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Marine habitat mapping of the Milford Haven Waterway, Wales, UK: Comparison of facies mapping and EUNIS classification for monitoring sediment habitats in an industrialized estuary

Drew A. Carey [a,*], Melanie Hayn [a], Joseph D. Germano [b], David I. Little [c], Blaise Bullimore [d]

[a] CoastalVision, 215 Eustis Avenue, Newport, RI 02840, USA
[b] Germano & Associates, 12100 SE 46th Place, Bellevue, WA, USA
[c] 28 School Lane, Swavesey, Cambridgeshire CB24 4RL, UK
[d] Deep Green Seas/Milford Haven Waterway Environmental Surveillance Group, UK

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ABSTRACT

A detailed map and dataset of sedimentary habitats of the Milford Haven Waterway (MHW) was compiled for the Milford Haven Waterway Environmental Surveillance Group (MHWESG) from seafloor images collected in May, 2012 using sediment-profile and plan-view imaging (SPI/PV) survey techniques. This is the most comprehensive synoptic assessment of sediment distribution and benthic habitat composition available for the MHW, with 559 stations covering over 40 km^2 of subtidal habitats. In the context of the MHW, an interpretative framework was developed that classified each station within a 'facies' that included information on the location within the waterway and inferred sedimentary and biological processes. The facies approach provides critical information on landscape-scale habitats including relative location and inferred sediment transport processes and can be used to direct future monitoring activities within the MHW and to predict areas of greatest potential risk from contaminant transport.

Intertidal sediment 'facies' maps have been compiled in the past for MHW; this approach was expanded to map the subtidal portions of the waterway. Because sediment facies can be projected over larger areas than individual samples (due to assumptions based on physiography, or landforms) they represent an observational model of the distribution of sediments in an estuary. This model can be tested over time and space through comparison with additional past or future sample results. This approach provides a means to evaluate stability or change in the physical and biological conditions of the estuarine system. Initial comparison with past results for intertidal facies mapping and grain size analysis from grab samples showed remarkable stability over time for the MHW.

The results of the SPI/PV mapping effort were cross-walked to the European Nature Information System (EUNIS) classification to provide a comparison of locally derived habitat mapping with European-standard habitat mapping. Cross-walk was conducted by assigning each facies (or group of facies) to a EUNIS habitat (Levels 3 or 5) and compiling maps comparing facies distribution with EUNIS habitat distribution. The facies approach provides critical information on landscape-scale habitats including relative location and inferred sediment transport processes. The SPI/PV approach cannot consistently identify key species contained within the EUNIS Level 5 Habitats. For regional planning and monitoring efforts, a combination of EUNIS classification and facies description provides the greatest flexibility for management of dynamic soft-bottom habitats in coastal estuaries. The combined approach can be used to generate and test hypotheses of linkages between biological characteristics (EUNIS) and physical characteristics (facies). This approach is practical if a robust cross-walk methodology is developed to utilize both classification approaches. SPI/PV technology can be an effective rapid ground truth method for refining marine habitat maps based on predictive models.

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1. Introduction

The Milford Haven Waterway (MHW) is the largest ria–estuary complex in the United Kingdom (UK) representing 34% of the UK's resource of this estuary type (Fig. 1). Of the 55 km^2 area, over 30% is intertidal habitat (Burton, 2008). The waterway and the adjacent nearshore waters are included in a European marine Special Area of Conservation

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* Corresponding author at: CoastalVision, 215 Eustis Avenue, Newport, RI 02840, USA. Tel.: +1 401 849 9236.
E-mail addresses: drew@coastalvisionllc.com (D.A. Carey), melaniehayn@gmail.com (M. Hayn), joe@remots.com (J.D. Germano), david.i.little@btinternet.com (D.I. Little), deepgreenseas.bb@gmail.com (B. Bullimore).

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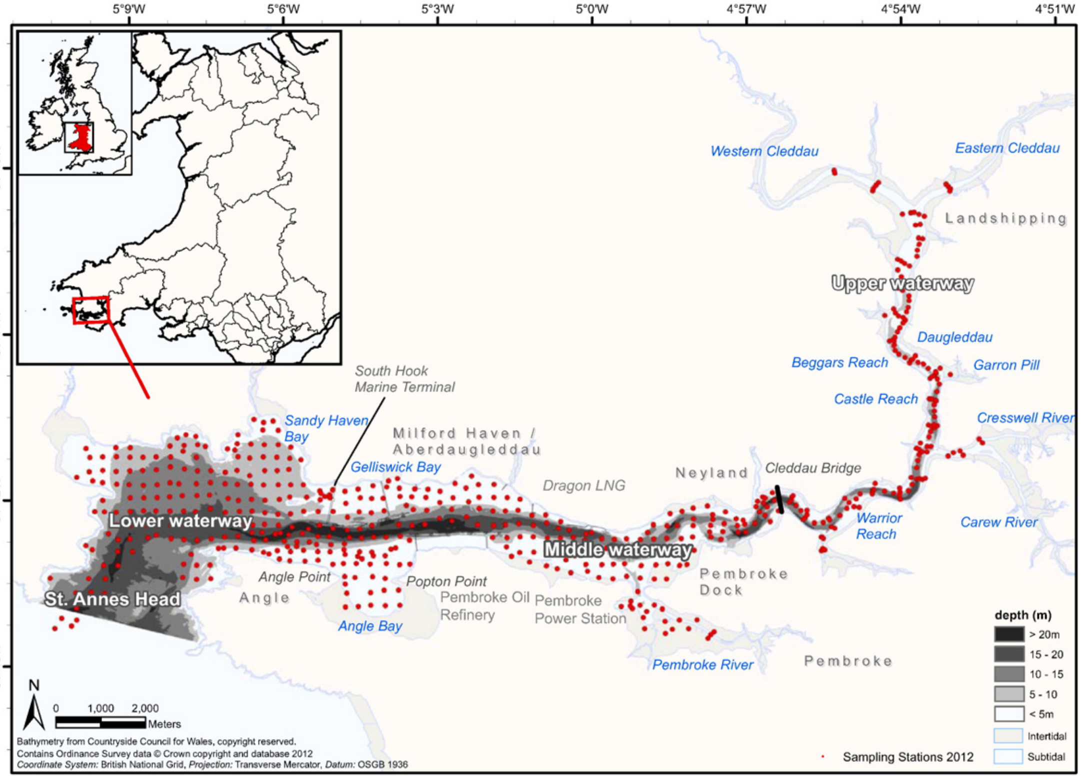


Fig. 1. Location map of Milford Haven Waterway, Pembrokeshire, Wales, UK and sampling stations occupied in 2012.

for several marine habitat types including estuaries; large shallow inlets and bays; and reefs. Management of the waterway must strive to secure the distinctive habitats and resources in the ria at a favorable conservation status while accommodating recreational and commercial uses (Countryside Council for Wales (CCW), 2009). Milford Haven is a natural deep water port that handled over 29% of the seaborne trade in oil and gas in the United Kingdom (UK) in 2012. Currently, it is the third largest port in the UK and the biggest in Wales (Milford Haven Port Authority, 2012). The waterway also supports extensive recreational use including boating, bird watching, diving and fishing. Sediment contamination from oil spills and port operations has been a major topic for monitoring in the waterway for four decades (Dicks, 1987; Hobbs and

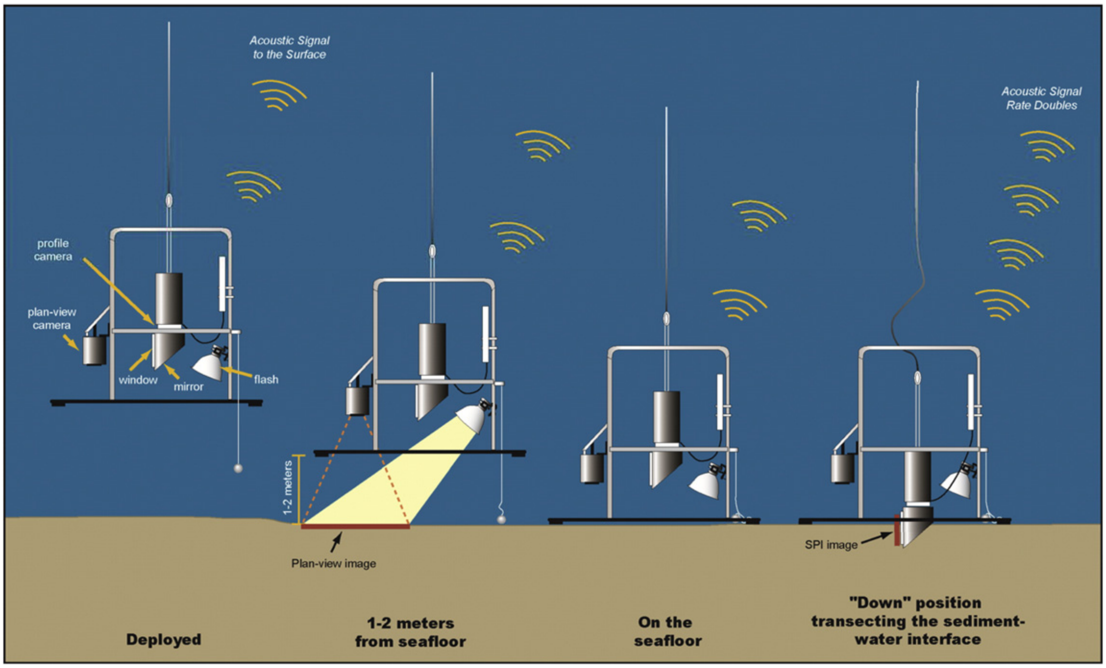


Fig. 2. Sediment profile camera (SPI) and plan view camera (PV) operation.

Table 1
Sediment facies classification table.
Modified from King (1977).

Location	Grain size	Phys/biol	Inferred process	Dominant biological	Rounding	Facies	Code	SPI/PV notes
Marginal facies		Physical			Angular	Talus of angular clasts	A1	Not sampled
						Mixed angular talus, sand and mud	A2	Not sampled
					Rounded	Talus of rounded clasts	A3	Not sampled
						Mixed rounded talus, sand and mud	A4	Shallow gravel layer over mixed muddy sand
					Sub-rounded	Mixed sub-rounded talus, sand, mud	A5	Cobble or pebble pavement
		Biological		Meadow grass		Grassed meadow margins	B1	Not sampled
				Salt marsh grass		Grassed salt marsh margins	B2	Not sampled
				Coquina/wrack		Chenier/algal wrack strandline	B3	Not sampled
Central facies	Mud	Physical		(Anemones)		Unvegetated mud	C	Fine silt some diatoms
		Biological	Biogenic low tidal current	*Spartina* sp.		'*Spartina*' dominated salt marsh	D1	Visible *Spartina* detritus
				Ulva and reds		Algae dominated mud	D2	*Ulva* and red algae/kelp
				Zostera		Seagrass dominated mud	D3	Zostera, silt
				Crepidula fornicata		Shell dominated mud	D4	Crepidula pavement, *Mytilus* sp. shells, shell hash
	Mixed	Physical	Relict lag with mud drapes	Mixed algae, hydroids and worms		Poorly sorted muddy sand with shells and pebbles	H1	Compact muddy fine sand, pebbles
			Episodic transport	Worms, burrowing anemones		Sand over mud	H2	S/M layering
	Sand	Physical	Currents			Current rippled sand	E1	Asymmetrical, linguoid
			Waves			Wave rippled sand	E2	Symmetrical ripples
			Swash			Parallel laminated sand	E3	Not sampled
		Biological	Moderate currents	*Arenicola marina*		'*Arenicola*' dominated sand	F1	Fecal coils, castings
			Freshwater	*Ulva intestinalis*		Algae dominated sand	F2	Algae, *Ulva*
			Shallow	*Zostera*		Seagrass dominated sand	F3	*Zostera*, sand
			Moderate currents	*Lanice conchilega*		*Lanice* dominated sand	F4	Tube crowns visible
			High currents	*Crepidula fornicata*		Shell dominated sand	F5	Crepidula pavement, *Mytilus* shells, shell hash, maerl
Channel facies	>Cobble	Physical	Streamflow			Stream bed gravel	G1	Not sampled
	<Cobble	Physical	Tidal currents		Rounded	Estuarine channel sand or gravel	G2	Well sorted coarse sand or gravel
	Mixed	Physical	Tidal currents			Estuarine channel mixed (sand gravel and cobbles)	G3	Poorly sorted sand matrix with isolated gravel and cobbles
	Cobble	Physical	Glacial meltwater overdeepening	Serpulids, hydroids	Rounded	Channel lag	G4	Cobble pavement
	Mud	Physical	Deposition			Channel mud	G5	Fine silt and light clay
	Mud	Biological	Biogenic	*Crepidula fornicata*		Channel mud with shells	G6	*Crepidula* pavement

Morgan, 1992; Little, 2009; Little et al., 1987; Rostron et al., 1987). A prime environmental management goal has been to utilize understanding of sediment transport pathways to monitor and protect benthic habitats from future contaminant impacts (Little, 2009; McLaren and Little, 1987). This management goal requires accurate and informative maps of benthic habitats and sediment processes.

Use of direct seafloor sampling to describe seafloor ecosystems has a long history (Elefteriou and McIntyre, 2005). The concept of describing 'facies', rock or sediment units with distinctive characteristics, was first used in 1838 and has expanded to include environmental and biological characteristics and the processes inferred to produce the unit (Reading, 1996). More recently, access to detailed physiographic data from acoustic systems and rapid collection of biological data using imaging systems has led to development of benthic habitat mapping approaches that integrate geological and biological data (Diaz et al., 2004). The challenge for the MHWESG was common to many coastal management efforts: best use of limited resources to produce detailed benthic habitat maps suitable for local management and capable of integration with regional mapping efforts.

A recent review of benthic habitat mapping (Brown et al., 2011) defined three primary strategies for development of effective benthic habitat maps: 1) Abiotic surrogate mapping; 2) Assemble first, predict later (unsupervised classification); and 3) Predict first, assemble later (supervised classification). The third strategy utilizes *in situ* biological and geological data to model habitat or biotope classes and then create maps of predicted distribution of habitat classes. One example of a geoform or biotope model that can be used to predict habitat distribution is the facies model (Reading, 1996). Because a facies model existed for the intertidal portion of the waterway (King, 1977, 1980), extension of this model into subtidal habitats was proposed as an effective approach for benthic habitat mapping of the waterway for MHWESG. Development of these predictive maps of habitats (strategy 3, *sensu* Brown et al., 2011) could be used to guide monitoring efforts, to refine understanding of the waterway and to meet the needs of the MHWESG's members and other local management organizations for fine-scale or very fine-scale habitat maps (mapping units on the scale of tens to hundreds of meters).

The development of a unified habitat classification approach for European marine waters has stimulated construction of habitat maps of the region at many scales utilizing historical information, predictive modeling, as well as new mapping efforts (MESH, 2010). The European Nature Information System (EUNIS) habitat classification model has been adopted by the Mapping European Seabed Habitats (MESH) project, and predictive modeling has been applied in a top-down, rule-based approach, combining environmental variables to classify areas into different habitats to predict habitat distribution in the region (Coltman et al., 2008). The EUNIS structure is based on three levels of environmental variables (substrate, biological zone, energy) that define a 'habitat envelope'; below these levels, information on biological communities is needed to classify further. The EUNIS classification utilizes component units from other classification systems in the framework but many mapping programs use statistical analysis of species records (bottom-up approach) to classify biological communities. This dichotomy of a hierarchical habitat envelope linked to a more open underlying classification provided an opportunity to utilize an existing framework (facies model) developed for the needs of the local environment and cross-walk to EUNIS classification to support larger scale habitat map development.

Sediment-profile and plan-view imaging (SPI/PV) is an *in situ* method to collect high resolution sample data using rapid assessment protocols (Germano et al., 2011). SPI was developed over three decades ago as a rapid reconnaissance tool for characterizing physical, chemical, and biological seafloor processes and has been used in numerous seafloor surveys throughout North America, Asia, Europe, and Africa (Diaz and Schaffner, 1988; Germano et al., 2011; Revelas et al., 1987; Rhoads and Germano, 1982, 1986, 1990; Valente et al., 1992). The sediment-profile camera works like an inverted periscope, the details of the operation are described in Germano et al. (2011). The SPI survey obtained images of cross-sections of the sediment–water interface and plan-view images of the seafloor surface. The results included grain-size information, evidence of sediment transport conditions, biological characteristics, and the effects of biological activity. SPI and PV can detect some conspicuous 'focal' (used to classify habitats) species but are primarily used to infer process from patterns of sedimentological and biological processes. The observed textures and patterns in the seafloor surface and subsurface provide evidence of the recent history of geological and biological processing that is relevant to management decisions (sediment and contaminant transport, distribution and condition of relevant marine habitat types).

A fine-scale survey of MHW was conducted to create a detailed physiographic map of the waterway with sediment and biological data to predict areas of greatest potential risk from contaminants and support management of potential contaminant transport; inform assessment of benthic communities and guide benthic sampling; and to inform environmental impact assessments. Following completion of the mapping, the classes were compared to EUNIS classification and to predictive models of EUNIS habitats.

The results from the SPI/PV technology survey provided a synoptic view of the sediment mosaic of the entire subtidal portion of the waterway; the most comprehensive assessment of sediment distribution and benthic habitat composition available for the MHW. The 559 subtidal stations complemented and largely endorsed the extensive intertidal and subtidal sediment data collections conducted prior to this study (Little, 2009; Rostron et al., 1987). A wide-ranging review of sediment contaminants and sediment transport in the MHW concluded that a fine-scale map of the waterway derived from SPI images would benefit management of the waterway (Little, 2009). A comprehensive review of the benthic ecology studies in the waterway concluded that benthic monitoring should adopt National Marine Monitoring Programme (now renamed the Clean Seas Environment Monitoring Programme; CSEMP) methods and focus on a small number of subtidal stations selected to have a representative geographical coverage and a representative range of community types (Warwick, 2006). The Joint Nature Conservation Committee (JNCC) has gathered benthic and sediment data from the coastal waters of the UK and published habitat maps including MHW (Coltman et al., 2008; McBreen et al., 2011). This study provides high resolution data classified by facies and explores linkages to the Mapping European Seabed Habitats (MESH) maps based on the EUNIS classification.

2. Materials and methods

2.1. Study site

The MHW is located in Pembrokeshire, Wales, UK. The study encompassed the ria–estuary from the main entrance channel off St. Anne's Head in 28 m of water to the junction of the western and eastern Cleddau in 4 to 6 m of water (Fig. 1). One of the unusual characteristics of the Milford Haven ria is that it includes large amounts of rocky substrate throughout the waterway. Habitats of particular interest within the ria include eelgrass and maerl beds. Eelgrass (*Zostera* spp.) is the only subtidal British marine flowering plant and is rare in Wales. The plants form very productive beds which stabilize mobile sediment and provide shelter for fish. Maerl is very slow growing, nodule forming, calcareous red alga that interlocks to form a loose lattice structure which provides a valuable microhabitat for other species. The waterway is home to one of the most diverse estuarine communities in the UK and the embayments and rivers provide winter feeding and summer breeding habitats for wetland birds. Wildfowl and wader coordinated counts routinely record nationally-important numbers of wintering shelduck, wigeon, and curlew and significant numbers of teal, greenshank, and redshank, with total numbers in winter sometimes reaching over

Table 2
Sediment facies classification table with best fit EUNIS habitats.

Location	Grain size	Facies	Code	SPI/PV notes	EUNIS best fit habitat			Level 5	Level 4	Level 3
					Inter-tidal	Infra-littoral	Circa-littoral			
Marginal facies		Mixed rounded talus, sand and mud	A4	Shallow gravel layer over mixed muddy sand	–	3.215	5.141	5.141—[*Pomatoceros triqueter*] with barnacles and bryozoan crusts on unstable circalittoral cobbles and pebbles 3.215—Dense foliose red seaweeds on silty moderately exposed infralittoral rock	5.14—Circalittoral coarse sediment 3.21—Kelp and seaweeds (moderate energy infralittoral rock)	5.1—Sublittoral coarse sediment 3.2—Moderately exposure boulders
		Mixed subrounded talus, sand, mud	A5	Cobble or pebble pavement	–	3.215	5.141	5.141—See above 3.215—See above	5.14—See above 3.22—See above	5.1—See above 3.2—See above
Central facies	Mud	Unvegetated mud	C	Fine silt some diatoms	2.33	5.3225.334	–	5.322—[*Aphelochaeta marioni*] and [*Tubificoides*] spp. in variable salinity infralittoral mud 5.334—[*Melinna palmata*] with [*Magelona*] spp. and [*Thyasira*] spp. in infralittoral sandy mud	2.33—Marine mud shores 5.32—Sublittoral mud in variable salinity 5.33—Infralittoral sandy mud	2.3—Littoral mud 5.3—Sublittoral mud
		Spartina salt marsh	D1	Visible *Spartina* detritus	2.554	–	–	2.554—Flat-leaved [*Spartina*] swards	2.55—Pioneer saltmarshes	2.5—Coastal saltmarshes
		Algae dominated mud	D2	*Ulva* and red algae/kelp	2.821	5.524	–	2.821—Ephemeral green and red seaweeds on variable salinity and/or disturbed eulittoral mixed substrata 5.524—[*Laminaria saccharina*], [*Gracilaria gracilis*] and brown seaweeds on full salinity infralittoral sediment	2.82—Ephemeral green or red seaweeds (freshwater or sand-influenced) on mobile substrata	2.8—Features of littoral sediment
		Seagrass dominated mud	D3	*Zostera*, silt	2.611	5.533	–	2.611—Mainland Atlantic *Zostera* sp. meadows 5.533—[*Zostera*] beds in full salinity infralittoral sediments	2.61—Seagrass beds on littoral sediments 5.53—Seagrass beds on infralittoral sediments	2.6—Littoral sediments dominated by aquatic angiosperms 5.5—Sublittoral macrophyte-dominated sediment
		Shell dominated mud	D4	Crepidula pavement, *Mytilus* shells, shell hash	2.31 2.32	5.422	–	5.422—[*Crepidula fornicata*] and [*Mediomastus fragilis*] in variable salinity infralittoral mixed sediment	5.42—Sublittoral mixed sediments in variable salinity	5.4—Sublittoral mixed sediments
	Mixed	Poorly sorted muddy sand with shells and pebbles	H1	Compact muddy fine sand, pebbles	2.41	–	–	No direct analog	2.41—[Hediste diversicolor] dominated gravelly sandy mud shores 5.44—Circalittoral mixed sediments	2.4—Littoral mixed sediments 5.4—See above
		Sand over mud	H2	S/M layering	2.24	–	–	No direct analog	2.24—Polychaete/bivalve-dominated muddy sand shores	2.2—Littoral sand and muddy sand 5.4—See above

(continued on next page)

Table 2 *(continued)*

Location	Grain size	Facies	Code	SPI/PV notes	EUNIS best fit habitat			Level 5	Level 4	Level 3
					Inter-tidal	Infra-littoral	Circa-littoral			
	Sand	Current rippled sand	E1	Asymmetrical, linguoid	–	5.134	–	5.134—[*Hesionura elongata*] and [*Microphthalmus similis*] with other interstitial polychaetes in infralittoral mobile coarse sand	5.13—Infralittoral coarse sediment	5.1—See above
		Wave rippled sand	E2	Symmetrical ripples	–	5.134	–	5.134—See above	5.13—See above	5.1—See above
		‘*Arenicola*’ dominated sand	F1	Fecal coils, castings	–	5.243	–	5.243—[*Arenicola marina*] in infralittoral fine sand or muddy sand	5.24—Infralittoral muddy sand	5.2—Sublittoral sand
		Algae dominated sand	F2	Algae, *Ulva*	2.821	5.521	–	2.821—See above 5.521—[*Laminaria saccharina*] and red seaweeds on infralittoral sediments	2.82—See above 5.52—Kelp and seaweed communities on sublittoral sediment	2.8—See above 5.5—Sublittoral macrophyte-dominated sediment
		Seagrass dominated sand	F3	*Zostera*, sand	–	5.533	–	5.533—See above	5.53—See above	5.5—See above
		Lanice dominated sand	F4	Tube crowns visible	–	5.137	–	5.137—Dense [*Lanice conchilega*] and other polychaetes in tide-swept infralittoral sand and mixed gravelly sand	5.13—See above	5.1—See above
		Shell dominated sand	F5	*Crepidula* pavement, *Mytilus*	–	5.431	–	5.431—[*Crepidula fornicata*] with ascidians and anemones on infralittoral coarse mixed sediment	5.43—Infralittoral mixed sediments	5.4—See above
				Shells, shell hash, maerl		5.515	–	5.515—Association with rhodoliths in coarse sands and fine gravels under the influence of bottom currents	5.51—Maerl beds	5.5—See above
Channel facies	<Cobble	Estuarine channel sand or gravel	G2	Well sorted coarse sand or gravel	–	5.134	5.12	5.134—See above	5.12—Sublittoral coarse sediment in variable salinity (estuaries) 5.13—See above	5.1—See above
	Mixed	Estuarine channel mixed (sand gravel and cobbles)	G3	Poorly sorted sand matrix with isolated gravel and cobbles	–	–	5.444	5.444—[*Flustra foliacea*] and [*Hydrallmania falcata*] on tide-swept circalittoral mixed sediment	5.44—See above	5.4—See above
	Cobble	Channel lag	G4	Cobble pavement	2.12	–	5.141 5.444	5.141—See above 5.444—See above	5.14—See above 5.44—See above	5.1—See above 5.4—See above
	Mud	Channel mud	G5	Fine silt and light clay	–	–	5.443	5.443—See above	5.44—See above	5.4—See above
	Mud	Channel mud with shells	G6	*Crepidula* pavement	–	5.422	–	5.422—See above	5.42—See above	5.4—See above
Classes			21		8	13	4	18	19	13

33,000, and averaging 23,422 between 2005 and 2010 (Holt et al., 2011).

The MHW has been industrialized in some form since at least the medieval period (Crane and Murphy, 2010) but substantial alterations to the waterway's sediment transport and contaminant loads likely began with the use of steam power in the mining and shipping industries in the 19th century. Alterations included construction of docks and shipyards, silting of harbors, dredging of channels and the massive oil fire that resulted from bombing the naval oil depot at Pembroke Dock in 1940. With one of the deepest natural harbors in the world, MHW has long been a busy shipping channel with ferries, cargo and cruise ship traffic making the port the largest in Wales (Milford Haven Port Authority, 2012).

Oil refineries and port facilities were constructed in Milford Haven as early as 1960 and the area still has two refineries, two large Liquefied Natural Gas (LNG) plants, jetties, pipelines, and one of the UK's largest storage terminals for bulk petroleum products. Beginning with shipments in 2009, Milford Haven became home to two LNG terminals. South Hook LNG is based on the former Esso refinery facility, while Dragon LNG is based on a brownfield site of the Gulf oil refinery, now also housing SEMLogistics chemicals (Fig. 1). Industrialization has resulted in apparent changes in sediment resuspension, transport and contaminant accumulation within the waterway (see reviews in Little, 2009; Little and Bullimore, 2015).

Sampling was limited to locations with sufficient water depth for the research vessel and camera equipment to function (2 m). With a peak spring tidal range of over 7 m, many of the shallow stations were located in intertidal areas. The deepest stations were located in a dredged channel in the central portion of the waterway which is nominally 20 m deep, but several stations exceeded that depth adjacent to the South Hook marine terminal, up to a maximum of 33 m. East of the dredged channel the thalweg (line of lowest elevation within the waterway) contains numerous reaches with narrow profiles (<50 m wide) and rocky substrata alternating with broad reaches (>500 m wide) with soft substrata (Fig. 1).

2.2. Field sampling

Between 15 and 26 May 2012, sediment-profile (SPI) and plan-view (PV) images were collected at 559 stations from the Environment Agency Survey Vessel *Coastal Guardian*.

An Ocean Imaging Systems Model 3731 sediment-profile (SPI) camera system and an Ocean Imaging Systems Model DSC16000 plan-view camera (PV) system each with a Nikon D7000 16.2-megapixel SLR camera were used for this survey. A total of 1733 sediment-profile and ca. 912 useable plan-view images were collected (Fig. 1) during the course of the survey (at least 3 replicates at each station). Both SPI and PV images were collected during each "drop" of the system (Fig. 2)

For this survey, the SPI images were acquired with the ISO-equivalent set at 640 and stored in compressed raw Nikon Electronic Format (NEF) files (approximately 20 MB each). At least three replicate images were taken at each station.

Two Ocean Imaging Model 400-37 Deep Sea Scaling lasers were mounted on the DSC16000 attached to the sediment-profile camera frame and used to provide a scale in plan-view photographs of the seafloor surface. The PV system consisted of Nikon D-7000 encased in an aluminum housing, a 24 VDC autonomous power pack, a 500 W strobe, and a bounce trigger. A weight was attached to the bounce trigger with a stainless steel cable so that the weight hung below the camera frame. The scaling lasers project 2 red dots that are separated by a constant distance (26 cm) regardless of the field of view of the PV, which can be varied by increasing or decreasing the length of the trigger wire. As the camera apparatus was lowered to the seafloor, the weight attached to

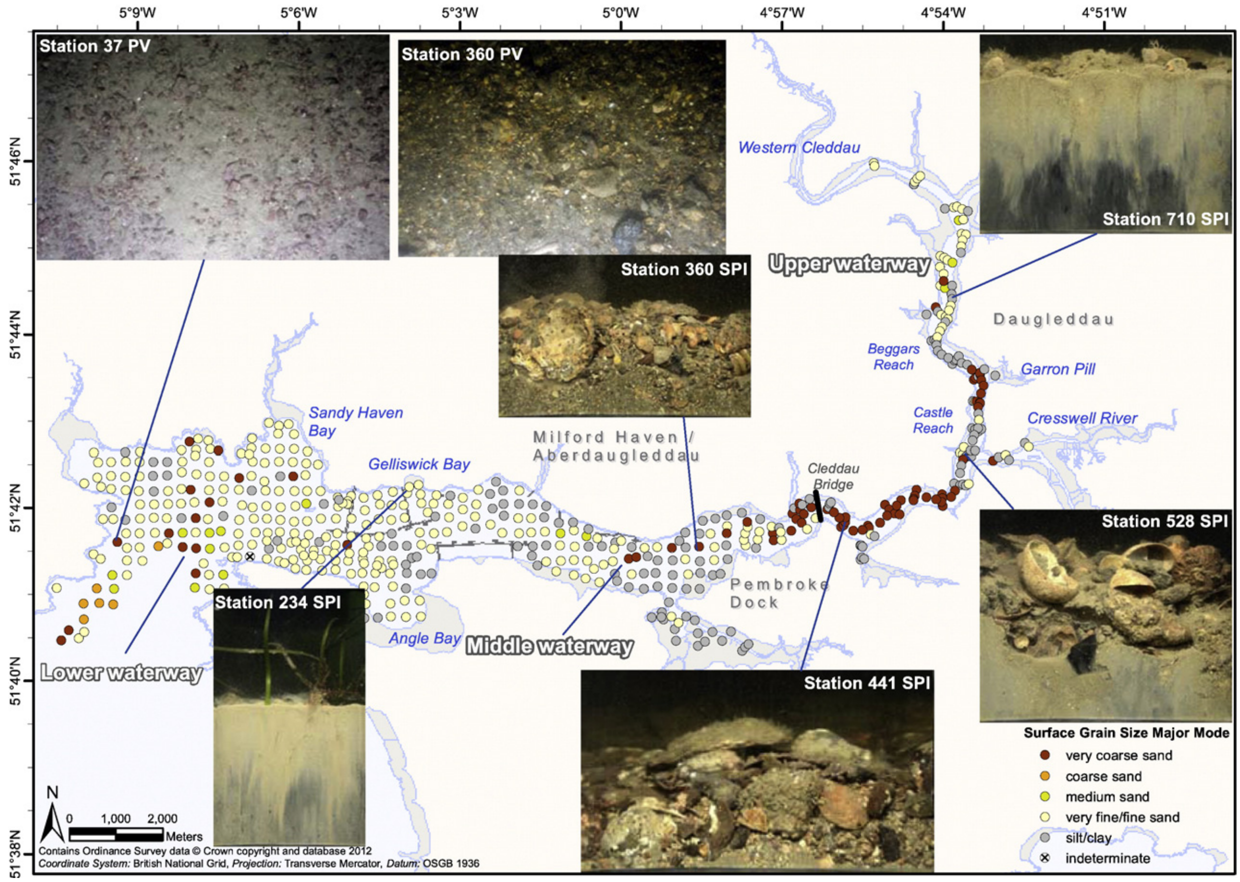
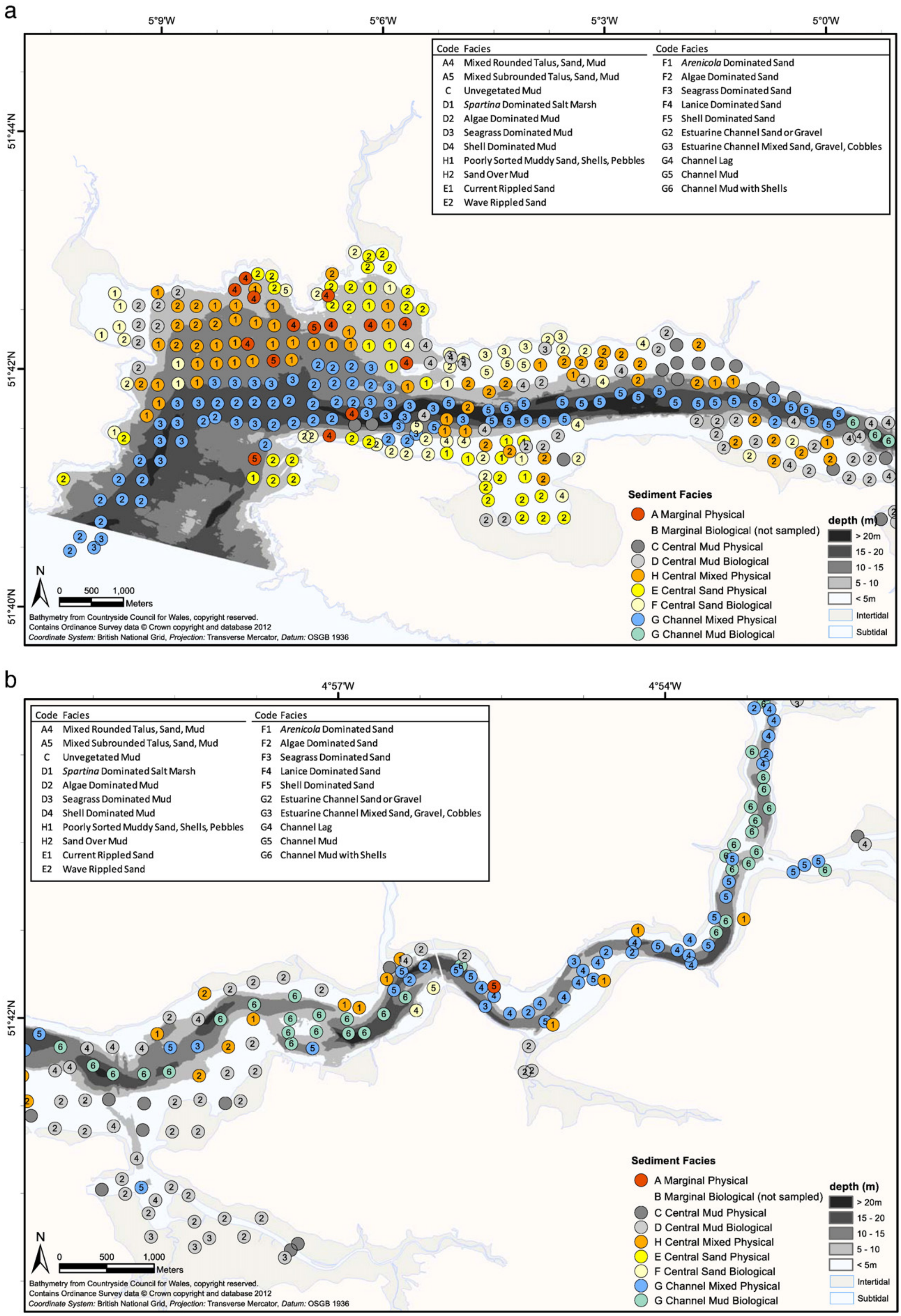


Fig. 3. Representative plan view and SPI images from sections of the Milford Haven Waterway in 2012.


a
5°9'W
5°6'W
5°3'W
5°0'W
51°44'N
51°42'N
51°40'N
Code Facies
A4 Mixed Rounded Talus, Sand, Mud
A5 Mixed Subrounded Talus, Sand, Mud
C Unvegetated Mud
D1 Spartina Dominated Salt Marsh
D2 Algae Dominated Mud
D3 Seagrass Dominated Mud
D4 Shell Dominated Mud
H1 Poorly Sorted Muddy Sand, Shells, Pebbles
H2 Sand Over Mud
E1 Current Rippled Sand
E2 Wave Rippled Sand
F1 Arenicola Dominated Sand
F2 Algae Dominated Sand
F3 Seagrass Dominated Sand
F4 Lanice Dominated Sand
F5 Shell Dominated Sand
G2 Estuarine Channel Sand or Gravel
G3 Estuarine Channel Mixed Sand, Gravel, Cobbles
G4 Channel Lag
G5 Channel Mud
G6 Channel Mud with Shells
Sediment Facies
A Marginal Physical
B Marginal Biological (not sampled)
C Central Mud Physical
D Central Mud Biological
H Central Mixed Physical
E Central Sand Physical
F Central Sand Biological
G Channel Mixed Physical
G Channel Mud Biological
depth (m)
> 20m
15 - 20
10 - 15
5 - 10
< 5m
Intertidal
Subtidal
N
0 500 1,000 Meters
Bathymetry from Countryside Council for Wales, copyright reserved.
Contains Ordinance Survey data © Crown copyright and database 2012
Coordinate System: British National Grid, Projection: Transverse Mercator, Datum: OSGB 1936
b
4°57'W
4°54'W
51°42'N
Code Facies
A4 Mixed Rounded Talus, Sand, Mud
A5 Mixed Subrounded Talus, Sand, Mud
C Unvegetated Mud
D1 Spartina Dominated Salt Marsh
D2 Algae Dominated Mud
D3 Seagrass Dominated Mud
D4 Shell Dominated Mud
H1 Poorly Sorted Muddy Sand, Shells, Pebbles
H2 Sand Over Mud
E1 Current Rippled Sand
E2 Wave Rippled Sand
F1 Arenicola Dominated Sand
F2 Algae Dominated Sand
F3 Seagrass Dominated Sand
F4 Lanice Dominated Sand
F5 Shell Dominated Sand
G2 Estuarine Channel Sand or Gravel
G3 Estuarine Channel Mixed Sand, Gravel, Cobbles
G4 Channel Lag
G5 Channel Mud
G6 Channel Mud with Shells
Sediment Facies
A Marginal Physical
B Marginal Biological (not sampled)
C Central Mud Physical
D Central Mud Biological
H Central Mixed Physical
E Central Sand Physical
F Central Sand Biological
G Channel Mixed Physical
G Channel Mud Biological
depth (m)
> 20m
15 - 20
10 - 15
5 - 10
< 5m
Intertidal
Subtidal
N
0 500 1,000 Meters
Bathymetry from Countryside Council for Wales, copyright reserved.
Contains Ordinance Survey data © Crown copyright and database 2012
Coordinate System: British National Grid, Projection: Transverse Mercator, Datum: OSGB 1936

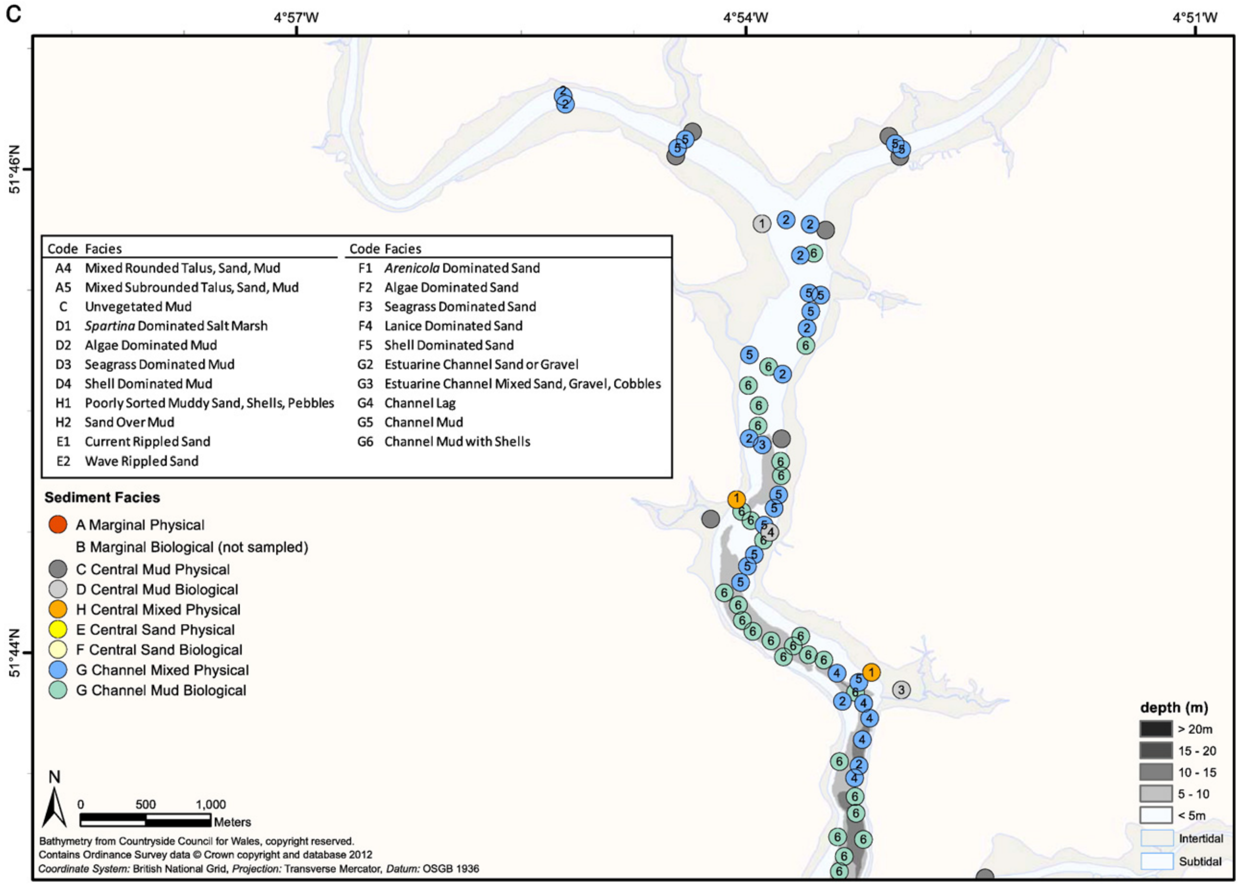


Fig. 4. a. Stations classified to facies in lower Milford Haven Waterway. Numbers in station markers refer to subfacies in upper legend. b. Stations classified to facies in middle Milford Haven Waterway. c. Stations classified to facies in upper Milford Haven Waterway.

the bounce trigger contacted the seafloor prior to the camera frame hitting the bottom and triggered the PV (Fig. 2).

The ability of the PV camera to collect usable images was dependent on the clarity of the water column. To minimize the effects of turbid bottom waters, the bounce trigger cable was shortened to 1 m in order to decrease the distance between the camera focal plane and the seafloor. By limiting the distance between the camera lens port and the intended subject, picture clarity was improved. Even with the short trigger cable, many PV images were not usable due to the highly turbid bottom waters.

Analysis was performed on one representative SPI and PV image replicate from each station due to the large number of stations. Replicates from 50 randomly selected stations were analyzed for assessment of variation within stations (Germano & Associates, 2013).

2.3. Analysis

Details of SPI imaging analytical methods have been described previously (Germano & Associates, 2013; Germano et al., 2011). The parameters most relevant to habitat mapping are described briefly.

2.3.1. Sediment type

The sediment grain size major mode and range were visually estimated from the color images by overlaying a grain size comparator at the same scale. This comparator was prepared by photographing, using the SPI camera, a series of seven Udden–Wentworth size classes expressed as particle diameter in mm on the $-\log_2$ or phi (ϕ) scale, as follows: >4 ϕ (silt-clay), 4–3 ϕ (very fine sand), 3–2 ϕ (fine sand), 2–1 ϕ (medium sand), 1–0 ϕ (coarse sand), 0–(−)1 ϕ (very coarse sand), <−1 ϕ (granule and larger). The lower limit of optical resolution of the photographic system was about 62 μm, allowing recognition of grain sizes equal to or greater than coarse silt (≥4 ϕ). The accuracy of this method has been documented by comparing SPI estimates with grain size statistics determined from laboratory sieve analyses (Germano et al., 2011). Notes are made of sediment layering (e.g., fine sand over silt/clay) but, in general, the major mode description represents that dominant grain size within the field of view (up to 15 cm below the surface). Special attention was paid to surface sediment layers in this study because of the complex sediment dynamics within the waterway.

The comparison of the SPI images with Udden–Wentworth sediment standards photographed through the SPI optical system was also used to map near-surface stratigraphy such as sand-over-mud and mud-over-sand. When mapped on a local scale, this stratigraphy can provide information on relative transport magnitude and frequency. When grain size is interpreted from plan-view images, only the sediment surface can be observed. For this study, estimates of dominant grain size in the surface sediments were converted to Folk size classes (Germano & Associates, 2013).

2.3.2. Apparent redox potential discontinuity depth

Aerobic near-surface marine sediments typically have higher reflectance relative to underlying hypoxic or anoxic sediments. Surface sands washed free of mud also have higher optical reflectance than underlying muddy sands. These differences in optical reflectance are readily apparent in SPI images; the oxidized surface sediment contains particles coated with ferric hydroxide (an olive or tan color when associated with particles), while reduced and muddy sediments below this oxygenated layer are darker, generally gray to black (Fenchel, 1969; Lyle, 1983). The boundary between the colored ferric hydroxide surface sediment and underlying gray to black sediment is called the apparent redox potential discontinuity (aRPD).

The depth of the aRPD in the sediment column is an important time-integrator of dissolved oxygen conditions within sediment pore waters. In the absence of bioturbating organisms, this high reflectance layer (in muds) will typically reach a thickness of 2 mm below the sediment–water interface (Rhoads, 1974). This depth is related to the supply rate of molecular oxygen by diffusion into the bottom and the consumption of that oxygen by the sediment and associated microflora. In sediments that have very high sediment oxygen demand (SOD), the sediment may lack a high reflectance layer even when the overlying water column is aerobic.

The aRPD depth also can be affected by local erosion. Scouring from tidal currents or waves can wash away fines and shell or gravel lag deposits, and can result in very thin surface oxidized layers. During storm periods, erosion may completely remove any evidence of the aRPD (Fredette et al., 1988).

Because the determination of the aRPD requires discrimination of optical contrast between oxidized and reduced particles, it is difficult, if not impossible, to determine the depth of the aRPD in well-sorted sands of any size that have little to no silt or organic matter in them (Germano et al., 2011). Measurements from SPI images in sand bottoms are mainly limited to grain size, prism penetration depth and boundary roughness. While oxygen no doubt penetrates the sand beneath the sediment–water interface because of physical forcing factors acting on surface roughness elements (Huettel et al., 1998; Ziebis et al., 1996), estimates of the mean aRPD depths in these types of sediments are indeterminate with conventional white light photography.

2.3.3. Infaunal successional stage and biological processes

The mapping of infaunal successional stages is readily accomplished using SPI technology. These stages are recognized in SPI images by the presence of dense assemblages of near-surface polychaetes and/or the presence of subsurface feeding voids; both may be present in the same image. Mapping of successional stages is based on the theory that organism–sediment interactions in fine-grained sediments follow a predictable sequence after a major seafloor perturbation. This theory states that primary succession results in “the predictable appearance of macrobenthic invertebrates belonging to specific functional types following a benthic disturbance. These invertebrates interact with sediment in specific ways. Because functional types are the biological units of interest…, our definition does not demand a sequential appearance of particular invertebrate species or genera” (Rhoads and Boyer, 1982). This theory is presented in Pearson and Rosenberg (1978) and further developed in Rhoads and Germano (1982) and Rhoads and Boyer (1982).

While the successional dynamics of invertebrate communities in fine-grained sediments have been well documented, the successional dynamics of invertebrate communities in sand and coarser sediments are not well known. Consequently, the insights gained from SPI technology regarding biological community structure and dynamics in sandy and coarse-grained bottoms are limited to descriptions of visible organisms and sediment patterns (burrows, pits, mounds).

The successional stage derived from SPI images is most frequently used for assessing the quality of benthic habitats (Germano et al., 2011). For mapping benthic habitats, evidence of successional stage is combined with descriptions of biological processes (presence of tubes, visible organisms, deep sediment mixing, aRPD depth) to refine habitat classes.

2.4. Plan-view image analysis

The PV images provide a much larger field of view than the sediment-profile images (SPI) and provide valuable information about the landscape ecology and sediment topography in the area around the SPI image. Unusual surface sediment layers/textures or structures detected in any of the SPI images can be interpreted in the wider context

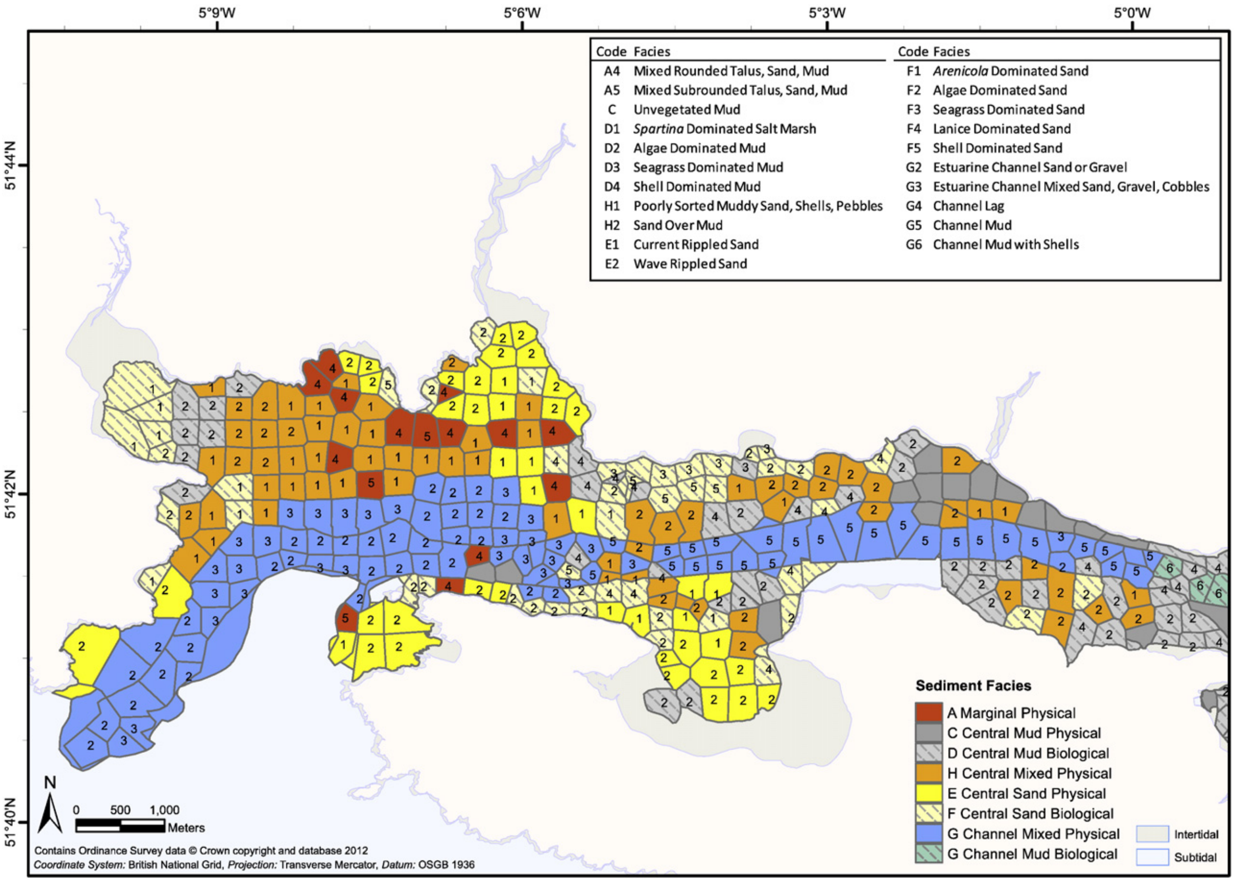


Fig. 5. Distribution of facies in Thiessen polygons.

of surface sediment features, e.g., whether a surface layer or topographic feature is a regularly occurring feature and typical of the bottom in this general vicinity or an isolated anomaly. The scale information provided by the underwater lasers allows accurate density counts (number per square meter) of attached epifaunal colonies, sediment burrow openings, or larger macrofauna or epibiota which may be missed in the matched SPI cross-section. Information on sediment transport dynamics and bedform wavelength may also be apparent from PV image analysis.

For the MHW survey two separate analyses of PV images were conducted: descriptions of surface features (epifauna, epiflora, tracks and trails); and a classification of sediment facies utilizing sediment textural data from SPI images and sediment patterns from PV images. Descriptive notes on each PV image were used for initial classification of sediment facies; the presence and abundance of bedforms, large cobbles and shells are easier to determine from plan-view images than from SPI images.

A series of categories was developed for description of surface features: sediment type, shell debris, bedforms, anthropogenic debris, red algae, brown algae, green algae, tubes, burrows, epi/infauna, and bentho-pelagic fauna. A modified Udden–Wentworth classification was used to describe sediment type, though the resolution of PV images does not permit the same grain size assessment as SPI images (Wentworth classification was converted to Folk classification for mapping; Germano & Associates, 2013). Shell debris was described as absent, scarce, present or abundant; the presence of maerl was noted. Bedforms were recorded as flat or rippled. Anthropogenic debris was described. Algal types were coded and recorded in terms of percent cover. Epi/infauna and bentho-pelagic fauna were coded and counted. To facilitate enumeration, examples of observed fauna and flora were collected into a reference table (Germano & Associates, 2013). Much of the biota could not be determined to species, or in extreme cases to phylum, from the PV images because of high water turbidity in many locations.

Notes on each PV image were also used for initial classification of sediment facies; the presence and abundance of bedforms, large cobbles and shells are easier to determine from plan-view images than from SPI images.

2.5. Classification: using imaging data to describe sediment facies

Facies are typically described from visual observation of exposed intertidal sediments (King, 1977), subtidal deposits or a combination of exposed rock outcrops and core samples (Reading, 1996). Facies can be strictly observational (often referred to as sub-facies) or may also include interpretation of the processes responsible for their formation (i.e., turbidite facies). Facies may be based on purely physical attributes (lithofacies) or biological or fossil components (biofacies). Facies descriptions have considerable value in grouping similar sediment or rock types within depositional environments (channel, delta, lagoon) to permit interpretation, mapping and predictive modeling (including prediction of habitat and contaminant distribution). Because facies generally scale to the dimensions of the basin (sediment units in estuaries are spatially limited compared to offshore basins), they are effective across a range of mapping scales.

Previous intertidal surveys of facies in MWH were hierarchical and driven firstly by location, then grain size and explicitly physical or biological dominants (King, 1977, 1980). Because the present survey was limited to subtidal stations and King's work was limited to the intertidal of one section of the MHW (but see Little, 2009 for additional intertidal), there was little overlap in locations or facies. After SPI and PV images had been described using the methods discussed above, a review was made of each station's characteristic location, grain size, dominant physical and biological features, and any evidence of inferred processes (i.e., current vs. wave ripples). The channel location was defined by a hand-contoured shapefile based on the change in slope between channel and shallow regions of MWH. When groups of characteristics could not be reliably assigned to an existing facies, new facies descriptions were developed and gathered into a reference table (Table 1). Sedimentary facies are distinguished by sedimentary, geochemical and biological processes which were inferred from visual evidence on the seafloor surface (ripples, erosional features, mud layers, biota) and sedimentary horizons below the sediment–water interface (sand over mud layers, lag deposits, deep bioturbation, aRPD depth, feeding voids).

2.5.1. EUNIS classification

Two independent methods were used to classify SPI/PV station data into EUNIS habitats: hierarchical and bottom-up. After assemblage of all classifications, the results were combined into a best fit classification (Table 2).

For the hierarchical approach, data points were classified through the EUNIS structure: Level 1: Marine, Level 2: Substrate/Depth; Rock/Sediment; Intertidal/Subtidal, and Level 3: Grain size/Energy; Coarse/Sand/Mixed/Mud; High/Moderate/Low (Davies et al., 2004; Moss, 2008). In a complex estuary, the boundary between ocean and estuarine salinity is a time dependent phenomenon, but maps of surface isohalines provided a guide (Nelson-Smith, 1965). The boundary between intertidal and subtidal also required interpretation since the 7 m tidal range was sufficient to permit sampling from a vessel in intertidal areas. Intertidal boundaries were obtained from MHWESG as shapefiles and compared to bathymetric data obtained from Countryside Council of Wales. The hierarchical approach could be extended by consideration of visible biological and physical conditions (angiosperms, salt marsh, algae, maerl, and specific infaunal and epifaunal species).

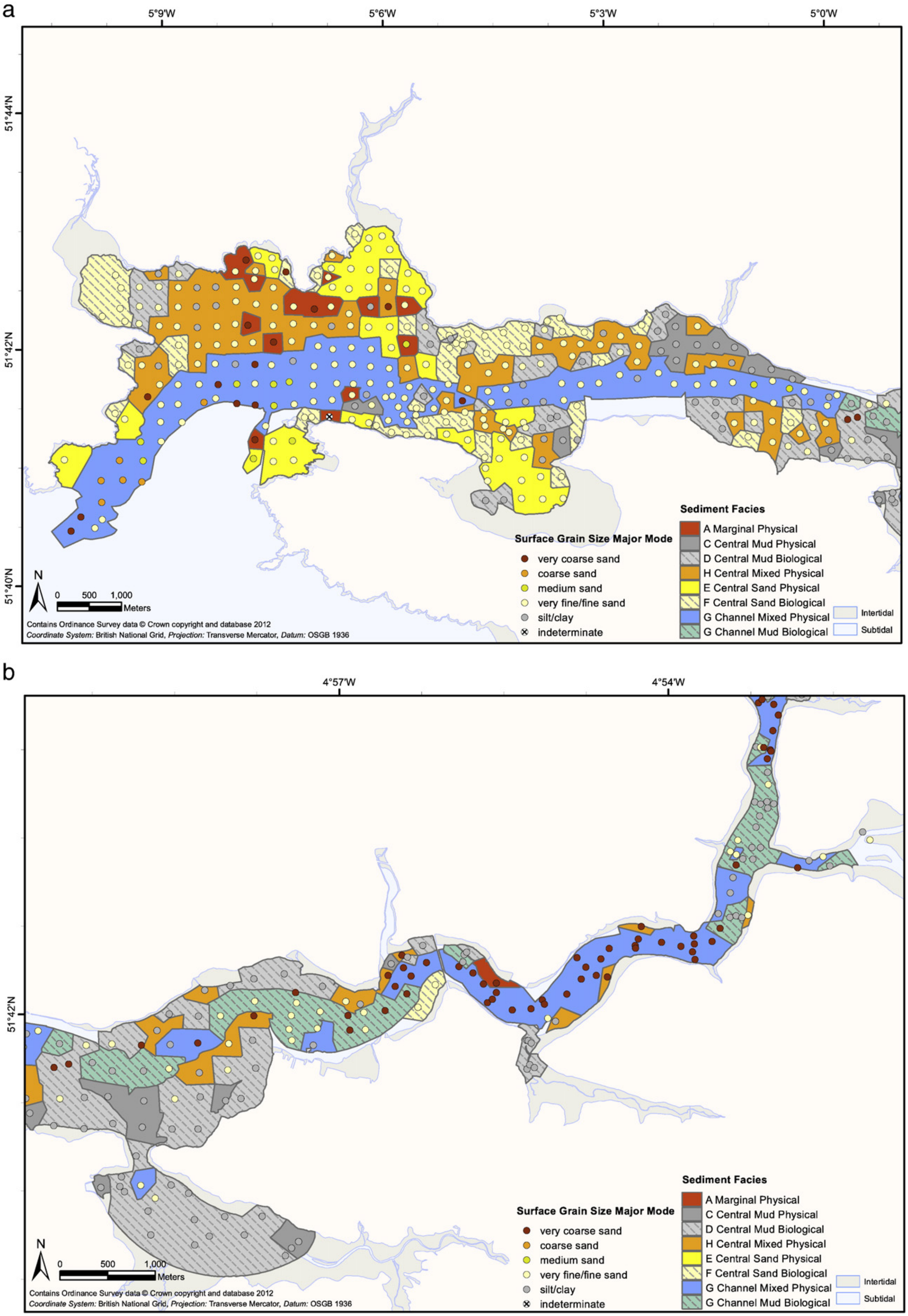
In the bottom-up approach, facies were matched to the best Levels 4 and 5 habitats based on expert interpretation and assembled into a cross-walk table (Table 2). Level 4 EUNIS marine habitats are distinguished by grain size/salinity/depth; fine/muddy/sandy; estuarine/marine/reduced/variable; infralittoral/circalittoral (Davies et al., 2004; Moss, 2008). At Level 5 the component units are drawn from other classification systems and are combined in the common framework. Each facies description (Germano & Associates, 2013) was compared directly to Joint Nature Conservation Committee (JNCC) references and EUNIS habitat descriptors (Connor et al., 2004; Davies et al., 2004). Biological elements observed to be found consistently within a facies but not used to define the facies provided key links between the two systems (e.g., *Flustra* spp., *Pomatoceros* sp.).

3. Results

3.1. Grain size

The waterway contains large numbers of shells on the surface, generally *Crepidula fornicata* (slipper limpet); however grain size estimation does not include shells that would be large enough to remove by hand from sieve analysis. When grain size is interpreted from PV images, only the sediment surface can be observed. Results presented here are based on the grain-size major mode from SPI.

The sediments within the MHW were highly variable ranging from a major mode of <-6 phi (cobble) to ≥ 4 phi silt/clay (Fig. 3). Despite the variation, there were major groupings of sediment types consistent with previous investigations (Rostron et al., 1987; Little, 2009; Germano & Associates, 2013; Appendix G). The channel at the mouth of the lower waterway contained medium to very coarse sand and gravel surrounded by bedrock (Station 37, Fig. 3), while the intertidal flats graded from very fine sand to silt clay and back to very fine sand in the shallowest portion. In the middle waterway from Sandy Haven Bay through Angle Bay and Gelliswick Bay the channel had only limited areas of coarse sand; much of this central part of the waterway was dominated by very fine to fine sand, often overlying silt/clay (Station 234, Fig. 3). The central channel near Pembroke Dock was lined with very coarse cobbles, pebbles, and shell over-sand or -mud (Station 360, Fig. 3) while the flats of the Pembroke River contained silt/clay.


a
5°9'W
5°6'W
5°3'W
5°0'W
51°44'N
51°42'N
51°40'N
Sediment Facies
A Marginal Physical
C Central Mud Physical
D Central Mud Biological
H Central Mixed Physical
E Central Sand Physical
F Central Sand Biological
G Channel Mixed Physical
G Channel Mud Biological
Intertidal
Subtidal
Surface Grain Size Major Mode
very coarse sand
coarse sand
medium sand
very fine/fine sand
silt/clay
indeterminate
N
0 500 1,000
Meters
Contains Ordinance Survey data © Crown copyright and database 2012
Coordinate System: British National Grid, Projection: Transverse Mercator, Datum: OSGB 1936
b
4°57'W
4°54'W
51°42'N
Sediment Facies
A Marginal Physical
C Central Mud Physical
D Central Mud Biological
H Central Mixed Physical
E Central Sand Physical
F Central Sand Biological
G Channel Mixed Physical
G Channel Mud Biological
Intertidal
Subtidal
Surface Grain Size Major Mode
very coarse sand
coarse sand
medium sand
very fine/fine sand
silt/clay
indeterminate
N
0 500 1,000
Meters
Contains Ordinance Survey data © Crown copyright and database 2012
Coordinate System: British National Grid, Projection: Transverse Mercator, Datum: OSGB 1936

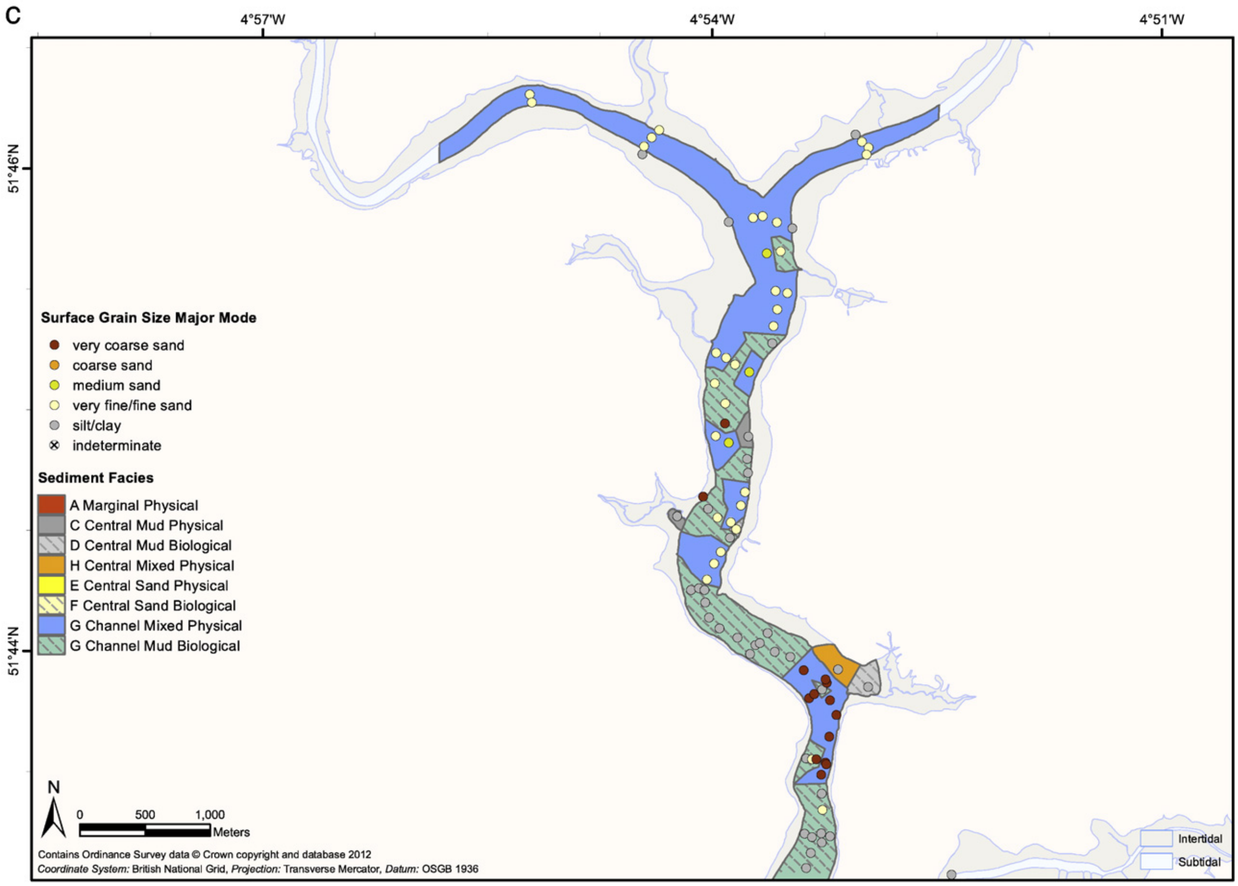


Fig. 6. a. Grouped Thiessen polygons of facies distribution with surface grain size major mode in lower Milford Haven Waterway. b. Grouped Thiessen polygons of facies distribution with surface grain size major mode in lower Milford Haven Waterway. c. Grouped Thiessen polygons of facies distribution with surface grain size major mode in lower Milford Haven Waterway.

Past Pembroke Dock the channel narrowed in cross section through Warrior Reach with areas almost exclusively covered with very coarse sand and gravel (a few shells) with little deposition of silt (Station 441, Fig. 3).

After the waterway bends north into the Daugleddau, the sediment surface was dominated by *Crepidula* shells. However the grain size major mode became silt where the Carew–Creswell Rivers enter the system and the cross section expanded. In Castle Reach, the sediment texture changed over short distances and often had coarse shells on silt in the southern section (Station 528, Fig. 3). North of the Carew–Cresswell Rivers up to Garron Pill, the cross section narrowed and gravel sized *Crepidula* shells with a mix of pebbles covered the waterway floor. Through Beggars Reach there was an area of silt deposition with shells on the surface transitioning to very fine sand with isolated patches of gravel throughout the upper estuary to the Western and Eastern Cleddau (Station 710, Fig. 3). This distinctive pattern of alternating coarse and fine sediment has been described in many studies of MHW reflecting the influence of wave action in the outer waterway, tidal re-suspension of the inner estuary (mixed sand and mud), and an estuarine turbidity maximum located above the high velocity zone (Little, 2009). This complex pattern of substrate characteristics can present problems for predictive modeling without fine-scale ground truth information.

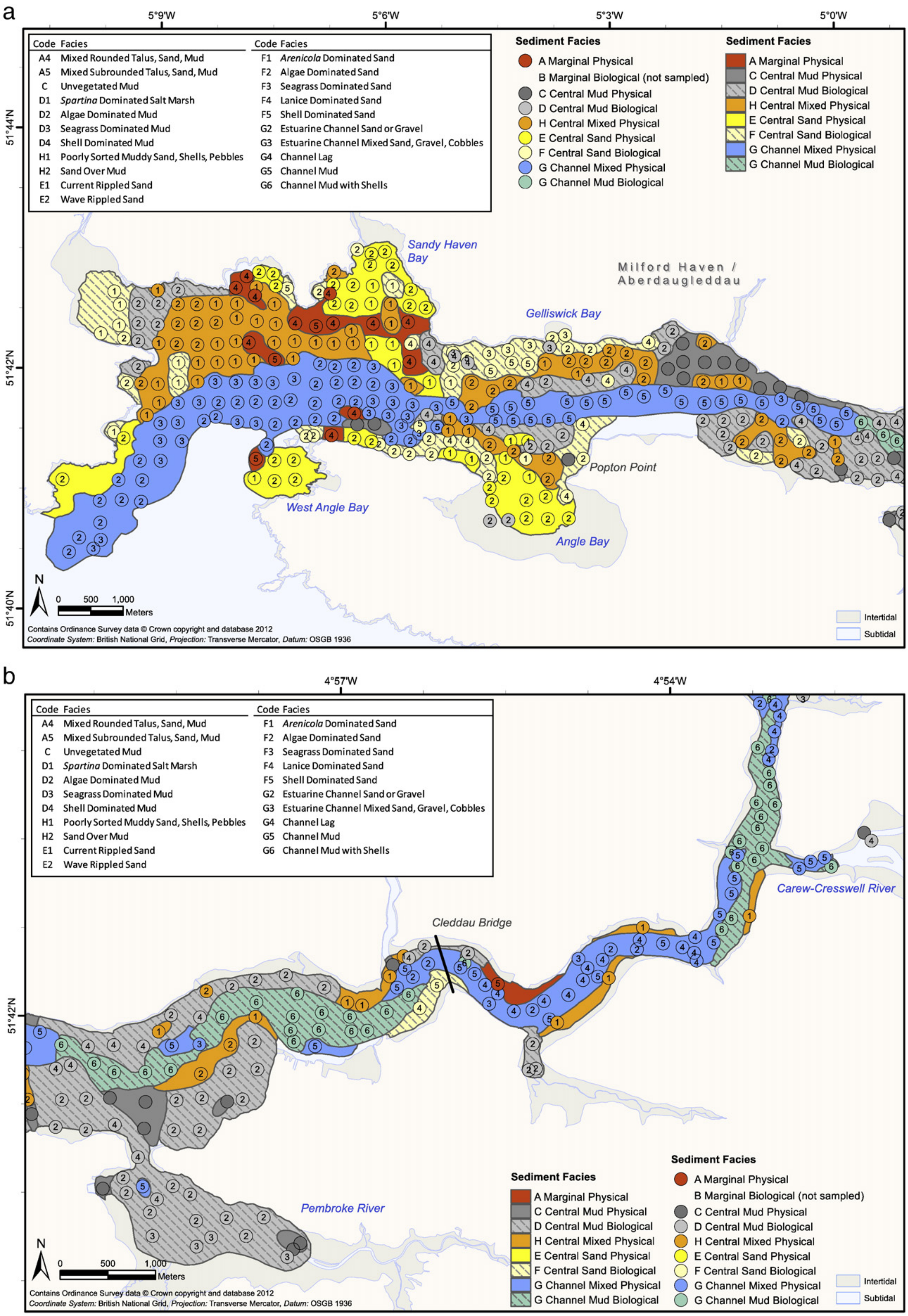
3.2. Apparent redox potential discontinuity depth

In general, the distribution of mean aRPD depths (where measurable) reflected the level of active bioturbation throughout the waterway; areas with the highest bioturbation activity had the deepest aRPDs. However, aRPD can also vary with the oxygen availability to surface sediments. Very shallow aRPD horizons (0–0.5 cm) only occurred in two locations on the margin of the channel. Shallow aRPDs (0.6–1.5 cm) were found in a patchy distribution on fine sand and silt throughout the waterway often mixed with stations with moderate (1.6–3.0 cm) and deep (>3.0 cm) aRPDs. Concentrations of stations with deep aRPDs were found in well-flushed sections of the waterway.

Many stations had indeterminate aRPD values due to the widespread occurrence of well-sorted, coarse sand and gravel with little fine sediment (Germano & Associates, 2013, Appendix A2).

3.3. Infaunal successional stage

The mapped distribution of infaunal successional stages demonstrated a very widespread presence of advanced successional stages (Germano & Associates, 2013). Evidence of Stage 3 activities (feeding voids, large burrows, and deep aRPDs) was present in the majority of stations that could be measured. Stations limited to Stage 1 successional seres (rapid colonizing surface deposit feeders) were only found in small patches at the margin of the channel and nearshore deposits and not at all in the upper Daugleddau. There were only two stations with evidence of Stage 2 successional seres that lacked evidence of Stage 3 activities (shallow burrowing or tube-building filter or deposit feeders). Any station with some evidence of Stage 3 activities was grouped with Stage 3. These results provided strong evidence of the presence of healthy benthic communities throughout the waterway, as generally found in previous studies (Hobbs and Morgan, 1992; Rostron et al., 1987; Warwick, 2006).


a
5°9'W
5°6'W
5°3'W
5°0'W
51°44'N
51°42'N
51°40'N
Code Facies
A4 Mixed Rounded Talus, Sand, Mud
A5 Mixed Subrounded Talus, Sand, Mud
C Unvegetated Mud
D1 Spartina Dominated Salt Marsh
D2 Algae Dominated Mud
D3 Seagrass Dominated Mud
D4 Shell Dominated Mud
H1 Poorly Sorted Muddy Sand, Shells, Pebbles
H2 Sand Over Mud
E1 Current Rippled Sand
E2 Wave Rippled Sand
F1 Arenicola Dominated Sand
F2 Algae Dominated Sand
F3 Seagrass Dominated Sand
F4 Lanice Dominated Sand
F5 Shell Dominated Sand
G2 Estuarine Channel Sand or Gravel
G3 Estuarine Channel Mixed Sand, Gravel, Cobbles
G4 Channel Lag
G5 Channel Mud
G6 Channel Mud with Shells
Sediment Facies
A Marginal Physical
B Marginal Biological (not sampled)
C Central Mud Physical
D Central Mud Biological
H Central Mixed Physical
E Central Sand Physical
F Central Sand Biological
G Channel Mixed Physical
G Channel Mud Biological
Sediment Facies
A Marginal Physical
C Central Mud Physical
D Central Mud Biological
H Central Mixed Physical
E Central Sand Physical
F Central Sand Biological
G Channel Mixed Physical
G Channel Mud Biological
Sandy Haven Bay
Milford Haven / Aberdaugleddau
Gelliswick Bay
Popton Point
West Angle Bay
Angle Bay
N
0 500 1,000 Meters
Contains Ordinance Survey data © Crown copyright and database 2012
Coordinate System: British National Grid, Projection: Transverse Mercator, Datum: OSGB 1936
Intertidal
Subtidal
b
4°57'W
4°54'W
51°42'N
Code Facies
A4 Mixed Rounded Talus, Sand, Mud
A5 Mixed Subrounded Talus, Sand, Mud
C Unvegetated Mud
D1 Spartina Dominated Salt Marsh
D2 Algae Dominated Mud
D3 Seagrass Dominated Mud
D4 Shell Dominated Mud
H1 Poorly Sorted Muddy Sand, Shells, Pebbles
H2 Sand Over Mud
E1 Current Rippled Sand
E2 Wave Rippled Sand
F1 Arenicola Dominated Sand
F2 Algae Dominated Sand
F3 Seagrass Dominated Sand
F4 Lanice Dominated Sand
F5 Shell Dominated Sand
G2 Estuarine Channel Sand or Gravel
G3 Estuarine Channel Mixed Sand, Gravel, Cobbles
G4 Channel Lag
G5 Channel Mud
G6 Channel Mud with Shells
Cleddau Bridge
Carew-Cresswell River
Pembroke River
Sediment Facies
A Marginal Physical
C Central Mud Physical
D Central Mud Biological
H Central Mixed Physical
E Central Sand Physical
F Central Sand Biological
G Channel Mixed Physical
G Channel Mud Biological
Sediment Facies
A Marginal Physical
B Marginal Biological (not sampled)
C Central Mud Physical
D Central Mud Biological
H Central Mixed Physical
E Central Sand Physical
F Central Sand Biological
G Channel Mixed Physical
G Channel Mud Biological
N
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Coordinate System: British National Grid, Projection: Transverse Mercator, Datum: OSGB 1936
Intertidal
Subtidal

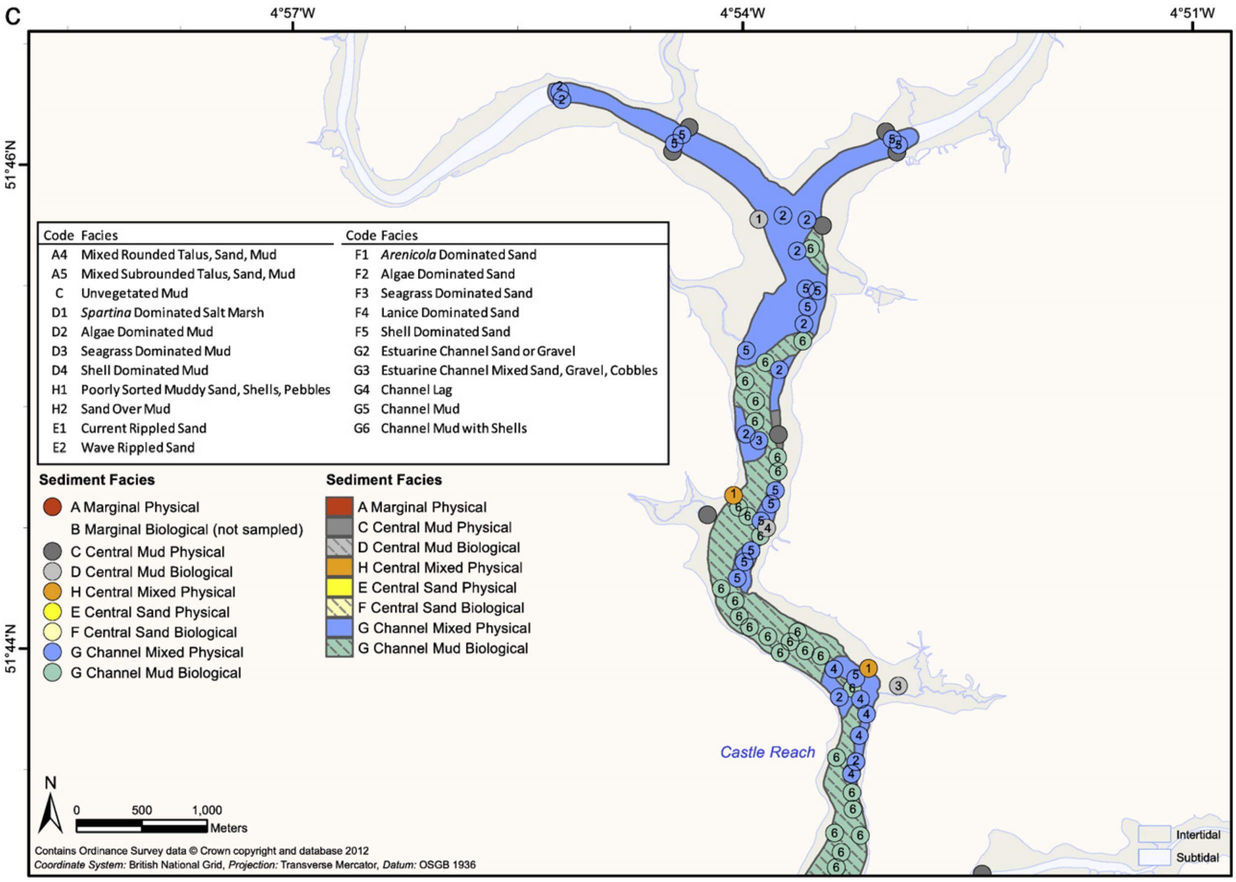


Fig. 7. a. Hand contoured polygons of facies distribution in lower Milford Haven Waterway. b. Hand contoured polygons of facies distribution in middle Milford Haven Waterway. c. Hand contoured polygons of facies distribution in upper Milford Haven Waterway.

3.4. Macrofauna and macroflora

The PV analysis included enumeration and tentative identification of macrofauna and macroflora. Poor visibility in many areas limited the information that could be obtained on species and density and so no attempt was made to map the distribution of individual species or assemblages. However, many genera could be tentatively or positively identified; particularly those that inhabit the sediment surface and can affect sediment transport, including *Arenicola*, *Crepidula*, *Lanice*, *Cerianthus*, *Zostera*, and *Ulva* (e.g., Carey, 1987).

Macroflora was widespread but difficult to identify to species. Two distinct taxa of green algae were recorded: *Ulva* sp. and *Ulva intestinalis* (Germano & Associates, 2013; Appendix C). *U. intestinalis* was clearly identified in SPI images in which the camera is much closer to the sediment surface. Only one brown alga was positively identified, *Himanthalia elongata*; brown algae were only separated based on form (flat pieces, elongated) some of which consisted of brown kelp (*Laminaria digitata*, *Laminaria* spp., or *Saccharina latissima*). None of the many red alga observed was identified to the species level except for *Phymatolithon calcareum* and *Lithothamnion corallioides* (maerl).

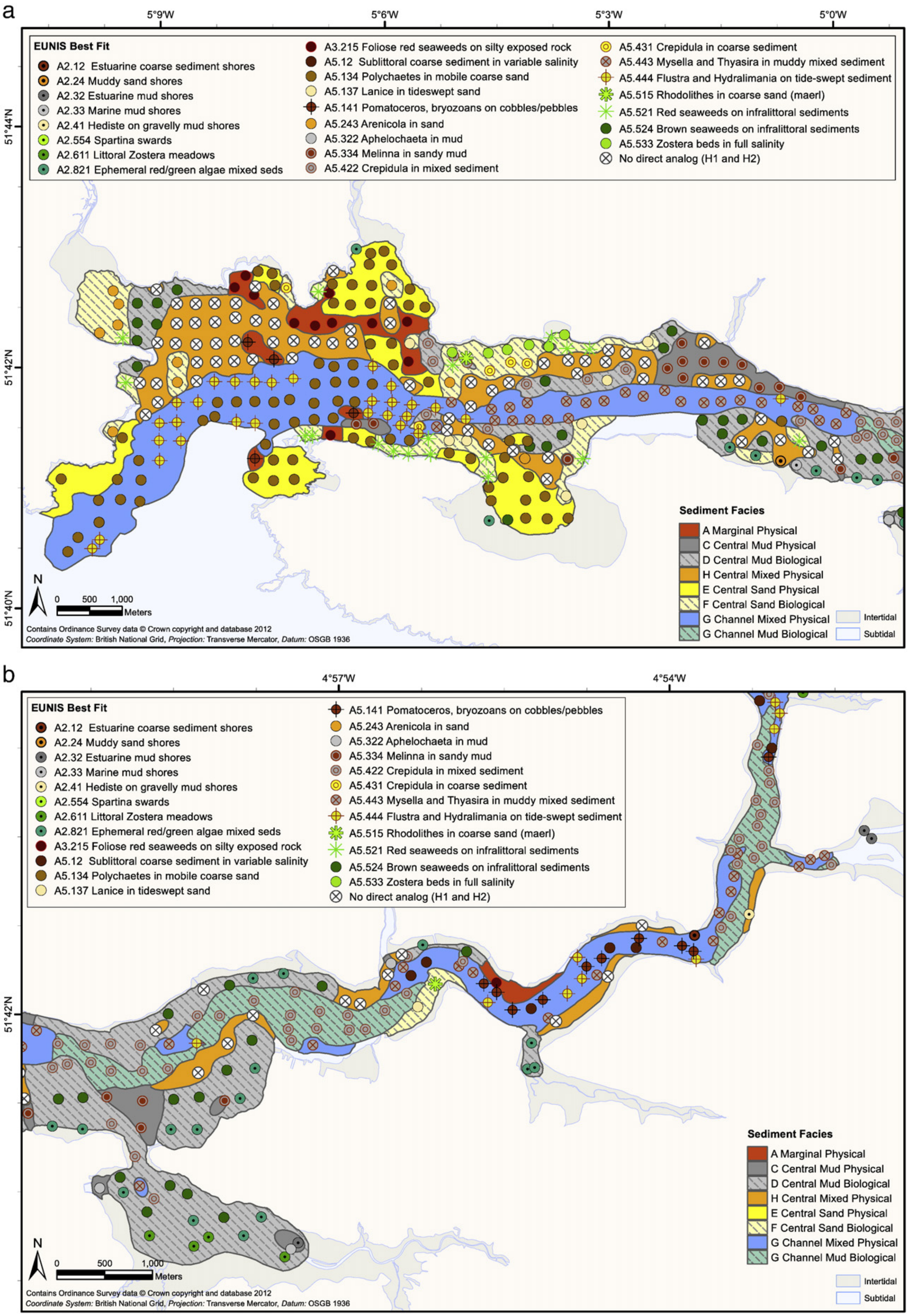
In addition to identification of macrofauna in plan-view images, some species were also identified in SPI images. An apparently cirratulid polychaete [possibly *Aphelochaeta* (*Tharyx*) sp.] was seen in a number of SPI images with a distinctive profile of a large burrow and thin, clear tentacles extending into the sediment.

3.5. Facies

Facies were defined for the entire waterway (Fig. 4a–c) in an integrated process of locating stations within broad areas of the waterway (marginal, central, channel; Table 1) and evaluating the dominant grain size, biological features and nature of the surface texture (mixed, layered, bedforms, etc.). The stations were evaluated initially by review of PV images and then confirmed using the higher resolution SPI images. Several facies described by King in the intertidal portion of Sandyhaven Pill (King, 1977) and later mapped in other intertidal areas by Little (2009 and personal communication) were not observed in this largely subtidal survey (A1, A2, A3, B1, B2, B3, E3, G1, and D1 only in the form of detritus; Table 1). Some stations sampled at high tide clearly had characteristics of intertidal sedimentary units but the majority of the stations were subtidal in character. Seven primary facies groups were observed in the subtidal portion of the waterway (Table 1).

The distribution of the primary facies groups was predictable based on the broad location classes (marginal, central, channel) but the most important addition to the facies table were mixed classes (H and G3, Table 1) within the central facies (axially central, flanked by marginal and bisected by channel) and channel facies. These classes were so distinct that they were important to include as new facies cf. King (1977, 1980). There were many stations located on the edge of the channel or marginal portions of the waterway that may represent more of a transitional facies; in such a large and dendritic system (i.e., tree-like main and tributary channels), choosing between marginal, central or channel was somewhat arbitrary, but see below for further definition.

One method for creating a model of facies distribution is to create polygons around each sample point constrained by relative distance or available information about key landforms (intertidal zone, channel boundary). The polygons are formed by the intersections between the relative distances between points (points close together form smaller polygons, points further apart from larger polygons). Thiessen or Voronoi polygons (polygons formed by one input point per polygon;


a
5°9'W
5°6'W
5°3'W
5°0'W
51°44'N
51°42'N
51°40'N
EUNIS Best Fit
A2.12 Estuarine coarse sediment shores
A2.24 Muddy sand shores
A2.32 Estuarine mud shores
A2.33 Marine mud shores
A2.41 Hediste on gravelly mud shores
A2.554 Spartina swards
A2.611 Littoral Zostera meadows
A2.821 Ephemeral red/green algae mixed seds
A3.215 Foliose red seaweeds on silty exposed rock
A5.12 Sublittoral coarse sediment in variable salinity
A5.134 Polychaetes in mobile coarse sand
A5.137 Lanice in tideswept sand
A5.141 Pomatoceros, bryozoans on cobbles/pebbles
A5.243 Arenicola in sand
A5.322 Aphelochaeta in mud
A5.334 Melinna in sandy mud
A5.422 Crepidula in mixed sediment
A5.431 Crepidula in coarse sediment
A5.443 Mysella and Thyasira in muddy mixed sediment
A5.444 Flustra and Hydralimania on tide-swept sediment
A5.515 Rhodolithes in coarse sand (maerl)
A5.521 Red seaweeds on infralittoral sediments
A5.524 Brown seaweeds on infralittoral sediments
A5.533 Zostera beds in full salinity
No direct analog (H1 and H2)
Sediment Facies
A Marginal Physical
C Central Mud Physical
D Central Mud Biological
H Central Mixed Physical
E Central Sand Physical
F Central Sand Biological
G Channel Mixed Physical
G Channel Mud Biological
Intertidal
Subtidal
N
0 500 1,000
Meters
Contains Ordinance Survey data © Crown copyright and database 2012
Coordinate System: British National Grid, Projection: Transverse Mercator, Datum: OSGB 1936
b
4°57'W
4°54'W
51°42'N
EUNIS Best Fit
A2.12 Estuarine coarse sediment shores
A2.24 Muddy sand shores
A2.32 Estuarine mud shores
A2.33 Marine mud shores
A2.41 Hediste on gravelly mud shores
A2.554 Spartina swards
A2.611 Littoral Zostera meadows
A2.821 Ephemeral red/green algae mixed seds
A3.215 Foliose red seaweeds on silty exposed rock
A5.12 Sublittoral coarse sediment in variable salinity
A5.134 Polychaetes in mobile coarse sand
A5.137 Lanice in tideswept sand
A5.141 Pomatoceros, bryozoans on cobbles/pebbles
A5.243 Arenicola in sand
A5.322 Aphelochaeta in mud
A5.334 Melinna in sandy mud
A5.422 Crepidula in mixed sediment
A5.431 Crepidula in coarse sediment
A5.443 Mysella and Thyasira in muddy mixed sediment
A5.444 Flustra and Hydralimania on tide-swept sediment
A5.515 Rhodolithes in coarse sand (maerl)
A5.521 Red seaweeds on infralittoral sediments
A5.524 Brown seaweeds on infralittoral sediments
A5.533 Zostera beds in full salinity
No direct analog (H1 and H2)
Sediment Facies
A Marginal Physical
C Central Mud Physical
D Central Mud Biological
H Central Mixed Physical
E Central Sand Physical
F Central Sand Biological
G Channel Mixed Physical
G Channel Mud Biological
Intertidal
Subtidal
N
0 500 1,000
Meters
Contains Ordinance Survey data © Crown copyright and database 2012
Coordinate System: British National Grid, Projection: Transverse Mercator, Datum: OSGB 1936

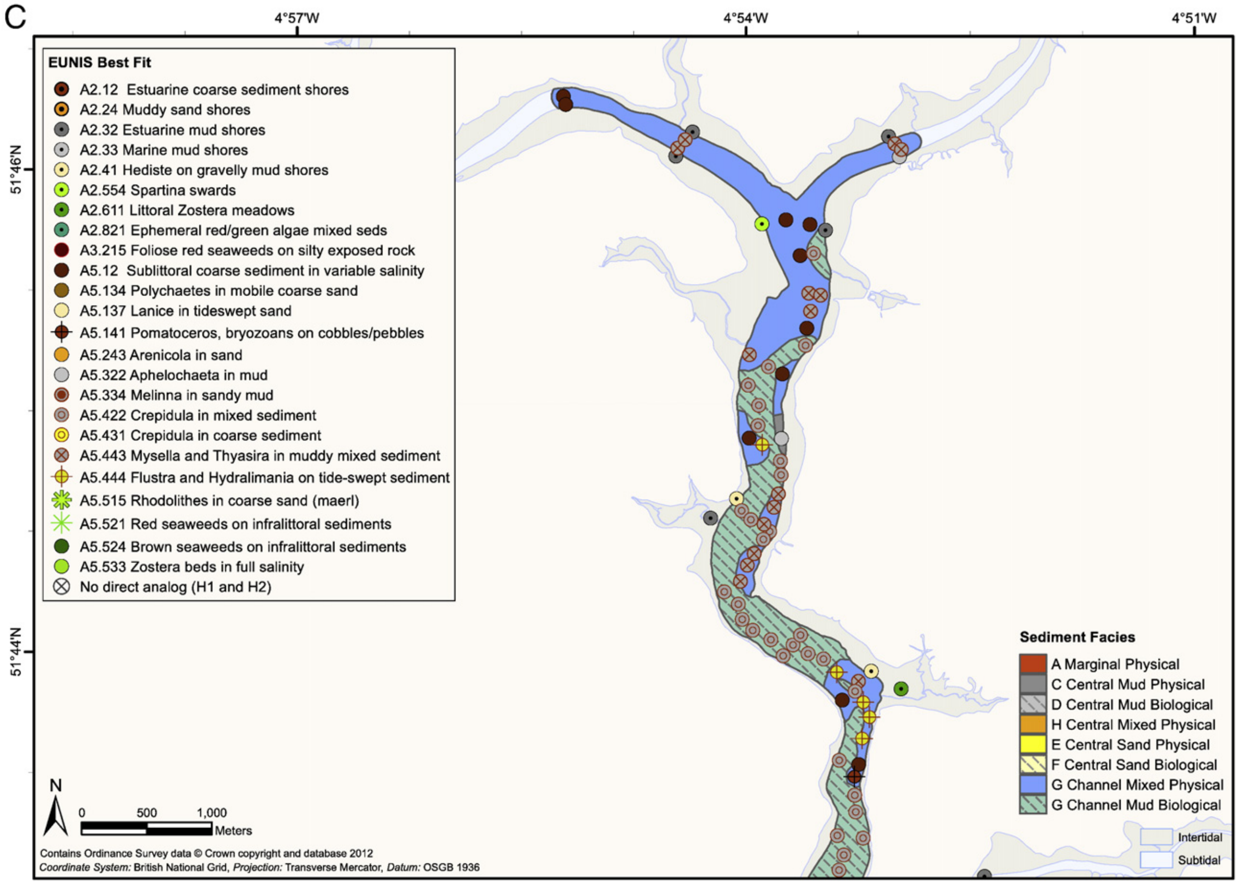


Fig. 8. a. Facies polygons compared to EUNIS classification from cross-walk in lower Milford Haven Waterway. b. Facies polygons compared to EUNIS classification from cross-walk in middle Milford Haven Waterway. c. Facies polygons compared to EUNIS classification from cross-walk in upper Milford Haven Waterway.

on the assumption that each point in the polygon is spatially closer to the input point than to the input point of any other polygon; Thiessen, 1911) formed from the secondary facies (lowest classification) provided a modeled mosaic of sediment types throughout the waterway (Fig. 5).

Polygons from the same primary facies (A–H) were merged to produce a smoother model of facies distribution and visualized with grain size major mode values to retain the detail of sediment distribution (Fig. 6a–c). This refined model provides a clearer distinction between the channel sediments in the central part of the waterway and the relative location of mud, mixed and sand facies groups (Fig. 6a). The distinction between physically dominated sediments and those affected by biological components is easier to visualize with merged polygons of primary facies (Fig. 6a). The distribution of extensive mud deposits in the Pembroke River and the adjacent main waterway becomes more apparent in this visualization (Fig. 6b). In the upper estuary, the channel includes almost all of the subtidal area and as a result the grain size values reflect closely the facies distribution within the channel (Fig. 6c).

A more realistic facies distribution was modeled by hand-contouring primary facies to correspond to acoustically derived bathymetry contours (courtesy of the Countryside Council of Wales). Moving from the Thiessen polygons (shape based on distance) to hand-contoured polygons (shape based on landscape) improved the relationship between observed landscape features (subtidal banks, channel, intertidal flats) and the descriptive facies (Fig. 7a–c). While it is possible to generate automated classification from acoustic data or conduct cluster analysis of measured variables (e.g. unsupervised classification sensu Brown et al., 2011; McBreen et al., 2011), this study explicitly utilized a supervised classification approach (Brown et al., 2011). Facies definition and mapping assumes familiarity and conformance to landscape features. Optimization of facies data to landscape features (tidal channels, flats, shoals) was then used to compare with station-specific EUNIS classification (Fig. 8a–c).

The primary and secondary facies were described in detail with representative images and 'type locations' (Germano & Associates, 2013; Appendix F). To facilitate comparison with EUNIS classes an abbreviated description is provided below and in Table 1.

3.5.1. Marginal physical facies (A)

The marginal physical facies is derived directly from King (1977) from a small sub-estuary but was only described from the lower waterway and one station in Warrior Reach (Fig. 7a, b). Most of MHW did not have deposits consistent with King's marginal facies, although a 'marginal' area of the estuary clearly existed. All of the stations were mixed rounded talus, sand and mud or mixed sub-rounded talus, sand and mud. In this context, talus implies coarse debris eroded and transported relatively short distances from rocky estuarine margins and around small islands and submerged reefs. These stations were represented by thin layers of gravel over mixed muddy sand or cobble pavements outside the channel (Table 1). Most of the margins of the waterway have banks or cliffs of rock and rounded clasts that are transported episodically onto shingle beaches, tidal flats and shallow subtidal areas. These rounded clasts are also found in central and channel facies. The marginal biological facies (B) consisted largely of salt marsh which, having been the subject of surveys conducted for MHWESG and others and because of inadequate water depth, was not sampled in the subtidal SPI/PV survey.

3.5.2. Central mud physical facies (C)

Unvegetated mud deposits occurred in areas that are sometimes 'marginal' to the waterway but sufficiently deep or soft to lack vegetation and not comparable to any of King's marginal facies (Fig. 7a–c). Many of these 30 stations had a fine layer of diatoms, drift algae or anemones but lacked attached macroalgae or rooted plants. The surface was usually marked by tracks and trails of epifaunal animals and had minor amounts of fine sand in the upper horizon. The C facies was always associated with camera penetration deeper than 10.5 cm. If the mud was mixed with poorly sorted sand it was classified as H1 (central mixed physical; poorly-sorted muddy sand, pebbles and shells). If there was sufficient sand in the upper horizon to form a distinct layer, this type of mud was classified as H2 (central mixed physical; sand over mud). When a silt or mud deposit was located within the channel, it was classified as G5 (channel mud).

3.5.3. Central mud biological facies (D)

Mud deposits that had a dominant presence of biological components (macroalgae, rooted plants, intact shells) were widespread but concentrated in the shallow portions of the waterway and margins of the channel in the upper Daugleddau (Fig. 7a–c). Many shallow stations had an abundance of macroalgae (microalgal films were excluded from this facies) and, because drift macroalgae can easily be dragged down by the SPI camera, the PV imagery was important for classification. A common observation was a 'turf' of short tufts of *U. intestinalis* that clearly influenced the mobility of the surface layer. Only six stations could be identified as seagrass dominated mud (Fig. 7a–c). Mud dominated by shells of *C. fornicata* (slipper limpet) or *Mytilus* sp. (blue mussel) occurred throughout the waterway on the margin of the channel. When shell dominated mud was found in the channel it was classified as G6 (channel mud with shells).

3.5.4. Central mixed facies (H)

An entirely new facies group was introduced in this study (compared to King, 1977). This facies is presented out of alphabetical sequence throughout the project to emphasize that it is transitional between mud and sand facies in the central region of the waterway (Table 1) and also to retain the original classes of King (1977). Mixed sediment types were very common throughout the central part of the waterway (Fig. 7a). One subgroup of H was formed of compact, poorly-sorted muddy fine sand with a surface layer of pebbles and shells (H1). These sediments were found throughout the waterway on the margin of the channel and also on the margin of the shoreline (Fig. 7a–c). We interpret this facies as transitional from marginal physical facies with many of the same characteristics (pebbles contributed from bluffs or winnowing, mud and sand from episodic sediment transport events). The other subgroup, H2, consisted of distinct sand over mud layering with the sand layer ranging from 1 to 4 cm. Many of the stations with sand over mud layering also had high densities of the anemone *Cereus pedunculatus* with some macroalgae. H2 was common in shallow areas exposed to wind waves and moderate currents (Fig. 7a, b). We interpret the distinct sand over mud facies as prograding beds of sand over mud that are found throughout the world in nearshore protected basins that have episodic transport (river bedload, runoff from land or beaches from heavy rain or unusually high tidal flux) but not generally common in fining-upwards sequences found in estuaries. Under these conditions, storms will transport fine sands quite easily and they will drop out in low energy environments. Both facies may also be found adjacent to areas disturbed by dredging or heavy commercial vessel traffic.

3.5.5. Central sand physical facies (E)

Sand deposits with evidence of physical processes (ripples) were only found on the edges of the lower waterway up to Angle Bay (Fig. 7a). Asymmetrical and linguoid ripples (associated with current dominated regimes) were limited to subtidal channels (Fig. 7a). Symmetrical ripples (associated with wave-dominated regimes) were found in exposed regions of Sandy Haven, West Angle and Angle Bays (Fig. 7a).

3.5.6. Central sand biological facies (F)

Sand deposits with dominant biological features (evidence of *Arenicola* castings, macroalgae, *Zostera*, *Lanice* tubes, shells) were found primarily in shallow areas in the lower waterway except for two stations west of the Cleddau Bridge (Fig. 7a, b). Castings of the large polychaete *Arenicola* sp. were found in moderate wave and current regimes (F1, Arenicola Dominated Sand, Fig. 7a). A few F1 stations also had another large polychaete, *Aphelochaeta* sp. Sand with abundant attached macroalgae was found in a wide range of shallow exposed areas of the lower waterway along the Angle peninsula (F2, algae dominated sand, Fig. 7a). The dominant algae were various reds with some areas with the 'turf' of *U. intestinalis*. These deposits often had high densities of burrowing anemones, and, if these were more dominant than algae, sediment facies were classified as H2 (mixed; sand over mud). Sand with seagrass (*Zostera* sp.) was only found along the shoreline between Sandy Haven and Gelliswick Bays (F3, seagrass dominated sand, Fig. 7a). The profile of these stations usually revealed a sand layer over mud. If evidence of a *Lanice conchilega* tube was found in sand, the station was classified as F4, *Lanice* dominated sand. These tubes were also observed in mud and between rocks but did not warrant an additional facies classification. *Lanice* sands were found in outer Sandy Haven Bay, on the flats north of the Angle peninsula, off Popton Point, south and east of Milford Haven as well as the sand flat southwest of Cleddau Bridge (Fig. 7a, b). Shell dominated sands usually consisted of broken shells (shell hash, or gravel to sand-size pieces) with some maerl (F5). These deposits were found north of the marine terminals west of Gelliswick Bay, on the edge of the channel north of Angle Point, and just southwest of the Cleddau Bridge (Fig. 7a, b). Often these deposits were adjacent to D4 (shell dominated mud) and F2 (algae dominated sand).

3.5.7. Channel facies (G)

The channel facies group was expanded from the two facies described by King (1977). King's stream bed gravel (G1) was not sampled (limited to stream beds in the intertidal zone of the sub-estuaries). From the channel region in the mouth of the waterway there was a progression from King's estuarine channel gravel (G2, channel sand or gravel) combined with a mixed estuarine channel deposit (G3, channel mixed-sand, gravel and cobbles) to depositional areas (G5, channel mud) to depositional areas dominated by shells (G6, channel mud with shells) to a mix of channel lag (G4, channel lag) and well sorted and mixed sediments (G2, G3). This alternation of depositional to lag deposits occurred twice moving up the waterway (Fig. 7a–c). This complex alternation of deposits confined to the channel (arbitrarily defined by a boundary of the steepest slope in the axially central portion of the waterway) was distinct from the central and marginal facies and required a departure from the physical/biological division. In essence all of the channel facies were largely physically dominated, but G6 had a biogenic component of large particles.

The presence of large shells in the channel, G6, was also associated with silt deposits even though the surface can appear to be a Crepidula 'pavement'. In some cases the surface horizon was a layer of fine sand with shells. Shelly silt deposits dominated the channel east of Cleddau Bridge and again north of the Carew–Creswell River (Fig. 7b). Shell deposits were common in Castle Reach usually with a surface layer of medium or fine sand (Fig. 7c).

3.6. EUNIS classification

An effective cross-walk to EUNIS habitats was constructed through a hybrid of hierarchical classification and best professional judgment from the SPI/PV data and facies results (Table 2). The top down hierarchical approach utilizing the online key was limited to Level 3 in most cases with 13 distinct habitats including littoral and sublittoral habitats. Through the addition of a functional distinction between infralittoral and circalittoral, mid and upper estuarine, full and variable salinity and the presence of some distinguishing features (e.g., macroalgae), Level 4 classification was possible, resulting in 19 classes. Eighteen Level 5 habitats were distinguished in 16 of the 19 Level 4 habitats (several Level 4 habitats were represented by more than one Level 5 habitat). Detailed assessment was conducted for each Level 5 habitat based on visual evidence available in SPI and PV imagery. This use of best professional judgment obviated use of detailed species lists or multivariate statistical modeling and also allowed assessment at a small scale that provided effective classification. In several cases, the hierarchical key created limited options (mobile vs. non-mobile, macroalgae) which could only be resolved through identification of a Level 5 match (Table 2). In most cases there were one-to-one matches between facies and Level 5 habitats, or one-to-many when considering intertidal versus infralittoral and circalittoral (Table 2).

The spatial distribution of EUNIS classes in the waterway broadly mirrored the facies classes but the distinctions between them revealed patterns of interest (Fig. 8a–c). The emphasis on specific organisms in Level 5 EUNIS habitats facilitates a transition from a process driven description (facies) to a biotope driven description (EUNIS habitat). The broad distribution of facies can be used as a predictor of EUNIS habitats with some distinctions. The central sand facies (E) and the channel facies (G) both contained broad expanses of mobile clean sand that best matched EUNIS habitat A5.13 (infralittoral coarse sediment) but these facies represent very distinct sediment transport processes (Fig. 8a). Another common EUNIS sediment type (A5.44 circalittoral mixed sediments) was widespread in both the central mixed facies (H) and channel facies (G) but facies did not always match Level 5 EUNIS habitats (Fig. 8a). In the middle section of the waterway, most EUNIS classes were a one-to-one match with facies (Fig. 8b). In the complex mix of silt, *Crepidula* shells and tide-swept bottom of the upper waterway, both facies types and EUNIS habitats were mixed (Fig. 8c).

Marginal facies were problematic to map in the main waterway because they represent a nearshore, largely intertidal facies influenced by supralittoral processes creating talus deposits that were described from a small sub-estuary (King, 1977). However, these talus deposits appeared to be present in several parts of the lower waterway below the intertidal (Fig. 4a). Subtidal talus deposits have been studied by diver surveys in the lower Daugleddau (Case, 1981) but were not targeted by the SPI sampling as they are known to be steep and hard. Distinction between the rounded and sub-rounded talus was not sufficient to reliably assign any classes except A3.215 and A5.141 based on the presence or absence of macroalgae (Table 2). Several genera were used in the facies classes to distinguish the presence of organisms that have the potential to alter flow or sediment transport (*Arenicola*, *Lanice*, *Crepidula*, *Zostera*, *Spartina*, maerl and macroalgae); these matched well with existing EUNIS classes. Other genera used to characterize EUNIS classes could be identified but were not used to define facies (*Aphelochaeta*, *Pomatoceros*, *Flustra*, *Hydrallmania*). A third group of genera could not be identified with certainty in SPI or PV imagery, so associated sediment types were used to classify the habitats (*Melinna*, *Mysella*, *Hediste*, *Hesionura*). In this latter group, the organisms occur as infauna in mixed sediments and contribute to the processes identified in the successional model (Pearson and Rosenberg, 1978; Rhoads and Germano, 1982, 1986). Some stations with Central Sand over Mud facies (H2) were strongly associated with dense populations of *C. pedunculatus* but the sediment characteristics did not fit the characteristics of any of the EUNIS habitats associated with *Cereus* sp. (A5.514, A5.525); nor was there a EUNIS habitat with this distinctive layering.

4. Discussion

The most significant result of the synoptic collection of SPI and PV images is the compilation and assessment of sediment facies in the subtidal regions of MHW. Sediment facies provide an integration of landscape features (channel, margin, central), sediment grain size, inferred physical processes and biological components, especially those that affect sediment transport and deposition. Because sediment facies can be projected over larger areas than individual samples (due to assumptions based on physiography, or landforms) they represent a predictive model of the distribution of sediments in the waterway. This model can be tested over time and space through comparison with additional samples or older sample results. This approach provides a means to evaluate stability or change in the physical and biological conditions of the waterway system. Indeed, initial comparison with past results show considerable stability over time (Little, 2009; Germano & Associates, 2013; Appendix G) but some evidence of anthropogenic sediment disturbance (Little and Bullimore, 2015).

The results were compared with studies of sediment distribution based on direct sediment sampling and sediment trend analysis (Little and McLaren, 1989; McLaren and Little, 1987; Rostron et al., 1987). The sediment trend analysis showed similar results to the facies analysis with fining of sediment along the flood-tide dominated transport path on the northern margin of the waterway, up the main channel and into tributary sub-estuaries (e.g. Pembroke River, Garron Pill and Western Cleddau; see Fig. 1). Fining along the southern shoreline was consistent with ebb-dominated transport toward the mouth of MHW with coarsening and signs of erosion on Pwllcrochan Flats. Equilibrium was observed in Angle Bay, with some evidence that fine sediment is being winnowed (Little and McLaren, 1989; McLaren and Little, 1987).

A notable exception was the distribution of the sand over mud facies (H2). Although occurring naturally in the waterway (e.g. Sandy Haven Bay and near Pembroke Dock), this facies was found to now extend from the LNG terminals in Gelliswick Bay east on the northern shelf and west on the southern shoreline from the terminal east of Popton Point at the mouth of Angle Bay (Fig. 8a). The presence of this facies (interpreted to occur in disturbed sediments and from episodic sand transport over fine sediments) adjacent to recent construction activity and dredging may indicate a short-term response to physical disturbance. Additionally, the confirmation of deposition of fine sediments in the main channel and tributaries has implications for studies of sediment-bound contaminants. The facies approach cannot detect contaminant distribution directly, but in combination with systematic assessments it can be used to guide detailed sampling and monitoring efforts (Galperin and Little, 2014; Little, 2009). Habitat mapping relies heavily on extrapolating from acoustic segmentation to matching very limited, expensive ground truth data to allow more detailed interpretation. While it is often assumed that SPI data cannot provide diagnostic benthic community composition, any approach that can bridge the gap between acoustic segments (often large in scale or indeterminate) and highly specific sampling techniques (grabs, cores, trawls) has value for refining predictive models. The addition of the plan view imaging (although often limited in field of view by turbidity in this particular waterway) adds a substantial dimension for habitat mapping (sedimentary features, epifauna, cobbles, boulders and rock).

The EUNIS maps provide a detailed view of the waterway that is compatible with MESH mapping approaches (Fig. 8a–c). The best fit expert matching between facies and EUNIS Level 5 habitats permitted construction of EUNIS habitat maps at a level of detail usually reserved for fine-scale studies (1–10 km length; MESH, 2010). This approach could also be used to improve predictive models of EUNIS habitats. Not every station had visible characteristics that provided diagnostic assignment to a Level 5 habitat. However, the robustness of the facies model increases the likelihood that the EUNIS predictive model is accurate at higher levels. This is because the characteristics of the facies are structured hierarchically by location, substrate, processes and biological characteristics that are broadly consistent with the EUNIS hierarchy. The facies approach has the advantage of utilizing landscape features that can be extrapolated from acoustic and visual data more easily than some of the criteria in the EUNIS top-down hierarchical approach (substrate defines Level 3 but Levels 4 and 5 require detailed description). The EUNIS system is flexible in the approaches to describe and populate the lowest levels of habitats, which enables use of facies models and

Table 3
Comparison of facies and EUNIS classification requirements.

Facies	EUNIS
Facies defined by location, grain size and inferred physical processes	Classes defined by depth, salinity, grain size, biology
Does not address salinity or depth explicitly	Need spatial data on salinity and functional depth (infralittoral/circalittoral)
Hierarchical structure allows mapping without detailed biota	Hierarchical structure allows mapping without biota to Level 3 or 4
Can be effectively extrapolated based on physiography	Some classes can be extrapolated based on physiography
Well-suited to shallow, complex systems	Well-suited to systems across depth and spatial scales
Does not require assumptions of 'habitat'	Biota assemblages require some assumptions of 'habitat' or biotope
Describe dynamics of habitat	Assume static composition of biotic components
Biota modify physical processes (seagrass, mussel beds)	Can be cross-walked from facies systems

visual data to provide a context for species data collection (Table 3). One of the strongest attributes of a blended approach is that they provide different and complementary information. When maps overlay EUNIS biotopes over physical facies models, the synthetic information facilitates generation of hypotheses about bio-physical relationships.

Development of cross-walk tables to link habitat classification schemes provides useful tools but can also reveal gaps in each system (e.g., Madden and Goodin, 2007; Moss, 2008). The twenty-one facies described in this study could be related to twenty-five EUNIS classes, in part because the facies models did not distinguish intertidal, infralittoral and circalittoral (Table 2). The EUNIS biotopes did not appear to distinguish current rippled sand, or wave rippled sand from channel sands (e.g., A5.134) nor did they recognize the mixed sand, mud and pebbles or prograding sand over mud facies in subtidal habitats. One distinct advantage of facies descriptions is that they include and utilize evidence of habitat dynamics (bedforms, small-scale stratigraphy) that can be lost in traditional sampling methods. Where possible, habitat classification is improved when evidence of dynamics can be integrated with assumptions of static physical and biological components (e.g., Greene et al., 2007a,b).

The sediment mosaic visualized in the integrated facies models and grain size estimates provides an effective planning tool for future sediment and benthic investigations. As a reconnaissance survey, the SPI and PV results form a synoptic, comprehensive characterization of the sediment features and habitats in MHW. The visualized data may be used to explore groupings of the contaminants and benthic assemblages at the landscape as well as site-specific scales. The cross-walk from facies to EUNIS provides an effective refinement of pre-existing habitat models based on acoustic segmentation and can be used to guide additional ground-truth data collection and monitoring activities. The use of rapid habitat assessment tools such as SPI/PV can provide high resolution ground-truth data to refine MESH maps based on predictive models. There are several limitations for this approach: SPI is ineffective in coarse sediments and hard bottom and PV is ineffective in highly turbid conditions (Germano et al., 2011). In many habitat mapping studies such as MHW, these limitations largely cancel out because hard bottom is well characterized with PV and sediments in turbid conditions are well characterized with SPI. While this technique lacks the definitive biological data required for full habitat characterization, refining the substrate and processes can provide an improved high-resolution base-map for acoustic interpretation and design of cost-effective direct biological sampling and monitoring. Facies could also be refined to incorporate EUNIS elements more comprehensively as well as informing EUNIS classes about habitat dynamics and abiotic processes.

5. Conclusions

The use of high resolution visual observation at high sample density can be used to rapidly construct predictive models consistent with EUNIS classification methods. Application of facies modeling approaches is highly effective in coastal systems dominated by complex sedimentary and biological processes that affect sediment and contaminant transport, fate and behavior. Facies model results can be readily cross-walked to EUNIS habitat classes. The combination of facies models and EUNIS habitat classification provides a powerful approach to mapping regional marine environments and can aid selection of monitoring stations, support management decision-making and track changes in habitats over time.

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Glossary

Facies: rock or sediment units with distinctive characteristics

Maerl: slow growing, nodule forming, calcareous red alga that interlocks to form a loose lattice structure

Thalweg: line of lowest elevation within the waterway

Dendritic: tree-like main and tributary channels

Linguoid: tongue-shaped ripples

Infralittoral: includes rock or sediment habitats which occur in the shallow subtidal zone and typically support seaweed communities

Circalittoral: includes rock or sediment habitats which occur in the subtidal zone below the depth that can support dense seaweed communities. The depth at which the circalittoral zone begins is directly dependent on the intensity of light reaching the seabed; in highly turbid conditions, the circalittoral zone may begin just below water level at mean low water springs (MLWS).