

Advice on the potential for increased sediment deposition on the Milford Haven maerl bed - Project report

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Crynodeb gweithredol

Mae'r unig wely maerl hysbys yn nyfroedd Cymru wedi'i leoli yn Aberdaugleddau yn Sir Benfro. Mae tystiolaeth i ddangos y bu'n bresennol yn Aberdaugleddau ers miloedd o flynyddoedd, ond mae gwaith monitro dros y 15-20 mlynedd diwethaf wedi nodi dirywiad sylweddol yn ehangder y maerl byw. Nid yw achos y dirywiad yn hysbys, ond mae'n hysbys bod maerl yn sensitif iawn i fygu o ganlyniad i ddyddodi gwaddod.

Comisiynwyd yr astudiaeth hon gan Cyfoeth Naturiol Cymru (CNC) i adolygu'r dystiolaeth sydd ar gael er mwyn deall a yw newidiadau i'r amgylchedd hydrodynamig a phrosesau cludo gwaddod yn cynyddu'r dyddodiad ar y gwely ac felly'n cyfrannu at y dirywiad. Roedd y tasgau astudio'n cynnwys y canlynol:

- Datblygu dealltwriaeth gysyniadol fer o hydrodynameg a chludiant gwaddod yn Aberdaugleddau, ac, yn benodol, y potensial ar gyfer dyddodi gwaddod yn ardal y gwely maerl yn seiliedig ar y data ac adroddiadau presennol;
- O'r adolygiad cychwynnol hwn a'r ddealltwriaeth gysyniadol, ystyried a allai newidiadau o faint digonol fod wedi digwydd nes newid patrymau dyddodi gwaddod yn ardal y gwely maerl;
- Os felly, ystyried a ellir defnyddio offerynnau modelu rhifiadol yn rhesymol i graffu ymhellach ar y newidiadau, ac ystyried yr achos a'r effaith.

Mae'r adroddiad hwn yn dogfennu'r ddealltwriaeth gysyniadol a gafwyd o ganlyniad i adolygu'r data hydrodynamig a'r data ac adroddiadau am waddod sydd ar gael ar gyfer Aberdaugleddau. Mae hefyd yn darparu crynodeb o'r dirywiad a fonitwyd yn y maerl ynghyd ag adolygiad byr o'r ffactorau sy'n effeithio ar iechyd maerl.

Mae'r data sydd ar gael yn darparu rhywfaint o dystiolaeth o newidiadau bach i'r hydrodynameg dros gyfnod yr asesiad. Fodd bynnag, ystyrir ei bod yn annhebygol y byddai newidiadau o'r fath yn ddigon i gynyddu'r siltio ar y gwelyau maerl yn sylweddol. Nid yw'r data sydd ar gael yn profi bod tystiolaeth o dueddiadau rhanbarthol, ehangach mewn perthynas â llwythi gwaddod crog .

Er nad oes tystiolaeth o newid yn y drefn hydrodynamig neu waddodol y gellid ei chysylltu â'r dirywiad yn y maerl, gallai digwyddiadau cyfnodol fod wedi arwain at fygu'r maerl. Mae cyfres o ddamcaniaethau wedi'u cyflwyno i dynnu sylw at achosion posibl. Mae'r rhain yn amrywio o newidiadau lleol sy'n deillio o waith morol, symudiadau cychod a charthu, i achosion posibl y tu hwnt i gwmpas yr astudiaeth hon, megis newidiadau i ansawdd dŵr, afiechyd ymhlith y maerl, neu ddylanwad rhywogaethau estron goresgynnol, ac, yn benodol, brenigen yr wystrys.

Trafodwyd y canfyddiadau mewn gweithdy mewnol (ABPmer) a oedd yn dwyn ynghyd arbenigwyr mewn bioleg forol a phrosesau arfordirol, ac mewn ail weithdy gydag arbenigwyr o CNC ar 1 Mawrth 2021. Cytunwyd bod angen ymchwilio ymhellach i'r berthynas bosibl rhwng cyfundrefn y broses gorfforol a dirywiad yn y maerl.

Amlinellwyd argymhellion ar gyfer monitro ac ymchwilio yn y dyfodol i helpu i lywio ystyriaeth bellach o'r achosion posibl. Mae'r argymhellion hyn yn canolbwyntio ar gasglu mwy o wybodaeth, yn ogystal â chynnal astudiaethau pellach a allai helpu i gadarnhau a yw 'llwybr' neu weithgaredd penodol yn gyfrifol am y dirywiad a welwyd yn y maerl ai peidio. Mae monitro'r gwelyau maerl eu hunain yn barhaus yn hanfodol er mwyn darparu set ddata tymor hwy ar newidiadau yn nosbarthiad y boblogaeth maerl fyw.

Executive summary

The only known maerl bed in Welsh waters is situated within Milford Haven in Pembrokeshire. There is evidence to show that it has been present within the Haven for thousands of years' but monitoring over the last 15-20 years has indicated a significant decline in extent of live maerl. The cause of the decline is unknown, but it is known that maerl is highly sensitive to smothering through sediment deposition.

This study was commissioned by Natural Resources Wales (NRW) to review available evidence to understand if changes to the hydrodynamic environment and sediment transport processes are increasing deposition at the bed and therefore contributing to the decline. The study tasks were to:

- Develop a brief conceptual understanding of the hydrodynamics and sediment transport of Milford Haven using existing data and reports, and in particular the potential for sediment deposition in the area of the maerl bed;
- From this initial review and conceptual understanding, consider whether changes of sufficient magnitude may have occurred to alter sediment deposition patterns in the area of the maerl bed; and
- If so, consider whether numerical modelling tools can be reasonably applied to scrutinise the changes further and consider cause and effect.

This report documents the conceptual understanding gained from a review of available hydrodynamic and sediment data and reports of Milford Haven. It also provides a summary of the monitored decline in the maerl (between 2005 and 2016), along with a brief review of factors that affect the health of maerl.

The available data provides some evidence of small changes to hydrodynamics over the period of assessment. However, it is considered unlikely that such changes would be enough to significantly increase siltation on the maerl beds. Evidence of wider, regional trends in suspended sediment loads is not proven with the available data.

Although there is no evidence of a change in the hydrodynamic or sedimentary regime which could be linked to maerl decline, episodic events could have resulted in smothering of the maerl. A series of hypotheses have been put forward to highlight potential causes. These range from local changes resulting from marine works, vessel movements and dredging, to possible causes outside of the scope of this study, such as changes to water quality, disease in the maerl, or the influence of Invasive Non Native Species (INNS), in particular, the Slipper Limpet (*Crepidula fornicata*).

The findings were discussed at an internal (ABPmer) workshop bringing together specialists in marine biology and coastal processes, and a second workshop with experts from NRW on the 01 March 2021. It was agreed that further investigation of the potential relationship between the physical process regime and maerl decline is required.

Recommendations for future monitoring and investigation have been outlined to help inform further consideration of the potential causes. These recommendations focus on collecting more information, alongside further studies, which may help to confirm if a particular 'pathway' (or activity) is responsible for the observed decline in the maerl. Continued monitoring of the maerl beds themselves is critical to provide a longer-term dataset on changes in distribution of the live maerl population.

1 Introduction

The only known maerl bed in Welsh waters is situated within Milford Haven in Pembrokeshire (Figure 1). There is evidence that it has been present within the Haven for thousands of years' but monitoring over the last 15-20 years has indicated a significant decline in extent of live maerl. The cause of the decline is unknown, but it is known that maerl is highly sensitive to smothering through sediment deposition (Wilson *et al.*, 2004).

ABPmer was commissioned by NRW to review available evidence to understand if changes to the hydrodynamic environment and sediment transport processes in the Haven are increasing deposition at the bed and therefore contributing to the decline.

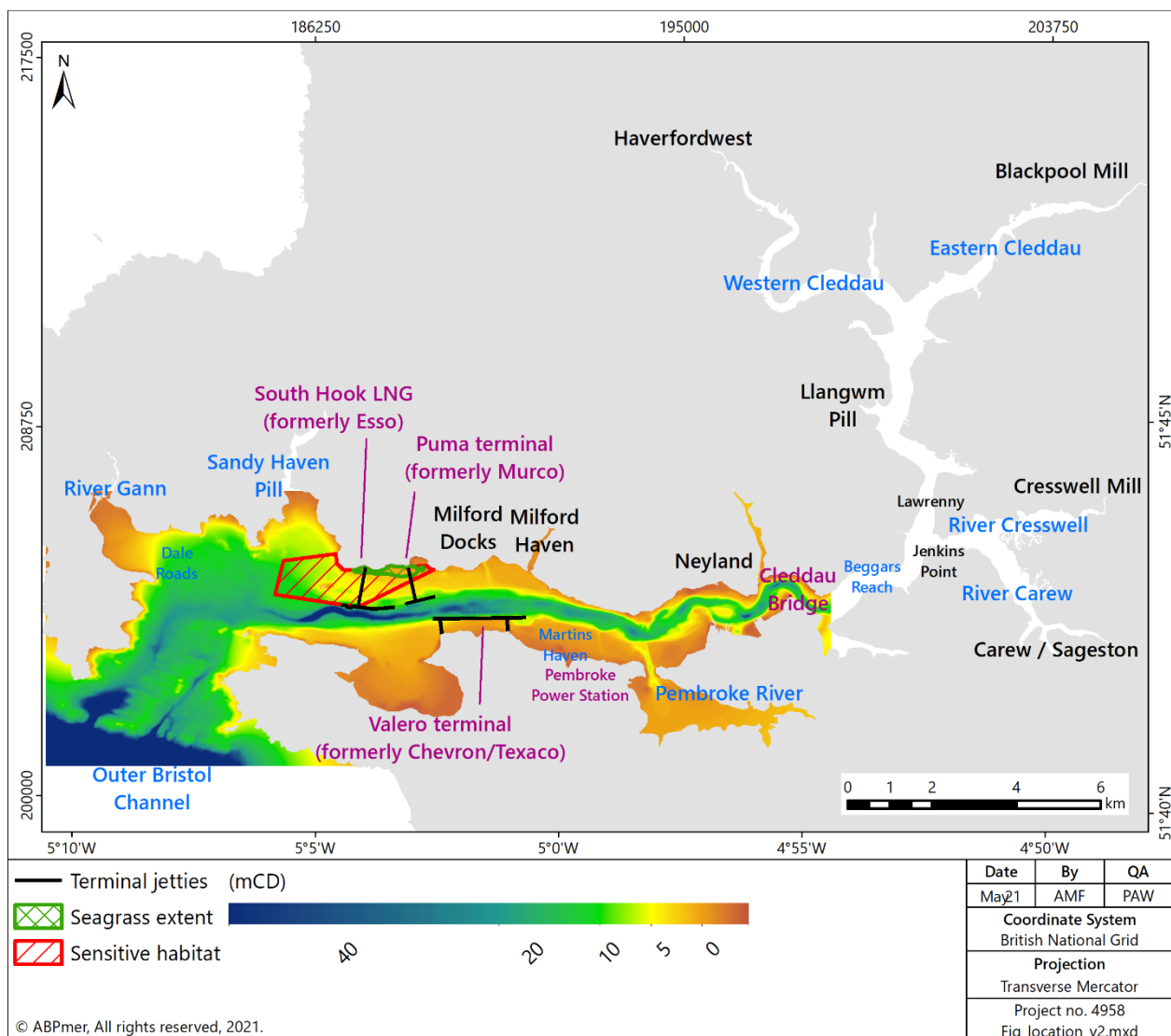


Figure 1. Approximate extent of sensitive habitat (around the maerl beds) within Milford Haven.

The scope of this review focuses on the assessment of the hydrodynamics and suspended sediment characteristics within the Haven. It specifically examines whether the potential for sediment deposition may have changed over the last 20 years or so due to changes in suspended sediment load (e.g. from natural causes, dredge and disposal operations, vessel movement), seabed roughness (e.g. due to increased presence of *Crepidula* in the

area) or changes in hydrodynamics (e.g. from marine infrastructure); each of which could lead to increased potential for deposition and or change to the hydrodynamic regime.

In particular, the maerl beds are in proximity to the Liquid Natural Gas (LNG) terminals and there may be an impact pathway between any dredging activities (noting the dredging strategy for the Haven) and/or disturbance of sediment by vessels during berthing manoeuvres. The local hydrodynamic regime may also have been changed due to jetty and other marine infrastructure development. This study reviews the available evidence to understand if natural and anthropogenic changes to the hydrodynamic environment and sediment transport processes could be increasing deposition at the bed and, therefore, potentially contributing to the decline.

The aim of this Phase 1 study is to:

- Develop a brief conceptual understanding of the hydrodynamics and sediment transport of Milford Haven based on existing data and reports and, in particular, the potential for sediment deposition in the area of the maerl bed;
- Consider whether changes of sufficient magnitude may have occurred to alter sediment deposition patterns in the area of the maerl bed;
- Assess whether modelling tools could reasonably be applied (in future study phases) to scrutinise the changes further and consider cause and effect; and
- Draft a scope for the modelling (if proposed), including advice on suitability of existing data or any additional data requirements.

To assist the interpretation of the available information the findings of the conceptual understanding were discussed at a an internal ABPmer workshop bringing together specialists in marine biology and coastal processes, and a second workshop with experts from NRW on the 01 March 2021. The workshops discussed the conceptual understanding, key conclusions and data gaps along with agreement on the next steps of investigation.

In providing these items, the remainder of this report is structured as follows:

Section 2. Data review;

Section 3. Conceptual Understanding;

Section 4. Implications for maerl beds; and

Section 5. Conclusions and Recommendations for further study phases.

2 Review of available data

To inform this study and gain a conceptual understanding of the processes influencing the Milford Haven, data has been reviewed from multiple sources as identified in the following sections.

Existing in-house (ABPmer) datasets were also reviewed and provided where appropriate. These include metocean data from ABPmer's SEASTATES hindcast wave and water level models, along with past environmental assessments/monitoring programmes that are deemed relevant to this work.

2.1 Data held by NRW

NRW reviewed its libraries and data archives and sourced a large number of priority datasets. These are generally associated with existing infrastructure and historical developments along with monitoring data within the estuary. These include:

- Particle Size Analysis (PSA) of sediment throughout the Haven;
- Suspended sediment concentration (SSC) monitoring at Pembroke power station;
- Port of Milford Haven (PoMH) / Milford Haven Port Authority (MHPA) dredging strategy documents (including historical dredging);
- Past and present marine licences for dredging activity;
- Hydrodynamic current studies;
- Academic literature on maerl;
- Macrobenthos reviews;
- Sediment contaminations studies;
- Sediment profile imaging;
- Single-beam and multi-beam bathymetric datasets; and
- Diving and Drop-down Video (DDV) survey reports throughout the existing maerl bed.

The following maps, reports and datasets were provided by the Milford Haven Waterway Environmental Surveillance Group:

- Germano and Associates, Inc (2013) Sediment-Profile Imaging Survey of Milford Haven Estuary, Wales, UK - May 2012, Report to MHWESG - Interactive pdf map showing sampling stations and SPI images from each station; and
- Little, 2009. Sediments contaminants and transport review.

2.2 Open-source datasets

A review of freely available datasets was also conducted. These included:

- National Tide and Sea Level Facility (NTSLF) historic records of water level (including surge component) throughout the estuary from 1967 to 2021.
- UK Hydrographic Office (UKHO) Inspire portal. Multiple seabed bathymetric datasets (both singlebeam and multibeam). Tidal diamonds from nautical charts have also been obtained.

- National River Flow Archive (NRFA) historic records of fluvial and riverine inputs to Milford Haven
- Joint Nature Conservation Committee (JNCC) data forms of designations within Milford Haven
- Department for Environment Food and Rural Affairs (Defra) Records from the dredge disposal database.
- Port of Milford Haven (PoMH) / Milford Haven Port Authority (MHPA) strategies of recreational activity use within Milford Haven.

Whilst numerous data sources have been accessed to inform this study, it is recognised that the list is not exhaustive, and that there are potentially additional sources of data that could be accessed for future work.

3 Conceptual understanding

The following sections review the available data sources (Section 2), to provide a brief conceptual understanding of the general setting, local hydrodynamic and sediment regimes and a summary of historic development within the Milford Haven study area.

3.1 Regional setting

Milford Haven is in Pembrokeshire, on the southwest Wales coast. The mouth of the waterway opens out into the outer approaches to the Bristol Channel, whilst up-estuary, the rivers Cresswell, Carew and Cleddau all feed into the Haven. These rivers are tidal for significant distances, with the tidal influence extending to Cresswell Mill (River Cresswell); Carew/Sageston (River Carew); Haverfordwest (Western Cleddau); and Blackpool Mill (Eastern Cleddau), see Figure 1, Figure 2, and Table 1.

Table 1: JNCC Classification for Milford Haven estuary (source www.estuaryguide.net)

JNCC name	Milford Haven
JNCC ID	15
JNCC grid reference	SM945035
JNCC geomorphological type	Ria
ERP2 geomorphological type	Ria
Tidal type	macrotidal
Shoreline length (km)	170.7
Channel length (km)	35.4
Core area (ha)	5447.5
Intertidal area (ha)	1710
Tidal range (m)	6.3

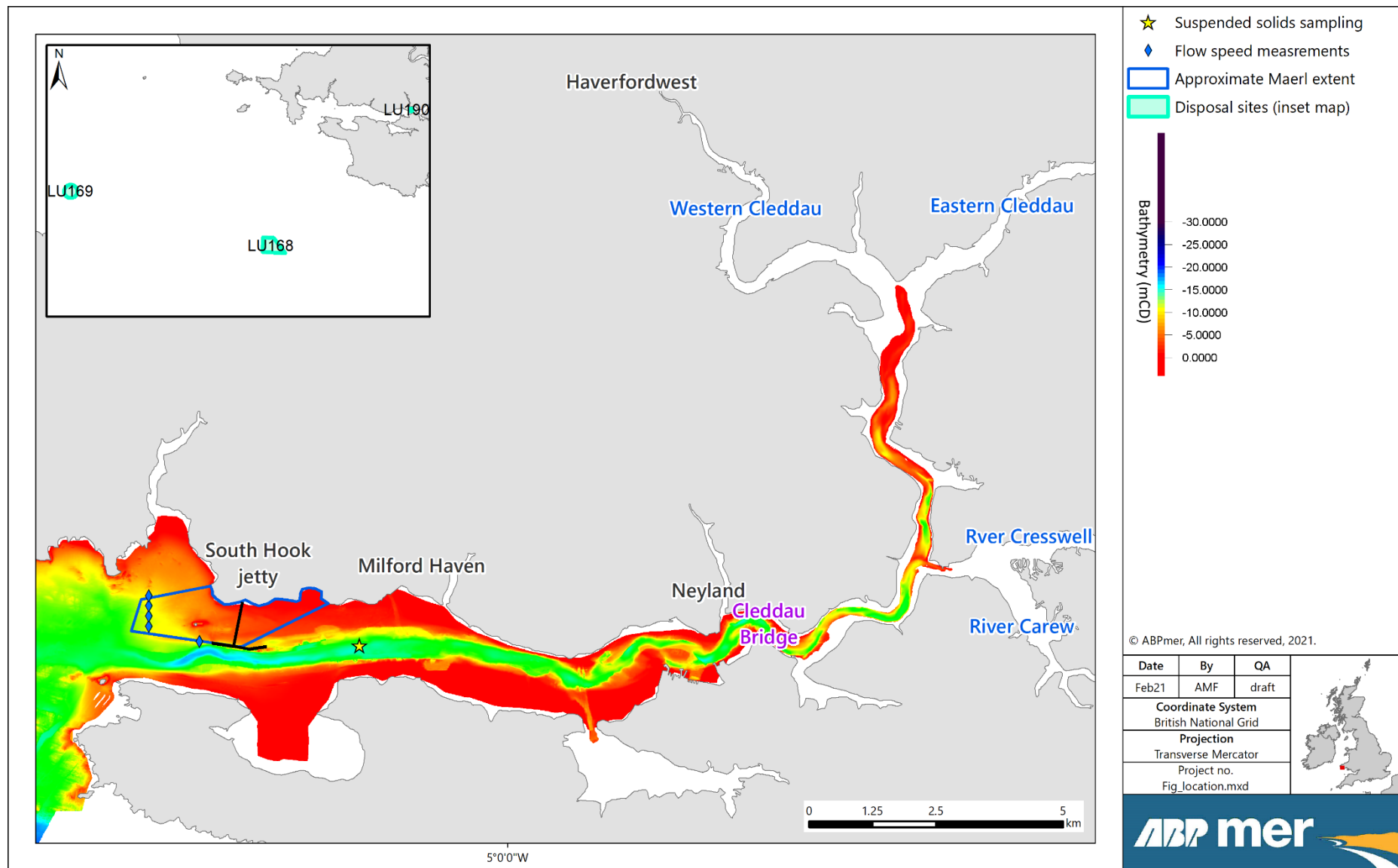


Figure 2. Location of river inputs, sampling locations and disposal sites within Milford Haven region.

The estuary is classified by JNCC as a Ria-type estuary (www.estuaryguide.net), formed from a drowned river valley, which was flooded at the end of the last Ice Age. Table 1 shows the JNCC classification information, along with some additional descriptive characteristics of Milford Haven.

Several studies have described the Milford Haven estuary, with some breaking down the estuary into regions based on general tidal characteristics, flow speed, salinity variability, sediment distribution and turbidity (e.g. Nash and Collins. 1982).

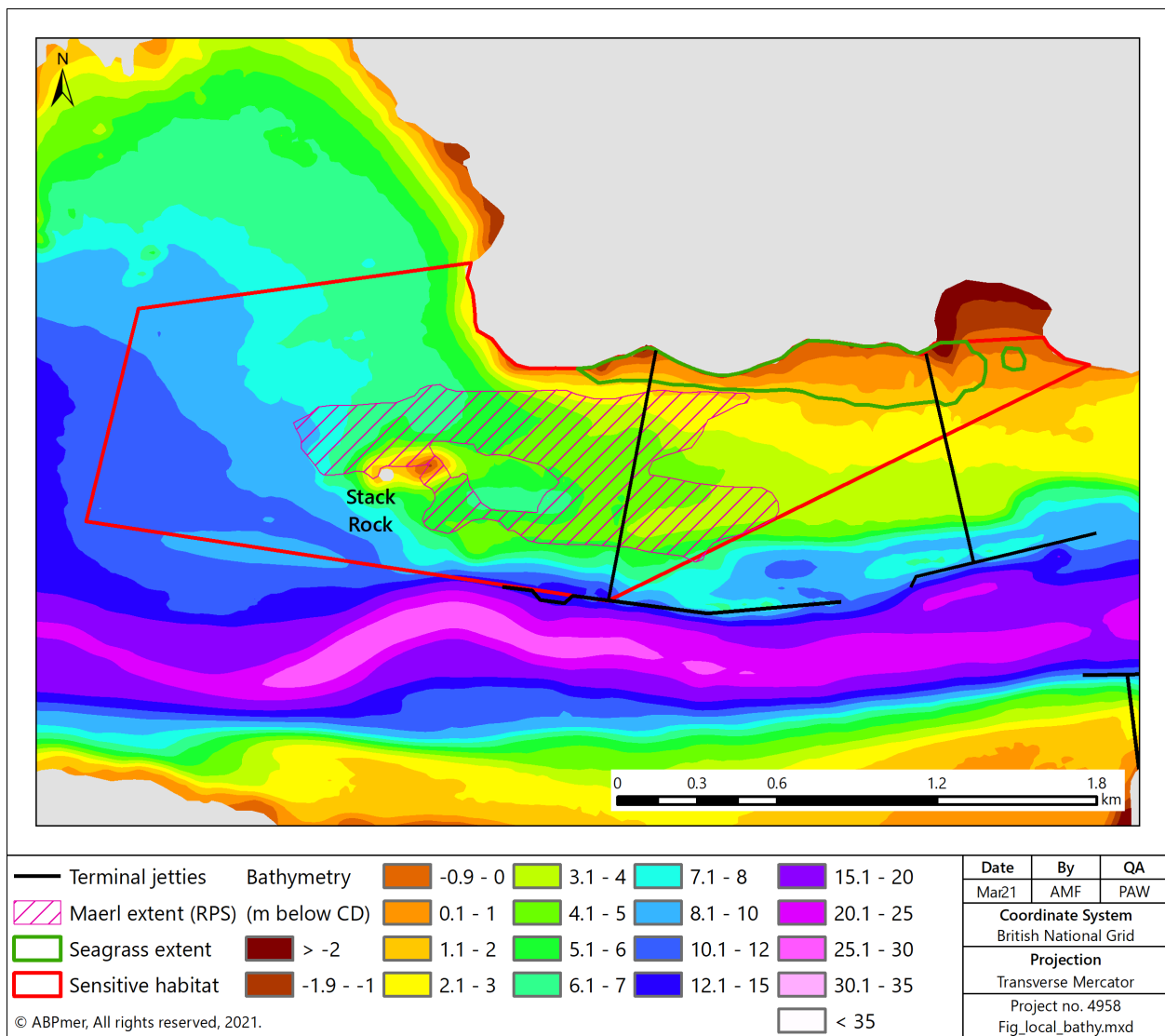
Within this description, the outer estuary region extends up-estuary from the mouth to Neyland (just to the west of the Cleddau Bridge). In this region, maximum currents occur at mid flood and mid ebb, characteristic of a standing tidal wave. Salinity remains high across the tidal cycle and, consequently, has a low range (typically between 34.0 and 34.4 ppt (Lee. 1960)). Current velocities are generally low, with maximum velocities at the mouth of 0.57 m/s and 0.27 m/s (on flood and ebb tides, respectively), increasing in magnitude with distance up-estuary. There is generally less than 50% mud in the deposits of the main channel, although mud flats associated with the Pembroke river are observed (Nash and Collins, 1982).

3.1.1 Bathymetry

The entrance to Milford Haven is divided into two channels, with minimum depths of around 17 m below Admiralty Chart Datum (CD) to the west and -15 mCD, to the east (Figure 1); the channels are separated by a series of rocks (Figure 1). Intertidal areas on either side of the entrance are generally represented by narrow rocky platforms with a covering of sand.

From Dale Roads to opposite Martins Haven (Figure 1), a central deep channel (in excess of -20 mCD) exists. However, at one of the narrowest points in this section of the estuary, the wide expanse of intertidal area at Martins Haven results in subtidal channel depths in excess of -5 mCD occurring for less than 50% of the cross-sectional width. In the section from Martins Haven to the Cleddau Bridge (Figure 1), the bed of the main channel undulates alternately between deep pockets in excess of -20 mCD and shallower areas with navigable depths of around -10 to -12 mCD. The shallowest depth in this section of the main channel, for navigational purposes, is shown on the Admiralty Chart as -9.1 mCD, located on Neyland Spit, between Neyland Point and Pembroke Dock (around Neyland, Figure 1).

Above the Cleddau Bridge, depths exceeding -10 mCD exist continuously up to the confluence with the Carew and Cresswell Rivers, where a bar in the river has formed at a level of -2.8 mCD. Upstream depths in the main channel vary from -4 to -15 mCD until rapidly decreasing to consistently less than -3 mCD above Llangwm Pill.



Source: Combined multibeam and single beam bathymetric surveys from 2009 and 2010

Figure 3. Regional bathymetry of Milford Haven and local to the existing maerl beds.

Within and around the area of the maerl beds, around the South Hook LNG jetty (western jetty structure in Figure 3), bed levels range from -10 mCD at the western corner, shallowing to around -7 mCD just inside the South Hook Jetty. Depths around Stack Rock are approximately -5 to -6 mCD, whilst depths further to the east shallow further to between 2 and -4 mCD.

3.1.2 Geology

The geology of Milford Haven and the adjacent offshore area can be simplified into two subdivisions comprising an older series of rocks of between 250 and 400 million years old (Pre-Mesozoic) and younger modern sediments either related to glacial activity or contemporaneous processes. The detailed geological listing of the area is given in Hancock (1983) and summarised in Hobbs and Morgan (1992).

Pre-Mesozoic sequences

The area surrounding Milford Haven is generally composed of Devonian red sandstones and Carboniferous limestones, grits and coal measures. These rocks are highly folded with their fold axes orientated NW-SE. The rocks were submerged below sea level sometime between the late Miocene and Pliocene periods (25 to 2 million years ago), during which they were planed flat, irrespective of their highly folded nature, by wave action.

Modern sediments and processes

On this planed surface, which is recognised over all of Pembrokeshire, the pre-glacial river drainage pattern was superimposed, with the River Cleddau draining through Milford Haven. However, it was with the drainage of glacial lakes (Teifi and Nevern) centred on Cardigan and Newport during the most recent glaciations that led to the over deepening of the Cleddau river channel through Milford Sound. The drainage from these lakes could not flow into the Irish Sea as they were held up by ice sheets extending across this sea. The subsequent rise in sea levels as the glaciers began to melt 12,000 years ago ultimately led to the drowning of Milford Haven to form a ria. The drowning and over-deepened nature of this Sound has lent itself to the development of the UK's only natural deep water sheltered anchorage.

3.2 Hydrodynamic regime

The following sections describe the characteristics of the local hydrodynamic regime, including tides, rivers, waves and meteorological storm surges.

3.2.1 Tidal levels

Standard tidal levels for the study area were taken from the UKHO Admiralty tide tables, using the Standard Port of Milford Haven (around 2-3 km to the east of the maerl beds). The tidal elevations are provided in Table 1.

As with the wider Bristol Channel region, the tidal ranges within Milford Haven are large (termed macro-tidal), with mean spring tide range of 6.3 m and a mean neap range of 2.7 m. Meteorological surge impacts could lead to larger tidal ranges, associated with storm events and extremes of barometric pressure (see below).

The large tidal range means that water movements through the wider estuary are significant. The length of tidal excursion varies throughout the estuary and is estimated to be approximately twice as great for springs as for neaps. Williams and Jolly (1975) have suggested an average value of 8 to 10 km on spring tides and 4 to 5 km on neap tides.

Table 2. Standard tidal levels for Milford Haven.

Tidal level	Elevation (mCD)	Elevation (mODN)	Range (m)
Highest Astronomical Tide (HAT)	7.8	4.09	n/a
Mean High Water Spring (MHWS)	7.0	3.29	n/a
Mean High Water Neap (MHWN)	5.2	1.49	n/a
Mean Sea Level (MSL)	3.85	0.14	n/a
Mean Low Water Neap (MLWN)	2.5	-1.21	n/a
Mean Low Water Spring (MLWS)	0.7	-3.01	n/a
Lowest Astronomical Tide (LAT)	0.0	-3.71	n/a
Astronomic range (HAT-LAT)	n/a	n/a	7.8
Mean spring range (MHWS-MLWS)	n/a	n/a	6.3
Mean neap range (MHWN-MLWN)	n/a	n/a	2.7

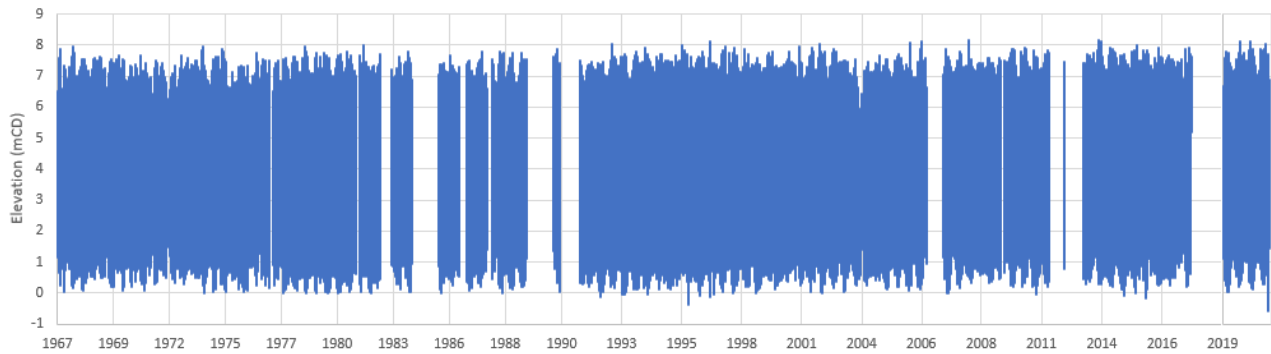
Source: UKHO Admiralty Tide Tables, 2020

Surge influence

Measured water level data from the National Tide and Sea Level Facility (NTSLF) tide gauge at Milford Haven were considered to assess the combined tide and meteorological surge influence. Figure 4 shows the available measured water level data between 1967 and 2021. Occurrences of low water levels below the LAT elevation and high-water levels above that of HAT are evident throughout the record.

The peak measured water level was 8.18 mCD, occurring on 10 March 2008 at 07:45. This coincided with the time of HW on a large spring tide, combined with a moderate surge tide of 0.77 m. The largest five water level events are provided in Table 3, giving a breakdown of the astronomic tide and meteorological surge component for each.

Each of the top five measured water levels result from a combination of HW on a large spring tide with the additional influence of a moderate meteorological surge. Larger surge events, coincident with lower astronomic water levels, do not generally appear to result in the largest measured water levels, suggesting that the astronomic tidal component dominates these events within the Milford Haven waterway.



Source: NTSLF

Figure 4. Milford Haven measured water levels (1967 to 2021).

Table 3. Top five peak measured water levels (1967 to 2021).

Date and Time	Measured Water Level (mCD)	Predicted Astronomic Tide (mCD)	Meteorological Surge Component (m)
10 March 2008 07:45	8.18	7.41	0.77
3 February 2014 08:30	8.14	7.56	0.58
2 March 2014 06:45	8.13	7.67	0.46
11 March 2020 19:30	8.13	7.53	0.60
30 September 2019 19:15	8.13	7.79	0.34

Source: NTSLF and UK Admiralty tide tables (2020)

Changes in water levels

Sea-level rise

Small magnitude changes in water levels over the period of interest will have resulted from sea level rise due to climate change. Using the marine projections from the UK Climate Projections (UKCP,2018), the water levels at the entrance to Milford Haven are expected to have increased by a matter of millimetres (RCP8.5, 50 percentile) between 2004 (the original maerl survey) and the repeat survey in 2016.

In isolation, it is considered unlikely that this slight change will have impacted the health of the maerl beds in Milford Haven.

Lunar Nodal cycle

Longer-term trends in tidal levels can be attributed to changes in the orbital path of the moon, termed the lunar nodal cycle. This cycle, with a period of 18.6 years, results in a slight change to the tidal range over this period. With regards the time periods of interest to this study, 2004 (when the original maerl surveys were conducted to inform the South Hook LNG jetty upgrade works) was close to the low-point in the lunar nodal cycle. In contrast, by the time of the repeat surveys in 2016, the cycle would have been close to the high-point. It is estimated that the tidal range during the 2016 survey would have been around 0.1 to 0.2 m larger than that experienced during the original survey, meaning the maerl beds will have been situated in slightly deeper water during the second survey period.

In isolation, it is considered unlikely that this slight change will have impacted the health of the maerl beds in Milford Haven.

Potential impact pathway

When taken in isolation, the changes to water levels over the period between maerl surveys is considered unlikely to have impacted the health of the maerl beds, it could be hypothesised that even small increases in water levels may have exposed the edges of intertidal mudflats to greater wave and tidal exposure, potentially increasing erosion and, consequently, sediment loads in the water column. The available evidence for sediment concentrations does not support this hypothesis (see Section 3.3.3), although this could be due to the approach to the sampling campaign (notably sample locations up-estuary of maerl beds and the intermittent nature of sample collection).

3.2.2 Tidal flows

Standard tidal flows for the study area were taken from the UKHO Admiralty tide tables, using the two tidal diamond locations within the main channel fronting the maerl beds. The mean tidal spring and neap flows are provided in

Table 4. Correspondence with UKHO confirms that this charted data is the same as on charts dated before 2004 and they have not been updated since.

Table 4. Mean tidal flows for Milford Haven in the vicinity of the maerl beds derived from tidal diamond A = SN050G (51°41.83'N 5°05.56'W) and tidal diamond B = SN050E (51°41.83'N 5°04.36'W).

Tidal state (hours)	Flow direction (°N) for A	Flow direction (°N) for B	Mean spring rate (m/s) for A	Mean spring rate (m/s) for B	Mean neap rate (m/s) for A	Mean neap rate (m/s) for B
-6	003	310	0.15	0.21	0.10	0.10
-5	060	073	0.31	0.21	0.15	0.10
-4	086	085	0.62	0.51	0.31	0.26
-3	088	089	0.87	0.77	0.41	0.36
-2	087	097	0.77	0.67	0.36	0.31
-1	084	098	0.46	0.57	0.21	0.26
HW	017	083	0.05	0.15	0.00	0.10
+1	266	294	0.21	0.21	0.10	0.10
+2	260	272	0.62	0.51	0.26	0.26
+3	260	263	0.87	0.57	0.41	0.26
+4	261	257	0.72	0.67	0.36	0.31
+5	265	263	0.51	0.62	0.26	0.31
+6	317	278	0.31	0.36	0.15	0.15

Source: UKHO Admiralty Tide Tables, 2020

Mean tidal flows tend to peak around 3 hours either side of HW, with flows of up to 0.87 m/s on a spring tide. Neap flows tend to be around half of those on the spring tides. These tidal diamond values refer to the astronomic tidal flows only. Meteorological surge impacts could lead to larger flow speeds, associated with storm events.

Flood and ebb current speed, on both spring and neap tides, increase with distance up-estuary from the mouth. Flows increase to a maximum, in the central estuary, off Jenkins Point and Beggars Reach, up-estuary of the Cleddau Bridge (Williams and Jolly, 1975), before decreasing with further distance upstream. Whilst the absolute flow speeds may have altered slightly since this historic study, the derived general patterns of relative flows will still be applicable. Measurements of flow speeds, undertaken in 1999, are provided below.

Flow speeds were measured in the vicinity of the maerl bed in 1999 using a series of current meters (Milford Haven Current Study, 1999) One deployment was located to the north of the main channel, approximately 900 m west of Stack Rock, and just to the west of the maerl bed extent. Results from this meter indicated peak spring flow speeds of 0.57 to 0.63 m/s, with equivalent values on the neap tide of 0.32 to 0.38 m/s. A second current meter located along the northern flank of the main channel, around 300 m to the south of Stack Rock, and to the south of the maerl bed extent, showed peak spring flows of up to 0.8 m/s, with speeds of up to 0.51 m/s on neap tides (Milford Haven Current Study, 1999).

Changes in tidal flows

As noted above, over the period between maerl surveys, sea level rise due to a combination of climate change and the relative position within the lunar nodal cycle, will have slightly increased the overall tidal prism of the Milford Haven estuary, although no measured data could be sourced to confirm this. This increased exchange volume will have also slightly increased flow speeds, particularly within the main channel, as this is where the majority of the tidal volume is exchanged. However, the small magnitude of the various changes estimated over the period suggests any associated changes to flow speeds would also have been very small. Maerl is known to be able to withstand changes in hydrodynamic conditions so it is considered unlikely that small increases in flow speeds over the maerl beds will have had a direct detrimental impact on their health over the period.

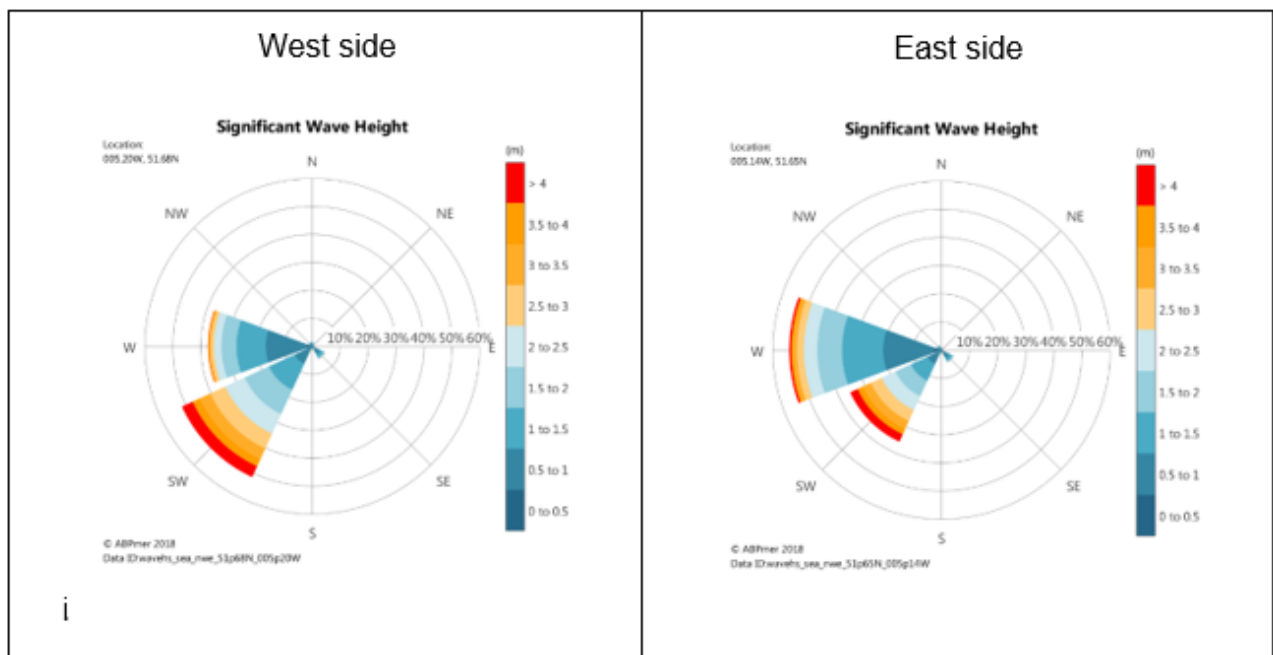
Potential impact pathway

Whilst small changes to flow speeds over the period between maerl surveys is considered unlikely to have directly impacted the health of the maerl beds, it could be hypothesised that even small increases in flow speeds may have resulted in increased erosion of the estuary bed material and, consequently, leading to increased sediment loads in the water column. It is noted, however, that the potential for increased suspended sediment concentrations and, subsequently, increased potential for settling of fine material on top of the maerl beds during slack water periods, is likely to be, at least partially offset by increased sweeping of the bed by faster flows over other parts of the tidal cycle.

The available evidence, however, does not support the hypothesis that faster flows have led to increased sediment concentrations (see Section 3.3.3), although this could be due to the approach to the sampling campaign (notably sample locations up-estuary of maerl beds and the intermittent nature of sample collection).

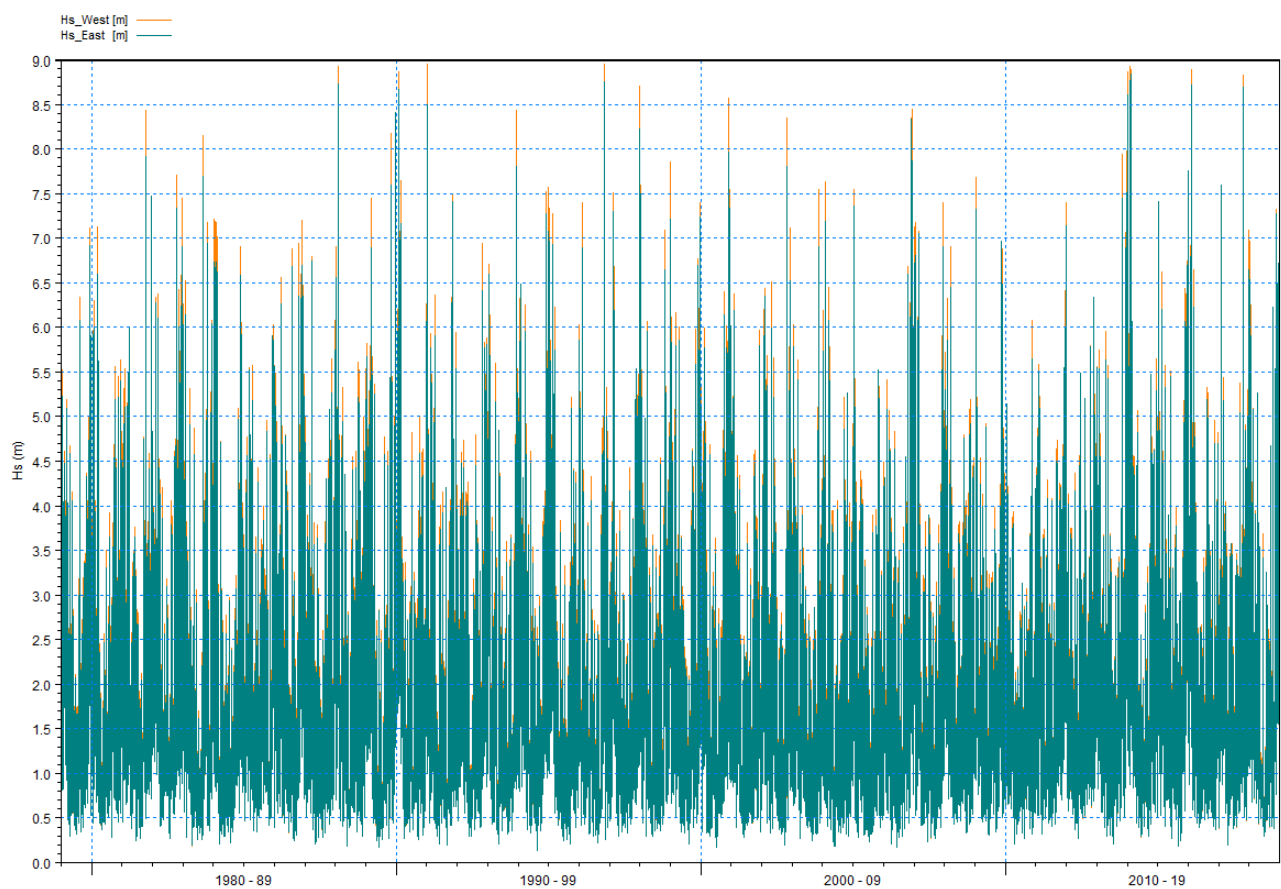
3.2.3 Waves

Wave conditions at the entrance to Milford Haven were assessed using the ABPmer SEASTATES wave hindcast model. The simulation period covers 40 years between 1979 and 2018 and includes wave growth over the full extent of the North Atlantic. The southwest coast of the UK, including Pembrokeshire, is exposed to extremely long fetch lengths across the Atlantic, resulting in the potential exposure of the coastline to large wind and swell waves. Wave roses from the SEASTATES hindcast model are provided in Figure 5, for the western and eastern sides of the Milford Haven entrance.



Source: ABPmer SEASTATES wave hindcast

Figure 5. Wave roses for the exposed coastline at the entrance to Milford Haven.



Source: ABPmer SEASTATES wave hindcast

Figure 6. Timeseries of Hs at the entrance to Milford Haven.

The roses reveal the largest waves approach from the southwest direction (the direction with the greatest fetch length). Relative sheltering effects from the southern tip of Ireland and the western tip of Cornwall result in slight changes to the prevailing wave directions at the entrance to the Milford Haven. To the western side, the influence of Ireland means the prevailing wave direction is from the southwest (the same direction of the largest waves); whilst on the eastern side, the relative sheltering influence from the Penzance peninsula (and an accompanied reduction in sheltering from Ireland) lead to a prevailing wave approach from a slightly more westerly direction.

A timeseries of wave heights, predicted over the 40-year SEASTATES hindcast period (Figure 6), indicates wave heights tended to be slightly higher to the western side of the entrance, with a peak Hs event of 8.95 m predicted to occur twice within the simulation period (January 1991 and October 1996). Events with peak Hs greater than 8.5 m were predicted to occur around 10 times across the hindcast period, with four of these occasions having been predicted since (and including) the winter storms of 2013-14 (Figure 6).

Within Milford Haven, the orientation of the headlands at the entrance combined with the local bathymetry along the coastline and the subsequent turning of the estuary to a roughly E-W orientation, suggests the majority of the Haven will be sheltered from the larger Atlantic swell at the entrance. The region of the maerl beds around Stack Rock is exposed to long fetch lengths through the entrance, but only over a very narrow approach direction, approximately west-southwest. The top five largest wave events predicted over the model period, approached the Milford Haven entrance from a southwest to west-southwest direction (230°N to 240°N).

Changes in wave climate

Whilst the timeseries plot in Figure 6 suggests there may be a small increasing trend in storminess over the 40-year hindcast period, changes over the time period of interest to this study are less evident. Whilst there have been a number of large storm events since the 2013/14 winter storms, it is also the case that the largest wave events at the entrance to the Haven pre-dated the original 2004 maerl survey. Without associated survey information on the historic health of the maerl beds, it is not possible to conclude that large storm events have an impact. It is possible that storms could have temporarily disturbed greater quantities of sediment that could have buried some areas of the maerl, causing death before being subsequently removed again by tidal flows and 'more normal' wave activity but there is no evidence to confirm this.

Potential impact pathway

As with the suggested impacts for currents and water level above, it could be hypothesised that larger storm waves potentially result in increased erosion and, consequently, higher suspended load, which could then result in an indirect impact on the health of the maerl. However, as noted above, the available evidence does not support this hypothesis (see Section 3.3.3), although this could be due to the approach to the sampling campaign (notably sample locations up-estuary of maerl beds and the intermittent nature of sample collection).

3.2.4 River flows

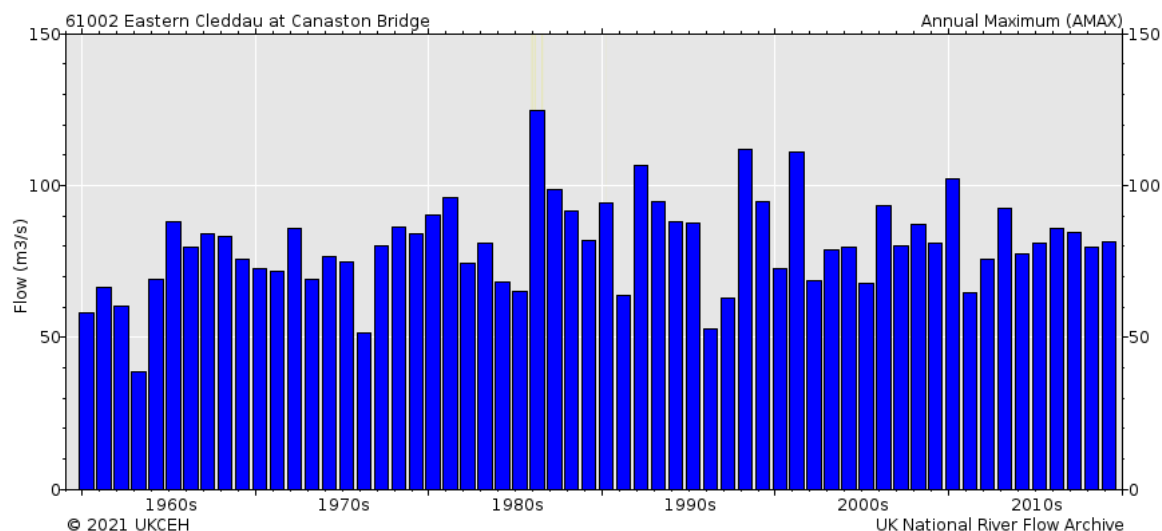
The overall flow of fresh water into the wider Milford Haven system is relatively small, when compared to the tidal input (*circa* 5% of spring tidal flows) (Bent, 2000). The main contribution is provided by the Eastern and Western Cleddau Rivers, which drain a combined catchment area of approximately 550 km². Together, these rivers provide around 75% of the freshwater input to the Haven, with a combined daily freshwater input estimated at between 0.3 million and 2.4 million m³ (Nelson-Smith, 1965), which varies seasonally with changes to rainfall. The rivers Cresswell and Carew, which enter the estuary up-estuary of the Cleddau Bridge, at Lawrenny, also provide a freshwater flux to the estuarine system. Relatively smaller freshwater inputs, into the lower Haven, come from Pembroke River, Sandy Haven Pill and the River Gann.

In general, the total volume of freshwater flow into the wider Milford Haven system is only equivalent to approximately 0.5% of the overall total volume within the Haven on a mean spring tidal (Nelson-Smith, 1965).

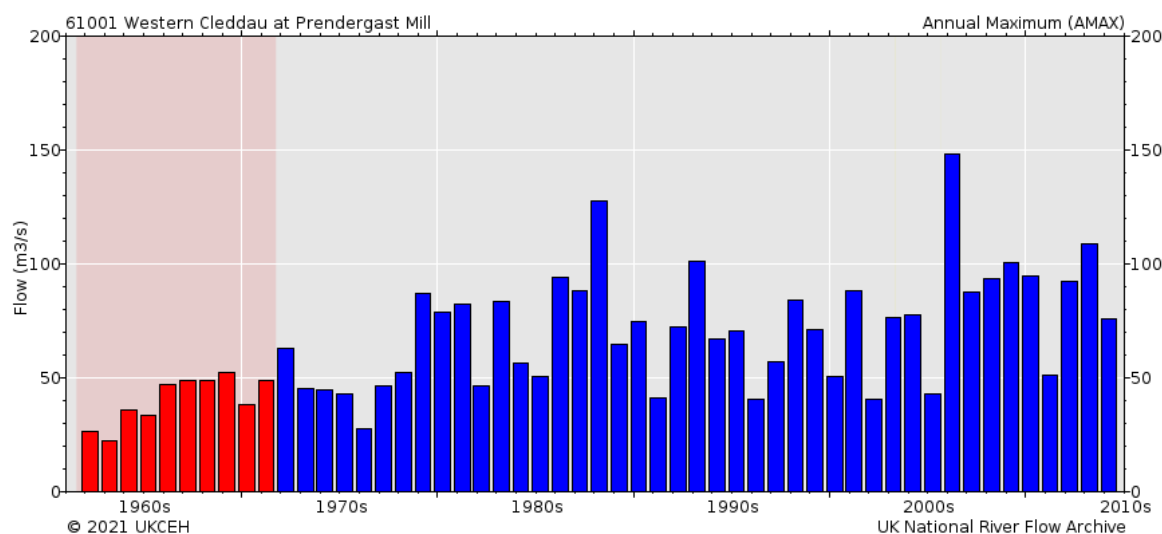
River flow data, extracted from the National River Flow Archive, shows in Figure 7, the Annual Maximum (AMAX) for the two available gauging stations:

- Station 61002: Eastern Cleddau at Canaston Bridge (data coverage 1959 to 2019); and
- Station 61001: Western Cleddau at Prendergast Mill (1961 to 2014).

61002: Eastern Cleddau at Canaston Bridge



61001: Western Cleddau at Prendergast Mill



Source: UK National River Flow Archive

Figure 7. Annual Maximum (AMAX) river flow values for the Eastern and Western Cleddau.

Changes in river flow

The annual maximum data suggests there may be an increasing trend in river flows entering the estuary from the Western Cleddau towards the end of the data period (up to 2014), but such a trend is less obvious in the more recent data from the Eastern Cleddau. Storm events which could lead to increased rainfall are evident in the hindcast wave data, which could have caused associated peaks in river runoff and a higher flux into the estuary. However, it is evident that the relative proportion of water in the estuary from

riverine sources is tiny when compared to the overall tidal prism. Consequently, any increased river flow will remain highly diluted by the tidal flux.

Potential impact pathway

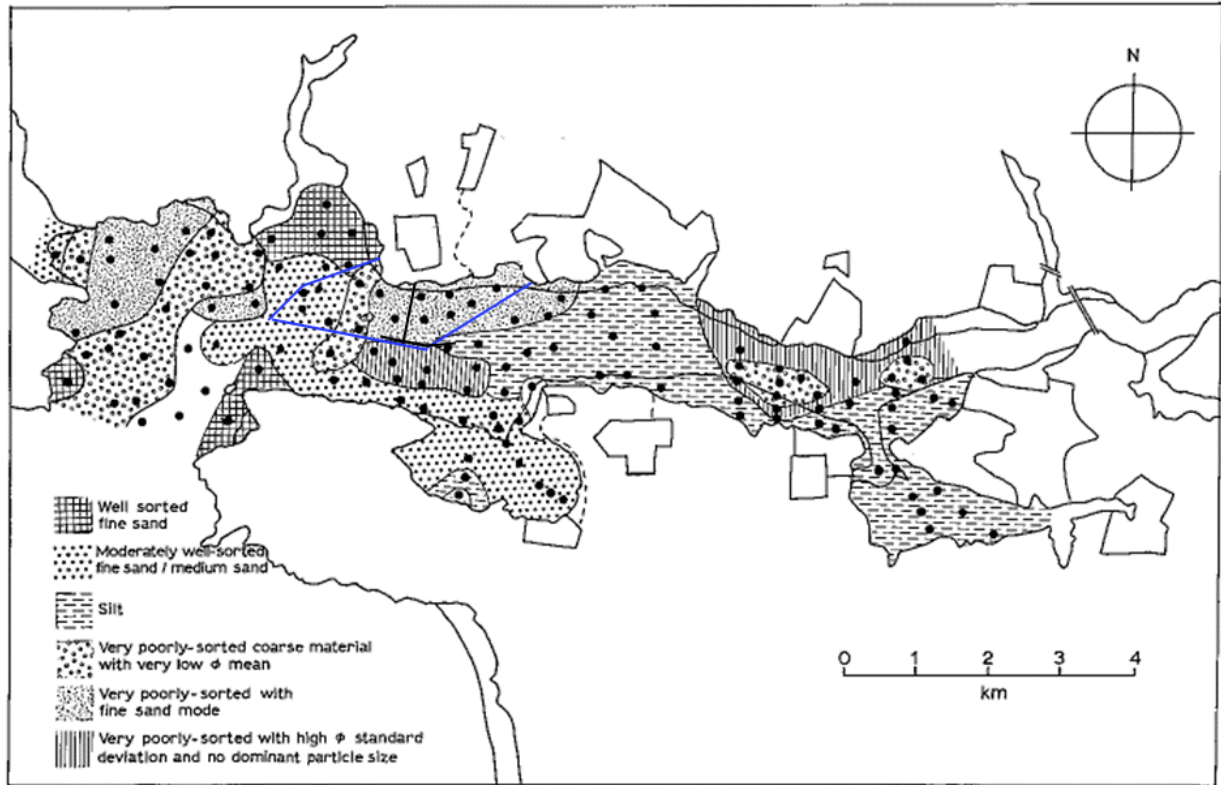
As noted above, the available river flow data alone does not support evidence of an increasing trend in suspended sediment load reaching the maerl beds from up-estuary (see Section 3.3.3).

3.3 Sediment regime

The local and regional geology coupled with the prevailing hydrodynamic conditions and fluvial inputs influence the sediment regime of the Milford Haven system. The following sections briefly summarise the understanding of the seabed sediment cover, the sediment transport pathways, and the suspended sediment across the study area.

3.3.1 Seabed sediments

The general distribution of seabed surface sediments in the lower part of Milford Haven is shown in Figure 8 (Rostron *et al.*, 1986). At the mouth, where the wave activity is greatest, the seabed and intertidal areas were largely composed of exposed Sandstone bedrock or with coverage of coarse boulders or pebbles. Where tidal currents are relatively strong (and/or wave activity is high), sediments tended to be poorly sorted, although some well-sorted sands could be located in sheltered areas, such as embayments. With increasing distance up-estuary, deposits varied through sands and shell/sand to muddier sediments within the inner Haven, up-estuary of Cleddau Bridge (Little *et al.*, 1987). Between the town of Milford Haven and Neyland, the intertidal area included extensive mud banks (containing varying proportions of sandy mud and gravel), which are exposed by larger (spring) tides (Little and Hiscock, 1987).

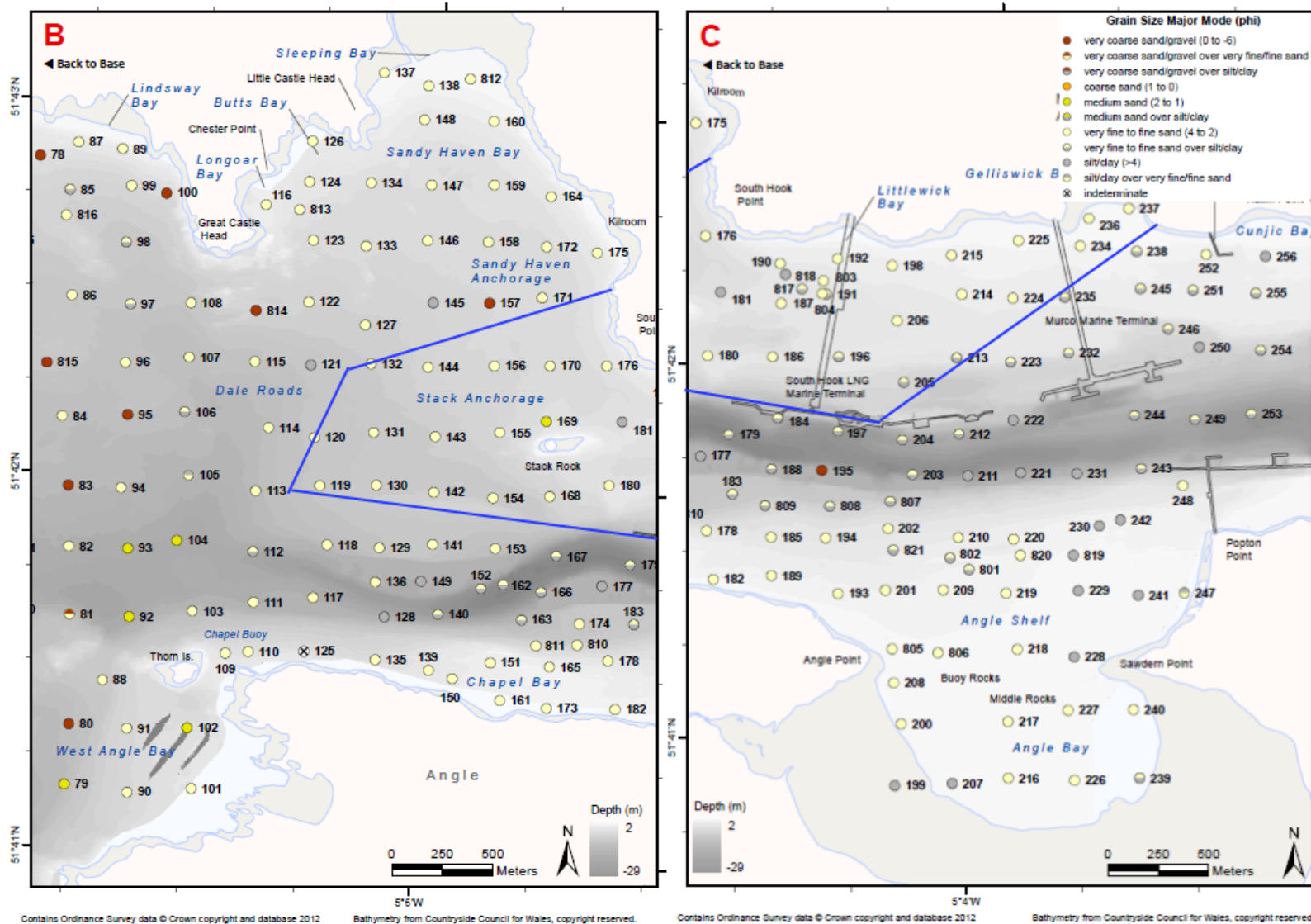


Source: Modified from Rostron *et al.*, 1986

Figure 8. General distribution of seabed sediments in Milford Haven.

In the area of the maerl beds, Rostron *et al.* (1986) indicates a mixture of poorly sorted coarse material to the west and poorly sorted fine sand material to the east.

Figure 8 shows a more detailed breakdown of sediment composition for the maerl bed area, derived from survey data collected by Germano and Associates (2012). This indicates sediment samples in and around the maerl bed comprised predominantly very fine to fine sand, very fine to fine sand over silt/clay, or silt/clay. In parts of the maerl bed, medium sand was observed and further up-estuary, within the main channel, samples tend to be mainly silt/clay.



Changes in sediment composition

The generalised mapping from Rostron *et al.* (1986) indicates a combination of fine sand and coarse material in and around the maerl beds, with the siltier material located further up-estuary around the entrance to Milford Haven Docks and within the main channel. In contrast, the 2012 survey results indicate a wider prevalence of fine sand material, with very little evidence of coarser material in and around the maerl beds. In addition, there are more samples with notable proportions of silt material in and around the area – particularly towards the edges of (and within) the main channel and some inshore sites to the west of the South Hook jetty. This could be (at least in part) a result of differences in the survey approaches between the two studies. It is also possible that between the surveys, the bed material in and around the maerl beds has become generally finer, with a reduction in coarser material at the surface and an increase in the extent of silts.

Six maerl monitoring dive sites were surveyed in 2005, 2010 and 2016 to help understand changes in the maerl bed community over time. At each site, divers studied factors including sediment composition, proportions of live and dead maerl, and epibiota and infauna living on and within the maerl bed. The dive sites were initially chosen to represent areas with highest recorded abundance of live maerl (sites 478 and 624) and sites representing variations in maerl bed character and extent.

Figure 11 shows the percentage of finer sediment fractions measured in diver cores at the six monitoring sites between 2005 and 2016. The sediment composition varies throughout the maerl bed and the greatest change in sediment composition occurred between 2010 and 2016, compared to the period before (2005-2010). Of particular note is the fining of sediments between 2010 and 2016 at the shallower sites 478, 624, 708 (3.5-4.3 m), situated either side of the South Hook Jetty, sites which included the highest proportions of live maerl. In contrast, sediment composition at deeper sites 405 and 410 (6.0-6.6 m), and to a lesser extent site 2195 (4.9 m) became coarser by a similar proportion. It should be noted this was a period that included significant storms (wave activity) which could have mobilised the finer sediments and pushed them up estuary. However, this would not explain changes pre-2010.

Monitoring undertaken around the jetty refurbishment (RPS, 2007) indicated that between the Winter 2005 and Winter 2006 the sediments became coarser in an up-estuary direction, generally the reverse of the longer trends indicated in Figure 11.

The analysis, which incorporated the change in epifaunal/floral and infaunal data could not determine whether the change was a result of the jetty refurbishment works or natural variability.

Particle size analysis indicated that although there was some separation between sites, there was no clear separation between years.

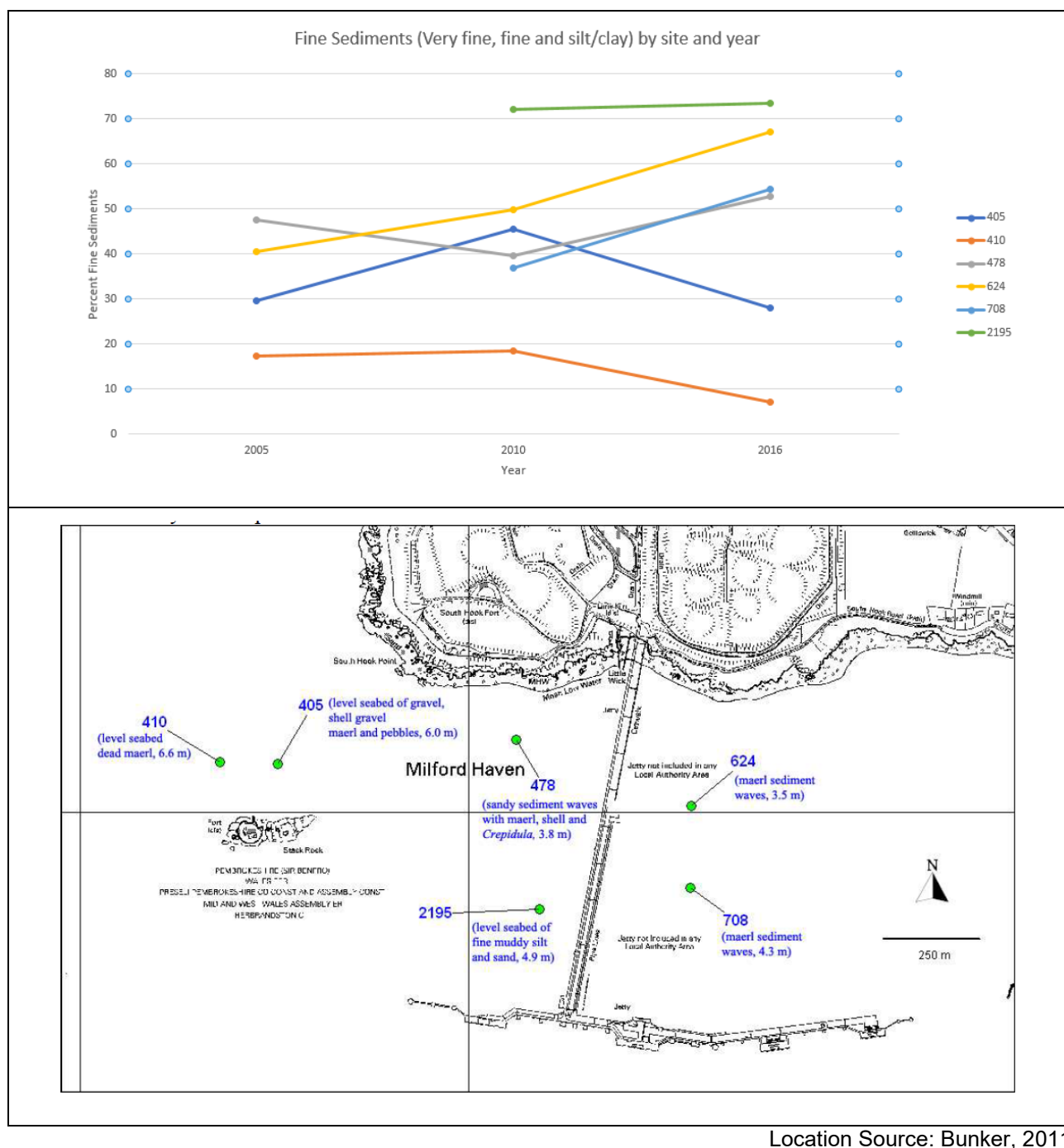


Figure 11. Change in fine sediment composition at maerl bed dive sites 2005 – 2016.

Potential impact pathway

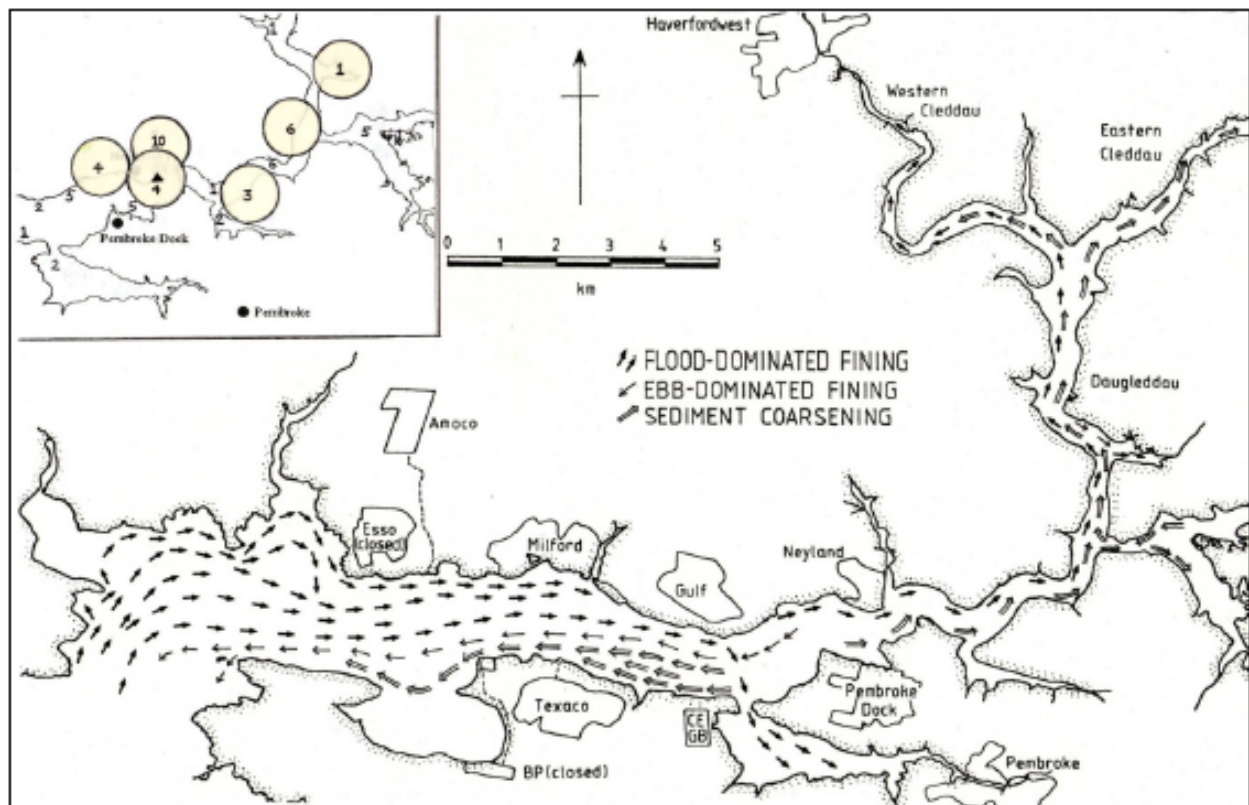
Whilst hypotheses of potential increases in erosion as a result of slight increases in water levels, flow speeds or isolated storm events have been put forward, the cause of any apparent change in seabed sediment composition is not readily evident from the available data.

In the absence of a robust explanation in the local hydrodynamics or riverine inputs, it is possible that alternative causes could be contributing to any potential change (although it should also be noted that direct evidence of any alternative cause is also not provided by the available data). These potential sources are discussed further in Section 5.1, but might

include impacts from invasive non-native species (INNS), local dredging and disposal activity, or other marine works within the Milford Haven estuary.

3.3.2 Sediment transport pathways

Sediment movement has been informed through studies using Sediment Trends Analysis (STA). The analysis indicates that bed material is transported in a flood direction, from the mouth, within the central channel and across the northern half of Milford Haven. In contrast, transport in the ebb direction is generally confined to the south shelf of Milford Haven (approximately down-estuary of the Cleddau Bridge). The summary map is provided in Figure 9.



Source: Little and McLaren, 1989 (in Little, 2009)

Figure 9. Primary sediment transport pathways of bed material across Milford Haven.

3.3.3 Suspended material

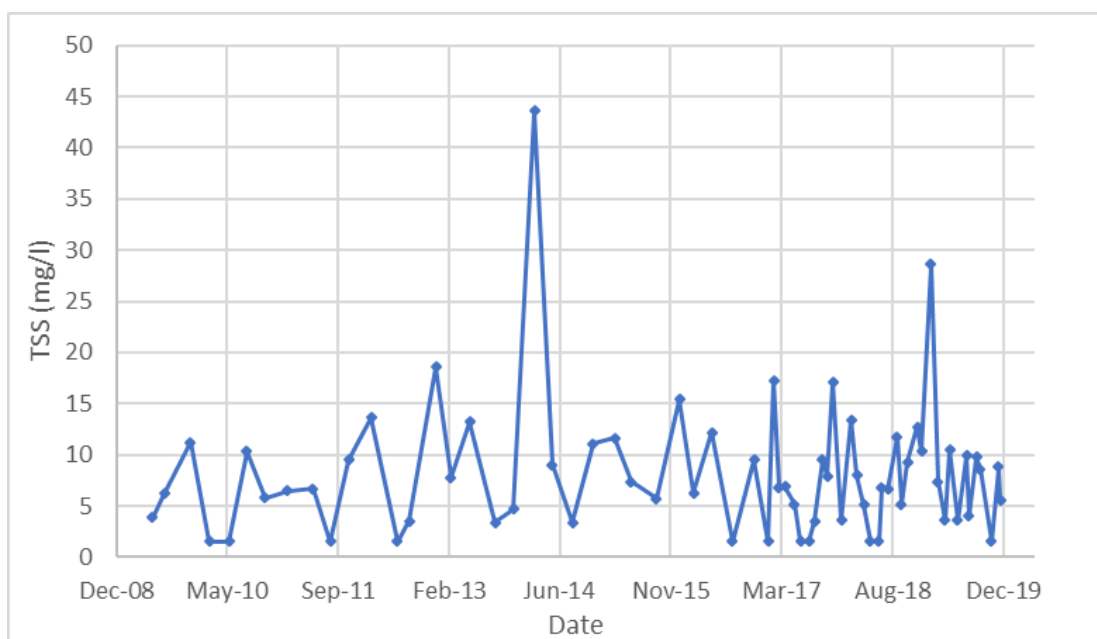
Suspended material inputs to the Milford Haven area come from a variety of sources, including urban and industrial developments at Milford Haven, Pembroke Dock and Haverfordwest, up-estuary from riverine flows and from the Outer Bristol Channel at the mouth. The Eastern and Western Cleddau rivers are estimated to contribute around 20,000 tonnes of suspended material per annum, whilst remote sensing data indicates that the lower estuary holds around 10,000 tonnes (ABP R&C, 1996). As noted in Section 3.2.4, it is possible that annual maximum flow data from the Western Cleddau shows some increase up to around 2014 (the extent of the available data), which may have also led to an increase in sediment supply to the wider estuary. However, the

available data does not allow for longer-term consideration of whether the sediment load has changed significantly over time. Turbidity is very variable, dependent on weather and tidal currents although, in general, the waters of Milford Haven are understood to have a lower suspended load than other, similar UK estuaries as a result of the high proportion of hard substrate evident over much of the lower estuary (ABP R&C, 1996).

Data from 1980s and 90s indicated that average concentrations of suspended material typically ranged between 20 and 25 mg/l, but can vary from around 4 to 60 mg/l. Further up-estuary, fronting the intertidal mudflats, concentrations were recorded as greater than 80 mg/l (Nash and Collins (1982) in Hobbs and Morgan (1992)). In the summer months, observed concentrations in the middle of the main channel were rarely greater than 10 mg/l. Overall, the suspended load tended to be greatest in the upper reaches of the estuary and within sheltered embayments where muddier material was more prevalent. Water quality monitoring at approximately 3-month intervals between June 2009 and December 2019 in the vicinity of the Pembroke Power Station shows a range in suspended sediment concentrations of 1 – 95 mg/l with an average of 10.5 mg/l. At the most down-estuary site (opposite Milford Haven Dock) the maximum recorded was 44 mg/l with an average of 8 mg/l (Figure 10) These data suggest that suspended matter concentrations have remained relatively consistent over time.

Changes in suspended material

Water sampling and analysis for Total Suspended Solids (TSS) has been undertaken by the Pembroke Power Station at a number of sample locations through the lower estuary between 2009 and 2019. The closest sample location is situated in the main channel, approximately 3 km up-estuary of Stack Rock and Figure 10 shows a varying timeseries of TSS concentrations over the sampling campaign.



Source: RWE Pembroke Power Station TSS sampling

Figure 10. Timeseries of total suspended solids (TSS) around 3 km up-estuary of Stack Rock.

The TSS results shows a varying signal, with levels generally lower than 10 to 15 mg/l, generally corroborating the findings of the studies quoted above. Peak concentrations are shown up to around 45 mg/l, measured on 2 March 2014. Review of the tidal elevations provided in Table 3 indicate that 2 March 2014 was a particularly high water level event, with a moderate surge component on top of a relatively large astronomical tide (just 0.1 m lower than an HAT tidal elevation), which may (at least partly) explain this high TSS concentration. More recently, a peak of almost 30 mg/l was measured on 22 January 2019. Although the peak water levels measured at the NTSLF gauge are flagged as 'uncertain' (a note that the data QC identified low confidence in the accuracy of the measurements), the predicted astronomic tidal range on 22 January 2019 was relatively large (around mid-way between a mean spring tide and an astronomic tidal range). These are the only two events with TSS concentrations significantly greater than 15 mg/l over the survey period.

Potential impact pathway

The data provided shows some potential indication of a slight increasing trend between 2008 to around 2016, before levelling off (or even reducing) in subsequent years; however, the trend is not obvious. It should be noted that the TSS sampling is not continuous; hence, it is unlikely to be sufficient to inform any meaningful analysis of longer-term trends – a total of 68 samples were collected over the period, with the sampling frequency increased to approximately one sample per month since the start of 2017). Consequently, the suggestion of a possible trend may simply be a factor of the shift in sampling frequency across the period.

3.4 Existing infrastructure and historical developments

The Milford Haven waterway has seen a number of varied developments throughout its history. From the site of a fifteenth Century French invasion, through designation as a seventeenth Century Royalist military base¹, to the more recent developments associated with the petrochemical industry, the Haven has been used for a range of anthropogenic activities. The following sections provide a brief history of recent and existing infrastructure and the dredging activities associated with them.

3.4.1 Existing infrastructure

Over the past three centuries Milford Haven has been a focus for a wide range of commercial activities, including fishing, limestone and coal quarrying/mining and export, military use and munitions manufacturing, ship building and repair, oil refining and fuel storage/processing. With the post-war growth of the UK oil-refining industry and the associated increase in vessel sizes, Milford Haven was developed into an oil port during the 1960's, with the main channel dredged to a depth of more than 18 m. By 2009 it was the largest port in Wales and one of the largest in UK. The Port of Milford Haven currently handles over 30 million tonnes of cargo per year (www.mhpa.co.uk).

The oil refining industry is perhaps the most prominent commercial user of the estuary and has undergone considerable growth since it was first established in 1960. The development of the oil industry in the 1970s saw Pembroke become the UK's largest oil

¹ en.wikipedia.org/wiki/Milford_Haven_Waterway

port in terms of tonnage of ships using the port and cargo handled; 99% of this was oil. Although the oil industry has declined since then, two of the five refineries built during the 1960's and 70's remain in operation (Little, 2009), with each providing deep water jetties for reception and transfer facilities.

The first (and most seaward) refinery to open was Esso Petroleum Company in 1960 with a rated capacity of 4.5 million metric tonnes per year (Mt/year). The terminal saw a peak in usage between the 1960's to the 1980's, with its capacity expanded to 8.7 Mt/year. Following the steady decline in the use of fossil fuels, the refinery closed in 1983. The site, including the refurbished Esso jetty, is now used by South Hook LNG, reopening as an LNG terminal in 2008 as discussed below.

Usage has increased since it was opened and, although still considerably less than the numbers seen during the peak oil refinery period, vessel calls to the terminal now average around two per week (AIS, 2017). Figure 11 shows Automatic Information System (AIS) record of vessel transits to Milford Haven for 2017.

3.4.2 South Hook approach jetty refurbishment

The jetty was originally built in 1959 as an oil jetty; it subsequently closed in 1983 and was decommissioned in 1990 (Dumortier, 2010). Refurbishment of the jetty approach trestle was undertaken in 2006 for the South Hook LNG Import Terminal. The refurbishment comprised:

- Hydro-demolition to remove areas of spalled concrete which exposed corroded reinforcement.
- The repair was completed by the application of shotcrete (sprayed concrete) to restore the crossheads. This was undertaken within essentially large steelwork boxes which were designed to enclose the bents and provide full debris containment, hence there was no concrete waste entering the marine environment.
- Demolition of an existing strong point that was located at approximately midway between the shore and the jetty head.

A new strongpoint was required to support an emergency shutdown valve for the LNG piping as the existing strongpoint was unsuitable for the large horizontal forces required. This involved removal of piles by cutting at or near seabed level and replacing with new piles being driven/drilled into the seabed. These activities re-mobilised sediment and created sediment plumes. This was undertaken from jack-up barges with spud-leg deployment over the maerl bed. The location of the strong point and the planned construction spud leg and anchor locations relative to the maerl bed are shown in Figure 12.

The 2006 Google Earth imagery (Figure 13) shows these activities creating plumes as well as prop-wash from manoeuvring ships over the maerl bed.

The new pile arrangements of the refurbished jetty, which predominantly occurred at the jetty head, in deep water, could also have resulted in a permanent but very localised change in the hydrodynamic and sediment regime. The potential for the jetty works to impact on the health of the maerl beds is discussed further in Section 5.

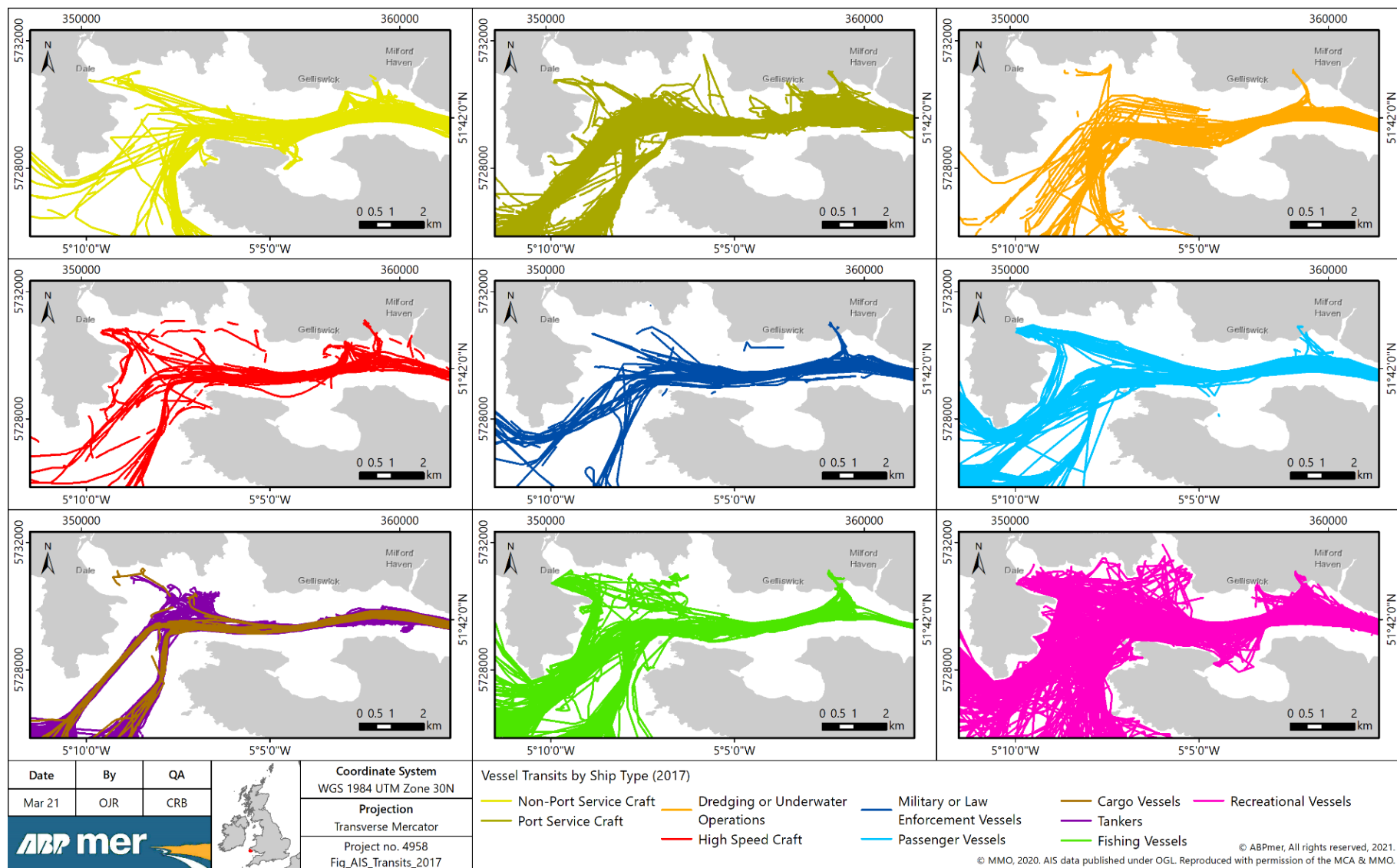
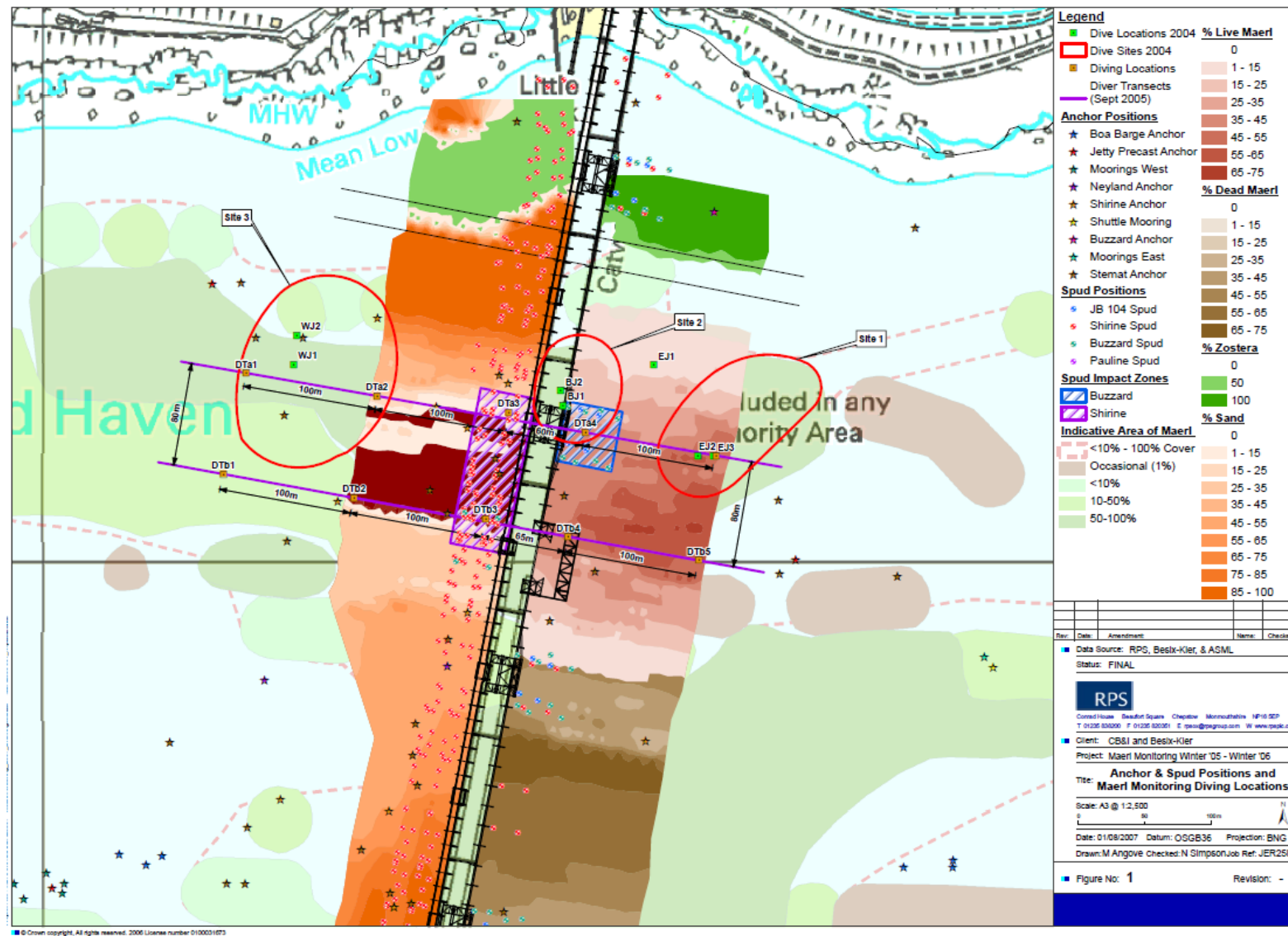


Figure 11. Automatic Information System (AIS) record of vessel transits to Milford Haven for 2017.



Source: RPS, 2007

Figure 12. Anchor and spud leg locations relative to maerl at time of South Hook Jetty refurbishment Possible causes of deterioration.

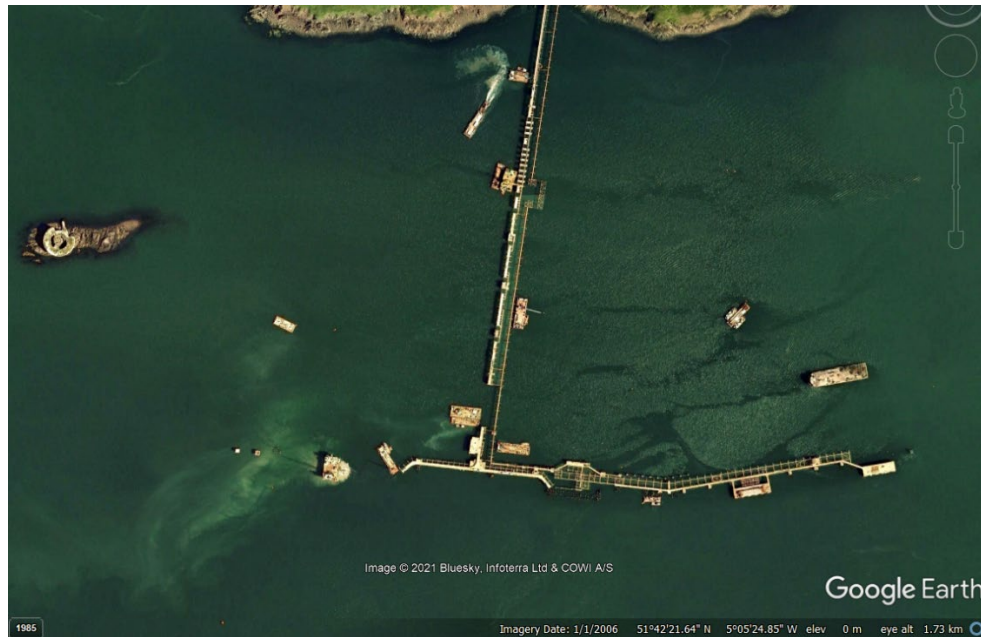


Figure 13. Evidence of sediment plumes from construction activities in aerial imagery from January 2006.

3.4.3 Dredging

As noted above, the Milford Haven waterway is a naturally deep-water estuary. Consequently, it has required relatively little dredging to maintain vessel access. The majority of works to widen the main channel (and associated dredging for berth deepening/maintenance) were largely completed prior to 1985 and, in some cases, works were undertaken as far back as the 1960's and 70's.

The most recent capital works included a small area of Phase 2 channel widening, undertaken in 2006 and the reinstatement of the intake and outfalls at Pembroke Power Station (MHPA 2011 and 2016). The closest dredging to the maerl beds was from parts of the channel widening and deepening works, which were completed on the south side of the main channel at Thorn and also on the south side of the channel at South Hook, opposite the LNG jetty (See Figure 14). Prior to this, the dredging in the vicinity of the maerl beds, including both sides of the main channel and the berth at the (formerly) Esso jetty, was completed prior to 1985.

Maintenance dredging in relation to Milford Haven docks and capital dredging that required a dredge disposal license (11/48/ML and DML 1646) indicate the predominant dredging methods used were Trailing Suction Hopper Dredgers (TSHD) with disposal at licenced deposit sites LU168 and LU169 outside of the Haven (see Figure 2) and supported by plough dredging and bed levelling. Other dredging operations that did not require a disposal license may have occurred, typically using plough dredging methods where dredged material is locally relocated rather than deposited off-site.

Deposit site LU168 is licensed for a maximum of 120,000 m³ of sand over 250 µm over a 5-year period. Site LU169 is licenced for the disposal of silt up to 300,000 m³ over the same 5-year period for all the different dredge locations within Port of Milford Haven /

Milford Haven Port Authority jurisdiction. The maintenance dredging for Neyland Yacht Marina (DML 1352 and 1743v3) is undertaken by Cutter Suction Dredging (CSD) discharging to the main channel at licenced deposit site LU190 off the marina (Figure 2). The dredging is limited to a maximum of 5,500 wet tonnes per year. The current licenced volumes/ tonnages are shown in Table 4.

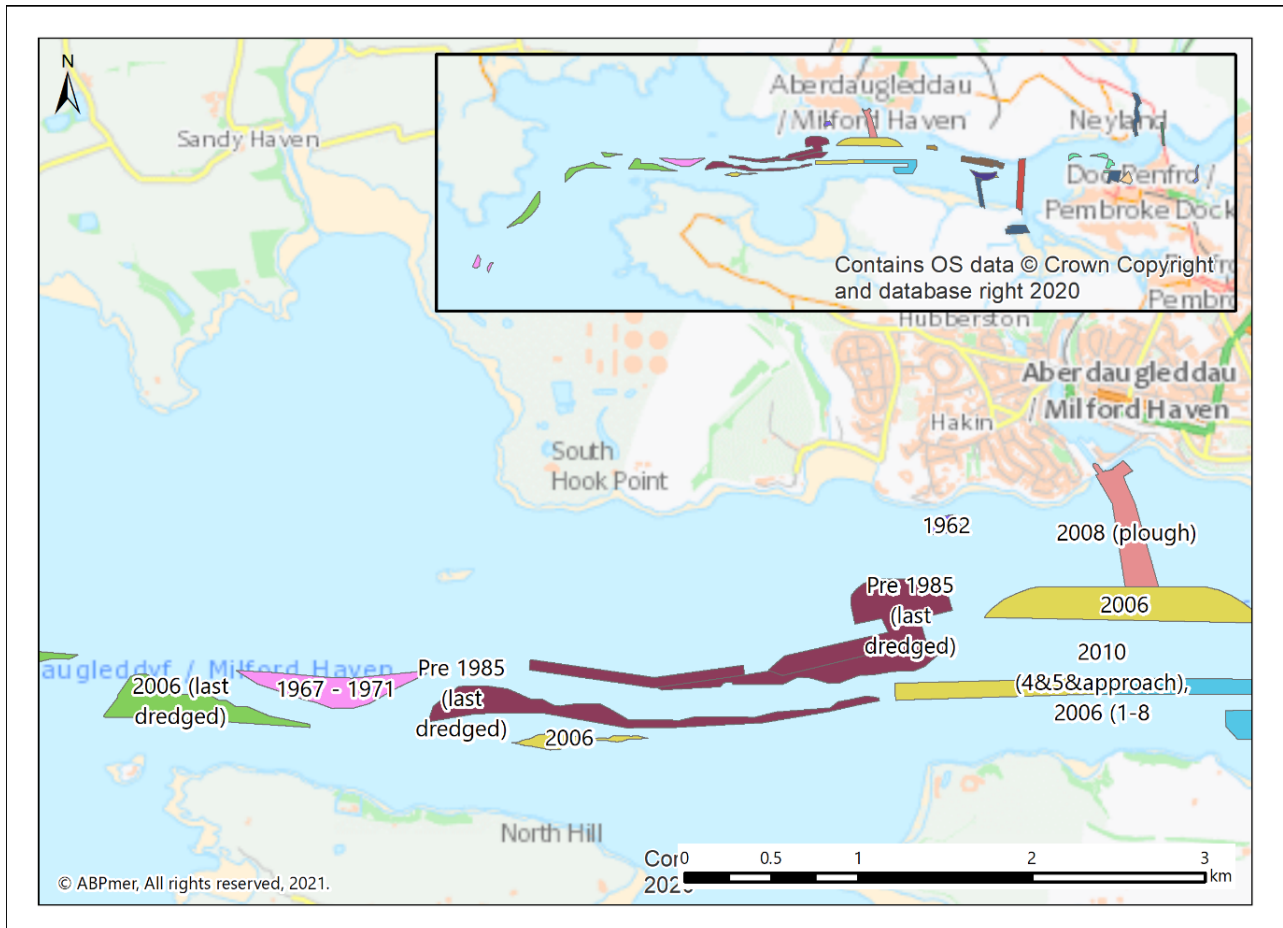


Figure 14. Map of dredging history within Milford Haven from 1960s until 2010 compiled and mapped by CCW from various sources.

Table 5. Maintenance dredging licences

Licence holder	Licence details	Licensed extraction	Disposal site
Port of Milford Haven (PoMH) / Milford Haven Port Authority (MHPA)	11/48/ML (2011 to 2016)	154,000 m ³ per annum between the sites	LU169 silt/fine sand
PoMH/MHPA	11/48/ML (2011 to 2016)	154,000 m ³ per annum between the sites	LU168 >250 µm
PoMH/MHPA	DML1646 (2017 to 2022)	300,000 m ³ of silt/fine sand over 5 years	LU169
PoMH/MHPA	DML1646 (2017 to 2022)	120,000 m ³ of sand >250 µm over 5 years	LU168
Neyland Yacht Haven	DML1352 (2014 to 2017)	5,500 tonnes per annum	LU190
Neyland Yacht Haven	DML1743v3 (2020 to 2029)	5,500 tonnes per annum	LU190

Source: NRW Marine Licence documentation

Interrogation of the Disposal at Sea (DAS) dredge disposal database provides the annual disposal tonnages (wet) (up to March 2019), for both capital and maintenance dredging activities, at each of the three disposal sites (Table 6).

Table 6. Disposal volumes (wet tonnes) at each of the three disposal sites. Note that data gaps (marked n/a) indicate either no dredging against a licence and/or no licence was in place.

Year	LU168 maintenance	LU168 capital	LU169 maintenance	LU169 capital	LU190 maintenance
1997	94,444	n/a	n/a	n/a	n/a
1998	43,092	n/a	10,038	n/a	n/a
2001	0	0	n/a	n/a	1,842

Year	LU168 maintenance	LU168 capital	LU169 maintenance	LU169 capital	LU190 maintenance
2002	14,161	0	42,245	74,934	0
2003	0	0	1,760	1,760	0
2004	0	0	n/a	n/a	3,772
2005	0	0	0	0	1,600
2006	76,872	900	182,646	45,284	4,000
2007	0	450	0	0	5,200
2008	0	0	99,161	25,660	5,190
2009	0	0	0	2,752	4,900
2010	n/a	n/a	104,281	158,146	4,169
2011	n/a	n/a	0	28,430	4,849
2012	n/a	n/a	n/a	n/a	2,250
2013	n/a	n/a	n/a	n/a	4,849
2014	n/a	n/a	n/a	n/a	n/a
2015	n/a	n/a	n/a	n/a	n/a
2016	n/a	n/a	n/a	n/a	3,300
2017	n/a	n/a	n/a	n/a	4,630

Source: DAS database up to March 2019

The disposal values provided in Table 5 show that the majority of maintenance and capital dredging using TSHD took place between 2002 and 2011. It also indicates that the use of the TSHD ceased around 2012. Since that time there is no record of disposal despite the licences. Consequently, Table 6 indicates that either any maintenance dredging undertaken within the PoMH/MHPA area since 2012 has been using plough dredging (effectively bed levelling) without associated removal of material to a disposal site, or that no dredging has been required during this period. In the case of ploughing, sediment would be disturbed to the natural flows of the Haven. It should be noted that the dredging strategy for Milford Haven (MHPA 2011 and 2016) states that it is possible that some years may require no disposal at all, as has happened historically as normal sedimentation rates are low. Between 1985 and 2010 the annual average rate was less than 29,000 m³ but in many years no dredging was required.

The channel locations that potentially require maintaining closest to the maerl beds were deepened and widened around the time of the South Hook Jetty refurbishment. Multibeam bathymetric surveys since 2008 have shown little sedimentation, even to the extent that the capital dredge marks are still evident (Moon, 2018). This, along with the fact that the present LNG vessels have smaller maximum draughts than the previous oil vessels, suggests the requirement for maintenance dredging near the maerl beds is very small. This is evident from the disposal data provided in Table 6.

Taking account of the channel bathymetry and estuary dynamics, it is unlikely that the maerl beds would be affected directly from dredge plumes from the main dredge areas, shown on Figure 17, with the exception of dredging from the Milford Dock Channel which is indicated to be plough dredged. The fine sediment disturbed would be within the flow streamlines that would pass through the areas of the maerl beds if the dredging works were undertaken on the ebb tide. There is no detail to indicate the frequency, magnitude and timing of these activities. Given the silty nature of the sediment disturbed and the more sandy nature around the maerl beds it is likely that much of any disturbed material would pass over the site without depositing in the area, although it remains possible that some fine material may remain. Pers. Comm. with Anthony Bates Partnership, who prepared the Milford Haven Port Authority Dredge Management Strategy, indicates that the use of a plough is usually very limited, with the overwhelming majority of dredging undertaken by the TSHD dredger, as necessary. This, along with the disposal values provided in Table 9, suggests that maintenance dredge requirements, within the Haven, have been minimal since 2012. It was also noted that since 1996, all TSHD dredging, when required, is undertaken within Milford Haven without overflowing the hopper, hence disturbance of sediment to the water column is minimised to drag head disturbance at the bed.

The cutter suction dredging works from Neyland (with disposal at LU190) show a slight increasing trend in volumes since 2001. Dependent on tidal state at (and around) the time of disposal, it is possible that disposal at the site just to the west of the Cleddau Bridge could act to increase the turbidity level down-estuary (and possibly around maerl areas). However, the regional pathways of sediment movement (Figure 9) indicate a general net up-estuary transport of material from the Neyland site; furthermore, any suspended material transported down-estuary on the ebbing tide would likely be mostly constrained to the main channel, thus bypassing the inshore maerl beds around Stack Rock.

Overall, although considered unlikely, the evidence does not completely rule out the effects of dredging as being a contributing factor to the decline of the maerl beds. Disposal values in Table 5 show relatively large dredge volumes in 2006, 2008 and 2010 (coincident with the timing of much of the jetty refurbishment works). Since 2012, it is likely that maintenance dredge requirements have been minimal, with no TSHD disposal and minimal plough dredging taking place. Consequently, any potential contribution to increased siltation at the maerl beds is likely to be limited to the period before 2010/12.

4 Maerl beds in Milford Haven

The data review and conceptual understanding of the hydrodynamic and sedimentary regime of Milford Haven (Section 3) has considered the available data in attempting to inform answers to the following questions:

- Is there any evidence of changes to the longer-term, wider hydrodynamic character that may have resulted in a general trend to higher sediment loads?
- If not, is there evidence of anything else that may have led to higher sediment loads in and around the maerl beds?

The focus in considering both questions is changes to siltation, since maerl is known to be very sensitive to even relatively thin layers of silt settling on it – siltation remaining for only a matter of days is sufficient to kill-off the maerl (Wilson et al 2004). In addition, it is known that the 2006 refurbishment of the South Hook approach Jetty took place in the vicinity of the maerl bed and would have potentially had some direct and indirect impact.

The following sections provide more detail on the decline in the maerl beds along with details on the tolerances of the maerl to the hydrodynamic and sedimentary environment.

4.1 History of maerl in Milford Haven

Through discussion with NRW, the following summary of the history of the maerl beds in Milford Haven has been developed:

- Some of the maerl in the Milford Haven area is over 2000 years old.
- Maerl was first dredged up in the Haven during the 1980's.
- The first formal monitoring of the maerl beds was conducted by the Countryside Council for Wales CCW (as was) and included drop-down video and diver monitoring surveys.
- The first surveys from 2004/05 (to inform the assessment of impacts from the South Hook LNG terminal proposals) revealed mostly dead maerl, with patches of live maerl beds in certain areas – mostly concentrated around the jetty structure (see Figure 15).
- The maerl beds exist where they are located (at least in part) because the area is tidally swept and exposed to wave action.
- Subsequent survey of the six locations in 2010 identified areas of small change at locations in deeper water and furthest from the South Hook Jetty but significant decline at the two locations closest to the inshore section of the approach jetty;
- Repeated surveys in 2016 revealed some improvements on the levels of infauna from the previous 2010 surveyed levels.
- A larger drop-down video survey undertaken as part of the wider monitoring campaign showed an overall approximately 90% reduction in live maerl between 2004/05 and 2016 surveys (see comparison in Figure 15).
- In general, more live maerl is found on the crests of sandwave bedforms (which appear to be relict stationary features). The troughs tend to collect dead shell and coarse sediment (Bunker, 2011) (see Figure 16).
- Whilst maerl is very tolerant to changes in local hydrodynamics and is able to survive for a period of time in relatively lower light levels (e.g. associated with a higher sediment load in the water column leading to more light attenuation), just a thin layer of silt settling on the maerl (and remaining for a matter of a few days) can be sufficient to kill it off.

Overall, the recent monitoring and analysis of the data collected shows a series of changes over time at the different locations. Most notable among these has been a decline in the amount of live maerl, and a large increase in populations of *Crepidula fornicata* and

an increase in both numbers of species and abundance of infauna in 2016 (associated with an increase in deposit feeders). There has also been a rise in the proportion of fine particles in the surface sediments at the sites with the most live maerl, mostly occurring post 2010.

This decline is discussed in more detail below.

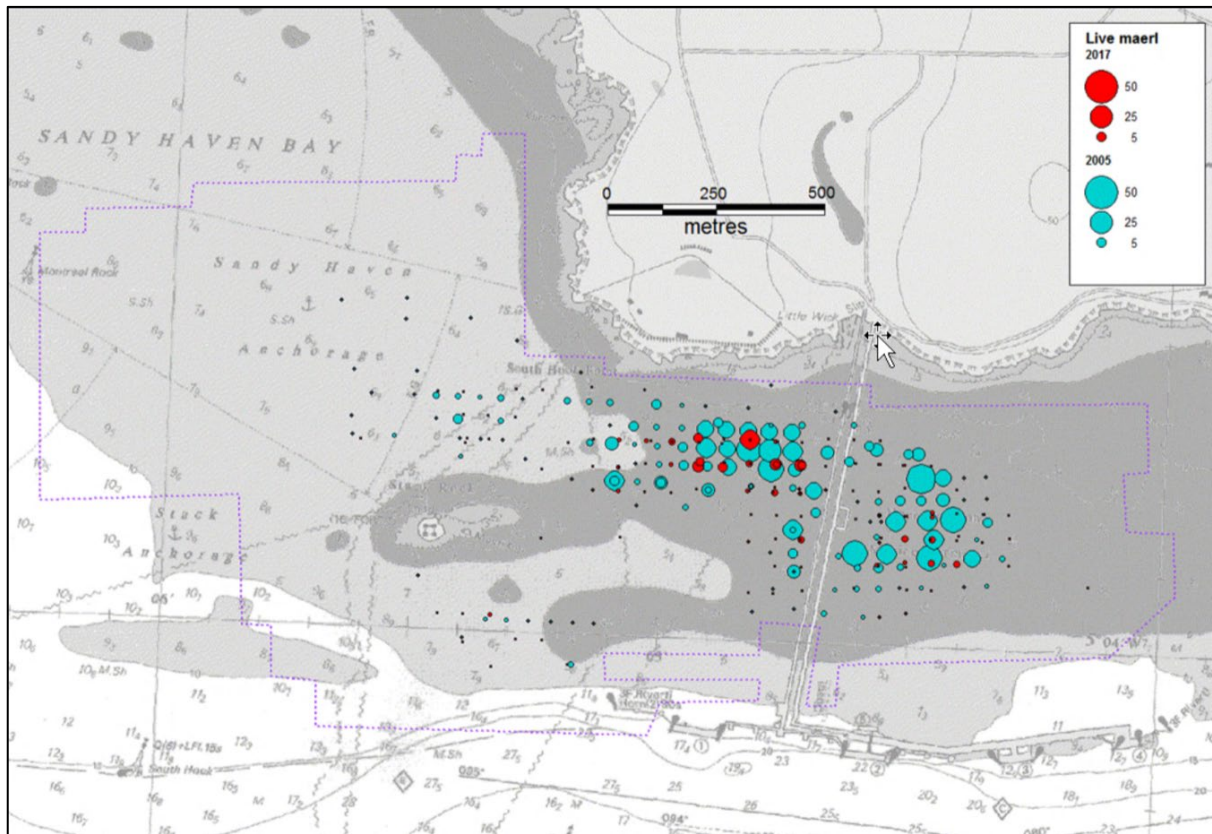


Figure 15. Comparison of distribution of live maerl in surveys from 2004/5 and 2016/17.



Figure 16. Maerl coverage concentrated on bedform crest with proportionally less in the troughs.

4.2 Monitoring data

The area of the maerl beds was first mapped in detail in 2004, associated with the proposed refurbishment of the South Hook Jetty in 2004. A monitoring program started in 2005 with subsequent repeat surveys in 2010 and 2016/17. Moore *et. al.* (2017) provides a summary statistic comparison for repeat drop down video surveys from 2005 and 2017 (Table 6). The results indicate that the maximum percentage cover of live maerl had reduced to 20% in 2017, compared to 40 % in 2005. The estimated area of live maerl was 2.5 ha in 2017, compared to 14 ha in 2005 (an 82% reduction). The estimated total area of maerl bed was 30 ha in 2017, compared with 58 ha in 2005 (a 48% reduction).

Table 7. Summary statistics from 2005 and 2017 drop down video surveys.

Maerl and <i>Crepidula fornicata</i> bed cover	2005	2017	% reduction
Average % live maerl - within survey area	1.1	0.2	82%
Average % dead maerl - within survey area	11.4	4.4	61%
Average % dead maerl - within maerl bed area	32.5	10.0	69%

Average % live maerl - within live maerl bed area	10.2	1.3	88%
Area of maerl bed (>10% cover) (ha)	58	30	48%
Area of live maerl bed (>5% cover) (ha)	14	2.5	82%
Area of <i>Crepidula fornicata</i> bed (>10% cover) (ha)	ND	22.8	n/a

Source: Moore *et. al*, 2017

Bunker *et. al.* (2017) provides analysis of repeat diver surveys at 6 locations from 2005, 2010 and 2016. Table 7 shows the change in the range of live maerl percentages from the quadrat surveys over this time for the locations shown on Figure 11. This data confirms the large reduction in the locations of the main maerl in 2005 (as represented by Locations 478 and 624) and suggests the most significant change occurred between 2005 and 2010 and has continued up estuary of the jetty up to 2016. It also indicates there has been little change at the other sites.

Table 8. Change in the range of live maerl percentages 2005, 2010 and 2016 from diver surveys.

Site and depth	708 (4.9m)	2195 (5m)	405 (5.9m)	410 (6.8m)	478 (3.7m)	624 (4.1m)
% live maerl 2005	1 to 4	0 to <1	<1	0 to <1	15 to 50	8 to 40
% live maerl 2010	1 to 2	0 to <1	<1 to 1	0 to <1	<1 to 3	4 to 12
% live maerl 2016	<1 to 5	0 to <1	<1	0 to <1	<1 to 3	<1 to 5

Source: Bunker *et. al.*, 2017

Table 9 concentrates on the average change in the area of most live maerl. This shows the rapid reduction in the live maerl between 2005 and 2010 to the west of the South Hook approach, whereas the change has been more gradual to the east of the jetty. Comparison with Figure 11 indicates that most change has occurred during the period of least change in the composition of the bed sediment, and less so during the period of finer bed sediments post 2010.

Table 9. Average percentage cover of live maerl calculated from all six quadrats at sites 478 and 624 (Sourced from Bunker *et al.*, 2017).

Location	478	478	478	624	624	624
Year	2005	2010	2016	2005	2010	2016
Average % live maerl	36.7	1.0	1.1	22.0	7.2	1.9

Table 10 shows the average percentage frequency of occurrence of live maerl within the 6 quadrats recorded at each site in the three years. This again confirms that most change occurred between 2005 and 2010 for the main live maerl locations (478 and 624) but the greatest decline in live maerl at the other sites occurred post 2010. This potentially indicates more than one potential cause for the overall decline of the maerl.

Table 10. Average cell-frequency of live maerl obtained from 6 quadrats at each sample location (Sourced from Bunker *et al.*, 2017).

Location	2005	2010	2016
708	47.3%	72%	10.7%
2195	2.7%	2%	0.7%
405	24.7%	25.3%	3.3%
410	0.7%	0%	1.0%
478	88.7%	74%	17.8%
624	89.3%	97.3%	9.0%

Whilst the maerl beds have declined, the area of *Crepidula fornicata* bed has significantly increased, covering 23 ha in 2017 having not been noted in 2004. It was noted (albeit in low abundance) in 2005 diver surveys but was conspicuous in 2010 and well established at every location.

In 2017 the *Crepidula fornicata* bed overlapped a substantial part of the area that was live maerl bed in 2005 (Figure 17), suggesting that it was out-competing maerl in that area. However, Moore *et. al*, 2017 note that competition with *Crepidula fornicata* could not explain all the recorded reduction in live maerl, since a large area of what was live maerl bed in 2005 (dead in 2017) was not yet populated by *Crepidula fornicata* in spring 2017.

Analysis of the epibiota results also show change has occurred over time. This is particularly apparent at the three monitoring sites which historically had the most live maerl. At each location, the total and average number of maerl epifloral species found in the samples show an increase for 2016 compared to 2010.

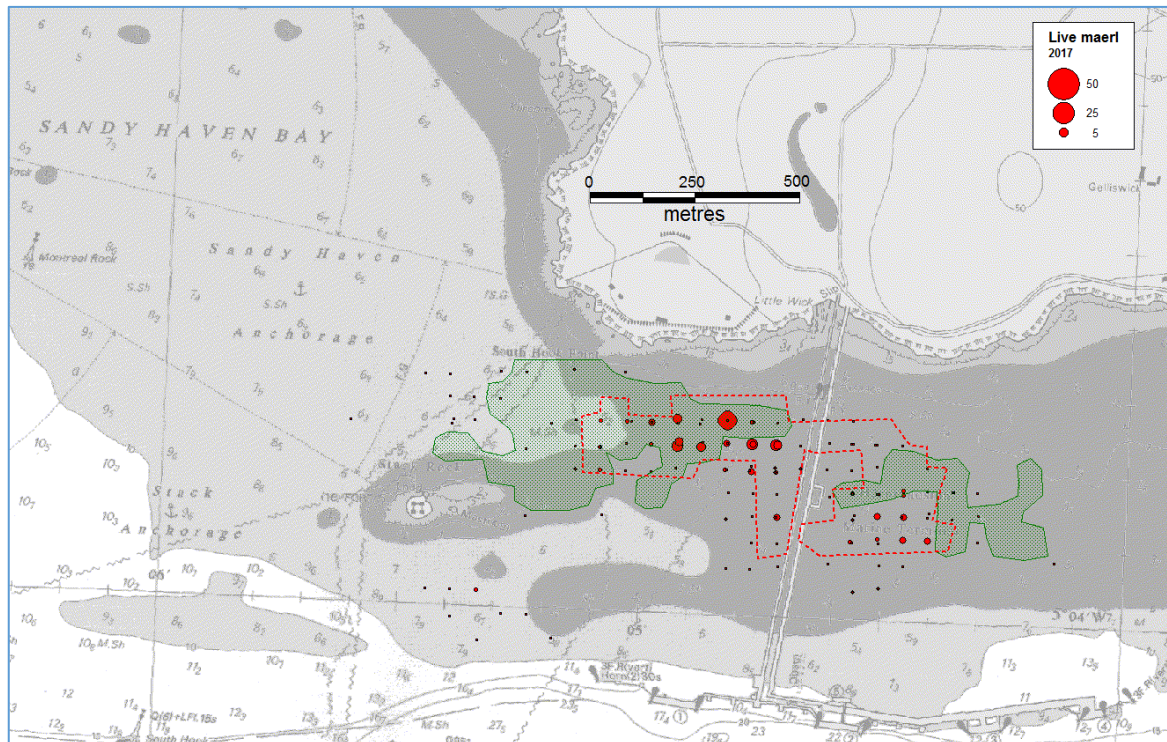


Figure 17. Percentage live maerl in 2017, defined area of live maerl bed, based on 2005 data (red dashed line) and defined area of *Crepidula fornicata* bed (green shaded areas). Sourced from Moore *et al.*, 2017.

4.3 Tolerances to hydrodynamic and sedimentary parameters

Maerl is a general term used for loose-lying subtidal beds of nodular coralline red algae which is ecologically fragile due to slow growth rates of approximately 1 mm per year. Previous studies (e.g. Bosence, 1979, which assessed maerl coverage in Mannin Bay, Galway) have found extensive maerl beds in areas where there are moderate to strong seabed currents, or in relatively open, yet sheltered, areas with sufficient wave action, such as coastal bays or inlets.

To investigate environmental tolerance, Wilson *et al.* (2004) exposed maerl species to a range of temperatures, salinities and light levels and to burial, fragmentation, desiccation and heavy metal treatments. The following provides a summary of the findings from these studies:

4.3.1 Temperature

In general, the various types of maerl tend to die at temperatures below about 2°C and do not grow until above 5°C with optimum growth around 12 - 15°C. Experiments indicate (*P. calcareum*) is not stressed at 25°C.

4.3.2 Salinity

Literature suggests maerl of the type at Milford Haven (*P. calcareum*) is impaired at salinities below 24 Practical Salinity Units (PSU). Experiments indicated acclimatisation occurred at around 15 PSU.

4.3.3 Irradiance

Irradiance requirements of maerl species are not known (Birkett *et al.*, 1998), however experiments (Wilson *et al.*, 2004) indicate (*P. calcareum*) is adapted to low photon irradiances. maerl showed little stress after being kept in the dark for 4 weeks and it was concluded that it is very likely that maerl can survive several months of darkness without deleterious effects.

4.3.4 Desiccation

Maerl are only found in subtidal, therefore it is assumed that they cannot withstand emersion (Birkett *et al.*, 1998). Experiments (Wilson *et al.*, 2004) confirmed this assumption.

4.3.5 Burial and sedimentation

The locations that maerl are found suggest that maerl beds require both shelter from wave action to prevent burial and enough water movement to prevent smothering with silt (Hall-Spencer, 1998).

The loss of live maerl following burial or sedimentation was thought to result from its death due to lack of light when buried (Steller and Foster, 1995; Hall-Spencer and Moore, 2000). The irradiance tests noted above appear to negate this as the only cause. Death of maerl is therefore more likely to be due to reduction of water movement and subsequent lowering of diffusion of metabolic wastes and gaseous exchange around the maerl, potentially caused by compaction of the maerl, sedimentation or chemical effects (Chapman and Fletcher, 2002; Wilson *et al.*, 2004).

Observations indicate that 8 cm of burial caused 70% death and recovery was not evident after 4 years. Experimental burial studies by Wilson *et al.* (2004), testing the impact of scallop dredging through a maerl bed, indicated maerl can tolerate burial in clean coarse maerl gravel or clean coarse sand at depths of 4 or 8 cm for 4 weeks. Burial in coarse gravel sediment (1-10 mm) had less severe effects than periods of burial in coarse sand (0.3-1 mm). However, burial by a shallow layer (0.25 or 2 cm) of muddy sand containing hydrogen sulphide was quickly detrimental (damage recorded within 1 week) and all maerl was dead by 2 weeks. Even maerl lying on the surface of this muddy sediment was dead within two weeks (Wilson *et al.*, 2004). Chapman and Fletcher (2002) found that even a 1 mm layer of sediment high in hydrogen sulphide was highly toxic to *Fucus* embryos even

when the overlying water was oxygenated. In this study a build-up of metabolic wastes and reduced diffusion over the embryos was considered the toxic mechanism, with levels of hydrogen sulphide in the sediment being a key determinant of embryo survival (Chapman and Fletcher, 2002).

Wilson *et al.*, (2004) state that these toxic effects on maerl of fine organic sediment and associated hydrogen sulphide explain the observed detrimental effects of *Crepidula fornicata* in Brittany, where these invasive gastropods have damaged Breton maerl beds (Chauvaud *et al.*, 2000; Grall and Hall-Spencer, 2003). This is therefore likely to be a similar situation occurring at Milford Haven.

In addition to the potential impact of *Crepidula fornicata*, wider changes to the local water quality of the Haven could also be a factor. The increased level of dissolved inorganic nitrogen (NRW, *pers. comm.*) in the Haven is known to have resulted in large increases in opportunistic macroalgae. The annual breakdown of this algae may subsequently result in increased siltation and/or changes to local water quality, either of which may be detrimental to the maerl beds. Whilst further assessment of the potential changes in the organic content of sediments (and of the wider water quality within the Haven) is outside the scope of this study, either could potentially be contributing to the observed deterioration in the maerl.

4.3.6 Heavy metal contamination

Experiments (Wilson *et al.*, 2004) indicted that maerl quickly recovered (1 week) from heavy metal pollution by sequestering the metals.

4.3.7 Conclusion

These studies indicate that maerl is very susceptible to burial causing death or significant stress, especially in fine or anoxic sediments (as can be produced from faeces and pseudofaeces produced by high densities of *Crepidula fornicata*). Maerl was much less susceptible to salinity and temperature extremes and heavy metal pollution.

Wilson *et al.* (2004) indicates that the main anthropogenic hazard for live maerl and the rich communities that depend on them is smothering by fine sediment (such as that produced by trawling or maerl extraction, from sewage discharges or shellfish and fish farm waste, and sedimentation resulting from disruption to tidal flow). Moreover, where the fine sediment also contains significant amounts of hydrogen sulphide, the potential impact to the maerl is increased.

At Milford Haven it is clear that the presence and increasing abundance of the invasive non-native species (INNS) slipper limpet (*Crepidula fornicata*) is a significant factor, with waste products potentially leading to increased fine sediment and a prevalence of hydrogen sulphide in the sediment.

5 Discussion and conclusions

5.1 Possible causes of deterioration

The scope of this study is focussed very specifically on the hydrodynamic (and associated sedimentary) regime in and around the outer Milford Haven. It has made use of a desk-based approach, using existing available datasets.

This study has found no robust evidence of any significant long-term changes to sediment load that can be identified as the cause of the observed decline in the maerl beds.

The impact of certain episodic events and activities cannot yet be ruled out as a contributing factor to the decline. The report has, however, provided hypotheses for potential causes of decline based upon the data along with circumstantial and anecdotal evidence and on expert understanding of the driving hydrodynamic and sediment processes of the wider study area.

The scope of the study does not include water quality, sediment quality/contaminants, changes in salinity or temperature or biological factors (disease, direct impact from competition with invasive species, etc.) which may also influence the health of the Milford Haven maerl beds. The longer-term health of the maerl beds is also unknown, and some of the maerl in the Haven is known to be around 2,000 years old. Consequently, the response of the wider population (and individuals) to previous changes in environmental conditions (hydrodynamic changes over a lunar nodal cycle, more recent impacts of longer-term climate-induced sea level rise, response to storm events, high rainfall/runoff conditions, previous developments etc.) is also unknown. Hence, it is unlikely that identification of a single (set of) cause(s) will be possible without further monitoring and assessment.

Based upon the conceptual understanding, the following potential causes are identified (Table 11), along with a summary of the evidence base collected as part of this study.

Table 11. Potential causes for maerl decline

Potential cause	Summary of evidence
Change in local seabed sediment composition	<i>Pathway:</i> Changes in the composition of the bed material, may have an associated impact on the maerl beds. An increased proportion of fine material (silts and muds) could lead to a general increase in suspended sediment load under peak flow or storm conditions. Subsequent slack water periods may then result in settling of the finer material on the maerl. Comparisons between regional mapping from 1986 and grab sampling from 2012 indicates a possible increase in finer bed material within and around the maerl beds. <i>Impact:</i> The cause of any apparent change in seabed sediment composition is not readily evident from the available data. In the absence of a robust explanation in the local hydrodynamics or riverine inputs, it is possible that alternative causes could be contributing to any potential change.

Potential cause	Summary of evidence
Increased flow speeds resulting in increased erosion and higher sediment loads.	<i>Pathway:</i> Increases in tidal prism (between the 2004 and 2016 maerl bed surveys) from combined influence of sea level rise and the lunar nodal cycle. Associated small increase in general flow speeds throughout the Haven. Local developments may have also had a localised impact on flow speeds (increases or decreases (see below entry). Potential for faster flows to increase bed erosion or for increased water levels to expose more intertidal mudflat to tide and wave action, also resulting increased erosion. <i>Impact:</i> Available evidence does not support a robust conclusion of a general increased trend in sediment load within the Outer Haven. No evidence available to confirm (or otherwise) localised increases in suspended sediment in the vicinity of the maerl beds.
Reduced flow speeds leading to a more accretionary environment in the area of the maerl beds.	<i>Pathway:</i> It could be hypothesised that local developments (such as the installation of additional piles at the head of the South Hook jetty during the upgrade works in 2006) may have resulted in local reductions in flows that may have led to increased accretion in the vicinity of the maerl beds. <i>Impact:</i> The available evidence does not support a conclusion of a local reduction in current speed over the maerl beds. The replacements of the jetty piles, and the alignment of the jetty head in relation to the east-west tidal stream vectors, suggests such an impact is unlikely.
Increased flows and/or storminess leading to physical damage to maerl.	<i>Pathway:</i> More energy imparted to the bed by faster flows and/or larger waves has the potential to uproot maerl from the bed or otherwise cause physical damage. Temporary increase in sediment could cause burial, particularly in bedform troughs. <i>Impact:</i> The available evidence from drop-down video and diver surveys does not indicate any such physical damage to the maerl, which remains concentrated on the bedform crests (Figure 16), suggesting such an impact is unlikely, although temporary burial could be possible.
Increased wave activity leading to increased erosion and higher sediment loads.	<i>Pathway:</i> Hindcast wave data at the entrance to Milford Haven shows no robust evidence for a change in storminess between the 2004 and 2016 maerl surveys. Individual storm events have occurred during the period, but the largest events in the 40-year hindcast period pre-date the 2004 maerl survey. Extreme storm conditions have the potential to disturb seabed sediment and/or lead to increased coastal erosion (and associated increases in suspended sediment concentration). <i>Impact:</i> Without an understanding of how maerl beds in Milford Haven have been impacted by (and subsequently responded to) previous large storm events, it is not possible to identify wave activity as a cause of the recently observed decline.

Potential cause	Summary of evidence
Increased sediment load from riverine inputs	<i>Pathway:</i> The available data from the Western Cleddau suggests some increasing trend in river flow up to the end of the data set in 2014. Increased river flux could lead to increased sediment input from the rivers, leading to an overall increase in suspended sediment in the lower parts of the Haven. <i>Impact:</i> The available evidence does not support a clear conclusion of a general increased trend in sediment load within the Outer Haven; a trend is possibly evident, but the data is too limited to provide a robust indication.
Marine developments in the vicinity of the maerl beds causing local increases to sediment load.	<i>Pathway:</i> It is hypothesised that the plant used during the construction phase of the South Hook jetty upgrades could have resulted in highly localised increases in suspended sediment from scour around the new piles, construction platform spud-legs and disturbance when the legs were lifted. <i>Impact:</i> Circumstantial evidence indicates that the majority of the maerl decline has taken place in the vicinity of the South Hook jetty. The available evidence indicates there was likely to have been a local direct seabed impact from the construction jack-up barge and associated craft, particularly along the jetty approach. Sediment plumes were evident during the construction but there is no direct evidence of sedimentation in the vicinity of the maerl beds.

Potential cause	Summary of evidence
Dredging activity (and associated disposal) within Milford Haven resulting in increased sediment loads.	<i>Pathway:</i> Maintenance and capital dredging has occurred during the period of monitoring. The activity has the potential to disturb material to the water column where it could be transported over the maerl beds. <i>Impact:</i> Capital dredging was mostly associated with widening of the main channel, offshore of the maerl beds with the majority of material being disposed offshore of Milford Haven. Previous modelling of dispersion from potential deposit grounds in similar locations suggest there will be negligible potential for return of the sediment to the maerl beds. The likely flow streamlines from the dredge area, along the channel, suggest a negligible potential for any disturbed sediment reaching the area where circumstantial evidence indicates that the majority of the maerl decline has taken place in the vicinity of the South Hook jetty. Maintenance dredging, mainly in the channel to Milford Haven Dock, could disturb sediment into flows that would pass through the areas of the maerl beds. Either no dredging was required at this location from 2012 to 2017, or the dredging method appeared to change post 2012 from methods requiring disposal to licensed disposal sites (TSHD), to methods not requiring licensed disposal (e.g. plough). If the latter, there would be a potential for increased dispersion loads compared with previous periods, although specific detail is unknown. Cutter Suction Dredging (CSD) from Neyland Marina discharging to the channel occurred in most years (generally January to March) during the monitoring period. The dispersion of the material is unknown but is most likely to be predominantly within the deeper channel. It is unlikely that sediment in any large quantity would be moved over the maerl sites particularly near the jetty. Plough/bed-levelling dredging has a small potential to increase sediment loads over some of the maerl areas, however it is unlikely that any settlement that could occur over slack water would remain following the peak flows. Any sedimentation is therefore unlikely to last more than a few hours for each event. Whilst it is not possible, based on the available evidence, to completely rule out an impact on the maerl from local dredging activities, it is considered unlikely that TSHD dredging within the main channel would result in sufficiently increased siltation over the study area to result in deterioration. Ploughing along the entrance to the Port of Milford Haven could result in increased sediments in suspension and, particularly during ebb tidal periods, this material would transit in the streamlines towards the maerl beds. However, it is considered likely that any associated increased siltation during slack water would be resuspended during subsequent peak flows. At this time, there is no evidence to link local dredging activity to the decline in the maerl.

Potential cause	Summary of evidence
Changes to vessel movements in the vicinity of the maerl beds leading to increased sediment loads.	<i>Pathway:</i> It is hypothesised that vessel calls to the South Hook jetty since the LNG terminal opened in 2008 could have resulted in localised increases in suspended sediment due to ship wash and/or tug use. <i>Impact:</i> From the available evidence, and without information on historic impacts from (and maerl response to) ship visits during the peak of the refinery between the 1960's and 1980's, it is not possible to identify local vessel movements as a cause of the recently observed decline.
Influence of invasive non-native species (INNS) resulting in direct or indirect changes to sediment loads	The influence of invasive non-native species (particularly the Slipper Limpet) should be considered further as a possible cause (alone or in combination with other factors) of the observed decline in the maerl population.
Other causes, such as changes to water/sediment quality, contaminants, salinity/ temperature, infection/ disease etc.	Outside the scope of this study. Other pathways should be considered as possible causes, including poor water quality (as identified in the evidence review of the trophic status of Milford-Haven, (NRW, 2018)).

5.2 Conclusions of cause and effect

This section summarises the conclusions which have been drawn from the study using the source-pathway-receptor relationship. These have been derived from an understanding of the sensitivity and tolerances of the maerl to different hydrodynamic and sedimentary parameters (the receptor) along with the conceptual understanding of the coastal processes operating in Milford Haven (pathway).

5.2.1 Changes or effects unlikely to have contributed to decline

The evidence from the video surveys suggests that physical damage, either from increased storminess or direct contact (e.g. vessel strike etc.), can be excluded as a cause of the maerl decline.

Small increases in tidal range between the 2004 and 2016 maerl surveys (resulting from the combination of climate change-induced sea level rise and the position within the lunar nodal cycle) may result in small increases to flow speed and an increased potential for local erosion. However, the magnitude of any potential changes is considered too small to significantly affect the maerl beds. Moreover, any potential increase in suspended material is likely to be (at least partially) offset by higher flows sweeping any newly settled material off the maerl beds on the next tide.

5.2.2 Potential pathways to decline

Sediment composition

There is tentative evidence of an increased proportion of fine sediment on the bed in and around the maerl beds between 1986 and 2012, although the cause of this apparent change is not readily apparent from the available data. Information from repeat diver surveys indicate further increases since 2010 in the proportion of fine sediments both sides of the South Hook Jetty but a coarsening in sediment composition further towards the Haven mouth. There is little evidence of significant changes to hydrodynamics or regional sediment load, but episodic storm effects cannot be discounted. In the absence of a robust explanation in the local hydrodynamics or riverine inputs, it is possible that alternative causes could be contributing to any potential change.

There is tentative evidence of increased background sediment load over the 2004-16 period in the available data, although this may be simply an artefact of the change in sampling frequency during the survey period. Overall, the trend is not obvious. It is also possible that individual event(s) have not been picked up in survey data and that may have contributed to a sudden decline in maerl (although evidence is not available to support or disprove this hypothesis).

Sediment dispersion

It is hypothesised that local dredging activities may have led to increased sediment load in the area of the maerl beds. The available evidence indicates that the majority of dredging is (and has been) undertaken by TSHD. A small quantity of maintenance dredging within the PoMH/MHPA area is believed to have been undertaken using plough dredging (effectively bed levelling without associated removal of material to a disposal site) from the deep main channel and the approach to Milford Haven Dock. Given this latter location of the channel, the fine sediment disturbed would be within the flow streamlines that would pass through the areas of the maerl beds if the dredging works were undertaken on the ebb tide. There is, however, no detail to indicate the frequency, magnitude and timing of these activities. However, given the silty nature of the sediment disturbed and the more sandy nature around the maerl beds (Figure 10), it is likely that any disturbed material would pass over this area without long-term deposition to the bed. Additionally, it should be noted that there has been negligible dredging post 2010, i.e. during the period when significant fining of sediments on the maerl bed has occurred.

It is hypothesised that the jetty upgrade works completed for the South Hook LNG terminal may have affected local flows, with the increased number of piles driven at the head of the jetty and the reconstruction of a jetty approach strong point potentially leading to reduced flow on the ebb tide over the maerl beds. However, a significant change due to this seems unlikely given that the new piles are similar in location and dimension to the original piles. Although more piles were added to the head of the jetty, these are generally aligned with the east-west flow vectors, so inshore flows are unlikely to have been affected. During construction, it is also possible that the spud-legs of the installation plant caused direct damage, whilst constructing the new strong point, and/or locally increased sediment concentrations as a result of scour and when they were raised. There is circumstantial evidence showing the majority of maerl bed decline is located in the vicinity of the LNG jetty along with aerial photography of sediment plumes crossing the maerl during the construction works.

It is hypothesised that vessel movements (either more generally or, specifically, during the jetty upgrade works) have disturbed the bed, increasing local sediment load and resulting in subsequent settling on maerl beds (anecdotal evidence of suspended material plumes arising from a range of anthropogenic uses around the South Hook jetty is shown in Figure 13). Vessel movements to the jetty would have dropped from their peak once the Esso refinery closed in 1983. Since South Hook LNG commenced operations in 2008, the vessel numbers have slowly increased again and are now at around two vessel visits per week. These vessel numbers remain significantly lower than during the peak refinery period (1960s-80s), although current vessel dimensions are likely to be larger now in length overall (LOA) but with similar or smaller draughts. This may result in an increased effect at the bed. In addition, larger vessels may require more assistance from tugs, which may also result in increased erosion if they need to manoeuvre in and around the maerl beds.

It is noted that the patchy cover of live maerl may mean that a very localised small change in sediment load could have a proportionally larger impact on the overall health of the wider population. For example, if most of the live maerl is confined to the jetty area (as evidenced in 2004/05 survey results in Figure 15), then highly localised impacts around the jetty (rather than a more wider, general trend in increased sediment load) may have led to the die-off of a relatively high proportion of viable individuals.

Invasive non-native species

The influence of INNS is also hypothesised to be a potential cause in the decline of maerl, either with respect to changes in bed roughness, impacts on local water quality or in resultant increased sediment load from waste products. In particular, the Slipper Limpet (*Crepidula fornicata*), is known to be present in and around the maerl beds. The first detailed maerl surveys in 2004 (RPS, 2004) did not note the occurrence. They were recorded in the 2005 surveys, but the numbers were too small to merit comment at that time. Since this time, the coverage and abundance has been shown to significantly increase in areas of former live as well as dead maerl. This species quickly occupies space, changes the bed roughness and increases the local suspended sediment load through waste excretion, which also creates anoxic conditions linked to hydrogen sulphide (another potential implication for local changes to water quality) (Grall, & Hall-Spencer, 2003; Wilson et al., 2004). This waste material also changes the nature of the bed material (increased fine content); each of these factors could (under existing levels of disturbance from prevailing baseline hydrodynamic conditions and/or local vessel movements) result in increased siltation on top of the maerl beds.

6 Future monitoring and studies

Within the scope of this study robust evidence of longer-term changes that can be defined as the cause of the observed decline in the health of the maerl beds has not been identified. However, the study has identified a number of potential issues which could be contributing to the decline of the maerl beds.

Further monitoring and investigations would be useful to provide more robust evidence of change at the maerl beds, and understand how human activities are contributing to the decline. The latter is particularly important for the management of the maerl beds in the short, medium and long term.

A programme of monitoring is recommended which is outlined in section 6.1 below. We also recommend a numerical modelling study to investigate the relationship between human activities and maerl decline and which could be used as a tool for future management. The scope for such a study is provided as section 6.2.

The following should also be considered:

- Investigate changes at other maerl beds such as the Fal Estuary and Solent (Bembridge) and determine if there are any similarities or management opportunities for Milford Haven.
- Investigate changes in water quality.

6.1 Site monitoring and survey

6.1.1 Long term monitoring

The study recommends that there is continued surveying and monitoring of the maerl beds. The collection of longer-term monitoring data, using a consistent methodology and area of coverage, would help to identify/confirm (or otherwise) trends in the distribution of live maerl across the study area. The monitoring should include:

- The health of the maerl beds.
- Seabed sediment composition. This would provide more evidence of seabed composition and identify if there is a trend for increasing silt in the bed sediment.
- Turbidity, changes in the suspended solids would help to inform an assessment of potential causes and consideration of associated impacts on the maerl. Monitoring of turbidity at the maerl beds in association with specific activities (such as dredging) or episodic events (e.g. storms) would also be important.
- Prevalence of (and future changes in) the distribution in notable INNS (specifically Slipper Limpet (*C. fornicata*)) in and around the maerl beds.
- Monitoring the effects of trial removals of Slipper Limpet (*C. fornicata*) on maerl.

6.1.2 Hydrodynamic survey

To support further investigations a hydrodynamic survey is recommended to provide details of the flow regime at the maerl beds. The survey would improve the baseline

understanding as well as provide important calibration data should a modelling study be commissioned. The survey should include:

- Two deployments of bed frames for a 1-month period over the winter to capture the impact of any storm events, and this period should be extended if no notable storms are recorded:
 - Location 1 - within the maerl bed area. Bed frame to collect levels and flows, waves, suspended sediments, dissolved oxygen, conductivity, temperature and density.
 - Location 2 - up-estuary of the Puma (formerly Murco) jetty. Bed frame to collect data on levels and flows, turbidity (to derive suspended sediments), dissolved oxygen, conductivity, temperature and density (no requirement for wave conditions at up-estuary location).
- Coincidental collection of seabed grab samples at each deployment location and (notionally) around 5 locations in between;
- Water sampling for total suspended solid analysis, for calibration of turbidity measurements;
- Should it prove possible, deployment of the bed frame equipment over a further 1-month period that included some channel dredging/ploughing activity (likely during calmer conditions between spring and autumn) would provide benefit to confirm the assumption that such works do not affect suspended sediments at the maerl bed.

6.2 Numerical modelling study

6.2.1 Scope

The desk study has used available monitoring and studies in and around Milford Haven. Whilst the maerl monitoring has provided valuable information on the potential change in sediment composition at the beds, there is no information on the local flow regime. A numerical modelling study could be used to provide more description of the local hydrodynamic and sedimentary regime around the maerl and understand if changes are of sufficient magnitude to alter sediment deposition patterns in the area of the maerl bed.

Using the standard 'Source > Pathway > Receptor' assessment methodology, the numerical model could then be used to identify pathways and test the potential implications of changes (natural and human) on the maerl beds.

The tests could examine climate change (increased river flow etc.) or activities such as dredging, marine works etc. The tests could, for example, consider the potential for:

- Increased suspended sediment concentrations over the maerl beds from dredging activity within the Haven. Further assessment could be undertaken to consider potential effects under varying tidal states (spring, neap, ebb, flood etc.), which may then inform mitigation for the dredging activity.
- Changes to local hydrodynamics (and possible associated changes to sedimentation) over the maerl beds as a result of future developments. These schemes could include changes, for example, to the existing jetty arrangements at the various terminals, addition of new schemes, changes to future baseline etc.

Although the numerical model could only provide a qualitative indication of potential increased sediment load in the vicinity of the area of interest. It could be used to confirm or eliminate some of the hypothesised pathways of change and understand the risk of different activities having an adverse effect on the maerl beds.

It is important to note that numerical models cannot be used to determine the detailed effects of previous activities as too many parameters are unknown. For example, the tidal regime at the time, exact sediment characteristics, release rates etc.

Models will also not be able to define quantitative changes at the bed or very local sediment patterns i.e. deposition/scour around Slipper Limpets or influence of maerl itself on deposition.

6.2.2 Specification

The modelling study can utilise any suitable package (there are no pre-requisites for use of existing/ available software) as long as it adequately resolves oceanographic and estuary processes. Software suits such MIKE by DHI is tailored for these environments and allow for the use of additional modules to investigate different parameters and activities. The modelling study could include:

- Understanding of the hydrodynamic regime across Milford Haven and flow speeds around the maerl beds.
- Understanding the sediment transport regime across Milford Haven with a focus on the area around the maerl beds.
- Particle tracking to investigate the source-pathway-receptor relationships between human activities (e.g. dredging or construction activities) and the maerl beds.
- A study of the contribution of waves to sediment distribution.
- An investigation of water quality.

It is recommended that any study should first focus on the hydrodynamic and sediment transport regime around the area of the maerl beds supported by particle tracking to investigate the plume dispersal from assessed dredging/ploughing activity.

In order to fully assess the potential impact of dredging/ploughing activities within the main channel, the hydrodynamic model should be run in 3D mode, with a suitable definition of the vertical layers that will allow (where necessary) for material to be transported in suspension in the deeper channel regions and close to the bed over the maerl bed areas. The alternative 2D depth-averaged mode would disperse any dredge plume throughout the water column. Given the deep natural channel within the Haven, it is likely that material dredged from the deeper regions will remain in the main channel and be dispersed up/down estuary with the tide. In such cases, the potential for this material to encroach onto the shallower shelf (and the maerl beds) is considered unlikely - hence the recommendation for 3D modelling.

In order to be able to inform as wide a range of studies as possible, the numerical model extent should cover the whole of Milford Haven from the Outer Approaches to the tidal limits of the river tributaries. Figure 18 shows a notional model extent that would inform management decisions within Milford Haven.

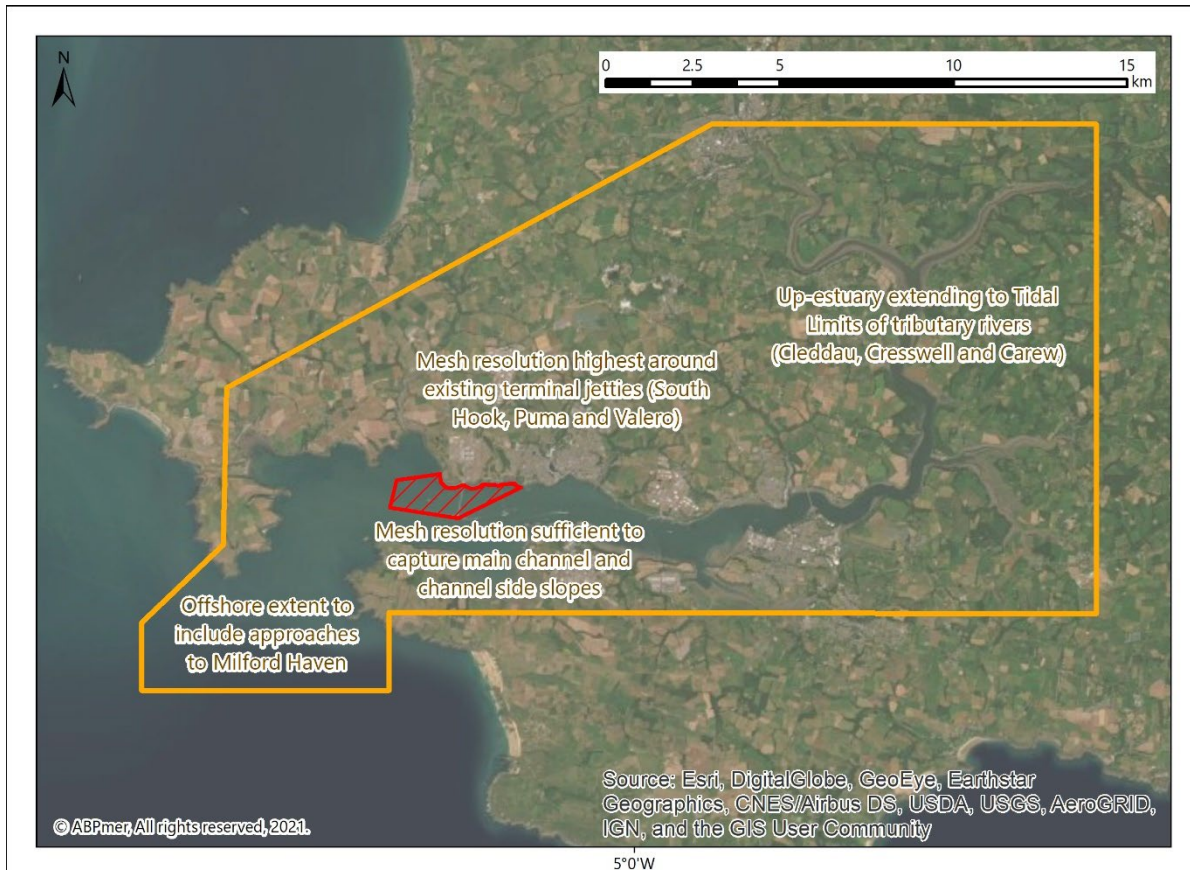


Figure 18. Notional model mesh extent for management studies within Milford Haven.

6.2.3 Model resolution

In order to take advantage of most efficient model run times, whilst still providing suitable detail around the primary area of interest, a variable resolution model mesh should be applied. Variable resolution will allow improved efficiency in model run times whilst also allowing suitable precision in prediction around the study area.

Areas of coarser resolution (around 300 to 500 m) may be applied to outer areas, such as the approaches to the Haven, with increased resolution (approximately 50 to 100 m) applied to the areas around the maerl beds and the main channel slopes. The highest resolution (around 10-20 m) can be placed along the alignments of the existing jetties within the Haven, to enable suitable implementation of the respective pile structures and associated berths.

Broad descriptions of the varying mesh resolutions across the proposed domain are also provided in Figure 18.

6.2.4 Input data

Input data for building the model should use available and suitable datasets (taking consideration of aspects such as age, coverage, resolution and reported accuracy of data). It is likely that the model build could be accomplished using existing data, including (but not specifically limited to):

- Bathymetric / topographic data - survey data available through the UKHO Marine Data Portal coupled with local port surveys (where available). Where available, high-resolution multibeam data may be used in preference to coarser single beam data. Topographic data for the bordering intertidal areas may be better sourced from available LiDAR data (e.g. the Welsh Government Lle data geoportal - <http://lle.gov.wales/home>).
- River input data (at the up-estuary boundaries) can use the available data from the National River Flow Archive (which provides data for the Eastern and Western Cleddau). Average flow rates from the Cresswell and Carew rivers might be sourced from available third-party reports.
- Offshore model boundaries for the hydrodynamic model will likely require a combination of spatially and temporally varying water levels and/or flow speeds. Such data is likely best sourced from existing, regional-scale numerical models, extracting predicted data along the defined model boundary (or boundaries) of the local Milford Haven model. Should wave modelling also be considered of interest, either a timeseries of wave conditions at the boundary, or an analysis of hindcast wave data (to define a series of specific wave events for assessment) would likely be required. Such data would likely be best sourced from existing, regional-scale hindcast wave models.
- Information related to structures associated with the existing terminal jetties (such as piles) should also be sourced for input to the model. Specifically, the locations and dimensions of the jetty piles can be implemented within the model to provide local effects on the flow regime around the jetties.

6.2.5 Calibration data

Any modelling tool will need to be calibrated against measured/predicted data in order to verify the ability to suitably represent real-world conditions. Calibration data can likely be sourced from a combination of existing data and new survey deployments, targeted specifically for the study.

Existing data could include:

- UKHO Admiralty tidal predictions for water levels and flows (speed and direction).
- Any third-party surveys undertaken (for example in support of the South Hook Terminal jetty works), that might be made available for model calibration purposes;
- Previous hydrodynamic surveys and ADCP measurements undertaken by PoMH.

To supplement the existing data, it is recommended that a new survey is commissioned, details of which are provided above.

6.2.6 Model scenarios

Specific model scenarios can be defined based on identified works (such as new developments, new jetty works or dredging activities). More general modelling scenarios to be tested could include:

- Baseline - modelling of the existing conditions within Milford Haven, verified by using the specified calibration data;

- Historic situation - it is unlikely to provide any assistance to future management decisions over the maerl beds, but it may be of background interest to test the historic situation before terminal jetties were implemented;
- General dredging activities could be tested - using a variety of dredge types (dredging, ploughing etc.), a range of locations (main channel, channel flanks, entrance channel to Milford Docks etc.), and for activities undertaken on a range of tidal conditions (spring, neap, ebb, flood etc.). Testing of releases could help to confirm whether or not any of the activities (under a given tidal state) has the potential to impact on the maerl beds and potentially help inform subsequent mitigation/management decisions.

Depending on the ultimate use of the outputs, modelling studies should be designed (where relevant) with consideration of the recent Guidance documents produced by NRW:

- GN041: Marine Physical Processes Guidance to inform Environmental Impact Assessment (EIA);
- Evidence Report No. 243: Guidance on Best Practice for Marine and Coastal Physical Processes Baseline Survey and Monitoring Requirements to inform EIA of Major Development Projects; and
- Evidence Report No. 208: Advice to Inform Development of Guidance on Marine, Coastal and Estuarine Physical Processes Numerical Modelling Assessments.

6.2.7 Costs and programme

Approximate survey costs for 2 x deployments of above equipment for each 1-month period would likely amount to around £30,000 - £35,000.

Numerical modelling costs to build, setup and calibrate a suitable model and run a discrete number of test scenarios (assumed between 3 and 5) are as follows:

- Hydrodynamics: £10,000-£15,000
- Waves: £10,000-£12,000
- Particle tracking or plume dispersion: £10,000-£12,000

Assuming the survey data had already been collected, an indicative modelling programme would be approximately three to four months depending upon the number of parameters and scenarios being investigated.

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8 Abbreviations

AMAX	Annual Maximum
CCW	Countryside Council for Wales
CD	Chart Datum
CSD	Cutter Suction Dredger
DAS	Disposal at Sea
DDV	Diving and Drop-down Video
HAT	Highest Astronomical Tide
HW	High Water
INNS	Invasive Non-Native Species
JNCC	Joint Nature Conservation Committee
LAT	Lowest Astronomical Tide
LNG	Liquefied Natural Gas
LOA	Length Overall
MHPA	Milford Haven Port Authority (also called Port of Milford Haven)
MHWESG	Milford Haven Waterways Environmental Surveillance Group
MHWN	Mean High Water Neap
MHWS	Mean High Water Spring
MLWS	Mean Low Water Neap
MLWS	Meal Low Water Spring
MSL	Mean Sea Level
NRFA	National River Flow Archive
NRW	Natural Resources Wales
NTSLF	National Tide and Sea Level Facility
ODN	Ordnance Datum Newlyn
PoMH	Port of Milford Haven

PSA	Particle Size Analysis
RCP8.5	Concentration of carbon that delivers global warming at an average of 8.5 watts per square meter across the planet
SSC	Suspended Sediment Concentration
STA	Sediment Trends Analysis
TSHD	Trailing Suction Hopper Dredger
TSS	Total Suspended Solids
UK	United Kingdom
UKCIP	UK Climate Impacts Programme
UKHO	UK Hydrographic Office

Cardinal points/directions are used unless otherwise stated.

SI units are used unless otherwise stated.

9 Appendices

9.1 Data Archive Appendix

No data outputs were produced as part of this project.