Centre for Environment Fisheries & Aquaculture Science

Cefas

Cefas components of the Joint Investigation into the crustacean mass mortality in Teesside and North Yorkshire in Autumn 2021

A report on modelling conducted for dredging and pyridine, and investigation into thermal shock, oxygen depletion and harmful algal blooms

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1.0	Redacted	14/09/2022	Editorial suggestions by
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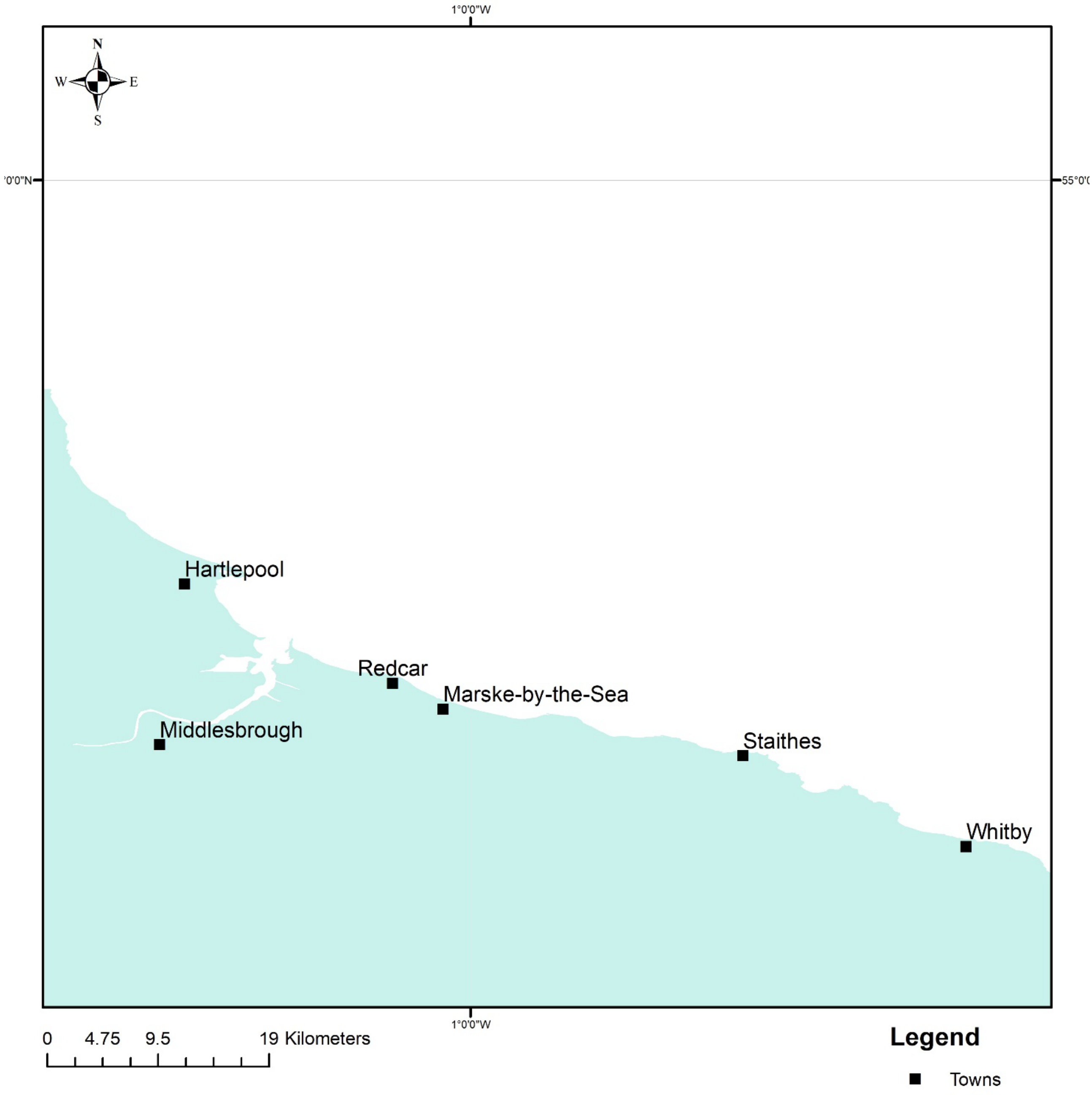
Table of Contents

This report should be read in conjunction with the main summary investigation report (published May 2022) into the crustacean mass mortality observed around the North Yorkshire coast in September – October 2021. This investigation was a joint agency venture including Cefas, the Environment Agency and the Marine Management Organisation, and involving Defra.

The summary report can be accessed here [download link]: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1079927/Joint_agency_investigation_into_Teesside_and_Yorkshire_Coast_Crab_and_Lobster_mortalities.pdf

1. Introduction

Extensive reports and photographs showed dead crustaceans washing ashore around the mouth of the Tees and further south along the coastline towards Whitby in Autumn 2021 (Figure 1). These extended over a period of days but were mainly concentrated in the period 28th Sept to 5th October 2021. This document aims to explore some of the potential causative mechanisms.



Potential causes of the event that are discussed in this report are:

- Thermal shock – sudden or extreme temperature change;
- Dredging - Release of sediment particles causing smothering
- Release of Pyridine;
- Oxygen depletion (hypoxia) – due to decay of a large bloom; and
- Presence of Harmful Algal Bloom (HAB) species in the vicinity.

2. Thermal Shock

2.1. Sea surface temperature and waves in the region

Daily sea surface temperatures are available from the Cefas Eutrophication viewer[1] as shown in Figure 1 for 5th Oct 2021. There appears to be no regional anomalies or strong gradient in the Tees region (Figure 2).

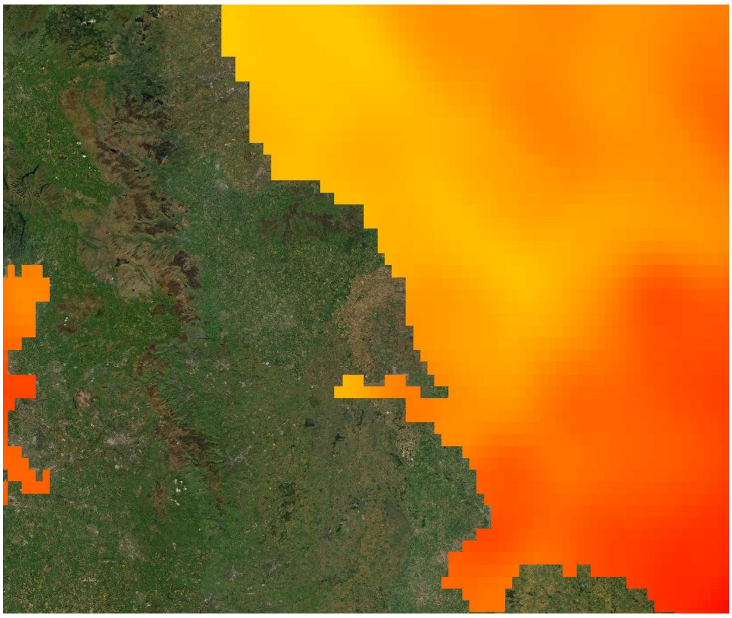


Figure 2 - Satellite image of sea surface temperature (OSTIA) from Cefas Eutrophication Data cube[1].

The sea surface temperature was recorded by the Tyne/Tees waverider buoy located at 54° 55.1’ N 00° 44.93’ W (Figure 3). Evident is that the temperature remains above 15 ° C until the 26th September which is later than average. There is then a rapid decrease of 2 °C over the period 26th Sept – 7th October.

[1] Cefas Eutrophication Viewer, available at: https://eutro-cube.cefas.co.uk/ (Accessed 14 September 22)

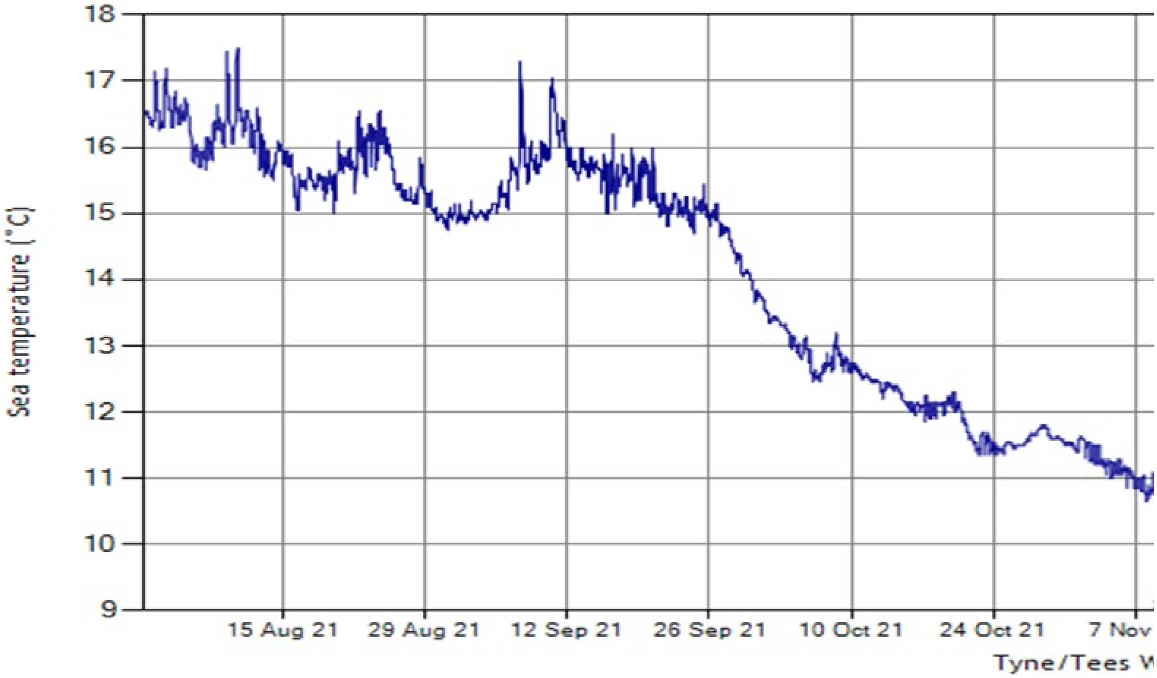
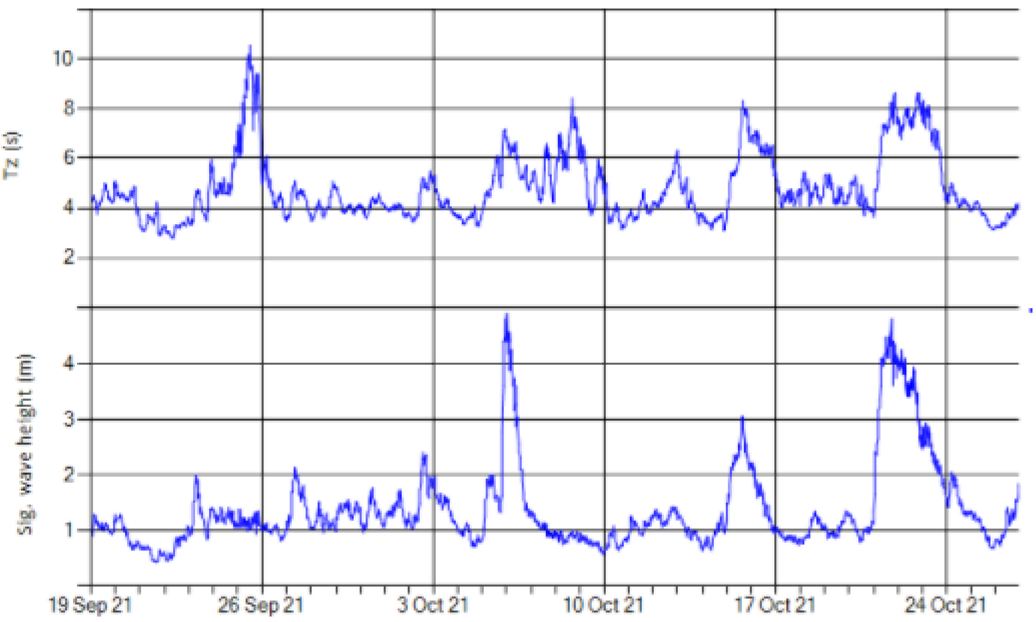

18
17
16
15
14
13
12
11
10
9
Sea temperature (°C)
15 Aug 21
29 Aug 21
12 Sep 21
26 Sep 21
10 Oct 21
24 Oct 21
7 Nov
Tyne/Tees W

Figure 3 - Time-series of surface seawater temperatures at the Tyne/Tees Wavenet site.



[2].

The waverider record (Figure 3) shows no particular strong wave activity until the 6th October when substantial waves of nearly 5m wave height were recoded, with another similar storm on the 23rd October. However, on the 26th Sep there is a period of longer duration waves, and therefore longer wavelengths waves which could have mixed the water column vertically contributing to cooling on the 26th.

2.2. Thermal shock in crabs.

There have been instances of crab mortalities associated with abnormally cold sea temperatures and stress, such as during the "*beast from the East*" period in February 2018[3]. However, while the surface temperature drop of 2°C in 8 days is dramatic, the sea bed temperatures are unlikely to be a problem for crustaceans as the surface is isolated from the sea bed by the seasonal thermocline in waters greater than 50m deep. Therefore, bed temperatures are unlikely to have changed rapidly around the time of the mass mortality events currently in question.

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[2] Data available from https://wavenet.cefas.co.uk/
[3] The Courier: "*What caused thousands of sea creatures to wash up dead on Courier Country shores?"* , available at: https://www.thecourier.co.uk/fp/business-environment/environment/618101/caused-thousands-sea-creatures-wash-dead-courier-country-shores/ (Accessed 14 September 22)

3. Modelling of the dredge disposal plume.

A potential impact pathway on crabs could be any suspended sediment plume from disposals associated with dredging of the Tees. In order to model the plumes associated with the discharge, the location, volume and particle size distribution of disposed sediment is required. Information of the dredging activity was provided by the MMO as regulator for such activities. Campaigns 5 and 6 can be excluded as they occurred after the crab event reports (Table 1). Campaign 1 was excluded due to a lack of information for volume

Table 1 shows the seven campaigns of dredging activity in the Tees with known estimates of volume extraction within the window of investigation.

Table 1 - Dredging Campaigns on the Tees in September and October 2021.

Campaign	Dates	Location (see Fig 4)	Approximate Volume (m^3)	Comments
1	3rd-20th Sept	8-12		
2	27-30th sept	7-9	32,500	
3	1-8th Sept	1, 7 and 11		
4	16-27th Sept	1, 2 and 9	17,200 for Sept	
5	5th Oct-31st October	7 and 9	32,000	
6	1st Nov - 8th Nov	3 and 9	5,000	
7	5th Sept – 5th October	11	67,000	Likely to be sandy as near mouth

As campaign 7 is likely mainly sand, and therefore having a likely lower contaminant load, due to sand's lower surface area to volume ratio compared to fine sediments (Karickhoff *et al.* 1979), this can be also rejected as a potential causal link. Campaign 3 is early in September and is therefore outside of the timings of the incident to be considered likely to be a cause. Campaign 2 and Campaign 4 do fit the timeline and are therefore considered further. Table 2 shows the IDs of samples relevant to campaigns 2 and 4. These samples refer to location 9 (Figure 5) and Table 3 shows their particle size characteristics[4].

Table 2 - Sediment Sampling Number for Campaign 4 at location 9.

Sampling Number
34396/090407
35097/110302
DCO/2014/00002
MLA/2015/00088

Table 3 - Particle size distribution by sample campaign for location 9. Gravel = >2mm diameter; Coarse Sand = 2mm – 500μm diameter; Medium Sand = 500μm – 250μm diameter; Fine Sand = 250μm – 63μm diameter; Silt = <63μm diameter.

Sampling Number	Mean % Gravel	Mean % Coarse Sand	Mean % Medium Sand	Mean % Fine Sand	Mean % silt
34396/090407	0.07	1.01	2.45	29.16	67.30
35097/110302	2.31	1.08	2.13	13.3	81.18
DCO/2014/00002	0.27	1.57	2.99	19.95	75.29
MLA/2015/00088	0.13	1.22	1.43	16.67	80.60

[4] The raw data informing this are publicly accessible on the MMO Public Register

Mean	**0.695**	**1.22**	**2.25**	**19.77**	**76.09**

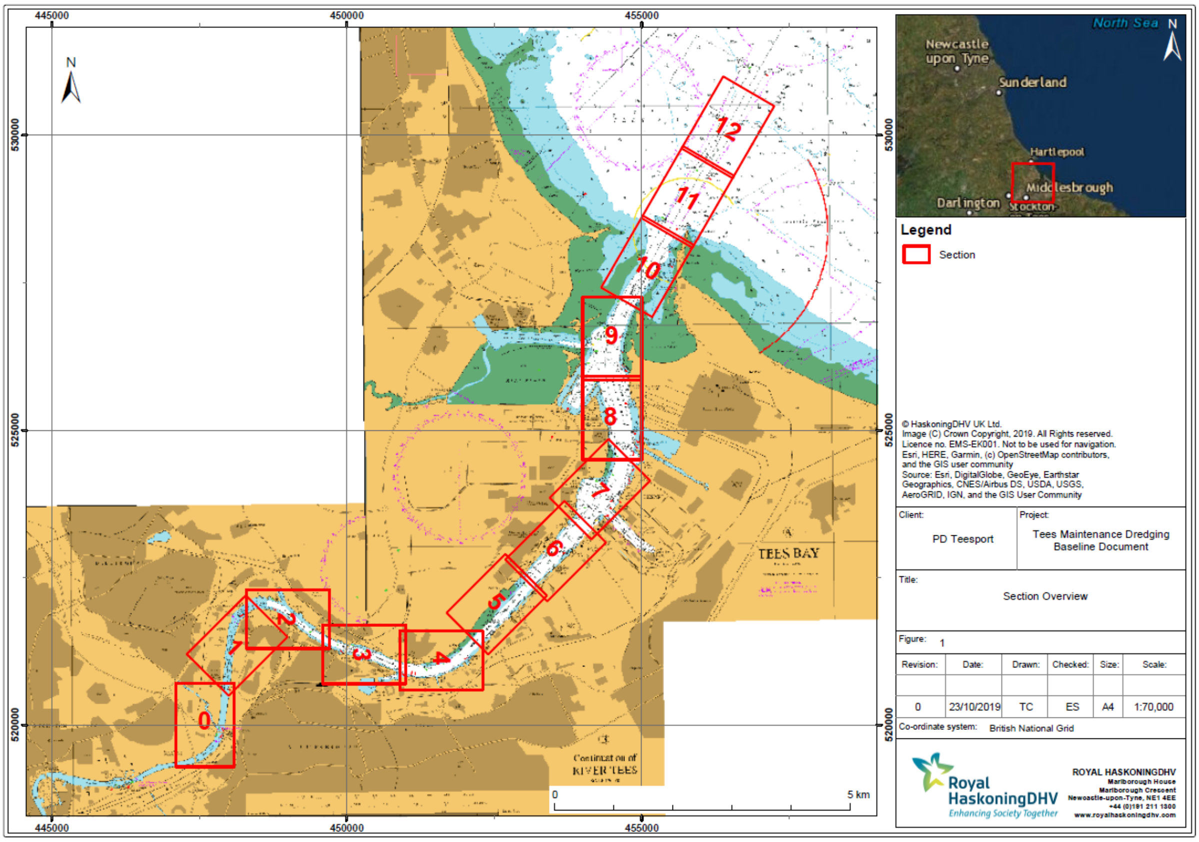


Figure 5 - Dredging area within the Tees estuary showing the location of each numbered area.

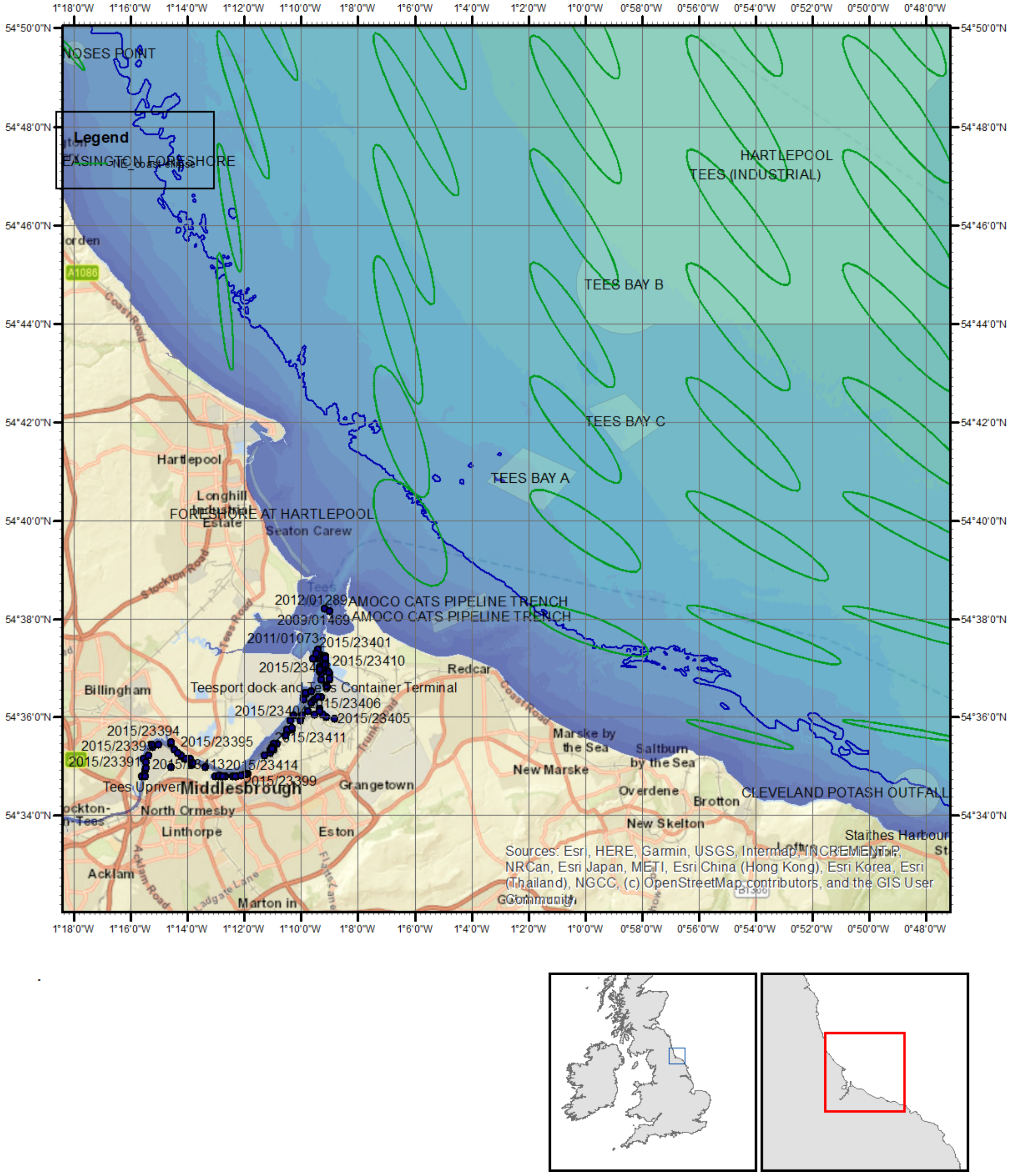
Evident from the analysis is that overall, 76% of the material from location 9 is silt, and thus fine grained.

3.1. Tidal Ellipses

The first step in the sediment plume modelling is to check the tidal ellipses which are shown in Figure 5 (sourced from the modelling software Telemac). These show that the ellipses rotate from shore parallel off Redcar to more Northerly and elongated off Hartlepool and appear correct from known measurements of the tidal conditions along this coast[5].

[5] National Oceanography Centre – UK Tide Gauge Network https://www.bodc.ac.uk/data/hosted_data_systems/sea_level/uk_tide_gauge_network/ (Accessed 10th October 2022)

Secondly, using the centre of the Inner (Tees Bay A) licensed disposal site at 54.682, -1.046, a release of 2500 particles was made at a spring slack water for 3 hours, as is typical for plume modelling and considering the disposal volumes as per Table 1. Figure 6 shows the position of the particles at the end of the run (72 hours).



Cefas

Figure 6 - Spring tidal ellipses from the North East coast of the UK. Also shown are the positions of the Particle size analysis sampling stations (in black). Only those from location 9 in the weeks upto the incident were used in the Suspended sediment modelling (see text).

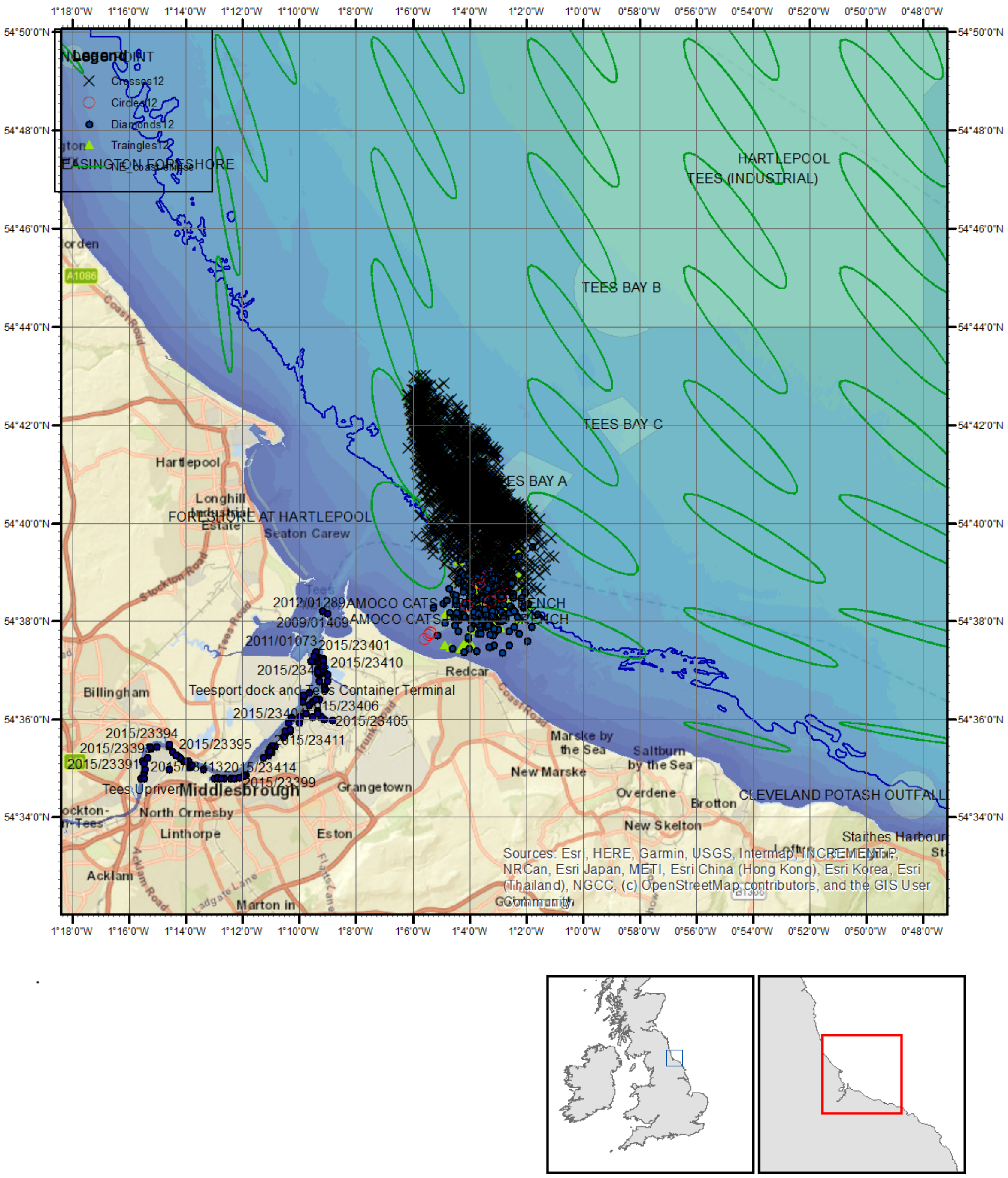


Figure 7 - Suspended sediment plume generated from the CEFAS plume model. Particles head in southern direction towards Redcar. The release point was the centre of the Inner (Tees Bay A) licensed disposal site at 54.682, -1.046

3.2. Discussion.

The virtual cloud of particles representing the suspended sediment plume follow the current ellipse at the site and head in a South-easterly/southerly direction towards Redcar (Figure 6). As the particles are fine i.e. 75% silts they remain in suspension for the duration of the simulation (72 hours). It should be noted that as the particles get closer to the coast the resolution of the model is somewhat poor in this location. Furthermore, along open lengths of coastline wind driven circulation can have an impact on the trajectory of the plume. As this process (wind) is not included in the model, it is recommended that further, more sophisticated numerical modelling is undertaken.

4. Pyridine Chemical release modelling

Elevated levels of Pyridine were identified in some tissue samples from Crabs in the region[6]. This chemical is therefore considered as a potential causative agent. Within Cefas, the Emergency response team have available the industry standard Chemical Spill model "CHEMMAP" developed by ASA (now part of the RPS group[7]). Pyridine was in the database of chemicals that have had their physical and chemical properties assessed. It states that pyridine:

- Is buoyant (in seawater)
- Is highly volatile
- Is highly soluble (in seawater).

A scenario was developed to explore the distribution and magnitude of a hypothetical release of pyridine. Three discharge volumes (hereafter referred to as "scenarios"), have been considered to help understand if Pyridine is a potential cause. To examine the potential for impacts from an acute release of Pyridine, a range of volumes were used; 100, 1000, 10,000. A release duration of 3 hours was selected to determine the likely worst-case scenario of an acute release, using expert judgment. Thus, the model is forced as:

[6] Joint Agency Investigation into Teesside and Yorkshire coast Crab and Lobster mortalities, May 2022, available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1079927/Joint_agency_investigation_into_Teesside_and_Yorkshire_Coast_Crab_and_Lobster_mortalities.pdf (Accessed 14 September 22)

[7] CHEMMAP, by RPS Group, available at: https://www.rpsgroup.com/services/oceans-and-coastal/modelling/products/chemmap/ (Accessed 14 September 22)

Parameter	Details
Date	5th Oct 2021 12:00
Release duration	3 hours
Release location	Centre of Tees Inner (Tees Bay A) disposal site (54.682N,1.046W)
Winds	Real winds from UKMO
Tidal currents	Sourced from Cefas Tidal database generated from a calibrated Telemac numerical model[8]
Duration of simulation	72 hours
Volumes	100, 1,000 and 10,000 litres

The outputs below show the distribution of pyridine in solution (at the end of 72 hours i.e., 8th Oct 2021 at 12:00) in mg/m^3. It should be noted that the centre of distribution is just north of the start location is only artifact of the duration chosen (the long term residual is to the SE) which can also be seen the animation in the reference section.

In Figure 7 with a 100 litre release, a concentration of up to 3 mg/m^3 can be observed after a simulation of 72 hours. The shape and orientation of the plume reflects that of the tidal ellipses (see above).

[8] Telemac Modelling Software http://www.opentelemac.org/ (Accessed 14 September 22)

In Figure 8, a 1,000 litre release is simulated with a maximum of 38 mg/m^3 and also an extension heading south probably due to northern winds at the time.

Similarly, in Figure 9, with a release of 10,000 litres this extension is more pronounced and covers the whole disposal site. The maximum concentration reaches 453 mg/m^3 at the end of the runs 8th Oct 2021 at 12:00 (i.e., the common comparison point).

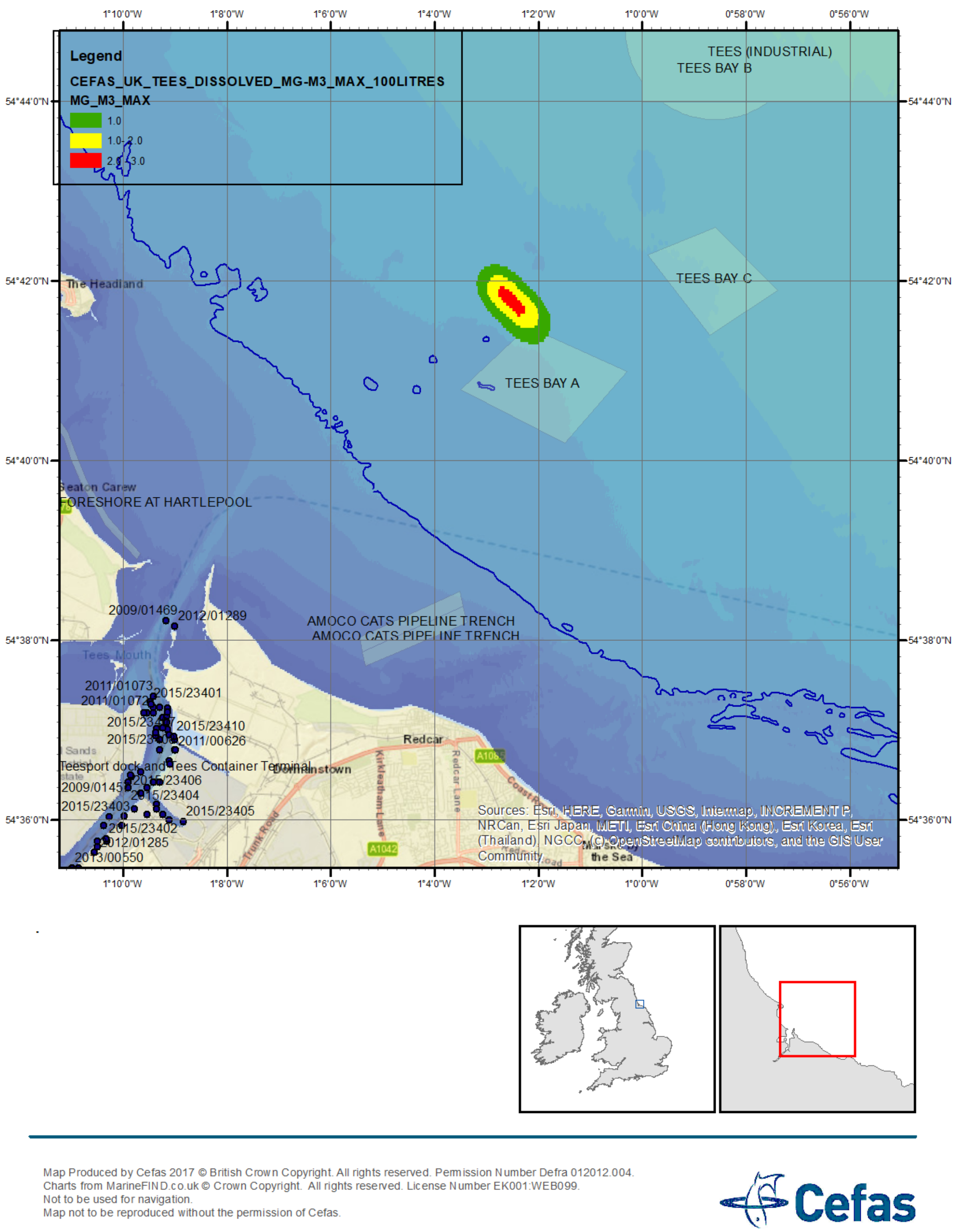


Figure 8 - CHEMMAP model output simulating a 100 litre Pyridine release in the centre of Tess Inner disposal site. The 20m depth contour is highlighted in dark purple. Note the Legend which is specific to each simulation. Legend transcription: modelled concentrations of acute pyridine release in mg/m³; green - <1; amber – 1 – 2; red 2 - 3.

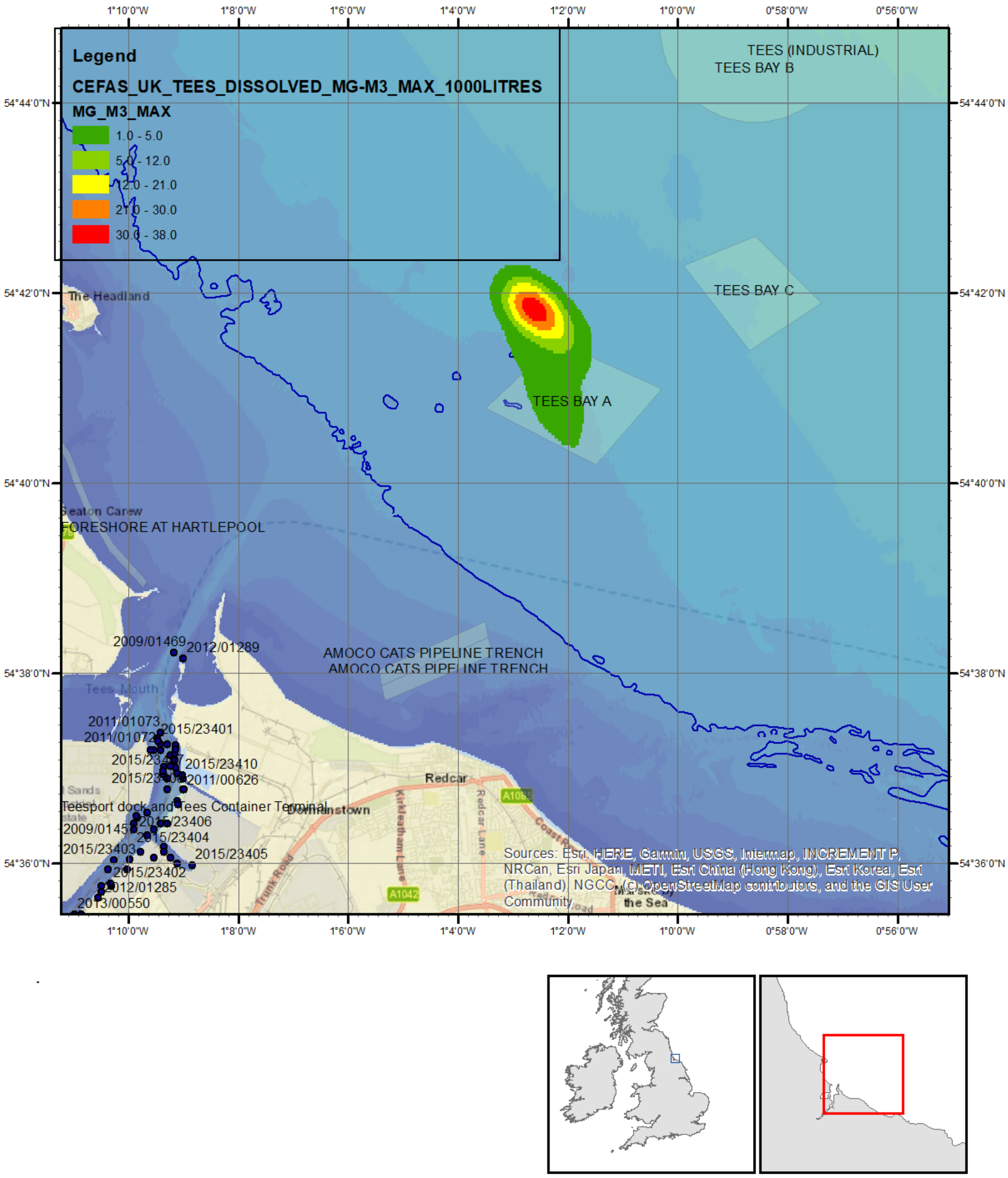


Figure 9 - CHEMMAP model output simulating a 1000 litre Pyridine release in the centre of Tess Inner disposal site. The 20m depth contour is highlighted in dark purple. Note the Legend which is specific to each simulation. Legend transcription: modelled concentrations

of acute pyridine release in mg/m³; green 1 – 5; light green 5 – 12; amber 12 – 21; orange 21 – 30; red 30 – 38.

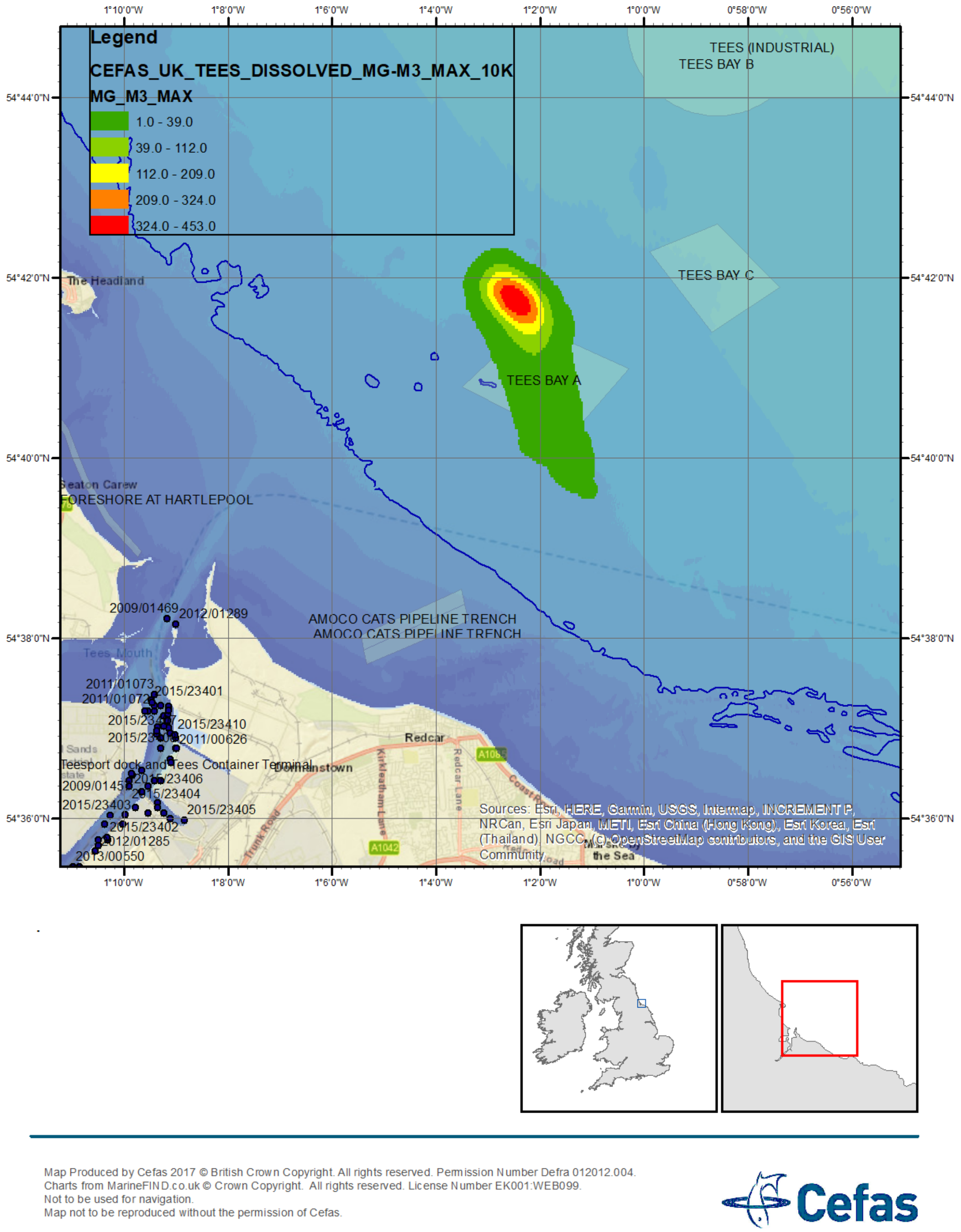


Figure 10 - CHEMMAP model output simulating a 10,000 litre Pyridine release in the centre of Tess Inner disposal site. The 20m depth contour is highlighted in dark purple. Note the Legend which is specific to each simulation. Legend transcription: modelled concentrations of acute pyridine release in mg/m³; green 1 – 39; light green 39 – 112; amber 112 – 209; orange 209 – 324; red 324 – 453.

4.1. Discussion

It must be noted that the modelling conducted for pyridine comprised the prediction of a spill or pollution incident of pyridine occurring at the disposal site in question, rather than the modelling of sediment contaminated with pyridine. Given the properties of pyridine (i.e. its high volatility and water-solubility), the authors consider it unlikely to sorb to sedimentary material as well as hydrophobic substances such as hydrocarbons or dioxins, as indicated by its registration dossier under the European Chemicals Agency (ECHA)[9]. As such, the modelling for pyridine contained within this report is considered a worst-case scenario, compared to the mobilisation of sediment contaminated with pyridine. At the time of writing there is no established method to confidently predict such mobilisation from sediment potentially contaminated with pyridine in the marine environment.

Evident from Figure 11, is that because Pyridine is highly soluble and buoyant, approximately 45% of the discharge stays on the surface which is rapidly lost by evaporation to the atmosphere. The remaining 55% is mixed throughout the water column. As the mixing is throughout the water column, dilution is very high, and therefore high levels of contaminant only occur near the discharge location as depicted in Figures 8 – 10, and would not occur at high concentration near the bed (where Crab and Lobster exist). The maximum concentration out of any of the three release scenarios would be 453 mg/m^3 (Table 4, Figure 10), confined to the North of the disposal site.

Table 4 – Maximum Concentration for each scenario.

Release volume (litres)	Maximum Dissolved concentration (mg/m^3)
100	3
1,000	38
10,000	453

[9] ECHA Registration Dossier – Pyridine https://echa.europa.eu/registration-dossier/-/registered-dossier/13681 (Accessed 10th October 2022)

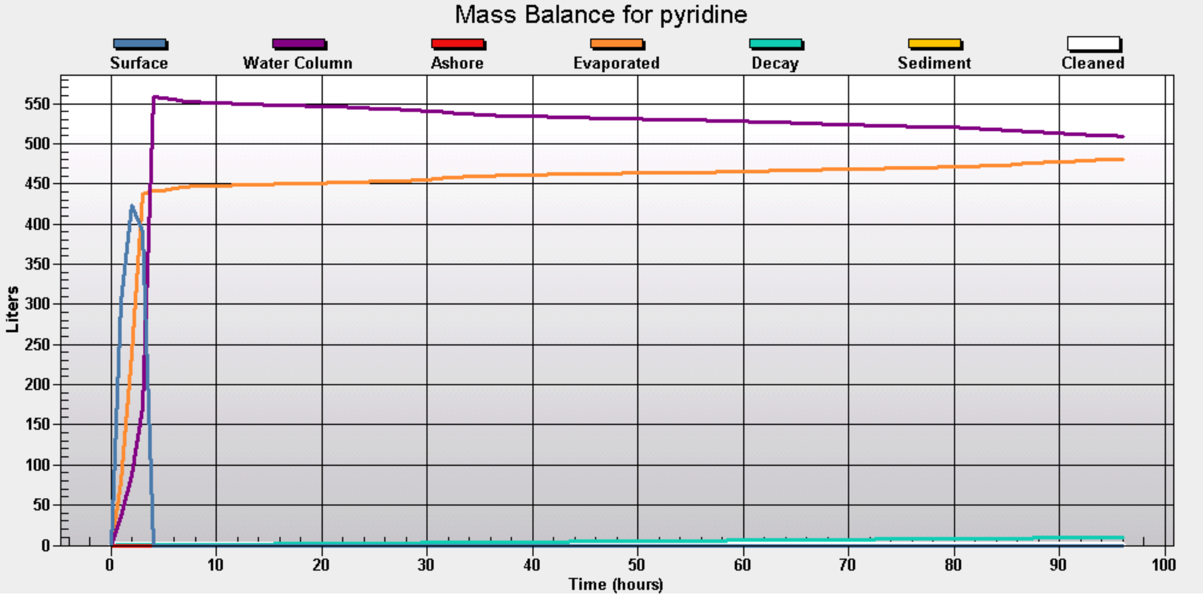


Figure 11 - Fate of Pyridine as computed by the CHEMMAP model for the 1000 litre scenario.

4.2. Conclusion of modelling

The desk based, indicative Cefas plume model shows the potential for the very fine particles to travel to the south of the area of concern. As the model is a generic model, it does not have particularly high resolution and does not include sediment suspension and resuspension issues. It is highly recommended that a high-resolution modelling assessment using the latest modelling techniques is undertaken (such as undertaken at Nab Tower last year). Thus, at present, these suspended sediment modelling results should be considered as low confidence.

However, what can be said is that for chemicals which are highly soluble like Pyridine then dilution is sufficiently high that they can be considered unlikely to constitute a potential cause.

5. Presence of Harmful Algal blooms

Figure 12 shows data collected by the Environment Agency (published separately) during their sampling of inshore stations. *Dinophysis Acuminata* and *Acuta* are species of HAB which are associated with Diarrhetic shellfish poisoning, with action levels at 500 cells per litres (i.e. low bio mass). *Karenia Mikimotoi* is a large biomass HAB typically large blooms have cells in excess of 100,000 cells per litre.

Evident from Figure 12 is that there were blooms of *Karenia* in the North part of the region in early September. It was therefore considered a possibility that such blooms may have travelled south on the prevailing residual currents which are South East along the coast.

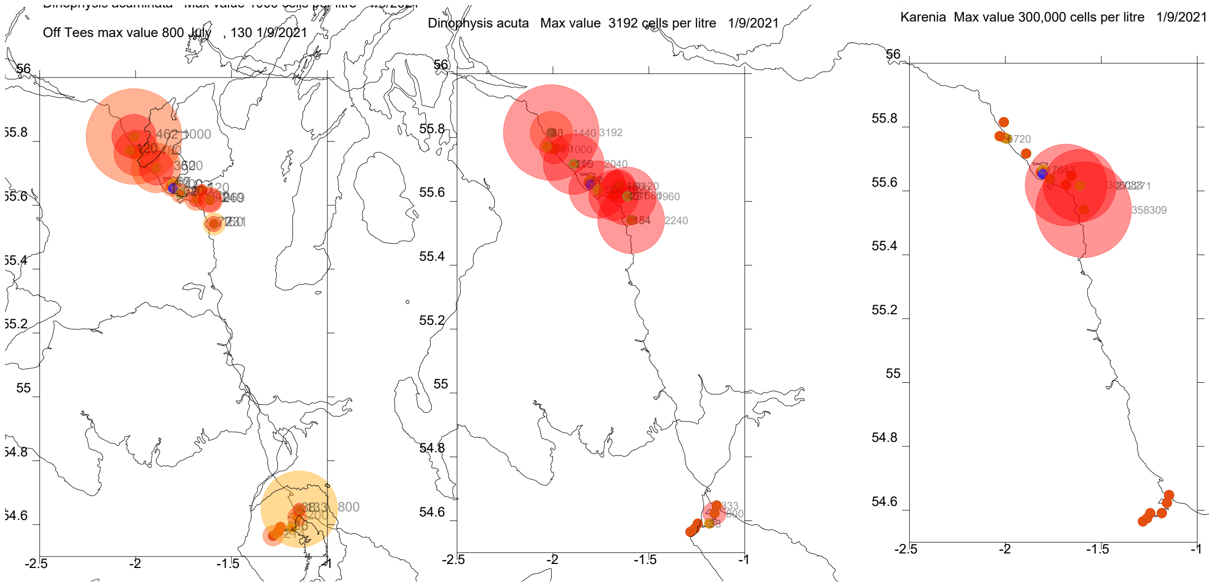
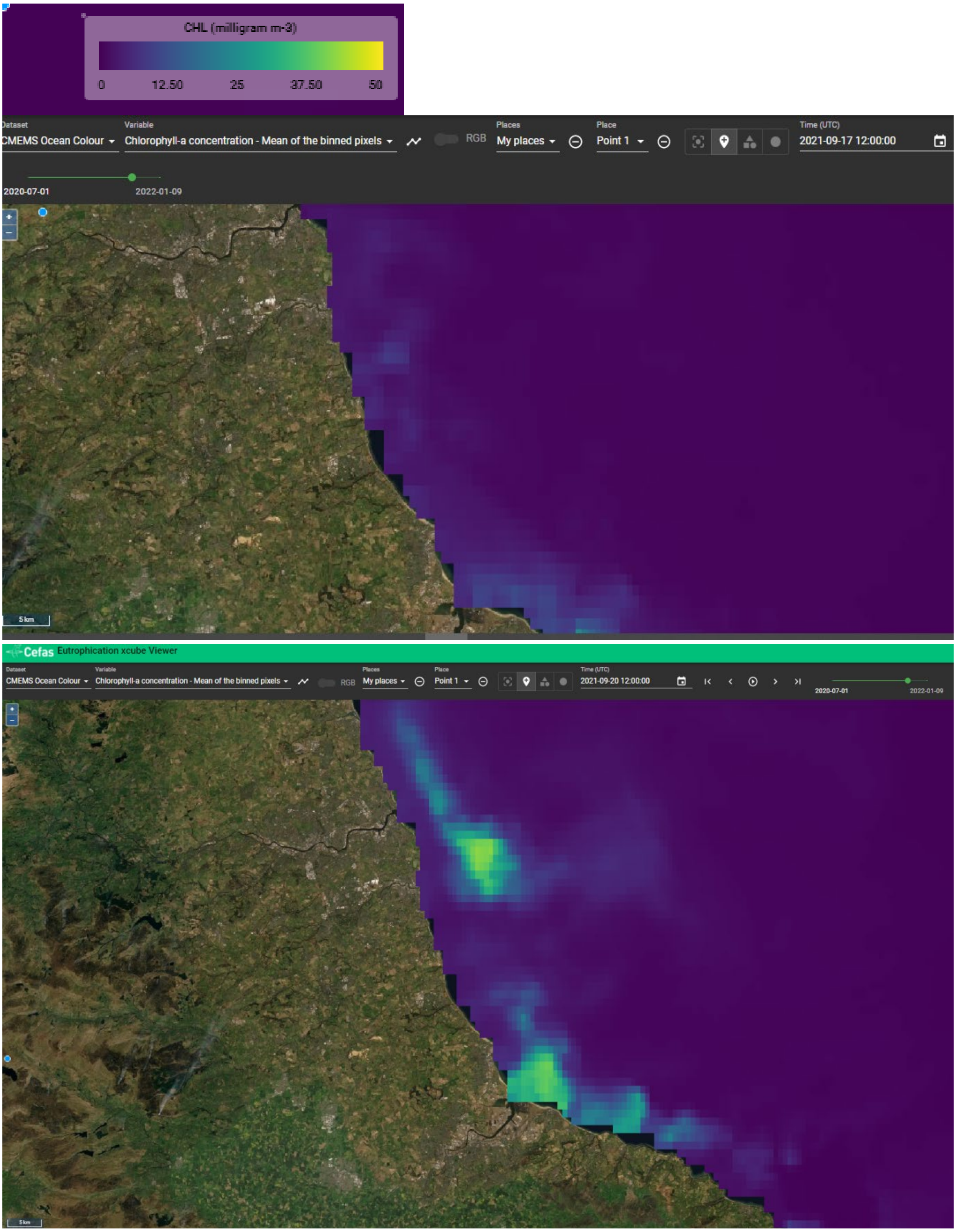


Figure 12 Distribution of harmful algal bloom species in the region. Circle size are proportional to the cell counts and the colour is time of year. Orange is early summer -red is September. (The actual cell count data is published by the EA).

5.1. Satellite imagery from CMEMS Ocean colour composite.


CHL (milligram m-3)
0
12.50
25
37.50
50
Dataset
CMEMS Ocean Colour
Variable
Chlorophyll-a concentration - Mean of the binned pixels
RGB
Places
My places
Place
Point 1
Time (UTC)
2021-09-17 12:00:00
2020-07-01
2022-01-09
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Cefas Eutrophication xcube Viewer
Dataset
CMEMS Ocean Colour
Variable
Chlorophyll-a concentration - Mean of the binned pixels
RGB
Places
My places
Place
Point 1
Time (UTC)
2021-09-20 12:00:00
2020-07-01
2022-01-09

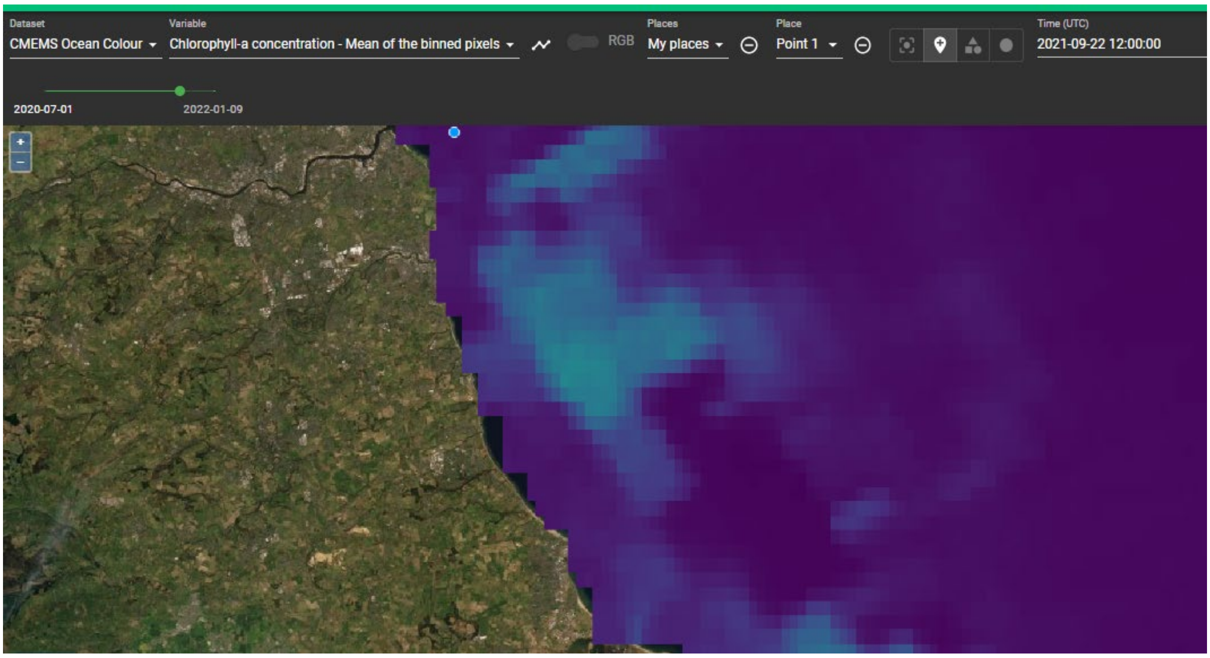

Figure 13 Satellite imagery daily composite. Available from Cefas Eutrophication Viewer, original data CMEMS Ocean Colour (Top 17/9, Middle 20/9, Bottom 22/9) provided by Copernicus.[10]

Figure 13 shows the daily composite imagery generated by Copernicus from satellites observing ocean colour. They use algorithms designed to reduce the influence of sediment but may still have problems near the coast when sediment is very high compared to chlorophyll. In addition in order to produce a complete coverage daily composite, there is interpolation in space between imagery which can produce false or unrealiable results.

Evident in the imagery on the 20th are patches of high concentrations of chlorophyll. One off coast of Newcastle and another substantial patch off the Tees, and close along the coast to the near south. This bloom appears relatively suddenly and then disappear (die off) with the apparent high concentration having reduced by 22nd September.

A different satellite algorithm (Figure 14) (same satellite, different algorithm) provided by NEODASS gives individual imagery rather than generating a composite.

[10] CEMEMS Ocean Colour Satellite Products Guide

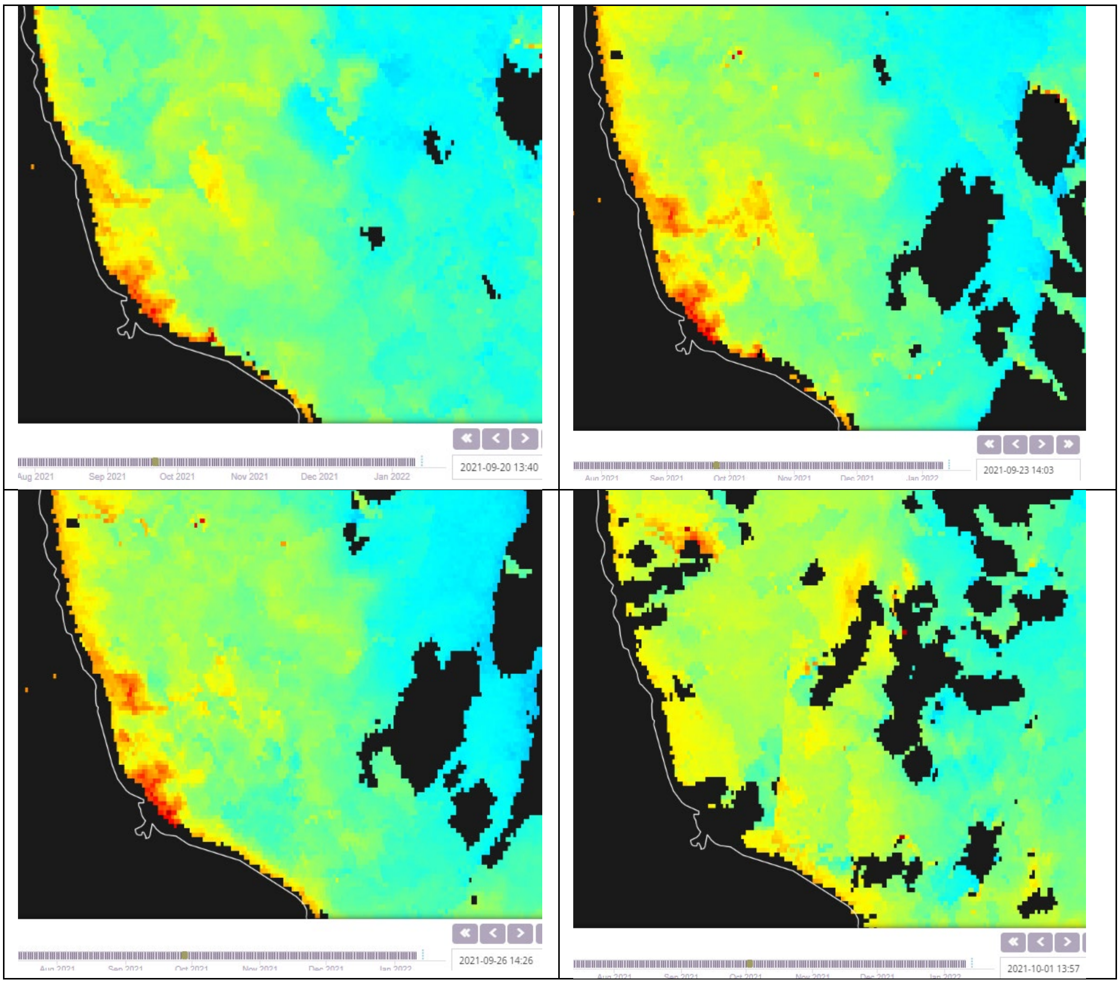

Figure 14 Satellite imagery of chlorophyll, (top left 20/9, top right, 23/9, bottom left 26/9 , bottom right 1/10).

Off Hartlepool, there does not appear to be evidence of very high levels (>10 mg/l) of elevated chlorophyll after the 26th September, but the moderate levels persisted along the coast until 1st October. This short duration is relatively unusual for a *Karenia Mikimotoi* bloom, which usually persist for a number of weeks, however, that is often at peak summer, rather than in the early Autumn. The size of the patch, off the Tees, is reasonably consistent with blooms seen in the Northern North Sea in recent years, the Scottish Association for Marine Science (SAMS) have developed tools to record and track its presence in Scottish waters www.habreports.org.

As shown in Figure 2, high temperatures existed until 26th September. These temperatures are likely to promote the growth of *Karenia*, as it benefits from warm stable environments (Van Houtte et al. (2008)). However, it should be stressed there are no direct measurements (e.g. insitu measurements) that indicate, that a *Karenia* bloom was present in the Tees region at the time.

One of the challenges for satellite derived chlorophyll is distinguishing from suspended sediment in the water column. There has been considerable success in recent years to develop algorithms to distinguish chlorophyll from suspended sediment, but in near coastal regions where the suspended sediment signal is strong, it can still be difficult to be confident that a signal is chlorophyll.

The daily composite image for Chlorophyll has an error map associated with it (Figure 14), which shows a high errors in the area(s) of interest.

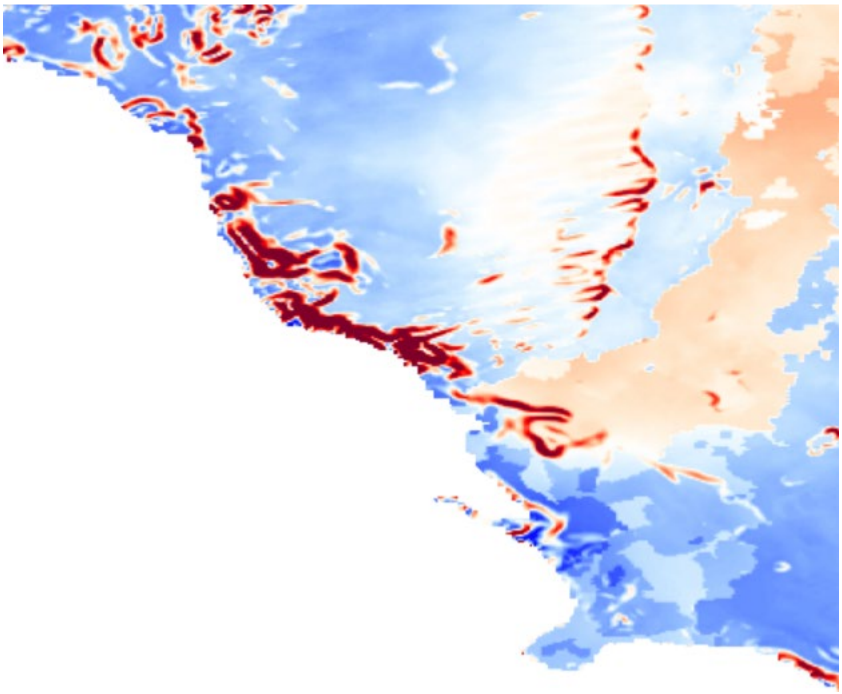

Figure 15 Error estimate for daily composite chlorophyll image 20/09/21. Note high error along the coastal strips. Provided by CMEMS.

While it is highly likely that there was an autumnal bloom in the region. Chlorophyll levels were more likely to be around the 5-6 ug/l (the Neodass values Figure 13) rather than the 40 ug/l, as indicated by the composite values (from Copernicus Figure 12). None the less, as we are wishing to consider all potential possible causes, low oxygen is considered next.

5.2. Can the decay of a bloom cause hypoxia

Boyle et al. (2008) have observed a Karenia Mikimotoi bloom causing oxygen problems on the west coast of Ireland, (Donegal Bay) which led to mortality of benthic species. There was also a calculation derived from a theoretical basis based on the Carbon, Nitrogen ratio, and theoretical decomposition of Karenia . Table 3 from their paper (Table 5 here) relates cell concentrations to BOD (Biological oxygen demand) and potential (i.e., theoretical) oxygen demand.

Table 5 Extracted from Boyle et al., 2016 Relationship between apparent oxygen utilisation and Karenia mikimitoi bloom size.

Table 3
Comparison between estimated potential oxygen utilisation (POU) based on a stoichiometric atomic ratio of −300 Oxygen: 106 Carbon: 16 Nitrogen (Anderson, 1995) and observed biochemical oxygen demand (BOD) at different *K. mikimitoi* cell concentration.

Bloom size (cells L^{-1})	Carbon content (mg L^{-1})	Carbon content (mole)	POU theoretical (mg L^{-1} O_2)	BOD observed (mg L^{-1} O_2)
10×10^3	0.003	2.74×10^{-7}	0.01	0.01
100×10^3	0.033	2.74×10^{-6}	0.12	0.14
500×10^3	0.165	1.37×10^{-5}	0.62	0.71
1000×10^3	0.329	2.74×10^{-5}	1.24	1.43
2500×10^3	0.823	6.85×10^{-5}	3.10	3.57
5000×10^3	1.645	1.37×10^{-4}	6.20	7.14
$10,000 \times 10^3$	3.290	2.74×10^{-4}	12.40	14.28

The main discussion point from Boyle valid to our case here is "*Based on the relationship derived here, cell densities would have to be in their millions of cells/L before having a significant impact on ambient oxygen conditions. Results indicate that DO concentrations in three areas (inner Dingle Bay, Kilkieran Bay and Donegal Bay) could have been seriously impacted by bloom collapse. Support for this is clearly evident in Donegal Bay, where the presence of hypoxic conditions of 2.2 mg/L O_2 in August is consistent with the estimated levels of POU of 4–5 mg/L O_2. Near bottom un-impacted background DO concentration in this area which stratifies in summer should be between 6.0 and 6.5 mg/L (O'Boyle and Nolan, 2010). In most other coastal areas, the level of estimated POU post bloom collapse was small at <1.0 mg/L (over 5-days). If near bottom background oxygen concentrations range from 6.0 to 6.5 mg/L O_2 in summer, a POU of <1.0 mg/L O_2 should leave a residual oxygen concentration of _5.0 mg/L O_2. This is unlikely to be harmful to most marine organisms since a concentration of 4.6 mg/L O_2 is considered sufficient to protect 90% of marine organisms (Vaquer-Sunyer and Duarte, 2008)*".

Typically, *Karenia* blooms exist in high biomass and form above the thermocline, most likely about 10 m thick. Van Houtte et al. (2008) reports observations and modelling of a *Karenia* bloom in the western channel and derived a relationship between observed chlorophyll and cell count.

In this case the peak satellite derived estimate is 40 ug/l, using the van Houtte relationship this gives: No cells = 53,000 + 31,000 * ug chl. i.e. for 40ug = 1300,000 cells per litre.

Using the Boyle (2016) relationship a bloom of this size would lead to an oxygen reduction of around 1.5 mg/l. It isn't known how thick the bloom off the North East coast was. The *Karenia* bloom while occurring above the thermocline, will die and sink to the sea bed. *Karenia*, emits toxins which discourages consumption, by zoo plankton, or small pelagics, so the entire bloom is likely to end up on the sea bed. Once dead, the decay of *Karenia* can occur rapidly with consumption within about 5 days. It is possible that that oxygen consumption could be higher than the 1.5 mg/l as the decay may be constrained to just near the bed.

Thus is it is likely that biological oxygen demand around 1.5 mg/l would have resulted in the specific areas beneath the high density regions, in reduced oxygen concentrations. From model outputs (CMEMS 7km resolution), which will reasonably well simulate oxygen concentrations due to temperature and some benthic consumption processes, but will not simulate HAB type blooms . Values were around 240- μ mol / m^3, equate to around 7.6 mg/l. - A reduction down to 5.6 mg/l is not likely to lead to wide spread oxygen problems, but the 1.5 mg/l reduction, is associated with each litre of *Karenia*, if the *Karenia* were 10 m thick, but consumption were occurring only in bottom 2m waters, then the reduction could be much greater. So it is possible that low oxygen would result beneath the patches of high chlorophyll.

Therefore, if this is a *Karenia* bloom (and there is no specific evidence that it is) it would be expected that deaths would result from 26th Sep + 5 days = 2nd October. These deaths would occur near shore but not actually at the shore line, so it would only be once these organisms are washed ashore that they would become visible. However, I would expect this affect to be relatively short lived, as the strong waves of the 6th October storm should mix the near shore shallow waters, and reoxyenate waters. Although this same storm would bring dead organisms to the shore.

Thus the sightings of early October would be consistent with this mechanism, but if deaths were occurring into November it would be difficult to see that they were associated with the same cause.

5.3. Conclusion

The direct cause of the mortalities upto October 5th are consistent with decay from a large bloom and evidence suggests an Algal bloom of some form was present in the region, although its' species and cell concentration is unknown. Due to the seasonal cooling and reduction in sunlight, it is unlikely that a HAB is the direct cause of mortalities beyond the 5th October.

6. References.

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