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Future of the Sea: Hazardous Chemicals and Physical Contaminants in the Marine Environment

Foresight – Future of the Sea
Evidence Review

Foresight, Government Office for Science

Hazardous Chemicals and Physical Contaminants in the Marine Environment

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July 2017

This review has been commissioned as part of the UK government's Foresight Future of the Sea project. The views expressed do not represent policy of any government or organisation.

Contents

Acknowledgements

This evidence review includes scientific information kindly provided by colleagues in Cefas, Defra, Environment Agency, Joint Nature Conservation Committee, Marine Biological Association of the UK, Marine Scotland, Natural Resources Wales, Northern Ireland Department of Agriculture, Environment and Rural Affairs, and the University of Plymouth's Marine Institute. Permission to include Figures 1 and 6 and Table 1 has been granted by OSPAR (www.ospar.org) and the European Environment Agency. The author also thanks the anonymous reviewers for their constructive comments on the draft version of this document.

Executive Summary

- This review considers the long-term evidence for and implications of chemical pollutants and physical contaminants (radioactivity, light, noise and thermal discharges) in the sea around the UK and the Overseas Territories.
- Pollutants and their impacts are generally driven by three external factors: economic activity (the use and disposal of chemicals in society), geography (run-off from land) and climate change (affecting pollutant behaviour and toxicity).
- There has been some recent success in reducing chemical pollution. For example inputs of lindane, a persistent organic pollutant historically used as an agricultural insecticide, reduced by approximately 80 per cent from 1990 to 2008. While there is evidence of ongoing risks from pollutants, the Ospar Convention (1992) and the Stockholm Convention (2001) have been successful overall in reducing the impacts of Persistent, Bioaccumulative and Toxic (PBT) chemicals.
- Seafood contamination is a key concern for monitoring PBTs. Recent research has highlighted the presence of persistent perfluorinated chemicals and brominated flame retardants in organisms used for food. Although there is no conclusive evidence of risks for human health from seafood, there are implications of pollutants for the industry. For example, cadmium is a toxic metal and cadmium levels in crabs have led to restrictions on UK exports to global seafood markets (e.g. China).
- A lack of data is a challenge for measuring marine pollutants and their impact. There is a growing body of evidence on contaminants that are not commonly monitored entering the marine environment. These include nanomaterials, personal care products and pharmaceuticals. Based on the limited data, some of these may have developmental and reproductive impacts in marine life, but more information is needed to understand their long-term impacts.
- Evidence suggests the risks to the UK marine environment from radioactivity are low. Although levels of certain radionuclides discharged from Sellafield increased during the mid-1990s, they have since declined by >90 per cent.
- While there is growing scientific concern regarding the long-term impacts of light and noise pollution on marine life, more information is needed to assess these impacts.
- Emerging technologies offer new tools to monitor the complex range of chemical and physical hazards in the sea, enabling innovative marine monitoring which also capitalises on citizen science in both the UK and the Overseas Territories. This has the potential to strengthen our capacity to monitor contaminants and their drivers.

1. Introduction

The health of the seas around the United Kingdom and the Overseas Territories is of vital importance in providing essential economic, cultural and social benefits, including food, energy, public health, recreation, tourism and trade. Against the backdrop of climate change adaptation, sea level rise and demographic pressures on our coastlines, understanding marine ecosystem function and health is critical to the UK economy (House of Commons 2007; Defra 2010a; Tornero and Hanke 2016). Marine pollution from chemicals, oil spills and radioactivity has been a high-profile issue since the *Torrey Canyon* oil tanker was shipwrecked on the UK coast in 1967. This reflected a reactive era in UK marine science, and policy over impacts on fisheries and marine life caused by hazardous chemicals (including synthetic chemicals, metals and natural toxins) and physical hazards (e.g. heat, light, noise and radionuclides) (Hutchinson et al. 2013). These hazards are considered in this evidence review, but litter and microplastics are not discussed in this document (for more information see Defra 2010b). Importantly, the UK has come a long way since raw sewage was discharged into many estuaries, severely depleting oxygen levels, and the UK has also moved away from sea disposal of fly ash, sewage sludge and industrial effluent (Matthiessen and Law 2002).

In the marine environment, the term 'pollutant' is normally used where the scientific evidence indicates a chemical has adverse impacts on marine life or poses risks for humans eating seafood (a key concern for persistent organic pollutants or POPs). In contrast, the term 'contaminant' is typically used to describe chemicals that increasingly sensitive analytical methods can detect in marine environments and seafood, but where current evidence suggests that no harm is caused to marine organisms and the absence of risks to humans (Hutchinson et al. 2013). It is important to note that, in broad terms, the application of evidence-based control measures since the 1980s have successfully led to declining levels of many classes of POPs in marine life (although there are some important exceptions as summarised in this evidence review) (Matthiessen and Law 2002; Law et al. 2012; Murphy et al. 2015; Jepson et al. 2016).

The health of marine life can be damaged by the adverse effects of hazardous chemicals (including synthetic chemicals, harmful algal toxins and metals) and physical contaminants (e.g. light, noise and radiation). Recent scientific evidence indicates that there are common pathways of adverse health impacts of several chemical and physical hazards (e.g. radionuclides, UV radiation and genotoxic chemicals may all cause genetic damage in marine organisms through the same pathways) (Jha et al. 2000; Lyons et al. 2010; Hylland et al. 2017a).

This evidence review also addresses both chemical warfare agents and conventional munitions which have been disposed of in UK seas since World War I, with over one million tonnes being disposed of in or around the Beaufort's Dyke in the Irish Sea up to the 1970s. Given the potential dangers these munitions pose to personnel in the fishing and expanding renewable energy industries, plus the risks of impacts from chemicals leaching from corroding ordnance into marine life, this remains an important aspect of assessing hazardous chemicals in the UK marine environment (Dixon and Dixon 1979; Beddington and Kinloch 2005; *Sanctuary* 2016).

The review also considers climate change and the UK seas; this relates to ocean acidification, storm surges, sea level rise and coastal erosion, which may all lead to increased exposures of hazardous chemicals from marine sediments and coastal or estuarine landfills. Disturbance of munitions shipwrecks close to the populated coastline should also be considered in this context

(Pope et al. 2011; Brooks et al. 2016). Biotoxins from harmful algal blooms are additionally an important aspect of climate change and impacts on marine life and commercial fisheries (Hallegraeff 1993; Stobo et al. 2008; Hall and Frame 2010). Modern technologies such as time-efficient passive samplers are an important innovation in monitoring such biotoxins and related hazardous chemicals whose exposure pathways will likely be affected by climate change (Pinnegar et al. 2006; Fux et al. 2009; Noyes et al. 2009; Sheahan et al. 2013; Mullon et al. 2016; Johnson et al. 2017).

Overall, the scientific evidence suggests that this range of physico-chemical hazards share common mechanisms of health impacts in marine life that warrant their assessment in an integrated manner. The informative OSPAR integrated chemical and biological assessment strategy is likely to be even more important in the future assessment of climate change, hazardous chemicals and physical hazards in marine ecosystems (Noyes et al. 2009; EEA 2011; Nadal et al. 2015; Hylland et al. 2017b). This review summarises the scientific evidence to inform future policy discussions and emphasises the opportunities for an innovative approach to benefit the UK economy and public engagement in marine conservation.

The available information for marine pollution in the seas of the UK Overseas Territories is also an important consideration. For example, there are some regions where there is evidence for legacy pollutants (e.g. TBT/tributyltin) causing health problems in commercial fisheries and marine life (Singh et al. 1992; Fernandez et al. 2007; Forster et al. 2011; Titley-O’Neal et al. 2011, 2013).

Finally, the UK is well placed today to invest in an innovative era in marine pollution monitoring and prevention, utilising ships of opportunity to monitor hazardous chemicals and developing commercially valuable technologies based on the skills and expertise in marine science (Ciriminna et al. 2015; Brumovský et al. 2016; Kim et al. 2016). There is also a strategic opportunity to add value to the current marine pollution monitoring by engaging citizen scientists in the UK and the Overseas Territories, as has been successfully demonstrated in many other areas of environmental monitoring (Bonney et al. 2009; Conrad and Hilchey 2011; Cigliano et al. 2015). Novel smart-phone technologies for marine contaminant monitoring are one example of the possible innovations ahead for professional and citizen scientists (Wei et al. 2014).

2. International and Regional Legislation

The UK is a signatory to the 2001 Stockholm Convention, a global treaty to protect human health and the environment which identified a list of POPs that governments are required to prioritise in taking measures to eliminate or reduce their release into the environment. The initial list of priority POPs includes eight pesticides (dieldrin, endrin, aldrin, chlordane, heptachlor, dichlorodiphenyltrichloroethane (DDT), mirex and toxaphene), two industrial chemicals (polychlorinated biphenyls and hexachlorobenzene), and two unintentionally produced chemicals (polychlorinated dibenzo-*p*-dioxins (PCDDs) and polychlorinated dibenzodifurans (PCDFs)). In 2009, the list was expanded to include polybrominated diphenyl ethers (PBDEs), pentachlorobenzene (PeCB), hexachlorocyclohexane (HCH), and perfluorooctane sulphonate (PFOS).

The OSPAR Convention for the Protection of the Marine Environment of the North-East Atlantic entered force in 1998 (Figures 1 and 2). Under the OSPAR Joint Assessment and Monitoring

Programme (JAMP) contracting parties are committed to monitor specific chemicals in the marine environment (water, sediment and biota). The OSPAR Hazardous Substances Strategy has a strategic objective, which is to move towards the cessation of discharges, emissions and losses of hazardous substances by 2020 with the aim of achieving concentrations in the marine environment of near-background values for naturally occurring substances and close to zero for man-made substances. The OSPAR List of Substances of Possible Concern is a dynamic working list and there are currently 315 substances listed. These substances were selected due to their Persistent, Bioaccumulative and Toxic (PBT) properties. The OSPAR list also includes endocrine disrupting chemicals (EDCs), defined as exogenous substances that cause adverse effects in an intact organism or its progeny, consequent to changes in endocrine function. EDCs encompass a wide variety of chemicals including alkylphenols, dioxins, metals (and organometals), PCBs and pesticides.

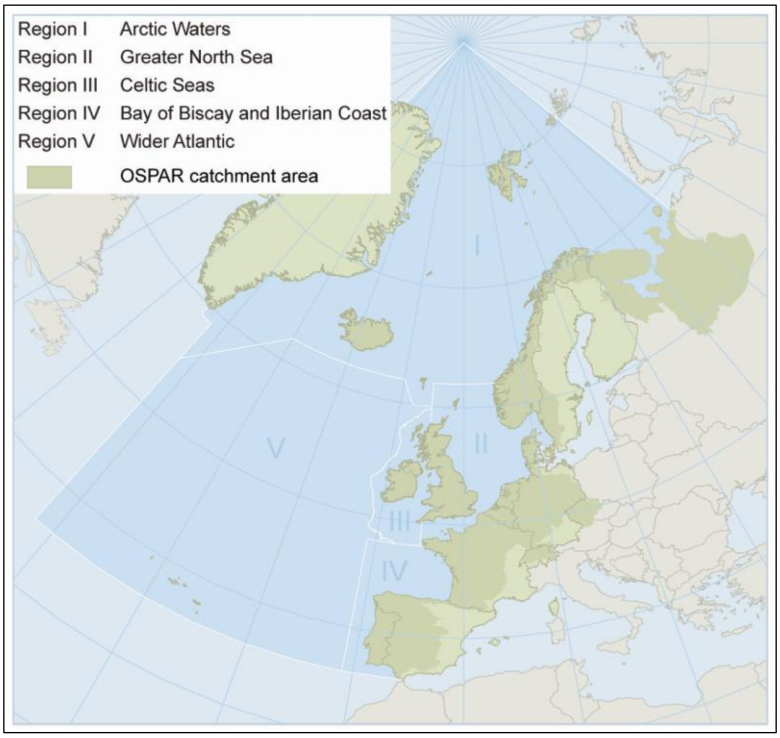
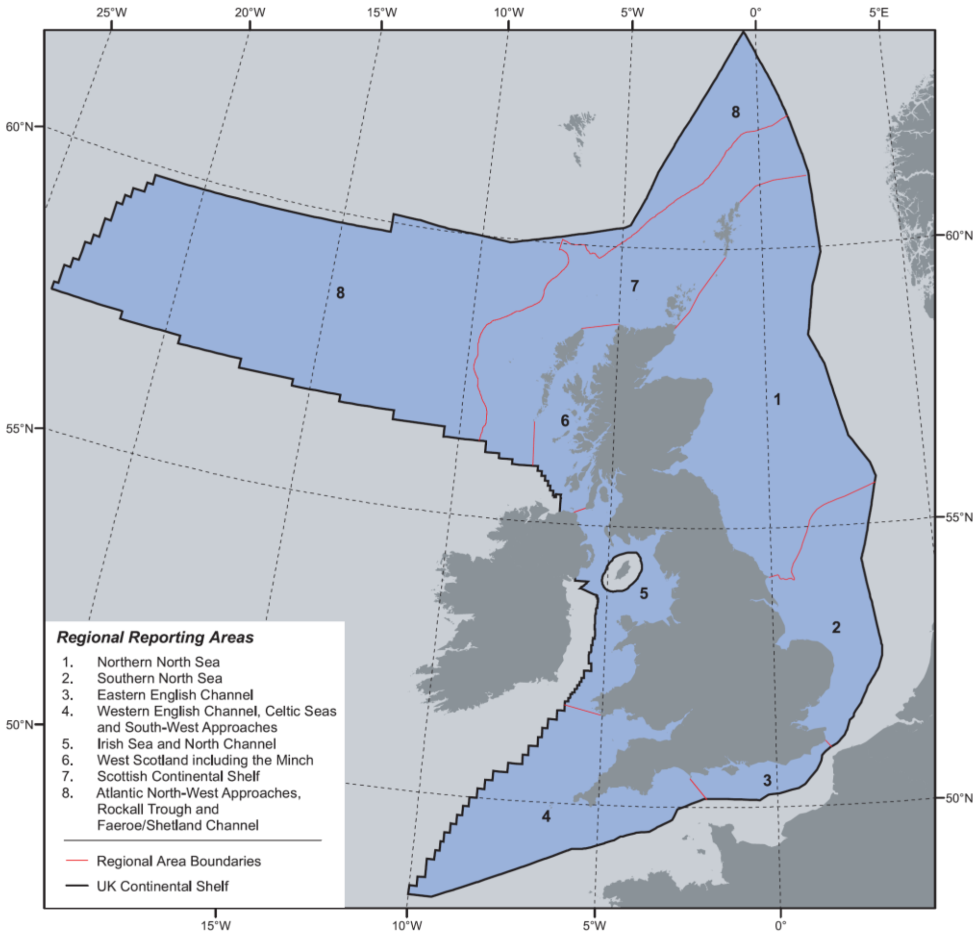


Figure 1. Geographic regions of the OSPAR Convention to protect the marine environment of the North-East Atlantic

Source: OSPAR (2010)



Note: The exact limits of the UK Continental Shelf are set out in orders made in Section 1(7) of the Continental Shelf Act 1994.

Figure 2. The UK seas regional reporting areas for marine monitoring including hazardous chemicals

Source: Defra (2005)

The Water Framework Directive (2000/60/EC) (WFD) was adopted by the European Parliament and the Council of the European Union on 22 December 2000. The aim of the WFD is to protect the status of all estuarine (‘transitional’) and coastal waters. The overall objective of the WFD is to achieve a good chemical status and a good ecological status, based on an integrated chemical and biological assessment strategy. Chemical-specific Environmental Quality Standards (EQSs) are established for the different water body types (fresh, transitional and coastal) as is the boundary between Good and Moderate status. EQSs are required to enable assessments of the chemical status of a water body to be made, supplemented by biological effects monitoring (Borja et al. 2010).

The Marine Strategy Framework Directive (2008/56/EC) (MSFD) aims to progressively reduce discharges, emissions and losses of hazardous substances to the marine and offshore environment, aiming to reach concentrations of such substances in the marine environment of near-background values for naturally occurring substances and close to zero for man-made synthetic substances. The aim of the MSFD is to achieve Good Environmental Status for our seas by 2020 based on an integrated chemical and biological assessment strategy for legacy pollutants and emerging chemicals (Thain et al. 2008; Lyons et al. 2010; Hylland et al. 2017b).

3. Seafood Quality and Chemicals

3.1 Current Issues

Protecting commercial fisheries and seafood is a key challenge. There is some evidence of seafood being a major route of some exposure to PBT chemicals (including perfluorinated chemicals and brominated flame retardants) of humans and marine mammals (Ross et al. 2009; Haug et al. 2010), although there is no conclusive evidence that it has a harmful effect. This strategic focus on PBTs in seafood remains an important aspect of marine pollution monitoring given the evidence, for example, that perfluorinated chemicals and brominated flame retardants may cause long-term developmental and reproductive health impacts on marine organisms. Monitoring metal contaminants is also of long-term importance for ensuring seafood safety and protecting marine life. Aggregate and harbour sediment-dredging-related activities may lead to the uptake of cadmium and other hazardous metals into shellfish populations (Hedge et al. 2009). Importantly, high cadmium levels in UK body tissues of edible crab populations are a scientific concern and have also been an issue for UK seafood export markets (Food Standards Agency 2013; BBC News, 2015; Bolam et al. 2016).

3.2 Key Drivers and Future Trends

Geographic and climate change are key drivers for PBTs in seafood. Published evidence suggests PBTs, metals and algal toxins will continue to be of potential future concern for fisheries and seafood due to climate change and increased pollutant run-off from terrestrial ecosystems into coastal waters (Sheahan et al. 2013; Robins et al. 2016) and enhanced bioaccumulation of methyl mercury in fisheries and marine life, with implications of human health and marine life (Bourdineaud et al. 2011; Johnson et al. 2017).

3.3 Implications for Marine Biodiversity, Fisheries and Seafood

Given this evidence, more information is needed of contaminant exposures in vulnerable commercial fish and shellfish stocks to support the seafood industry and further promote public confidence in the high quality of UK seafood. Looking to the long term (>50 years), the four UK alternative climate change scenarios (‘World Markets, Global Commons, Fortress Britain and Local Stewardship’) (Pinnegar et al. 2006) offer a useful foresight tool to address the future potential impacts of chemical pollution on seafood supplies.

4. Legacy Pollutants in UK Seas and Overseas Territories

4.1 Current Issues

The term ‘legacy pollutants’ refers to a range of high-profile synthetic and natural chemicals and metals known to exhibit PBT properties and thus have the focus of international legislation. For UK seas, current evidence suggests that, while the levels of some chemicals (e.g. lead) in marine fish are in steady decline, in contrast, cadmium levels in fish are increasing at some marine monitoring sites and certain PCBs are still being found at concentrations in fish livers that may pose a health risk to fish and to their predators (Defra 2010b; Nicolaus et al. 2016a, 2016b) (Figure 3; Tables 1 and 2).

Inputs of hazardous organochlorine pesticides such as lindane into the North-East Atlantic have been reduced by approximately 80 per cent from 1990 to 2008 (Figures 4–6) (EEA, 2011). Many hazardous chemicals accumulate in the fatty tissues of marine organisms, particularly in predatory species, and thus may contaminate commercially important fish and shellfish species at levels of dietary concern for humans. Notable examples of these PBT chemicals include polychlorinated biphenyls (PCBs) and brominated flame retardants (deca-BDE).

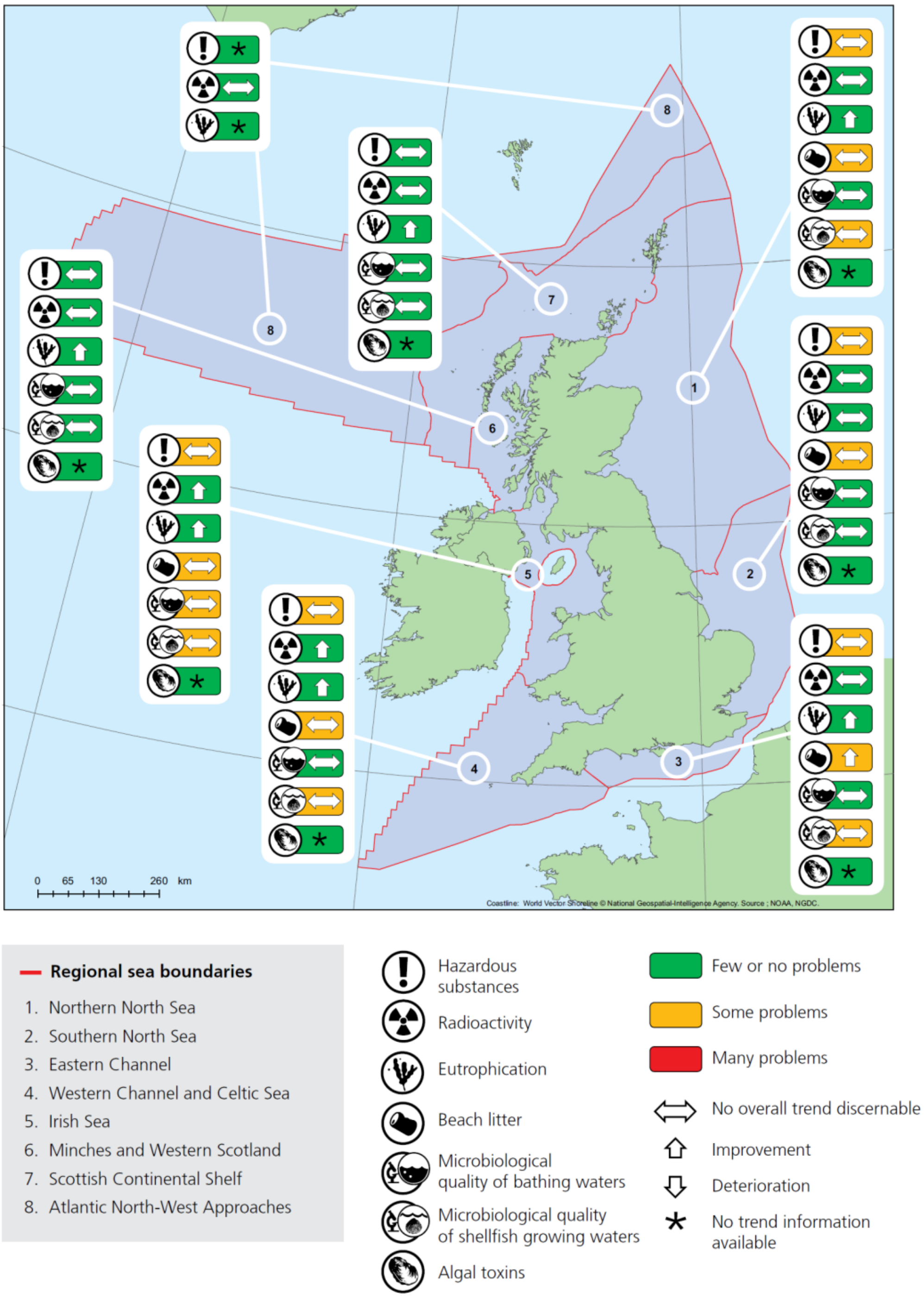


Figure 3. Overview of the trends in hazardous chemicals, radioactivity and other marine contaminants in the UK seas using the OSPAR regional descriptors

Source: Defra (2010b)

Table 1. OSPAR priority chemicals, key sources and main regulatory actions.

		Key sources	OSPAR measures		EU legislation					International instruments		
			BAT/ BEP	Use restrict-tion	Pollution control: IPPC/ EPER	Use restrictions: Market-ing/use	Use restrictions: Biocide	Use restrictions: Pesticide	Water quality: WFD priority	UNECE LRTAP POP and HM Protocol	UNEP Stock-holm POPs Conv.	Rotter-dam PIC Conv.
Metals	Cadmium	Metallurgic processes, fossil fuel	●	●	●	●			●	●		
Metals	Lead and organic lead compounds	Mining, petrol	●		●	●			●	●		
Metals	Mercury and organic mercury compounds	Metallurgic industry, fossil fuel, incineration, chlor-alkali industry, dental amalgam	●	●	●	●		●	●	●		●
Organometals	Organic tin compounds	Antifoulants, consumer products, polymer industry	●	●	⊙	⊙	⊙	⊙	⊙			⊙
Organohalogens	Short-chain chlorinated paraffins	Rubber working plants, products, waste streams		●		●			●	○	○	
Organohalogens	Perfluorooctane sulphonates (PFOS)	Industrial applications, waste streams				●			○	○	●	
Organohalogens	Polychlorinated dibenzodioxins and dibenzofurans (PCDDs, PCDFs)	Incineration	●		●	●			○	●	●	
Organohalogens	Polychlorinated biphenyls (PCBs)	Industrial products, oils, legacies		●	●	●			○	●	●	●
Organohalogens	Certain brominated flame retardants	Manufacture, products, waste streams			⊙	⊙			⊙	⊙	⊙	
Organohalogens	Tetrabromobisphenol-A	Polymer industry, products, wastes										
Organohalogens	Trichlorobenzenes	Industrial processes			●	●			●			
Pesticides/biocides	Endosulfan	Pesticides, biocides, industrial processes, legacies					●	●	●	○	○	
Pesticides/biocides	HCH isomers				●	●	●	●	●	●	●	●
Pesticides/biocides	Dicofol							●	○	○		
Pesticides/biocides	Methoxychlor							●				
Pesticides/biocides	Pentachlorophenol (PCP)				●	●		●	●	○		●
Pesticides/biocides	Trifluralin				●			●	●	○		
Phenols	2,4,6-tri-*tert*-butylphenol	Industrial processes, Oil production										
Phenols	Nonylphenol / Nonylphenol-ethoxylates	Industrial applications, products, oil production		●	●	●		●	●			
Phenols	Octylphenol	Industrial applications, products, oil production			●	●			●			
Phthalates	Dibutylphthalate (DBP), diethylhexyl-phthalate (DEHP)	Polymer industry, products			⊙	●			⊙			
Polycyclic aromatics	Polycyclic aromatic hydrocarbons (PAHs)	Oil production, fossil fuel	●	●	⊙	●		⊙	⊙	●	●	
Pharmaceuticals, personal care, and other substances	Clotrimazole	Domestic and hospital waste water										
Pharmaceuticals, personal care, and other substances	Musk xylene	Domestic waste water				●			○			
Pharmaceuticals, personal care, and other substances	4-(dimethylbutylamino) diphenylamin (6PPD)	Abrasion from products (tires)										
Pharmaceuticals, personal care, and other substances	Neodecanoic acid, ethenyl ester	Paints, coatings, adhesives				●						

Source: OSPAR 2010. Updates available at www.ospar.org

Key: covered by regulatory framework (●); one or more individual substances of a group covered by regulatory framework (⊙); group or individual substance under review for inclusion in regulatory framework (○).

Table 2. Temporal trends for ΣPCBS, ICES7CBs and CB118

Location	CSEMP station	Latitude	Longitude	Sampling period	No of years	Total 25 CBs	ICES7CBs	CB118
Amble	244	55.495	-1.127	1999-2009	10	↓	↓	↓
North Dogger 1	283	55.289	2.904	2003-10	8	↔	↔	↔
North Dogger 2	284	55.065	2.082	2001-10	9	↔	↔	↔
West Dogger	286	54.777	1.295	1998-2010	12	↘	↘	↘
Dogger Central	287	54.527	2.699	2000-10	11	↘	↘	↔
Tees Bay	294	54.756	-1.136	2001-10	9	↗	↗	↑
Flamborough	344	54.245	0.499	1999-2009	11	↘	↘	↘
Off Humber	346	54.071	1.797	1998-2010	11	↔	↔	↘
Outer Humber	377	53.323	0.425	1998-2008	7	↔	↔	↔
Indefatigable Bank	378	53.563	2.083	2003-10	8	↘	↔	↘
Thames (Gabbard)	475	52.048	2.098	2000-09	7	↔	↔	↔
Rye Bay	486	50.825	0.798	1999-2009	11	↔	↔	↔
Off Newhaven	494	50.756	-0.056	2005-10	1	↘	↘	↘
Inner Lyme Bay	534	50.614	-2.93	2005-09	4	↔	↔	↔
South Eddystone	584	50.107	-4.101	2005-10	6	↔	↔	↔
Carmarthen Bay	616	51.548	-4.605	2003-10	8	↔	↔	↔
North Cardigan Bay	649	52.708	-4.524	2002-10	6	↓	↓	↘
South Cardigan Bay	654	52.191	-4.494	2003-07	4	↔	↔	↔
Inner Cardigan Bay	656	52.298	-4.273	1997-2007	9	↓	↓	↓
Off Cardigan Bay	665	52.396	-4.895	1999-2004	4	↘	↘	↘
Inner Liverpool Bay	706	53.471	-3.358	1998-2010	13	↘	↘	↓
Liverpool Bay	715	53.472	-3.699	2000-10	10	↘	↘	↘
St Bees Head	769	54.512	-3.794	2003-09	7	↔	↘	↔
Red Wharf	776	53.375	-4.13	1998-2010	13	↔	↔	↔
Morecambe Bay	796	53.905	-3.41	1998-2010	13	↘	↘	↘
SE Isle of Man	805	54.056	-3.875	2000-2009	9	↔	↔	↔

Trends: ↓ significant downward; ↑ significant upward; ↔ no significant trend; x non-significant downward; x non-significant upward

Source: Cefas (2012)

4.2 Key Drivers and Future Trends

Climate change is anticipated to be a key driver of chemical exposure in the future, with ocean acidification affecting the behaviour and toxicity of metals (Millero et al. 2009; Pascal et al. 2010; Zeng et al. 2015) and the toxicity of contaminated sediments around the UK (Roberts et al. 2013). Geographic and economic drivers are also relevant (Pinnegar et al. 2006). Despite the historical adoption of regulatory controls for these chemicals, recent scientific evidence suggests that the levels of PCBs in UK populations of some marine mammals (including dolphins and killer whales) are sufficiently high as to damage the reproductive organs and immune systems of these marine predators (Defra 2010b; Law et al. 2012; Murphy et al. 2015; Jepson et al. 2016). Elsewhere there is evidence that co-exposure of marine mammals to PBTs (e.g. neurotoxic organochlorine pesticides) and natural biotoxins from harmful algae can have cumulative adverse health impacts (Tiedeken and Ramsdell 2010). More evidence is needed in order to adequately understand the potential harm to marine life of chemical mixtures (e.g. mixtures of metals and synthetic biocides have been reported to cause synergistic toxic effects in marine life (Bao et al. 2008)).

4.3 Implications for Marine Biodiversity, Fisheries and Seafood

There is limited scientific information on the concentrations of hazardous chemicals in the seas and marine life of the Overseas Territories. However, scientific evidence has recently been published suggesting that the collapse of shellfisheries in part of the Caribbean is associated with the legacy chemical tributyltin (despite the 2003 International Maritime Organisation (IMO) ban on using this chemical for antifouling control on boats and ships) (Titley-O'Neal et al. 2011, 2013). Overall, there is extensive scientific evidence that POP and PBT legacy chemicals in the seas of the UK and Overseas Territories continue to be a concern in terms of legal obligations and governance, public perception of contaminated seafood – which may impact on the success of the fishing and seafood (aquaculture) industries – protecting biodiversity and natural capital, and in terms of marine life health and public wellbeing (Singh et al. 1992; Fernandez et al. 2007; Forster et al. 2011).

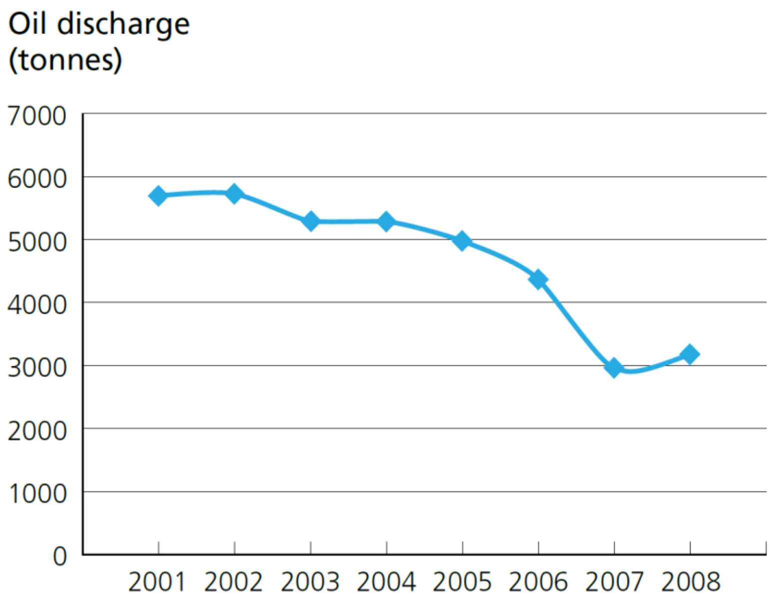


Figure 4. Oil discharged in produced water by the UK offshore oil and gas industry 2001–2008

Source: Defra (2010b)

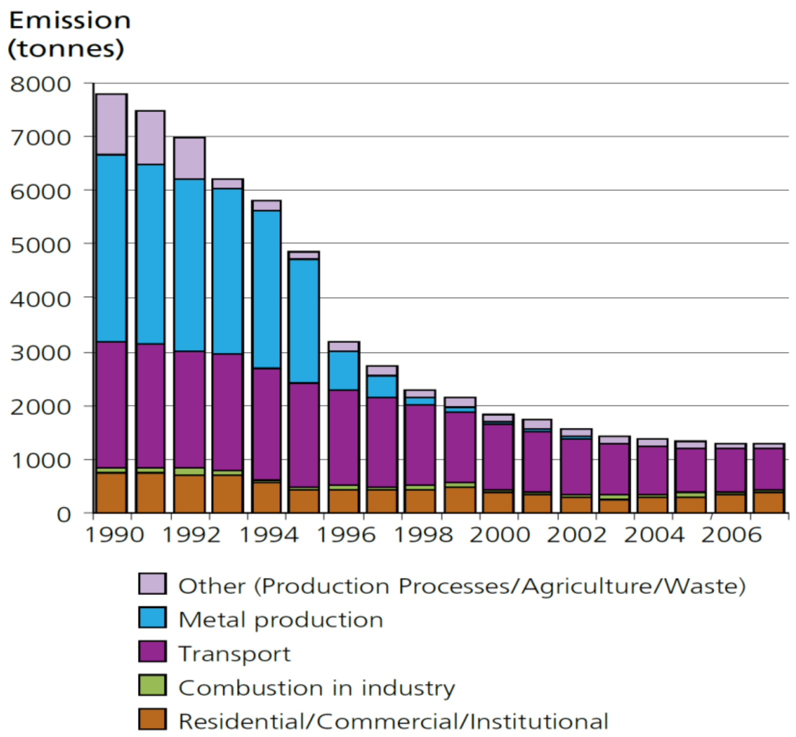


Figure 5. Emissions of polycyclic aromatic hydrocarbons (PAHs) to the UK atmosphere 1990–2007

Source: Defra (2010b)

Figure 6. Inputs of hazardous substances (via riverine loads and direct discharges) into the North-East Atlantic 1990–2008

Source: OSPAR (2010), also cited in EEA (2011)

5. Emerging Chemicals in UK Seas and Overseas Territories

5.1 Current Issues

Recent scientific advances in chemical monitoring methods have demonstrated the presence at typically low levels of a wide range of non-regulated synthetic chemicals in marine environments, including antibiotics, endocrine disrupters, industrial chemicals, personal care products, pesticides and pharmaceuticals (Balaam et al. 2009; Brausch and Rand, 2011; Zhu et al. 2011; Hutchinson et al. 2013; Gaw et al. 2014). Many of these generally non-persistent chemicals have been assessed in laboratory-based environmental safety testing programmes through other regulatory regimes (e.g. Biocidal Products Directive, Plant Protection Products Regulation and Registration, Evaluation, Authorisation and Restriction of Chemicals).

5.2 Key Drivers and Future Trends

While the currently available evidence for individual chemicals does not suggest significant concerns for the marine life in the seas, there is scientific concern about the potential cumulative impacts of complex chemical mixtures on marine life (Defra 2010b; EEA 2011; Hylland et al. 2017b). A key challenge in this respect is to establish passive sampling techniques that allow time-integrated concentration data for chemicals that cannot be reliably measured by traditional sampling techniques (Webster et al. 2010). Given the increasing sensitivity of modern analytical chemistry methods, there arises a concomitant scientific challenge to integrate the chemical monitoring data into a biological context (Borja et al. 2010; Zarbl et al. 2010). With a perspective on addressing and preventing chemical pollution across the global aquatic and terrestrial environments, the OECD (2013) has adopted the 'Adverse Outcome Pathway' (AOP) approach to be applied to a wide range of natural and synthetic chemicals that have common mechanisms of toxicity (e.g. neurotoxic insecticides and algal biotoxins or oestrogenic industrial chemicals and pharmaceuticals). This state-of-the-art approach to toxicology is empowered not only by marine science but also by new insights from biomedical and human health, thereby representing an innovative opportunity to improve the cost-effectiveness of marine pollution monitoring (Hutchinson et al. 2013; Hylland et al. 2017b).

5.3 Implications for Marine Biodiversity, Fisheries and Seafood

As novel consumer products, nanomaterials and pharmaceuticals are introduced to the UK economy and healthcare system, there is a future potential for increasingly complex chemical mixtures to enter coastal and estuarine ecosystems adding to the legacy chemicals residing in marine sediments (Sheahan et al. 2013). The potential impacts of these diverse chemical mixtures on marine life and fisheries warrants further monitoring.

6. Climate Change and Hazardous Chemicals

6.1 Current Issues

There is currently significant concern over the impacts of coastal erosion, sea level rise and storm surges affecting the remobilisation of hazardous chemicals into estuarine and coastal waters with ensuing risk to marine life (Pope et al. 2011; Sheahan et al. 2013).

6.2 Key Drivers and Future Trends

Climate change related storm surges, sea level rise and coastal erosion may all lead to increased exposures of hazardous chemicals from marine sediments and coastal or estuarine landfills (Pope et al. 2011; Brooks et al. 2016). Global impacts of climate change are also predicted to lead to greater exposures to mercury and other PBT chemicals in marine life with concerns for seafood safety (Haug et al. 2010; Nadal et al. 2015; Johnson et al. 2017). Specifically, the risks of storm surge disturbance of munitions ship wrecks close to populated coastlines (e.g. the *SS Kielce* and *SS Richard Montgomery*) should be considered in this context (Dixon and Dixon 1979; Beddington and Kinloch 2005; Callaway et al. 2011).

6.3 Implications for Marine Biodiversity, Fisheries and Seafood

Climate change related storm surges, sea level rise and coastal erosion collectively have the potential to increase the complexity of chemical mixtures, which may impact on marine life and contaminate UK fisheries and seafood supplies. Further evidence is required to understand the potential impacts of these factors.

7. Radioactivity and Ultraviolet Radiation

7.1 Current Issues

Radioactivity in the marine environment is a consequence of both natural processes and human activity (including licensed discharges from defence facilities, nuclear fuel reprocessing facilities, nuclear power stations and radiopharmaceutical manufacturing) (Defra 2010b). Naturally occurring radionuclides in produced water arising from oil and gas extraction are also a consideration (Hosseini et al. 2012). Marine monitoring programmes are well established in UK waters for radioactivity, observing low levels of radionuclides in some locations but at levels suggesting no adverse health impacts (Figure 7; McCubbin et al. 2001; Defra 2010b).

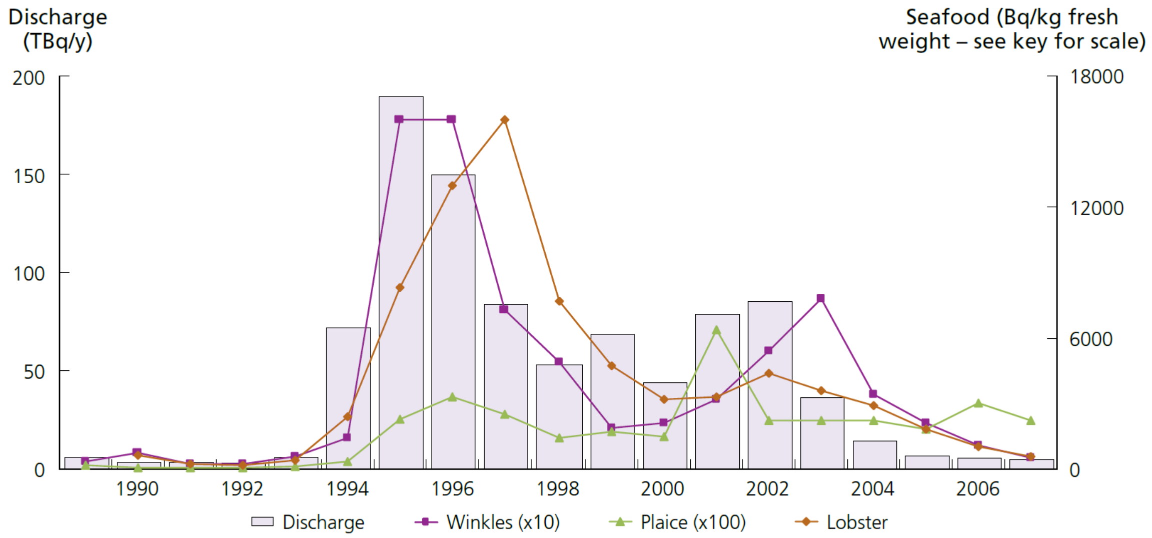


Figure 7. Annual ^{99}Tc liquid discharge from Sellafield and concentrations in finfish (plaice) and shellfish (lobster and winkles) collected near Sellafield

Source: Defra (2010b)

7.2 Key Drivers and Future Trends

As the nuclear energy infrastructure expands around the coast of the UK, inputs of radioactivity into coastal environments may potentially increase (Pinnegar et al. 2006). Ongoing radiological monitoring is therefore important, as is the targeted biological monitoring of fish and invertebrates for genotoxicity and disease (an integrative approach also relevant to radionuclide exposure, genotoxic chemicals such as polycyclic aromatic hydrocarbons and important natural factors such as ultraviolet radiation) (Häder et al. 1994; Jha et al. 2000; Chiang et al. 2003; Hagger et al. 2005; Tedetti and Sempéré 2006). Assessing health impacts on marine animals caused by radioactivity and other genotoxic hazards is clearly within the conceptual domain of the OECD (2013) Adverse Outcome Pathways approach.

7.3 Implications for Marine Biodiversity, Fisheries and Seafood

Radiological monitoring of sea water, sediments and marine life is an important long-term activity to understand potential impacts of radioactivity on marine life and seafood supplies. It is also of future importance in terms of public health and public perception regarding the safety of UK seafood.

8. Thermal Effluent Discharges into Coastal Areas

8.1 Current Issues

The expansion in electricity generation capacity around the UK is based on the use of directly cooled power stations which abstract large volumes of cooling water from coastal and estuarine locations. Biocides are required to prevent serious problems caused by biofouling organisms (Chelossi and Faimali 2006) and typically cooling water is discharged at 8–12.5°C above the water intake temperature (Wither et al. 2012).

8.2 Key Drivers and Future Trends

Recognising the extensive scope of environmental impact assessments for the growing number of power stations around the UK coastline, the existing biological monitoring approaches are ideal for providing evidence of safety to commercial fisheries and marine life in general (Lyons et al. 2010; Hylland et al. 2017b).

8.3 Implications for Marine Biodiversity, Fisheries and Seafood

Integrated chemical and biological monitoring of marine life and fisheries is an important long-term activity to understand potential impacts of power station discharges on marine life and seafood supplies. This is a reflected in the value of existing integrated monitoring programmes (Defra 2010a; Hylland et al. 2017b).

9. Marine Disposal of Munitions

9.1 Current Issues

Since World War I, both chemical and conventional munitions have been disposed of in the seas around the UK (Dixon and Dixon 1979). Over several decades, it is plausible that corrosion of munitions casings will lead to hazardous chemicals being released into the marine environment. As noted by Beddington and Kinloch (2005), these chemical weapons can be categorised into (i) chemicals that are directly soluble in water and are therefore unlikely to present significant problems; (ii) chemicals that contain high arsenic content with the potential for concentration in the food web; and (iii) chemicals such as mustard gas where polymerisation is possible and breakdown of material is unlikely and thus will remain in the disposal location unless moved by oceanographic factors. The authors also noted that there seems evidence to indicate that following corrosion certain types of munitions can float and that these can wash ashore.

9.2 Key Drivers and Future Trends

Given the long-term risks of climate change related increases in storm surges and coastal erosion, which may lead to disturbance of these highly hazardous chemicals, it is important to invest in integrated chemical and biological monitoring approaches for these scenarios (Martin and Smith 2007; Callaway et al. 2011; Sanderson et al. 2012; Landquist et al. 2013; Liehr et al. 2013; Baršienė et al. 2016; Briggs et al. 2016). Efficiently assessing health impacts on marine animals caused by neurotoxic chemicals from munitions (alongside neurotoxic pesticides and biotoxins from harmful algae) could be usefully achieved using the OECD (2013) Adverse Outcome Pathways approach. Attention also needs to be given to the dangers to the public, fisherman and marine life of coastal artillery ranges (*Sanctuary* 2017).

9.3 Implications for Marine Biodiversity, Fisheries and Seafood

Integrated chemical and biological monitoring of marine life and fisheries is an important long-term activity to understand potential impacts of munitions disposal on marine life and seafood supplies. Again, this is a reflected in the value of existing integrated monitoring programmes (Defra 2010d; Hylland et al. 2017b).

10. Light

10.1 Current Issues

Recent reports suggest that 54 per cent of the coastline of Europe is affected by artificial light pollution (Davies et al. 2014), with potential consequences including disrupting the natural colours, cycles and intensities of night-time light, each of which guide important processes in commercial fish species and other marine organisms (Naylor 1999; Marchesan et al. 2005; Navarro-Barranco and Hughs, 2015). At the current time, there is a paucity of information on how light pollution affects marine species and their behaviours that have evolved in the context of the natural intensity, colour spectra and periodicity of night-time light (Hölker et al. 2010; Davies et al. 2014).

10.2 Key Drivers and Future Trends

Further work is required to address the potential long-term impact of light pollution on commercial fish species and marine life in general. Considering the stress aspect of such physical factors, together with other physical stressors (e.g. noise) and chemicals, the cumulative health impacts need to be addressed for marine life in coastal regions.

10.3 Implications for Marine Biodiversity, Fisheries and Seafood

Quantifying the extent of the implications of light pollution is currently unknown due to lack of evidence.

11. Noise

11.1 Current Issues

Anthropogenic noise is recognised as a global problem in the marine environment, sources of which include shipping, sonar from fishing trawlers or military vessels, pile driving during windfarm construction, and seismic survey airguns used in offshore oil and gas exploration (Williams et al. 2015). Evidence is growing that underwater noise causes negative effects in diverse taxa, including marine mammals (Williams et al. 2014), commercial fish species (Debusschere et al. 2014) and crustaceans (Wale et al. 2013).

11.2 Key Drivers and Future Trends

Again, assessing health impacts on marine animals caused by noise and other physical hazards (e.g. light) and chemicals could be usefully achieved using the OECD (2013) Adverse Outcome Pathways approach, building on established evidence on stress and disease (Selye 1950, 1955) and the environment and disease (Hill, 1965).

11.3 Implications for Marine Biodiversity, Fisheries and Seafood

Again, quantifying the extent of the implications of noise pollution is currently difficult due to lack of evidence.

12. Conclusions

This review was commissioned to address the key drivers of change for the future of the sea with respect to hazardous chemicals and physical contaminants (namely anthropogenic radiation, light, noise and thermal discharges). It is not an exhaustive review of the global marine scientific evidence, but is strategically focused on the seas of the UK and Overseas Territories, however, and the supporting references provide a direct route to further specialist information if required.

Briefly, the available evidence suggests that for hazardous chemicals and physical contaminants, three key drivers (summarised as ‘economic’, ‘geographic’ and ‘climate change’ drivers) are particularly relevant to protecting the future of marine biodiversity and natural capital, human health (seafood supplies), UK maritime industries (fishing, coastal energy infrastructure and harbour dredging), and legal obligations such as the Ospar Convention (1992) and Stockholm Convention (2001). In terms of scientific projections in the decades ahead, a highly useful approach has been described in terms of future scenarios for UK marine ecosystems by Pinnegar et al. (2006). Taking one aspect, the climate change driver and the future of the sea, recent studies suggest that this will be a key driver of chemical exposure, with a positive relationship between ocean acidification and pollution, including increased toxicity of contaminated sediments (Roberts et al. 2013; Zeng et al. 2015).

In conclusion, there is growing scientific understanding of the need to address the future combined impacts of both natural and synthetic hazardous chemicals, together with physical contaminants (including anthropogenic radioactivity, light, noise, vibration and thermal discharges). The integrated chemical and biological assessment approach is a scientifically robust one for marine monitoring to protect the future of the sea (Hylland et al. 2017b) and can be augmented by innovative approaches from the biomedical and human health arenas (OECD 2013). Finally, novel technologies offer new tools to monitor the complex range of chemical and physical hazards in the sea, enabling innovative marine monitoring, which also capitalises on citizen science in both the UK and the Overseas Territories. This has the potential to strengthen our capacity to protect the marine environment and seafood supplies from the combined impacts of hazardous chemicals and physical contaminants as key economic, geographic and climate change drivers affect the future of the sea.

References

Bao, V.W.W., Leung, K.M.Y., Kwok, K.W.H., Zhang, A.Q. and Lui, G.C.S. (2008) Synergistic Toxic Effects of Zinc Pyrithione and Copper to Three Marine Species: Implications on Setting Appropriate Water Quality Criteria. *Marine Pollution Bulletin* 57, 616−623.

Balaam, J.L., Chan-Man, Y., Roberts, P.H. and Thomas, K.V. (2009) Identification of Nonregulated Pollutants in North Sea-Produced Water Discharges. *Environmental Toxicology & Chemistry* 28, 1159–1167.

Baršienė, J., Butrimavičienė, L., Grygiel, W., Stunžėnas, V. et al. (2016) Environmental Genotoxicity Assessment along the Transport Routes of Chemical Munitions Leading to the Dumping Areas in the Baltic Sea. *Marine Pollution Bulletin* 103, 45–53.

BBC News (2015) Chinese Ban Imposed on ‘Contaminated’ Crabs. *BBC News* 20 August. http://www.bbc.co.uk/news/uk-wales-north-west-wales-34006259 (accessed 18 January 2017).

Beddington, J. and Kinloch, A.J. (2005) Munitions Dumped at Sea: A Literature Review. Imperial College Consultants, Imperial College London. 90 pp.

Bolam, T., Bersuder, P., Burden, R., Shears, G. et al. (2016) Cadmium Levels in Food Containing Crab Brown Meat: A Brief Survey from UK Retailers. *Journal of Food Composition & Analysis* 54, 63–69.

Bonney, R., Cooper, C.B., Dickinson, J., Kelling, S. et al. (2009) Citizen Science: A Developing Tool for Expanding Science Knowledge and Scientific Literacy. *BioScience* 59 (11), 977–984.

Borja, A., Elliott M., Carstensen J., Heiskanen A.S. and van de Bund W. (2010) Marine Management – Towards an Integrated Implementation of the European Marine Strategy Framework Directive and the Water Framework Directive. *Marine Pollution Bulletin* 60 (12), 2175–2186.

Bourdineaud, J.-P., Fujimura, M., Laclau, M., Sawada, M. and Yasutake, A. (2011) Deleterious Effects in Mice of Fish-Associated Methylmercury Contained in a Diet Mimicking the Western Populations' Average Fish Consumption. *Environment International* 37, 303–313.

Brausch, J.M. and Rand, G.M. (2011) A Review of Personal Care Products in the Aquatic Environment: Environmental Concentrations and Toxicity. *Chemosphere* 82, 1518–1532.

Briggs, C., Shjegstad, S.M., Silva, J.A.K. and Edwards, M.H. (2016) Distribution of Chemical Warfare Agent, Energetics, and Metals in Sediments at a Deep-Water Discarded Military Munitions Site. *Deep Sea Research II: Topical Studies in Oceanography* 128, 63–69.

Brooks, S.M., Spencer, T., McIvor, A. and Möller, I. (2016) Reconstructing and Understanding the Impacts of Storms and Surges, Southern North Sea. *Earth Surface Processes & Landforms* 41 (6), 855–864.

Brumovský, M., Bečanová, J., Kohoutek, J., Thomas, H. et al. (2016) Exploring the Occurrence and Distribution of Contaminants of Emerging Concern through Unmanned Sampling from Ships of Opportunity in the North Sea. *Journal of Marine Systems* 162, 47-56.

Callaway, A., Quinn, R., Brown, C.J., Service M. and Benetti S. (2011) Trace Metal Contamination of Beaufort’s Dyke, North Channel, Irish Sea: A Legacy of Ordnance Disposal. *Marine Pollution Bulletin* 62, 2345–2355.

Cefas 2012. Monitoring of the Quality of the Marine Environment, 2008–2010. Science Series Aquatic Environment Monitoring Report 63. Lowestoft: CEFAS. 111pp.

Chelossi, E. and Faimali, M. (2006) Comparative Assessment of Antimicrobial Efficacy of New Potential Biocides for Treatment of Cooling and Ballast Waters. *Science of the Total Environment* 356 (1–3), 1–10.

Chiang, W.L., Au, D.W.T., Yu, P.K.N. and Wu, R.S.S. (2003) UV-B Damages Eyes of Barnacle Larvae and Impairs their Photoresponses and Settlement Success. *Environmental Science & Technology* 37, 1089–1092.

Cigliano, J.A., Myer, R., Ballard, H.L., Freitag, A. et al. (2015) Making Marine and Coastal Citizen Science Matter. *Ocean & Coastal Management* 115, 77-87.

Ciriminna, R., Bright, F.V. and Pagliaro, M. (2015) Ecofriendly Antifouling Marine Coatings. *ACS Sustainable Chemical Engineering* 3, 559−565.

Conrad, C.C. and Hilchey, K.G. (2011) A Review of Citizen Science and Community-Based Environmental Monitoring: Issues and Opportunities. *Environmental Monitoring and Assessment* 176, 273–291.

Davies, T.W., Duffy, J.P., Bennie, J. and Gaston, K.J. (2014) The Nature, Extent and Ecological Implications of Marine Light Pollution. *Frontiers in Ecology and the Environment* 12, 347–355.

Debusschere, E., De Coensel, B., Bajek, A., Botteldooren, D. et al. (2014) *In Situ* Mortality Experiments with Juvenile Sea Bass (*Dicentrarchus labrax*) in Relation to Impulsive Sound Levels caused by Pile Driving of Windmill Foundations. *PLoS ONE* 9 (10), 1–9.

Defra (2005) Charting Progress: An Integrated Assessment of the State of the UK Seas. Defra Report PB9911. 120 pp.

Defra (2010a) UK Marine Science Strategy: Shaping, Supporting, Co-ordinating and Enabling the Delivery of World Class Marine Science for the UK 2010–2025. Defra Report PB13347. 50 pp.

Defra (2010b) Charting Progress 2 – The State of UK Seas. Defra Report PB13420. 194 pp.

Dixon, T.R. and Dixon, T.J. (1979) Munitions in British coastal waters. *Marine Pollution Bulletin* 10, 352–357.

EEA – European Environment Agency (2011) Hazardous Substances in Europe's Fresh and Marine Waters. Technical Report 8/2011. Copenhagen: EEA. 66 pp.

Fernandez, A., Singh, A. and Jaffé, R. (2007) A Literature Review on Trace Metals and Organic Compounds of Anthropogenic Origin in the Wider Caribbean Region. *Marine Pollution Bulletin* 54 (11), 1681–1691.

Food Standards Agency (2013) Cadmium in Brown Meat from Crabs and Products made from the Brown Meat from Crabs. Food Standards Agency Information Sheet 02/13. https://www.food.gov.uk/sites/default/files/multimedia/pdfs/publication/cadmium_crabs_fsis.pdf (accessed 23 February 2017).

Forster, J., Lake, I.R., Watkinson, A.R. and Gill, J.A. (2011) Marine Biodiversity in the Caribbean UK Overseas Territories: Perceived Threats and Constraints to Environmental Management. *Marine Policy* 35, 647–657.

Fux, E., Bire, R. and Hess, P. (2009) Comparative Accumulation and Composition of Lipophilic Marine Biotoxins in Passive Samplers and in Mussels (*M. edulis*) on the West Coast of Ireland. *Harmful Algae* 8 (3), 523–537.

Gaw, S., Thomas, K.V. and Hutchinson, T.H. **(**2014) Sources, Impacts and Trends of Pharmaceuticals in the Marine and Coastal Environment. *Philosophical Transactions of the Royal Society B* 369 (1656).

Hagger, J.A., Atienzar, F.A. and Jha, A.N. (2005) Genotoxic, Cytotoxic, Developmental and Survival Effects of Tritiated Water in the Early Life Stages of the Marine Mollusc, *Mytilus edulis*. *Aquatic Toxicology* 74 (3), 201–217.

Hall, A.J. and Frame, E. (2010) Evidence of Domoic Acid Exposure in Harbour Seals from Scotland: A Potential Factor in the Decline in Abundance? *Harmful Algae* 9, 489–493.

Hall, A.J., Hugunin, K., Deaville, R., Law, R.J. et al. (2006) The Risk of Infection from Polychlorinated Biphenyl Exposure in The Harbour Porpoise (*Phocoena phocoena*): A Case-Control Approach. *Environmental Health Perspectives* 114 (5), 704–711.

Hallegraeff, G.M. (1993) A Review of Harmful Algal Blooms and their Apparent Global Increase. *Phycologia* 32 (2), 79–99.

Haug, L.S., Thomsen, C., Brantsaeter, A.L., Kvalem, H.E. et al. (2010) Diet and Particularly Seafood are Major Sources of Perfluorinated Compounds in Humans. *Environment International* 36 (7), 772–778.

Häder, D.P., Worrest, R.C., Kumar, H.D. and Smith, R.C. (1995) Effects of Increased Solar Ultraviolet Radiation on Aquatic Ecosystems. *Ambio* 24, 174–180.

Hedge, L.H., Knott, N.A. and Johnston, E.L. (2009) Dredging Related Metal Bioaccumulation in Oysters. *Marine Pollution Bulletin* 58, 832–840.

Hill, A.B. (1965) The Environment and Disease: Association or Causation? *Proceedings of the Royal Society of Medicine* 58, 295–300.

House of Commons (2007) Science & Technology Select Committee Report 'Investigating the Oceans'. House of Commons London, Stationary Office report HC 470-I. 151 pp.

Hölker, F., Wolter, C., Perkin, E.K. and Tockner, K. (2010) Light Pollution as a Biodiversity Threat. *Trends in Ecology & Evolution* 25, 681–682.

Hosseini, A., Brown, J.E., Gwynn, J.P. and Dowdall, M. (2012) Review of Research on Impacts to Biota of Discharges of Naturally Occurring Radionuclides in Produced Water to the Marine Environment. *Science of the Total Environment* 438, 325–333.

Hutchinson, T.H., Lyons, B.P., Thain, J. and Law, R.J. (2013) Evaluating Legacy Contaminants and Emerging Chemicals in Marine Environments using Adverse Outcome Pathways and Biological Effects-Directed Analysis. *Marine Pollution Bulletin* 74 (2), 517–525.

Hylland, K., Burgeot, T., Martínez-Gómez, C., Lang, T. et al. (2017a) How Can We Quantify Impacts of Contaminants in Marine Ecosystems? The ICON project. *Marine Environmental Research* 124, 2–10.

Hylland, K., Robinson, C.D., Burgeot, T., Martínez-Gómez, C. et al. (2017b) Integrated Chemical and Biological Assessment of Contaminant Impacts in Selected European Coastal and Offshore Marine Areas. *Marine Environmental Research* 124, 130–138.

Jepson, P.D., Deaville, R., Barber, J.L., Aguilar, A. et al. (2016) PCB Pollution Continues to Impact Populations of Orcas and Other Dolphins in European Waters. *Scientific Reports* 6; doi: 10.1038/srep18573

Jha, A.N., Cheung, V.V., Foulkes, M.E., Hill, S.J. and Depledge, M.H. (2000) Detection of Genotoxins in the Marine Environment: Adoption and Evaluation of an Integrated Approach using the Embryo Larval Stages of the Marine Mussel, *Mytilus edulis*. *Mutation Research* 464, 213–228.

Johnson, S., Andersson, A., Nilsson, M.B., Skyllberg, U. et al. (2017) Terrestrial Discharges Mediate Trophic Shifts and Enhance Methylmercury Accumulation in Estuarine Biota. *Science Advances* 3 (1), e1601239.

Kim, H.J., Lee, J.H., Hur, Y.B., Lee, C.W. et al. (2016) Marine Antifreeze Proteins: Structure, Function and Application to Cryopreservation as a Potential Cryoprotectant. *Marine Drugs* 15 (2), 27; doi:10.3390/md15020027

Landquist, H., Hassellöv, I.M., Rosén, L., Lindgren, J.F. and Dahllöf, I. (2013) Evaluating the Needs of Risk Assessment Methods of Potentially Polluting Shipwrecks. *Journal of Environmental Management* 119, 85–92.

Law, R.J., Barry, J., Barber, J.L., Bersuder, P. et al. 2012. Contaminants in Cetaceans from UK Waters: Status as Assessed Within the Cetacean Strandings Investigation Programme from 1990 to 2008. *Marine Pollution Bulletin* 64 (7), 1485–1494.

Liehr, G.A., Heise, S., Ahlf, W., Offermann, K. and Witt, G. (2013) Assessing the Risk of a 50-Year Old Dump Site in the Baltic Sea by Combining Chemical Analysis, Bioaccumulation, and Ecotoxicity. *Journal of Soils & Sediments* 13, 1270–1283.

Lyons, B., Thain, J.E., Stentiford, G.D., Hylland, K. et al. (2010) Using Biological Effects Tools to Define Good Environmental Status under the European Union Marine Strategy Framework Directive. *Marine Pollution Bulletin* 60 (10), 1647–1651.

Martin, J.R. and Smith, G., (2007) Munitions Contamination of Marine Renewable Energy Sites in Scottish Waters: A Study for the Scottish Executive. Farnborough: QinetiQ. Report QINETIQ/D&TS/SEA/EIA0613056. 42 pp.

Matthiessen, P. and Law, R.J. (2002) Contaminants and their Effects on Estuarine and Coastal Organisms in the United Kingdom in the Late Twentieth Century. *Environmental Pollution* 120 (3), 739–757.

McCubbin, D., Leonard, K.S., Bailey, T.A., Williams, J. and Tossell, P. (2001) Incorporation of Organic Tritium (^3H) by Marine Organisms and Sediment in the Severn Estuary/Bristol Channel (UK). *Marine Pollution Bulletin* 42, 852–863.

Marchesan, M., Spoto, M., Verginella, L. and Ferrero, E.A. (2005) Behavioural Effects of Artificial Light on Fish Species of Commercial Interest. *Fisheries Research* 73 (1–2), 171–185.

Millero, F.J., Woosley, R., DiTrolio, B. and Waters, J. (2009) Effect of Ocean Acidification on the Speciation of Metals in Seawater. *Oceanography* 22 (4), 72–85.

Mullon, C., Steinmetz, F., Merina, G., Fernandes, J.A. et al. (2016) Quantitative Pathways for Northeast Atlantic Fisheries Based on Climate Change, Ecological-Economic and Governance Modelling Scenarios. *Ecological Modelling* 320, 273–291.

Murphy, S., Barber, J.L., Learmonth, J.L., Read, F.L. et al. (2015) Reproductive Failure in UK Harbour Porpoises *Phocoena phocoena*: Legacy of Pollutant Exposure? *PLOS One* 7 (10), 031085.

Nadal, M., Marquès, M., Mari, M. and Domingo, J.L. (2015) Climate Change and Environmental Concentrations of POPs: A Review. *Environmental Research* 143, 177–185.

Navarro-Barranco, C. and Hughs, L.E. (2015) Effects of Light Pollution on the Emergent Fauna of Shallow Marine Ecosystems: Amphipods as a Case Study. *Marine Pollution Bulletin* 94 (1–2), 235–240.

Naylor, E. (1999) Marine Animal Behaviour in Relation to Lunar Phase. *Earth, Moon & Planets* 85–86, 291–302.

Nicolaus, E.E.M., Wright, S., Bolam, T.P.C., Barber, J.L. et al. (2016a) Spatial and Temporal Analysis of the Risks Posed by Polychlorinated Biphenyl and Metal Contaminants in Dab (*Limanda limanda*) Collected from Waters around England and Wales. *Marine Pollution Bulletin* 112 (1–2), 399–405.

Nicolaus, E.E.M., Bendall, V.A., Bolam, T.P.C., Maes, T. and Ellis, J.R. (2016b) Concentrations of Mercury and Other Trace Elements in Porbeagle Shark *Lamna nasus*. *Marine Pollution Bulletin* 112 (1–2), 406–410.

Noyes, P.D., McElwee, M.K., Miller, H.D., Clark, B.W. et al. (2009) The Toxicology of Climate Change: Environmental Contaminants in a Warming World. *Environment International* 35 (6), 971–986.

OECD – Organisation for Economic Co-operation and Development (2013) Guidance Document on Developing and Assessing Adverse Outcome Pathways, Series on Testing and Assessment 184. Paris: OECD. 45 pp.

OSPAR (2010) Quality Status Report 2010. London: OSPAR Commission. 176 pp. Available from www.ospar.org.

Pascal, P.-Y., Fleeger, J.W., Galvez, F. and Carman, K.R. (2010) The Toxicological Interaction between Ocean Acidity and Metals in Coastal Meiobenthic Copepods. *Marine Pollution Bulletin* 60, 2201–2208.

Pinnegar, J.K., Viner, D., Hadley, D., Dye, S. et al. (2006) Alternative Future Scenarios for Marine Ecosystems: Technical Report. Lowestoft: Cefas. 109 pp.

Pope, N.D., O'Hara, S.C.M., Imamura, M., Hutchinson, T.H., Langston, W.J. (2011) Influence of a Collapsed Coastal Landfill on Metal Levels in Sediments and Biota – A Portent for the Future? *Journal of Environmental Monitoring* 13 (7), 1961–1974.

Roberts, D.A., Birchenough, S.N.R., Lewis, C., Sanders, M.B. et al. (2013) Ocean Acidification Increases the Toxicity of Contaminated Sediments. *Global Change Biology* 19 (2), 340–351.

Robins, P.E., Skov, M.W., Lewis, M.J., Gimenez, L. et al. (2016) Impact of Climate Change on UK Estuaries: A Review of Past Trends and Potential Projections. *Estuarine, Coastal & Shelf Science* 169, 119–135.

Ross, P.S., Couillard, C.M., Ikonomou, M.G., Johannessen S.C. et al. (2009) Large and Growing Environmental Reservoirs of Deca-BDE Present an Emerging Health Risk for Fish and Marine Mammals. *Marine Pollution Bulletin* 58, 7–10.

Sanctuary (2016) Gower Peninsular Dealing with a Potentially Explosive World War II Legacy. *Sanctuary: The Ministry of Defence Sustainability Magazine* 45, 30–31.

Sanderson, H., Fauser, P., Thomsen, M. and Larsen, J.B. (2012) Weight-of-Evidence Environmental Risk Assessment of Dumped Chemical Weapons after WWII along the Nord-Stream Gas Pipeline in the Bornholm Deep. *Journal of Hazardous Materials* 215–216, 217–226.

Selye, H. (1950) Stress and the General Adaptation Syndrome. *British Medical Journal* 1 (4667), 1383–1392.

Selye, H. (1955) Stress and Disease. *Science* 122 (3171), 625–631.

Sheahan, D., Maud, J., Wither, A., Moffat, C. and Engelke, C. (2013) Impacts of Climate Change on Pollution (Estuarine and Coastal). *MCCIP Science Review* 2013, 244–251.

Singh, J.G., Chang-Yen, I., Stoute, V.A. and Chatergoon, L. (1992) Hydrocarbon Levels in Edible Fish, Crabs and Mussels from the Marine Environment of Trinidad. *Marine Pollution Bulletin* 24 (5), 270–272.

Stobo, L.A., Lacaze, J.-P.C.L., Scott, A.C., Petrie, J. and Turrell, E.A. (2008) Surveillance of Algal Toxins in Shellfish from Scottish Waters. *Toxicon* 51 (4), 635–648.

Tedetti, M. and Sempéré, R. (2006) Penetration of Ultraviolet Radiation in the Marine Environment: A Review. *Photochemistry & Photobiology* 82 (2), 389–397.

Thain, J.E., Vethaak, A.D. and Hylland, K. (2008) Contaminants in Marine Ecosystems: Developing an Integrated Indicator Framework using Biological-Effect Techniques. *ICES Journal of Marine Science* 65 (8), 1508–1514.

Tiedeken, J.A., Ramsdell, J.S. (2010) Zebrafish Seizure Model Identifies *p,p'*-DDE as the Dominant Contaminant of Fetal California Sea Lions that Accounts for Synergistic Activity with Domoic Acid. *Environmental Health Perspectives* 118 (4), 545–551.

Titley-O'Neal, C.P., MacDonald, B.A., Pelletier, E., Saint-Louis, R. and Phillip, O.S. (2011) The Relationship between Imposex and Tributyltin (TBT) Concentration in *Strombus gigas* from the British Virgin Islands. *Bulletin of Marine Science* 87 (3), 421–435.

Titley-O'Neal, C.P., Spade, D.J., Zhang, Y., Kan, R. et al. (2013) Gene Expression Profiling in the Ovary of Queen Conch (*Strombus gigas*) Exposed to Environments with High Tributyltin in the British Virgin Islands. *Science of the Total Environment* 449, 52–62.

Tornero, V. and Hanke, G. (2016) Chemical Contaminants Entering the Marine Environment from Sea-Based Sources: A Review with a Focus on European Seas. *Marine Pollution Bulletin* 112 (1–2), 17–38.

Wale, M.A., Simpson, S.D. and Radford, A.N. (2013) Noise Negatively Affects Foraging and Antipredator Behaviour in Shore Crabs. *Animal Behaviour* 86 (1), 111–118.

Webster, L., Robinson, C.D., Russell, M. Walsham and Moffat, C. (2010) A Review of Hazardous Substances in the Scottish Marine Environment: Update 2010. *Scottish Marine and Freshwater Science* 1 (10). 105 pp.

Wei, Q., Nagi, R., Sadeghi, K., Feng, S. et al. (2014) Detection and Spatial Mapping of Mercury Contamination in Water Samples using a Smart-Phone. *ACS Nano* 8 (2), 1121–1129.

Williams, R., Erbe, C., Ashe, E., Beerman, A. and Smith J. (2014) Severity of Killer Whale Behavioural Responses to Ship Noise: A Dose-Response Study. *Marine Pollution Bulletin* 79 (1–2), 254–260.

Williams, R., Wright, A.J., Ashe, E., Blight, L. et al. (2015) Impacts of Anthropogenic Noise on Marine Life: Publication Patterns, New Discoveries, and Future Directions in Research and Management. *Ocean & Coastal Management* 115, 17–24.

Wither, A., Bamber, R., Colclough, S., Dyer, K. et al. (2012) Setting New Thermal Standards for Transitional and Coastal (TraC) Waters. *Marine Pollution Bulletin* 64 (8), 1564–1579.

Zarbl, H., Gallo, M.A., Glick, J., Yeung K.Y. and Vouros P. (2010) The Vanishing Zero Revisited: Thresholds in the Age of Genomics. *Chemico-Biological Interactions* 184 (1–2), 273–278.

Zeng, X., Chen, X. and Zhuang, J. (2015) The Positive Relationship between Ocean Acidification and Pollution. *Marine Pollution Bulletin* 91 (1), 14–21.

Zhu, X., Zhou, J. and Cai, Z. (2011) TiO_2 Nanoparticles in the Marine Environment: Impact on the Toxicity of Tributyltin to Abalone (*Haliotis diversicolor supertexta*) Embryos. *Environmental Science & Technology* 45 (8), 3753–3758.

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