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Knights, Antony

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Plymouth — A World Harbour through the ages

Antony M. Knights[a,*], Louise B. Firth[b], Richard C. Thompson[a], Anna L.E. Yunnie[c], Keith Hiscock[d], Stephen J. Hawkins[d,e]

[a] School of Marine Science & Engineering, Plymouth University, Drake Circus, Plymouth, PL4 8AA, UK

[b] School of Geography, Earth & Environmental Science, Plymouth University, Drake Circus, Plymouth, PL4 8AA, UK

[c] Plymouth Marine Laboratory, Prospect Place, The Hoe, Plymouth, PL1 3DH, UK

[d] The Marine Biological Association of the United Kingdom, The Laboratory, Citadel Hill, Plymouth PL1 2PB, UK

[e] Ocean and Earth Science, National Oceanography Centre Southampton, Waterfront Campus, University of Southampton, European Way, Southampton, SO14 3ZH, UK

HIGHLIGHTS

- The history of Plymouth Sound as a hub of maritime and marine science is described.
- The contribution of Plymouth institutions to scientific research is highlighted.
- The ecological and conservation importance of Plymouth Sound and estuaries is described.

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ABSTRACT

Plymouth Sound and adjacent estuaries, UK has been used as a working harbour throughout the ages and has a place in maritime history as the port from where the Pilgrim Fathers left for North America in 1620 on the *Mayflower* and Charles Darwin departed from on the HMS *Beagle* on his trip to Galapagos in 1831. Today, it remains a working harbour, home to the largest naval base in Western Europe, the host of numerous cruise ships and recreational boats, yet its complex of estuaries (Tamar, Plym, Lynher) and creeks is nationally and internationally recognised as of conservation importance due to its physical characteristics and flora and fauna. Here, we briefly recount the history and importance of Plymouth through the ages in terms of its historic use as a harbour, its marine science heritage and importance on the international stage. We also briefly describe its ecology.

1. Plymouth Sound and estuaries—a historically important harbour

Plymouth has long been a maritime community with an international significance and outlook in terms of trade, emigration, conflict, exploration and ocean science, and its culture is grounded in maritime tradition. The City of Plymouth is located on the south coast of England and is at the point where several rivers flow into Plymouth Sound (Fig. 1). The Sound and its estuaries provide a significant natural harbour fronting onto the English Channel. It is protected from the sea by the Plymouth Breakwater, which was built in the early half of the 19th Century. Geologically, the bulk of the city is built upon Upper Devonian slate and shale and the headlands at the entrance to Plymouth Sound are formed of Lower Devonian slates, which can withstand the power of the sea. A band of extensively quarried Middle Devonian limestone runs west to east from Cremyll to Plymstock including the Hoe. To the north and north east of the city is the granite mass of Dartmoor.

Plymouth has a long history of human occupation and exploitation of natural resources. The earliest reported settlement is from the Bronze Age (2500–800 BC), located at Mount Batten on the west of the Sound at the mouth of the River Plym (Cunliffe, 1988). This settlement continued to grow as a fishing port during the Iron Age (800–1 BC) and was an important trading post for the Roman Empire (27–476 AD), before becoming a major port of trade during the Renaissance (16th century). The ancient town of Plymouth grew around Sutton Pool (Charter in 1254). It had a population of ∼3500 in the early 16th century, increasing to ∼5000 in 1588, and by the time of the civil war in 1642, the population is estimated to have surpassed 7000

* Corresponding author. Tel.: +44 0 1752 587889.
E-mail address: antony.knights@plymouth.ac.uk (A.M. Knights).

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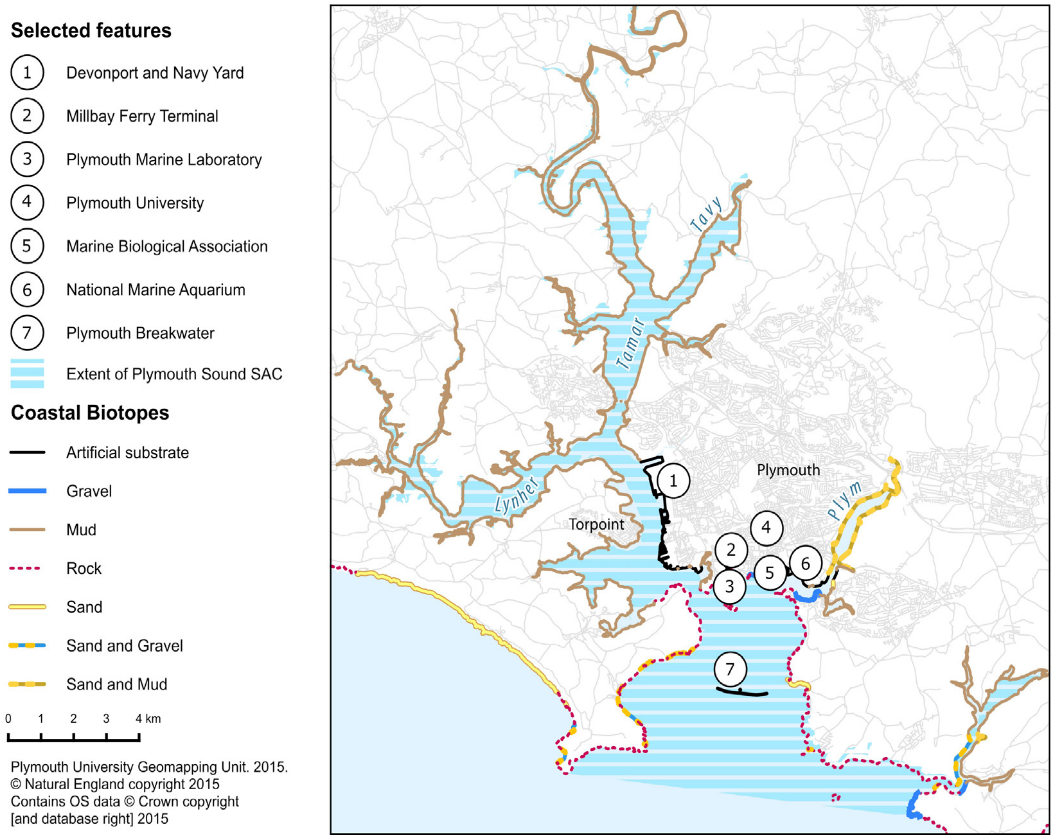

Fig. 1. Map of Plymouth Sound SAC (blue hatching) designated for Annex I habitats and Annex II species under the EU Habitats Directive (92/43/EEC) and some selected features. Coastal biotopes are shown to indicate hardening of the coastline under urbanisation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Lambert, 2015), by which time Plymouth, Devonport and Stonehouse had amalgamated into the Borough (1914) then City of Plymouth (1928). The population continued to grow rapidly reaching 16,000 in 1801, 108,000 in 1901 and 241,000 in 2001 (Plymouth UA, 2001). Today, Plymouth is home to 259,175 residents (Plymouth City Council, 2014). The growth of the Royal Navy contributed greatly to this expansion from its earliest days in the 16th Century, establishing an early military presence in Plymouth.

1.1. Plymouth's naval and shipping history

Plymouth has long been an important location for embarkation and discovery, shipping and the Royal Navy. Sir William Hawkins established trade between England and West Africa and North America as a representative of English East India Company, with ships departing from Plymouth and other west country ports. His brother, Sir John Hawkins, was the chief architect and Vice Admiral of the Elizabethan navy, which in 1588, set sail to fight the Spanish Armada through the mouth of the River Plym. He was supported by his cousin, Sir Francis Drake, who was the first Englishman to sail around the world and played a prominent role in the harrying and ultimate defeat of the Spanish Armada. In 1620, the Mayflower departed Plymouth and established the first successful English colony on mainland America. In 1768, James Cook departed from Plymouth-Dock (Devonport) on-board HMS Endeavour on his voyage of discovery (1768–1771) to the South Pacific. In 1831, Charles Darwin spent two months in Plymouth waiting for the weather to improve so that HMS Beagle could begin its journey to South America. The ship finally left on 27 December and Darwin later wrote of that "horrid Plymouth" and that those two months were "the most miserable which I ever spent" (Darwin, 1887).

Today, Plymouth is home to one of the largest naval bases in Western Europe and is an international ferry port (Fig. 2). Her Majesty's Naval Base (HMNB) Devonport was constructed in 1691 by order of William III and, today, covers 2.6 km^2 of the Tamar shoreline and occupies more than 6.4 km of waterfront, housing 15 dry docks, 25 tidal berths and five basins (Fig. 1). Over the centuries, the neighbouring Millbay Dock has served as a commercial dock, coaling station, shipbuilding yard and point of embarkation for ocean-going liners. Today, Millbay operates ferry services to Roscoff, France and Santander, Spain.

1.2. Plymouth—a marine research hub

Plymouth has a reputation for being a global centre for marine research. This esteem stems back to the construction of the *Marine Biological Association of the UK* (MBA) laboratory, which was completed in 1888. The first edition of the *Journal of the Marine Biological Association* was published in 1887 and includes an extensive account of the fish and fisheries of the Plymouth area. Between 1888 and today, the staff of from the MBA conducted investigations into the physical, chemical, and biological components (ranging from plankton and fish to benthic and intertidal assemblages) of the western English Channel ecosystem (for reviews of both science and institutional history, see Southward and Roberts, 1987, Southward et al., 1995, Southward et al., 2005, Hawkins et al., 2009, Hawkins et al., 2013, Mieszkowska et al., 2014). This long history of ecological research in Plymouth has led to records of more than 8400 species today; ~2.8 × more than the number recorded in other larger harbours such as Sydney Harbour, Australia and the Ria de Vigo, Spain (~3000 spp.; Pearson et al. submitted). More recent contributions on climate change come from the Continuous

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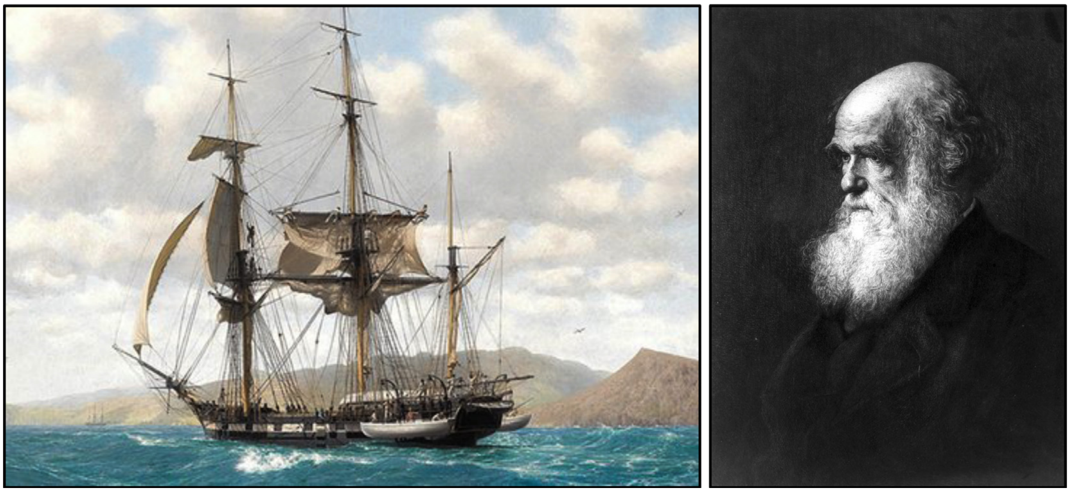

Fig. 2. The HMS *Beagle* in Galapagos (painted by John Chancellor in 1835) (**left**) and Charles Darwin in 1880 (**right**; artist unknown).

Plankton Recorder (CPR) Survey, which moved to Plymouth on the establishment of the Institute of Marine Environmental Research (IMER) in the 1970 (now the Sir Alister Hardy Foundation for Ocean Science (SAHFOS)). IMER undertook strategic and applied research on the marine environment, taking a multidisciplinary approach encompassing physics, chemistry, computer science and biology to address shelf and estuarine ecosystems marine pollution questions. IMER was established in response to growing concern about marine pollution, prompted in part, by the *SS Torrey Canyon* oil spill in 1967 and the subsequent clean-up effort (Smith, 1968; Southward and Southward, 1978; Hawkins et al., 2003).

The Plymouth Marine Laboratory (PML) was formed in 1988 by merger of IMER with parts of the MBA to undertake sustained observations and contributing to the UK's national capability and monitoring programmes. The long-term work by the various institutes in Plymouth constitute a unique data series—one of the longest and most comprehensive set of sustained observations of environmental and marine biological variables in the world (Southward et al., 2005), which are now formalised as the Western Channel Observatory (http://www.westernchannelobservatory.org.uk). IMER and PML took an integrated approach from the sub-cellular to ecosystem level. They pioneered eco-toxicology research, the measurement and statistical analysis of biodiversity (including Clarke's PRIMER software) and its influence on ecosystem functioning. In recent years in collaboration with staff at the University of Plymouth and MBA, work on ocean acidification has been pioneered (e.g. work by Hall-Spencer, Spicer and Widdicombe).

1.3. Marine education in plymouth

The Marine Institute at Plymouth University represents >3000 staff, researchers and students and was the first such multidisciplinary institute in the UK and one of the largest in Europe. It conducts research on a variety of marine topics ranging from understanding marine and coastal systems, to assessing and predicting environmental change and the sustainable use and protection of our seas and coasts. The university boasts world-class marine biology degree programmes and the largest cohort of marine biology students in the UK. Many of the staff associated with the globally recognised Marine Biology and Ecology Research Centre (MBERC). Pioneering work from this research group include work on ocean acidification (with PML) and some of the first studies on pollution by plastic (see the case study below).

The MBA also has a long history of education and sharing information about marine biological, science and sustainable use of the ocean, including running a public aquarium for over 100 years, which was an early inspiration for many of today's leading marine biologists. Outreach programmes with schools and local community include the 'Shore Thing' and 'Blue Sound' projects as well as annual work experience and local Bioblitzes. The MBA are actively involved in promoting Ocean Literacy through Europe and the UK as co-founders of the European Marine Science Educators Association (EMSEA) and through links with the National Marine Educators Association (NMEA) in the United States. The MBA was also instrumental in the foundation of the National Marine Aquarium, which opened in 1998, which does much to promote interest in marine life. Early on, a link between climate fluctuations and ecosystem changes was established (Southward, 1980). This led to early realisation of the likelihood of anthropogenic climate change affecting marine ecosystems (Southward et al., 1995). The MBA was also a base for fundamental biological sciences using marine organisms as model systems. Some of this work was done by in-house staff; but much was accomplished by visiting scientists including the Nobel prize-winner Alan Hodgkin (after Hodgkin and Huxley) on the basis of neuronal transmission (the action potential) using the squid giant axon as a model system (e.g. Baker et al., 1970). This tradition continues with ground-breaking work by Brownlee and his team on calcium signalling (e.g. Brownlee and Taylor, 1992; Brownlee, 2000; Collingridge et al., 2013).

1.4. Devon and Cornwall mining and quarrying

Plymouth Sound and the River Tamar had a particularly important transportation role for the mining industry of Devon and Cornwall. Mining for tin (and subsequently arsenic, copper and tungsten) began in the region during the Bronze Age, but it was not until the 17th and 18th centuries when technological advances led to the rapid growth of the mining industry. In 1867, the Hemerdon tungsten–tin deposit was discovered (Devon County Council), but it was not until WW1 (1917) when tungsten was in short supply, did construction of a 14,000 tonne yr^{-1} opencast mine begin. The scale of the industry tripled with the onset of WW2, with 90,000 tonnes extracted in 1941. At its zenith in the 19th century, Devon and Cornwall mines were supplying two-thirds of the world's copper supply, before foreign competition depressed the price of copper and tin leading to mine closures. Eventually, tin mining in the Southwest ceased in 1998 with the closure of the South Crofty Mine (Europe's last tin mine) and all metalliferous mining ceased in 2007. Due to its global importance, the Cornwall and West Devon mining landscape was listed as a UNESCO World Heritage site in 2006. In 2015, Plymouth

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returned to the world-mining scene with the reopening of the Drakelands Mine (previously Hemerdon Mine). Situated just 10 km from Plymouth, this is one of the largest tungsten deposits in the world, which when fully operational, is expected to produce 3% of the world's tungsten (www.wolfminerals.com.au). The Plymouth region has been a centre for quarrying of limestone for hundreds of years. This continues with exports of aggregate from quarries in the Plymstock area, with shipping and Plymouth Harbour continuing to play an important role in the global distribution of this products.

2. Plymouth—a 'green' city

Plymouth prides itself on being a green city. Over 32% of the city is given over to green space and Plymouth City Council has just launched its 'Green Infrastructure' plan which aims to ensure that any future developments is sustainable and has minimal impact on surrounding areas. Described as Britain's 'Ocean City', Plymouth is also a 'blue' city, situated right on the sea. Of the 75 km of coastline within Plymouth Sound (to junction with Tamar and Lynher rivers), 25 km (33%) is classed as artificial (including the Breakwater), predominantly comprising seawall and rock armour revetment (Fig. 1). With such a high proportion of artificial coastal infrastructure and the formidable Breakwater, Plymouth is also at the forefront of urban ecology and green and ecological engineering research, particularly on artificial coastal defence structures (see case study below).

3. Plymouth Sound: physical description, ecology and designations

Plymouth Sound and its associated estuaries, creeks and marine lakes comprise a complex of marine inlets of considerable biological and historical importance (Fig. 1). The sound is an open bay with a steeply sloping, rocky coastline to the east and west with the inner sound sheltered by an artificial breakwater. The navigation channels in Plymouth Sound are the ancient river gorges from a time when sea level was several tens of metres lower than today. The Sound and the lower Tamar is a 'ria' – a submerged river valley – and the steeply sloping submerged reefs thus created support species characteristic of such unusual wave sheltered but tidal stream exposed habitats. The River Tamar provides the dominant freshwater input to the Sound and estuaries system. Annual flows are in the region of 30 $m^3\ s^{-1}$ (Ackroyd, 1983), but can vary seasonally between 5 and 38 $m^3\ s^{-1}$ (Uncles et al., 1983) with instantaneous flows exceeding 100 $m^3\ s^{-1}$ in some cases (Bale et al., 2007). The Rivers Tavy and Lynher contribute ~30% and ~20% of the Tamar input (Uncles et al., 1983). The upper part of the Tamar and Lynher estuaries are unmodified by locks or weirs and characterised by a well developed estuarine gradient, such that they exhibit one of the finest examples of salinity graded communities in the UK (English Nature, 2000) and contain sedimentary and reef habitats of international marine conservation importance. Plymouth Sound is home to a number of rare or unusual species for the UK, several of which are at the edge or near the edge of their geographic ranges (Fig. 4).

3.1. Environmental management and conservation

Plymouth Sound and Estuaries is a designated area for protection or conservation under a combination of UK and European environmental policies. It is notified as a Site of Special Scientific Interest (SSSI) for the coastal cliff exposures comprising classic sections of Lower Devonian to early Middle Devonian geology including slates and limestone (Natural England, 2015). The area is also a European Marine Site (EMS; defined in the Conservation (Natural Habitats) Regulations 1994), which includes

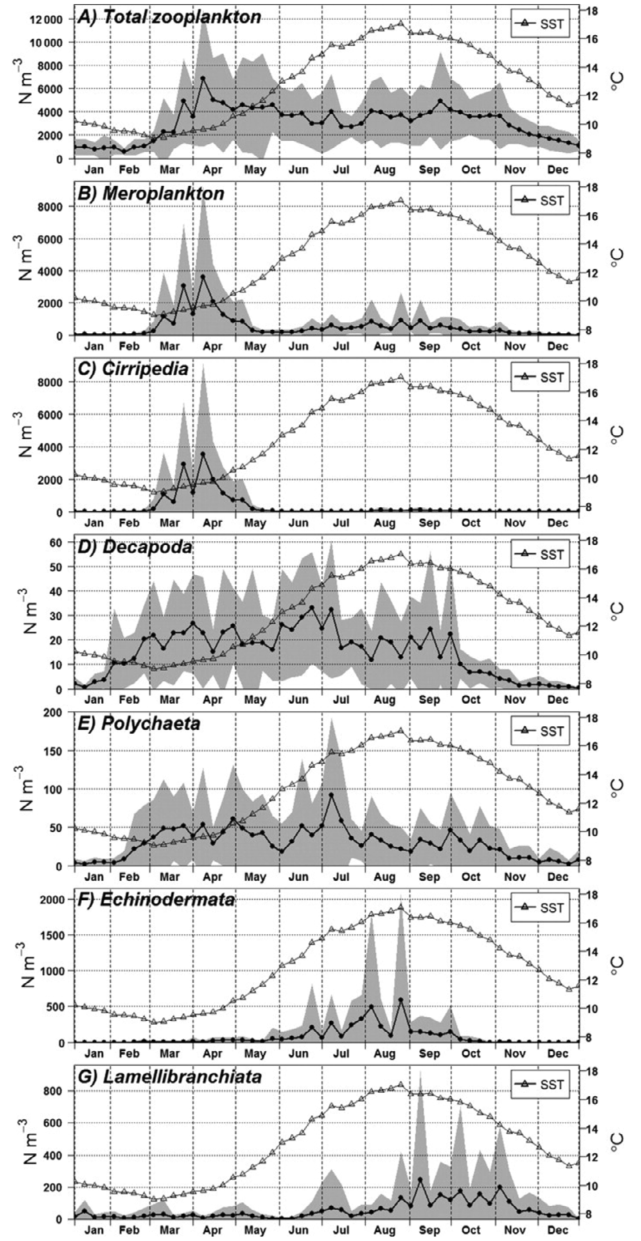

Fig. 3. Changes in weekly average abundance (N m^{-3}) of total zooplankton over the annual cycle at Station L4. Solid line indicates mean; grey band indicates ± 1 SD. Mean weekly sea surface temperature (°C) also shown. **NB** different *y*-axis scales. Seasonal dynamics of meroplankton assemblages at station L4. Journal of Plankton Research 32: 681–691 by permission of Oxford University Press.
Source: Reproduced from Highfield et al. (2010).

a Special Area of Conservation (SAC) (Fig. 1) under the EU Habitats Directive for a number of habitats and species and a Special Protection Area (SPA) under the EU Birds Directive (79/409/EEC) for supporting nationally important numbers of migrant birds including little egrets (*Egretta garzetta*) and avocets (*Recurvirostra avosetta*). The River Tamar, Lynher and Tavy complex (Fig. 1) is classified as an Area of Outstanding Natural Beauty. Just outside Plymouth Sound is the Wembury Marine Conservation Area; the fauna and flora of which have been extensively studied (Colman, 1933; Kitching et al., 1934; Arenas et al., 2006b; Noel et al., 2009) and the site of some of the first scientific diving in the UK (Kitching et al., 1934; Norton, 2000).

The Marine Management Organisation (MMO) of the UK is responsible for introducing byelaws in English inshore waters to protect European Marine Sites and Marine Conservation Zones (MCZs)

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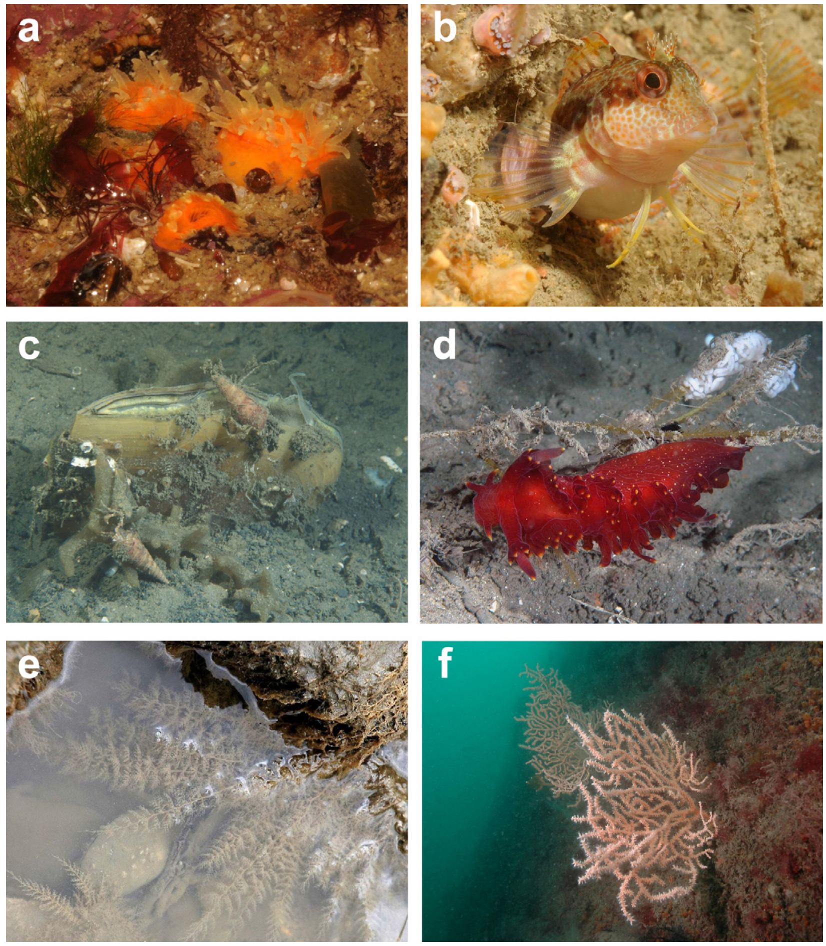

Fig. 4. Nationally rare, scarce, unusual and charismatic species from Plymouth Sound. (a) Scarlet and gold star coral (*Balanophyllia regia*); (b) variable blenny (*Parablennius pilicornis*); (c) fan mussel (*Atrina fragilis*); (d) sea-slug (*Lomanotus genei*); (e) estuarine hydroid (*Hartlobella gelatinosa*); (f) pink sea fan (*Eunicella verrucosa*). Photos copyright: Keith Hiscock (Marine Biological Association of the UK).

from activities that may harm them. Normally, MMO byelaws are used to manage fishing activity from 6 to 12 nautical miles (www.gov.uk/marine-conservation-byelaws). However, it is the regional Inshore Fisheries and Conservation Authorities (IFCA) that are responsible for the sustainable use of marine fisheries and environmental management of inshore waters and estuaries under the Marine and Coastal Access Act 2009, for example enforcing IFCA byelaws such as the protection of bass nursery areas (The Bass (Specified Areas) (Prohibition of Fishing) Order 1990 (no. 1156) http://www.legislation.gov.uk/uksi/1990/1156/made/data.pdf). The over-arching mission of the IFCA's is to "lead, champion and manage a sustainable marine environment and inshore fisheries by successfully securing the right balance between social, environmental and economic benefits to ensure healthy seas, sustainable fisheries and a viable industry". They not only regulate but also undertake research, which adds to our knowledge of the distribution of seabed habitats and their quality, and contributes to a better understanding of the biology of exploited species.

Other designations include the notification of Start Point to Plymouth Sound and Eddystone as a Site of Community Importance (SCI) in 2014 to protect and prevent further deterioration of its bedrock reefs (Annex I, Directive 92/43/EEC) from bottom-towed fishing between 6 and 12 nautical miles of the coast. It is one of only four SCIs in the UK.

3.2. Biological communities: Phytoplankton, Fish, and Benthos

Plymouth Sound has an especially rich flora and fauna because of the wide range of habitats that occur there and because of the mixture of warm and cold temperate species. Many habitats are especially characteristic of flooded river valleys including extensive rocky habitats sheltered from wave action and exposed to strong tidal currents in predominantly full salinity conditions. The Breakwater (Fig. 1) creates shallow habitats very sheltered from waves and tides so that mud accumulates in unusually shallow waters. Of great importance is the long history of study (see Hiscock, 1998) that has led to the documentation of the plants and animals present in the Sound since the 19th century, and which continues today (for instance, Boswarva, 1862, Marine Biological Association, 1904, Mieszkowska et al., 2006, Firth et al., 2009, Hawkins et al., 2013). The range of seabed habitats and associated communities in Plymouth Sound and estuaries were surveyed as part of a programme of work for the Nature Conservancy Council and described in Hiscock and Moore (1986).

The phytoplankton community of Plymouth Sound was first extensively described by Mommaerts (1969); 135 species were named, of which, 94 were typically marine, 10 brackish and 7 freshwater species. The remaining 24 species were littoral/benthic species, which Mommaerts assumed were mixed into the water column by sediment resuspension events (described by Tattersall et al., 2003). Jackson et al. (1987) undertook an extensive plankton survey of the brackish (<8 psu) water region of the Tamar. This revealed dominance by the 'freshwater' diatom *Cyclotella atomus* and to a lesser extent, *C. striatica*, although on occasion can become dominated by 'marine' diatoms and dinoflagellates such as *Rhizosolenia delicatula*, *Heterocapsa triquetra* and *Amphidinium* sp (see Fig. 5).

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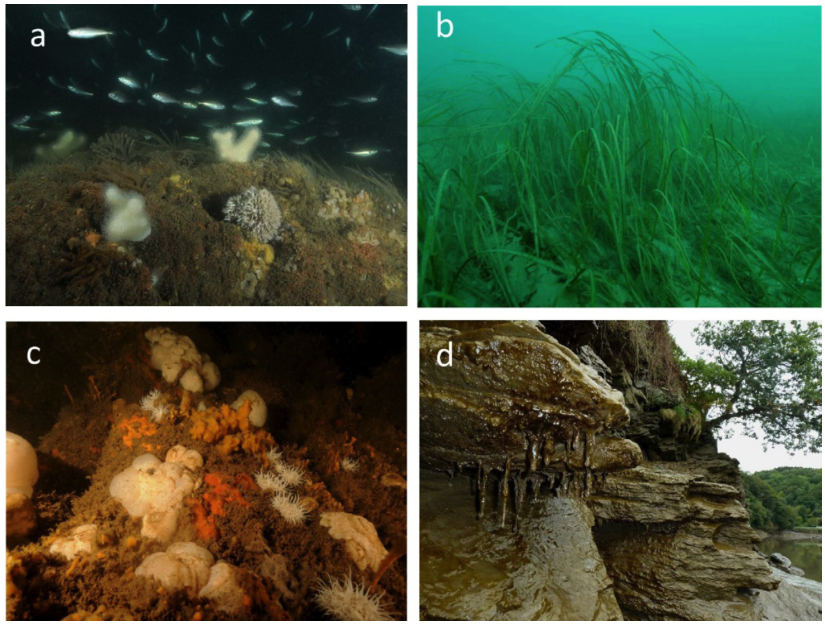

Fig. 5. Characteristic seabed communities of Plymouth Sound and the Tamar Estuary. (a) Ria community (colonial sea squirts, soft coral, filigree worm and sponges) near the entrance to the Tamar; (b) Seagrass, Zostera marina bed; (c) Lower estuarine community (plumose anemones, sponges, hydroids) under the Tamar rail bridge at Saltash; (d) estuarine rock with the hydroid Cordylophora caspia at Cothele on the River Tamar. Photos copyright: Keith Hiscock (Marine Biological Association of the UK).

Holoplankton and meroplankton have been the focus of study in the Western English Channel (Stations L4 and L5 approx. 16 km southwest of Plymouth) for over a century (e.g. Southward, 1980, Southward et al., 1995, Hawkins et al., 2003, Genner et al., 2010, Widdicombe et al., 2010). Marked changes in plankton community structure have been observed over that time, with alternations between a cold-water community (pre-1930s, 1960s–1980s) and warm-water community (1940s–1950s); changes that were associated with fluctuations in climatic warming (Southward et al., 1995; Hawkins et al., 2003). In recent years, there have been few changes in community structure with little interannual variability in abundance or species (Highfield et al., 2010). In general, there is a seasonal trend with greatest total zooplankton and meroplankton abundance in March to May, coinciding with the onset of sea surface temperature increases (Fig. 3) with changes in species abundance determined by their reproductive period.

Fish populations have been studied off Plymouth since the foundation of the MBA in the late 19th Century and into the 20th Century (Coombs and Halliday, 2011). Holme undertook extensive benthic surveys in the 1950s and 1960s, which were published in *Plymouth Marine Fauna* and included a description of some of the collecting grounds around Plymouth. There are particularly valuable century-long time series of fish from around L4, which have enabled disentangling the effects of climate change from fishing pressure (Genner et al., 2004, 2010) and have also shed light onto shifts in phenology with climate fluctuations (Sims et al., 2001, 2004).

The intertidal communities of the rocky shores in and around Plymouth Sound have also been well studied with various surveys of individual species by Moore and colleagues in the 1930s (Moore, 1935a,b, 1938; Moore and Kitching, 1939; Moore, 1940) and descriptions of zonation patterns by Evans (1947). Of particular note are the long-term observations of fluctuations in barnacles on the shores in and around Plymouth and the wider southwest by A.J. Southward and in recent years, younger colleagues (Southward and Crisp, 1954, 1956; Southward, 1967; Southward et al., 1995; Mieszkowska et al., 2014). Following up on work first done in the 1930s by Moore and Kitching (1939), Southward showed that in the warmer conditions of the 1950s, the boreal northern species of barnacle, *Semibalanus balanoides* had become much rarer and was replaced by *Chthamalus* sp.; a change that then reversed again in the colder 1960s (Southward, 1967). Subsequently, when warming became very apparent in the late 1980s, *Chthamalus* sp. became much more abundant again and exceeded levels of the 1950s in the 1990s–2000s (Southward et al., 1995; Hawkins et al., 2008; Mieszkowska et al., 2014). These studies and species have been valuable as indicators of climate change as they also reflect the broader changes that have occurred offshore in the region.

4. Human use of Plymouth Sound: A threat to the ecosystem?

The use of Plymouth Sound by industry and transport over the centuries has led to significant changes in its environmental characteristics. In particular the mining and shipping industries have left a lasting legacy on the region.

4.1. Pollutant concentrations

The extent of the mining industry has led to high levels of residual contamination by Arsenic (*Ar*), Copper (*Cu*), Lead (*Pb*) and Zinc (*Zn*) in the streams and rivers flowing into Plymouth Sound (Colbourn et al., 1975; Langston et al., 2003). Despite the use of treatment schemes, drainage channels and adits (e.g. Burt et al., 2011a,b), run-off from former mine sites and remobilisation of metal-rich sediment (Tattersall et al., 2003) continues to impact marine sites (Langston et al., 2003) reflected in concentrations of some metals an order of magnitude greater than other regions of the UK (see Table 1 in Colbourn et al. (1975)). Suspended sediment concentrations in the lower Tamar (estimated using depth-averaged optical backscatter sensors) indicate concentrations are relatively low (∼0.02 kg m^{-3}) for most of the tidal cycle, but on spring tides, concentrations can increase 20-fold up to 0.40 kg m^{-3} either side of low water (Tattersall et al., 2003).

Much of the upper estuary is nutrient-rich, with the majority of nutrients from diffuse sources including agricultural run-off and sewerage discharge, although annual mean concentrations of NO_x–N, NH_4–N, PO_4–P and SiO_2–Si are similar to other UK rural rivers (Tappin et al., 2013). Concentrations have largely

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increased significantly since the 1940s peaking in 1974, but since then concentrations have reduced by ~60% of the 1974 values. Nevertheless, concentrations of NO_x–N remain high (between 1032 and 3477 kg N km^{-2} yr^{-1}) emphasising continued diffuse pollution (Uncles et al., 2002; Tappin et al., 2013) and surface water concentrations greatly exceed those required under current water quality legislation (Howden and Burt, 2009; Burt et al., 2011a).

High nutrient levels have led to periodic low levels of dissolved oxygen (DO) of <3% in the upper Tamar Estuary, notably during summer low river flow conditions (Harris, 1988, 1992; Darbyshire, 1996) and in some instances leading to deaths of salmonids. Darbyshire (1996) suggested that a strong and persistent seasonal halocline, preserved over the entire tidal cycle, coupled with oxygen demand of the sediments accounts for oxygen-depletion zones near to the bed. However, Morris et al. (1978) also hypothesised that the rapid saltwater influx with the tide leads to freshwater algal mortality, releasing large quantities of dissolved organic carbon (DOC) resulting in low DO as oxygen-utilising bacteria degrade the newly available DOC. To date, the low DO phenomenon has yet to be fully explained.

The use of anti-fouling paints was first restricted under UK legislation in 1987 on vessels <25 m and all TBT-based anti-fouling paints were subsequently banned in 2001 under the International Convention on the Control of Harmful Anti-fouling Systems on Ships (IMO, 2001). Much of the early work on the toxicity of anti-fouling paints was done in Plymouth at the MBA and PML (e.g. Bryan and Gibbs, 1980, Gibbs and Bryan, 1986). Organotins, such as tributyl-tin (TBT and various other forms) may be of significance, although generally the concentrations reported in Plymouth's marinas are now below detection levels (100 ng l^{-1} TBT). High concentrations of TBT had been reported in the harbour waters, in some cases exceeding 880 ng l^{-1} TBT (Cleary and Stebbing, 1985), which exceeds the lethal concentration (LC_{50}) for several species (e.g. the copepod *Acartia tonsa*, Uren, 1983), although more recent evidence suggests TBT concentrations have since then diminished (0.7–7.0 ng l^{-1}) (Langston et al., 2003). Dogwhelk (*Nucella lapillus*) populations that were badly affected by TBT (Bryan and Gibbs, 1986, Spence et al., 1990) in Plymouth Sound are recovering well (Hawkins et al., 2003) although some legacy issues remain, with continued dredging and resuspension of sediments in the Sound, Cattewater and Tamar rivers.

Polycyclic aromatic hydrocarbons (PAHs) and certain pesticides have been reported in high concentration in some parts of Plymouth Sound. In the marine environment, PAHs are a product of incomplete combustion processes and petrochemical pollution from anthropogenic sources such as boat traffic, contributing to high concentrations of fuel in water and sediments (King et al., 2004). Maritime activity has been shown to be a useful proxy for PAH contamination, and areas of Plymouth Sound (e.g. the Plym Estuary) experience >1500 vessels yr^{-1} (QHM, 2006) leading to PAH concentrations in excess of 200 μg l^{-1} (Dissanayake and Bamber, 2010). High PAH concentrations have been shown to disrupt the foraging behaviour of some species (e.g. *Carcinus maenas*, for example, increasing the handling time of prey, Dissanayake et al., 2010).

Plymouth is also a major centre for work on contamination of the marine environment by solid items of debris. Indeed, some of the first work published on microplastics was conducted by researchers for Plymouth University who documented the presence of microscopic fragments of common polymers in intertidal and subtidal sediments (Thompson et al., 2004). Their subsequent work demonstrated that microplastics were also present in surface waters (Sadri and Thompson, 2014) and on the shorelines of the River Tamar (Browne et al., 2010). Critically, the work showed that in some locations, microplastic is now the most numerically abundant type of marine debris (Browne et al., 2010). Based on these initial findings, scientists from Plymouth University showed that microplastics contaminated shorelines worldwide and had even accumulated in the deep sea (Woodall et al., 2014) and in arctic sea ice (Obbard et al., 2014). Sampling around a former sewage sludge dumping ground near to Plymouth showed substantial accumulations of microplastics implicating sewage discharges as a potential source of this debris (Browne et al., 2011). Routine sampling has shown the presence of microplastics in commercially important fish (Lusher et al., 2013). Work on this topic is on-going with a considerable body of research to examine the potential toxicological consequence of this debris (e.g. perhaps more importantly there is a growing body of interdisciplinary research to examine the potential for education and behavioural change to help reduce inputs of plastic to the ocean Wright et al., 2013, Bakir et al., 2014, Hartley et al., 2015). Collectively this research is underpinning international policy on marine litter (Galgani et al., 2010).

4.2. Invasive species introductions: human vectors and climate change

The long-running history of marine biological research in Plymouth as well as its importance as a port has led to many non-native species (NNS) first being reported here. Hull fouling and carriage in ballast water and associated sediments on commercial ships are today considered a primary means of introduction (Carlton, 1985; Wonham et al., 2005) and it has been estimated that ~10,000 species are transported globally per day by these methods alone (Carlton, 1999). Recreational vessels and marinas have also recently been shown to act as intermediate habitats, or 'stepping stones' (Arenas et al., 2006a,b; Floerl et al., 2009) facilitating the spread of invaders away from initial points of entry (Floerl et al., 2009). In a study of recreational boats in Plymouth in 2009 (J. Bishop pers. comm.), an average of 3.8 NNS per boat were found below the water line. An expanded survey to other marinas outside Plymouth revealed an average of 8.4 NNS per site (Bishop et al., 2015), strongly suggesting connectivity between Plymouth and other marinas that is facilitated by human vectors (Woodin et al., 2014).

Of the many fouling species in the UK, many have been first recorded in Plymouth or recorded concurrently or soon after other south coast ports such as Falmouth and Portsmouth, with Plymouth often the link between ports in the far west of the country and the ports and harbours to the east. Moreover, the English Channel is a region where many Lusitanian, or warm-water southern species reach their limits (Lewis, 1964). An increase in sea surface temperatures (SST) effectively shifts the thermal barrier of warmer water species allowing them persist once introduced or to expand into previously unoccupied pole-ward habitats (Burrows et al., 2011). Global SSTs are predicted to rise between 0.3 and 6.4 °C in the next 100 years, with European seas predicted to experience the most rapid warming (IPCC, 2014). Plymouth's location in the far south-west of the country and its proximity to mainland Europe has meant that with current sea temperature rises, it is often among the first to see species undergoing pole-ward range extensions from across the English Channel, such as the kelp *Laminaria ochroleuca* (Parke, 1948). Many NNS do better in a warmer and more extreme world. For example, the Pacific oyster, *Crassostrea gigas*, was deliberately introduced in the UK for aquaculture during the cold period of 1960s and 1970s, on the grounds that it could not reproduce naturally at those temperatures. However, subsequent higher water temperatures enabled successful reproduction and the establishment of feral populations, particularly on quay walls around Plymouth and extensive reefs in the nearby Yealm Estuary.

Successful NNS are frequently characterised as opportunistic and vigorously competitive (Dijkstra et al., 2007) and are often associated with artificial structures such as seawalls, marinas and docks, which are known to provide habitat for and facilitate the spread of NNS (Bulleri and Airoldi, 2005; Glasby et al., 2007; Griffiths and Robinson, 2014; Airoldi et al., 2015). In fact, often the fauna and flora associated with artificial structures are fundamentally different to the assemblages found on natural substrates (Firth et al., 2013a; Evans et al., 2016). The societal and economic importance of Plymouth has led to significant investment to harden its coastline to afford it protection from erosion by weather. As a result, a significant proportion (33%) of Plymouth Sound is 'hardened', thereby offering substantial 'real-estate' for fouling fauna and especially NNS.

One of the first 20th century arrivals to be documented was *Bugula neritina*, a dark brown/red erect bryozoan. In 1911, Orton (1914) observed that the species "grows into huge colonies in the inner basin at the Great Western Docks" (the former name given to Millbay Docks) and is one of the earlier studies linking artificial structures with invasive species. The enclosed design of the inner basin leads to increased summer water temperatures, which may have facilitated the establishment of this warm water species (Ryland et al., 2011).

Eno et al. (1997) stated that no NNS of bryozoan occurred in Britain in 1997, but in Plymouth in 2015, at least 6 species have been recorded suggesting a rapid expansion of this phyla in recent decades. Five species included in the *Great Britain Non-Native Species Secretariat* (a subgroup of the *Department of Environment, Food & Rural Affairs*, DEFRA) list of 'species of concern' are present, or have been present in Plymouth. This includes the leathery sea squirt, *Styela clava*; Japanese wireweed, *Sargassum muticum*; Wakame, *Undaria pinnatifida*; the slipper limpet, *Crepidula fornicata*, and the carpet sea squirt, *Didemnum vexillum* (currently not present). Several other NNS also occur in the area but are less conspicuous and are therefore often unrecorded despite their presence. Clearly the threat of NNS in Plymouth is great, with new introductions occurring frequently as well as an ever-increasing areal extent of artificial habitat. Efforts to understand and improve the ecological value of artificial structures are a key component of on-going research in Plymouth.

4.3. *Biodiversity on artificial structures of Plymouth Sound*

Plymouth was at the forefront of environmental engineering with the completion of the Breakwater in 1841. While introduced to provide the sound with shelter, there was a significant change in the ecology, oceanography and habitat types inside the breakwater but less of an influence on some of the features that characterise this ria and estuary (see Hiscock, 1998 for a review). In the years since, there has been a considerable increase in the extent of coastal defence structures around Plymouth, leading to some of the earliest studies and continuing research investigating the impact of artificial structures on biodiversity.

Some of the first work on artificial habitats was done by Orton & Moore in the 1930s who examined grazing on a concrete jetty near the Lido. Southward and Orton (1954) subsequently conducted a comprehensive survey of the 1.4 km Plymouth Breakwater. In the 1980s, work on the breakwater continued when Hawkins et al. (1983) studied succession on the large concrete blocks deployed on the breakwater. Researchers from Plymouth University and the Marine Biological Association subsequently developed pioneering surveys and experiments under the DELOS project (2001–2005, www.delos.unibo.it). Moschella et al. (2005) provided one of the first synoptic reviews of the ecology of low-crested coastal defence structures (LCS). In this comprehensive article, the authors described the relationship between biodiversity and physical variables at a range of different scales. Building on DELOS, the European Union-funded THESEUS (www.theseusproject.eu) and URBANE (www.urbaneproject.org) projects progressed our understanding of the processes underpinning the patterns of biodiversity on artificial structures at a range of spatial scales from small (mm–cm) (e.g. Bracewell et al., 2013, Coombes et al., 2013, Coombes et al., 2015), medium (cm–m) (Martins et al., 2010; Firth et al., 2013b, 2014a) and large geographic scales (Firth et al., 2014a, 2015).

Fig. 6. Experiments near Plymouth showed the potential for small-scale habitat modification to influence intertidal assemblages. Subsequent work in the Azores showed that these modifications could increase the abundance of commercially exploited species of molluscs (photo courtesy of G. Martins).

Furthermore, these projects developed ecological engineering techniques to promote biodiversity enhancement in the built environment. Firth et al. (2014b) summarised a range of ecological engineering projects which trialled the creation of novel habitats, on otherwise featureless artificial structures. Much of this work evolved from projects initiated in and around Plymouth. For example, work by Thompson (reported in Witt et al., 2012) demonstrated that small pits (14 and 32 mm in diameter) in the surface of otherwise smooth concrete could substantially increase species richness in the intertidal. These modifications were later used in experiments in the Azores showing which showed that small scale heterogeneity could significantly enhance the abundance of a commercially overexploited species of limpet, *Patella candei* (Martins et al., 2010, Fig. 6). Subsequently a full-scale engineering trial with the UK Environment Agency incorporated habitats into a flood defence wall at Shaldon, Devon (reported in Firth et al., 2014b) and provided a key example for planning, design and construction (Naylor et al., 2011). All of this work is underpinned by creation of habitats that provide refuges, either from physical stresses such as extremes of temperature or desiccation during low tide; or from predation, for example by crabs on the limpets in the Azores (Fig. 6). Work to test new habitats is on-going in collaboration with the Ministry of Defence and SERCO who manage and maintain the breakwater.

As man-made structures including coastal defences and renewable energy devices proliferate around the world, there is considerable potential to achieve secondary ecological outcomes in terms of biodiversity, enhancement of commercially important species and education. A key challenge is to take some of the initial intertidal research into the subtidal (Witt et al., 2012).

5. Users and management of Plymouth Sound and its estuaries

The users of Plymouth Sound and its surrounds are wide-ranging from the Royal Navy, commercial shipping, recreational boating, scientific research, commercial and recreational fishers, and scientific and recreational diving to name a few. The value of the Sound and its estuaries and its use is explicitly recognised in the Dockyard Port of Plymouth Order 1999 that puts in place a number of controls to accommodate the wide-range of users and regulations to ensure public health and safety. This recognises The Queen's Harbour Master (QHM) as the regulatory authority of the waterspace.

Despite the range of stakeholders, there is limited conflict between users and implementation of the environmental policies in place to protect the environment due to mutual recognition of the value of the region by various stakeholders. The Tamar Estuaries Consultative Forum (TECF; see http://www.plymouth.gov.uk/tecf for more information on the management plan), in particular, plays an important role in the management of the area, providing a mechanism for consultation and dialogue between key stakeholders including the Ministry of Defence (MoD), local authorities and responsible bodies. Membership is made up from all organisations with statutory powers or functions relating to the estuary, and is the mechanism used to deliver integrated management of the Tamar estuaries and surrounding coastal areas. TECF's goal is 'long-term sustainability' and includes the implementation of Plymouth Sound and Estuaries European Marine Site management. Conflict is minimised by way of 'partnership action' to integrate different policy and management actions. This approach is successful due to "buy-in" by stakeholders, the use of appropriate information to underpin decisions, the inclusion of advisory bodies (including the Port of Plymouth Marine Liaison Committee and Wembury Voluntary Marine Conservation Area Advisory Group) and other stakeholders in the decision-making process, and transparent actions (Knights et al., 2014).

6. Synopsis

As part of the World Harbour Project led by the Sydney Institute of Marine Science (SIMS; http://sims.org.au/research/long-term-projects/world-harbour-project) research on the marine environment, usage and societal value of Plymouth Sound and estuaries will continue into the future. Further information on Plymouth and its harbours and on-going research can be obtained by contacting the authors or following the progress of the World Harbour Project.

Plymouth's setting has attracted human use from earliest times for trade and defence. Its varied hydrography and biodiversity have attracted marine scientists for over 100 years. It thus remains a superb natural laboratory for study of the seas and increasingly societal interactions with our oceans.

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