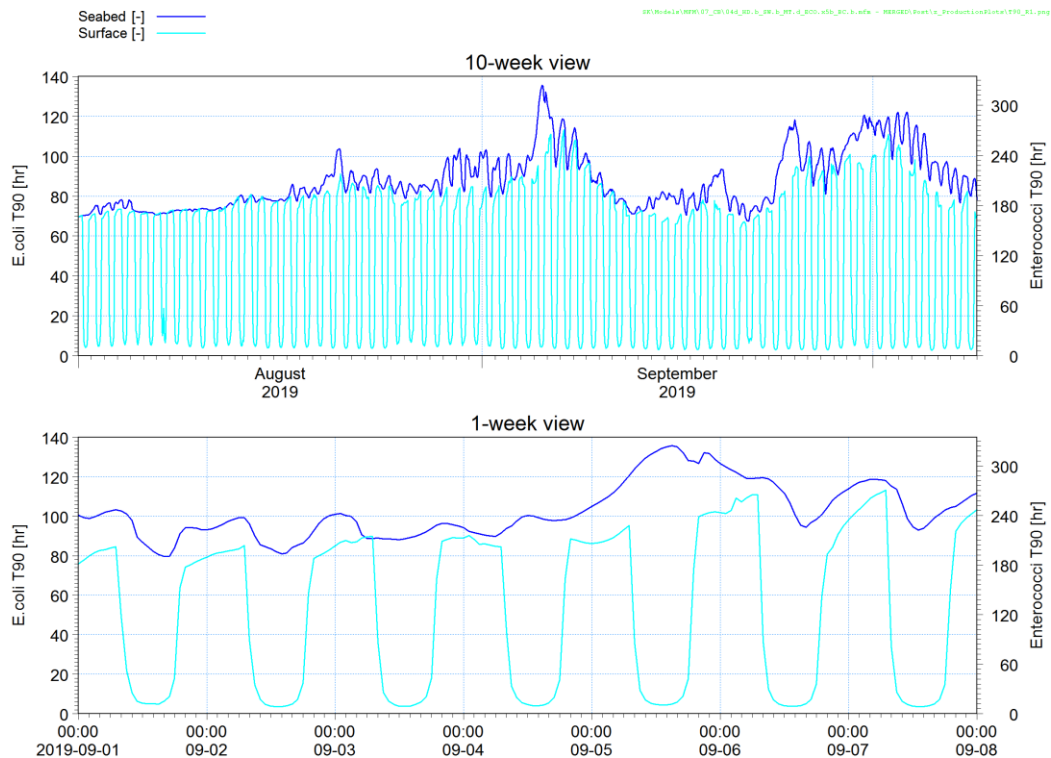


Figure 6-7: Winter/spring: Surface and seabed T_{90} values for E.coli and enterococci.

A significant diurnal variation in die-off rates due to the solar radiation can be observed at the surface, while the seabed remains mostly unaffected due to light attenuation. In the absence of light, the seawater temperature dominates the die-off processes and the stratification determines the gradient between the surface and seabed T_{90} values.

Based on the DEA guidelines (Table 3-5), the model outputs of bacterial concentrations were further processed to extract the 90th percentile concentration at each horizontal and vertical element of the computational mesh for the full simulation period. The 90th percentiles were only sampled during daylight hours (between 07:00 to 18:00) to emulate the recommended microbiological sampling regime in the guidelines.

6.1.3.1 E.coli

Figure 6-8, Figure 6-9 and Figure 6-10 present the 90th percentile E.coli concentrations at the seabed, mid-depth and surface. Concentrations greater than 500 CFU/100 ml are shown in orange as this is the guideline for E.coli as discussed in Section 3.4.2. Concentrations less than 500 CFU/100 ml are shown in shades of blue. Although these are less than the guideline, they provide information on the far-field behaviour of the plume. A time series of highest E.coli concentrations at any depth at five key locations (Camps Bay, Glen Beach,

Maiden's Cove, Clifton 4th and Clifton 1st) is shown in Figure 6-11. The locations are shown in the contour plots.

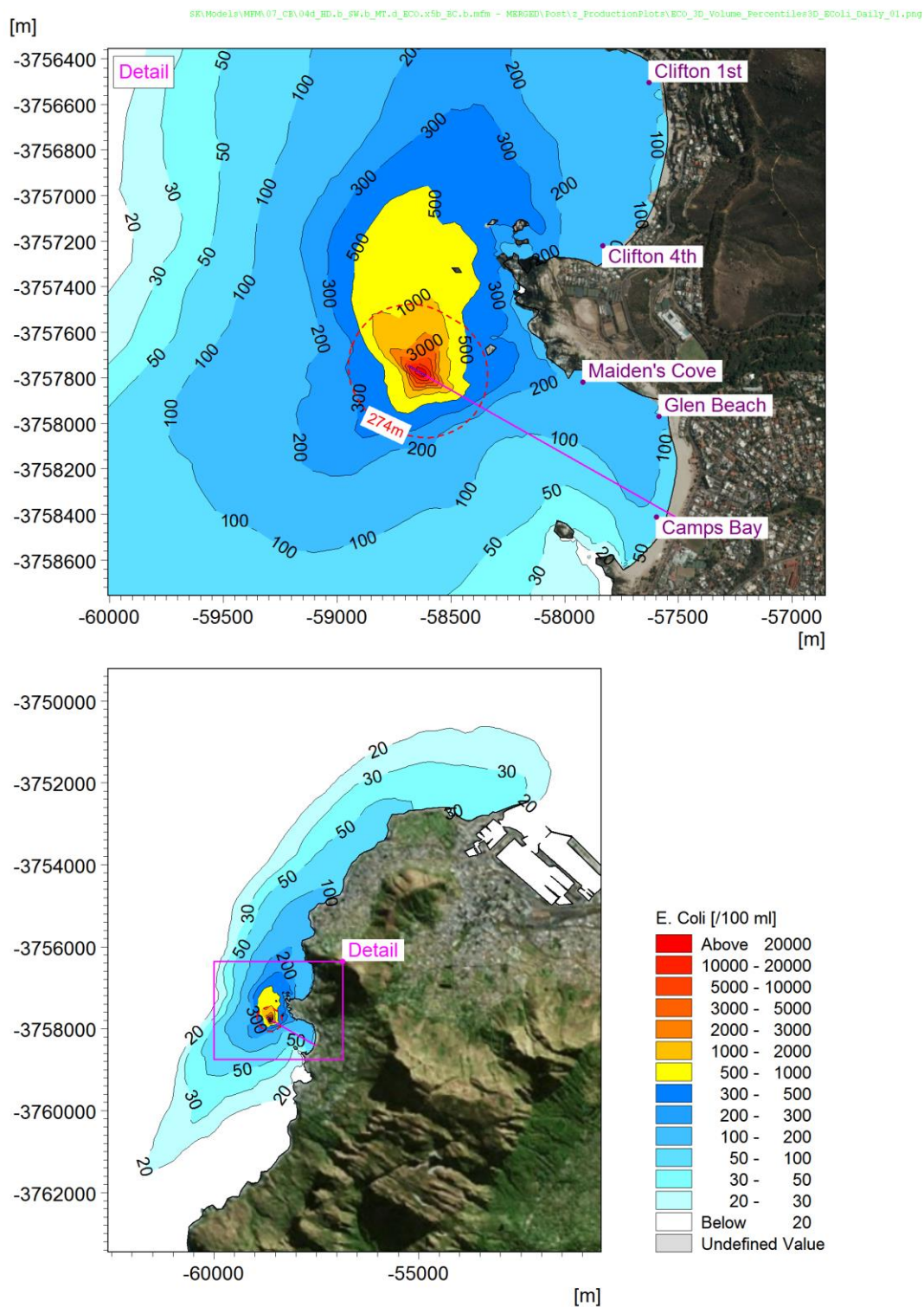


Figure 6-8: Winter/spring: E.coli concentration at the seabed, 90th percentile for daylight hours (07:00 – 18:00).

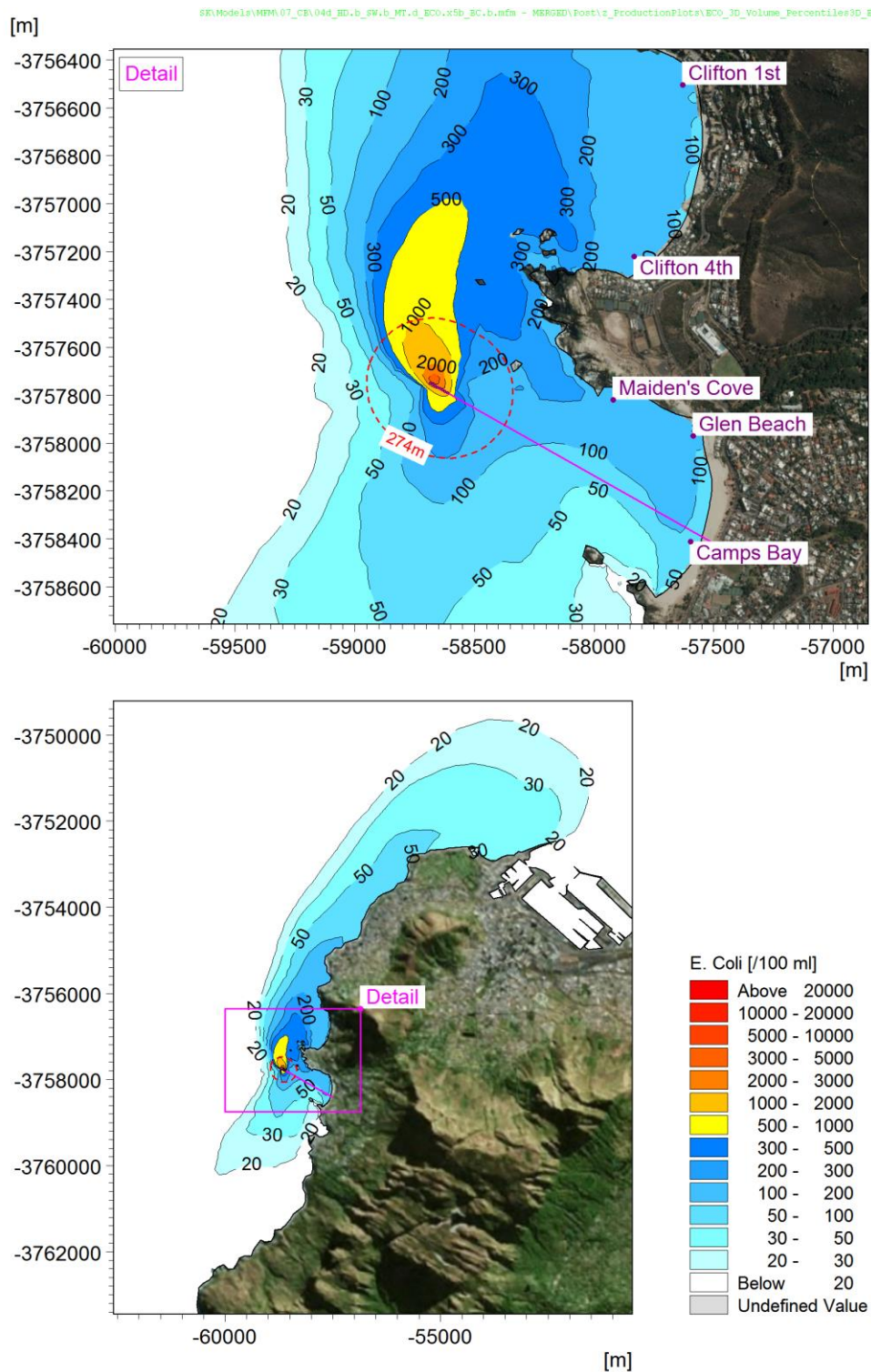


Figure 6-9: Winter/spring: E.coli concentration at mid-depth, 90th percentile for daylight hours (07:00 – 18:00).

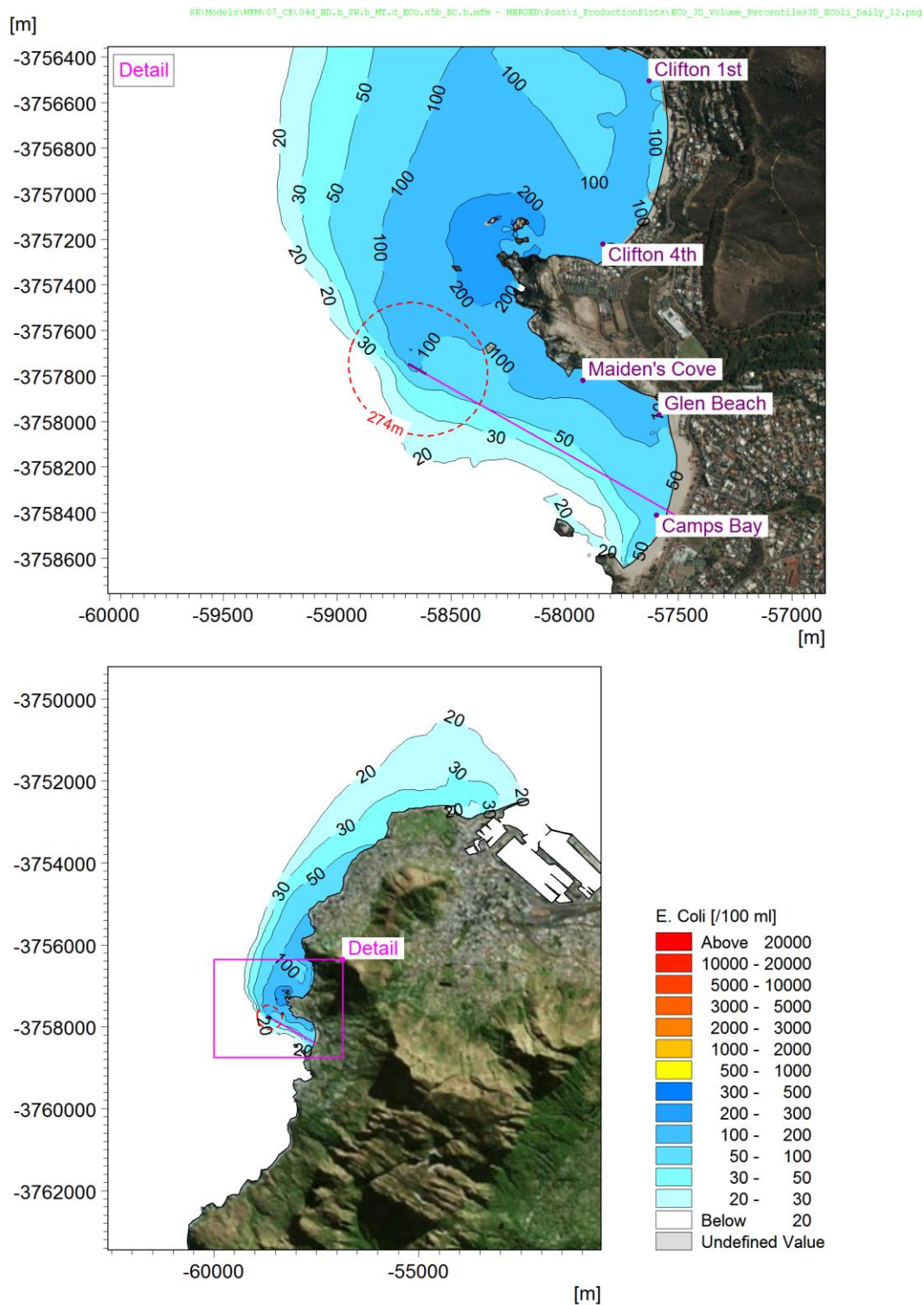


Figure 6-10: Winter/spring: E.coli concentration at the surface, 90th percentile for daylight hours (07:00 – 18:00).

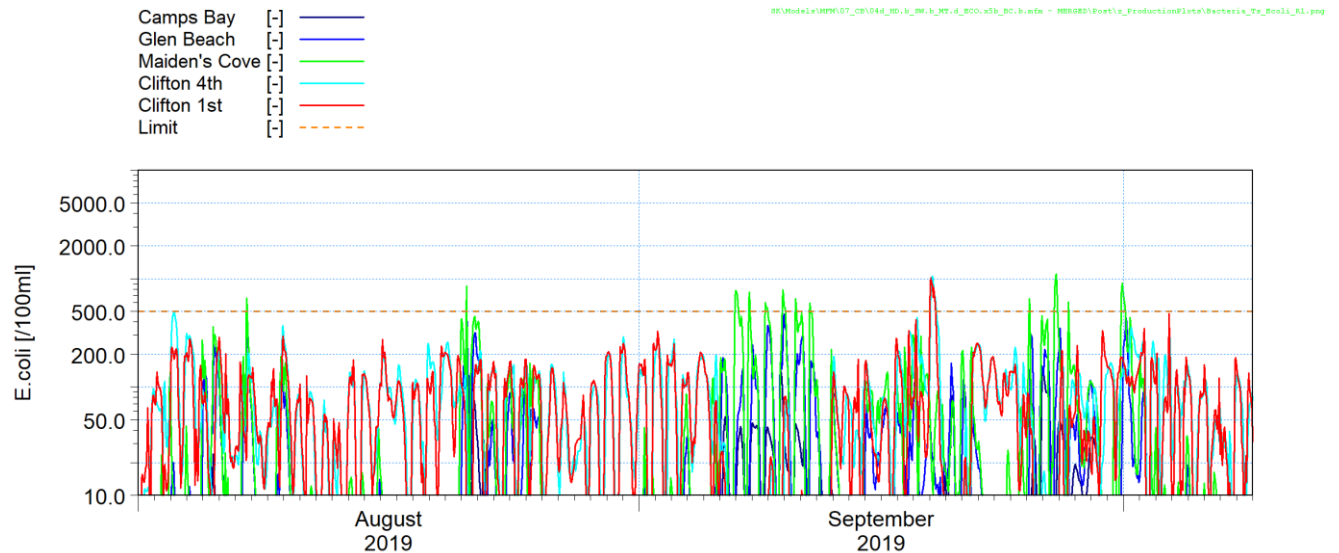


Figure 6-11: Winter/spring: Time series of highest E.coli concentration at any depth at five key locations. The water quality guideline (500 CFU/100 ml 90th percentile in daylight) is also shown in orange.

A mixing zone distance of 800 m was required to meet the 90th percentile water quality guideline of 500 CFU/100 ml. The contour plots show that the 90th percentile E.coli concentrations were the highest at the seabed and concentrations above the 500 CFU/100 ml guideline did not intersect with the shoreline. The time series plot shows that although Maidens Cove, Clifton 1st and Clifton 4th are briefly exposed to concentrations above 500 CFU/100 ml on a number of occasions, the duration of these events was less than 10% of the daylight time and therefore met the water quality guidelines.

6.1.3.2 Enterococci

Figure 6-12, Figure 6-13 and Figure 6-14 present the 90th percentile enterococci concentrations at the seabed, mid-depth and surface. Concentrations greater than 185 CFU/100 ml are shown in orange as this is the guideline for enterococci as discussed in Section 3.4.2. Concentrations less than 185 CFU/100 ml are shown in shades of blue. Although these are less than the guideline, they provide information on the far-field behaviour of the plume. A time series of enterococci concentrations at five key locations is shown in Figure 6-15.

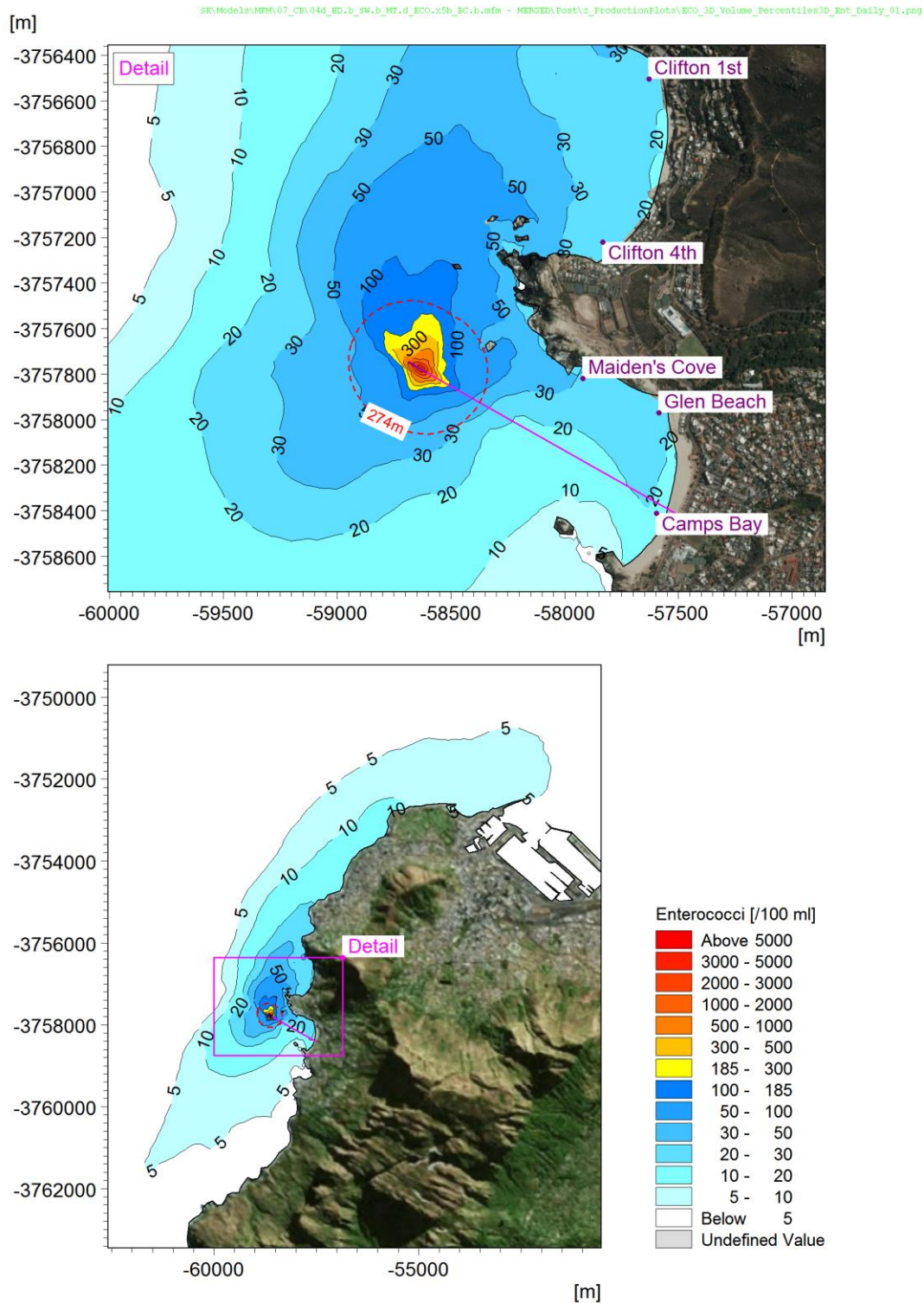


Figure 6-12: Winter/spring: Enterococci concentration at the seabed, 90th percentile for daylight hours (07:00 – 18:00).

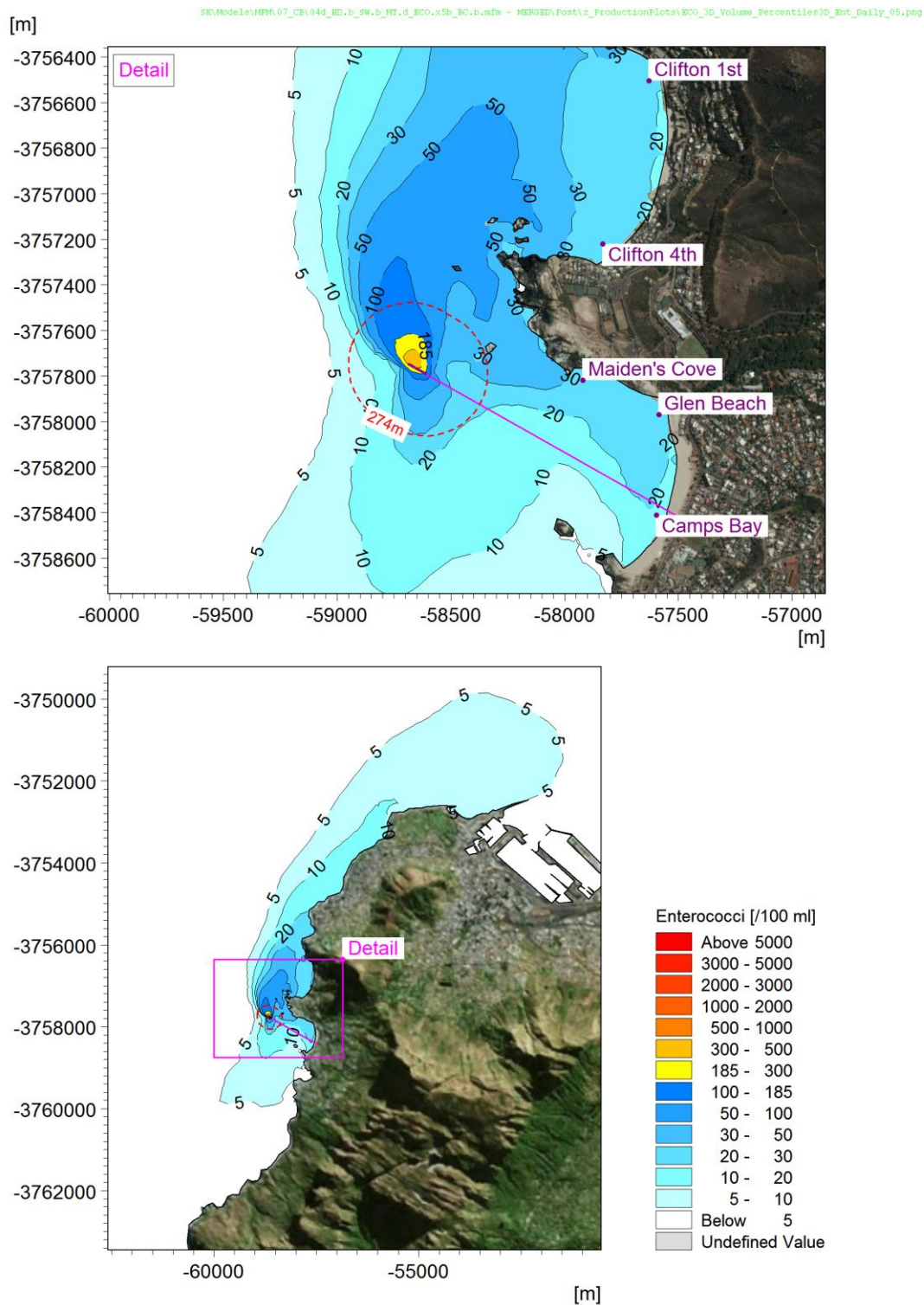


Figure 6-13: Winter/spring: Enterococci concentration at mid-depth, 90th percentile for daylight hours (07:00 – 18:00).

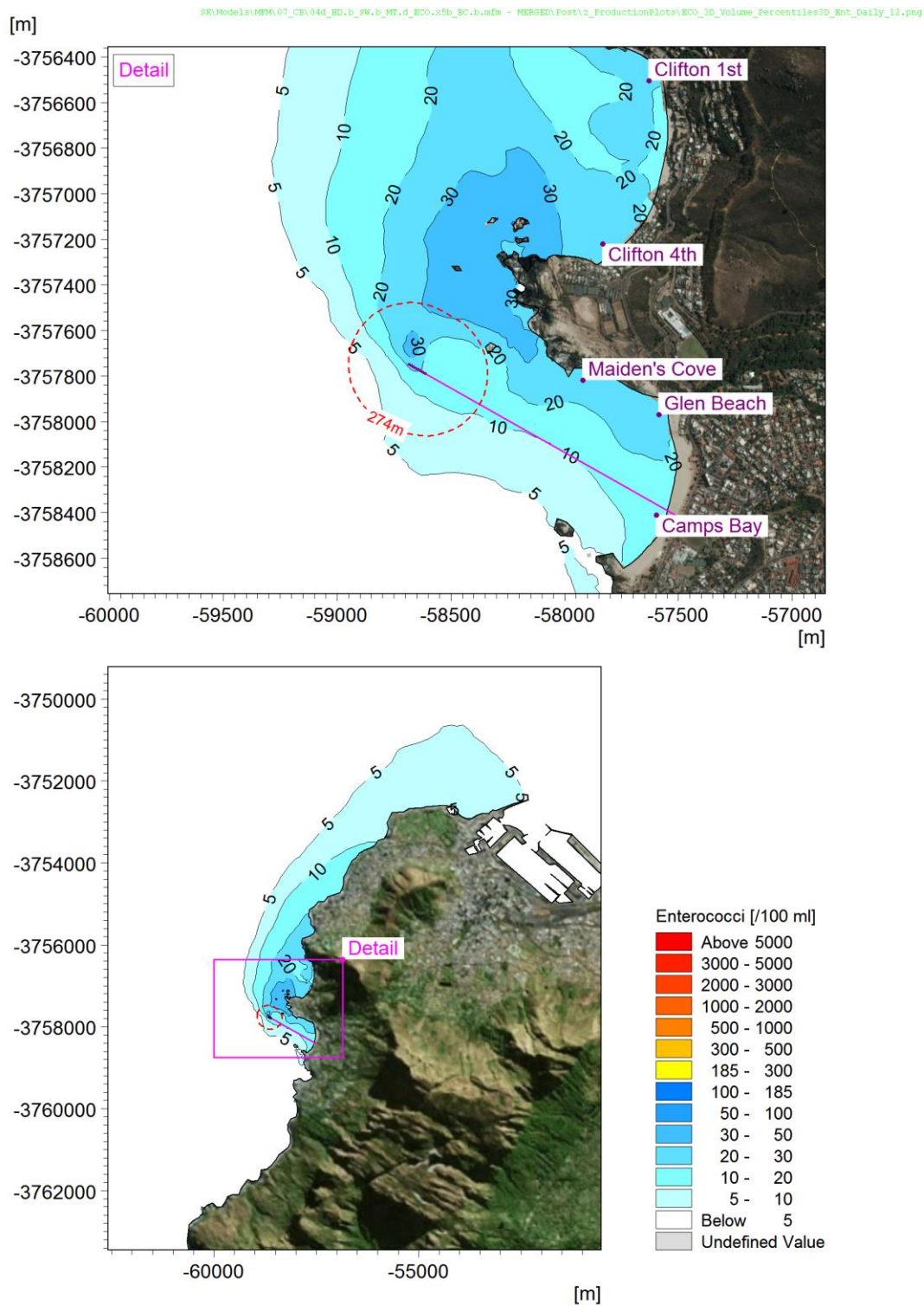


Figure 6-14; Winter/spring: Enterococci concentration at the surface, 90th percentile for daylight hours (07:00 – 18:00).

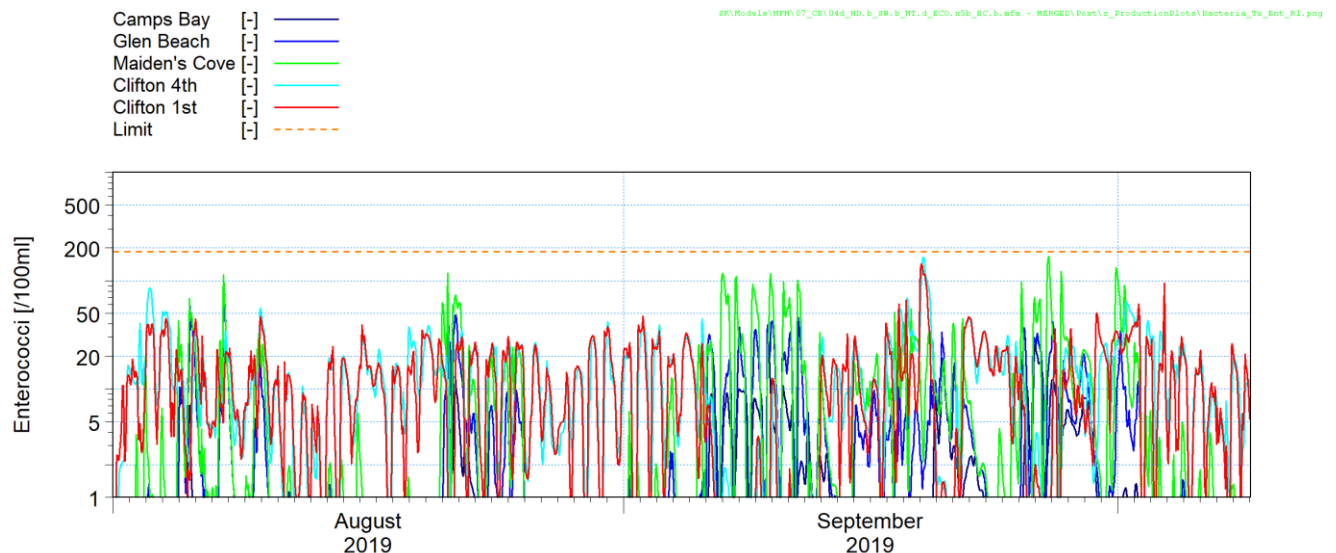


Figure 6-15: Winter/spring: Time series of highest enterococci concentration at any depth at five key locations. The water quality guideline (185 CFU/100 ml 90th percentile in daylight) is also shown in orange.

A mixing zone distance of 260 m was required to meet the 90th percentile water quality guideline of 185 CFU/100 ml. The contour plots show that the 90th percentile enterococci concentrations were the highest at the seabed and concentrations above the 185 CFU/100 ml guideline did not intersect with the shoreline. The time series plot shows that the enterococci concentrations at the key locations did not exceed 185 CFU/100 ml during the 10-week winter/spring period.

6.1.3.3 Discussion

Based on the applicable water quality guidelines (discussed in Section 3.4.2), E.coli requires a greater mixing zone distance to meet the guidelines compared to enterococci.

The bacteria plumes have higher concentrations on the seabed than the surface due to the trapping of the plume near the seabed as well as the lower bacteria die-off near the seabed (illustrated in Figure 6-7).

During typical conditions the plume is advected with the longshore current in a predominantly northward direction. Onshore movement occurs when the plume becomes entrained in horizontal currents or eddies arising from a combination of wind and breaking waves. Occasional upwelling events could also contribute to onshore transport, but these events are less frequent in the winter/spring period.

6.1.4 Total suspended solids

The concentrations of TSS were modelled in the water column and specifically where these were deposited on the seabed. This is a proxy for the fate of pollutants that adsorb to solid particles, e.g. heavy metals.

Figure 6-16 presents the bed mass of TSS at the end of the 10-week simulation. The deposited mass in the main depo-centres (demarcated in red) are summarised in Table 6-3. The table also includes the total mass of TSS that were advected outside of the model domain through the boundaries and TSS in suspension at the end of the run.

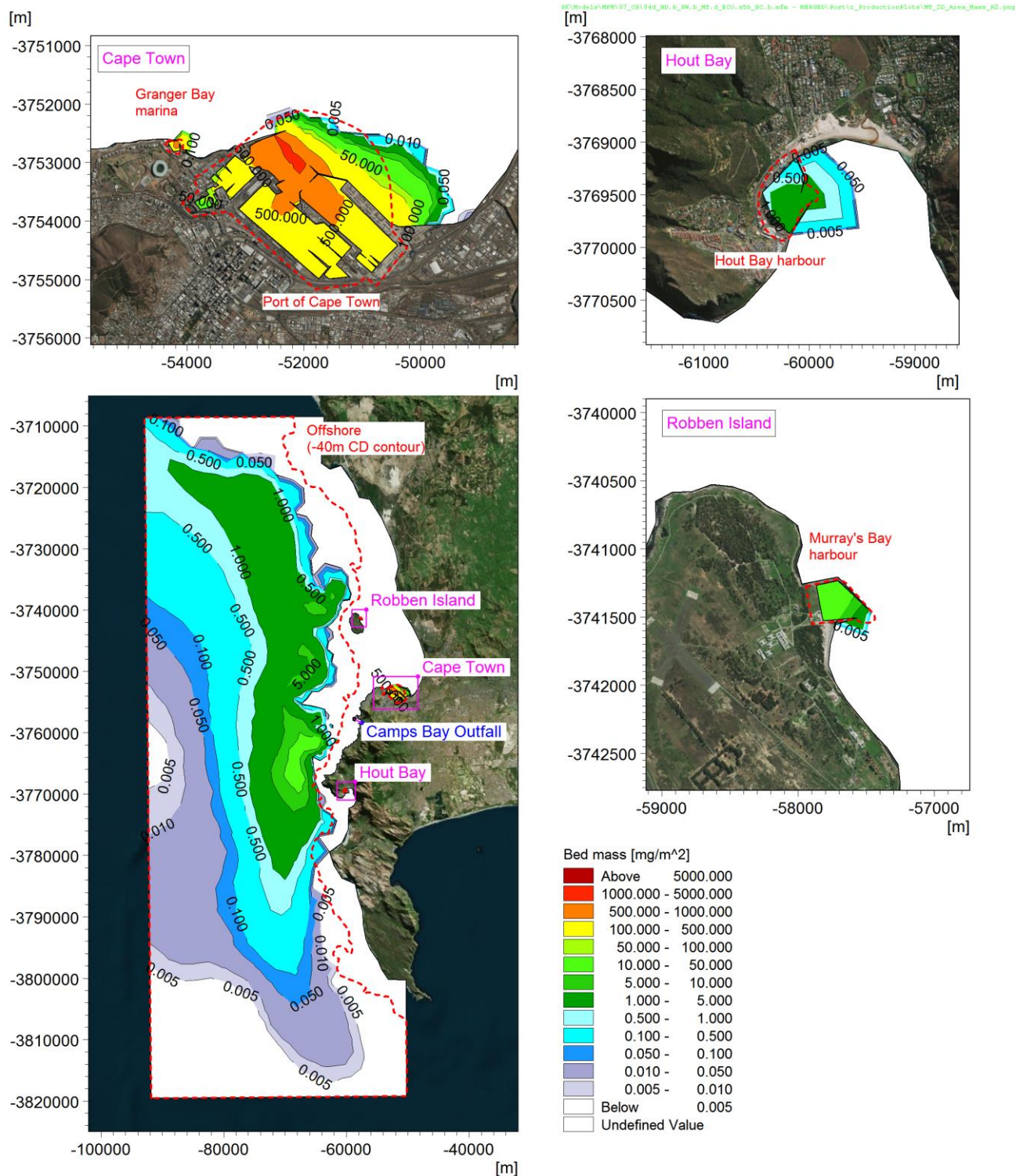


Figure 6-16: Winter/spring: Bed mass of TSS distribution at the end of the 10-week period.

Table 6-3: Winter/spring: Integrated mass at the end of the 10-week simulation period.

Area	Mass [kg]	% released
Port of Cape Town	1 800	4.5%
Murray's Bay Harbour	1.09	< 0.1%
Granger Bay	13	< 0.1%
Hout Bay	0.19	< 0.1%
Offshore (-40 m CD contour)	2 530	6.4%
Out of domain	22 100	55.6%
Suspended	13 240	33.4%
Total mass released	39 700	100%

The highest concentrations are observed in the sheltered depo-centres, i.e. the Port of Cape Town, Granger Bay marina, Murray's Bay harbour and Hout Bay harbour where the bed shear stress due to waves and currents are sufficiently low to allow deposition. Accumulation also occurs in exposed areas where the water depth is greater than approximately 40 m due to the wave orbital velocities not exerting sufficient stress on the seabed to resuspend the sediment particles.

The largest depo-centre is the Port of Cape Town with approximately 4.5% of the TSS released from the Camps Bay outfall accumulating in the port. These results can be used in the design and interpretation of sediment quality sampling studies.

6.2 Summer/autumn

The outfall dispersion model was run for a 10-week period between 13 February 2020 and 23 April 2020, coinciding with the calibration period, to represent environmental conditions for summer and autumn.

The model outputs are the concentrations of E.coli, enterococci, TSS and a conservative tracer in each horizontal and vertical element of the computational mesh at 1-hour intervals throughout the simulation period.

6.2.1 Plume dynamics

Figure 6-17 and Figure 6-18 present examples of the current vectors and E.coli plume at a moment in time for south-easterly and north-westerly wind conditions. These results show the complex 3D dynamic behaviour of the plume.

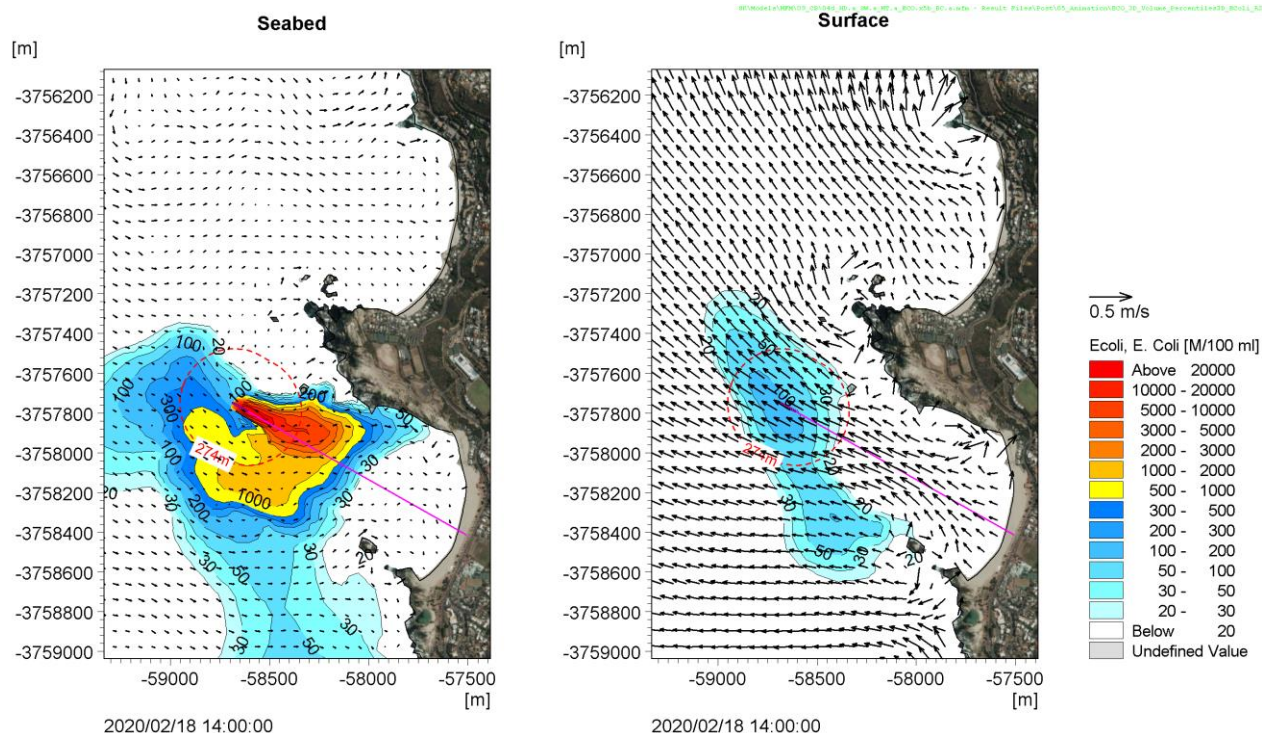


Figure 6-17: Summer/autumn: Current vectors and E.coli plume at a moment in time during a south-easterly wind condition.

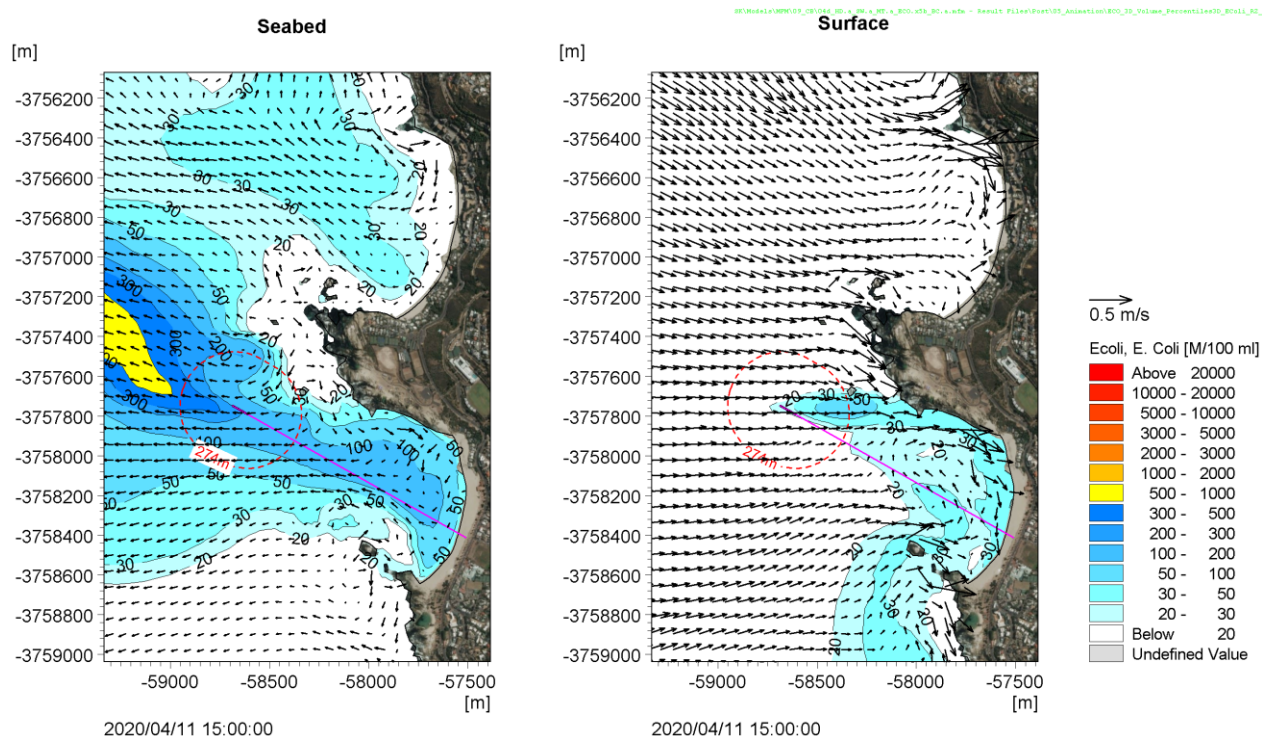


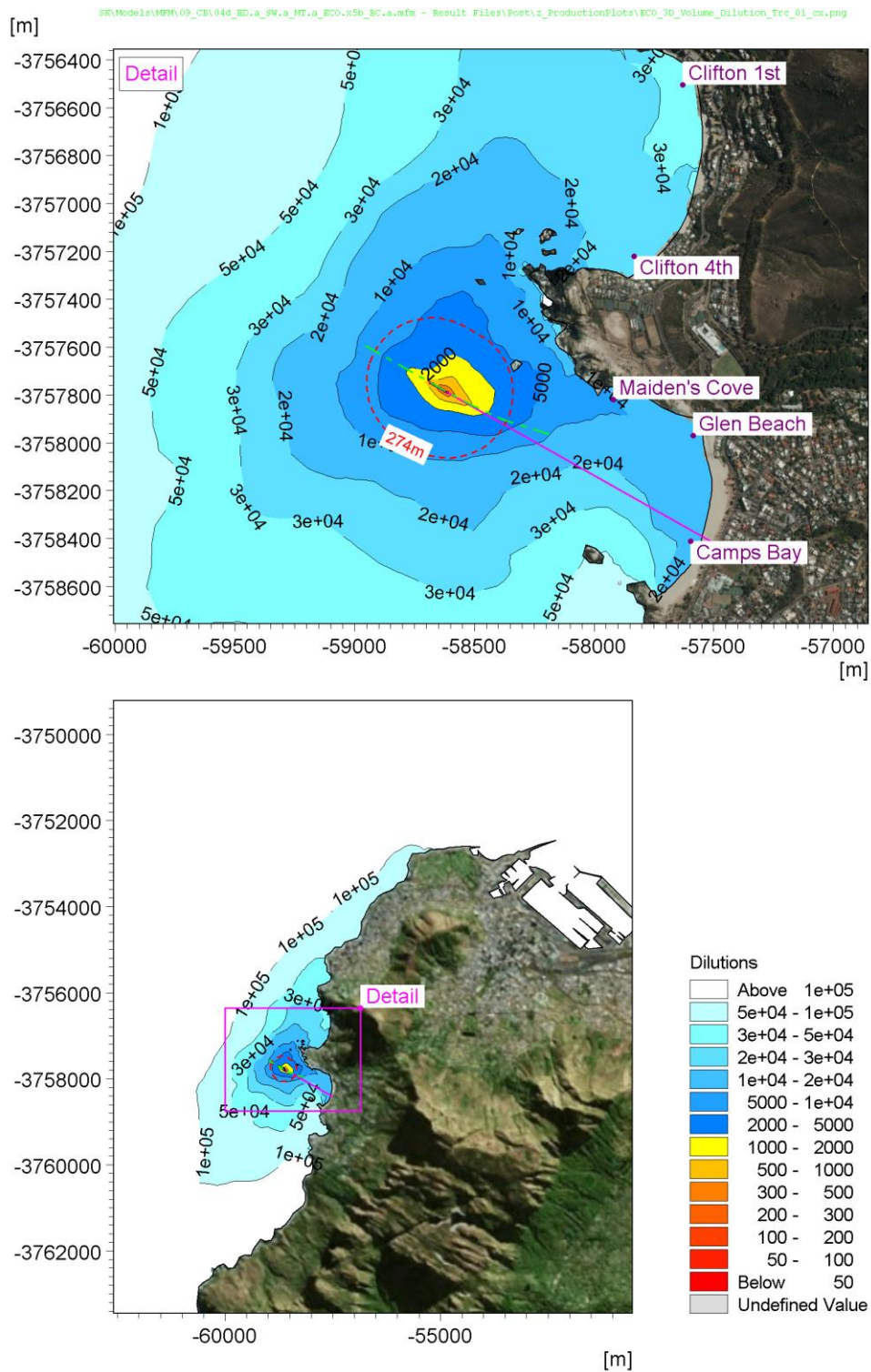
Figure 6-18: Summer/autumn: Current vectors and E.coli plume at a moment in time during a north-westerly wind condition.



6.2.2 Dilutions

The concentrations from the conservative tracer were processed to obtain the 5th percentile number of dilutions in each horizontal and vertical element of the computational mesh as discussed in Section 6.1.2.

Figure 6-19, Figure 6-20 and Figure 6-21 present the 5th percentile dilutions at the seabed, mid-depth (this is the depth below the surface equal to 60% of the local water depth) and surface. Figure 6-22 shows a cross section of the 5th percentile number of dilutions extracted along the longest axis of the plume (marked by the dashed green line on the contour plots). Dilutions less than 2 000 are shown in orange as this is close to the dilution required for TSS of 1 550 as discussed in Section 3.4.1. Dilutions greater than 2 000 are shown in shades of blue. Although these exceed the required dilutions for the identified critical constituents, they provide information on the far-field behaviour of the plume.



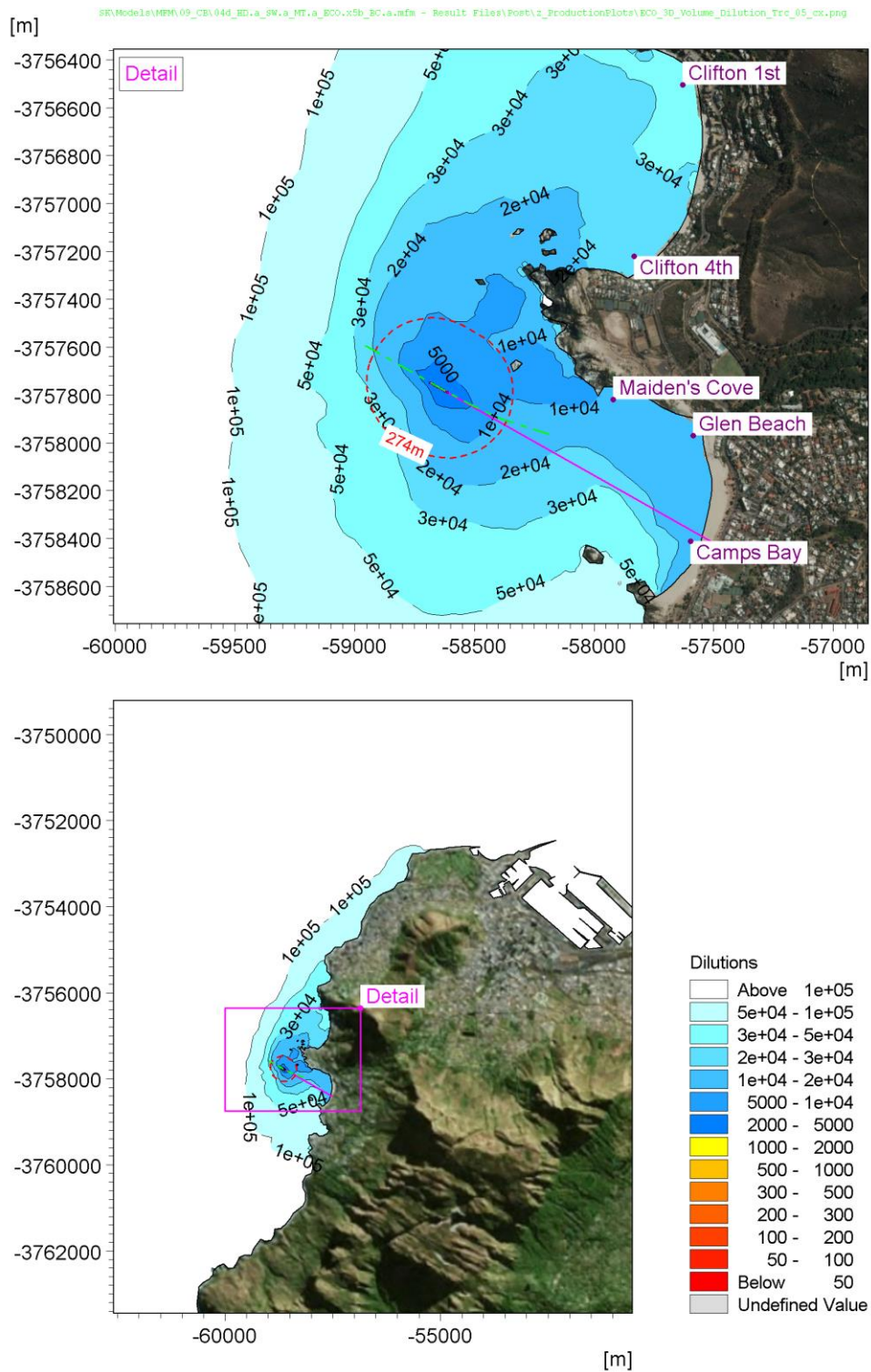


Figure 6-20: Summer/autumn: Number of dilutions at mid-depth, 5th percentile.

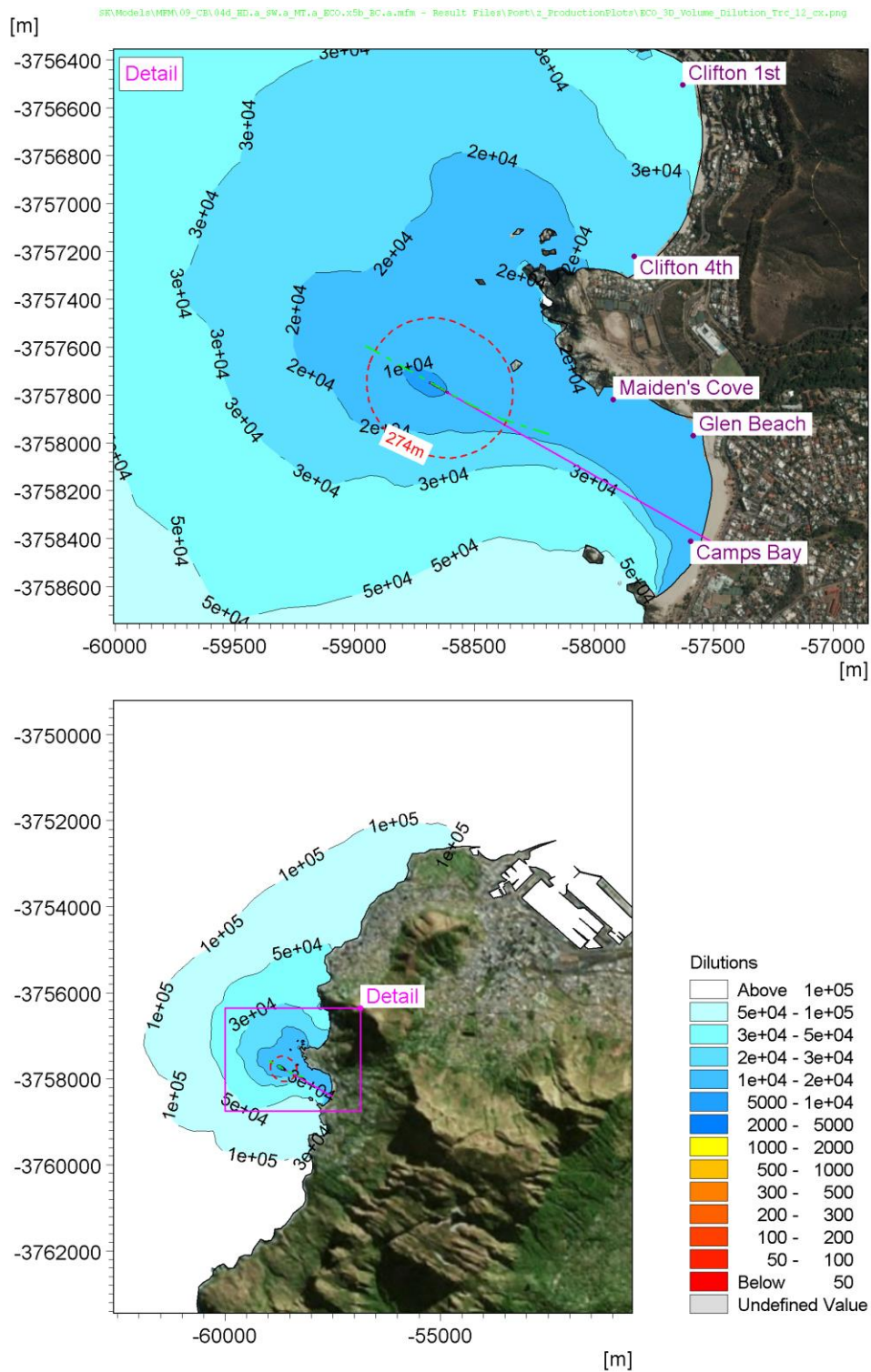


Figure 6-21: Summer/autumn: Number of dilutions at the surface, 5th percentile.

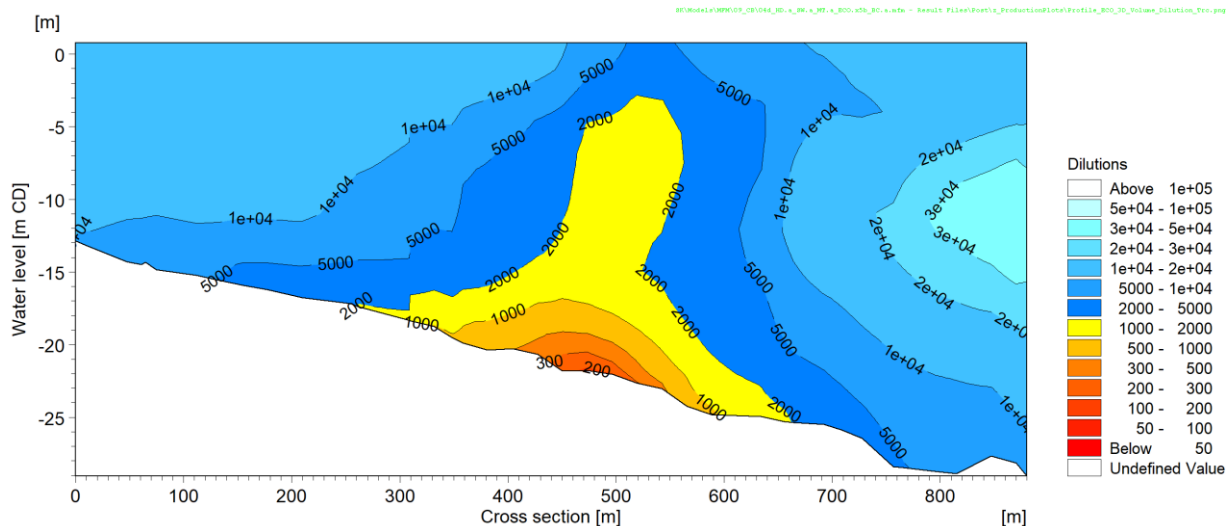


Figure 6-22: Summer/autumn: Cross section of 5th percentile number of dilutions along the longest axis of the plume.

The minimum dilutions achieved at the edge of the mixing zone was extracted from the 5th percentile dilutions and is presented Table 6-4.

Table 6-4: Summer/autumn: Minimum number of dilutions achieved at the edge of the mixing zone.

Parameter	Value
Minimum number of dilutions achieved at any depth along the edge of the allowable mixing zone (radius = 274 m), 5 th percentile	2 700

The distance from the diffuser to achieve the required dilutions for the three critical constituents (Table 3-4) are presented in Table 6-5.

Table 6-5: Summer/autumn: Distance to achieve dilutions, 5th percentile.

Constituent	Dilutions required	Distance
Ammonia	154	< 25 m
COD	48	< 25 m
TSS	1 550	160 m

As discussed in the winter/spring period the dilutions are the lowest near the seabed due to the low discharge rates from the diffuser ports. Predominantly northward currents spread the plume in a longshore direction while strong south-easterly winds, which are more frequent in the summer months, spread the surface plume offshore. Upwelling events associated with these south-easterly winds push the more concentrated seabed plume onshore (e.g. Figure 6-17). In contrast, downwelling events associated with north-westerly winds forces the less concentrated surface plume onshore and the seabed plume offshore (e.g. Figure 6-17).

The minimum number of dilutions achieved in the allowable mixing zone is 2 700. The constituent requiring the highest dilutions is TSS, which achieved the 1 550 required dilutions 160 m from the diffuser. Ammonia and COD achieved the required dilutions in within 25 m. Note that distances smaller than 25 m could not be measured in the model, due to the mesh resolution.

6.2.3 Bacteria

Figure 6-23 presents the surface and seabed T_{90} values for E.coli and enterococci, extracted in the middle of the Camps Bay diffuser at a depth of -22.1 m CD. Recall from Section 2.3.2.1 the median T_{90} ratio of enterococci to E.coli is 2.39.

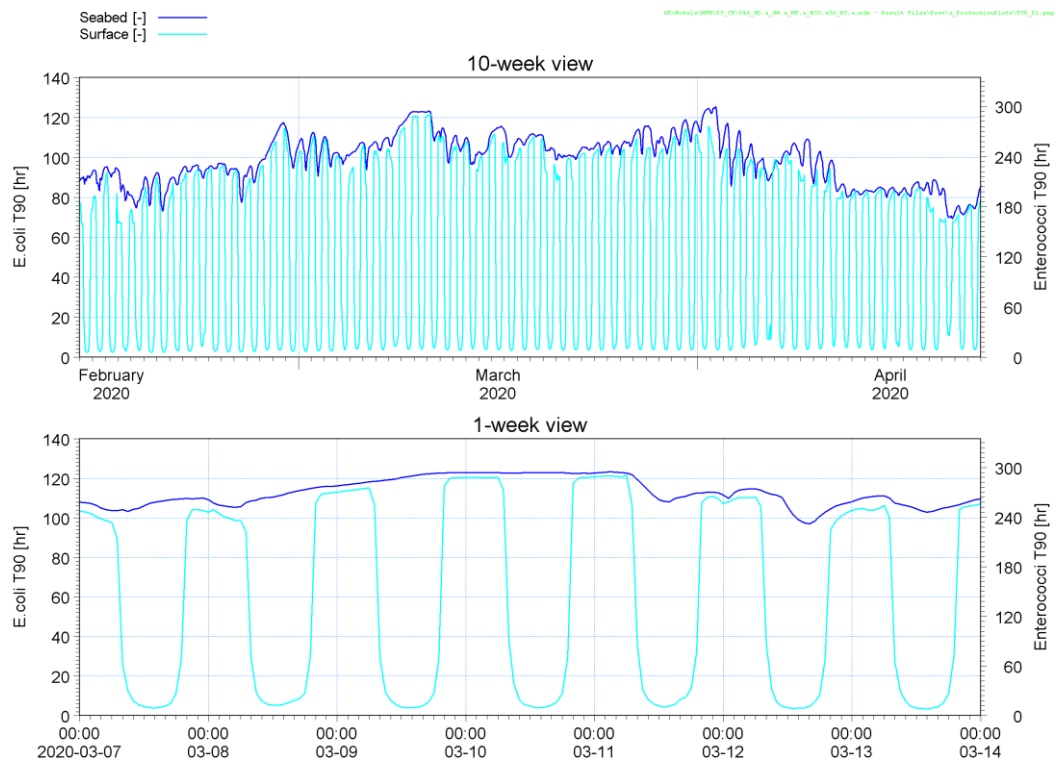


Figure 6-23: Summer/autumn: Surface and seabed T_{90} values for E.coli and enterococci.

A significant diurnal variation in die-off rates due to the solar radiation can be observed at the surface, while the seabed remains mostly unaffected due to light attenuation. In the absence of light, the seawater temperature dominates the die-off processes and the stratification determines the gradient between the surface and seabed T_{90} values.

The model outputs of bacterial concentrations were processed to extract the 90th percentile during daylight hours (between 07:00 to 18:00) to emulate the recommended microbiological sampling regime in the guidelines.

6.2.3.1 E.coli

Figure 6-24, Figure 6-25 and Figure 6-26 present the 90th percentile E.coli concentrations at the seabed, mid-depth and surface. Concentrations greater than 500 CFU/100 ml are shown in orange as this is the guideline for E.coli as discussed in Section 3.4.2. Concentrations less than 500 CFU/100 ml are shown in shades of blue. Although these are less than the guideline, they provide information on the far-field behaviour of the plume. A time series of highest E.coli concentrations at any depth at five key locations (Camps Bay, Glen Beach, Maiden's Cove, Clifton 4th and Clifton 1st) is shown in Figure 6-27. The locations are shown in the contour plots.

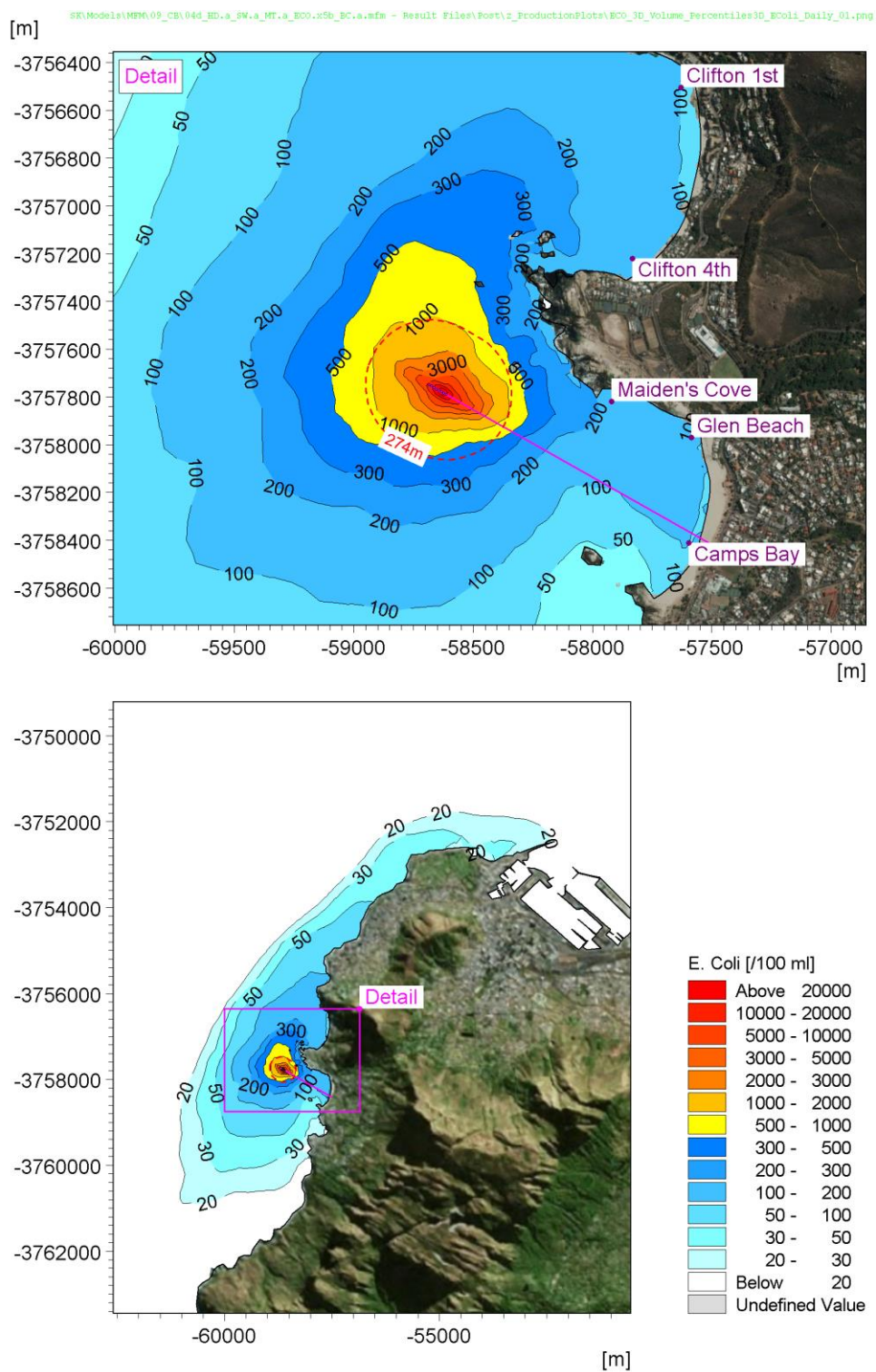


Figure 6-24: Summer/autumn: E.coli concentration at the seabed, 90th percentile for daylight hours (07:00 – 18:00).

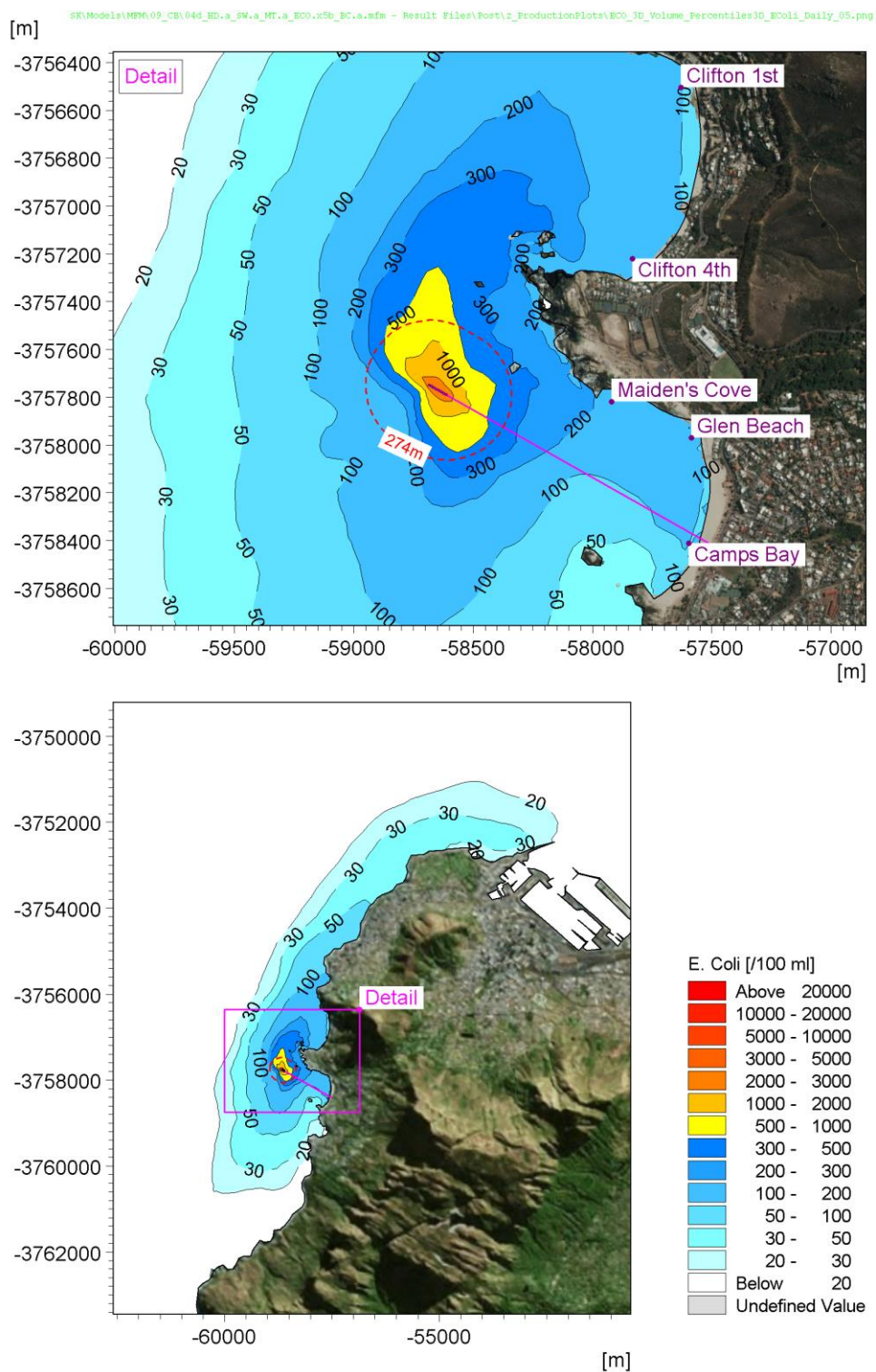


Figure 6-25: Summer/autumn: E.coli concentration at mid-depth, 90th percentile for daylight hours (07:00 – 18:00).

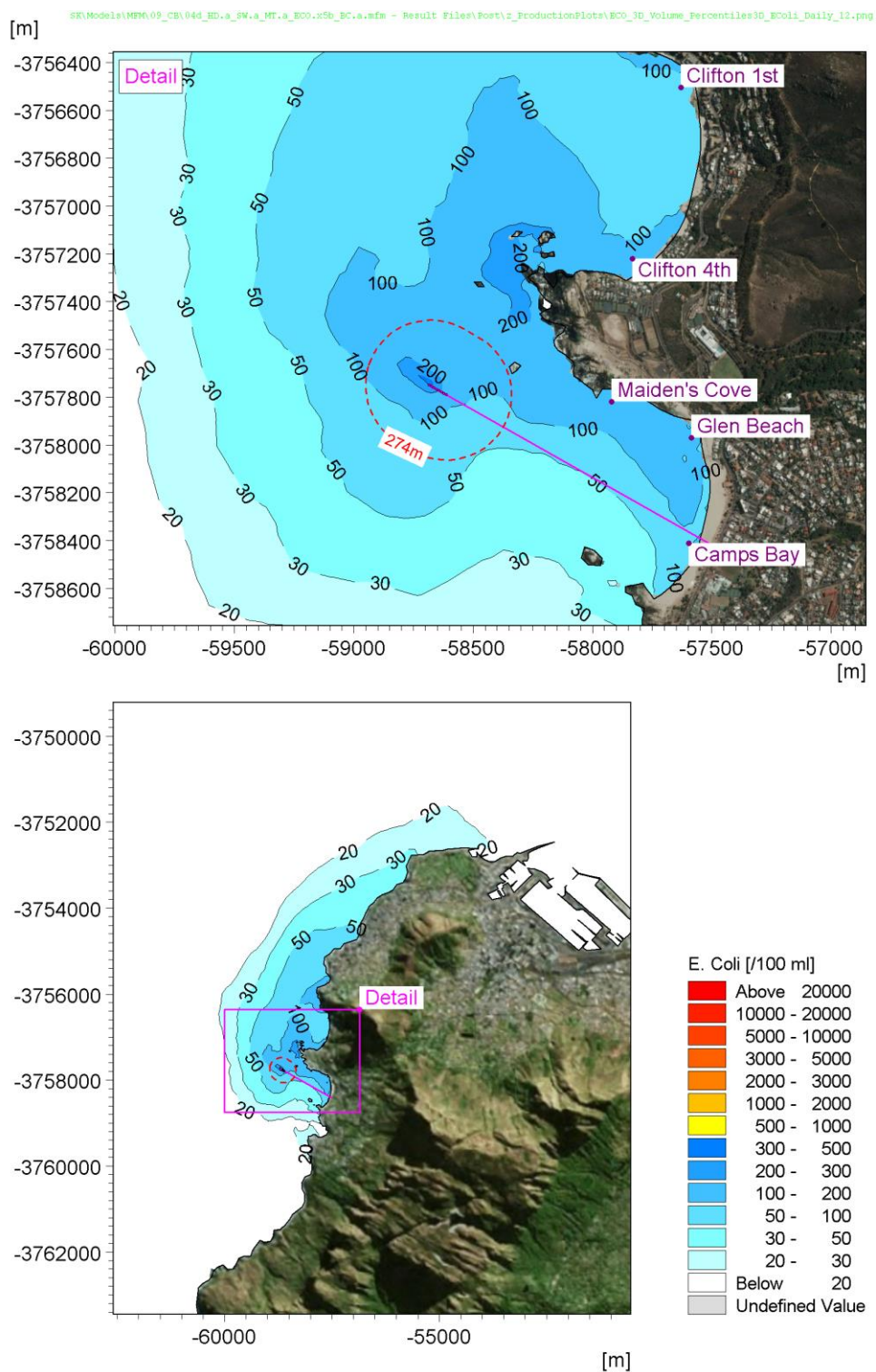
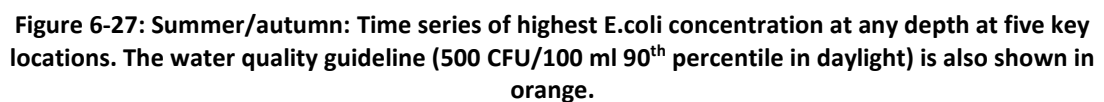


Figure 6-26: Summer/autumn: E.coli concentration at the surface, 90th percentile for daylight hours (07:00 – 18:00).



6.2.3.2 Enterococci

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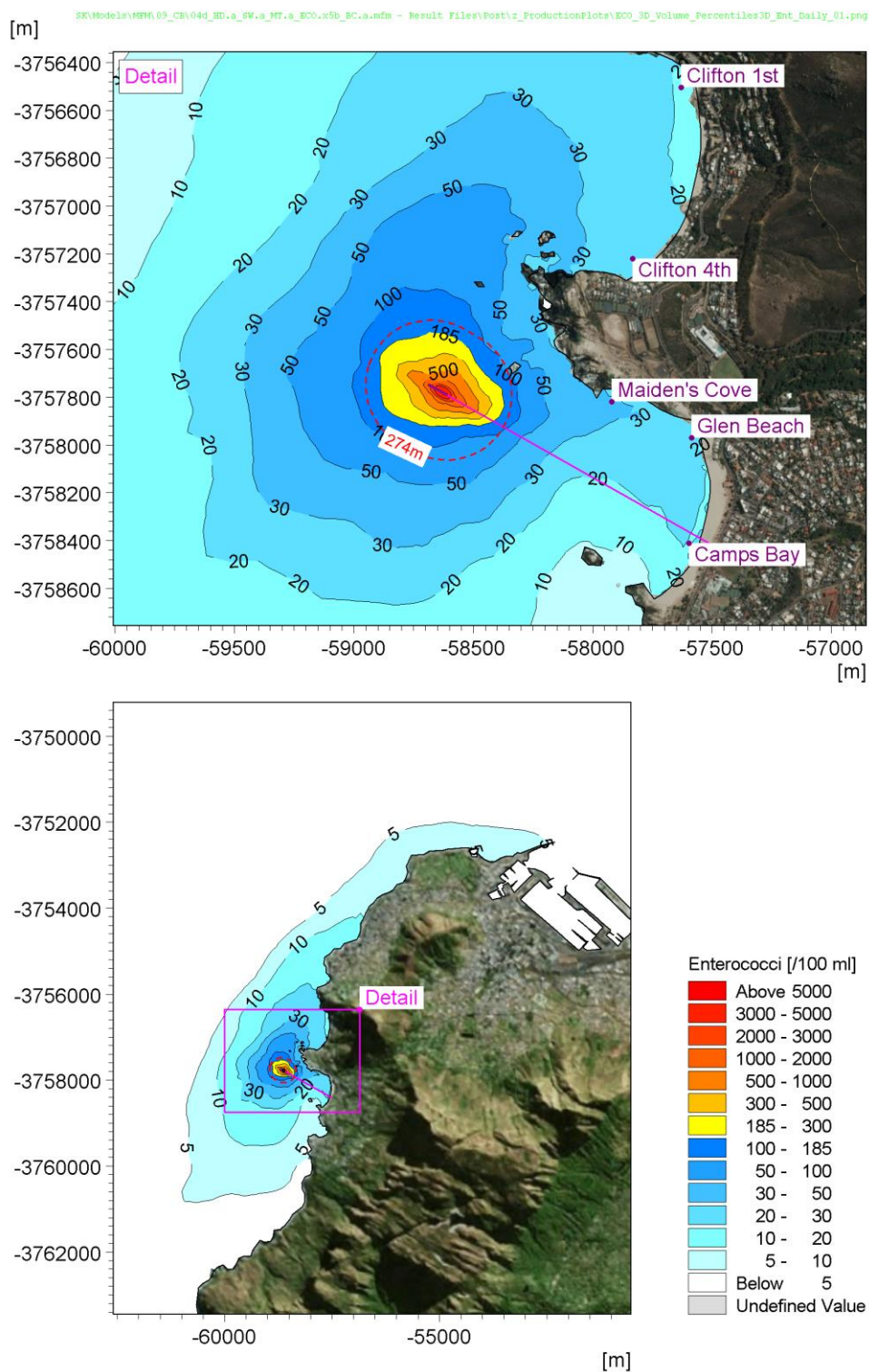


Figure 6-28: Summer/autumn: Enterococci concentration at the seabed, 90th percentile for daylight hours (07:00 – 18:00).

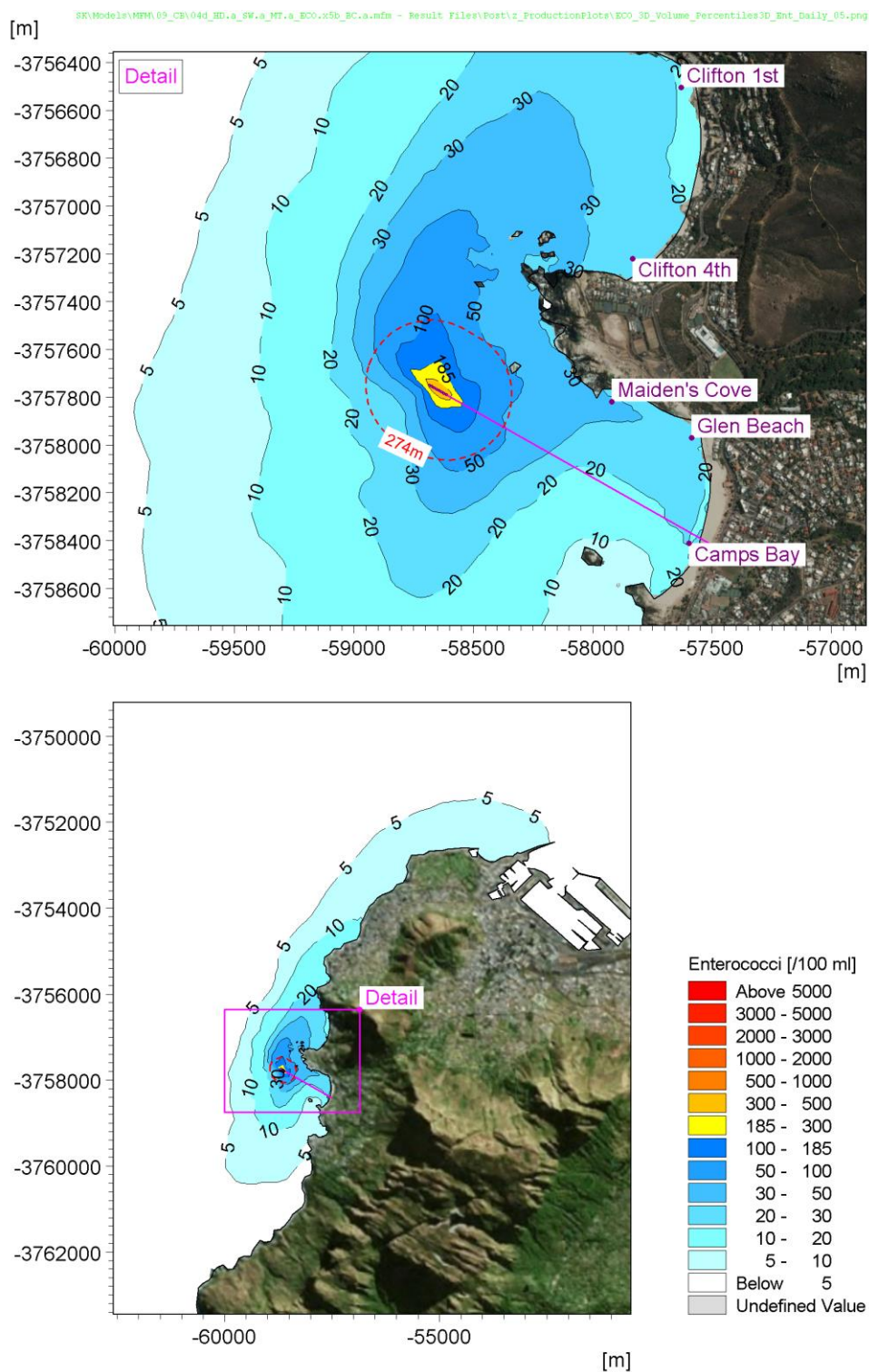


Figure 6-29: Summer/autumn: Enterococci concentration at mid-depth, 90th percentile for daylight hours (07:00 – 18:00).

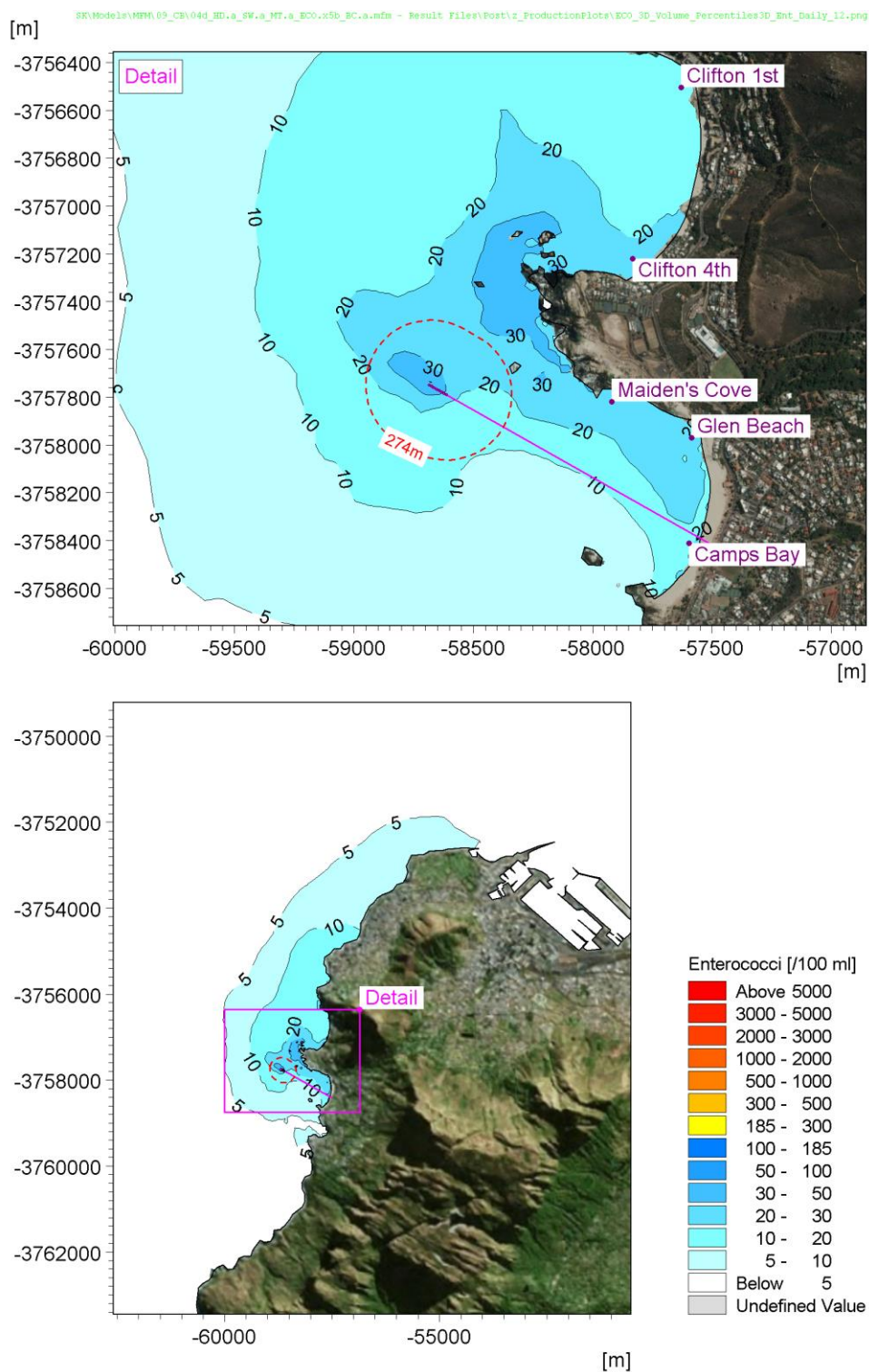


Figure 6-30; Summer/autumn: Enterococci concentration at the surface, 90th percentile for daylight hours (07:00 – 18:00).

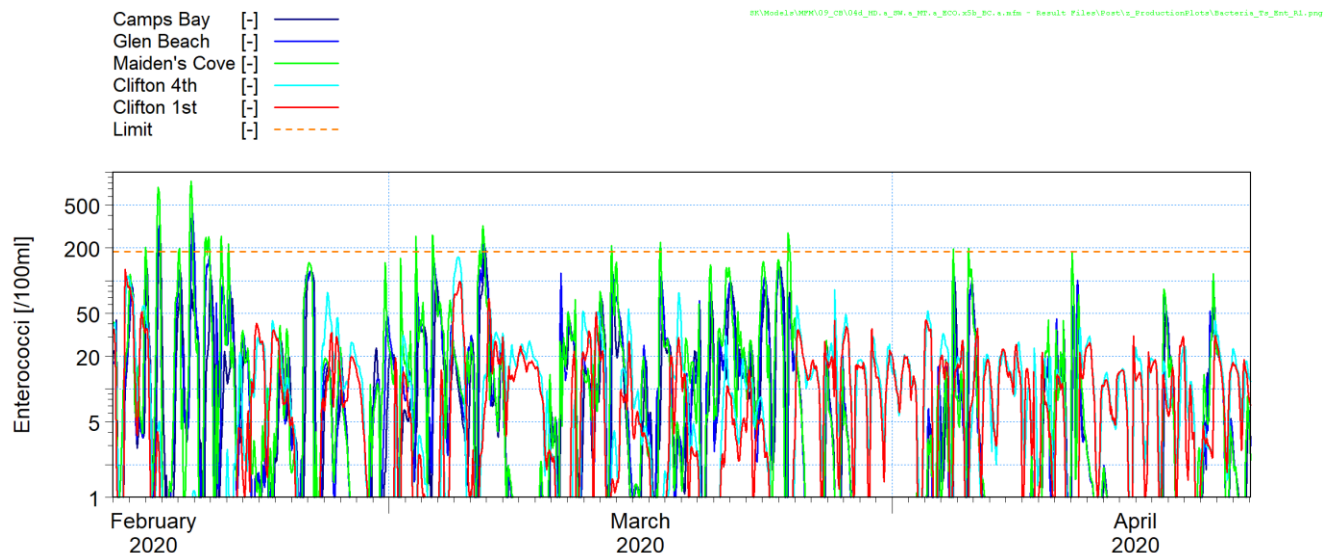


Figure 6-31: Summer/autumn: Time series of highest enterococci concentration at any depth at five key locations. The water quality guideline (185 CFU/100 ml 90th percentile in daylight) is also shown in orange.

A mixing zone distance of 250 m was required to meet the 90th percentile water quality guideline of 185 CFU/100 ml. The contour plots show that the 90th percentile enterococci concentrations were the highest at the seabed and concentrations above the 185 CFU/100 ml guideline did not intersect with the shoreline. The time series plot shows that the enterococci concentrations at the key locations briefly exceeded concentrations above 185 CFU/100 ml on a number of occasions, but the duration of these events was less than 10% of the daylight time and therefore met the water quality guidelines.

6.2.3.3 Discussion

Based on the applicable water quality guidelines (discussed in Section 3.4.2), E.coli requires a greater mixing zone distance to meet the guidelines compared to enterococci.

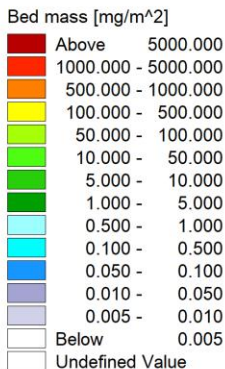
The bacteria plumes have higher concentrations on the seabed than the surface due to the trapping of the plume near the seabed as well as the lower bacteria die-off near the seabed (illustrated in Figure 6-27).

During typical conditions the plume is advected with the longshore current in a predominantly northward direction. Upwelling events associated with south-easterly winds, which are frequent in the summer, force the concentrated seabed plume onshore. During these events key locations are often exposed to bacteria concentrations above the guideline, but the average daylight time concentrations do not exceed the water quality guidelines due to the intermittent nature of the upwelling events.

6.2.4 Total suspended solids

The concentrations of TSS were modelled in the water column and specifically where these were deposited on the seabed. This is a proxy for the fate of pollutants that adsorb to solid particles, e.g. heavy metals.

Figure 6-16 presents the bed mass of TSS at the end of the 10-week simulation. The deposited mass in the main depo-centres (demarcated in red) are summarised in Table 6-3. The table also includes the total mass of TSS that were advected outside of the model domain through the boundaries and TSS in suspension at the end of the run.



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Table 6-6: Summer/autumn: Integrated mass at the end of the 10-week simulation period.

Area	Mass [kg]	% released
Port of Cape Town	1 100	2.8%
Murray's Bay Harbour	1.00	< 0.1%
Granger Bay	11	< 0.1%
Hout Bay	2.77	< 0.1%
Offshore (-40 m CD contour)	9 260	23.9%
Out of domain	18 000	46.3%
Suspended	10 400	26.9%
Total mass released	38 200	100%

The highest concentrations are observed in the sheltered depo-centres, i.e. the Port of Cape Town, Granger Bay marina, Murray's Bay harbour and Hout Bay harbour where the bed shear stress due to waves and currents are sufficiently low to allow deposition. Accumulation also occurs in exposed areas where the water depth is greater than approximately 40 m due to the wave orbital velocities not exerting sufficient stress on the seabed to resuspend the sediment particles.

The largest depo-centre is the Port of Cape Town with approximately 2.8% of the TSS released from the Camps Bay outfall accumulating in the port. These results can be used in the design and interpretation of sediment quality sampling studies.



7. CONCLUSIONS

A 3D coupled near- and far-field hydrodynamic, water quality, suspended sediment and wave model has been set up for the Camps Bay outfall.

The model has been calibrated against wave, water level, current and seawater temperature measurements for a 6-week winter/spring period and a 10-week summer/autumn period.

The plume dispersion was then simulated for a 10-week winter/spring period and a 10-week summer/autumn period. The model results show the following:

- The low port discharge rates and low port velocities result in the effluent being trapped near the seabed resulting in the lowest dilutions and highest bacteria concentrations occurring near the seabed.
- During typical conditions the plume is advected with the longshore current in a predominantly northward direction. Upwelling events associated with south-easterly winds, which are frequent in the summer, force the concentrated seabed plume onshore into Camps Bay.
- The minimum number of dilutions achieved at the edge of the 274 m radius mixing zone is 3 480 in winter/spring and 2 700 in summer/autumn (5th percentile dilution).
- The required dilution of 1 550 for TSS is met at a distance of 115 m from the diffuser in winter/spring and 160 m in summer/autumn (5th percentile dilution).
- E.coli requires a distance 800 m to meet the applied guidelines in winter/spring and 600 m in summer/autumn (500 CFU/100 ml for the 90th percentile concentration during daylight hours).
- Locations such as Maidens Cove, Clifton 1st and Clifton 4th are briefly exposed to E.coli concentrations above 500 CFU/100 ml on a number of occasions in winter/spring. Maidens Cove, Glen Beach and Camps Bay Beach are exposed to concentrations above 500 CFU/100 ml on many occasions during summer/autumn, indicating that there is a risk to bathers and surfers. However, the cumulative duration of these events is less than 10% of the daylight time and the applied water quality guidelines are thus met at all locations along the shoreline (500 CFU/100 ml for the 90th percentile concentration during daylight hours).
- The applied guidelines for enterococci result in a smaller zone of impact compared to E.Coli.
- The largest depo-centre is the Port of Cape Town with approximately 4.5% of the Total Suspended Solids released from the Camps Bay outfall accumulating in the port in winter/spring and 2.8% in summer/autumn.



8. RECOMMENDATIONS

Based on the model results the following recommendations are made:

- The diffuser should be modified to mix the effluent higher up into the water column to improve the initial dilutions and prevent concentrated effluent being upwelled towards the shoreline. The effectiveness of these modifications should be tested in the model.
- Consideration should be given to lengthening the pipeline to reduce the occurrence of the plume reaching the Camps Bay and Clifton shorelines.
- These results assume that the pipeline and diffusers are operating as designed and that there are no breakages, leaks or blockages. Regular underwater surveys are recommended to ensure that this is the case.
- Consideration should be given to operationalising the model to provide forecasts of bathing water quality, as is done in other countries including Denmark, Sweden and New Zealand, e.g. <http://newkbh.badevand.dk>. The forecast would identify one or two days in advance the occasions when the effluent plume is likely to reach specific bathing beaches or surf spots, which would facilitate mitigation of the associated risks to the public.

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11 APPENDIX G: FINAL HYDRODYNAMIC MODELLING REPORT FOR GREEN POINT

SAMPLING AND ANALYSIS OF THE CITY OF CAPE TOWN'S MARINE OUTFALLS AT GREEN POINT, CAMPS BAY AND HOUT BAY

Final Report on Dispersion Model Calibration and Results for Green Point

REV.00

01 October 2020



Lwandle Technologies (Pty) Ltd / City of
Cape Town
Cape Town, South Africa



CITY OF CAPE TOWN
ISIXEKO SASEKAPA
STAD KAAPSTAD

SAMPLING AND ANALYSIS OF THE CITY OF CAPE TOWN'S MARINE OUTFALLS AT GREEN POINT, CAMPS BAY AND HOUT BAY

Final Report on Dispersion Model Calibration and Results for Green Point

S2101-RP-CE-007-R0

01 October 2020

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Cape Town, South Africa



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1. INTRODUCTION

1.1 Background

The City of Cape Town (CoCT) has appointed Lwandle Technologies (Pty) Ltd (Lwandle) to perform sampling and analysis of the CoCT's marine outfalls at Green Point, Camps Bay and Hout Bay for a period of three years (Tender 124s/2018/19). Lwandle has sub-contracted PRDW South Africa (Pty) Ltd (PRDW) to undertake dispersion modelling for the three outfalls.

1.2 Scope and objectives

The scope of the study is to perform three-dimensional (3D) hydrodynamic and dispersion modelling for the Green Point, Camps Bay and Hout Bay marine outfalls operated by the CoCT. The objectives of the study are as follows:

- Provide imagery and animations of the effluent plume suitable for overlaying the sampling and monitoring data.
- Determine the dilutions achieved in the near- and far-field for a conservative tracer representing dissolved constituents in the effluent such as nutrients, etc. This includes a probabilistic description of the Zone of Initial Dilution (ZID) taking into account variations in metocean conditions and variations in effluent flows and/or concentrations.
- Determine the probability of the plume reaching the shoreline and the concentrations of faecal indicator bacteria (enterococci and E.coli) during these events.
- Determine the concentrations of discharged Total Suspended Solids (TSS) in the water column and where these are deposited on the seabed. This is a proxy for the fate of pollutants that adsorb to solid particles, e.g. heavy metals.

The model results can be used by Lwandle and the CoCT for the following:

- To refine the location of sampling stations (for the second year of sampling).
- To assist interpretation of sampling results, e.g. are observed concentrations likely to have had an outfall as a source or rather stormwater or other sources.
- To predict the metocean conditions when plume may impact bathers.
- To define the size of the ZID and the spatial extent of particulate deposition zones for the Coastal Waters Discharge Permit application.
- To determine how many dilutions are achieved by the time that the plume reaches desalination plant intakes.



Future applications of the models (outside the scope of this study) could include:

- Testing the impacts of changes in flow rates, effluent density (e.g. due to the addition of desalination brine) and effluent concentrations on the dispersion.
- Test options to improve the dispersion, e.g. modifications to the diffuser, lengthening of the pipeline, etc.
- The models could also be operationalised to provide forecasts of bathing water quality as is done in Denmark, Sweden and New Zealand, e.g. <http://newkbh.badevand.dk>. The concept is that if the effluent from the outfalls is impacting bathing beaches a limited number of times per year, then a forecast may be the best short- to medium-term approach to mitigate the associated risk.

1.3 Deliverables

PRDW's deliverables comprise the following:

- Deliverable 1: Progress report on model setup (one report for each outfall).
- Deliverable 2: Progress report on model calibration for winter/spring (August – September 2019) and preliminary results (one report for each outfall).
- Deliverable 3: Final report including model calibration for summer/autumn (February – April 2020) and final results (one report for each outfall).

This report is Deliverable 3 for Green Point. This report supersedes the Deliverable 1 and Deliverable 2 reports as all the information contained in the previous reports is included and updated here. Similar reports are provided for Camps Bay and Hout Bay.

1.4 Report structure

Section 2 presents a description of the models, which include a hydrodynamic, water quality, suspended sediment and wave model. Section 3 presents the discharge characterisation which describes the diffuser, effluent and water quality guidelines. Section 4 describes the model setup which includes the mesh, bathymetry, wind, boundary conditions and model settings. The model calibration is presented in Section 5 followed by the model results in Section 6. Conclusions and recommendations are provided in Sections 7 and Section 8.



2. DESCRIPTION OF THE MODELS

2.1 Overview

The modelling was undertaken using the MIKE modelling system developed by DHI in Denmark. PRDW has 15 years of experience in applying these models. The MIKE system is widely used by international engineering consultancies and includes a number of features that makes it an appropriate model for this application, including:

- A dynamic coupling of a near-field jet model within the 3D far-field hydrodynamic model;
- the ability to dynamically couple different sub-models to include all the relevant physical and biogeochemical processes; and
- the use of a flexible mesh which allows refinement around the outfalls.

The following four sub-models were used:

- Hydrodynamic model: 3D hydrodynamics including tides, wind, waves, temperature and salinity. Includes an integral jet model for each port with dynamic two-way coupling of near- and far-field dispersion.
- Water quality model: 3D water quality model for modelling the far-field advection-dispersion of:
 - a conservative tracer representing dissolved constituents in the effluent such as nutrients, etc
 - Faecal indicator bacteria (E.coli and enterococci) including die-off.
- Suspended sediment model: 3D model for modelling Total Suspended Solids (TSS) - advection-dispersion-settling-deposition-resuspension based on combined current-wave bed stresses.
- Spectral wave model: wave refraction and breaking to generate wave-driven currents and wave bed stresses.

2.2 Hydrodynamic model

2.2.1 General description

The three-dimensional MIKE 3 Flow Flexible Mesh Model was used for the hydrodynamic modelling. The application of the model is described in the User Manual (DHI, 2020a), while full details of the physical processes being simulated and the numerical solution techniques are described in the Scientific Documentation (DHI, 2020b).

The model is based on the numerical solution of the three-dimensional incompressible Reynolds averaged Navier-Stokes equations invoking the assumptions of Boussinesq and of hydrostatic pressure. The model consists of the continuity, momentum, temperature, salinity and density equations and is closed by a $k-\epsilon$ vertical turbulence closure scheme. Horizontal eddy viscosity is modelled with the Smagorinsky formulation.

The time integration of the shallow water equations and the transport equations is performed using a semi-implicit scheme, where the horizontal terms are treated explicitly and the vertical terms are treated implicitly. In the vertical direction a structured mesh, based on a sigma-coordinate transformation is used, while the geometrical flexibility of the unstructured flexible mesh comprising triangles or quadrangles is utilised in the horizontal plane.



The model includes the following physical phenomena:

- Currents due to tides;
- Currents due to wind stress on the water surface;
- Currents due to density gradients;
- Currents due to waves; the second order stresses due to breaking of short period waves are included using the radiation stresses computed in the Spectral Wave model;
- Coriolis forcing;
- Bottom friction;
- Flooding and drying;
- Sources and sinks including dynamic near and far-field coupling; and
- Heat exchange.

2.2.2 Near and far-field coupling

An important feature of the model is a dynamic coupling of a near-field jet model and the 3D far-field hydrodynamic model. The near-field solution based on the integral jet model equations by Jirka (2004). Entrainment into the jet is using Distributed Entrainment Sink Approach by Choi and Lee (2007). At the end of the near-field the diluted discharge is released into far-field model as a source, as shown in Figure 2-1.

In order to determine, when the jet/plume becomes passive and thus a part of the ambient flow, a number of stop criteria are invoked:

1. If the jet reaches the water surface.
2. If the jet reaches the bottom.
3. If the jet momentum is smaller than or close to the ambient flow induced momentum.
4. If the jet dies out in the stagnant conditions.
5. If the jet experiences buoyancy reversal twice.
6. If the trajectory of the jet exceeds a maximum travel distance as specified by the user.
7. If the jet exhibits strong curvature, such as going into strong opposing ambient flow.
8. If the jet reaches a domain boundary (open or close).
9. If the jet reaches dried cells.

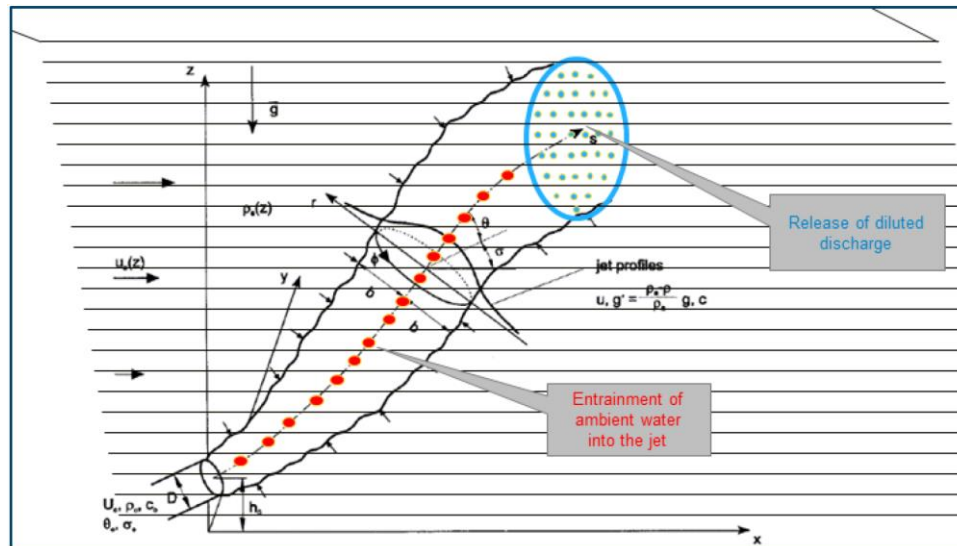


Figure 2-1: Dynamic coupling of near-field and far-field models: entrainment sinks along the plume trajectory and distributed sources at the release location.

2.3 Water quality model

2.3.1 General description

The MIKE 3 ECO Lab Model was used to simulate the far-field dispersion of a conservative tracer and faecal indicator bacteria (E.coli and enterococci). The application of the model is described in the User Manual (DHI, 2020c) while full details of the physical processes being simulated and the numerical solution techniques are described in the Scientific Documentation (DHI, 2020d).

The model simulates the transport and fate of constituents in three dimensions based on advection-dispersion and non-conservative processes. The model can be used to describe chemical, biological, ecological processes and interactions between state variables and also the physical process of sedimentation of components can be described. The hydrodynamics (water levels, currents, temperature, salinity, vertical, dispersion, horizontal dispersion and release location at the end of the near-field) are obtained via an online coupling to the MIKE 3 Flow Flexible Mesh Model and the same three-dimensional grid is used.

An ECO Lab template is used to describe the non-conservative processes relevant for each specific constituent. Since the conservative tracer undergoes advection and dispersion only without any non-conservative processes, no template is required for the conservative tracer. Faecal indicator bacteria (E.coli and enterococci) require an ECO Lab template to simulate die-off, as described below.

2.3.2 Bacteria die-off

In addition to physical dilution, the concentration of faecal indicator bacteria (E.coli and enterococci) reduces due to die-off. The die-off was implemented in the ECO Lab model as described below.



2.3.2.1 ECO Lab model equations

First order decay:

Bacterial decay can be described by the first order decay function for a duration t :

$$C(t) = C_0 e^{-k \cdot t} \quad (1)$$

where

- C = bacteria concentration [CFU.100ml⁻¹]
- C_0 = initial bacteria concentration ($t = 0$) [CFU.100ml⁻¹]
- t = time [hours]
- k = linear decay rate [hours⁻¹]

The decay rate is often expressed as T_{90} : the time needed for the 90% of the bacterial concentration to decay.

Therefore, if $t = T_{90}$, $\frac{C}{C_0} = 0.1$:

$$T_{90} = \frac{\ln(0.1)}{k} \quad (2)$$

where

- T_{90} = time needed for the 90% of the bacterial concentration to decay [hours]

E.coli decay model:

Erichsen, et al. (2006) adopted an E.coli decay model from Jensen (1990). The model describes the decay contributions from dark and light conditions:

$$k_{coli} = k_m + K_l \cdot I_l \quad (3)$$

where

- k_{coli} = E.coli decay rate [days⁻¹]
- k_m = decay coefficient for dark conditions [days⁻¹], see equation 4
- K_l = decay coefficient for light conditions [m².W⁻¹.days⁻¹], see equation 5
- I_l = Solar irradiance [W.m⁻²], see equation 6

The dark decay term is expressed as a function of water temperature:

$$k_m = a_T \cdot T - k_{m0} \quad (4)$$

where

- T = water temperature [°C]
- a_T = temperature dependency constant for dark reaction [h⁻¹.°C⁻¹]
- k_{m0} = initial coliform decay rate for dark reaction [h⁻¹]



The light decay coefficient is expressed as a function of water temperature, and salinity:

$$K_l = S_m \cdot \frac{b_T \cdot T + K_{l0}}{a \cdot S_m - (a-1) \cdot S} \quad (5)$$

where

- S = water salinity [PSU]
- S_m = reference salinity [PSU]
- a = correction for salinity [-]
- b_T = temperature dependency constant for light reaction [$\text{m}^2 \cdot \text{W}^{-1} \cdot \text{h}^{-1} \cdot ^\circ\text{C}^{-1}$]
- K_{l0} = initial coliform decay rate for light reaction [$\text{m}^2 \cdot \text{W}^{-1} \cdot \text{h}^{-1}$]

In a water body, light attenuation can be described as a function of depth using the Lambert-Beer law:

$$I_l = I_0 \cdot e^{-E_{ta} \cdot z} \quad (6)$$

where

- I_l = solar irradiance at depth z below surface [$\text{W} \cdot \text{m}^{-2}$]
- I_0 = surface solar irradiance [$\text{W} \cdot \text{m}^{-2}$]
- z = depth below surface [m]
- E_{ta} = light attenuation coefficient [m^{-1}]

Enterococci decay model:

The enterococci decay rate is expressed relative to the E.coli decay rate:

$$k_{ent} = k_{coli} \cdot r \quad (7)$$

where

- r = decay rate ratio of E.coli to enterococci [-]
- k_{ent} = enterococci decay rate [days^{-1}]

Literature indicates that enterococci decay slower than E.coli: based on 16 samples from 6 studies – e.g. Sinton, et al. (1994) – the median value for r was 0.42 (T_{90} equivalent ratio of 2.39), which has been adopted for this study. It is noted that r ranged from 0.21 to 2.5, indicating the uncertainty level for this value.

2.3.2.2 Validation of die-off model

The ECO Lab model described above was calibrated against measurements to confirm the required constants for this study. The constants are:

- $S_m = 34.5$ PSU
- $a = 1.54$
- $a_T = 2.425 \times 10^{-3} \text{ h}^{-1} \cdot ^\circ\text{C}^{-1}$
- $k_{m0} = 4.167 \times 10^{-3} \text{ h}^{-1}$
- $b_T = 6.25 \times 10^{-5} \text{ m}^2 \cdot \text{W}^{-1} \cdot \text{h}^{-1} \cdot ^\circ\text{C}^{-1}$
- $K_{l0} = 3.13 \times 10^{-4} \text{ m}^2 \cdot \text{W}^{-1} \cdot \text{h}^{-1}$

The measurements were obtained from Bellair, et al. (1977) and included 162 measurement samples of hourly decay rates (T_{90}) of E.coli on the seawater surface at Balmoral Bay near Sydney, Australia. The ECO Lab model assumed a constant water temperature and salinity representative of the measured conditions. Time-

varying solar radiation was obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 global atmospheric model (ECMWF, 2020). Figure 2-2 presents the a comparison of modelled and measured E.coli decay at Balmoral Bay. Also shown are measurements of T_{90} in sewage at Durban from Livingstone et al. (1990).

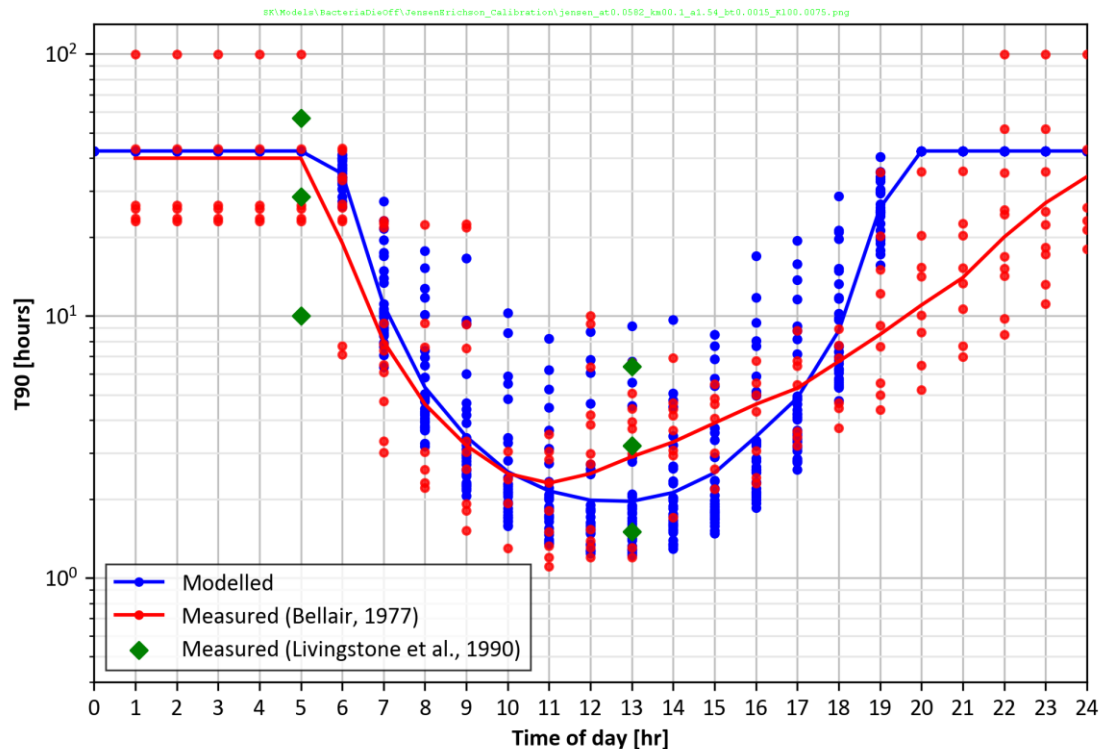


Figure 2-2: Measured and ECO Lab model comparison of E.coli decay at Balmoral Bay. The geometric mean is shown with a solid line. Also shown are measurements at Durban from Livingstone et al. (1990).

The comparison shows that the model is able to reproduce the measurements with satisfactory accuracy. Note the scatter from the model is directly proportional to the solar radiation intensity, whereas the measurements in addition include some variability in the seawater temperature, salinity and statistical randomness.

2.3.3 Model inputs

For the present Cape Town outfall study, a time and space varying surface solar irradiance I_0 was obtained from ECMWF. A constant light attenuation coefficient $E_{ta} = 0.6$ was applied, based on the annual average of Secchi disk measurements in Table Bay provided by Lwandle. Time and space-varying seawater temperature and salinity were obtained from the coupled hydrodynamic model.

2.4 Suspended sediment model

2.4.1 General description

The MIKE 3 Mud Transport Flexible Mesh Model was used to model the concentrations of discharged Total Suspended Solids (TSS) in the water column and where these are deposited on the seabed. This is a proxy for the fate of pollutants that adsorb to solid particles less than $63 \mu\text{m}$, e.g. heavy metals.



The application of the model is described in the User Manual (DHI, 2020e) while full details of the physical processes being simulated and the numerical solution techniques are described in the Scientific Documentation (DHI, 2020f). The hydrodynamics (water levels, currents, temperature, salinity, vertical, dispersion, horizontal dispersion and release location at the end of the near-field) are obtained via an online coupling to the MIKE 3 Flow Flexible Mesh Model and the same three-dimensional grid is used.

The following processes are included in the simulations:

- 3D advection-dispersion of suspended sediment by currents;
- Settling of sediment through water column and deposition onto the seabed, dependent on the critical shear stress for deposition;
- Resuspension of sediment from the seabed, dependent on the critical shear stress for resuspension and the erosion coefficient;
- Bed shear stress due to combined currents and wave orbital velocities, as obtained through direct coupling with the hydrodynamic and spectral wave models.

2.4.2 Model settings

The input parameters used to model the TSS has been obtained from a previous study in Table Bay by PRDW (2017). The study calibrated a suspended sediment model to measured TSS concentrations in the water column and locations of fine sediment depo-centres. The modelled sediment comprises fine cohesive organic and inorganic particles with diameters less than 63 μm . The input parameters are listed in Table 2-1

Table 2-1: Input parameters used in the modelling of TSS.

Parameter	Unit	Value
Settling velocity of suspended sediment	m/s	5×10^{-5}
Critical shear stress for resuspension	N/m ²	0.2
Critical shear stress for deposition	N/m ²	0.1
Resuspension rate	kgDW/m ² /s	1×10^{-4}
Bulk density of dry sediment	kg/m ³ bulk	400

2.5 Wave model

2.5.1 General description

The MIKE 21 Spectral Waves (SW) Flexible Mesh model was used for simulating wave transformation to the nearshore. The application of the model is described in the User Manual (DHI, 2020g), while full details of the physical processes being simulated and the numerical solution techniques are described in the Scientific Documentation (DHI, 2020h). The model simulates the growth, decay and transformation of wind-generated waves and swells in offshore and coastal areas using unstructured meshes. The model used the same mesh as the hydrodynamic model. The model is fully spectral and can be run in either quasi-stationary or instationary mode, depending on the size of the model domain.



The model included the following physical phenomena:

- Dissipation due to bottom friction;
- Dissipation due to depth-induced wave breaking;
- Nonlinear energy transfer amongst the different wave components (quadruplet-wave interactions);
- Refraction and shoaling due to depth variations; and
- Generation of local wind-waves; and
- The effect of time-varying water depth due to the tide - the water depth at each time-step is computed in the hydrodynamic model including tidal and wave-setup.

2.5.2 Model settings

Bottom friction was modelled using a constant Nikuradse roughness of $k_N = 0.5$ m. The modelled water level from the hydrodynamic model was coupled to the wave model. The model was run in the fully spectral, quasi stationary formulation excluding the effect of additional wave generation within the model due to wind.



3. DISCHARGE CHARACTERISATION

3.1 Diffuser configuration

The Green Point diffuser is located in a depth of -26.0 m CD as shown in Figure 4-3. Table 3-1 presents the diffuser geometry and individual port configuration. The model assumes that the pipeline and diffusers are operating as described below and that there are no breakages, leaks or blockages.

Table 3-1: Diffuser geometry and flow distribution for Green Point.

Diffuser		Ports							
Section no.	Inside diameter [mm] ⁽¹⁾	Port no. ⁽²⁾	Port diameter [mm] ⁽¹⁾	Flow distribution [%] ⁽³⁾	Discharge per port [l/s] ⁽⁵⁾	Port velocity [m/s] ⁽⁵⁾	Spacing [m] ⁽¹⁾	Level above seabed [mm]	Port configuration ⁽¹⁾
1	355	1	150	5.8%	16.1	0.91	10	200 mm	Effluent is discharged horizontally through an elbow bend (illustrated below) with alternating discharge directions  (4)
		2	150	5.8%	16.2	0.92			
		3	150	6.0%	16.6	0.94			
		4	150	6.3%	17.5	0.99			
2	500	5	150	6.9%	19.1	1.08			
		6	150	7.0%	19.5	1.10			
		7	150	7.3%	20.1	1.14			
		8	150	7.6%	21.0	1.19			
3	630	9	125	5.5%	15.3	1.24			
		10	125	5.6%	15.6	1.27			
		11	125	5.7%	15.8	1.29			
		12	125	5.8%	16.2	1.32			
4	700	13	125	6.0%	16.6	1.35			
		14	125	6.1%	16.9	1.38			
		15	125	6.2%	17.2	1.40			
		16	125	6.3%	17.5	1.43			

Notes:

- (1) Source: CSIR (1992).
- (2) The ports are arranged from offshore (port no.1) to inshore (port no. 16).
- (3) Based on diffuser hydraulics modelling undertaken by the CoCT
- (4) Schematic representation of port configuration
- (5) Calculated using the 50th percentile winter/spring discharge rates in Table 3-2.

3.2 Discharge rates

Measured flow rates were provided by the CoCT for input to the dispersion model. The measurements comprise average flow rates at 30-minute intervals and covers the model simulation period. This will ensure that the model results account for diurnal variations in flows.

Figure 3-1 and Figure 3-2 present time series plots of the Camps Bay effluent discharge rate for the winter/spring and summer/autumn periods respectively. A statistical summary is provided in Table 3-2.

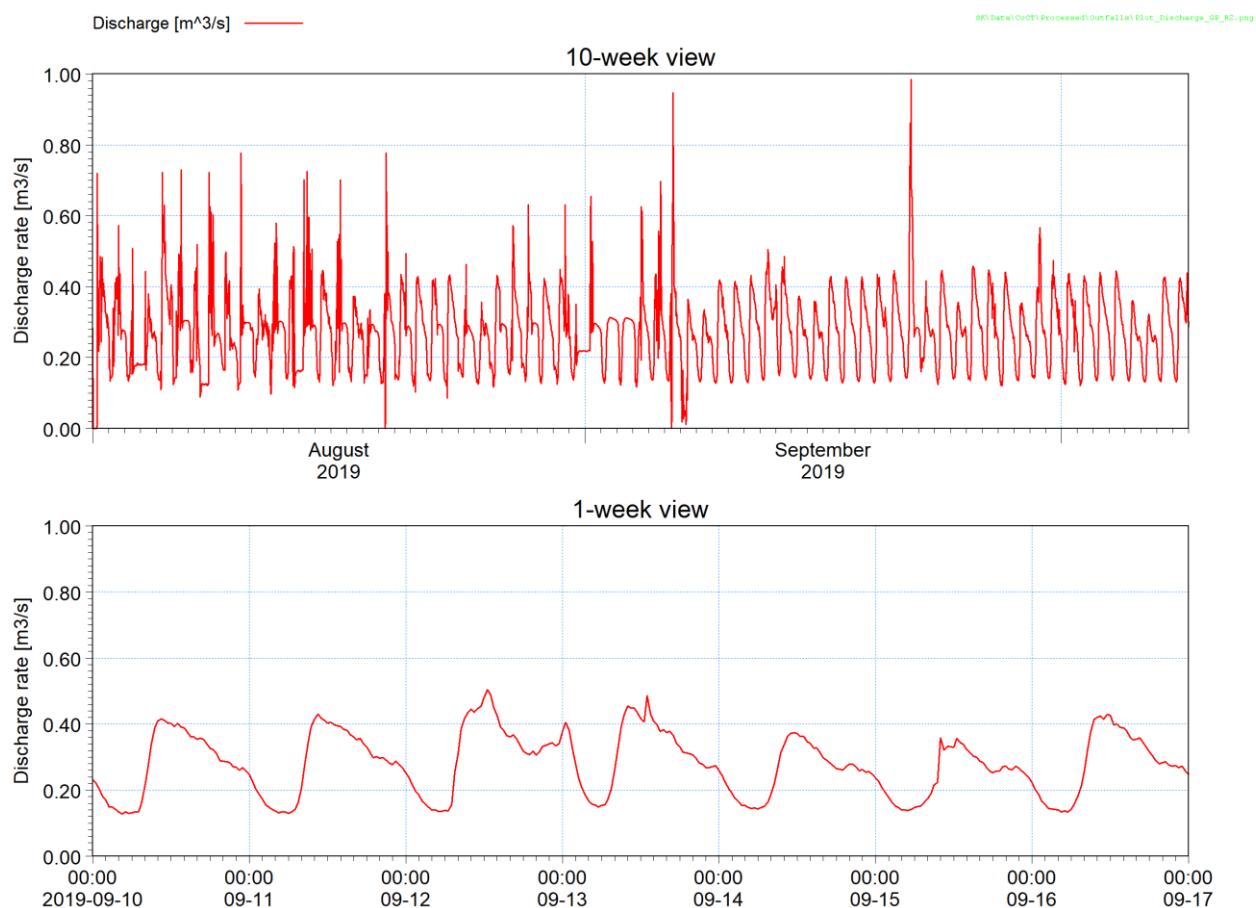


Figure 3-1: Time series of Green Point effluent discharge rate for the winter/spring period.

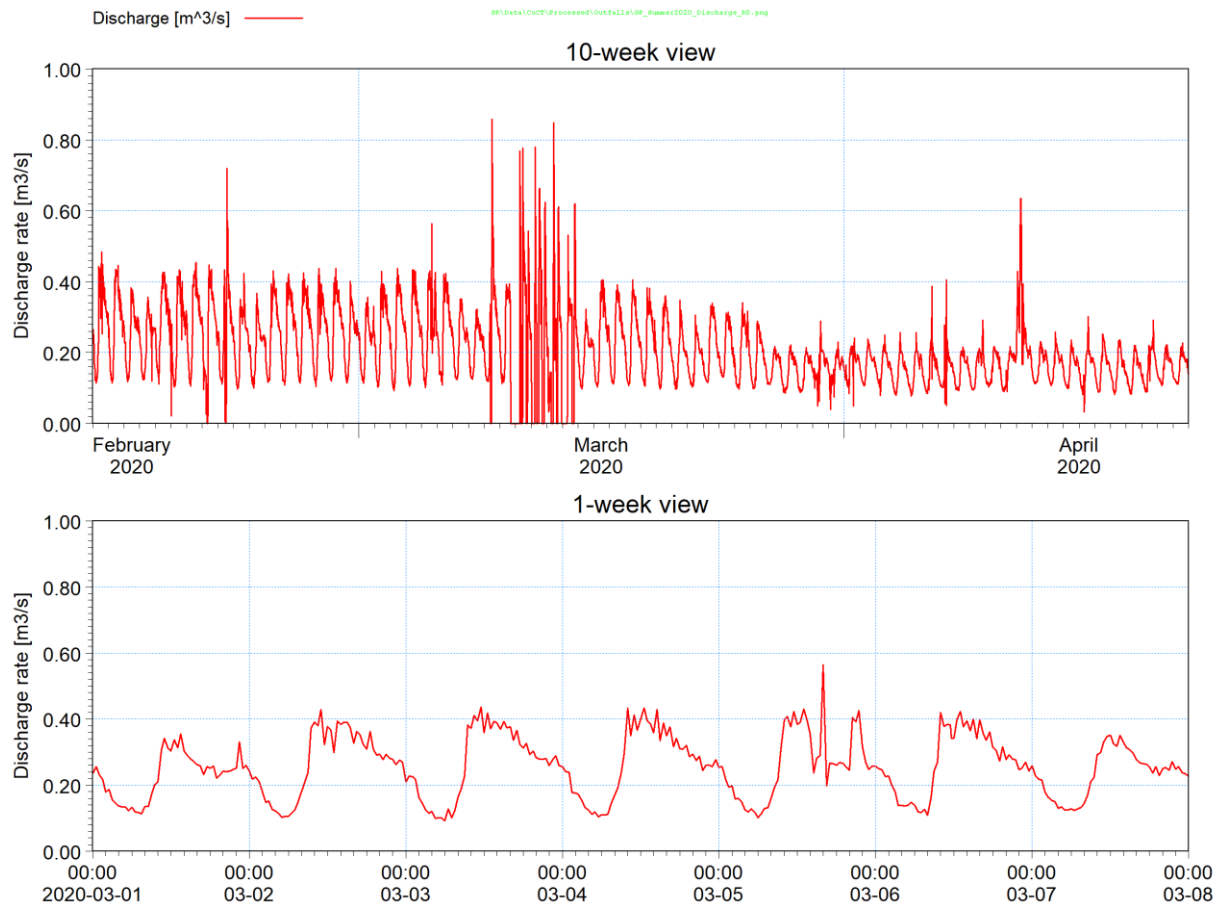


Figure 3-2: Time series of Green Point effluent discharge rate for the summer/autumn period.

Table 3-2: Green Point effluent discharge rate statistics.

Parameter	Discharge rate	
	Winter/spring	Summer/autumn
Average	23 800 m³/d	18 100 m³/d
5 th percentile	0.134 m³/s	0.086 m³/s
50 th percentile	0.277 m³/s	0.191 m³/s
95 th percentile	0.430 m³/s	0.391 m³/s

A significant reduction in effluent discharge rates could be observed from 23 March 2020 due to a national lockdown enforced in response to the COVID-19 pandemic resulting in fewer people in the city.



3.3 Effluent concentrations

The effluent concentrations applied in the model are shown in Table 3-1

Table 3-3: Modelled effluent concentrations.

Constituent	Concentration	Comments
E.coli	1 x10 ⁷ CFU/100 ml	Kay et al. (2008), CSIR (2017).
Enterococci	1.3 x10 ⁶ CFU/100 ml	Kay et al. (2008)
TSS	359 mg/l	Provided by CoCT based on the average measured value in the Green Point effluent (1 August 2014 – 31 October 2019)
Tracer	100 units	All other constituents will be modelled as a conservative tracer which will have a nominal concentration of 100 units and will be used to model the achieved dilutions.

The effluent temperature was set equal to the seawater temperature at the diffuser and the effluent salinity was set to 0 psu.

3.4 Water quality guidelines

3.4.1 Required dilutions

The analysis of the constituent concentrations in the effluent, the associated water quality guidelines and the required dilutions was undertaken by the CoCT. Based on this analysis the CoCT provided PRDW with three critical constituents as listed in Table 3-4. These required dilutions will be compared to the achieved dilutions obtained from the model.

Table 3-4: Required effluent dilutions.

Constituent	Dilutions
Ammonia	106
Chemical Oxygen Demand (COD)	51
TSS	1 753

The CoCT determined the allowable mixing zone to be within a radius of 256 m from the diffuser.

3.4.2 Bacteria concentrations

The CoCT confirmed that the target values for microbiological indicators for recreational waters in the coastal marine environment should be based on the Department of Environmental Affairs guidelines (DEA, 2012), as shown in Table 3-5.

Table 3-5: Guideline concentrations for enterococci and E.coli to meet the sufficient or fair category for recreational waters in the coastal marine environment.

Constituent	90 th percentile concentration [CFU/100 ml]
Enterococci	≤ 185
E.coli	≤ 500

4. MODEL SETUP

4.1 Model mesh

The WG19 horizontal coordinate system was used for this study. All spatial plots include x and y axes showing the x and y coordinates in metres in the WG19 system. True north is always pointing upwards.

The model mesh comprises triangles with a resolution varying from about 3 km at the offshore boundary to 50 m in the vicinity of the diffuser. Quadrangular elements with a resolution of 25 m were used around the diffuser to resolve the effluent release into the far-field model. The vertical mesh is comprised of twelve sigma layers with equal layer thicknesses.

Figure 4-1 and Figure 4-2 and represent the three-dimensional and horizontal views of the mesh used for the outfall dispersion modelling.

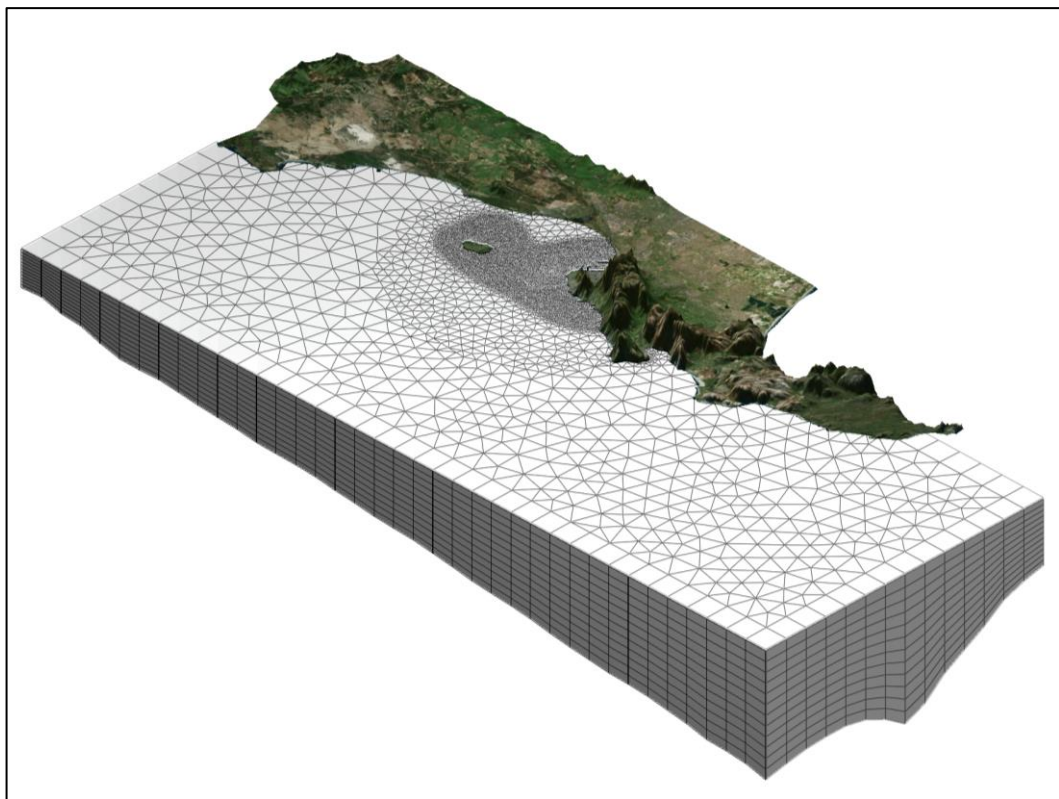


Figure 4-1: Three-dimensional representation of mesh used for the outfall dispersion modelling. Note the vertical axis is not to scale.

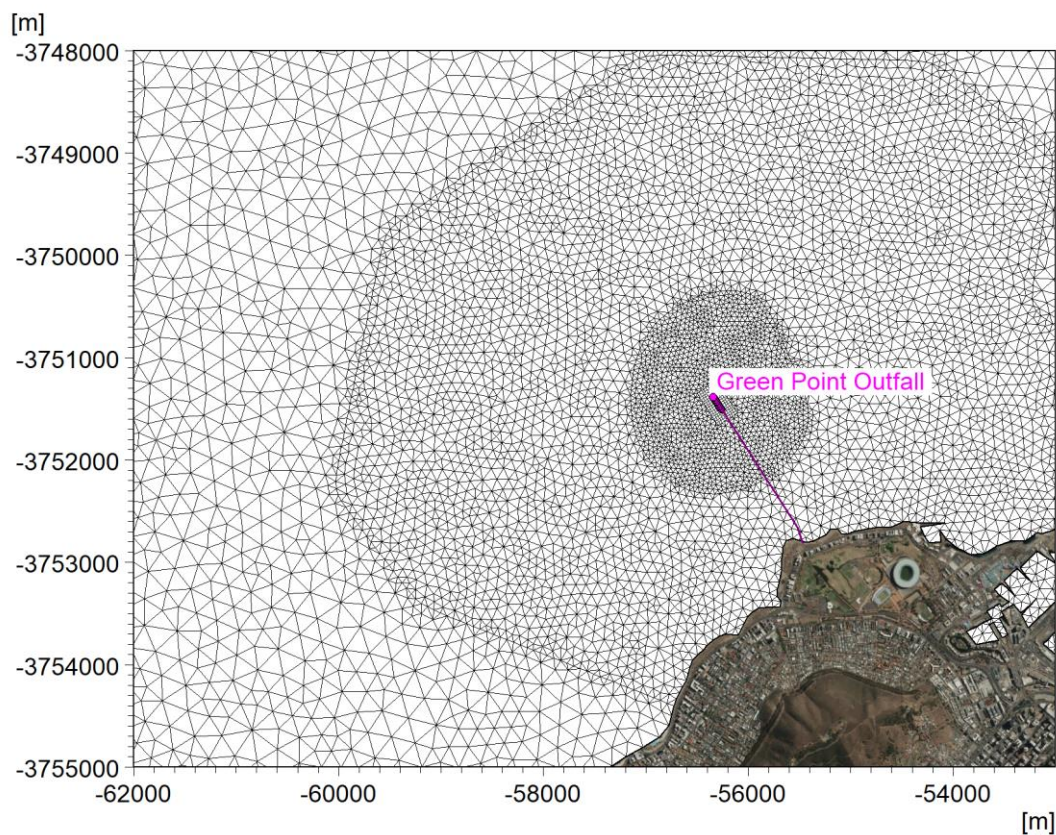
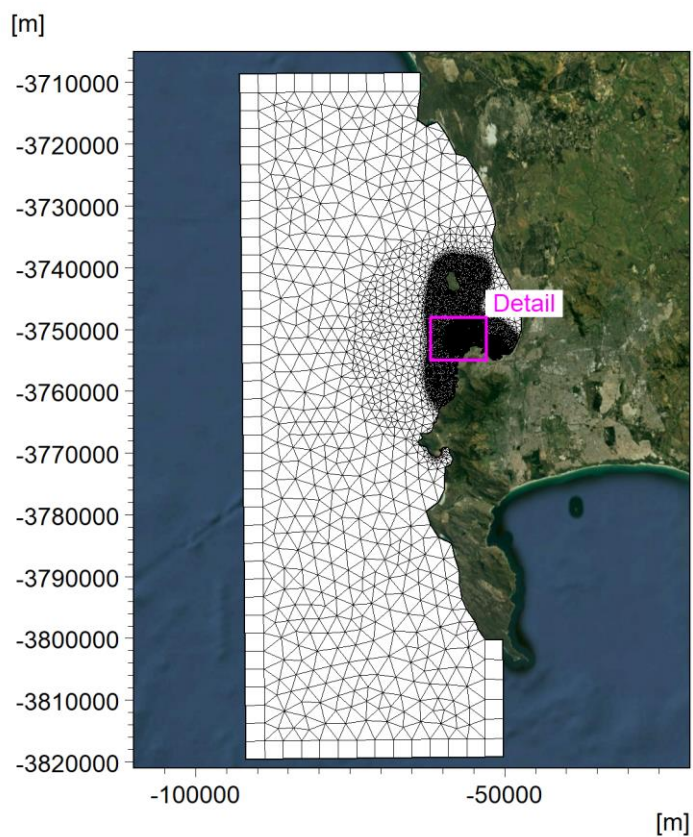


Figure 4-2: Horizontal mesh used for the outfall dispersion modelling.



4.2 Bathymetry

The vertical datum adopted in this study is Chart Datum (CD). CD is 0.825 m below Land Levelling Datum (LLD) which is also known as Mean Sea Level (MSL).

The model bathymetry has been obtained from the following sources:

- CMAP electronic hydrographic charts
- LIDAR topographic surveys landward of the high water mark

Figure 4-3 shows the model bathymetry and the locations of the ADCP and thermistor deployments used for the calibration of the model.

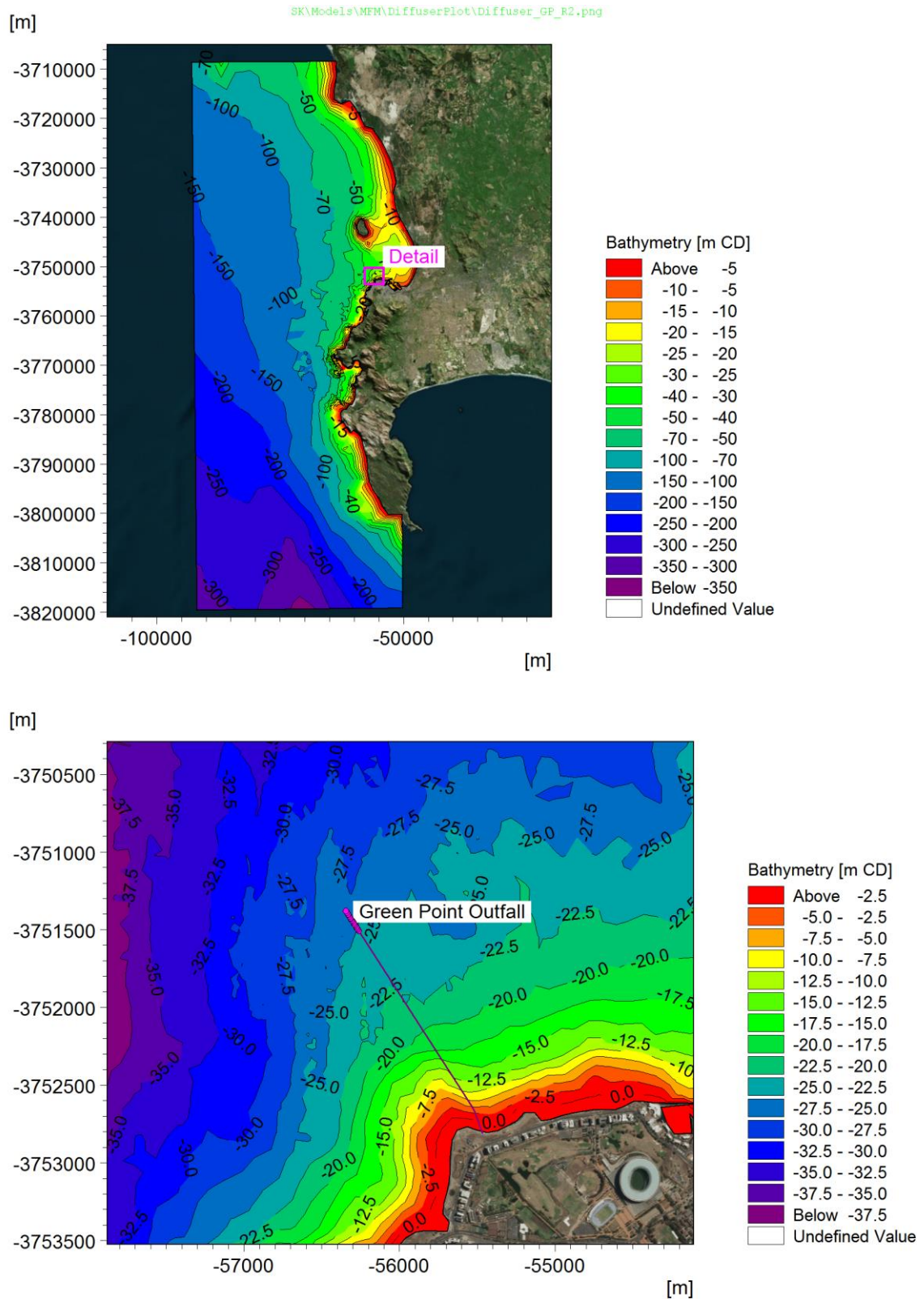


Figure 4-3: Model bathymetry.



4.3 Wind

Wind is an important forcing mechanism for currents, vertical mixing and upwelling – and thus the effluent dispersion. The wind fields near the outfalls are influenced by the surrounding mountains which require a high spatial resolution to resolve.

The Climate System Analysis Group at the University of Cape Town has kindly provided wind data from the Weather Research and Forecasting (WRF) model with a spatial resolution of 4 km and a temporal resolution of 1 hour.

Figure 4-4 shows two snapshots in time illustrating the high spatial variability in the 4 km resolution modelled winds around Cape Town.

Figure 4-5 to Figure 4-8 show comparisons between the modelled winds and measured winds at three locations around Cape Town (Cape Town International Airport, Cape Point and Koeberg) for the winter/spring and summer/autumn modelling periods.

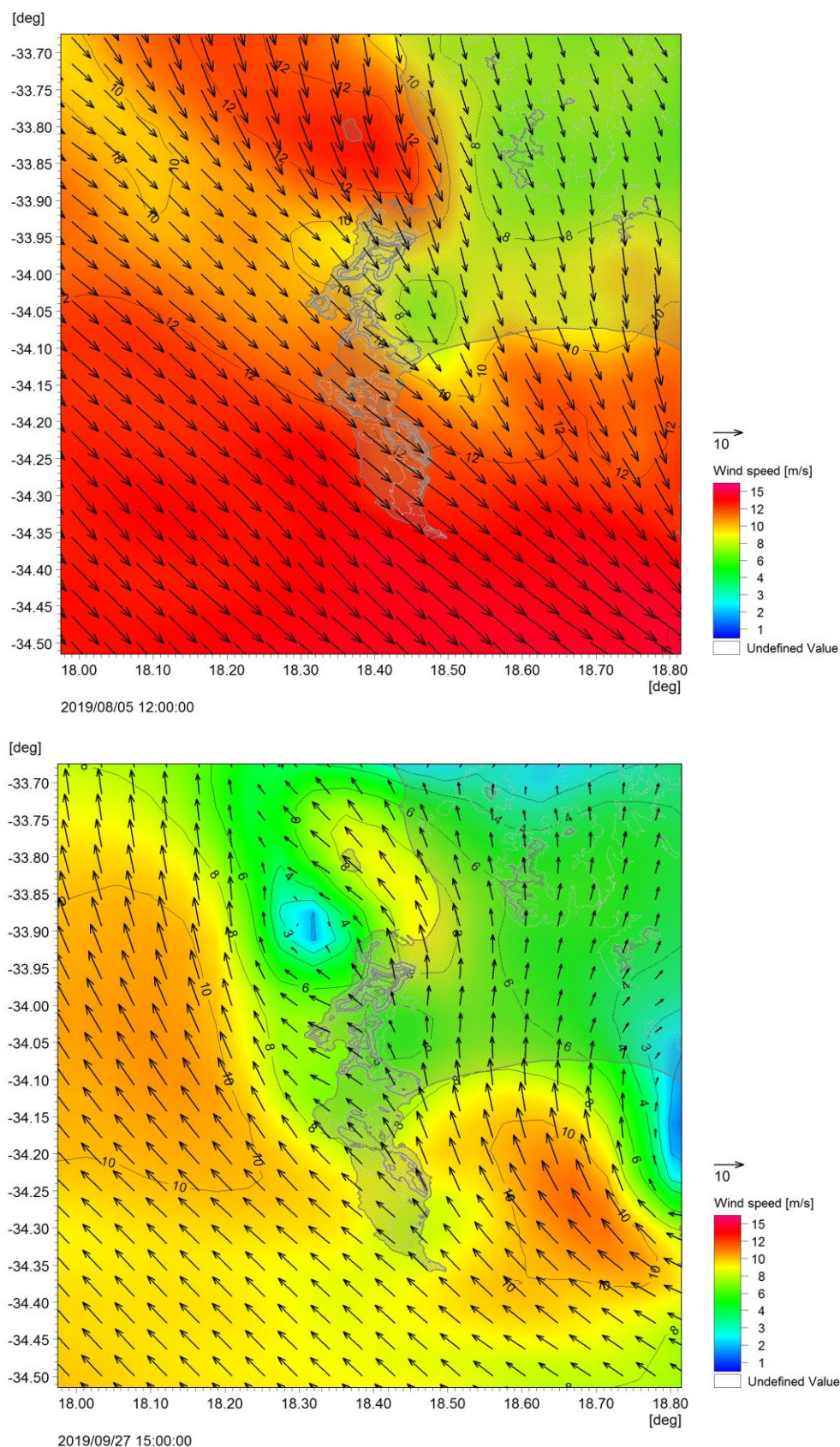


Figure 4-4: Snapshots illustrating the high spatial variability in the 4 km resolution modelled winds around Cape Town (grey lines show topography at 100 m intervals).

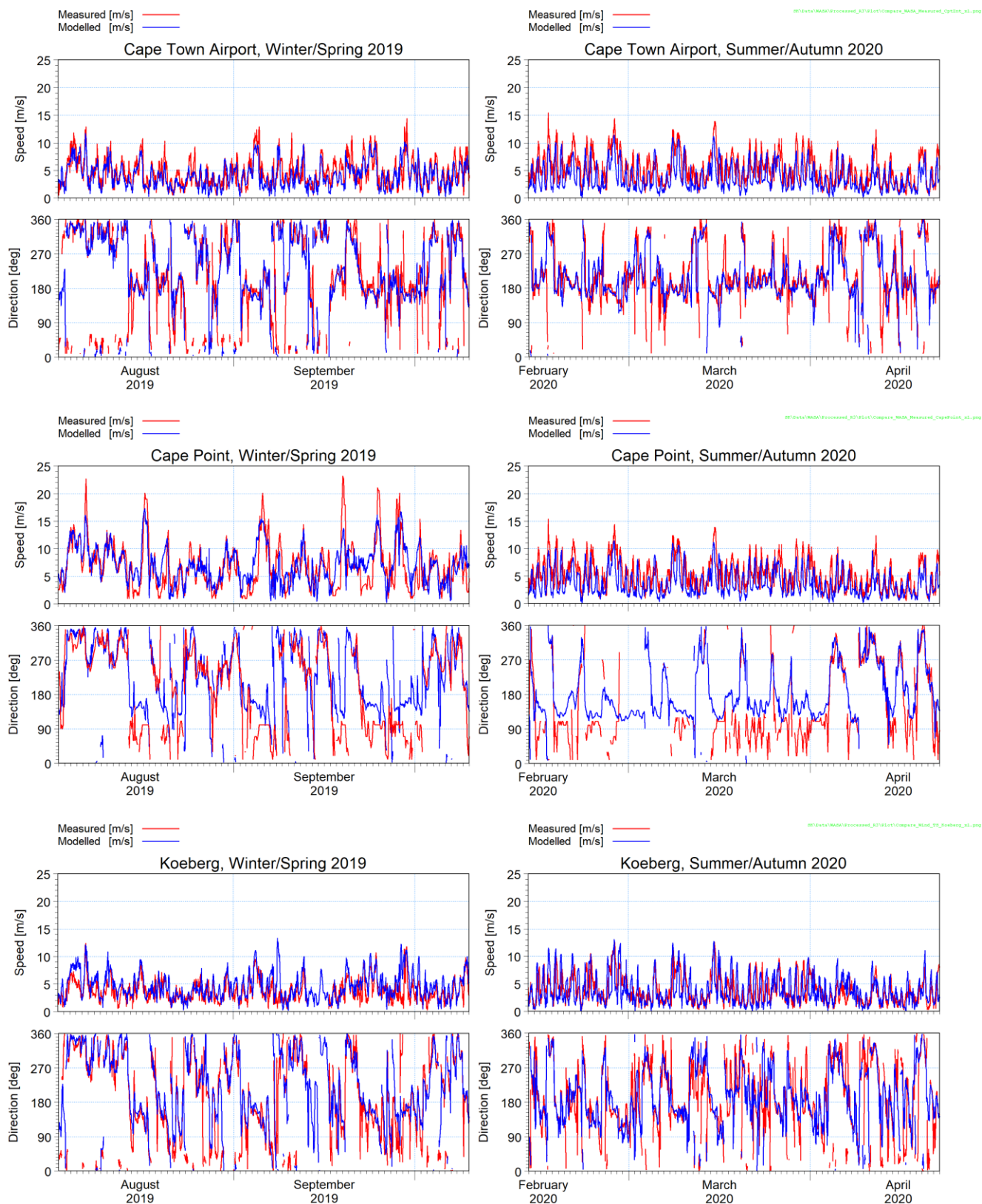


Figure 4-5: Time series of modelled compared to measured winds at Cape Town International, Cape Point and Koeberg.

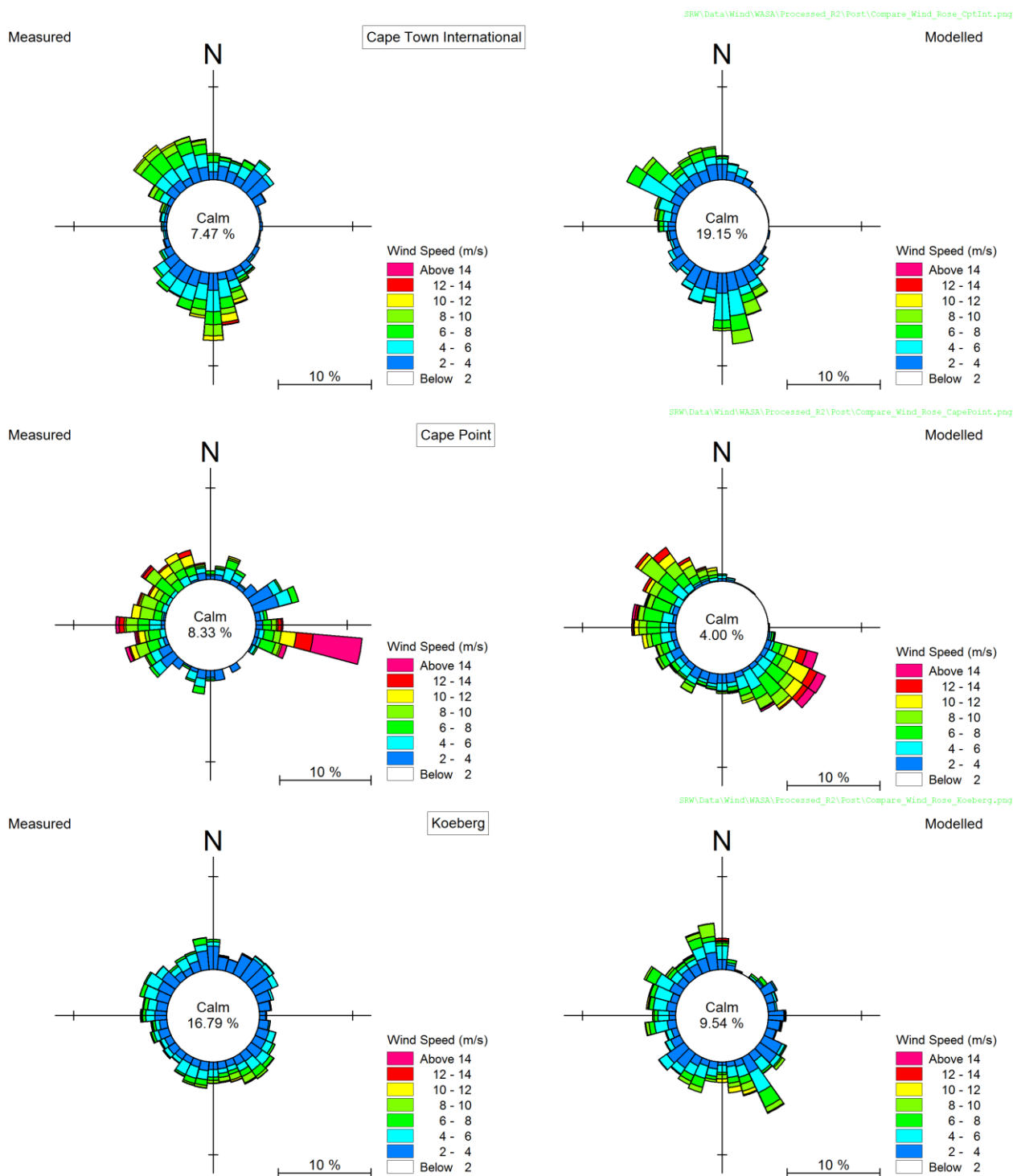


Figure 4-6: Roses of modelled compared to measured winds at Cape Town International, Cape Point and Koeberg for the winter/spring 2019 period.

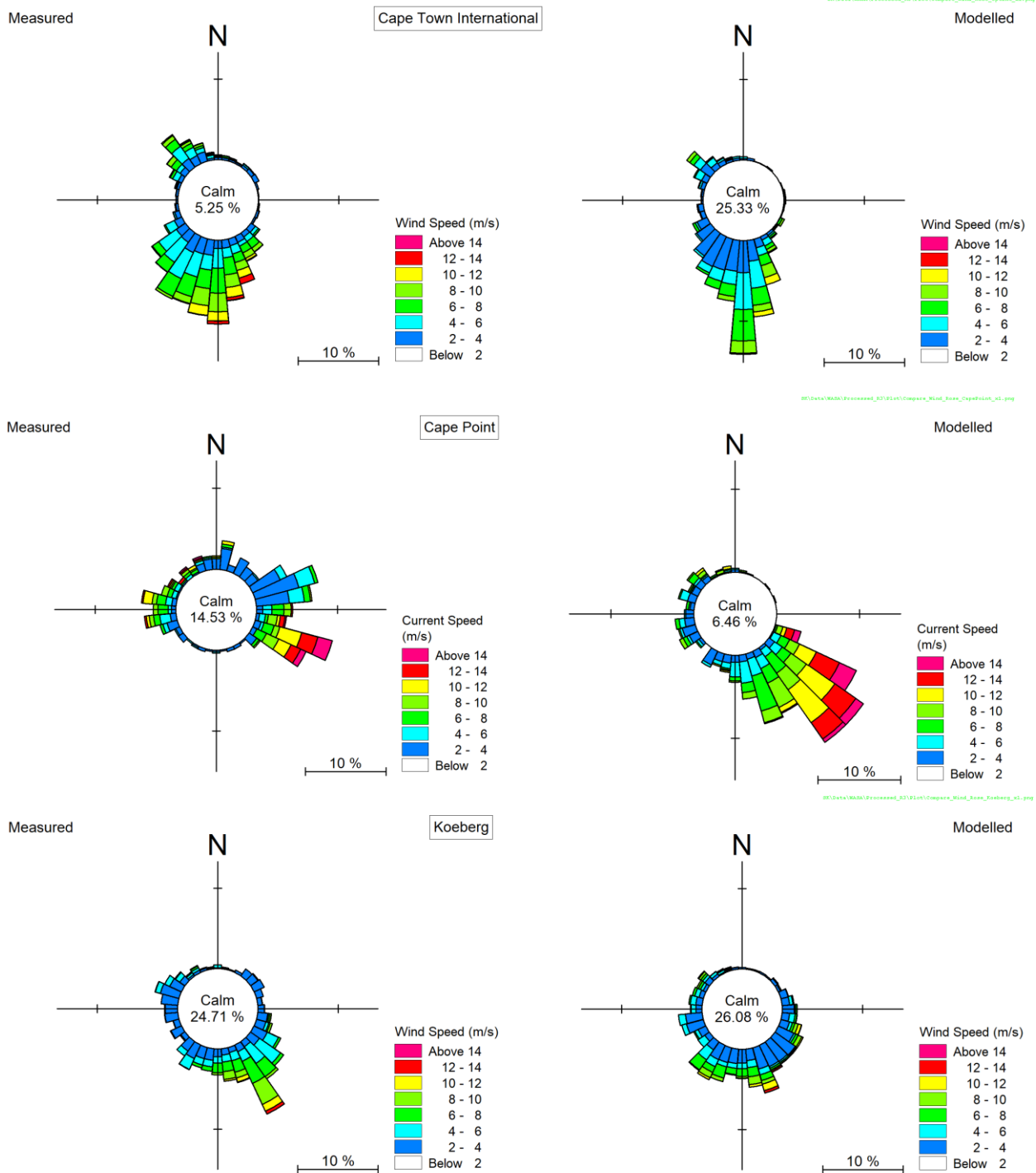


Figure 4-7: Roses of modelled compared to measured winds at Cape Town International, Cape Point and Koeberg for the summer/autumn 2020 period.

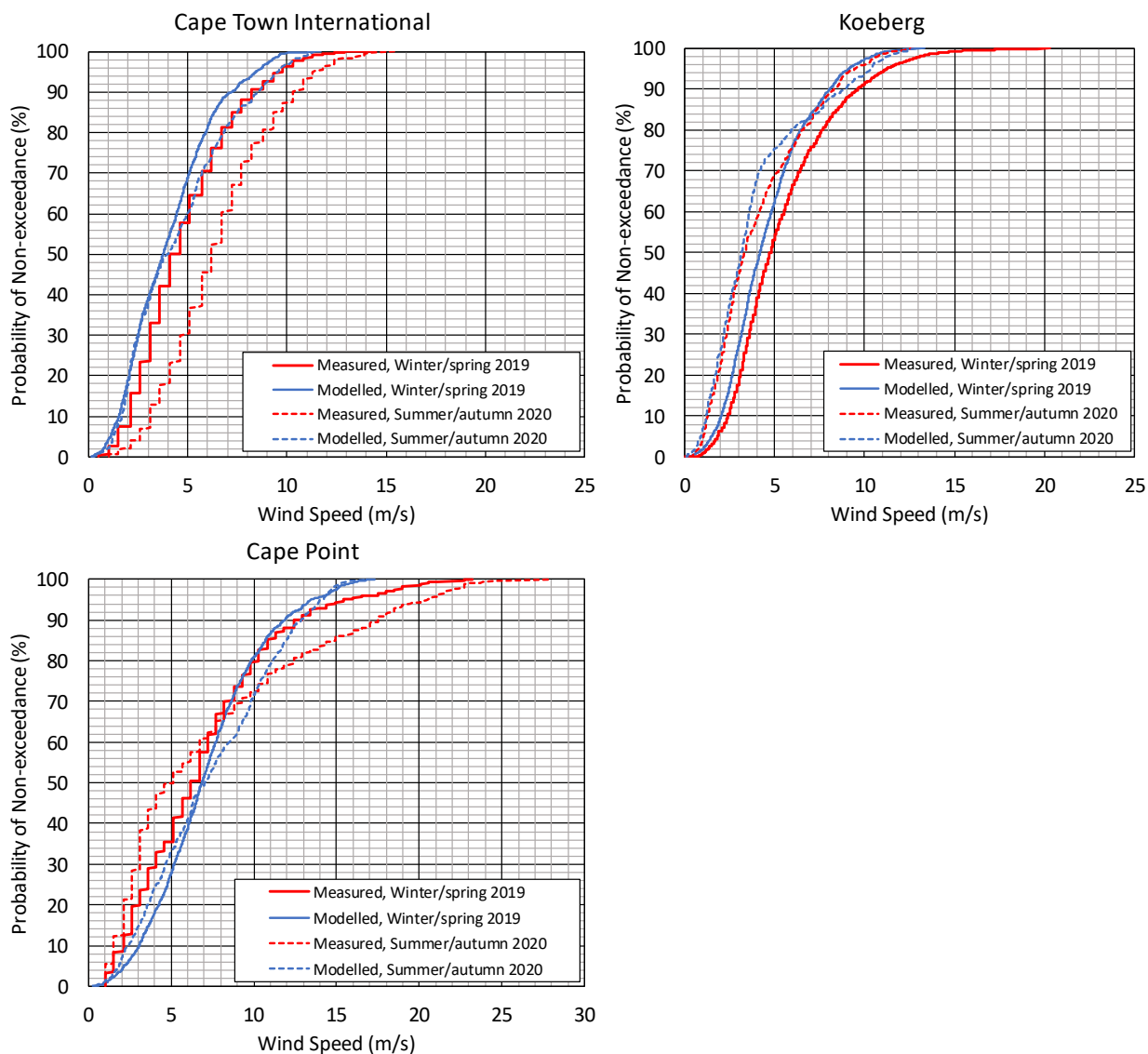


Figure 4-8: Wind speed exceedance of modelled compared to measured winds at Cape Town International, Cape Point and Koeberg.

These results indicate that the WRF modelled winds compare well to the measured winds at three different locations across Cape Town. The main discrepancies are the wind directions at Cape Point which is likely due to the steep cliffs at this location, and the modelled wind speed being approximately 1 m/s to 2 m/s lower than the measurements at Cape Town International.



4.4 Boundary conditions

The model boundary conditions are extracted from global hindcast models as described in Table 4-1:

Table 4-1: Global hindcast models used for the model boundary conditions.

Model	Parameter	Spatial resolution [°]	Temporal resolution [hrs]
HYbrid Coordinate Ocean Model (HYCOM) global ocean circulation model (HYCOM, 2020).	Non-tidal water levels	0.08	3
	Non-tidal ocean currents		
	Seawater temperature		
	Seawater salinity		
DTU10 (Technical University of Denmark) global tidal model (DTU, 2010).	Predicted tides	0.125	Predicted from constituents.
	Predicted tidal currents	0.25	
European Centre for Medium-Range Weather Forecasts (EMCWF) ERA5 global atmospheric model (ECMWF, 2020).	Air temperature	0.25	1
	Humidity		
	Solar radiation		
National Centers for Environmental Prediction (NCEP) global wave forecast model (NCEP, 2020).	Wave spectra	0.5	3

4.5 Model settings

The vertical eddy viscosity was computed using the $k-\epsilon$ vertical turbulence closure scheme, while the vertical eddy dispersion was set to 0.1 times the vertical eddy viscosity. This scaling factor was applied to compensate for additional vertical mixing caused by the use of only 12 vertical layers and the associated smoothing of the vertical density gradients.

The wind friction coefficient and seabed roughness were tuned to physically realistic values which yielded the best agreement between modelled and measured currents at Green Point.

5. MODEL CALIBRATION

5.1 Winter/spring

The model was calibrated to metocean data measured by Lwandle during a 6-week period between 21 August 2019 and 3 October 2019. The measurements used for the model calibration comprise:

- ADCP measurements, including:
 - Currents measured across the depth profile in 1 m bins at 10-minute intervals.
 - Fully spectral waves, available at hourly intervals.
 - Seawater temperature at 10-minute intervals.
- Seawater temperature measured from a thermistor string, available at 5 discrete depth levels between 3 m and 14 m above the seabed. The data is only available for the first week of measurements.

The ADCP (X = -56 401 m, Y = -3 751 487 m) and thermistor string (X = -56 403 m, Y = -3 751 495 m) were deployed approximately 100 m southwest of the diffuser at a depth of -27.6 m CD. The locations are shown in Figure 5-1.

5.1.1 Waves

A wave refraction plot for a west-south-westerly wave event is shown in Figure 5-1.

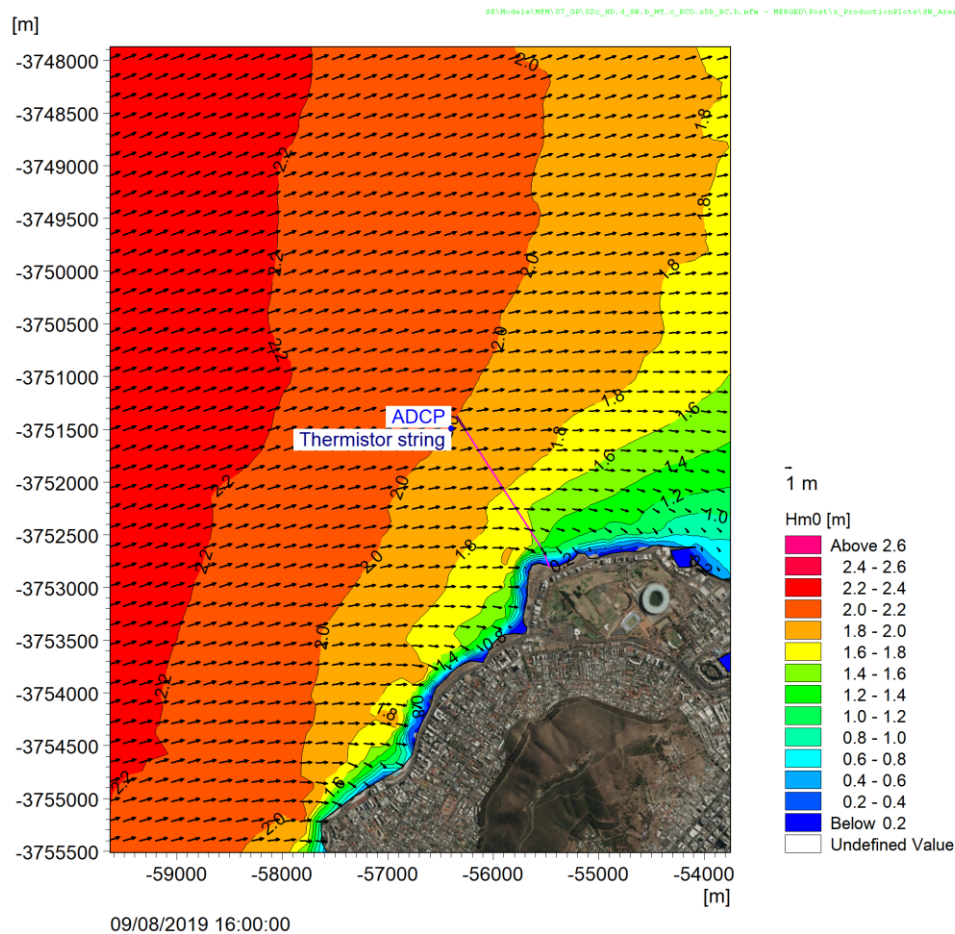


Figure 5-1: Winter/spring: Wave refraction plot for a west-south-westerly wave event. The modelled wave condition at the ADCP is $H_{m0} = 2.14$ m, $T_p = 10.2$ s, $D_{MP} = 259^\circ$.



Figure 5-2 presents a time series comparison of measured and modelled wave parameters at the ADCP. Measured and modelled wave roses are shown in Figure 5-3. By convention, wave direction is the direction from which the wave is coming, measured clockwise from true north.

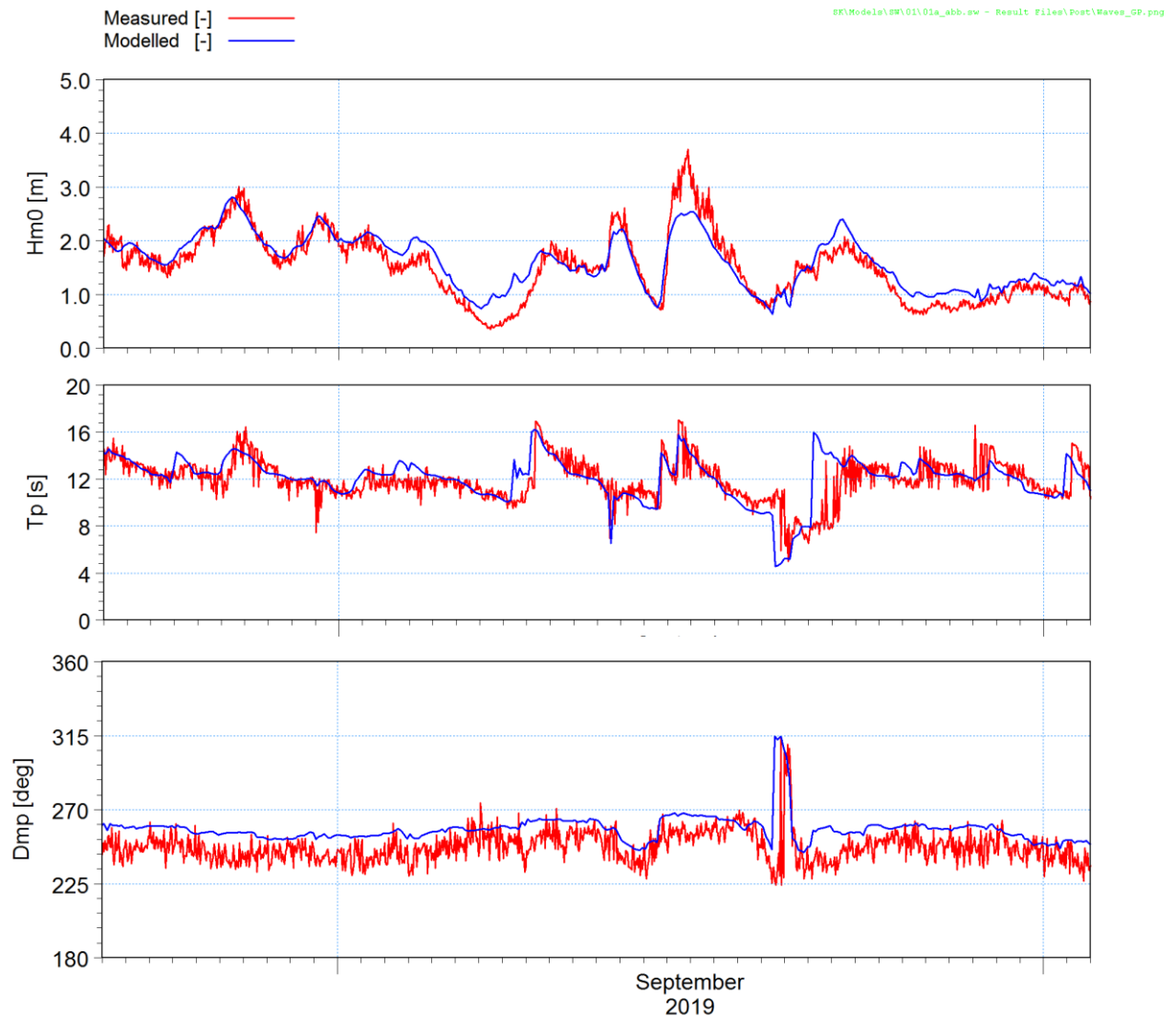


Figure 5-2: Winter/spring: Time series of measured and modelled significant wave height (H_{m0}), peak wave period (T_p) and mean wave direction at T_p (D_{MP}) at the location of the ADCP.

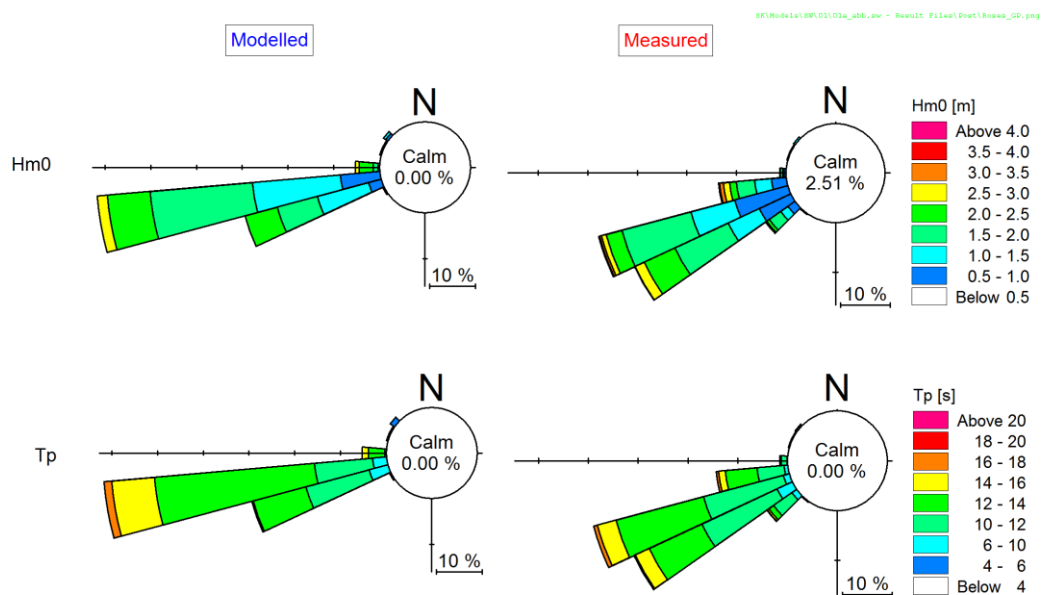


Figure 5-3: Winter/spring: Wave roses of measured and modelled H_{m0} and T_p for the 6-week deployment period at the location of the ADCP.

A good overall comparison could be observed from the time series and wave rose plots. Occasional over- or underprediction of wave heights can be observed, but there is no bias in either direction. The modelled peak wave period compared well to the measurements. The modelled mean wave direction shows a constant offset of about 10° compared to the measurements. The agreement between the ADCP measurements and the wave model outputs shows the model to be adequately calibrated for the purposes of this study

5.1.2 Water levels

The predicted tidal levels at the Port of Cape Town ($X = -539\,934\text{ m}$, $Y = -3\,752\,769\text{ m}$) were extracted from the MIKE by DHI CMAP Electronic Charts Database (DHI, 2020i). Figure 5-4 presents a time series comparison of modelled water levels to predicted tides at the Port of Cape Town. A water level probability of non-exceedance plot is shown in Figure 5-5 for the Port of Cape Town.

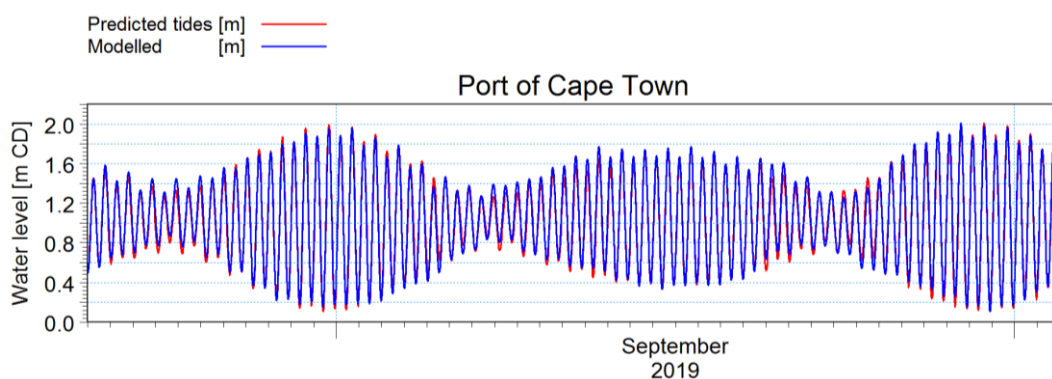


Figure 5-4: Winter/spring: Time series comparison of modelled water levels to predicted tides at the Port of Cape Town.

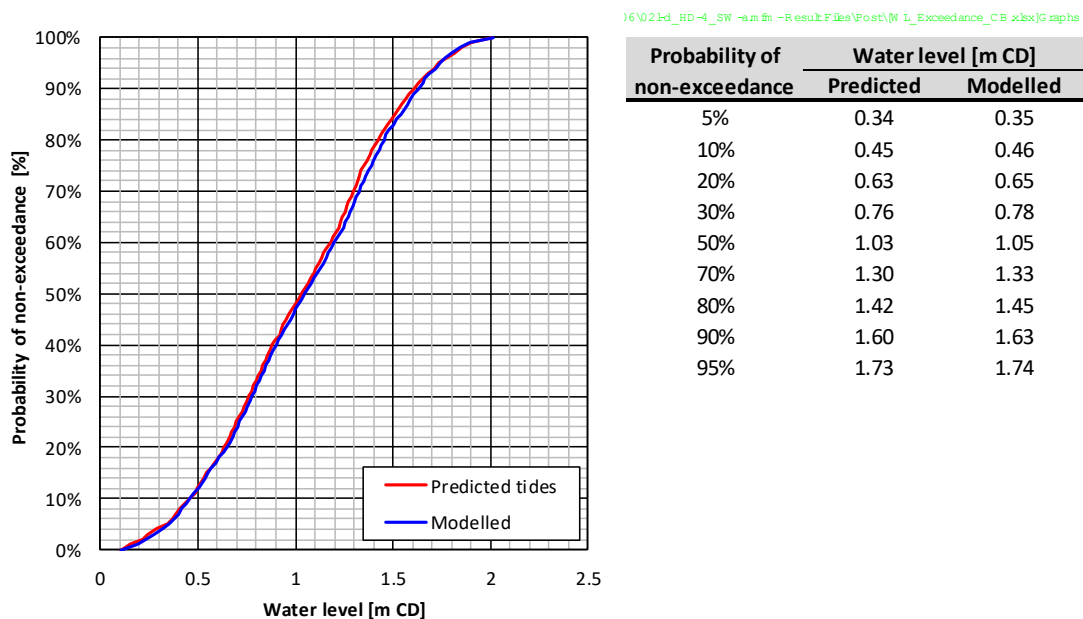


Figure 5-5: Winter/spring: Probability of non-exceedance for predicted tides and modelled water levels for the 6-week deployment period at the Port of Cape Town.

The comparison shows a good overall model prediction in both tidal phase and amplitude.

5.1.3 Currents

A contour plot of instantaneous currents during a west-south-westerly wave/north-westerly wind event is shown in Figure 5-6. The modelled currents were compared to the measurements near the seabed (3.8 m above the seabed) and near the surface (23.8 m above the seabed). Figure 5-7 presents a time series comparison of the modelled and measured currents at the ADCP. Non-exceedance curves of current speed for the 6-week period are shown Figure 5-8. Current rose comparisons of modelled and measured currents are presented in Figure 5-9. Note that current direction is by convention the direction towards which the current is flowing.

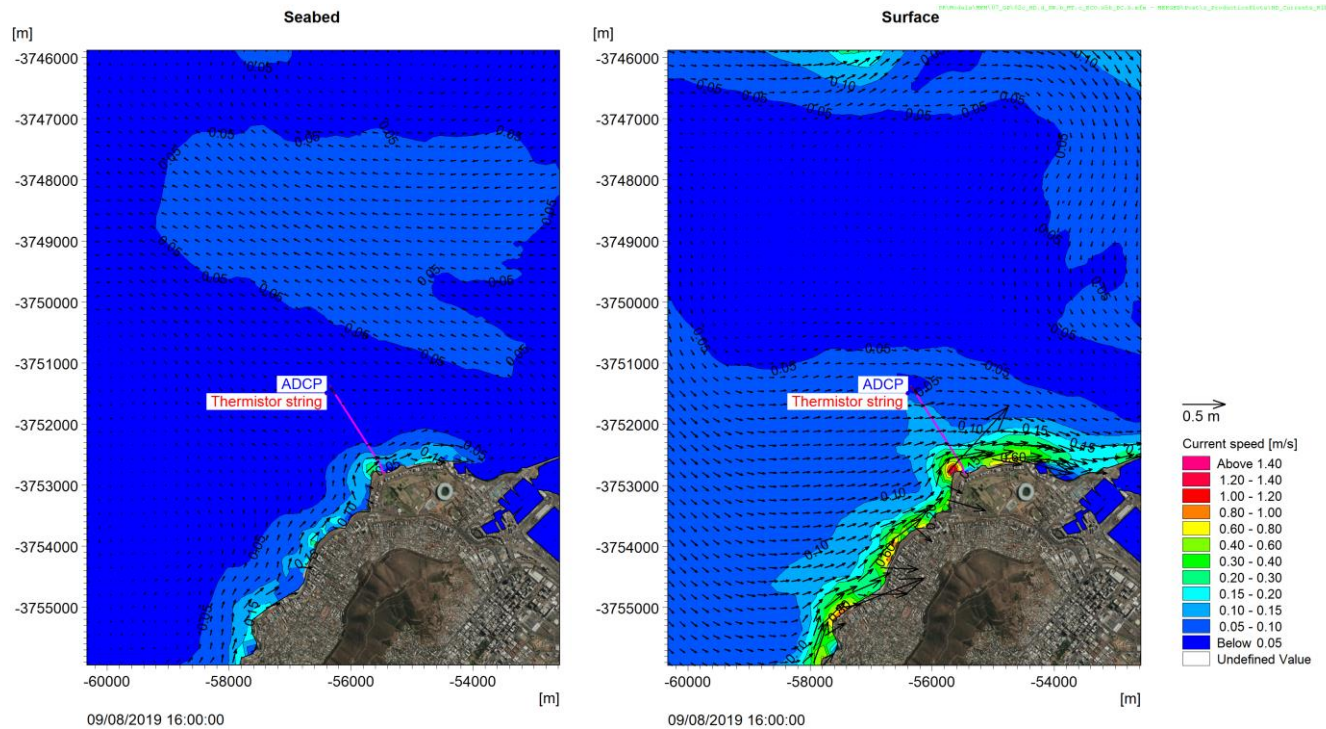


Figure 5-6: Winter/spring: Contour plot of instantaneous seabed (left) and surface (right) currents during a west-south-westerly wave/north-westerly wind event (shown in Figure 5-1).

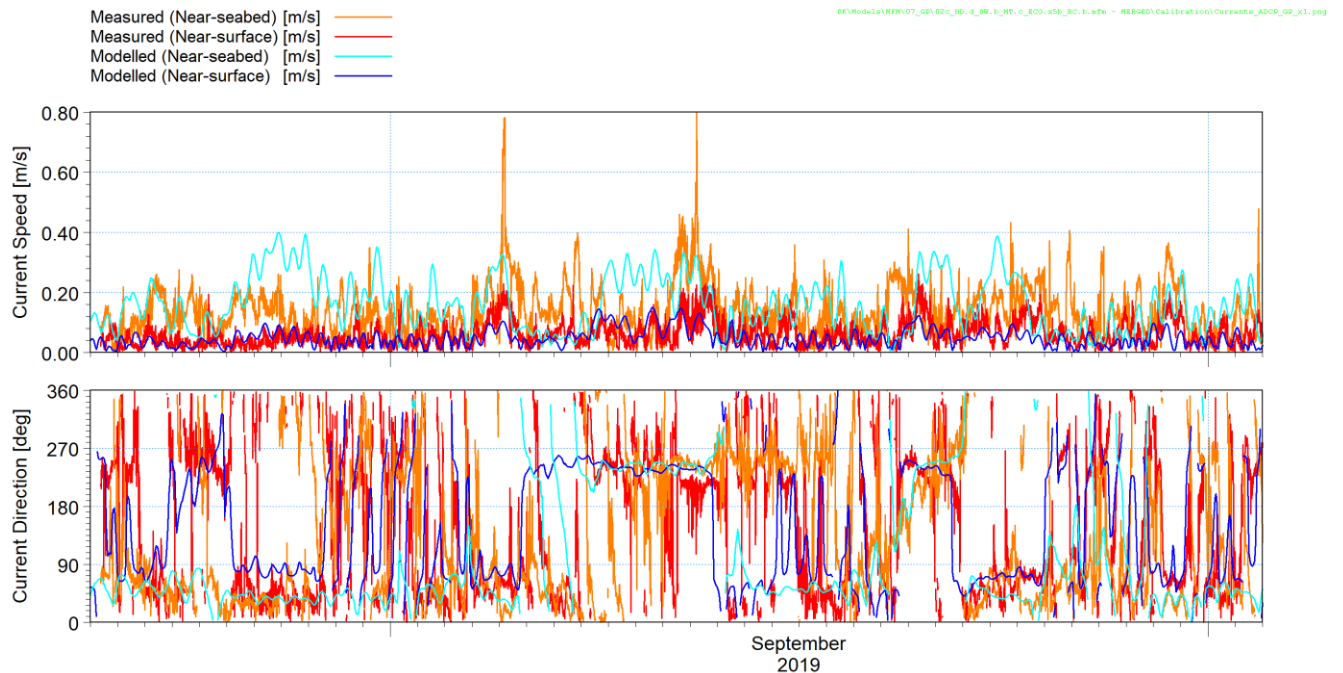


Figure 5-7: Winter/spring: Time series comparison of measured and modelled current speed and direction at the ADCP.

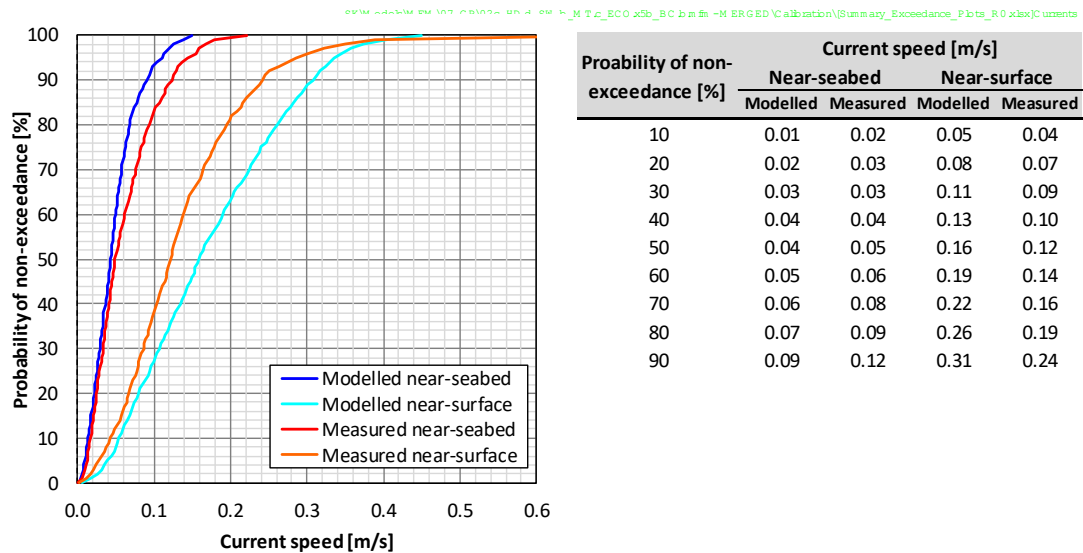


Figure 5-8: Winter/spring: Probability of non-exceedance for measured and modelled current speed for the 6-week deployment period at the ADCP.

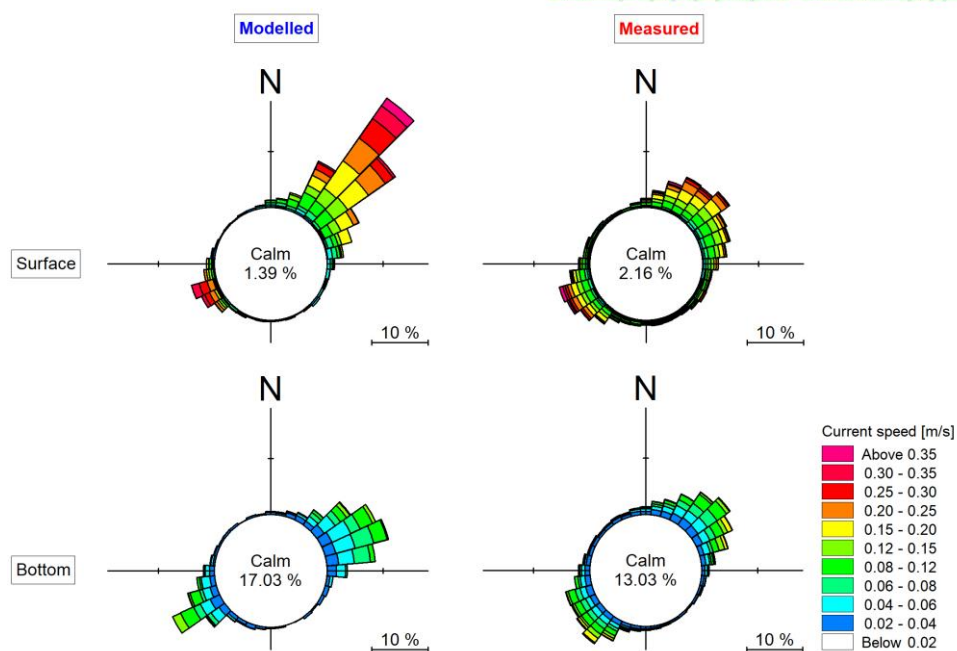


Figure 5-9: Measured and modelled current roses for the 6-week deployment period at the ADCP.

The model shows a tendency to overpredict the operational current speeds near the surface and underpredict the stronger currents near the seabed. The dominant current directions are well represented at both depths, although the model tends to underpredict the occurrence of south-westerly currents near the surface. Note that that more directional spreading is expected in the measurements due to high frequency processes such as eddies and edge waves that are not included in the model boundary conditions.

Overall the model is able to reproduce the main features of the currents and is considered to be acceptable for the purposes of this study.

5.1.4 Temperature

The modelled seawater temperatures were compared to one week of thermistor string measurements near the seabed (3.0 m above the seabed) and at mid-depth (14.0 m above the seabed) and to ADCP measurements near the seabed for the full calibration period. Figure 5-10 presents a time series comparison of the modelled and measured seawater temperatures. Non-exceedance curves of seabed and mid-depth temperatures for the 6-week period are shown Figure 5-11. Figure 5-12 presents a non-exceedance curve of stratification (seabed to mid-depth) from the modelled temperatures. Note that the thermistor string measurements were excluded from the exceedance curves due to the limited data availability.

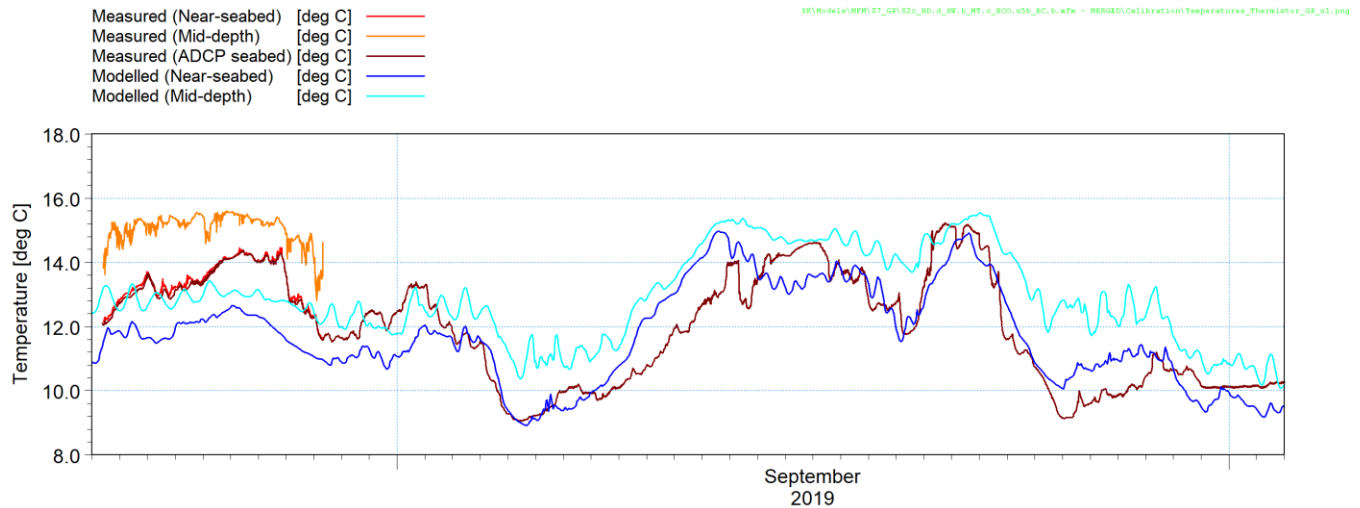


Figure 5-10: Winter/spring: Time series of measured and modelled seawater temperatures.

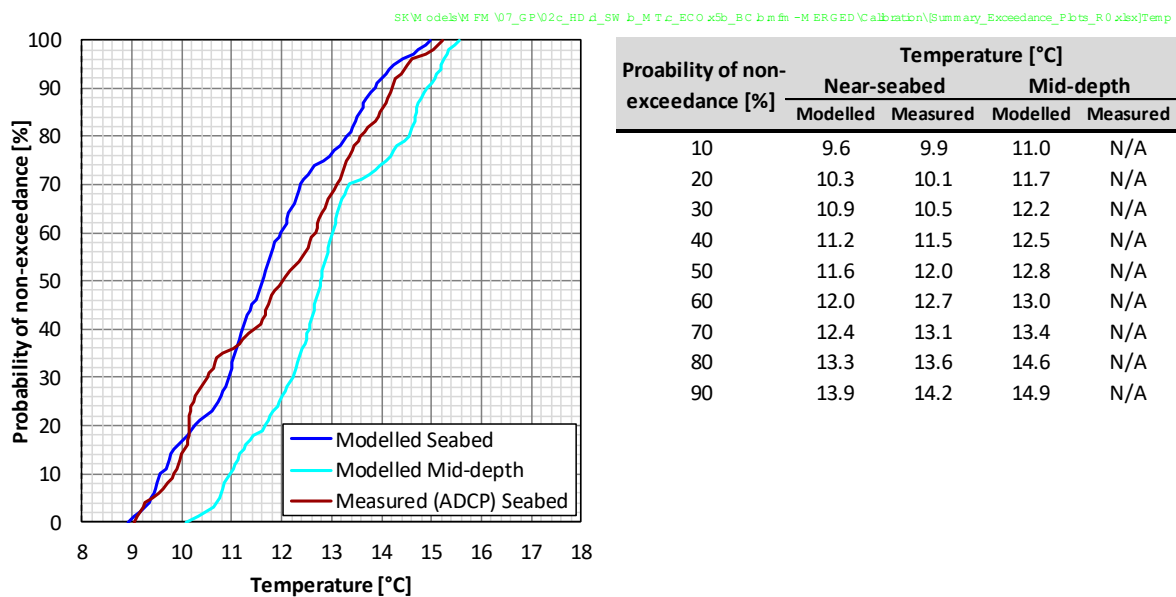


Figure 5-11: Winter/spring: Probability of non-exceedance of measured and modelled seawater temperatures for the 6-week deployment period.

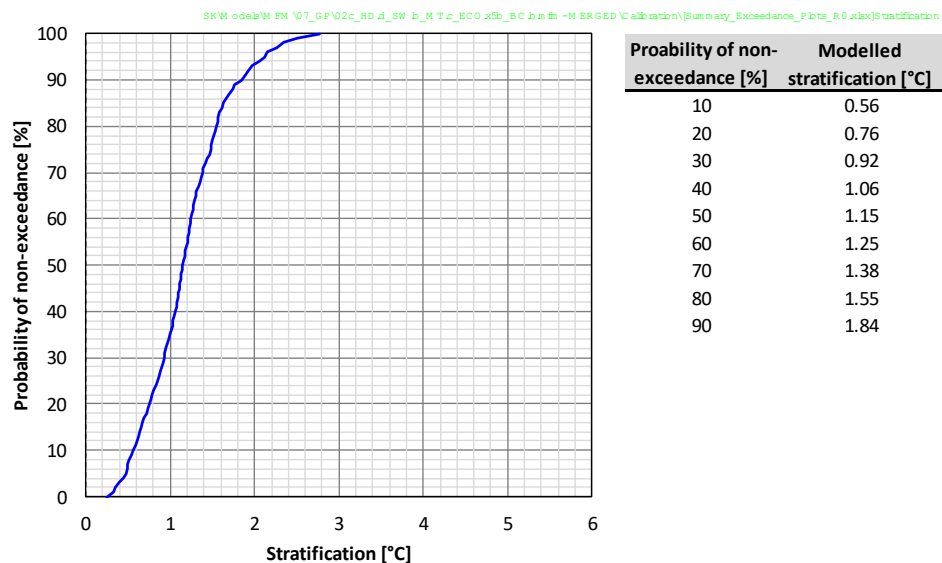


Figure 5-12: Winter/spring: Probability of non-exceedance of modelled seawater temperature stratification (near-seabed to mid-depth) for the 6-week deployment period.

The measured time series shows that the seawater temperatures are complex and vary over a range of time-scales due to upwelling, solar radiation and other dynamic processes. The model is able to predict the mean trend in seabed seawater temperatures including some of the discrete dynamic events. Periodic over- or underprediction of seabed temperatures can be observed, however the model shows a good statistical distribution of temperatures. The accuracy of the modelled stratification is inconclusive due to the limited availability of thermistor string measurements. The model is considered to be adequately calibrated for seawater temperature for the purposes of this study.

5.2 Summer/autumn

The model was calibrated to metocean data measured by Lwandle during a 10-week period between 13 February 2020 and 23 April 2020. The measurements used for the model calibration comprise:

- ADCP measurements, including:
 - Currents measured across the depth profile in 1 m bins at 10-minute intervals.
 - Fully spectral waves, available at hourly intervals.
- Seawater temperature measured from a thermistor string, available at 5 discrete depth levels from 3 m above the seabed to the surface.

The ADCP (X = -56 401 m, Y = -3 751 482 m) and thermistor string (X = -56 409 m, Y = -3 751 488 m) were deployed approximately 100 m southwest of the diffuser at a depth of -27.6 m CD. The locations are shown in Figure 5-13.

5.2.1 Waves

A wave refraction plot for a west-south-westerly wave event is shown in Figure 5-13.

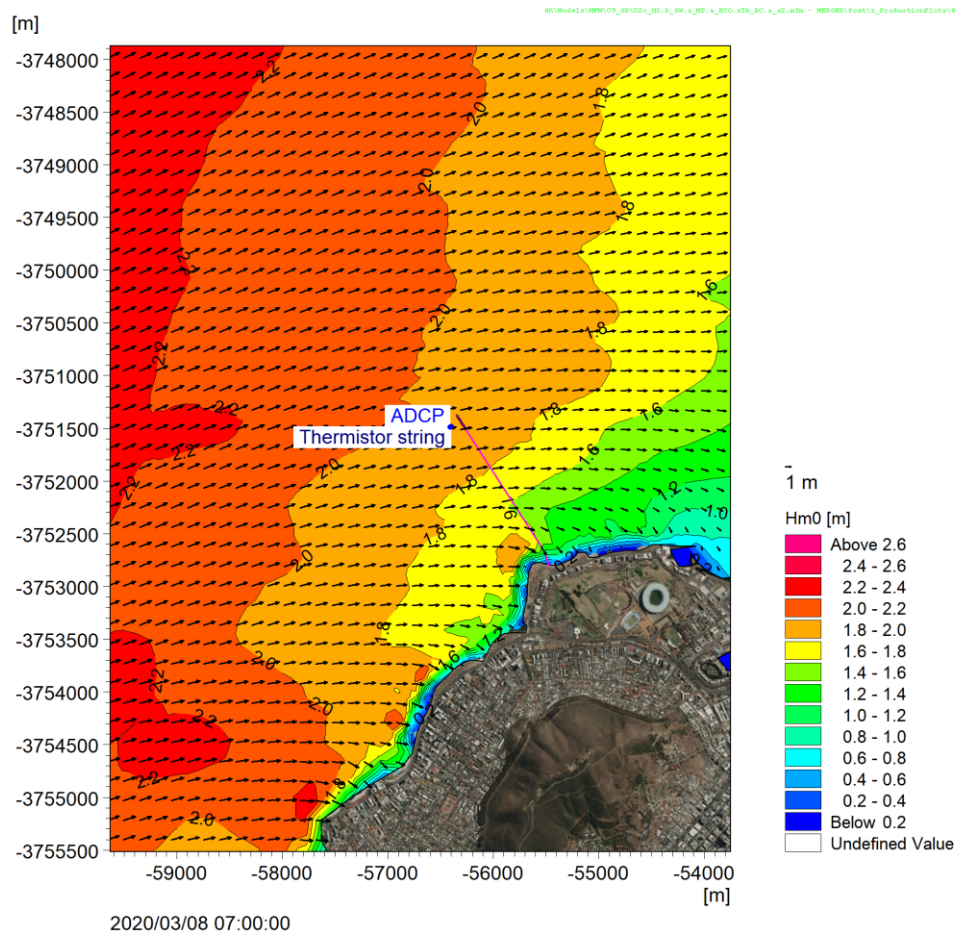


Figure 5-13: Summer/autumn: Wave refraction plot for a west-south-westerly wave event. The modelled wave condition at the ADCP is $H_{m0} = 1.94$ m, $T_p = 15.1$ s, $D_{MP} = 259^\circ$.

Figure 5-14 presents a time series comparison of measured and modelled wave parameters at the ADCP. Measured and modelled wave roses are shown in Figure 5-15.

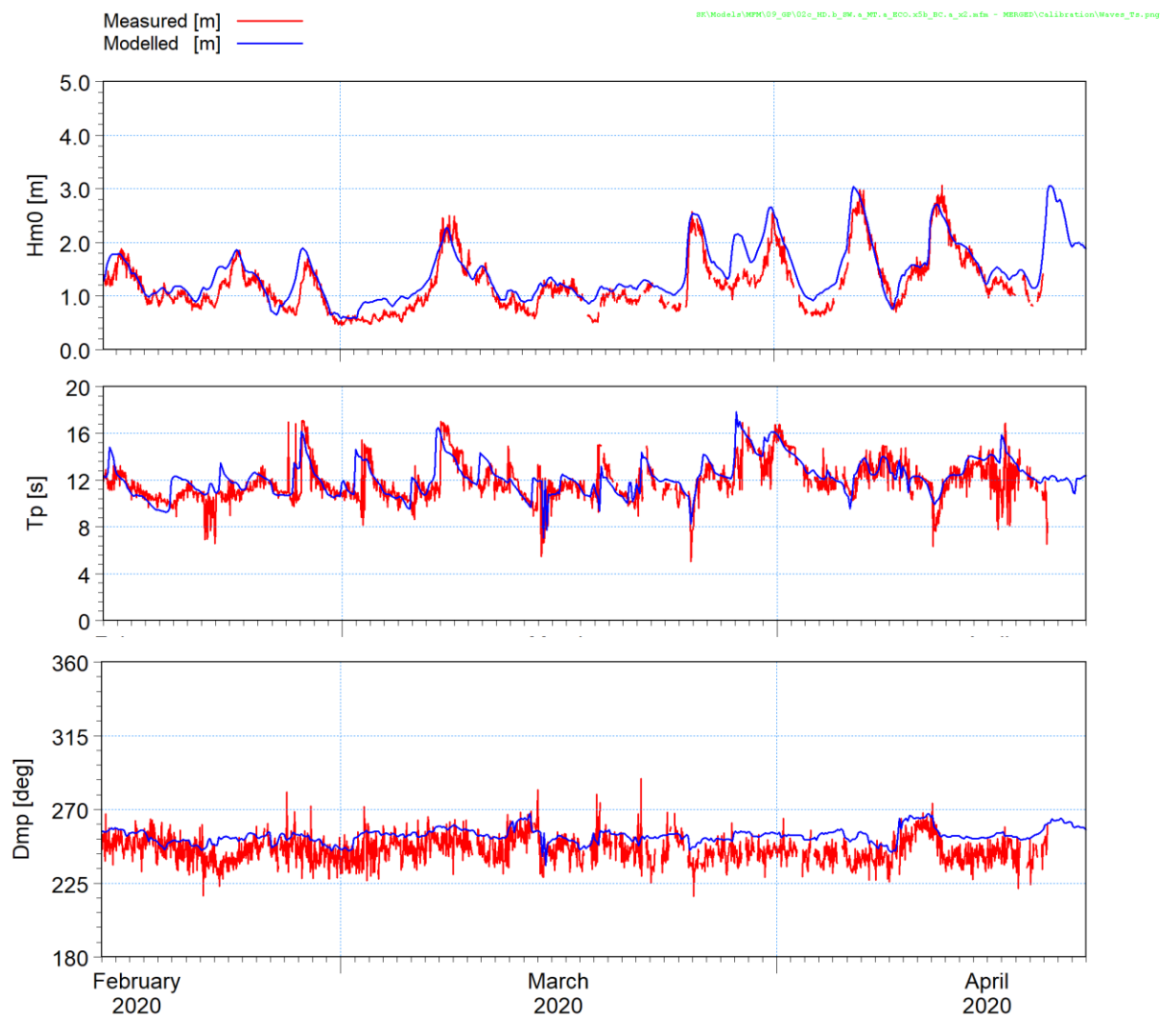


Figure 5-14: Summer/autumn: Time series of measured and modelled significant wave height (H_{m0}), peak wave period (T_p) and mean wave direction at T_p (D_{MP}) at the location of the ADCP.

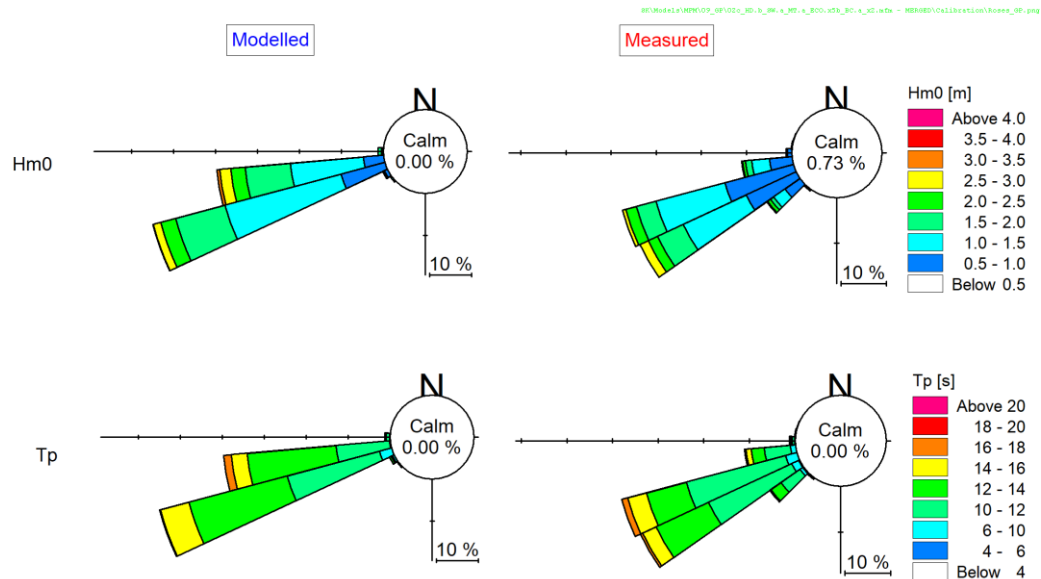


Figure 5-15: Summer/autumn: Wave roses of measured and modelled H_{m0} and T_p for the 10-week deployment period at the location of the ADCP.

The significant wave height is occasionally over- or underpredicted by the model, but there is no systematic bias. There is a good correlation between modelled and measured peak wave period and wave directions, but the latter shows a constant offset of about 10° . Overall the model shows sufficient for the purposes of this study.

5.2.2 Water levels

The predicted tidal levels at the Port of Cape Town (X = -539 934 m, Y = -3 752 769 m) were extracted from the MIKE by DHI CMAP Electronic Charts Database (DHI, 2020i). Figure 5-16 presents a time series comparison of modelled water levels to predicted tides at the Port of Cape Town. A water level probability of non-exceedance plot is shown in Figure 5-17 for the Port of Cape Town.

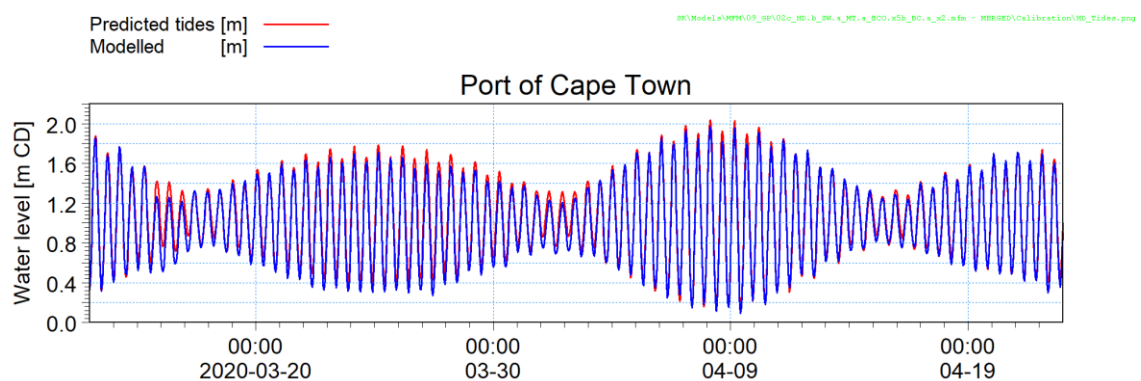
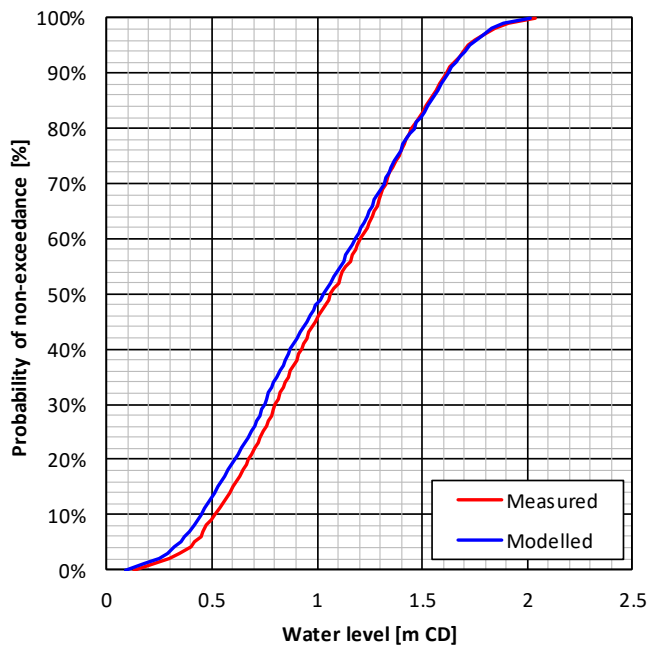


Figure 5-16: Summer/autumn: Time series comparison of modelled water levels to predicted tides at the Port of Cape Town.



\\x5b_B C a_x2 m fm -M ERGED\\Calibration\\CompamTs_HD_Tides.xlsx\\Graphs

Probability of non-exceedance	Water level [m CD]	
	Measured	Modelled
5%	0.42	0.35
10%	0.51	0.45
20%	0.67	0.61
30%	0.80	0.75
50%	1.07	1.03
70%	1.32	1.32
80%	1.45	1.46
90%	1.62	1.62
95%	1.72	1.73

Figure 5-17: Summer/autumn: Probability of non-exceedance for predicted tides and modelled water levels for the 10-week period at the Port of Cape Town.

The model shows a good overall model prediction in both tidal phase and amplitude. The slight setdown observed during the first half of the calibration period is likely due to wind effects which are included in the model but not in the predicted tide.

5.2.3 Currents

A contour plot of instantaneous currents during a west-south-westerly wave/southerly wind event is shown in Figure 5-18. The modelled currents were compared to the measurements near the seabed (5.0 m above the seabed) and near the surface (25 m above the seabed). Figure 5-19 presents a time series comparison of the modelled and measured currents at the ADCP. Non-exceedance curves of current speed for the 10-week period are shown Figure 5-20. Current rose comparisons of modelled and measured currents are presented in Figure 5-21.

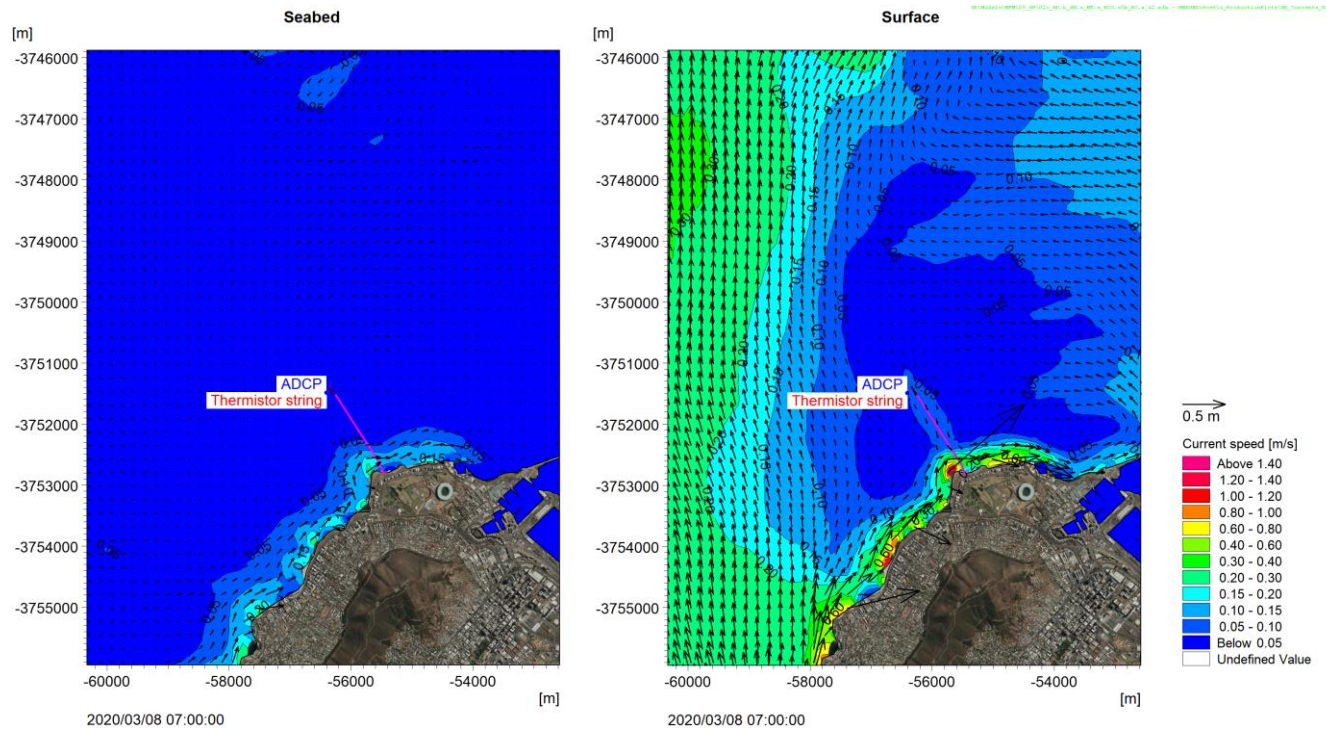


Figure 5-18: Summer/autumn: Contour plot of instantaneous seabed (left) and surface (right) currents during a west-south-westerly wave/southerly wind event (shown in Figure 5-13).

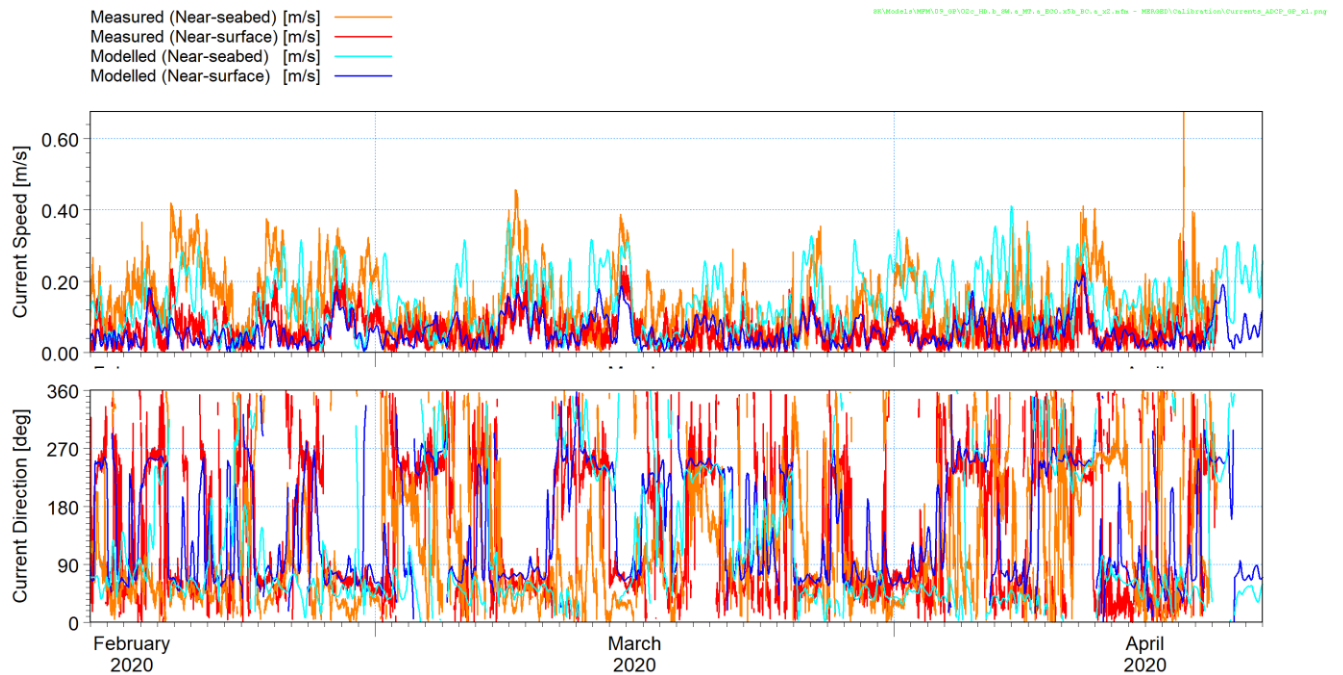


Figure 5-19: Summer/autumn: Time series comparison of measured and modelled current speed and direction at the ADP.

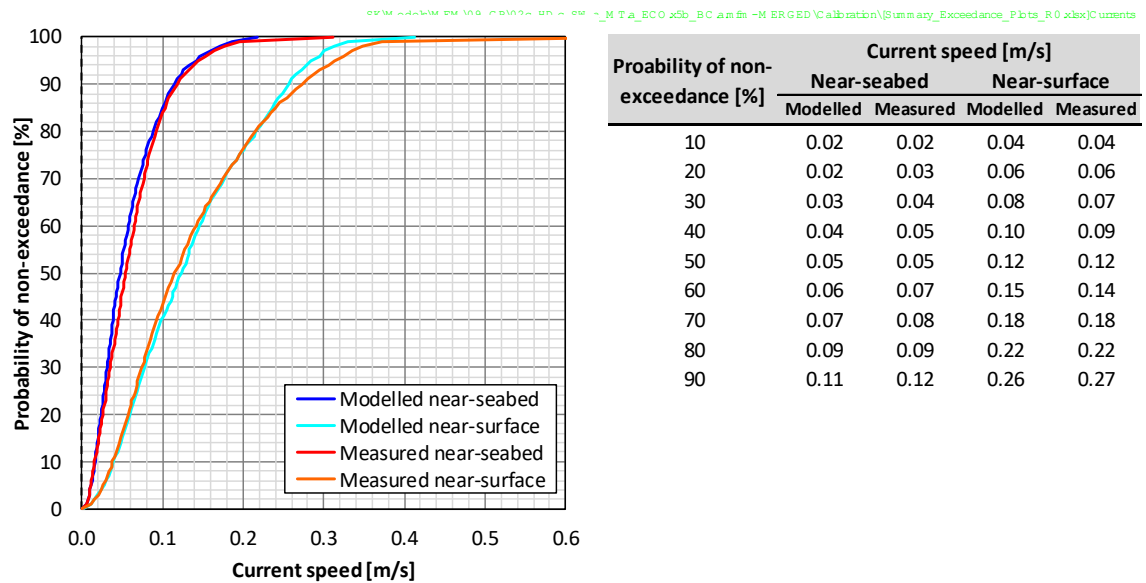


Figure 5-20: Summer/autumn: Probability of non-exceedance for measured and modelled current speed for the 10-week deployment period at the ADCP.

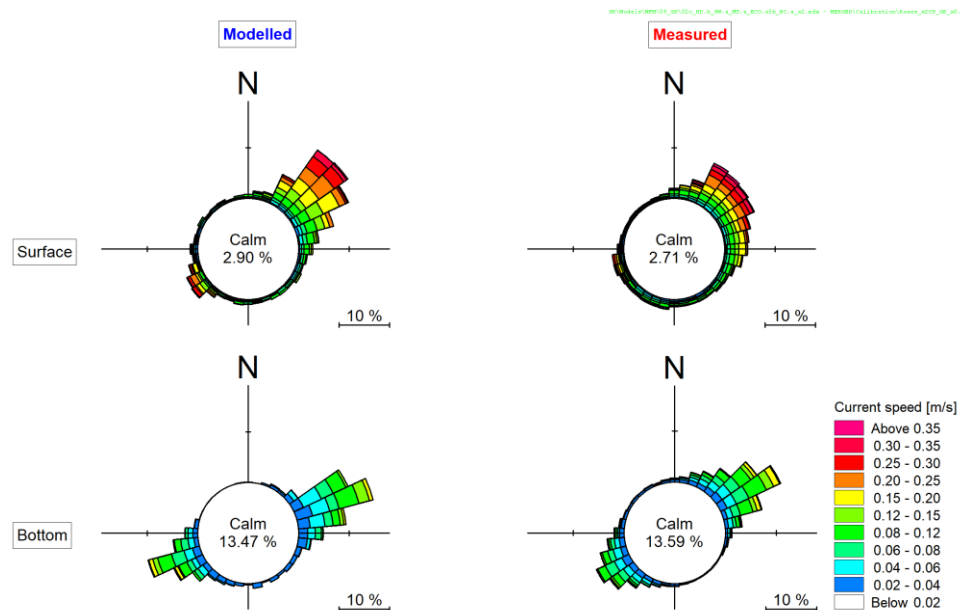


Figure 5-21: Summer/autumn: Measured and modelled current roses for the 10-week deployment period at the ADCP.

The model shows a good correlation with the measured operational current speeds while underpredicting some of the stronger near-surface currents. The dominant current directions are well represented at both depths.

The model is able to reproduce the main features of the currents and is considered to be acceptable for the purposes of this study.



5.2.4 Temperature

The modelled seawater temperatures were compared to measurements near the seabed (1.9 m above the seabed), mid-depth (11.6 m above the seabed) and at the surface (0.5 m to 1 m below the surface). Figure 5-22 presents a time series comparison of the modelled and measured seawater temperatures. Non-exceedance curves of seabed, mid-depth and surface temperatures for the 10-week period are shown Figure 5-23. Figure 5-24 presents a non-exceedance curve of stratification (near-seabed to mid-depth and near-seabed to surface) from the measured and modelled temperatures.

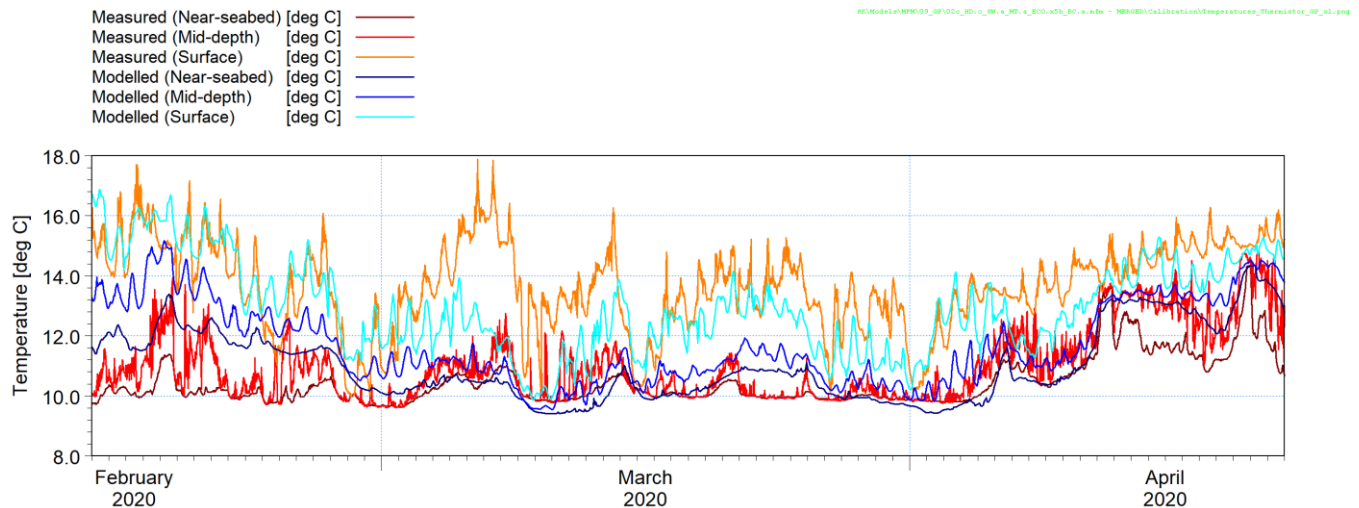


Figure 5-22: Summer/autumn: Time series of measured and modelled seawater temperatures.

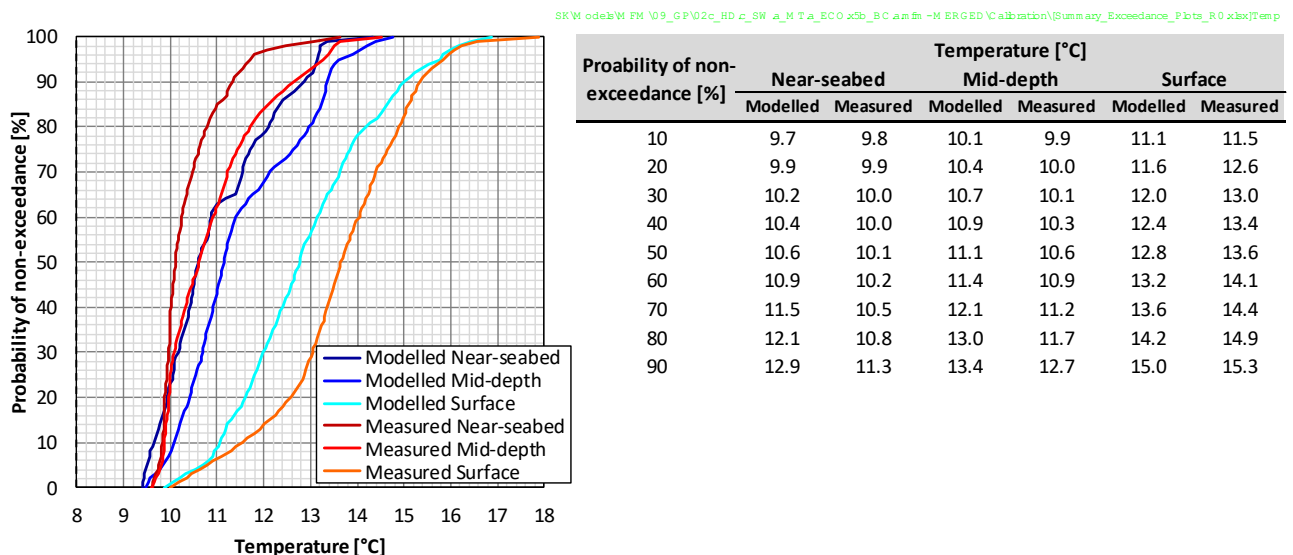


Figure 5-23: Summer/autumn: Probability of non-exceedance of measured and modelled seawater temperatures for the 10-week deployment period.

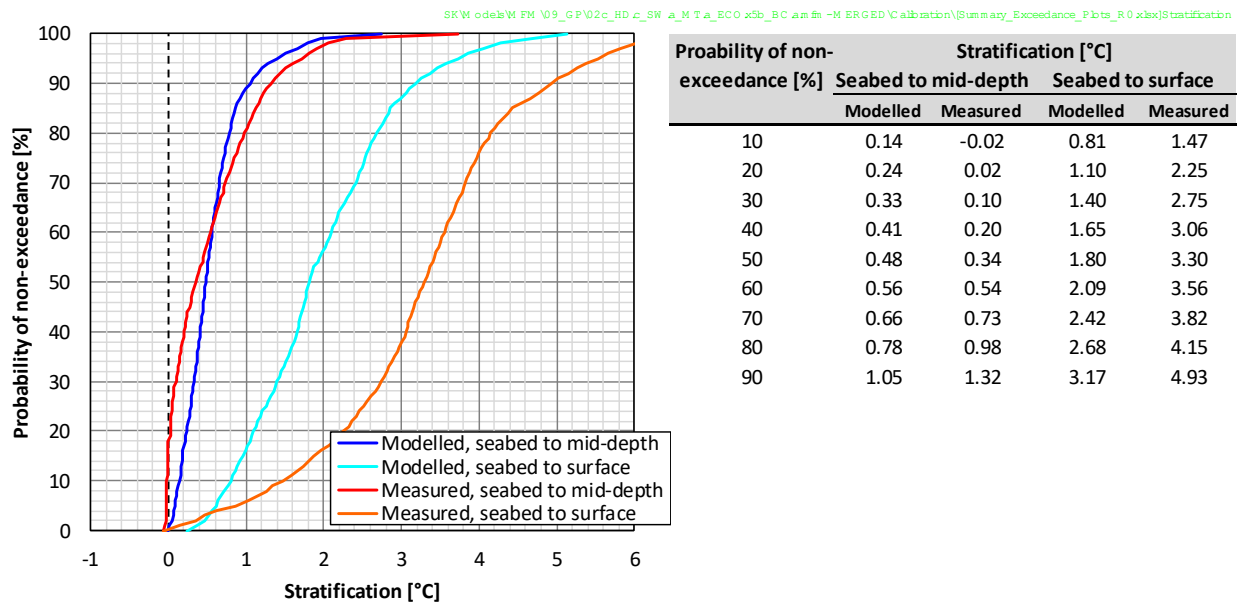


Figure 5-24: Summer/autumn: Probability of non-exceedance of measured and modelled seawater temperature stratification (near-seabed to mid-depth and near-seabed to surface) for the 10-week deployment period.

The measured time series shows that the seawater temperatures are complex and vary over a range of time-scales due to upwelling, solar radiation and other dynamic processes. The model is able to predict the mean trend in seabed seawater temperatures including some of the discrete dynamic events. The model shows the sub-surface temperatures tend to be overpredicted while the surface temperatures tend to be underpredicted. Note that the surface temperature was measured between 0.5 m and 1 m below the surface, whereas the surface temperature of the model is averaged over 2.3 m due to the vertical mesh resolution. The modelled near-seabed to mid-depth stratification varies between over- and under-prediction but shows a fair comparison to the measurements, while the seabed to surface stratification is underpredicted by the model. Since the near-field mixing is more sensitive to temperature gradients closer to the diffuser, i.e. lower in the water column, the model is considered to be adequately calibrated for seawater temperature for the purposes of this study.

6. MODEL RESULTS

6.1 Winter/spring

The outfall dispersion model was run for a 10-week period between 1 August 2019 and 9 October 2019 to represent environmental conditions for winter and spring.

The model outputs are the concentrations of E.coli, enterococci, TSS and a conservative tracer in each horizontal and vertical element of the computational mesh at 1-hour intervals throughout the simulation period.

6.1.1 Plume dynamics

Figure 6-1 and Figure 6-2 present examples of the current vectors and E.coli plume at a moment in time for a southerly and north-westerly wind condition. These results show the complex 3D dynamic behaviour of the plume.

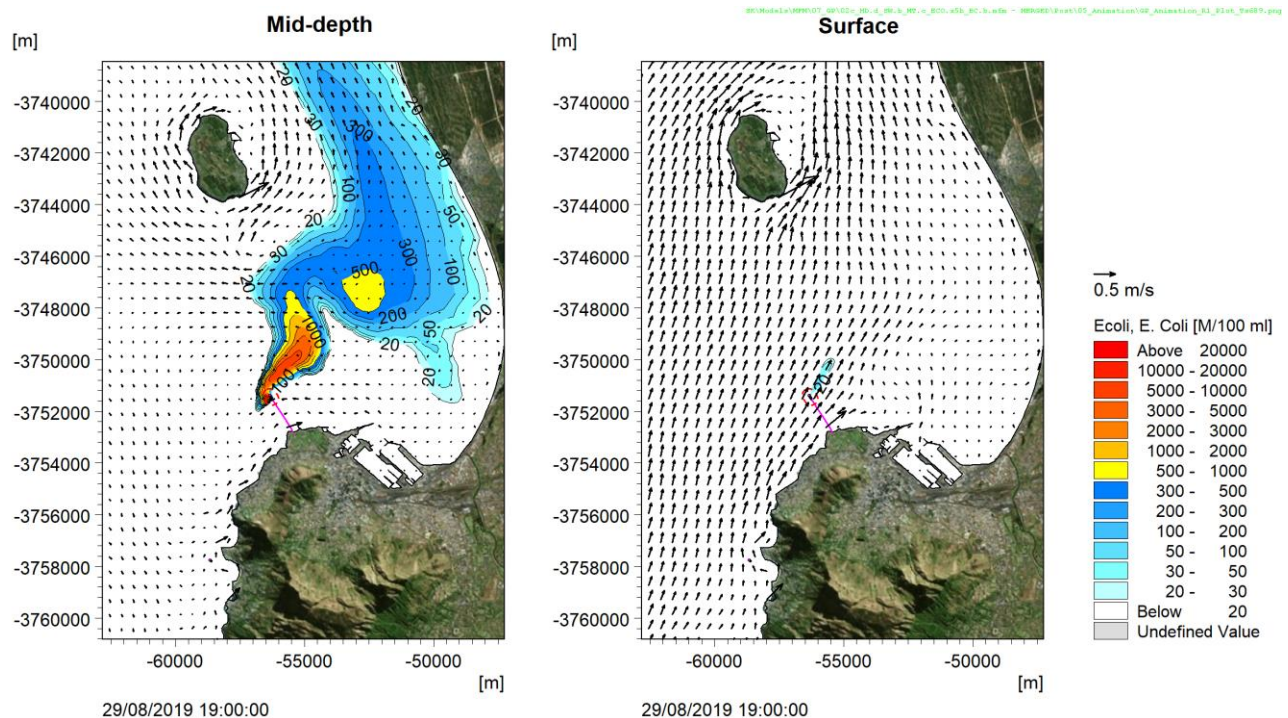


Figure 6-1: Winter/spring: Current vectors and E.coli plume at a moment in time during a southerly wind condition.

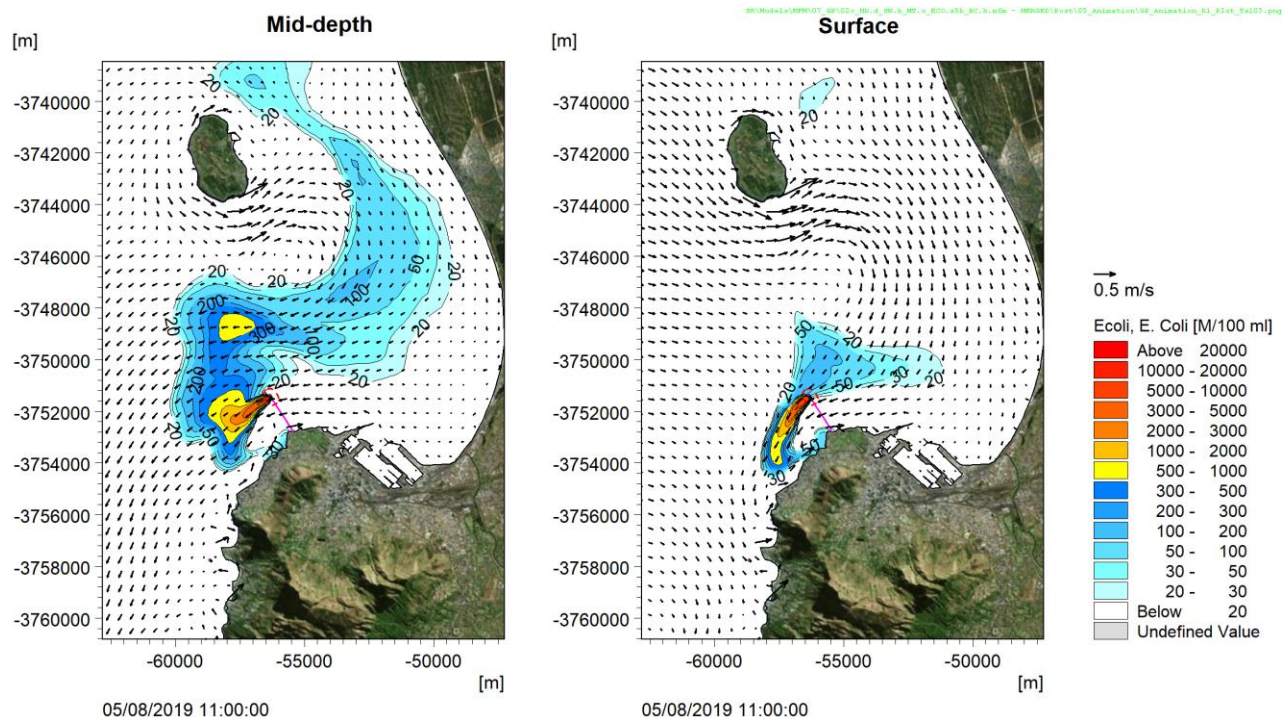


Figure 6-2: Winter/spring: Current vectors and E.coli plume at a moment in time during a north-westerly wind condition.

6.1.2 Dilutions

The concentrations from the conservative tracer were processed to number of dilutions using the equation:

$$\text{Number of dilutions} = \frac{\text{Effluent concentration}}{\text{Dispersed concentration}}$$

The modelled outputs were further processed to extract the 5th percentile number of dilutions in each horizontal and vertical element of the computational mesh. The 5th percentile number of dilutions will be exceeded 95% of the time and are thus close to the expected minimum number of dilutions (i.e. close to the worst case).

Figure 6-3, Figure 6-4 and Figure 6-5 present the 5th percentile dilutions at the seabed, mid-depth and surface. Mid-depth is the depth below the surface equal to 60% of the local water depth, which was selected as the worst dilutions at Green Point occurred at this depth. Figure 6-6 shows a cross section of the 5th percentile number of dilutions extracted along the longest axis of the plume (marked by the dashed green line on the contour plots). Dilutions less than 2 000 are shown in orange as this is close to the dilution required for TSS of 1 753 as discussed in Section 3.4.1. Dilutions greater than 2 000 are shown in shades of blue. Although these exceed the required dilutions for the identified critical constituents, they provide information on the far-field behaviour of the plume.

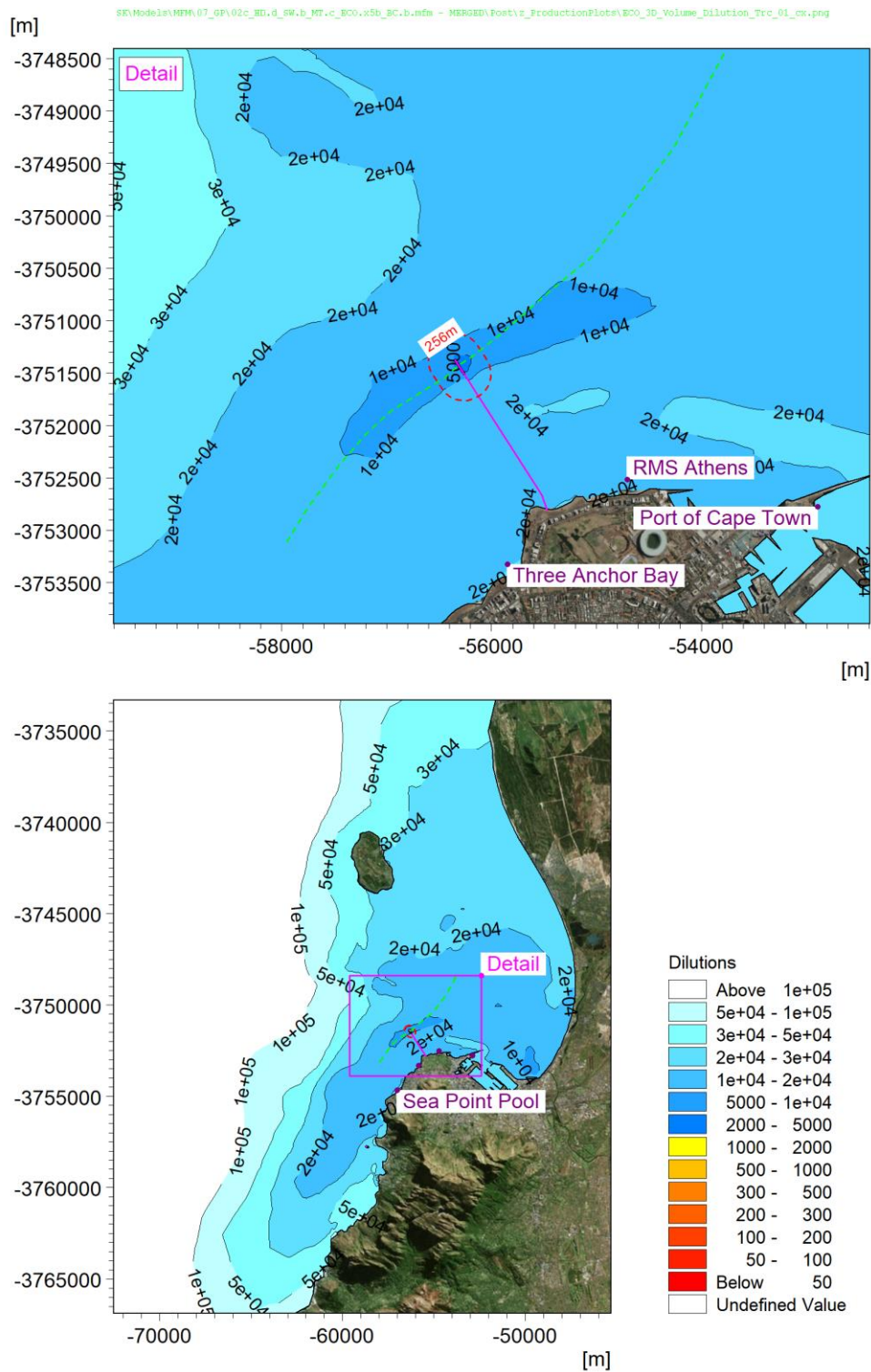


Figure 6-3: Winter/spring: Number of dilutions at the seabed, 5th percentile.

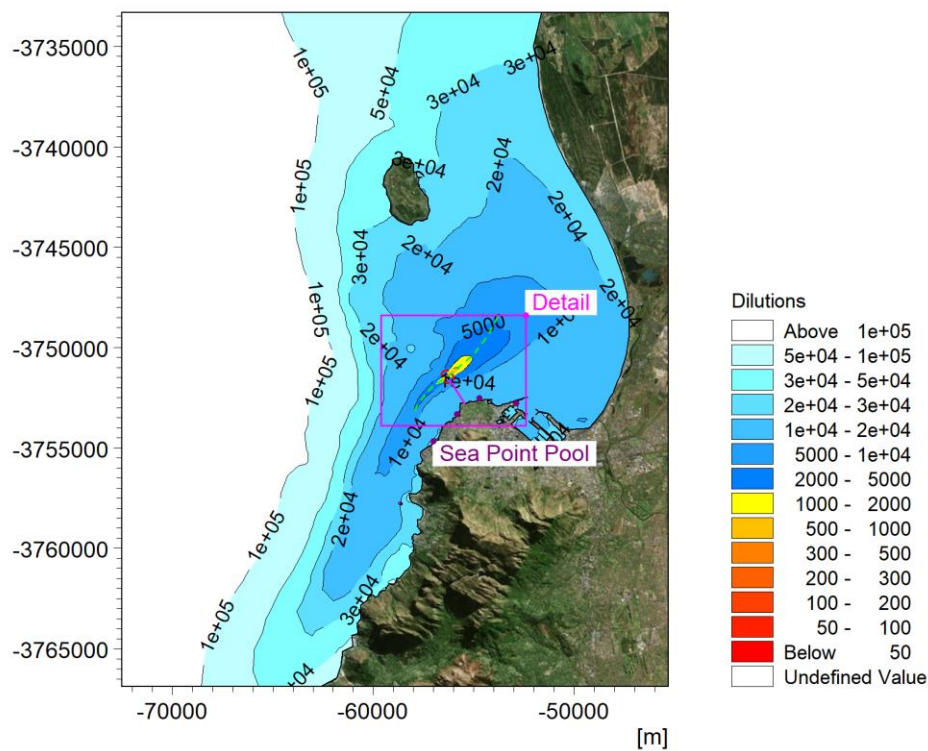
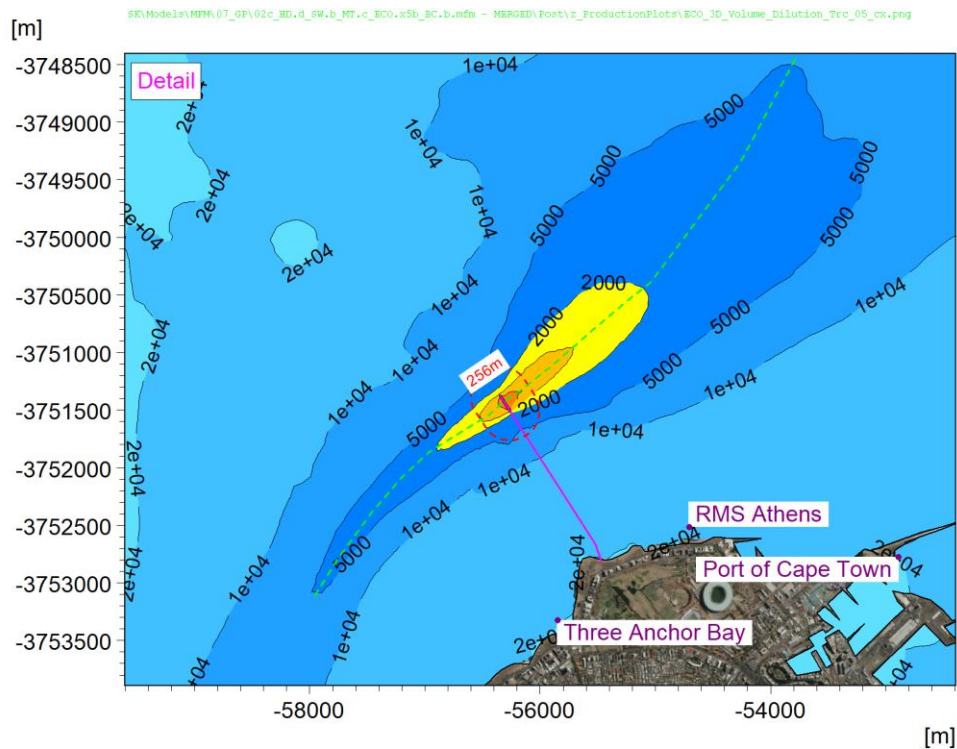


Figure 6-4: Winter/spring: Number of dilutions at mid-depth, 5th percentile.

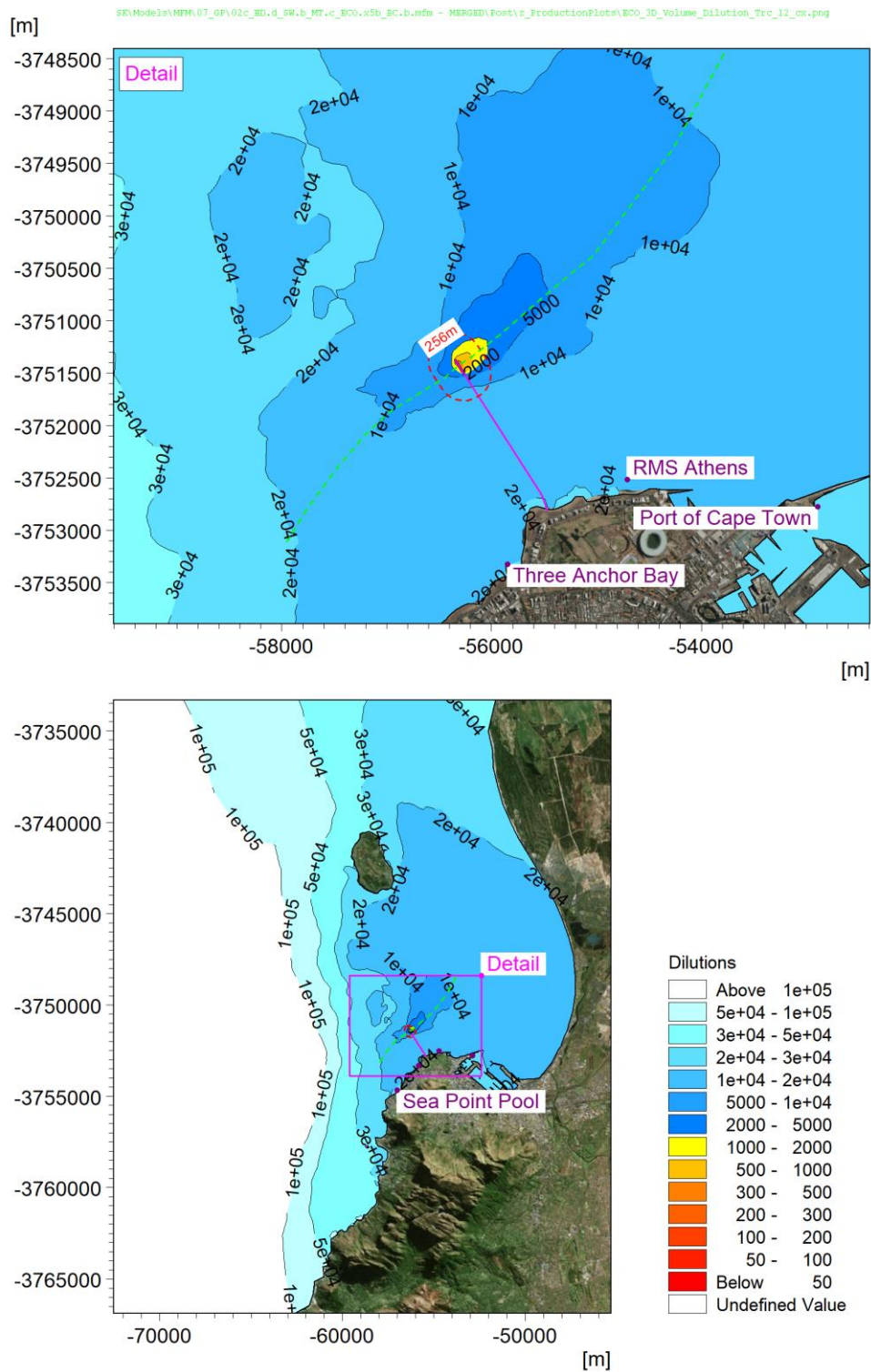


Figure 6-5: Winter/spring: Number of dilutions at the surface, 5th percentile.

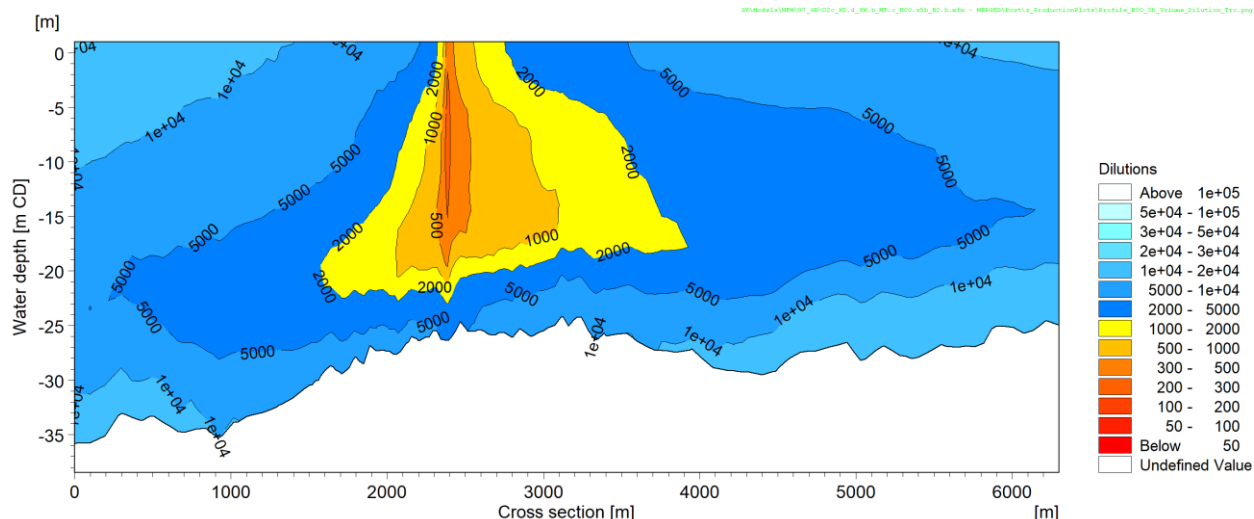


Figure 6-6: Winter/spring: Cross-section of 5th percentile number of dilutions.

The minimum dilutions achieved at the edge of the mixing zone was extracted from the 5th percentile dilutions and is presented Table 6-1.

Table 6-1: Winter/spring: Minimum number of dilutions achieved at the edge of the mixing zone.

Parameter	Value
Minimum number of dilutions achieved at any depth along the edge of the allowable mixing zone (radius = 256 m), 5 th percentile	528

The distance from the diffuser to achieve the required dilutions for the three critical constituents (Table 3-4) are presented in Table 6-2.

Table 6-2: Winter/spring: Distance to achieve dilutions, 5th percentile.

Constituent	Dilutions required	Distance
Ammonia	106	< 25 m
COD	51	< 25 m
TSS	1 753	1 400

The spreading of the mixing zone is dominated by the longshore currents. South-west of the diffuser the currents are characterised by a narrower stream following the coastline. North-east of the diffuser the currents exhibit more two-dimensional features (i.e. variability in flow directions and horizontal eddies as the plume is advected towards Table Bay) which increases the mixing and spreading of the plume.

The effluent plume rises due to its buoyancy and usually becomes passive at mid-depth due to mixing with the ambient currents or trapping by stratification. Periodic surfacing of the plume happens during periods of high effluent flows or stagnant hydrodynamic conditions.

The minimum number of dilutions achieved in the allowable mixing zone is 528. The constituent requiring the highest dilutions is TSS, which achieved the 1 753 required dilutions 1 400 m from the diffuser. Ammonia and COD achieved the required dilutions in within 25 m. Note that distances smaller than 25 m could not be measured in the model, due to the mesh resolution.

6.1.3 Bacteria

In addition to dilutions by hydrodynamic processes the bacterial concentrations are further reduced due to bacterial die-off (as described in Section 2.3.2). Figure 6-7 presents the surface and seabed T_{90} values for E.coli and enterococci, extracted in the middle of the Green Point diffuser at a depth of -26.0 m CD. Recall from Section 2.3.2.1 the median T_{90} ratio of enterococci to E.coli is 2.39.

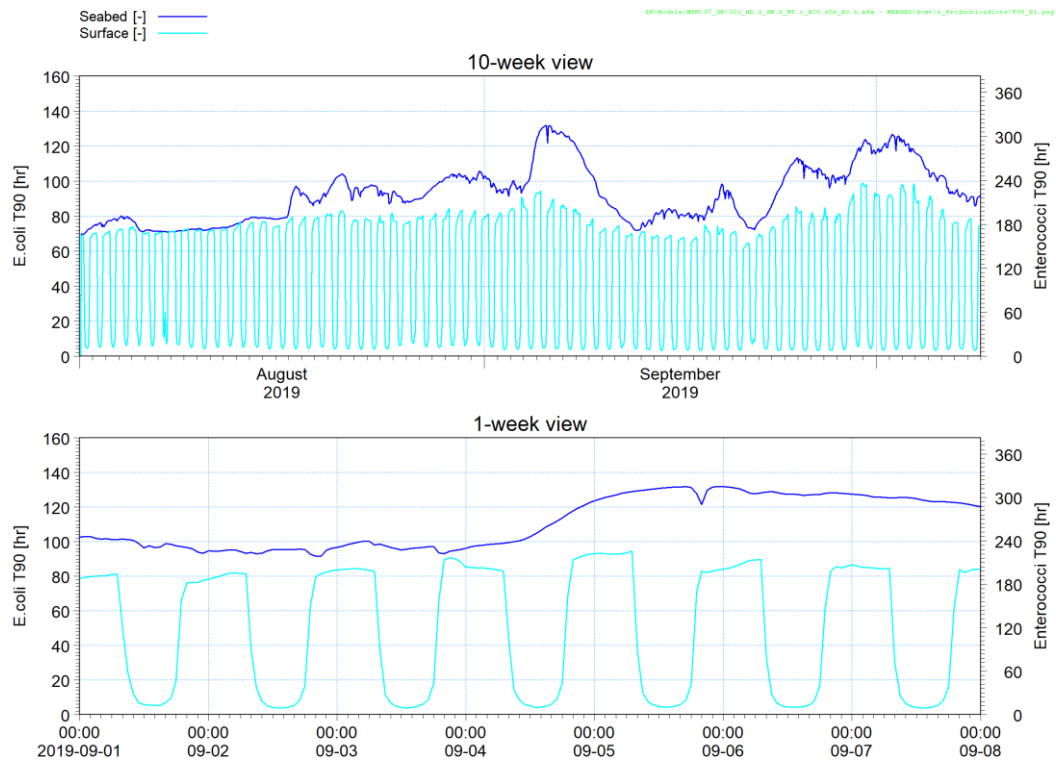


Figure 6-7: Winter/spring: Surface and seabed T_{90} values for E.coli and enterococci.

A significant diurnal variation in die-off rates due to the solar radiation can be observed at the surface, while the seabed remains mostly unaffected due to light attenuation. In the absence of light, the seawater temperature dominates the die-off processes and the stratification determines the gradient between the surface and seabed T_{90} values.

Based on the DEA guidelines (Table 3-5), the model outputs of bacterial concentrations were further processed to extract the 90th percentile concentration at each horizontal and vertical element of the computational mesh for the full simulation period. The 90th percentiles were only sampled during daylight hours (between 07:00 to 18:00) to emulate the recommended microbiological sampling regime in the guidelines.

6.1.3.1 E.coli

Figure 6-8, Figure 6-9 and Figure 6-10 present the 90th percentile E.coli concentrations at the seabed, mid-depth and surface. Concentrations greater than 500 CFU/100 ml are shown in orange as this is the guideline for E.coli as discussed in Section 3.4.2. Concentrations less than 500 CFU/100 ml are shown in shades of blue. Although these are less than the guideline, they provide information on the far-field behaviour of the plume. A time series of highest E.coli concentrations at any depth at four key locations (Port of Cape Town, RMS

Athens wreck (Thermopylae surf spot), Three Anchor Bay and Sea Point Pool) is shown in Figure 6-11. The locations are shown in the contour plots.

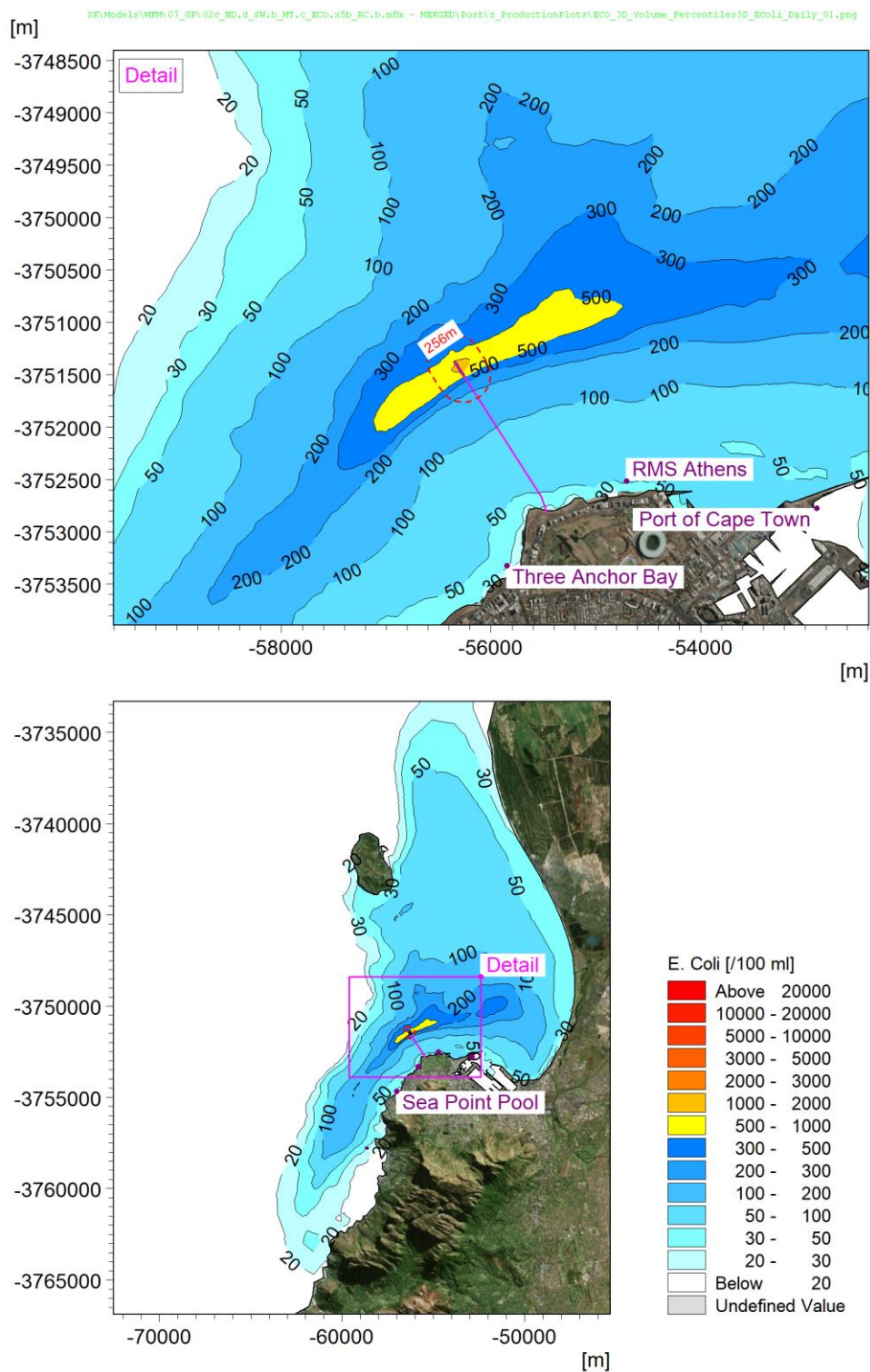


Figure 6-8: Winter/spring: E.coli concentration at the seabed, 90th percentile for daylight hours (07:00 – 18:00).

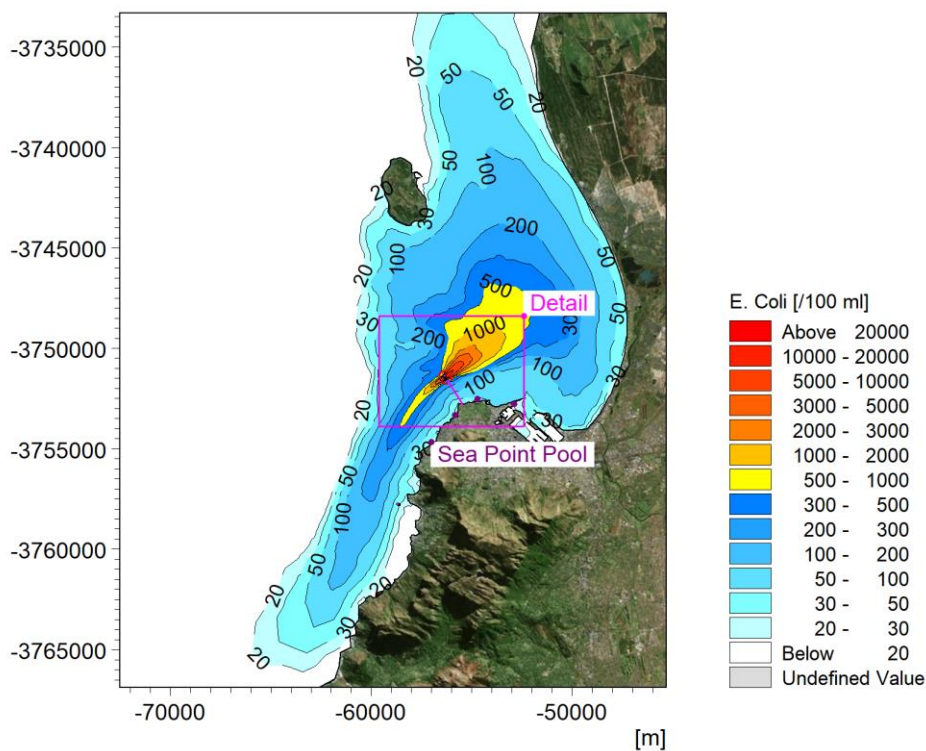
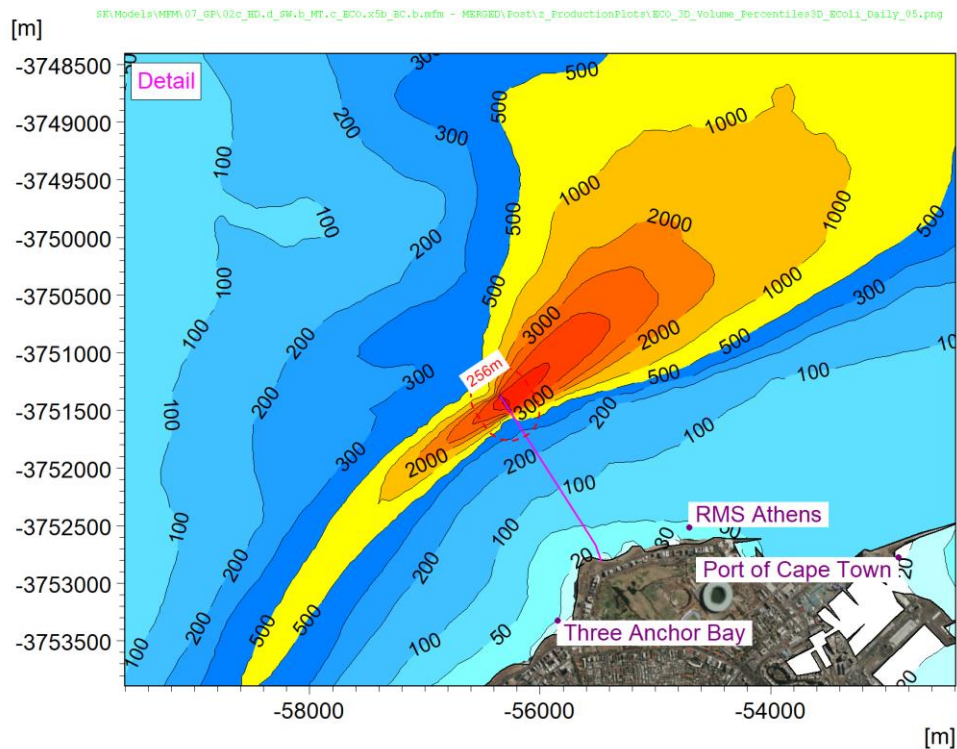


Figure 6-9: Winter/spring: E.coli concentration at mid-depth, 90th percentile for daylight hours (07:00 – 18:00).

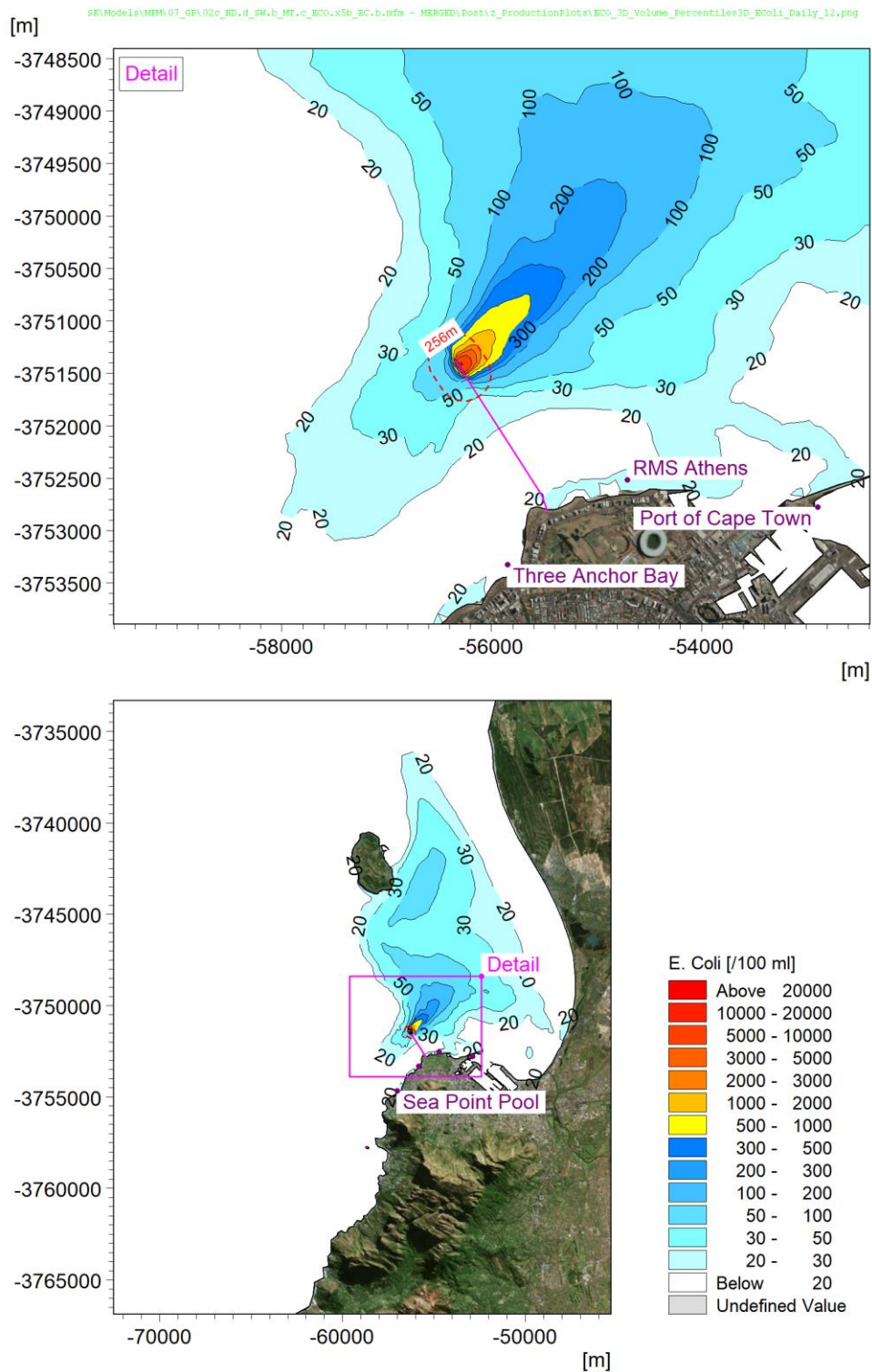


Figure 6-10: Winter/spring: E.coli concentration at the surface, 90th percentile for daylight hours (07:00 – 18:00).

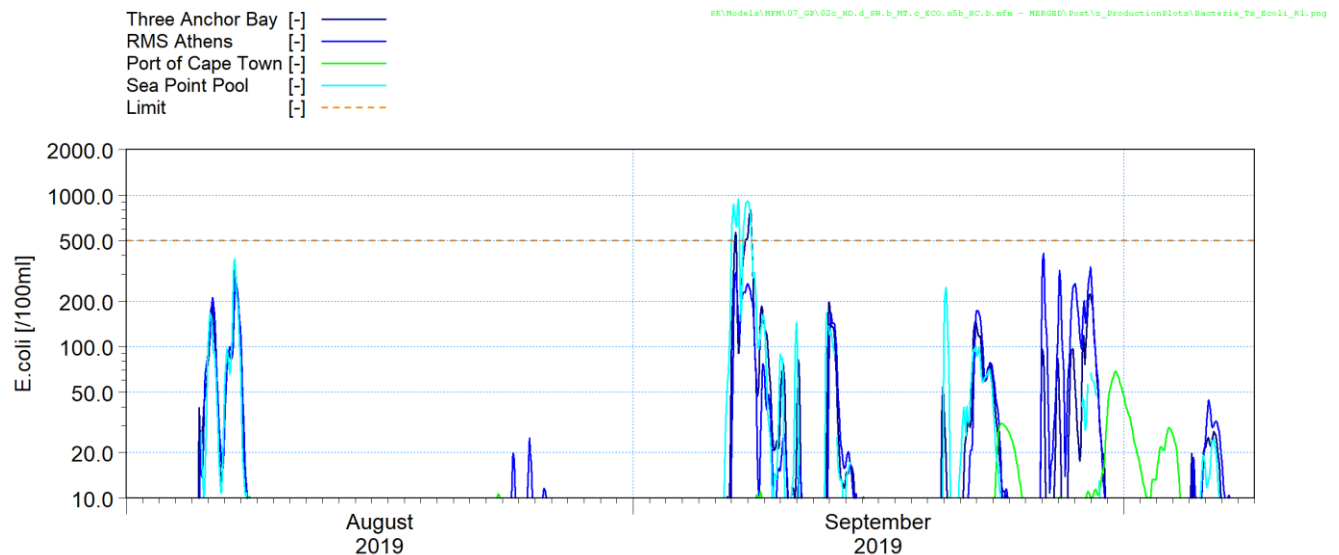


Figure 6-11: Winter/spring: Time series of highest E.coli concentration at any depth at four key locations. The water quality guideline (500 CFU/100 ml 90th percentile in daylight) is also shown in orange.

A mixing zone distance of 6 300 m was required to meet the 90th percentile water quality guideline of 500 CFU/100 ml. The contour plots show that the 90th percentile E.coli concentrations were the highest at mid-depth and concentrations above the 500 CFU/100 ml guideline did not intersect with the shoreline. The E.coli concentrations at the key locations only exceeded 500 CFU/100 ml on two occasions in the 10-week winter/spring period. Since the duration of this event was less than 10% of the daylight time these locations met the water quality guidelines.

6.1.3.2 Enterococci

Figure 6-12, Figure 6-13 and Figure 6-14 present the 90th percentile enterococci concentrations at the seabed, mid-depth and surface. Concentrations greater than 185 CFU/100 ml are shown in orange as this is the guideline for enterococci as discussed in Section 3.4.2. Concentrations less than 185 CFU/100 ml are shown in shades of blue. Although these are less than the guideline, they provide information on the far-field behaviour of the plume. A time series of enterococci concentrations at four key locations is shown in Figure 6-15.

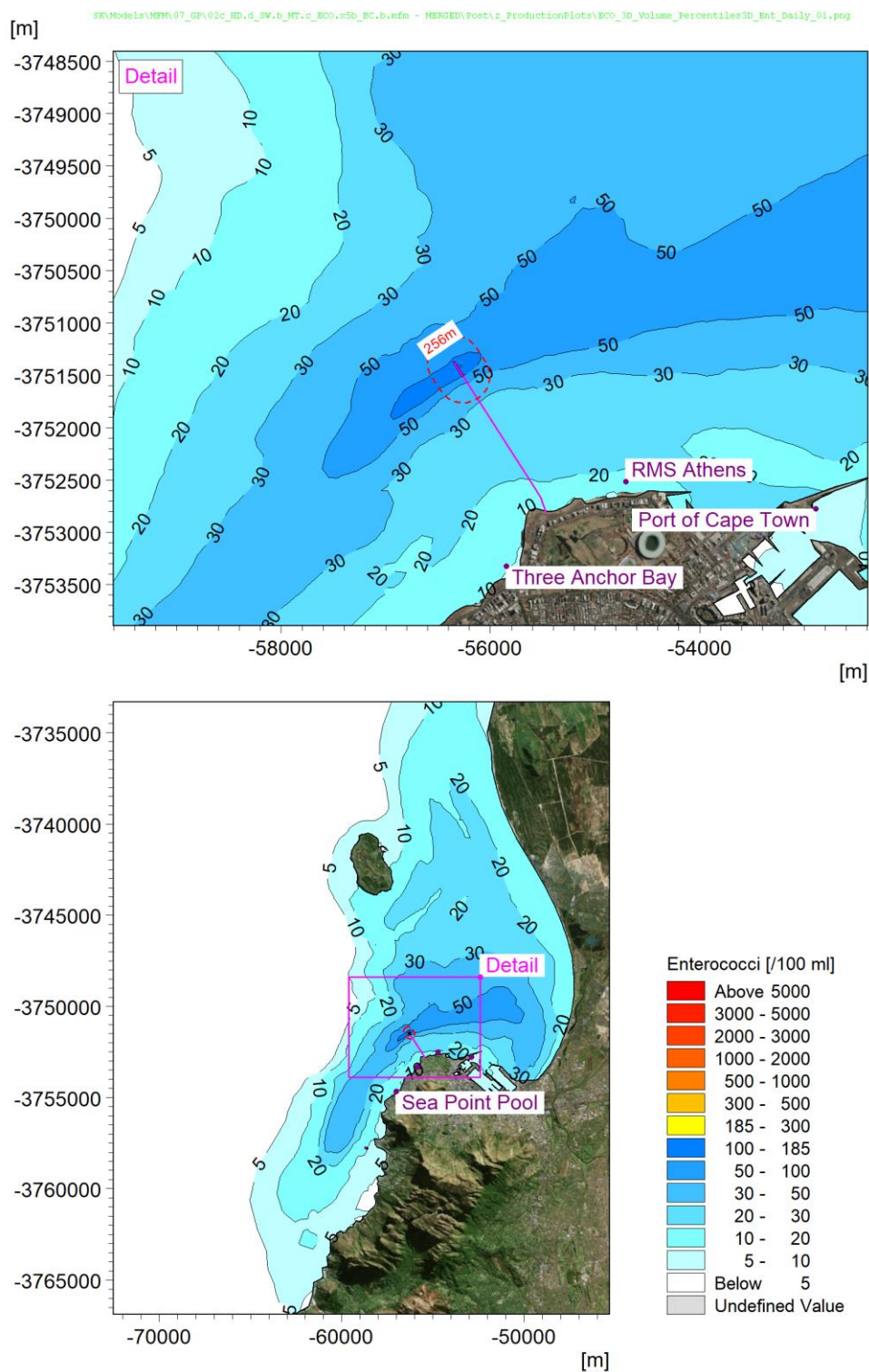


Figure 6-12: Winter/spring: Enterococci concentration at the seabed, 90th percentile for daylight hours (07:00 – 18:00).

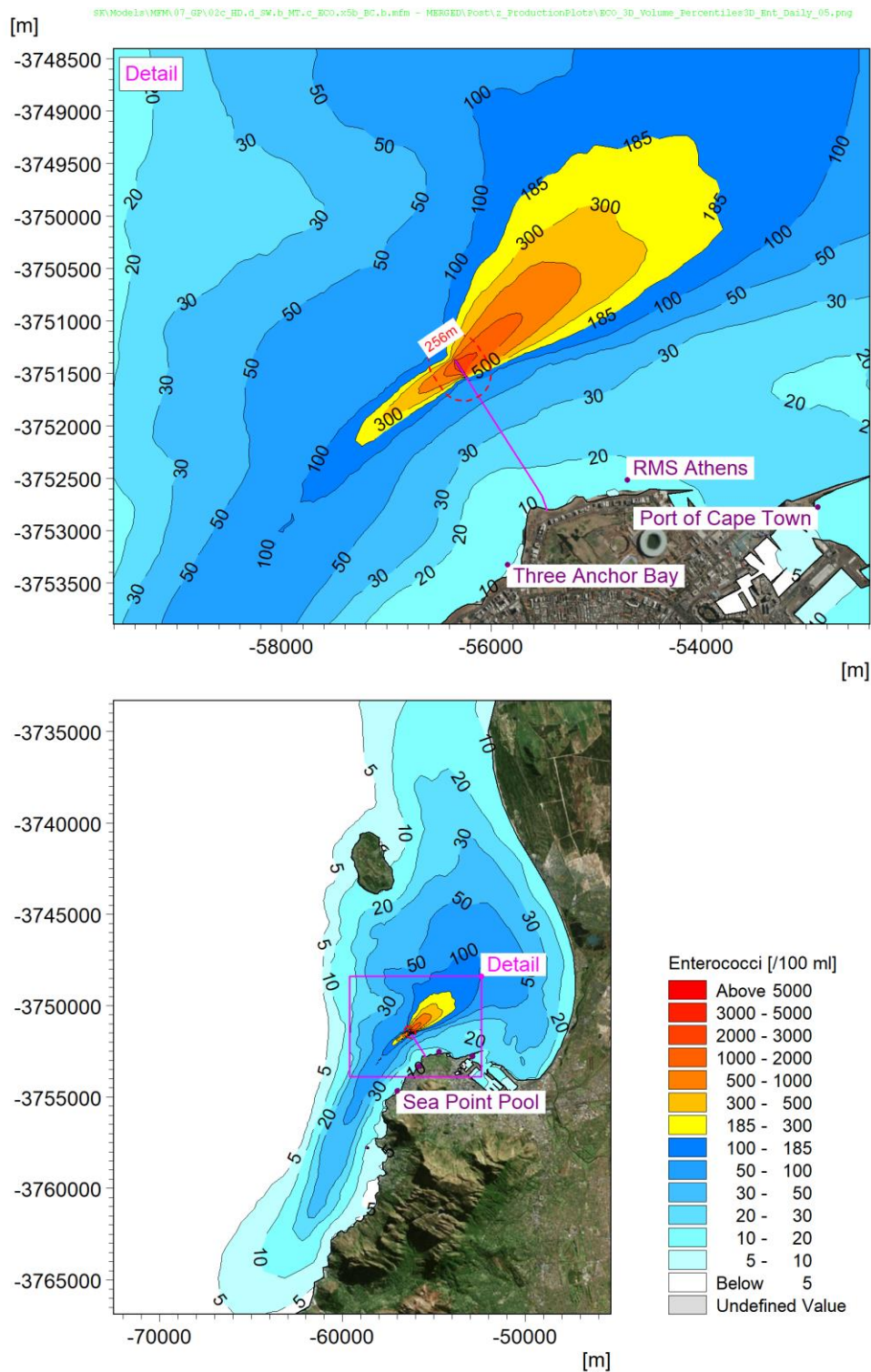


Figure 6-13: Winter/spring: Enterococci concentration at mid-depth, 90th percentile for daylight hours (07:00 – 18:00).

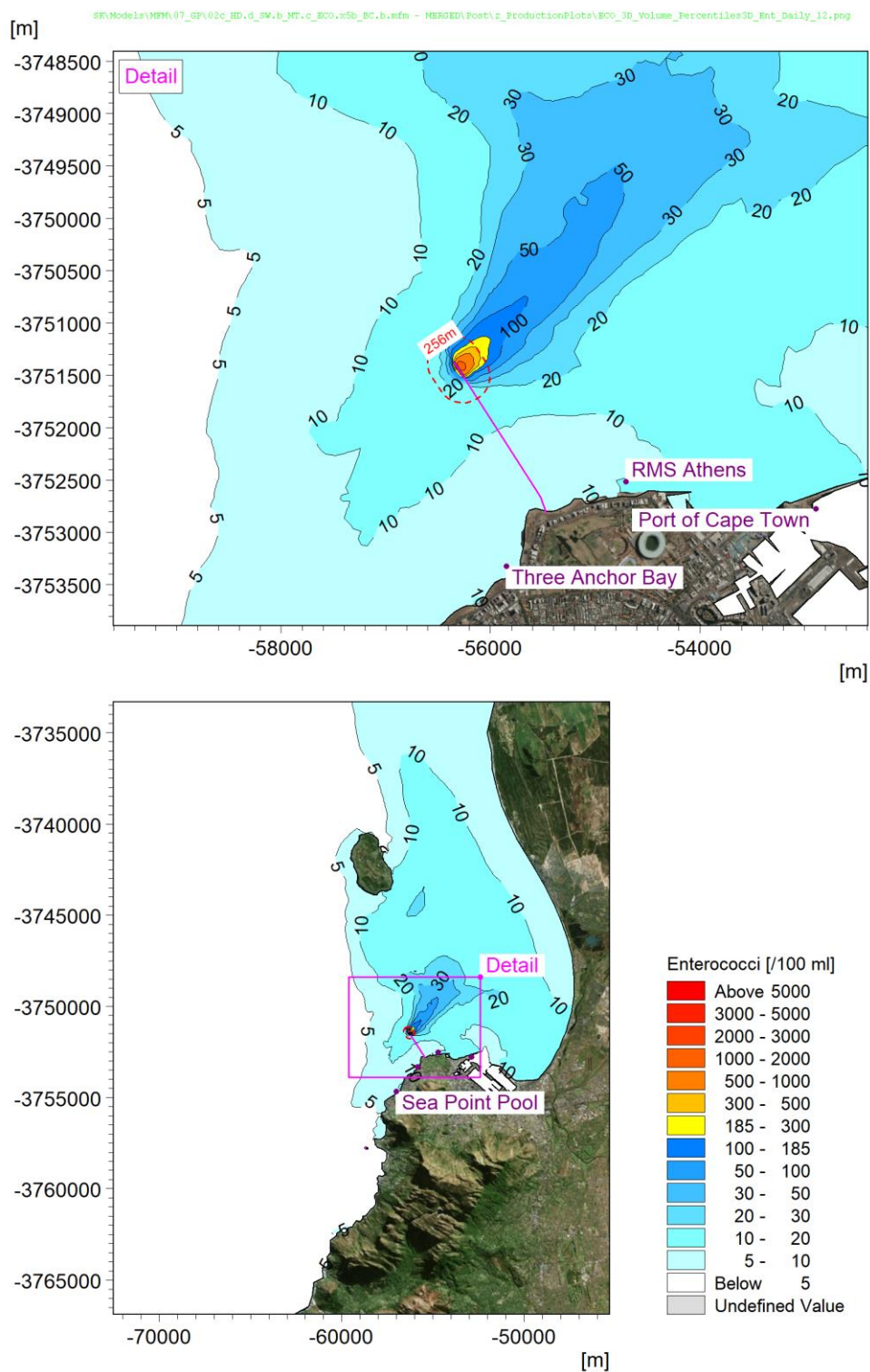


Figure 6-14; Winter/spring: Enterococci concentration at the surface, 90th percentile for daylight hours (07:00 – 18:00).

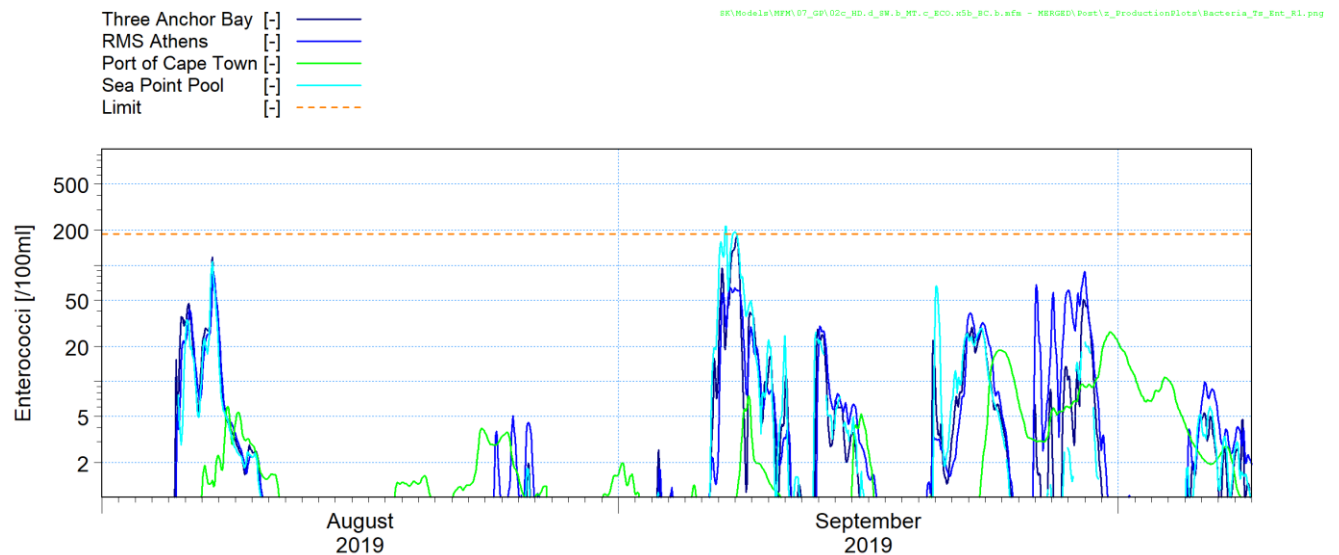


Figure 6-15: Winter/spring: Time series of highest enterococci concentration at any depth at four key locations. The water quality guideline (185 CFU/100 ml 90th percentile in daylight) is also shown in orange.

A mixing zone distance of 3 200 m was required to meet the 90th percentile water quality guideline of 185 CFU/100 ml. The contour plots show that the 90th percentile enterococci concentrations were the highest at mid-depth and concentrations above the 185 CFU/100 ml guideline did not intersect with the shoreline. The enterococci concentrations at the key locations only exceeded 185 CFU/100 ml on two occasions in the 10-week winter/spring period

6.1.3.3 Discussion

Based on the applicable water quality guidelines (discussed in Section 3.4.2), E.coli requires a greater mixing zone distance to meet the guidelines compared to enterococci.

The bacteria plumes have the highest concentrations at mid depth (the depth below the surface equal to 60% of the local water depth) where the plume usually becomes trapped. Solar radiation further reduces concentrations closer to the surface (illustrated in Figure 6-7).

During typical conditions the plume will be advected alongshore. Onshore movement can occur during certain north-westerly wind conditions (e.g. current direction reversal causing the plume to approach the coastline in the process) or during local upwelling events associated with south-westerly winds.

6.1.4 Total suspended solids

The concentrations of TSS were modelled in the water column and specifically where these were deposited on the seabed. This is a proxy for the fate of pollutants that adsorb to solid particles, e.g. heavy metals.

Figure 6-16 presents the bed mass of TSS at the end of the 10-week simulation. The deposited mass in the main depo-centres (demarcated in red) are summarised in Table 6-3. The table also includes the total mass of TSS that were advected outside of the model domain through the boundaries and TSS in suspension at the end of the run.

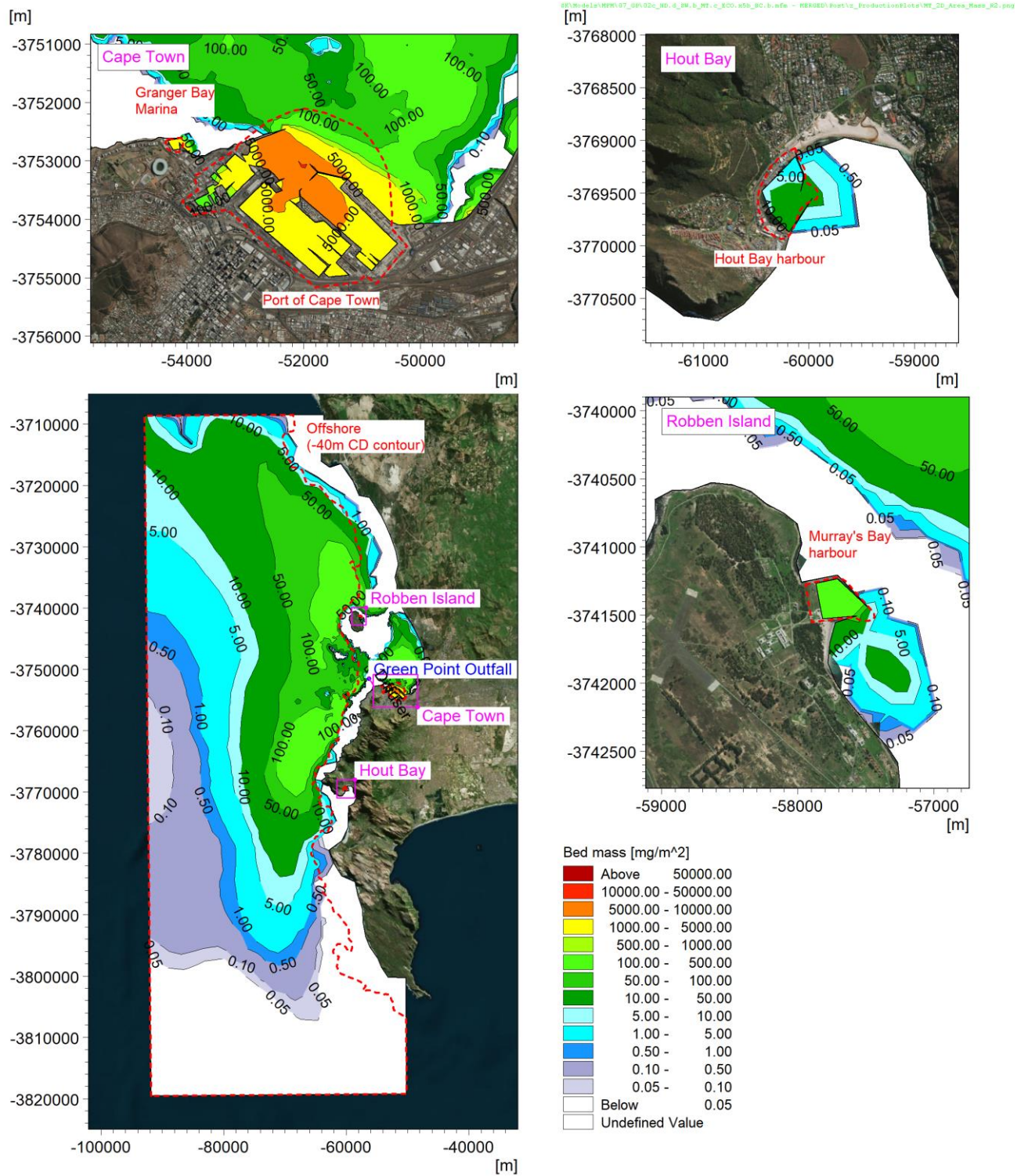


Figure 6-16: Winter/spring: Bed mass of TSS distribution at the end of the 10-week winter/spring period.

Table 6-3: Winter/spring: Integrated mass at the end of the 10-week simulation period.

Area	Mass [kg]	% released
Port of Cape Town	17 200	3.0%
Murray's Bay Harbour	24	< 0.1%
Granger Bay	69	< 0.1%
Hout Bay	1.9	< 0.1%
Offshore (-40 m CD contour)	74 500	12.8%
Out of domain	324 000	55.9%
Suspended	164 000	28.2%
Total mass released	589 000	100%

The highest concentrations are observed in the sheltered depo-centres, i.e. the Port of Cape Town, Granger Bay marina, Murray's Bay harbour and Hout Bay harbour where the bed shear stress due to waves and currents are sufficiently low to allow deposition. Accumulation also occurs in exposed areas where the water depth is greater than approximately 40 m due to the wave orbital velocities not exerting sufficient stress on the seabed to resuspend the sediment particles.

The largest depo-centre is the Port of Cape Town with approximately 3.0% of the TSS released from the Green Point outfall accumulating in the port. These results can be used in the design and interpretation of sediment quality sampling studies.

6.2 Summer/autumn

The outfall dispersion model was run for a 10-week period between 13 February 2020 and 23 April 2020, coinciding with the calibration period, to represent environmental conditions for summer and autumn.

The model outputs are the concentrations of E.coli, enterococci, TSS and a conservative tracer in each horizontal and vertical element of the computational mesh at 1-hour intervals throughout the simulation period.

6.2.1 Plume dynamics

Figure 6-17 and Figure 6-18 present examples of the current vectors and E.coli plume at a moment in time for a south-easterly and north-westerly wind condition. These results show the complex 3D dynamic behaviour of the plume.

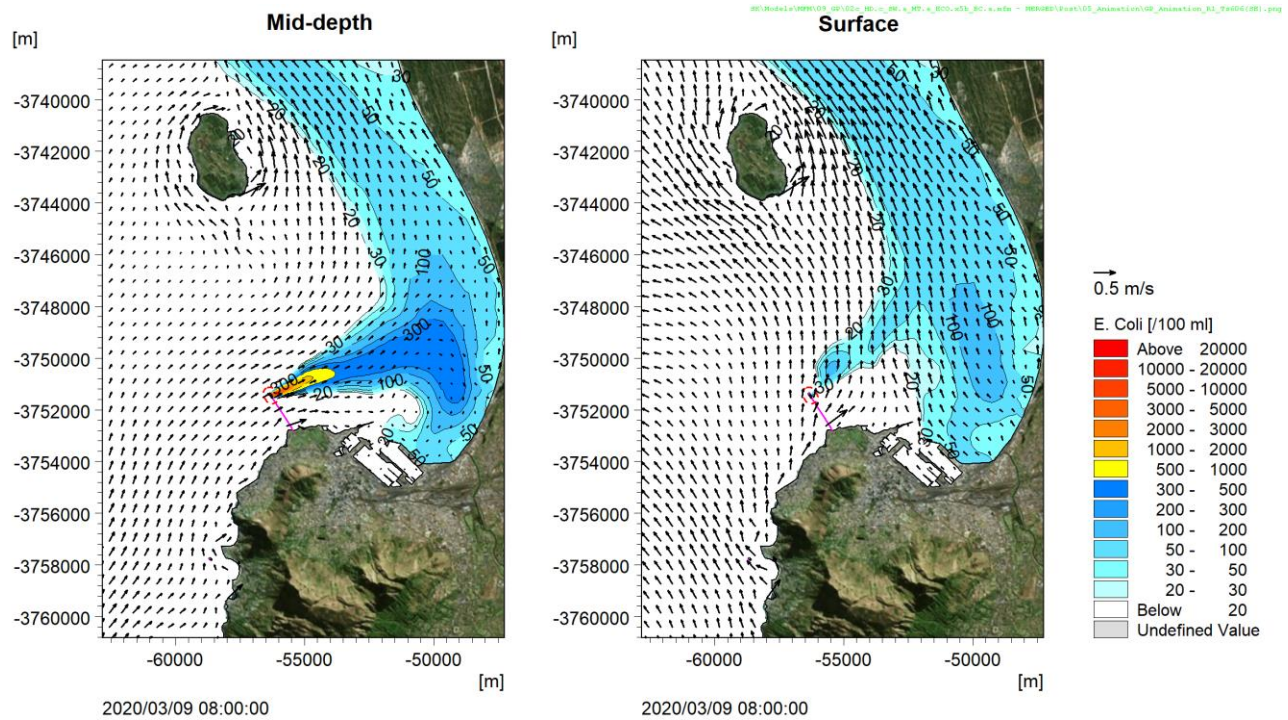


Figure 6-17: Summer/autumn: Current vectors and E.coli plume at a moment in time during a south-easterly wind condition.

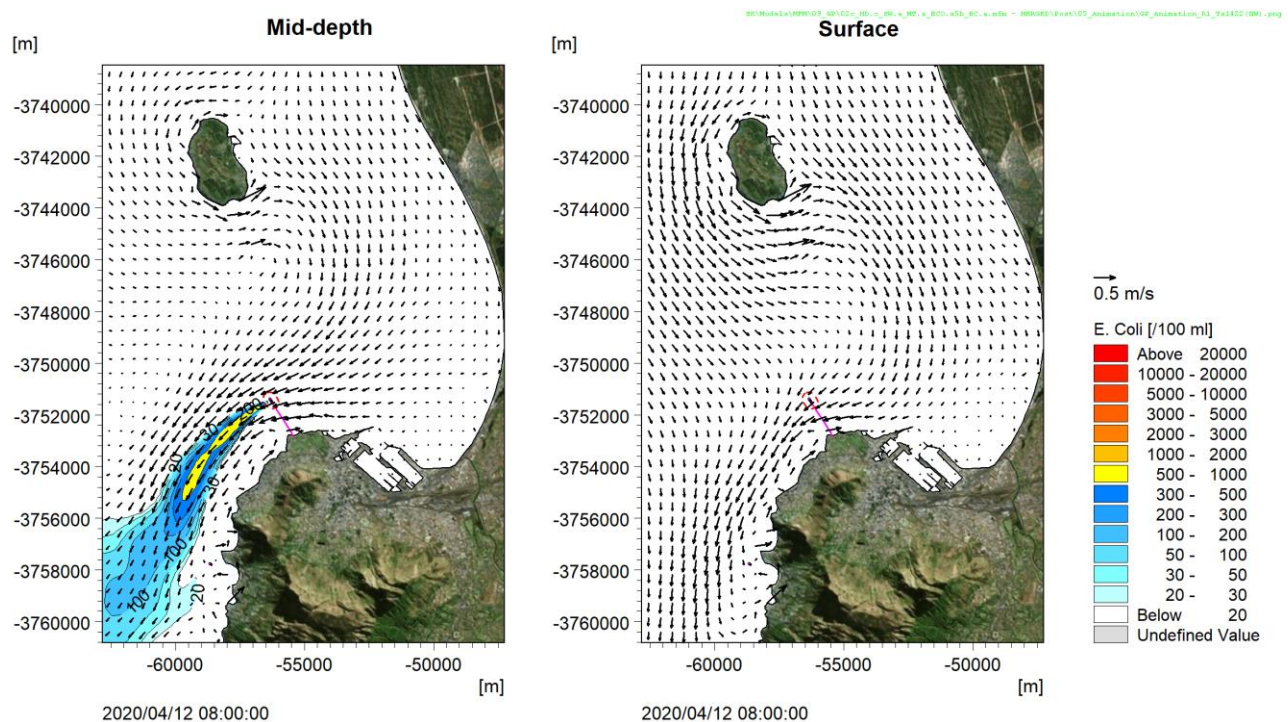


Figure 6-18: Summer/autumn: Current vectors and E.coli plume at a moment in time during a north-westerly wind condition.



6.2.2 Dilutions

The concentrations from the conservative tracer were processed to obtain the 5th percentile number of dilutions in each horizontal and vertical element of the computational mesh as discussed in Section 6.1.2.

Figure 6-19, Figure 6-20 and Figure 6-21 present the 5th percentile dilutions at the seabed, mid-depth and surface. Mid-depth is the depth below the surface equal to 55% of the local water depth, which was selected as the worst dilutions at Green Point occurred at this depth. Figure 6-19 shows a cross section of the 5th percentile number of dilutions extracted along the longest axis of the plume (marked by the dashed green line on the contour plots). Dilutions less than 2 000 are shown in orange as this is close to the dilution required for TSS of 1 753 as discussed in Section 3.4.1. Dilutions greater than 2 000 are shown in shades of blue. Although these exceed the required dilutions for the identified critical constituents, they provide information on the far-field behaviour of the plume.

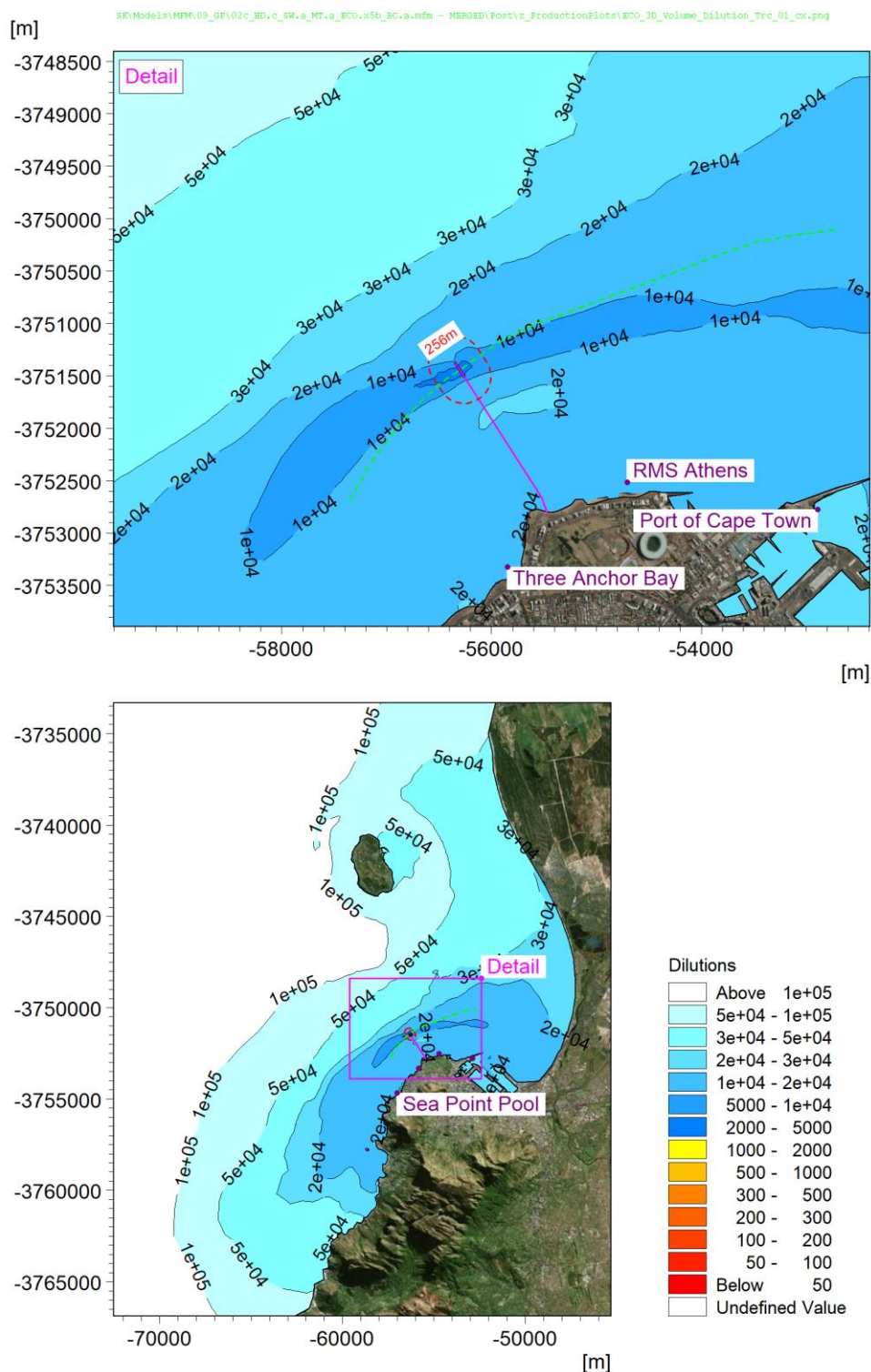


Figure 6-19: Summer/autumn: Number of dilutions at the seabed, 5th percentile.

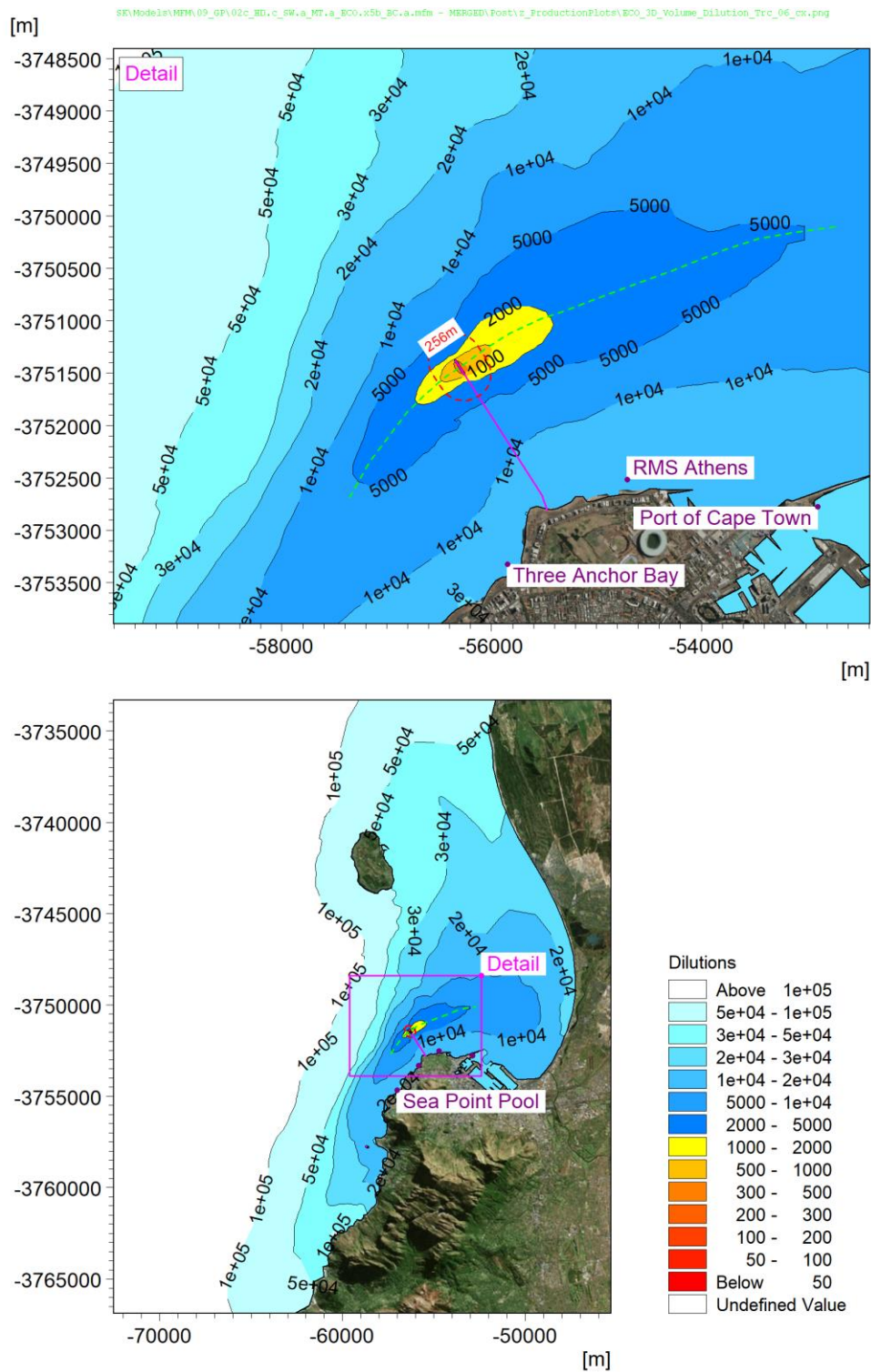


Figure 6-20: Summer/autumn: Number of dilutions at mid-depth, 5th percentile.

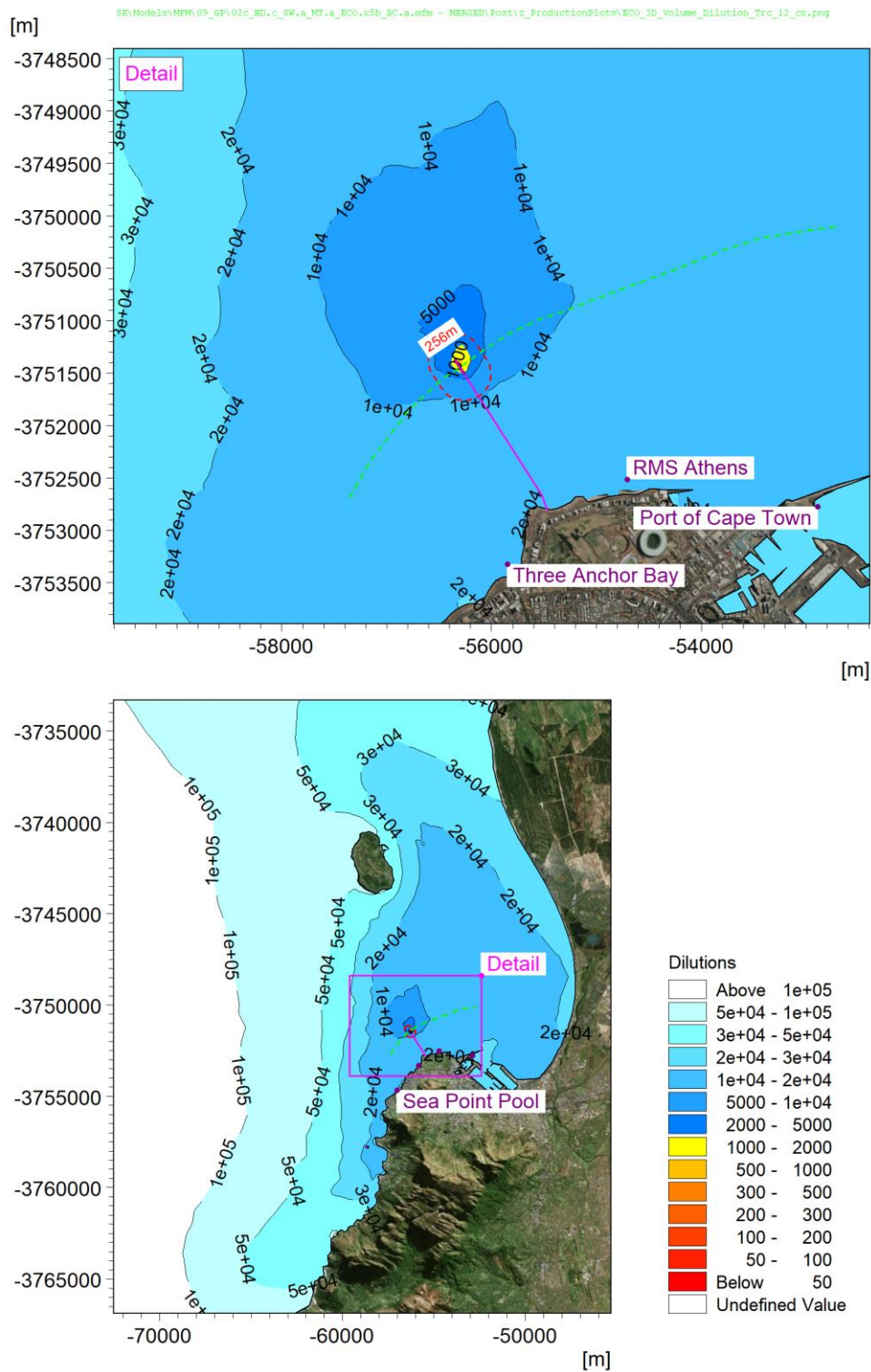


Figure 6-21: Summer/autumn: Number of dilutions at the surface, 5th percentile.

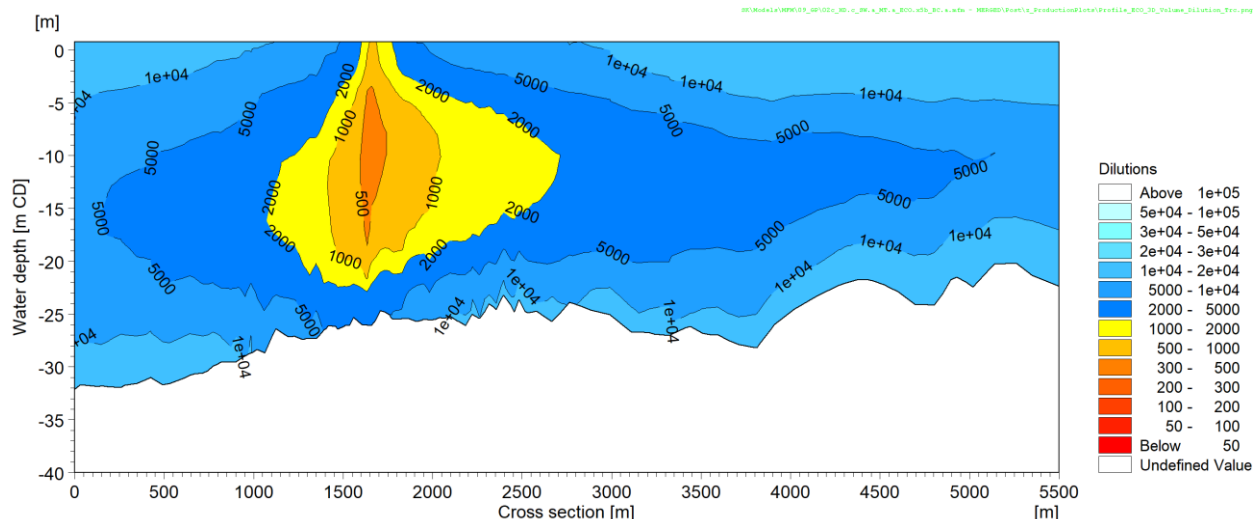


Figure 6-22: Summer/autumn: Cross-section of 5th percentile number of dilutions.

The minimum dilutions achieved at the edge of the mixing zone was extracted from the 5th percentile dilutions and is presented Table 6-4.

Table 6-4: Summer/autumn: Minimum number of dilutions achieved at the edge of the mixing zone.

Parameter	Value
Minimum number of dilutions achieved at any depth along the edge of the allowable mixing zone (radius = 256 m), 5 th percentile	687

The distance from the diffuser to achieve the required dilutions for the three critical constituents (Table 3-4) are presented in Table 6-5.

Table 6-5: Summer/autumn: Distance to achieve dilutions, 5th percentile.

Constituent	Dilutions required	Distance
Ammonia	106	< 25 m
COD	51	< 25 m
TSS	1 753	940

The spreading of the mixing zone is dominated by the longshore currents. South-easterly winds, which are frequent in the summer, advect the plumes east into Table Bay and then northward with the longshore current. As observed in Section 6.1.2, the lowest dilutions are at mid-depth, due to mixing with the ambient currents or trapping by stratification. Periodic surfacing of the plume happens during periods of high effluent flows or stagnant hydrodynamic conditions

The minimum number of dilutions achieved in the allowable mixing zone is 687. The constituent requiring the highest dilutions is TSS, which achieved the 1 753 required dilutions 940 m from the diffuser. Ammonia and COD achieved the required dilutions in within 25 m. Note that distances smaller than 25 m could not be measured in the model, due to the mesh resolution.

6.2.3 Bacteria

In addition to dilutions by hydrodynamic processes the bacterial concentrations are further reduced due to bacterial die-off (as described in Section 2.3.2). Figure 6-23 presents the surface and seabed T₉₀ values for

E.coli and enterococci, extracted in the middle of the Green Point diffuser at a depth of -26.0 m CD. Recall from Section 2.3.2.1 the median T_{90} ratio of enterococci to E.coli is 2.39.

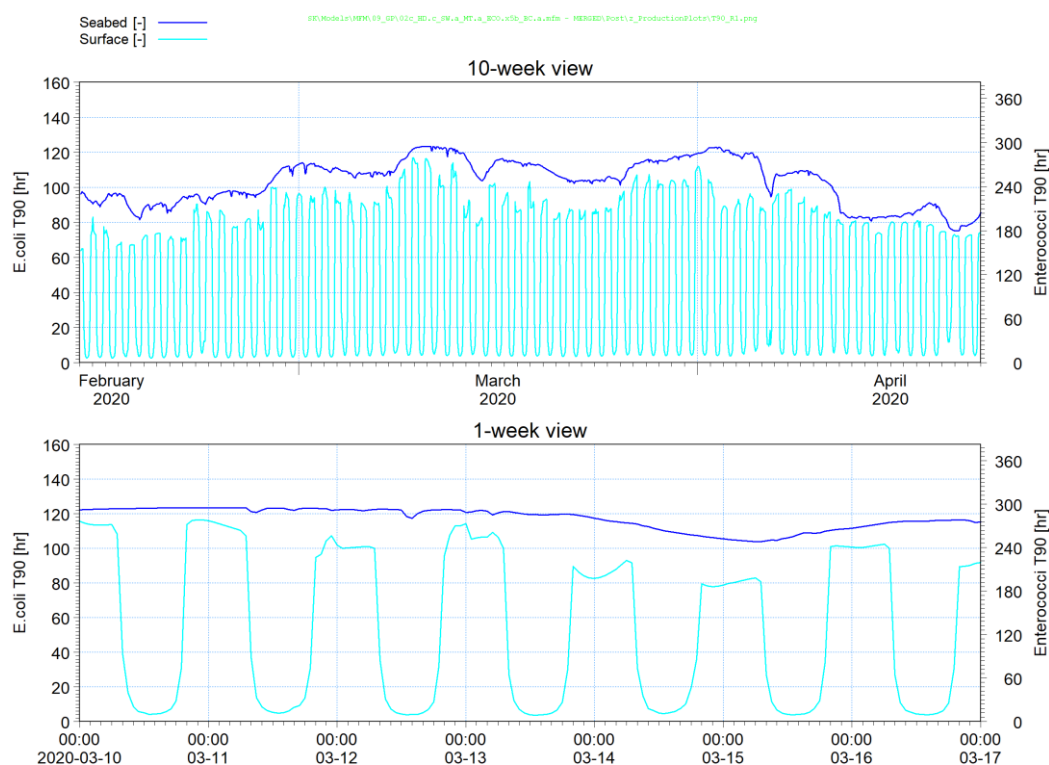


Figure 6-23: Summer/autumn: Surface and seabed T_{90} values for E.coli and enterococci.

A significant diurnal variation in die-off rates due to the solar radiation can be observed at the surface, while the seabed remains mostly unaffected due to light attenuation. In the absence of light, the seawater temperature dominates the die-off processes and the stratification determines the gradient between the surface and seabed T_{90} values.

The model outputs of bacterial concentrations were processed to extract the 90th percentile during daylight hours (between 07:00 to 18:00) to emulate the recommended microbiological sampling regime in the guidelines.

6.2.3.1 E.coli

Figure 6-24, Figure 6-25 and Figure 6-26 present the 90th percentile E.coli concentrations at the seabed, mid-depth and surface. Concentrations greater than 500 CFU/100 ml are shown in orange as this is the guideline for E.coli as discussed in Section 3.4.2. Concentrations less than 500 CFU/100 ml are shown in shades of blue. Although these are less than the guideline, they provide information on the far-field behaviour of the plume. A time series of highest E.coli concentrations at any depth at four key locations (Port of Cape Town, RMS Athens wreck (Thermopylae surf spot), Three Anchor Bay and Sea Point Pool) is shown in Figure 6-27. The locations are shown in the contour plots.

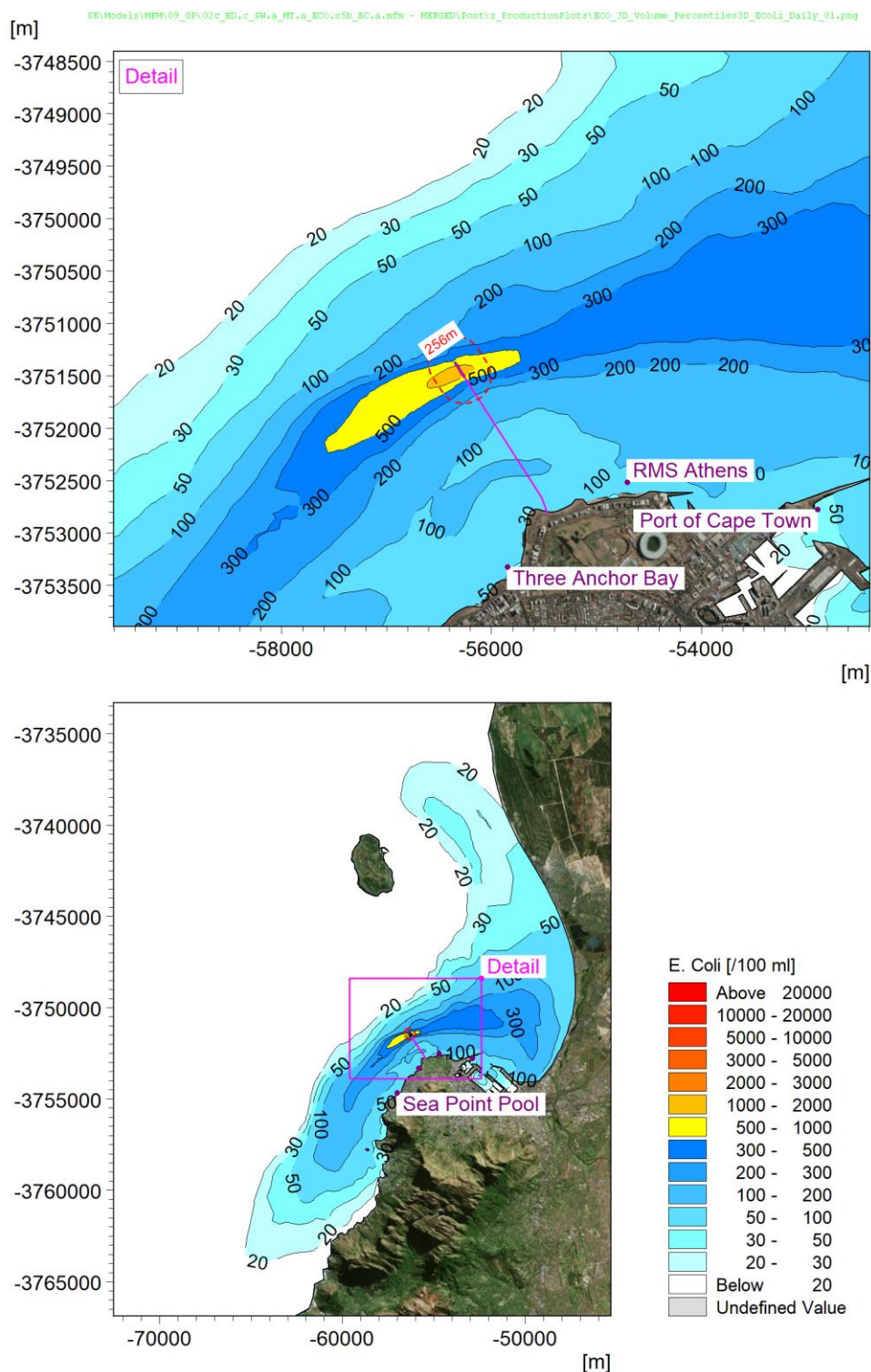


Figure 6-24: Summer/autumn: E.coli concentration at the seabed, 90th percentile for daylight hours (07:00 – 18:00).

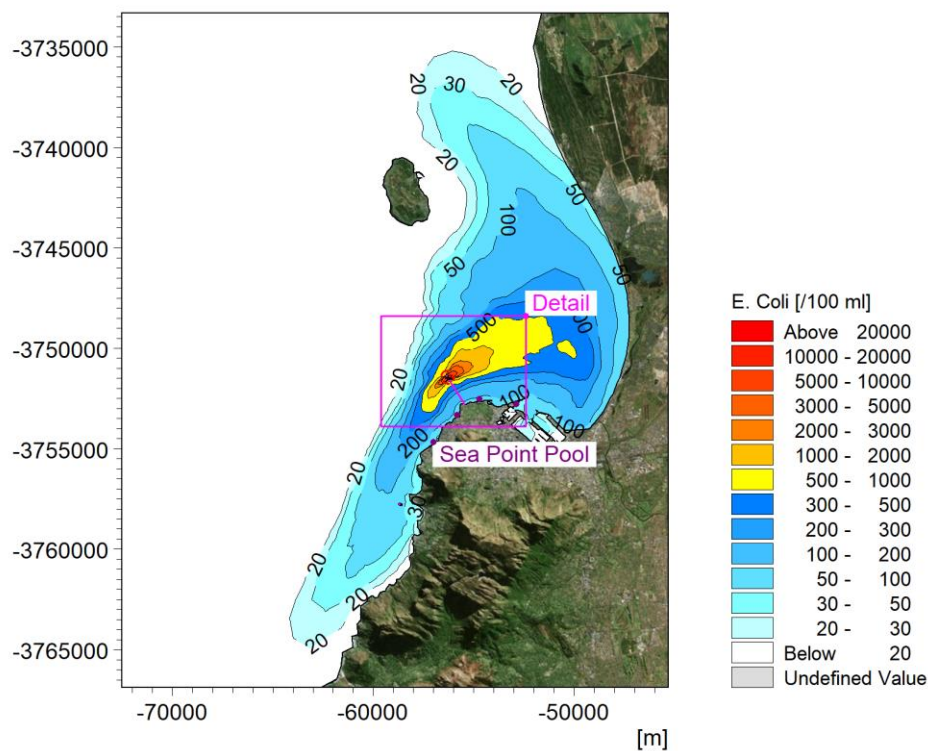
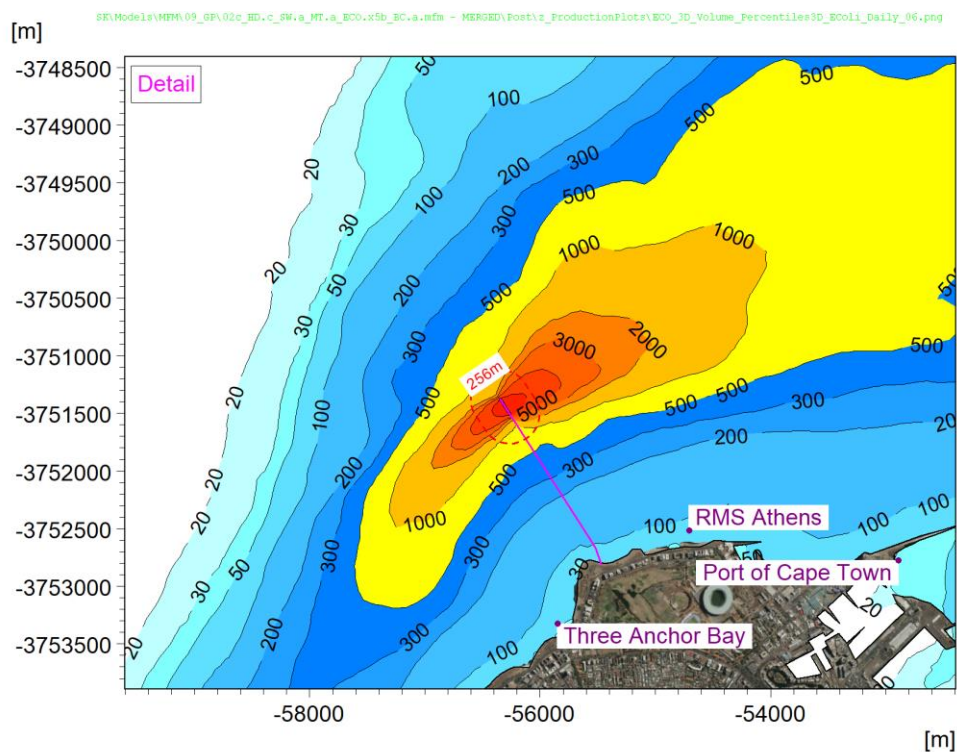


Figure 6-25: Summer/autumn: E.coli concentration at mid-depth, 90th percentile for daylight hours (07:00 – 18:00).

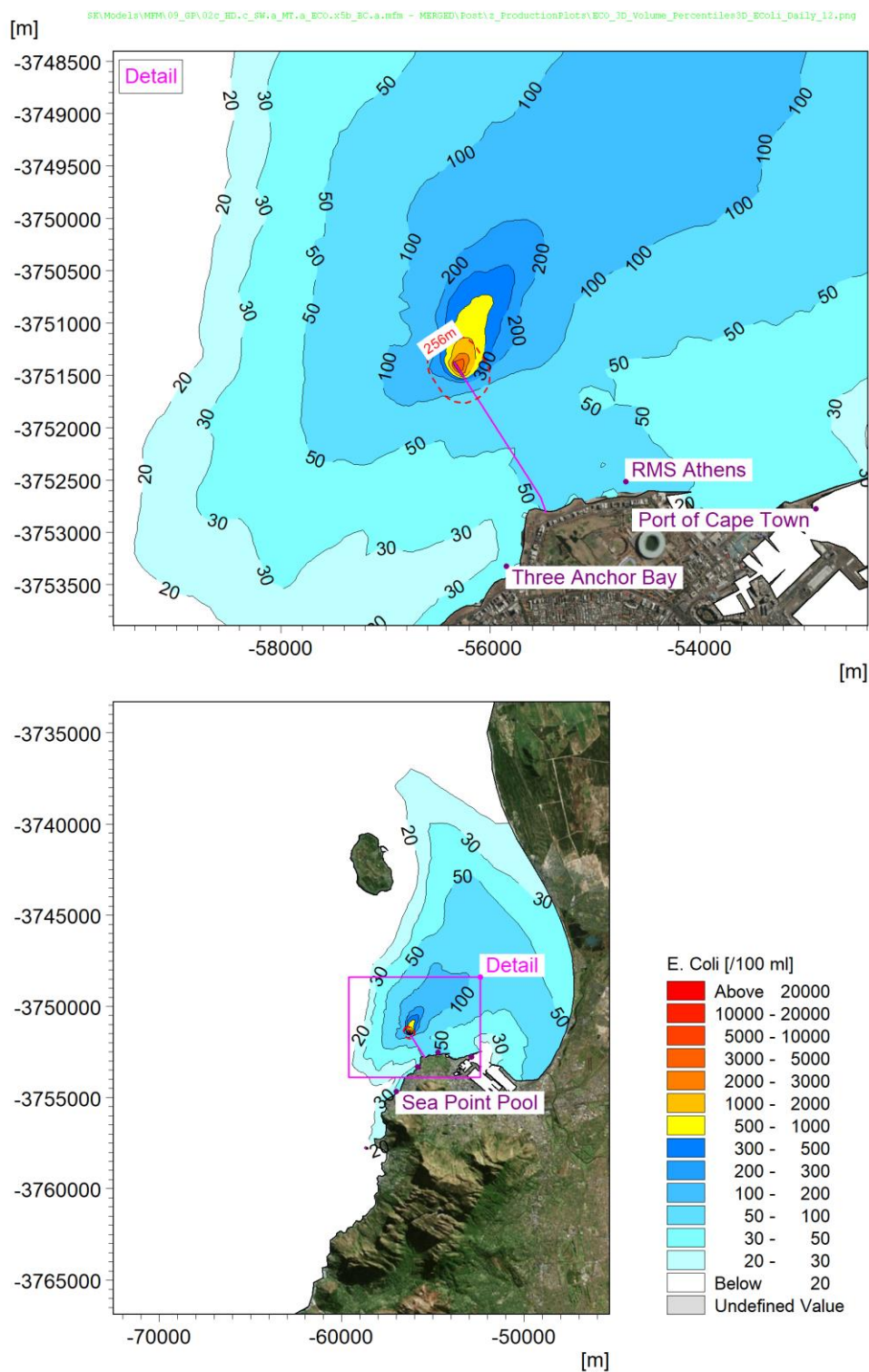


Figure 6-26: Summer/autumn: E.coli concentration at the surface, 90th percentile for daylight hours (07:00 – 18:00).

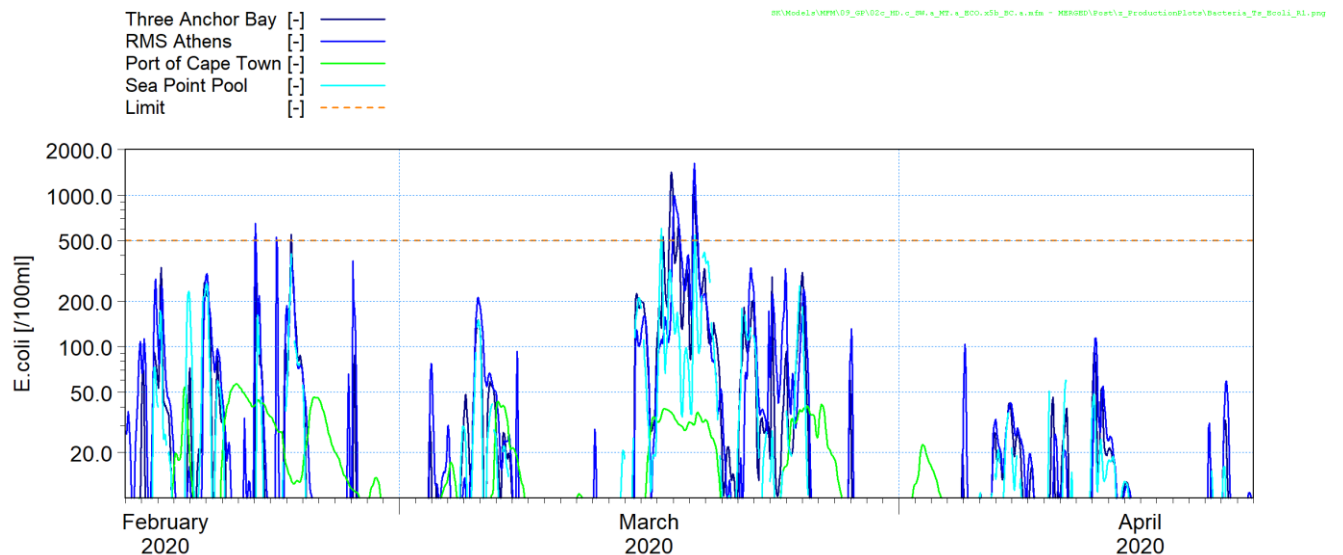


Figure 6-27: Summer/autumn: Time series of highest E.coli concentration at any depth at four key locations. The water quality guideline (500 CFU/100 ml 90th percentile in daylight) is also shown in orange.

A mixing zone distance of 6 600 m was required to meet the 90th percentile water quality guideline of 500 CFU/100 ml. The contour plots show that the 90th percentile E.coli concentrations were the highest at mid-depth and concentrations above the 500 CFU/100 ml guideline did not intersect with the shoreline. Locations such as Three Anchor Bay, RMS Athens (Thermopylae surf spot) and the Sea Point Pool were briefly exposed to E.coli concentrations above 500 CFU/100 ml on a number of occasions. Since the duration of these events was less than 10% of the daylight time these locations met the water quality guidelines.

6.2.3.2 Enterococci

Figure 6-28, Figure 6-29 and Figure 6-30 present the 90th percentile enterococci concentrations at the seabed, mid-depth and surface. Concentrations greater than 185 CFU/100 ml are shown in orange as this is the guideline for enterococci as discussed in Section 3.4.2. Concentrations less than 185 CFU/100 ml are shown in shades of blue. Although these are less than the guideline, they provide information on the far-field behaviour of the plume. A time series of enterococci concentrations at four key locations is shown in Figure 6-31.

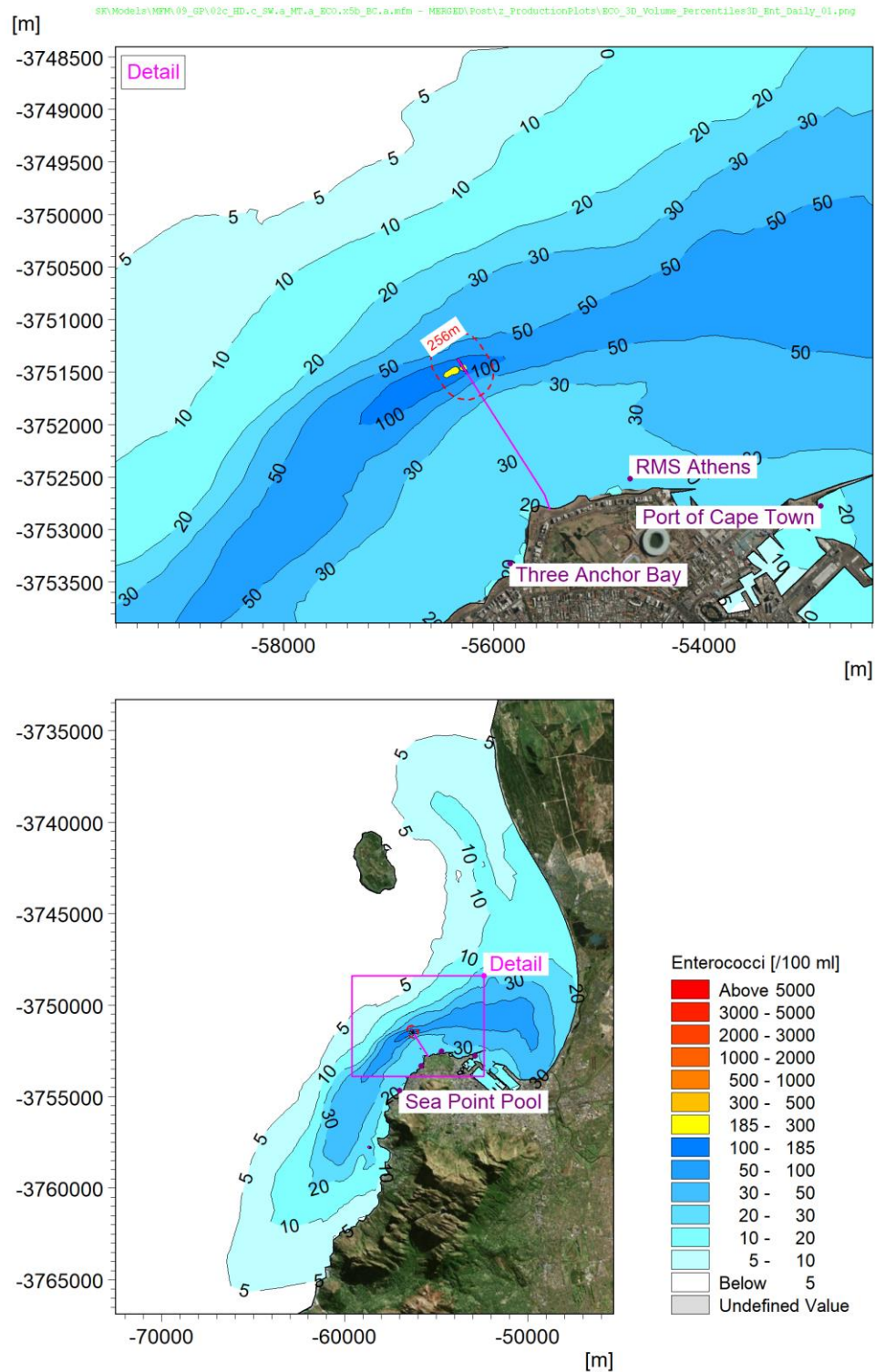


Figure 6-28: Summer/autumn: Enterococci concentration at the seabed, 90th percentile for daylight hours (07:00 – 18:00).

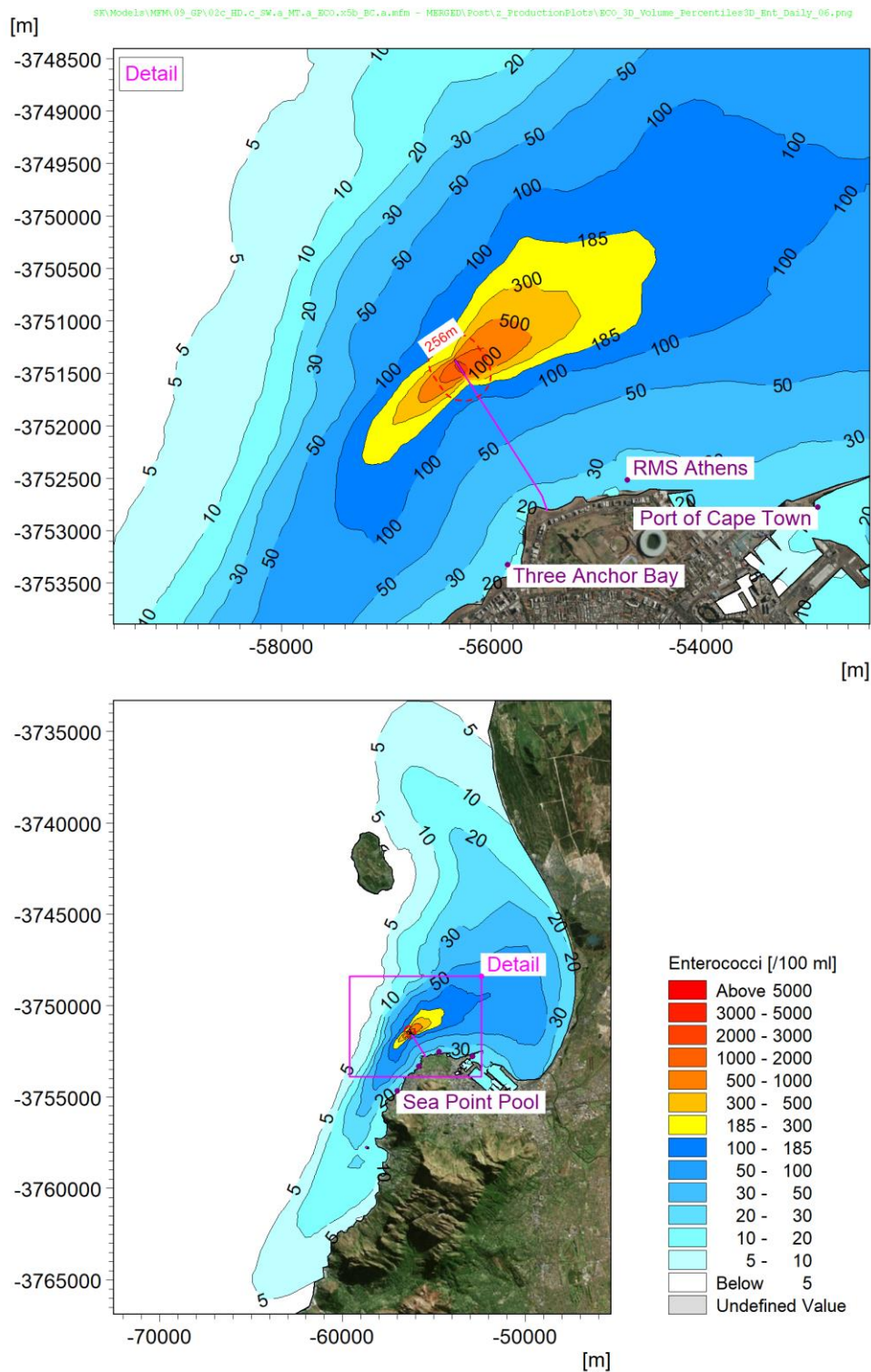


Figure 6-29: Summer/autumn: Enterococci concentration at mid-depth, 90th percentile for daylight hours (07:00 – 18:00).

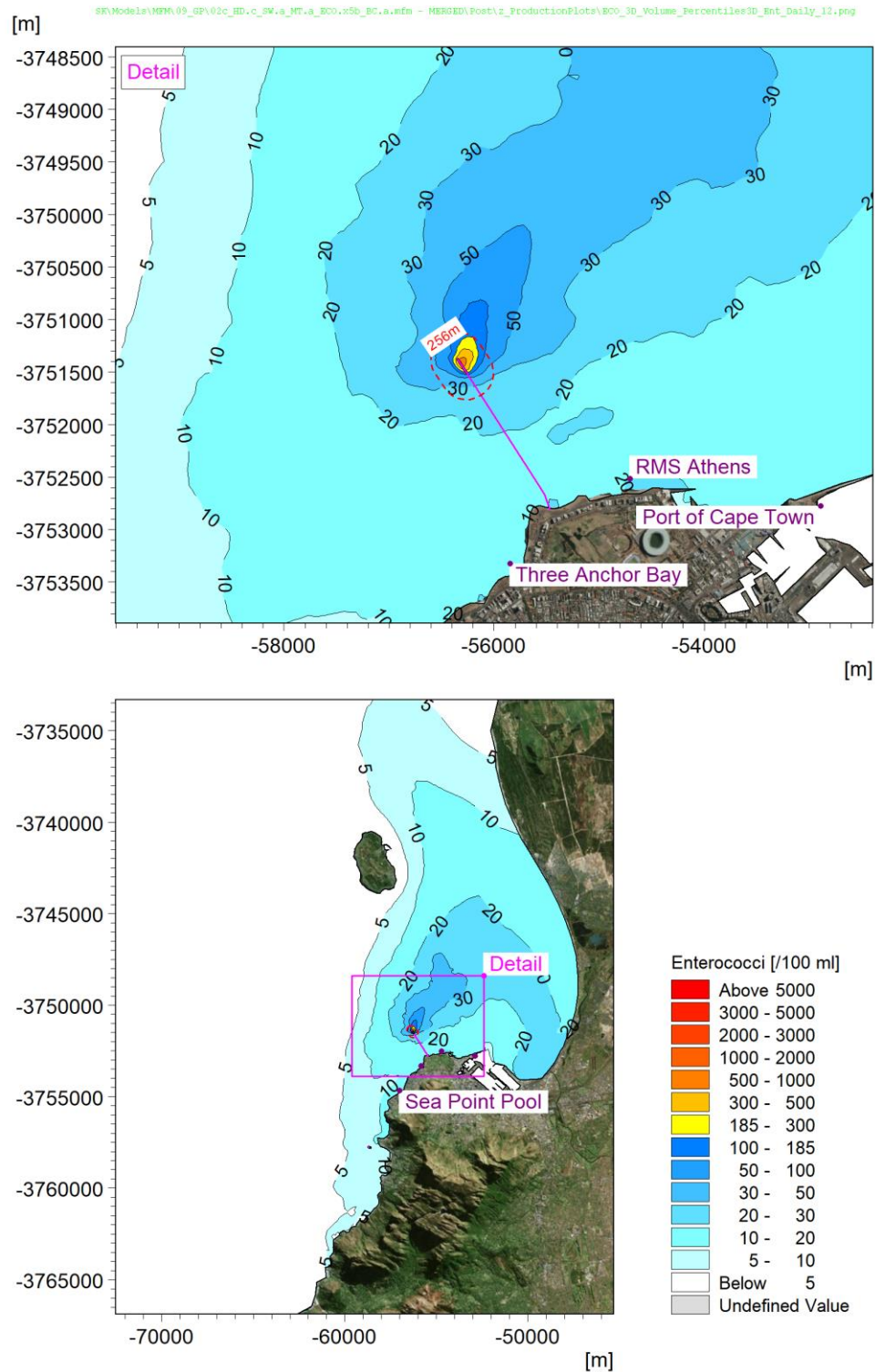


Figure 6-30; Summer/autumn: Enterococci concentration at the surface, 90th percentile for daylight hours (07:00 – 18:00).

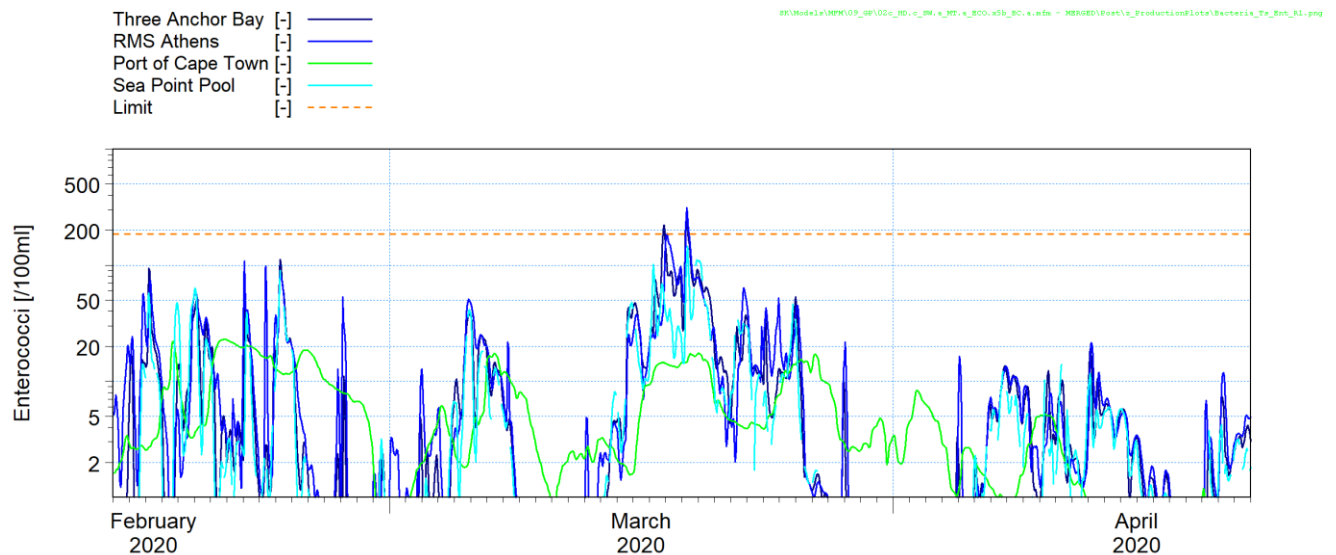


Figure 6-31: Summer/autumn: Time series of highest enterococci concentration at any depth at four key locations. The water quality guideline (185 CFU/100 ml 90th percentile in daylight) is also shown in orange.

A mixing zone distance of 2 300 m was required to meet the 90th percentile water quality guideline of 185 CFU/100 ml. The contour plots show that the 90th percentile enterococci concentrations were the highest at mid-depth and concentrations above the 185 CFU/100 ml guideline did not intersect with the shoreline. The enterococci concentrations at the key locations only exceeded 185 CFU/100 ml on two occasions in the 10-week summer/autumn period

6.2.3.3 Discussion

Based on the applicable water quality guidelines (discussed in Section 3.4.2), E.coli requires a greater mixing zone distance to meet the guidelines compared to enterococci.

The bacteria plumes have the highest concentrations at mid depth (the depth below the surface equal to 55% of the local water depth) where the plume usually becomes trapped. Solar radiation further reduces concentrations closer to the surface (illustrated in Figure 6-7).

During typical conditions the plume will be advected alongshore. South-westerly winds advects the bacteria plumes east into Table Bay but the processes of dispersion and bacteria die-off reduces the bacteria concentrations to below the applicable water quality guidelines before the plumes reach the shore in Table Bay. As discussed in Section 6.1.3.3, onshore movement usually occurs during certain north-westerly wind conditions or local upwelling events associated with south-westerly winds.

6.2.4 Total suspended solids

The concentrations of TSS were modelled in the water column and specifically where these were deposited on the seabed. This is a proxy for the fate of pollutants that adsorb to solid particles, e.g. heavy metals.

Figure 6-32 presents the bed mass of TSS at the end of the 10-week simulation. The deposited mass in the main depo-centres (demarcated in red) are summarised in Table 6-6. The table also includes the total mass of TSS that were advected outside of the model domain through the boundaries and TSS in suspension at the end of the run.

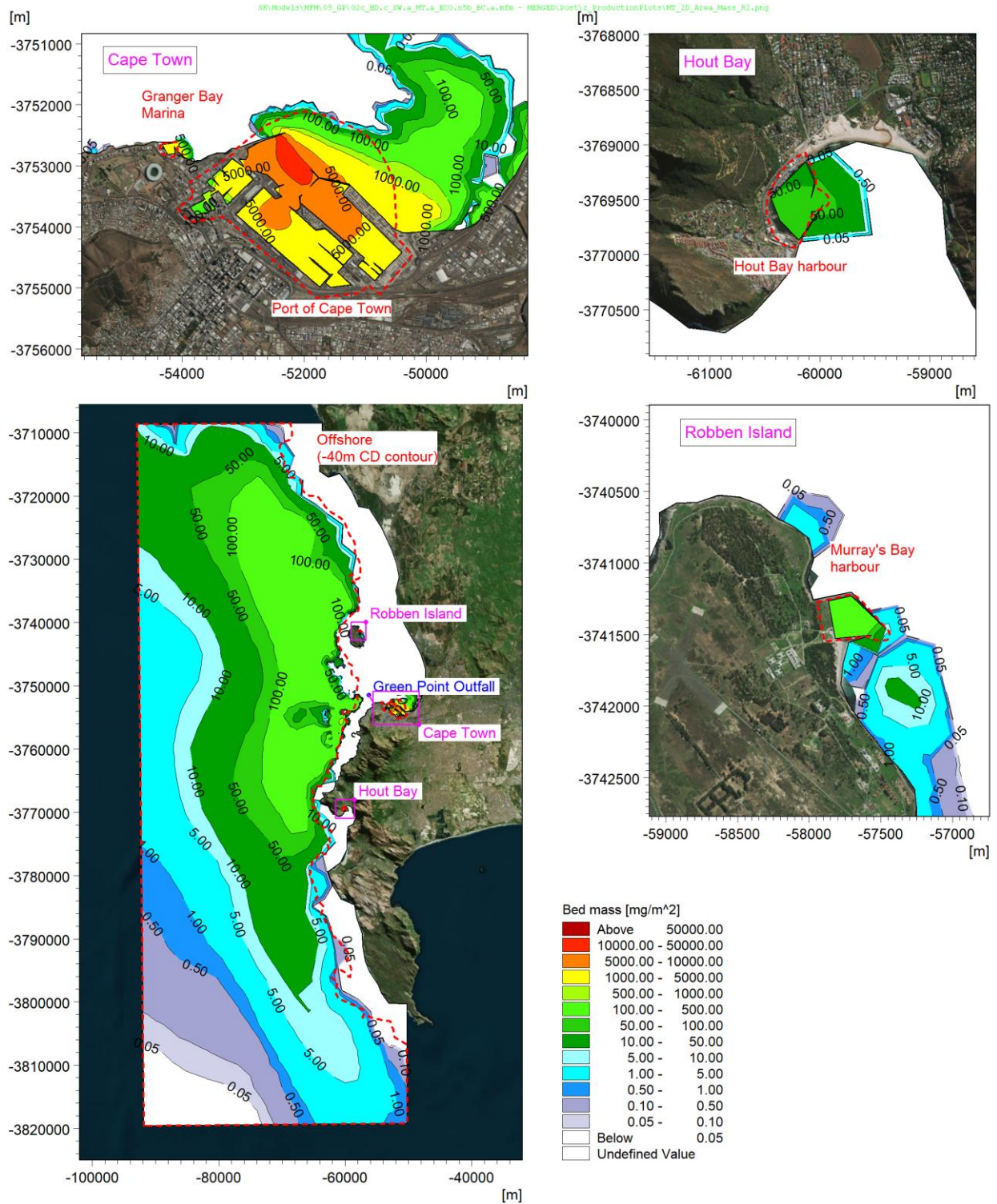


Figure 6-32: Summer/autumn: Bed mass of TSS distribution at the end of the 10-week winter/spring period.



Table 6-6: Summer/autumn: Integrated mass at the end of the 10-week simulation period.

Area	Mass [kg]	% released
Port of Cape Town	25 100	5.0%
Murray's Bay Harbour	23.6	< 0.1%
Granger Bay	107	< 0.1%
Hout Bay	11.8	< 0.1%
Offshore (-40 m CD contour)	141 000	28.1%
Out of domain	263 000	52.5%
Suspended	71 800	14.3%
Total mass released	500 000	100%

The highest concentrations are observed in the sheltered depo-centres, i.e. the Port of Cape Town, Granger Bay marina, Murray's Bay harbour and Hout Bay harbour where the bed shear stress due to waves and currents are sufficiently low to allow deposition. Accumulation also occurs in exposed areas where the water depth is greater than approximately 40 m due to the wave orbital velocities not exerting sufficient stress on the seabed to resuspend the sediment particles.

The largest depo-centre is the Port of Cape Town with approximately 5.0% of the TSS released from the Green Point outfall accumulating in the port. These results can be used in the design and interpretation of sediment quality sampling studies.



7. CONCLUSIONS

A 3D coupled near- and far-field hydrodynamic, water quality, suspended sediment and wave model has been set up for the Green Point outfall.

The model has been calibrated against wave, water level, current and seawater temperature measurements for a 6-week winter/spring period and a 10-week summer/autumn period.

The plume dispersion was then simulated for a 10-week winter/spring period and a 10-week summer/autumn period. The model results show the following:

- The plume has the lowest dilutions and highest bacteria concentrations at mid depth (the depth below the surface between 55% and 60% of the local water depth) where the plume usually becomes trapped.
- During typical conditions the plume will be advected alongshore. South-easterly winds, which are frequent in the summer, advect the bacteria plumes eastwards into Table Bay. Onshore movement can occur during certain north-westerly wind conditions (e.g. current direction reversal causing the plume to approach the coastline in the process) or during local upwelling events associated with south-westerly winds.
- The minimum number of dilutions achieved at the edge of the 256 m radius mixing zone is 528 in winter/spring and 687 in summer/autumn (5th percentile dilution).
- The required dilution of 1 753 for TSS is met at distance of 1 400 m from the diffuser in winter/spring and 940 m in summer/autumn (5th percentile dilution).
- E.coli requires a distance of 6 300 m to meet the applied guidelines in winter/spring and 6 600 m in summer/autumn (500 CFU/100 ml for the 90th percentile concentration during daylight hours).
- Locations such as Three Anchor Bay and the Sea Point Pool are briefly exposed to E.coli concentrations above 500 CFU/100 ml on two occasions in winter/spring. Three Anchor Bay, RMS Athens (Thermopylae surf spot) and the Sea Point Pool are briefly exposed to E.coli concentrations above 500 CFU/100 ml on a few occasions in summer/autumn. However, the cumulative duration of these events is less than 10% of the daylight time and the applied water quality guidelines are thus met at all locations along the shoreline (500 CFU/100 ml for the 90th percentile concentration during daylight hours).
- The applied guidelines for enterococci result in a smaller zone of impact compared to E.Coli.
- The largest depo-centre is the Port of Cape Town with approximately 3.0% of the Total Suspended Solids released from the Green Point outfall accumulating in the port in winter/spring and 5.0% in summer/autumn.



8. RECOMMENDATIONS

Based on the model results the following recommendations are made:

- Compared to Camps Bay and Hout Bay, the Green Point outfall has significantly lower dilutions due to the larger discharge rate. An assessment should be made on how future increases in discharge rate will further reduce the dilutions and increase the bacterial concentrations at Green Point.
- These results assume that the pipeline and diffusers are operating as designed and that there are no breakages, leaks or blockages. Regular underwater surveys are recommended to ensure that this is the case.
- Consideration should be given to operationalising the model to provide forecasts of bathing water quality, as is done in other countries including Denmark, Sweden and New Zealand, e.g. <http://newkbh.badevand.dk>. The forecast would identify one or two days in advance the occasions when the effluent plume is likely to reach specific bathing beaches or surf spots, which would facilitate mitigation of the associated risks to the public.



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