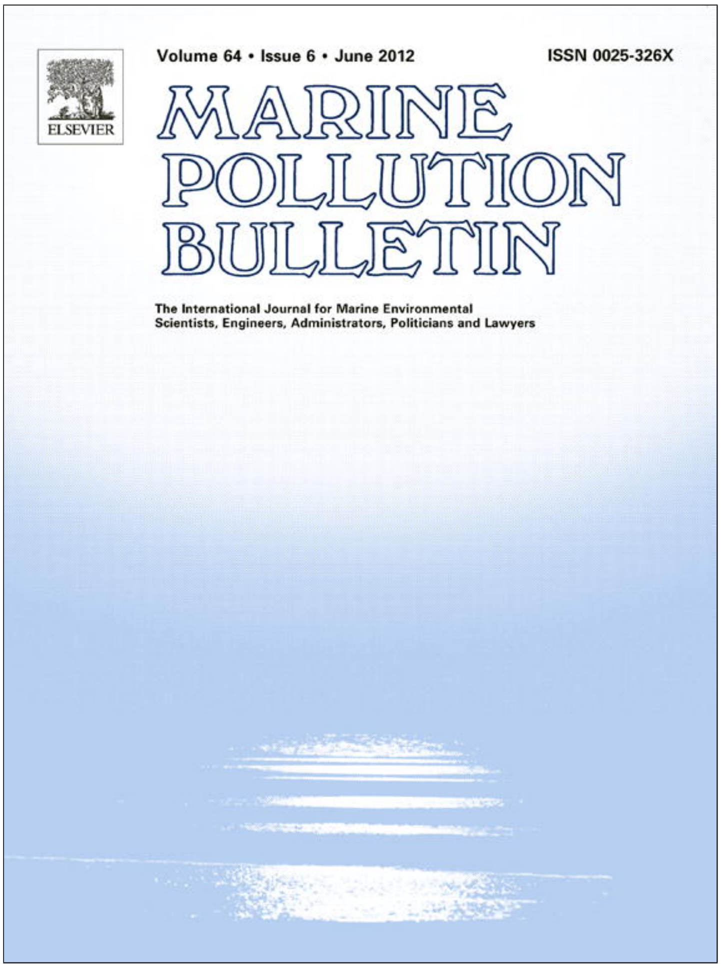
Volume 64 • Issue 6 • June 2012
ISSN 0025-326X
ELSEVIER
MARINE POLLUTION BULLETIN
The International Journal for Marine Environmental Scientists, Engineers, Administrators, Politicians and Lawyers

Marine Pollution Bulletin 64 (2012) 1085–1095

Contents lists available at SciVerse ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Review

Review of oil and HNS accidental spills in Europe: Identifying major environmental monitoring gaps and drawing priorities

T. Neuparth [a,*], S.M. Moreira [a], M.M. Santos [a,b], M.A. Reis-Henriques [a]

[a] CIMAR/CIIMAR – Interdisciplinary Centre of Marine and Environmental Research, University of Porto, Rua dos Bragas 177, 4050-123 Porto, Portugal
[b] FCUP – Department of Biology, Faculty of Sciences, University of Porto, Rua do Campo Alegre, 4169-007 Porto, Portugal

ARTICLE INFO

Keywords:
Oil spills
HNS spills
European Atlantic waters
Environmental monitoring programmes
Monitoring gaps and priorities

ABSTRACT

The European Atlantic area has been the scene of a number of extensive shipping incidents with immediate and potential long-term impacts to marine ecosystems. The occurrence of accidental spills at sea requires an effective response that must include a well executed monitoring programme to assess the environmental contamination and damage of the affected marine habitats. Despite a number of conventions and protocols developed by international and national authorities that focused on the preparedness and response to oil and HNS spills, much remains to be done, particularly in relation to the effectiveness of the environmental monitoring programmes implemented after oil and HNS spills. Hence, the present study reviews the status of the environmental monitoring programmes established following the major spill incidents over the last years in European waters, aiming at identifying the key monitoring gaps and drawing priorities for an effective environmental monitoring of accidental spills.

1. Introduction

Due to the immediate and potential long-term adverse effects inflicted on marine habitats and ecosystems, marine pollution resulting from accidental spills is a global concern. Although there is evidence for a decrease in number of maritime incidents causing significant oil spills and, probably HNS spills since the end of 1980s (Huijer, 2005; Burgherr, 2007), some important incidents still occurred in the last two decades (e.g. *Aegean Sea* 1992, *Sea Empress* 1996, *Ievoli Sun* 2000, *Prestige*, 2002, *MSC Napoli*, 2007, etc.). The serious threat posed by shipping-related accidental spills, has led international and national authorities to develop a number of measures to prevent and minimize environmental and economical consequences caused by these incidents. Regarding oil pollution, the International Convention on Oil Pollution Preparedness, Response and Co-operation (OPRC Convention) was adopted in 1990 and came into force on May 13, 1995 (Singhota, 1995). More recently, along with the recognition that HNS spills could have similar environmental consequences as oil spills, a new protocol aiming at improving the response to major HNS incidents was also developed. In this context, the Protocol on Preparedness, Response and Co-operation to Pollution Incidents by Hazardous and Noxious Substances (OPRC–HNS Protocol) was adopted by the IMO (2000) and entered into force in 2007. Despite these conventions and protocols, much remains to be done regarding preparedness and response to oil and HNS spills. Of particular concern is the effectiveness of environmental monitoring programmes implemented after oil and HNS spills, crucial in the case of the latter. Indeed, while the environmental impacts of oil spills can be identified from the response experiences and the lessons learnt from past major oil spills, the potential ecological hazards and risks posed by HNS spills are much less recognized and understood (Kirby and Law, 2010; Neuparth et al., 2011). The information available on HNS spills illustrates the poor documentation or mistreatment of many HNS incidents and, in most cases, no monitoring programmes were implemented following the incident (Purnell, 2009).

As soon as an accidental spill occurs, a monitoring programme aiming at quantifying the environmental impacts of the spill is usually launched. The assessment of the environmental impact is crucial for the decision-making process over the selection and implementation of a prominent response and restoration plans (Kirby and Law, 2010). In addition, from a legal standpoint, the development of adequate monitoring tools are of chief importance, since they can be used to demonstrate ecological damage and economic losses in the context of spill-related claims and compensations. Depending on the formulated objectives, environmental monitoring programmes may include different methodologies to monitor the chemical contamination of the various compartments (e.g. sediments, water, biota) and evaluate the biological and ecological impacts of the spill. Hence, it is crucial to learn lessons from previous monitoring programmes to upgrade our knowledge and, consequently, propose improved methodologies and corresponding environmental impact assessment tools.

* Corresponding author. Tel.: +351 223 401 818; fax: +351 223 390 608.
E-mail address: tneuparth@ciimar.up.pt (T. Neuparth).

0025-326X/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.marpolbul.2012.03.016

The present work aims at providing a review and analysis of the monitoring programmes that were established following the six major spill incidents that occurred over the last years in European coastal regions (*Sea Empress*, *Erika*, *Ievoli Sun*, *Prestige*, *Ece* and *MSC Napoli*). Furthermore, this study aims at identifying considerable environmental monitoring gaps and principal priorities with regards to the lessons learnt from previous spill experiences: an essential step towards the establishment of a more effective preparedness and response to spill incidents.

2. Analysis of monitoring programmes set up following spill incidents

2.1. General details and approach

General details of the six analysed spill incidents are summarized in Table 1. This table includes three oil spills: *Sea Empress* (1996, UK), *Erika* (1999, France), *Prestige* (2002, Spain); and three chemical spills: *Ievoli Sun* (2000, Channel), *Ece* (2006, Channel), *MSC Napoli* (2007, UK).

In the case of *Ievoli Sun* and *Ece* spills, two of the major recent HNS incidents in the European coast, despite the implementation of some environmental monitoring approaches during the incident (i.e. since the vessels sank until the wrecks were de-polluted), no post-incident monitoring were implemented; hence, no data is available for analysis. In the remaining four incidents, the methodologies, procedures and biological targets used to quantify the magnitude of the spill impacts in the different marine compartments are evaluated and compared. From the published monitoring studies analysed, three common types of scientific approaches were identified:

(A) Chemical contamination monitoring: measurement of the chemical concentration in the various marine compartments.
(B) Biological monitoring – responses at sub-individual and individual level: physiological and epidemiological markers, biomarkers of exposure/effect and/or biological responses in ecotoxicological assays.
(C) Ecological monitoring: monitoring studies at population or community level (population dynamic and/or community structure parameters).

Additionally, the following categorization of the ecological domains was used:

(a) pelagic;
(b) benthic;
(c) birds;
(d) marine mammals.

2.2. Sea Empress

2.2.1. Brief overview of the incident

The tanker *Sea Empress* grounded in south-west Wales on February 1996. 72,000 tonnes of forties blend crude oil and 480 tonnes of heavy fuel oil were spilt. Oil came ashore along 200 km of coastline in an area of exceptional conservation interest for its wildlife and natural beauty (SEEEC, 1998).

2.2.2. Scientific approaches of the monitoring programme

Following the *Sea Empress* incident, a series of studies were conducted as part of the Sea Empress Environmental Evaluation Committee (SEEEC, 1998) that involved several agencies, organisations and individuals to assess the environmental impact of the spill on the marine life. The main findings of the scientific approaches implemented in the *Sea Empress* spill are presented in Table 2.

2.2.3. Main conclusions

Despite the large amount of oil spilled in a particularly sensitive area, the impact was far less severe than initially anticipated. The Sea Empress Environmental Evaluation Committee (SEEEC, 1998) suggested that this was due to a combination of factors: (a) the time of the year: the spill occurred in February at a time of low environmental use, tourists were few and many wildlife species had migrated; (b) the wind direction: as the wind was blowing from the north, 87% of oil was pushed away from the coast; (c) the type of oil spilled: the light crude oil from Forties field is easier to disperse and treat chemically than other type of oil and (d) the success of chemical dispersants: the success of the dispersants was due to the properties of the oil involved.

Nevertheless, despite these mitigating factors, the environmental impacts in the region were still significant. The main impacts were (SEEEC, 1998): (a) the death of a great number of crustacean and molluscs due to the oil that came ashore (e.g. limpets) or due to the high levels of hydrocarbons in the water column; (b) the disappearance of amphipod populations from some areas near the grounding site; (c) several thousand of oiled birds, many of them dead, were washed ashore with the most severely affected population being the local common scoter (*Melanitta nigra*) which presented a very slow recovery; (d) the loss of feeding grounds significantly affecting some migratory species and resulting in a poor re-establishment of some species and (e) a significant decrease in the population of the cushion starfish (*Arterina phylactica*).

In an evaluation of the state of the marine environment in SW Wales 10 years after the *Sea Empress* oil spill, Moore (2006) concluded that the post-spill wildlife and natural habitat monitoring studies around the Pembrokeshire coast had greatly improved our awareness about oil spill impacts and how to study them. The

Table 1
General details of the six analysed incidents.

Tanker name	*Sea Empress*	*Erika*	*Prestige*	*Ievoli Sun*	*Ece*	*MSC Napoli*
Year	1996	1999	2002	2000	2006	2007
Local	Milford Haven, Wales	Brittany, France	Galicia, Spain	Channel France	Channel France	Lyme Bay, UK
Chemicals transported	Forties Blend (light crude); heavy fuel oil	Heavy fuel oil	Heavy fuel oil	Styrene, methyl-ethyl-keton; isopropanol; heavy fuel oil	Phosphoric acid; heavy fuel oil	Dangerous chemicals; heavy fuel oil; diesel oil
Cargo (tonnes)	130,824	31,000	77,000	6000	10,000	2394 containers; 3780 t heavy oil; 45 t diesel oil
Spill size	72,000 t light crude; 480 t heavy fuel oil	19,000 t	63,000 t	2000 t methyl-ethyl-keton; isopropanol voluntarily released	8000 t phosphoric acid voluntarily released	300 t oil

Table 2
Scientific approaches applied in the monitoring programme of the *Sea Empress* oil spill.

Chemical monitoring		Water and sediments: elevated total hydrocarbons concentrations (THCs) in seawater, with a decrease (below 100 µg/l) to levels near background 1 month after the incident; elevated THCs in intertidal sediments from Angle Bay and Pembroke River until August 1998 (SEEEC, 1998)
		Fish and shellfish: low total PAHs concentration (TPAHs) in muscle of salmon throughout the incident (12–186 µg/kg); TPAHs concentrations in edible crabs, spider crabs and lobsters were found between 100–2450 µg/kg from February to April 1996, and declined to levels below 100 µg/kg in September–October 1996, TPAHs in mussels were above 1000 µg/kg until the end of 1996 (Law and Kelly, 2004)
Biological monitoring		DNA damage: no detectable increase in DNA adducts in invertebrates (*Halichondria panicea* and *Mytilus edulis*); increase of DNA damage in teleosts (*Lipophrys pholis*, *Limanda limanda* and *Pleuronectes platessa*) that recovered 17 months after the spill (Lyons et al., 1997; Harvey et al., 1999)
		Biochemical markers: elevated EROD levels in liver of flatfish (*Limanda limanda* and *Pleuronectes platessa*) 2 weeks and 3 months after the spill, but no clear relationship to PAHs contamination was determined (Kirby et al., 1999)
		Immune function: severe immunosuppression in *Mytilus edulis* with recovery by May 1996; the immune function of mussels was again reduced later due to the rising of combustion-derived PAHs concentrations (Dyrynda and Symberlist, 2000)
		Lysosomal stability: cell injury was detected in blood cells of mussels by neutral red retention assay after 4 months of the incident (Fernley et al., 2000)
		Scope for growth: Reduction of *Mytilus edulis* physiological fitness with a recovery by October 1996 (Widdows et al., 2002)
Ecological monitoring	Marine mammals	No evidence of pollution-related seal mortality, or visible evidence of breeding habitat degradation were identified during the incident (Kiely et al., 2000)
	Birds	More than 6000 dead or alive oiled birds were collected after the incident; most of the cleaned birds died soon after the release (Edwards and White, 1999)
		Breeding colonies of guillemots and razorbills were reduced during 1997 and the population of scoters was reduced until 1998 (Moore, 2006)
	Fish/shellfish	No significant mortality on commercially fish and shellfish populations was reported (Moore, 2006)
		A large number of dead or moribund shellfish (molluscs) were washed ashore after the oil spill (SEEEC, 1998)
		Abundance, biometrics and other condition factors of herring population were not affected by the spill (Ellis and Rogers, 2002)
	Benthos	A severe impact, with 90% mortality, of amphipod fauna (*Ampelisca brevicornis*), and molluscs (*Cerastoderma edule*, *Patella vulgata*) was recorded; mortality of topshells and periwinkles was also observed, but in lower numbers; the recovery of these populations was observed by 2001 (Moore, 2006)
		Cushion starfish populations (*Asterina phylactica*) suffered a high mortality but recovered by 2001; the rock-pool prawn (*Palaemon elegans*) was also affected and showed a slow recovery (Moore, 2006)

analysis also highlighted a number of knowledge gaps, such as: (a) an inadequate understanding of sublethal oil exposure effects for the majority of the concerned species; (b) the unknown effects on a number of populations of more sensitive species (e.g. shallow sub-tidal bivalves) and (c) the unavailability of key information on the biology and distribution of some vulnerable species (e.g. scoter). Most importantly, Moore (2006) suggested that many of the impacts and effects that were detected would not have been noticed without the considerable amount of detailed work and baseline data available for the Pembrokeshire coast.

2.3. Erika

2.3.1. Brief overview of the incident

On December 1999, the tanker *Erika* loaded with 31,000 tonnes of heavy fuel oil, broke 30 miles off the French coast. About 19,000 tonnes of fuel was released in the sea. Four hundred kilometres of Francés Atlantic coast were impacted (Amat et al., 2005).

2.3.2. Scientific approaches of the monitoring programme

The French government implemented a monitoring programme focusing on the ecological and ecotoxicological consequences of the *Erika* oil spill. The main findings of the scientific approaches implemented in the *Erika* monitoring programme are presented in Table 3.

2.3.3. Main conclusions

The monitoring programme provided a good insight into the impact of the *Erika* incident on different areas of the littoral ecosystems. Several chemical and biochemical endpoints were validated for the French coast. However, the research teams involved in this monitoring programme were challenged by the data analysis due to the lack of knowledge about the structure and functioning of the local ecosystems prior to the oil spill (Laubier et al., 2004). The difficulties detected were: (a) to demonstrate spill effects without knowing the effects of chronic pollution in the area; (b) to distinguish change in the ecosystem caused by the oil spill from natural variations and (c) to consider that the natural variability of a population introduces considerable uncertainty into the assessment of the impact following accidental pollution.

Laubier et al. (2004) pointed out that novel littoral observation networks focusing on living biota and communities should be implemented following the *Erika* monitoring programme. In addition, these authors highlighted the need for pre-spill reference data and for the prolongation of the monitoring programmes on the ecological impacts of a pollution incident.

In summary, the *Erika* oil spill accentuates the need for a better understanding of the reference state of marine habitats. An improved knowledge of the structure and functioning of marine ecosystems prior to the incidents and of the effects of chronic contamination, through the implementation of long-term monitoring studies, should allow a better discrimination of the effects related to the oil spills (Law et al., 2005).

2.4. Prestige

2.4.1. Brief overview of the incident

On November 2002, the *Prestige*, laden with 77,000 tonnes of heavy fuel oil sank off the Galician coast (NW Spain) and resulting in a spill of 63,000 tonnes of heavy oil, which lasted 3 months. It affected all the Galician coasts (except the inside of the Rías Bajas), the Spanish part of the Bay of Biscay and even part of the French coast (Diez et al., 2007).

2.4.2. Scientific approaches of the monitoring programme

A R&D special action focused on the *Prestige* oil spill (AEU) was launched by the Spanish Government in 2003, followed by annual call for proposals for 3 year projects on accidental marine pollution (VEM) to improve the knowledge and technology related to the assessment and mitigation of the consequences of oil spills (Laffon

Table 3
Scientific approaches applied in the monitoring programme of *Erika* oil spill[a]

Chemical monitoring		Water and sediments: in 2000, concentrations of TPAHs and total alkyl-substituted PAHs (TC-PAHs) in water ranged from 3.8 to 19ηg/l and 17 to 118 ηg/l, respectively, with significantly decline after July 2001; only some intertidal and subtidal sediments were contaminated by the spill; the median concentrations of TPAHs and TC-PAHs were 963 and 111µg/kg, respectively (Tronczynski *et al*., 2004). Molluscs: the highest levels of TPAHs and TC-PAHs were recorded in *Mytilus edulis* (6944 µg/kg and 83481 µg/kg, respectively, values that compared with pre-spill data increased by a factor of 22 and 171 times respectively); in 2002, the TPAHs and TC-PAHs decreased but were still above reference concentrations (353 µg/kg and 104 µg/ kg, respectively) (Tronczynski *et al*., 2004). Nickel concentrations in mollusc tissues (*Mytilus edulis* and *Crassostrea gigas*) did not show any significant increase while vanadium concentrations showed a peak 5 months after the spill (Chiffoleau *et al*., 2004). Seabirds: vanadium concentrations in liver and kidney were not increased in affected birds (*Uria aalge*, *Melanitta nigra* and *Somateria mollissima*) (Kammerer *et al*., 2004).
Biological monitoring		DNA damage: elevated levels of DNA adducts in *Solea solea* and *Mytilus edulis* during 2 and 6 months after the spill, with recovery values 9 months after the spill (Bocquené *et al*., 2004; Budzinski *et al*., 2004). Biochemical markers: during the 6 months after the spill, no significant reductions were observed in GST or CAT activities in *Mytilus edulis*, though the levels of MDA were high and the levels of AChE were significantly lower; two months after the spill, CYP1A activity was enhanced in *Asterias rubens*, with a decrease two years after the spill (Bocquené *et al*., 2004; Joly-Turquin *et al*., 2009). Immune function: severe immunological alternations were detected two months and one year after the spill in the starfish (*Asterias rubens*) and oysters, (*Crassostrea gigas*) respectively (Auffret *et al*., 2004; Joly-Turquin *et al*., 2009).
Ecological monitoring	Marine mammals	No mortality was found; grey seals and dolphins displayed no symptoms related to the oil spill (Ridoux *et al*., 2004).
	Birds	About 74000 oiled birds (32000 alive and 42000 dead) were recorded ashore; only 2000 of the birds were released after cleaning (Cadiou *et al*., 2004). The common guillemot (*Uria aalge*) appeared to be the most affected specie with nearly 70000 birds being found dead or oiled on beaches (Cadiou *et al*., 2004).
	Benthos	A remarkable increase in the abundance of two macroalgae *Ulva* sp. and *Grateloupia doryphora* occurred 3 weeks after the spill, following a 100% mortality of sea urchins; the sea urchin densities recovered to pre-spill levels only after 3 years (Barillé-Boyer *et al*., 2004). The density and the species richness of benthic foraminifera were very low during the 21 months following the spill (Morvan *et al*., 2004). Species richness and abundance of amphipods and isopods were low till August 1999 (Hir & Hily, 2002).

[a] GST - glutathione-S-tranferase; CAT - catalase; MDA - malondialdehyde; AChE - acetylcholinesterase

et al., 2006). The main findings of the scientific approaches implemented in the *Prestige* monitoring programme are presented in Table 4.

2.4.3. Main conclusions

A large effort was carried out to monitor the effects of the *Prestige* oil spill along the Northern Spanish coast. However, most post-incident monitoring studies were performed only up to 2004 and long term impacts were not fully assessed. As stated by Albaigés et al. (2006), the main conclusion taken from the *Prestige* monitoring studies was that, with exception of the coastal areas that were directly oiled by the spill, it was difficult to identify major physical (e.g. water/sediment contamination) and biological/ecological impacts in the sub-tidal zone and the continental shelf. This may be ascribed to the physical characteristics of the oil. According to Albaigés et al. (2006), apart from the most affected area (Costa da Morte), the PAHs profiles were similar to those generally found in coastal areas influenced by urban/industrial runoff; even in that area, PAHs in wild mussel populations declined to background levels in about 6 months after the spill. Populations of benthic species in Costa da Morte (e.g. megrim, lobster and shrimp) decreased in 2003 but recovered in 2004, whereas no significant effects were detected in demersal communities (Albaigés et al., 2006).

2.5. MSC Napoli

2.5.1. Brief overview of the incident

On January 2007, the *MSC Napoli*, was towed to Lyme Bay, Devon (UK) after getting severely damaged due to extreme weather conditions. The cargo was very diverse, including 3780 tonnes of heavy fuel oil (IFO 380) and 45 tonnes of diesel oil, many non-hazardous goods (e.g. cars, gearboxes, paper, etc.) and a wide variety of hazardous materials (e.g. chemicals, solvents, personal care products and pesticides). More than 1600 tonnes of the chemical products transported are classified by IMO as dangerous goods (e.g. bisphenol A, epichlorohydrin-epoxy resin, alkylphenols, isophoronediamine nonylphenol, propaquizafop, profenofos, carbendazim, hexamethylindanopyran, and dibutyltinoxide, lambda-cyhylothrin, as well as organic solvents, acids, and corrosive materials) (Law, 2008).

2.5.2. Scientific approaches of the monitoring programme

The monitoring programme developed after the *MSC Napoli* spill was based on three main assumptions (Law, 2008): (a) oil was lost and could have affected the local environment and hence, hydrocarbons should be monitored; (b) during the salvage operation, any of the hazardous chemicals aboard may have been lost and, therefore, a monitoring of those compounds could be necessary in water, sediments and biota and (c) as Lyme Bay is of major nature conservation importance there would be a need to assess the damage to the local flora and fauna. The main findings of the scientific approaches implemented in the *Napoli* monitoring programme are presented in Table 5.

2.5.3. Main conclusions

Overall, the impact of the *MSC Napoli* incident was less severe than initially anticipated by the first study on the hazardous chemicals transported. Most of the oil fuels aboard were safely transhipped and removed and no dangerous good containers were lost into the sea. The concentrations of chemicals that were released into the sea during the incident were considered to represent a low risk for toxic impacts. Contamination of both the water column and shellfish in Lyme Bay due to oil lost from *MSC Napoli* was not significant, was localised and not expected to persist (Law, 2008). The evidences indicated that the sensitive areas of Lyme Bay were not significantly impacted. All containers remaining aboard following the grounding were transferred to Portland Port for processing and onward transfer, recycling or disposal of both containers and contents (Law, 2008).

Table 4
Scientific approaches applied in the monitoring programme of *Prestige* oil spill.[a]

Chemical monitoring		Water and sediments: in December 2002, the levels of TPAHs measured in seawater were between 0.19-28.8 μg/l equiv. oil; these values decreased till <0.05–2.86 μg/l equiv. oil in September 2003(González et al., 2006); soon after de incident, concentrations of copper (2.8–8.5 ηM) and lead (0.10–0.78 ηM) measured in seawater were up to eight times higher than reference values (Prego and García, 2004); the levels of TPAHs (sum of 13 parent components) in surface sediments were in the range of 0.9–422 μg/kg, being the highest values measured close to urban areas suggesting that the contamination was more related with the impact of harbour activities than the effects of the spill (Franco et al., 2006); concentrations of chromium, nickel, copper, iron, lead, and vanadium measured in saltmarsh soils were between 2 and 2500 times higher than reference values; levels of TPAHs in estuarine polluted soils ranged from 34 to 1850 times higher than those measured in unpolluted areas (Andrade et al., 2004)
		Plankton: no oil accumulation was observed on plankton from the Galician Coast during 2003, with the exception of the station Costa da Morte (Salas et al., 2006)
		Benthos: the concentration of TPAHs (sum of 13 parent components) in *Mytilus galloprovincialis* from Costa da Morte were up to 7780 μg/kg and recovered to reference values in November 2003 (Viñas et al., 2005)
		Birds: in 2004, TPAHs measured in blood samples of *Larus michahellis* from oiled colonies was 120% higher than in unoiled colonies, with a decrease by a third in 2005 (Perez et al., 2008)
		The TPAHs in Peregrine falcon eggs ranged from 21.2 ng/g to 461.1 ng/g, which were high enough to cause the death of embryos and poisoning of adult birds (Zuberogoitia et al., 2006)
Biological monitoring		DNA damage: significant higher levels of DNA damage (comet assay) were measured in *Mytilus galloprovincialis* collected from August 2003 to June 2004 compared to reference mussels, both before and after a recovery period of 7 days; this recovery period allowed a significant reduction of DNA damage in contaminated mussels but was not sufficient to eliminate the significant difference between contaminated and reference mussels (Laffon et al., 2006)
		Biochemical markers: five months after the Prestige incident, the activity of the enzymatic biomarkers EROD, GST, GR and CAT measured in liver tissues of two fishes (*Lepidorhom busboscii* and *Calliony muslyra*) indicated that fish were exposed to Prestige oil; a significant reduction of these enzymatic activities were observed 2 and 3 years after the spill (Martínez-Gómez et al., 2006, 2009). In 2002 and 2003, an inhibitory effect on brain AChE activity was measured in the common guillemot *Uria aalge* (16%) and razorbill *Alca torda* (22%), but not in Atlantic puffin *Fratercula arctica* (4%) (Oropesa et al., 2007)
		Lysosomal stability: Lysosomal enlargement and lysosomal membrane stability reduction were measured in *Mytilus galloprovincialis* collected in the summer of 2003; intracellular accumulation of neutral lipids was evident in digestive tubules of mussels collected in July with a further increase in September (Orbea et al., 2006)
		Immune function: the Prestige oil affected the immune capacity of *M. galloprovincialis* at least until December 2004 (Novas et al., 2007)
		Histopatological markers: a high prevalence of haemocytic infiltration of follicles and severe oocyte atresia was found in mussels collected from impacted sites in 2003; a reduction in the size of follicles were detected in 2004, both in male and female mussels; therefore, mussels gamete alterations were detected during 2003–2004 and a recovery trend was observed afterwards (Ortiz-Zarragoitia et al., 2011).Severe pathological lesions were observed in 2465 injured seabirds soon after the spill: dehydration and emaciation, hemosiderin deposits, aspergillosis and ulcers in the ventriculus, etc. (Balseiro et al., 2005)
		Ecotoxicological assays: a 60 days bioassay conducted 2 years after the incident with *Sparus aurata* in sediment samples from affected areas showed a significant increase of the EROD activity until day 30 and histological alterations in gills and liver all the assay (Morales-Caselles et al., 2007)
Ecological monitoring	Marine mammals	One month after the spill, the bodies of 27 cetaceans of seven different species were found; in only one case, oil pollution appear to be the direct cause of death. 16 turtles were also found dead (Garcia, 2003)
	Birds	Around 25,000 sea birds were found dead or injured (75% died and only 10% of the birds alive were saved). Most of the victims were guillemots, puffins, razorbills, gannets, shags and gulls (Garcia, 2003)
		An increase in the number of failed breeding attempts and a high population turnover rate was observed in Peregrine falcon population (Zuberogoitia et al., 2006)
	FishShell-fish	Significant reductions in the abundance of the Norway lobster (*Nephrops norvegicus*), Pandalid shrimp (*Plesionika heterocarpus*) and four-spot megrim (*Lepidorhombus boscii*) were detected in the spill maximum impacted area, with recovery in 2004 (Sánchez et al., 2006).
	Benthos	A decrease in the densities of several epibenthic species was measured after the spill, with a recovery in 2004; changes in infaunal species densities were not detected, but data prior to the spill were not available (Serrano et al., 2006)
		Most organisms living in rocky shore sites, particularly molluscs, were nearly extinct; despite this bottleneck, affected populations of *Littorina saxatilis* had no significant reduction in genetic diversity; some genetic effects were detected for quantitative shell traits and AFLPs (Pineira et al., 2008)
	Plankton	No significant changes were detected in plankton community structure (chlorophyll, primary production, zooplankton biomass and phytoplankton or zooplankton species composition) (Varela et al., 2006)

[a] EROD – ethoxyresorufin-O-deethylase; GST – glutathione-S-tranferase; GR – glutathione reductase; CAT – catalase and AChE – acetylcholinesterase.

3. Comparative analysis of the methodologies and procedures used in the monitoring approaches

Although there is a general agreement in the use of similar scientific approaches (chemical, biological and ecological monitoring) and ecological domains (pelagic, benthic, birds and marine mammals) to conduct a monitoring programme after an oil spill, a range of methodologies and biological targets are usually used. Table 6 summarizes the methodologies and biological targets applied in the monitoring programmes of the four spill incidents reviewed.

From the analysis of Table 6 it becomes evident that, among oil spills, there is little uniformity in the type of compounds measured to assess the chemical contamination. Furthermore, differences among sea compartments (water, sediments or biota) are also noticeable. For instance, while the total hydrocarbon concentrations were considered in the water monitoring of the *Sea Empress* spill, the total PAHs and trace metals were used to evaluate the contamination levels of the same compartment in the *Prestige* incident. Considering the case of *Erika*, the total C-PAHs and total PAHs were used to assess water and sediments contamination whereas the total PAHs and trace metals were taken for the analysis of biota.

In all monitoring programmes analysed, similar biomarkers were used to assess the biological response, but different methodologies were applied. As is evident in Table 6, the two biochemical endpoints most frequently used are DNA damage and detoxification metabolism-related enzymatic activities (especially the EROD activity). As regard DNA damage, two methodologies were used: DNA adducts in *Sea Empress* and *Erika* incidents, and comet assay in the *Prestige* and *MSC Napoli* incidents. Amid oil spills, DNA damage and EROD are reckoned as reliable biomarkers since organic contaminants, such as polycyclic PAHs, are well-known carcinogen and inductors of genotoxicity through the formation of activated PAHs (e.g. epoxides and quinones) and ROS in the course of enzymatic monooxygenase detoxification (Miller and Ramos, 2001). Furthermore, several PAHs are known to up regulate CYP 1A and, thus, induce an increase in EROD activity. Other biomarkers, relevant to improve the assessment of the fitness condition of exposed biota, such as oxidative stress (Catalase, Glutathione reductase, etc.), immune function or lysosomal stability markers, were also consistently used. Besides the use of biomarkers, in some circumstances, the monitoring of biological alterations addressed several other responses (physiological, toxicological, pathological alterations, etc.). For instance, scope for growth, ecotoxicological and histopathological assays were implemented in the *Sea Empress* and *Prestige* spills, respectively.

As presented in Table 6, the ecological monitoring approaches involved diverse parameters related to the community and population levels which differed, among oil spills, according to the biological targets evaluated. In the analysed oil spill monitoring programmes, the impacts on the benthic, intertidal and/or rocky shoreline ecosystems was assessed through community structure analysis. In most cases, the studies focused on invertebrates (commercial crustaceans and/or molluscs) yet commercial fishes, plankton, or echinoderms were also occasionally considered. The methodologies applied were based on the estimation of different parameters such as abundance, specific richness and/or biomass that, in general, are well established as relevant indices to draw a diagnostic on the status of the communities. At population level, since seabirds are one of the most affected organisms during spills, the mortality of seabirds was systematically monitored. Additionally, in most cases the survey of marine mammals' population was considered.

Several reasons can be pointed out to justify the application of different methodologies in the monitoring programmes analysed in the present work: the objectives of the monitoring studies, the availability of research teams availability to conduct the monitoring studies and their scientific interests, the coordination structure, the available funding, the nature of the oil spilled and the particular circumstances of the incident (Calvez, 2007). Hence, a standardization of monitoring methodologies is essential to optimize post-incident monitoring. Recently, in the scope of PREMIAM project, monitoring guidelines for UK have been produced (Law et al., 2011). Strategies such as the PREMIAM project will be an important step for the standardisation of post-spill monitoring methodologies and, therefore, improve the quality and effectiveness of environmental monitoring programmes.

Compared to oil spills, the implementation of monitoring programmes following HNS spills is less common. From the three HNS spills considered in this review (*Ievoli Sun*, *Ece* and *MSC Napoli*) only in the case of *MSC Napoli* (which was a combination of oil and HNS spill) a limited monitoring of HNS was performed. As is pointed out in Table 6, the screening of HNS chemicals in seawater samples and the acute toxicity assays with copepods and diatoms were the only two analyses carried out to assess the effects of the HNS involved in this incident.

4. Identification of major gaps and environmental monitoring priorities

Considering the main findings issued from this review, the following major gaps and environmental monitoring priorities can be drawn:

4.1. Lack of information related with the hazards and consequences of HNS spills—Priority to gather information on the ecological hazards of HNS and to set up monitoring studies following major HNS spills

An understanding of the ecological hazards involved in HNS spills is not as well recognized as in the case of oil pollution (Kirby and Law, 2010; Neuparth et al., 2011). While most oils float on the sea surface and are immiscible with seawater, HNS chemicals exhibit a wider range of behaviours (i.e. gas, dissolves, evaporates, floats, sinks) and toxicities to marine organisms. In comparison with oil, there is a lower investment in research and development (R&D) dealing with HNS pollution. As a result, there is a current lack of knowledge about the effects of HNS on marine biota and the scarce available ecotoxicological data that exist derive mainly from experiments conducted with freshwater organisms. Therefore, it becomes difficult to extrapolate the data to the marine field and predict the effects on marine organisms in order to prepare contingency plans for these substances (Neuparth et al., 2011). Due to the high number and diversity of HNS transported by sea, it is, in practice, unrealistic to consider a full scientific ecotoxicological data survey for all such chemicals. Prioritization methodologies to select HNS that are likely to cause severe marine environmental effects are needed and this should be considered as an essential step towards the establishment of a more effective preparedness and response to HNS incidents. In the context of the ARCOPOL project, a weight-of-evidence approach was developed with the aim to prioritize HNS that pose major environmental risks to European waters. The approach took into consideration the occurrence probability of HNS spills in European Atlantic waters and the severity of exposure associated with their physico-chemical properties and toxicity to marine organisms (Neuparth et al., 2011). Furthermore, the work included the collection of marine toxicological data available for the 23 HNS identified as priority and the creation of a database that can assist relevant bodies to predict HNS adverse effects in the marine environment. Neuparth et al. (2011) concluded that marine chronic toxicity data was lacking for most of the priority HNS and,

Table 5
Scientific approaches applied in the monitoring programme of *MSC Napoli* spill.

Chemical monitoring		Water: TPAHs in the seawater ranged from very high levels (~57 μg/l) in the vicinity of the ship, down to trace levels at a distance of 15 km radius from the wreck. Offshore stations in the vicinity of the wreck exhibit concentrations up to 642.2 ηg/l (Guitart et al., 2008); the PAHs distribution patterns in the seawater samples was characterized by a high percentage of naphthalene and its alkylated homologues (>60% of the TPAHs) with phenanthrene and dibenzothiophene series comprising 18% and 12%, respectively (Guitart et al., 2008); chemicals other than petroleum related compounds were not presented (Guitart et al., 2008)
		Shellfish: between January and May 2007, THC and summed PAHs concentrations in shellfish (*Cancer pagurus*, *Maia squinado*, *Pecten maximus* and *Mytilus edulis*) ranged from 0.9–48 mg/kg and 7–568 μg/kg, respectively; concentrations in scallops and mussels were higher than in crabs, but only samples collected very close to the wreck showed signs of contamination from the spill (Kelly et al., 2008)
Biological monitoring		DNA damage, biochemical, cytotoxicity and immune function markers: significant differences were measured in a range of biological responses (namely biomarkers of cellular function, oxidative stress, acetylcholinesterase activity and DNA damage-comet assay) in the limpets (*Patella vulgata* collected from Lyme Bay sites during January and July 2007, reflecting more stressful conditions compared with control sites (Law, 2008))
		Ecotoxicological assays: to provide an assessment of the chemicals on board of MSC Napoli, acute toxicity tests of water from the vessel were undertaken with the copepod *Tisbe battagliai* and the diatom *Skeletonema costatum*; Results showed that after day 55 post-incident, the water from the vessel did not show significant levels of acute toxicity to the copepod, but the levels of algal growth inhibition were observed until day 93 post-incident (Kirby et al., 2008)
Ecological monitoring	Birds	1020 oiled birds were found in the week after the spill, mostly guillemots and razorbills; the 485 birds that survived after being cleaned were released back into the wild (IMO, 2007); analyses on the oiled bird carcasses were undertaken to determine the impact upon seabirds populations affected (Grantham and Newson, 2007)
	Benthos	A survey undertaken in August 2007 using a drop-down video system was carried out to monitor the benthic ecology of the area potentially impacted by the MSC Napoli; a total of 48 stations were analysed; although this benthic survey found evidence of damage to the benthic environment surrounding the *MSC Napoli*, it was not able to definitively link that damage with the *MSC Napoli* grounding (Law, 2008)

in some cases, only fresh water acute toxicity data was available supporting the need to conduct research to gather additional toxicological data.

The implementation of monitoring programmes after a HNS spill is uncommon, as it has been highlighted in the present review. The implementation of appropriate conventions and protocols, such as the OPRC–HNS protocol, may serve as a guide to improve current practices in terms of preparedness and response to HNS spills. However, this protocol just entered into force in 2007 and therefore, many European countries may not be operationally prepared to respond to HNS incidents. In fact, out of the 12 EU members that ratified the OPRC–HNS protocol, only 3 reported to have specialized capability to respond to HNS spills (IMO, 2010).

Therefore, it is essential to undertake studies to gather information on the ecological hazards and consequences of HNS spills, including acute and chronic toxicity of chemicals to species representative of key marine taxa, in order to improve our knowledge on the significance of HNS spills to the marine environment. Additionally, data on the fate, behaviour and weathering of priority HNS in seawater and shoreline environments is also urgently needed.

4.2. Lack of research coordination—Priority to multidisciplinary studies rather than to particular scientific interests

When an accidental spill occurs, many of the resources available are usually applied to set up a monitoring programme implementing mainly the three scientific approaches identified earlier (chemical contamination, biological responses and ecological monitoring). However, this is not always done in a coordinated way and consequently, despite the effort and ever-increasing costs, the opportunity of acquiring very valuable information is not well explored. A strong research coordination among the involved working groups of the scientific community and the environmental agencies is essential to: (a) ensure that important lines of evidence are not overlooked; (b) avoid gaps or discontinuities between studies enabling integrated response strategies; (c) guarantee an efficient resource use and reduction in the global effort and, most importantly (d) give rise to enhanced conclusions (Carballeira, 2003; Kirby and Law, 2010). As highlighted by Kirby and Law (2010), the establishment of a fully co-ordination mechanism through the creation of environmental groups for overseeing all the practical aspects of the monitoring programme is absolutely necessary.

At local and national level, a list of R&D experts for the various components of a monitoring programme and environmental impact assessment should be previously defined to facilitate coordination during spill response. Priority should be given to multidisciplinary studies rather than to particular scientific interests of individual working groups.

4.3. Lack of reference/baseline data—Priority to set up reference databases by performing long-term monitoring programmes

Marine ecosystems are highly complex and natural ecological fluctuations are not always known. With this background, it is difficult to estimate the precise level and duration of environmental damage caused by an accidental marine pollution event and to distinguish such impacts from changes related with a variety of other factors, both natural (e.g. climatic or hydrographical) or man-made (e.g. other sources of contamination). In the case of a spill, having long-time series of well-validated baseline reference data is clearly important for assisting decision makers (a) analysing the environmental impact and recovery pattern; (b) deciding on mitigation and remediation measures and (c) evaluating the damage to maximise the benefit from available compensation funds (Hawkins et al., 2002). However, the lack of baseline reference data was a recurrent observation in the environmental monitoring programmes analysed in the present study. Therefore, it is very important to set up reference (i.e. baseline) databases by performing long-term monitoring programmes in order to distinguish spill pollution effects from other confounding factors, such as the natural fluctuations and chronic pollution.

A systematic approach for setting up an environmental monitoring programme is essential in order to use funding and resources in an effective manner. Several countries have already established baseline databases for coastal ecosystems. In the scope of the EROC-IPS project (Emergency Response to Costal Oil, Chemical and Inert Pollution from Shipping, funded by Interreg IIIB) environmental monitoring protocols were developed (i.e. protocols for selection of monitoring areas, selection of sentinel species, advice on selecting the type of monitoring and seasonality) to be used as a reference for pre-incident conditions (Moreira et al., 2007; Lima et al., 2008; Santos et al., 2010).

Table 6
Monitoring approaches used in the *Sea Empress*, *Erika*, *Prestige* and *MSC Napoli* spill incidents.

Spill incident	Monitoring approaches		
	Chemical	Biological	Ecological
Sea Empress	– THCs (water) – Individual PAHs–sum of 13 components, trace metals (sediments) – Total PAHs or individual PAHs (fish, crustacean and molluscs)	– DNA damage: DNA adducts (molluscs, sponges and fish) – Biochemical markers: EROD (fish) – Immune function, lysosomal stability and scope for growth (molluscs)	– Mortality, recruitment (marine mammals) – Mortality, recruitment, abundance (birds) – Mortality, abundance, biometric indices (fish) – Mortality (echinoderms and crustaceans) – Mortality, densities, shell lengths, shell shapes, size frequency, recruitment (molluscs)
Erika	– Total C-PAHs and total PAHs (water and sediments) – Total PAHs and trace metals (molluscs) – Trace metals: vanadium (seabirds)	– DNA damage: DNA adducts (molluscs and fish) – Biochemical markers: EROD, GST, CAT, AChE, MDA (molluscs and echinoderms) – Immune function (molluscs and echinoderms)	– Mortality (marine mammals, birds) – Abundance, density (echinoderms) – Abundance, species richness (crustaceans) – Density (macroalgee) – Density, species richness (foraminifera)
Prestige	– Total PAHs and trace metals (water) – Individual PAHs–sum of 13 components–and trace metals (sediments) – Individual PAHs–sum of 14 components (plankton, molluscs) – Total PAHs (birds)	– DNA damage: comet assay, immune function and lysosomal stability (molluscs) – Biochemical markers: EROD, GST, CAT, GR (fish) and AChE (birds) – Ecotoxicological assays (fish) – Histopathology (birds, molluscs)	– Mortality (marine mammals) – Mortality, breeding (birds) – Abundance, density, distribution, feeding pattern (fish and crustaceans) – Density, genetic diversity (molluscs) – Primary production, biomass, species richness (plankton)
MSC Napoli	– Total PAHs and HNS (water) – Screening of HNS present in MSC Napoli (water) – Total PAHs and individual PAHs (crustacean and molluscs)	– DNA damage: comet assay (molluscs) – Biochemical markers: GR, AChE, immune function and lysosomal stability (molluscs) – Ecotoxicological assays to provide an assessment of HNS on board (copepods and diatoms)	– Mortality (birds) – Abundance, species richness, habitat degradation (benthos)

Within the European Water Framework Directive and the European Marine Strategy, each member state must develop strategies (both chemical and ecological) for a detail assessment of the state of the environment, including the establishment of clear environmental targets and monitoring programmes. Once this is in place, baseline data is more likely to be available (Kerambrun et al., 2006).

4.4. Lack of knowledge on the biology of the selected species—Priority to use well validated and ecological relevant indicator species

The impact assessment of an accidental spill should be focused on indicator species, especially when a monitoring of biological responses at sub-individual and individual level is applied. However, an important gap observed in some of the analysed monitoring programmes is the lack of knowledge concerning the biology of the selected sentinel species that are commonly used. This information is central in order to predict recovery, understand sublethal and long-term effects, physiological changes and bioaccumulation processes. Local knowledge is also important for the species selection process.

The importance of selecting appropriate sentinel species has been previously recognized during the EROCIPS project and a number of criteria have been identified as most relevant (Cunha and Guilhermino, 2006). Considering those criteria, significant steps have been taken by our research team to validate the use of a ubiquitous intertidal fish species, the shanny *Lipophrys pholis*, for organic pollutants monitoring within the northwestern Atlantic coast rocky shores (Lima et al., 2008; Solé et al., 2008; Ferreira et al., 2009; Santos et al., 2010).

4.5. Lack of knowledge on long-term effects of the spills—Priority to set long-term monitoring programmes and funding allocation

The potential long-term impacts of spills will depend on several factors, including, among others, the type of chemicals involved, the severity of the spill and the ecological sensitivity of the affected area.

The monitoring programmes conducted following the analysed spill incidents in this work were able to demonstrate a range of short-term effects, but in most cases, the potential for long-term impacts was overlooked and poorly understood. It is likely that spills cause ecological impacts in the long-term but, usually, the end of funding allocation to extend the monitoring efforts for more than a few years compromises the long-term impact assessment. The assessment of long-term impacts is further impaired by the difficulty of clearly assigning adverse effects to the spill rather than to other local contamination sources and chronic inputs. Moreover, the high levels of natural variability in biological systems may mask the potential effects and add further difficulties in the assessment of spill impacts (Law et al., 2005). Therefore, the achievement of robust baseline databases is essential.

Hence, in certain spill scenarios, such as in cases where ecologically sensitive areas or important commercial resources are affected, priority should be given to the implementation of monitoring programmes for extended periods of time to allow the identification of long-term impacts and funds should be allocated with that purpose.

4.6. Standardisation of procedures for conducting monitoring programmes following a spill

Every accidental spill is unique and, therefore, any monitoring programme will need to have certain elements adapted to the local circumstances in order to consider all lines of evidence and specificities of the incident. Nevertheless, although monitoring programmes should be flexible, the establishment of guidelines and standard procedures for conducting monitoring programmes would be of great benefit. This would assure that the best approach is implemented during the spill crisis and an effective coordination and preparation of all involved actors is guaranteed (Kirby and Law, 2010). Efforts have been done in some regions to establish standardized procedures for monitoring and environmental impact assessment. For instance, in France, an "operation guide for ecological monitoring of accidental pollution" (Girin, 2007) was developed to standardize the methods of design, management and carrying out an emergency monitoring programme. Yet, the protocols and procedures required for the effective monitoring and impact assessment are still lacking. In UK, a "Post-incident monitoring guidelines" (Law et al., 2011) was recently published with an overarching set of essential monitoring considerations and procedures including the definition of a monitoring programme (why, what, where, and how frequently should we monitor) and the implementation of a monitoring programme (survey design, sampling strategies and methods, standard methodologies and protocols for surveying and monitoring key biological resources, etc.). The implementation of such guidelines are essential to strengthen monitoring programmes in terms of speed, cost effectiveness, identification of the expertise needed, use of the best practices and improve co-ordination and integration.

5. Conclusions

This paper analysed and reviewed the status of the monitoring programmes set up following the major spill incidents over the last years in European waters, with the aim to identify the key monitoring gaps and highlight the priorities to an effective monitoring of accidental spills. This work was developed under the European project ARCOPOL (The Atlantic Region's Coastal Pollution Response), framed within the INTERREG Atlantic Area Transnational Programme, which focused fundamentally on the improvement of local responders' prevention, response and mitigation capabilities against oil and HNS spills (see http://www.arcopol.eu/ for further information). Initiatives such as ARCOPOL and other national and transnational projects like PREMIAM (Pollution Response in Emergencies – Marine Impact Assessment and Monitoring) will help to establish a more effective preparedness and response to oil and HNS incidents.

The effectiveness of any monitoring programme will depend on a range of factors, as presented in Section 4, but two very important issues to consider are the need to establish pre-incident baseline databases and to extend the monitoring programmes in order to assess the long-term status of the marine environment (Kirby and Law, 2010). In addition, the establishment of guidelines, as standardised as possible, and the definition of a mechanism to coordinate the operational implementation of the monitoring programme are also key elements to strengthen these programmes. The guidelines recently produced by Law et al. (2011) are an important advancement to overcome the considerable gaps of the monitoring programmes. These guidelines should be developed or adapted in other European countries and be, in time, integrated with the response plans, including the national contingency plans.

Given the lack of reliable information on the ecological hazards and consequences of HNS spills, including acute and chronic toxicity of HNS in representative species of key marine taxa, a better and relevant understanding of the risks inherent to HNS spills is a priority. Therefore, studies to gather HNS-related toxicological data on marine biota should be afforded a greater attention.

We believe that the analysis of the major gaps and environmental monitoring priorities presented in this study will contribute to optimize the monitoring programmes and establish more effective preparedness and response capabilities to deal with future accidental spills in European waters.

Acknowledgements

The ARCOPOL – The Atlantic Regions' Coastal Pollution Response Project (contract nr. 2008-1/061) is funded by the Atlantic Area Transnational Programme (Priority 2: Marine Environment and Renewable Energy) with support of the European Regional Development Fund (ERDF). Teresa Neuparth was supported by the Postdoctoral fellowships, from ARCOPOL project (BPD/2008-1/061/2009-004) and Portuguese Science and Technology Foundation – FCT (SFRH/BPD/77912/2011).

References

Albaigés, J., Morales-Nin, B., Vilas, F., 2006. The Prestige oil spill: a scientific response. Marine Pollution Bulletin 53, 205–207.
Amat, A., Burgeot, T., Castegnaro, M., Pfohl-Leszkowicz, A., 2005. Genotoxic impact of 'Erika' petroleum fuel on liver of the fish *Solea Solea*. Environmental Chemistry 68, 743–756.
Andrade, M.L., Covelo, E.F., Vega, F.A., Marcet, P., 2004. Effect of the Prestige oil spill on salt marsh soils on the Coast of Galicia (Northwestern Spain). Journal of Environmental Quality 33, 2103–2110.
Auffret, M., Duchemin, M., Rousseau, S., Boutet, I., Tanguy, A., Moraga, D., Marhic, A., 2004. Monitoring of immunotoxic responses in oysters reared in areas contaminated by the "Erika" oil spill. Aquatic Living Resources 17, 297–302.
Balseiro, A., Espí, A., Márquez, I., Pérez, V., Ferreras, M.C., García Marín, J.F., Prieto, J.M., 2005. Pathological features in marine birds affected by the Prestige's oil spill in the North of Spain. Journal of Wildlife Diseases 41, 371–378.
Barillé-Boyer, A.L., Gruet, Y., Barillé, L., Harin, L., 2004. Temporal changes in community structure of tide pools following the "Erika" oil spill. Aquatic Living Resources 17, 323–328.
Bocquené, G., Chantereau, S., Clérendeau, C., Beausir, E., Ménard, D., Raffin, B., Minier, C., Burgeot, T., Pfohl Leszkowicz, A., Narbonne, J.F., 2004. Biological effects of the "Erika" oil spill on the common mussel (*Mytilus edulis*). Aquatic Living Resources 17, 309–316.
Budzinski, H., Mazéas, O., Tronczynski, J., Désaunay, Y., Bocquené, G., Claireaux, G., 2004. Link between exposure of fish (*Solea solea*) to PAHs and metabolites: application to the "Erika" oil spill. Aquatic Living Resources 17, 329–334.
Burgherr, P., 2007. In-depth analysis of accidental oil spills from tankers in the context of global spill trends from all sources. Journal of Hazardous Materials 140, 245–256.
Cadiou, B., Riffaut, L., McCoy, K., Cabelguen, J., Fortin, M., Gélinaud, G., Le Roch, A., Tirard, C., Boulinier, T., 2004. Ecological impact of the "Erika" oil spill: determination of the geographic origin of the affected common guillemots. Aquatic Living Resources 17, 369–377.
Calvez, I., 2007. Ecological impact assessment of oil spill on marine benthic environment: approaches and methodologies. In: Paper presented at the Pollutant Monitoring and Ecological Impact Assessment Following Accidental Oil and Other Chemical Spills in Marine Waters, Cedre, Brest, October 9–1, 2007.
Carballeira, A., 2003. Considerations in the design of a monitoring program of the biological effects of the Prestige oil spill. Ciencias Marinas 29, 123–139.
Chiffoleau, J.F., Chauvaud, L., Amouroux, D., Barats, A., Dufour, A., Pécheyran, C.H., Roux, N., 2004. Nickel and vanadium contamination of benthic invertebrates following the "Erika" wreck. Aquatic Living Resources 17, 273–280.
Cunha, I., Guilhermino, L., 2006. Protocol for Selection of Sentinel Species and Collection of Specimens. EROCIPS Project – Emergency Response to Coastal Oil, Chemical and Inert Pollution from Shipping, INTERREG IIIB/168/EROCIPS. <http://www.erocips.org/pt/7.2.1_protocol_sentinel_species_erocips.pdf>.
Diez, S., Jovier, E., Bayona, J.P.M., Albaiges, J., 2007. Prestige oil spill III Fate of a heavy oil in the marine environment. Environmental Science and Technology 41, 3075–3082.
Dyrynda, P., Symberlist, R., 2000. Sea Empress oil spill. <http://www.swan.ac.uk/empress/help.htm#Contents>.
Edwards, R., White, I., 1999. The Sea Empress oil spill: environmental impact and recovery. In: Proceedings of the International Oil Spill Conference, 7–12 March 1999, Seattle, USA. American Petroleum Institute, Washington, DC, USA, pp. 97–102.
Ellis, J.R., Rogers, S.I., 2002. Report on the results of sampling Milford Haven Herring during the 2002 Season. Report from CEFAS Lowestoft Laboratory, p. 11.
Fernley, P.W., Moore, M.N., Lowe, D.M., Donkin, P., Evans, S., 2000. Impact of the Sea Empress oil spill on lysosomal stability in mussel blood cells. Marine Environmental Research 50, 451–455.
Ferreira, F., Santos, M.M., Castro, L.F.C., Reis-Henriques, M.A., Lima, D., Vieira, M.N., Monteiro, N.M., 2009. Vitellogenin gene expression in the intertidal blenny *Lipophrys pholis*: a new sentinel species for estrogenic chemical pollution monitoring in the European Atlantic coast? Comparative Biochemistry and Physiology C 149, 58–64.
Franco, M.A., Viñas, L., Soriano, J.A., de Armas, D., González, J.J., Beiras, R., Salas, N., Bayona, J.M., Albaigés, J., 2006. Spatial distribution and ecotoxicity of petroleum hydrocarbons in sediments from the Galicia continental shelf (NW Spain) after the Prestige oil spill. Marine Pollution Bulletin 53, 260–271.
Garcia, R., 2003. The Prestige: one year on, a continuing disaster. Marine Officer, WWF-Spain.
Girin, M., 2007. Ecological monitoring of accidental water pollution. Operational Guide, Centre of Documentation, Research and Experimentation on Accidental Water Pollution (Cedre), p. 37.
González, J.J., Vinas, L., Franco, M.A., Fumega, J., Soriano, J.A., Grueiro, G., Muniategui, S., López-Mahía, P., Prada, D., Bayona, J.M., Alzaga, R., Albaigés, J., 2006. Spatial and temporal distribution of dissolved/dispersed aromatic hydrocarbons in seawater in the area affected by the Prestige oil spill. Marine Pollution Bulletin 53, 250–259.
Grantham, M.J., Newson, S.E., 2007. Post-mortem analysis of bird corpses from the grounding of the MSC Napoli. The British Trust for Ornithology Research, Report No, 466.
Guitart, C., Frickers, P., Horillo-Carballo, J., Law, R.J., Readman, J.W., 2008. Characterisation of the surface microlayer chemical contamination after shipping accidents. Environmental Science and Technology 42, 2275–2282.
Harvey, J.S., Lyons, B.P., Page, T.S., Stewart, C., Parry, J.M., 1999. An assessment of the genotoxic impact of the Sea Empress oil spill by the measurement of DNA adduct levels in selected invertebrate and vertebrate species. Mutation Research 441, 103–114.
Hawkins, S.J., Gibbs, P.E., Pope, N.D., Burt, G.R., Chesman, B.S., Bray, S., Proud, S.V., Spence, S.K., Southward, A.J., Langston, W.J., 2002. Recovery of polluted ecosystems: the case for long-term studies. Marine Environmental Research 54, 215–222.
Hir, M.L., Hily, C., 2002. First observations in a high rocky-shore community after the Erika oil spill (December 1999, Brittany, France). Marine Pollution Bulletin 44, 1243–1252.
Huijer, K., 2005. Trends in oil spills from tanker ships 1995–2005. In: Paper presented at the 28th Arctic and Marine Oil spill Program (AMOP) Technical Seminar, Calgary, Canada, June 7–9, 2005.
IMO – International Maritime Organization, 2000. Protocol on Preparedness, Response and Co-operation to Pollution Incidents by Hazardous and Noxious Substances (OPRC–HNS Protocol).
IMO – International Maritime Organization, 2010. Are HNS spills more dangerous than oil spills? A white paper for the Interspill 2009 Conference and the Fourth IMO R&D Forum, May 2009, Marseille, France.
Joly-Turquin, G., Dubois, P., Coteur, G., Danis, B., Leyzour, S., Le Menach, K., Budzinski, H., Guillou, M., 2009. Effects of the Erika oil spill on the common starfish *Asterias rubens*, evaluated by field and laboratory studies. Archives of Environmental Contamination and Toxicology 56, 209–220.
Kammerer, M., Mastain, O., Le Drean-Quenech'du, S., Pouliquen, H., Larhantec, M., 2004. Liver and kidney concentrations of vanadium in oiled seabirds after the Erika wreck. Science of the Total Environment 333, 295–301.
Kelly, C.A., Law, R.J., Baker, K.L., Lunn, M.M.E., Mellor, P.K., 2008. PAH in commercial shellfish following the grounding of the MSC Napoli in Lyme Bay UK in 2007. Marine Pollution Bulletin 56, 1215–1233.
Kerambrun, L., Laruelle, F., Calvez, I., 2006. Determining the priorities for post sill studies. In: Interspill Conference, 12–14 May, Marseille, France.
Kiely, O., Lidgard, D., McKibben, M., Connolly, N., Baines, M., 2000. Grey Seals: Status and Monitoring in the Irish and Celtic Seas. Maritime Ireland/Wales INTERREG Report No. 3, Measure 1.3: Protection of the Marine and Coastal Environment and Marine Emergency Planning.
Kirby, M.F., Neall, P., Tylor, T., 1999. EROD activity measured in flatfish from the area of Sea Empress oil spill. Chemosphere 38, 2929–2949.
Kirby, M.F., Devoy, B., Law, R.J., Ward, A., Aldridge, J., 2008. The use of a bioassay based approach to the hazard/ risk assessment of cargo derived toxicity during shipping accidents:a case study – the MSC Napoli. Marine Pollution Bulletin 56, 781–786.
Kirby, M.F., Law, R.J., 2010. Accidental spills at sea – Risk, impact, mitigation and the need for co-ordinated post-incident monitoring. Marine Pollution Bulletin 60, 797–803.
Laffon, B., Rábade, T., Pásaro, E., Méndez, J., 2006. Monitoring of the impact of Prestige oil spill on *Mytilus galloprovincialis* from Galician coast. Environment International 32, 342–348.
Laubier, L., Le Moigne, M., Flammarion, P., Thybaud, E., Cossa, D., 2004. The monitoring programme of the ecological and ecotoxicological consequences of the "Erika" oil spill. Aquatic Living Resources 17, 239–241.
Law, R.J., Kelly, C., 2004. The impact of the "Sea Empress" oil spill. Aquatic Living Resources 17, 389–394.
Law, R.J., 2008. Environmental monitoring conducted in Lyme Bay following the grounding of MSC Napoli in January 2007 with an assessment of impact. Science Series Aquatic Environmental Monitoring Report, Cefas Lowestoft 61, 36.
Law, R., Kelly, C., Roose, P., Tronczynski, J., Vinas, L., Webster, L., 2005. Assessing the long-term impact of oil spills: an examination of recent incidents. In: ICES Annual Science Conference, ICES CM 2005/S, 20–24 September, Aberdeen, UK.
Law, R.J., Kirby, M.F., Moore, J., Barry, J., Sapp, M., Balaam, J., 2011. PREMIAM – Pollution Response in Emergencies Marine Impact Assessment and Monitoring: post-incident monitoring guidelines. Science Series Technical Report, Cefas, Lowestoft, 146, p. 164.
Lima, D., Santos, M.M., Ferreira, A.M., Micaelo, C., Reis-Henriques, M.A., 2008. The use of the shanny *Lipophrys pholis* for pollution monitoring: a new sentinel species for the northwestern European marine ecosystems. Environment International 34, 94–101.
Lyons, B.P., Harvey, J.S., Parry, J.M., 1997. An initial assessment of the genotoxic impact of the Sea Empress oil spill by the measurement of DNA adduct levels in the intertidal teleost *Lipophrys pholis*. Mutation Research 390, 263–268.

Martínez-Gómez, C., Campillo, J.A., Benedicto, J., Fernández, B., Valdés, J., García, I., Sánchez, F., 2006. Monitoring biomarkers in fish *(Lepidorhombus boscii and Calliony muslyra)* from the northern Iberian shelf after the Prestige oil spill. Marine Pollution Bulletin 53, 305–314.

Martínez-Gómez, C., Fernández, B., Valdés, J., Campillo, J.A., Benedicto, J., Sánchez, F., Vethaak, A.D., 2009. Evaluation of 3 year monitoring with biomarkers in fish following the Prestige oil spill (N Spain). Chemosphere 74, 613–620.

Miller, K.P., Ramos, K.S., 2001. Impact of cellular metabolism on the biological effects of benzo[a]pyrene and related hydrocarbons. Drug Metabolism Reviews 33, 1–35.

Moore, J.J., 2006. State of the marine environment in SW Wales, 10 years after the Sea Empress oil spill. A Report to the Countryside Council for Wales from Coastal Assessment, Liason & Monitoring, Cosheston, Pembrokeshire. CCW Marine Monitoring Report No. 21, pp. 1–30.

Morales-Caselles, C., Jiménez-Tenorio, N., Riba, I., Sarasquete, C., DelValls, A.T., 2007. Kinetic of biomarker responses in juveniles of the fish *Sparus aurata* exposed to contaminated sediments. Environmental Monitoring Assessment 131, 211–220.

Moreira, S., Santos, M., Cunha, I., Sousa, A., Lima, D., Coimbra, J., Reis-Henriques, M.A., Guilhermino, L., 2007. EROCIPS Report for Task 7.3.5: Environmental monitoring report. <http://www.erocips.org/7.3_environmental_monitoring report_erocips-2.pdf >.

Morvan, J., Le Cadre, V., Jorissen, F., Debenay, J.P., 2004. Foraminifera as potential bio-indicators of the "Erika" oil spill in the Bay of Bourgneuf: field and experimental studies. Aquatic Living Resources 17, 317–322.

Neuparth, T., Moreira, S., Santos, M.M., Reis-Henriques, M.A., 2011. Hazardous and Noxious Substances (HNS) in the marine environment: prioritizing HNS that pose major risk in a European context. Marine Pollution Bulletin 62, 21–28.

Novas, A., Barcia, R., Ramos-Martínez, J.I., 2007. After the Prestige oil spill modifications in NO production and other parameters related to the immune response were detected in hemocytes of *Mytilus galloprovincialis*. Aquatic Toxicology 85, 285–290.

Orbea, A., Garmendia, L., Marigómez, I., Cajaraville, M.P., 2006. Effects of the 'Prestige' oil spill on cellular biomarkers in intertidal mussels: results of the first year of studies. Marine Ecology Progress Series 306, 177–189.

Oropesa, A.L., Pérez-López, M., Hernández, D., Jesús-Pablo García, J.P., Fidalgo, L.E., Beceiro, A.L., Soler, F., 2007. Acetylcholinesterase activity in seabirds affected by the Prestige oilspill on the Galician coast (NW Spain). Science of the Total Environment 372, 532–538.

Ortiz-Zarragoitia, M., Garmendia, L., Barbero, M.C., Serrano, T., Marigomez, I., Cajaraville, M.P., 2011. Effects of the fuel oil spilled by the Prestige tanker on reproduction parameters of wild mussel populations. Journal of Environmental Monitoring 13, 84–94.

Pérez, C., Velando, A., Munilla, I., López-Alonso, M., Oro, D., 2008. Monitoring Polycyclic aromatic hydrocarbon pollution in the marine environment after the Prestige oil spill by means of seabird blood analysis. Environmental Science and Technology 42, 707–713.

Pineira, J., Quesada, H., Rolan-Alvarez, E., Caballero, A., 2008. Genetic impact of the Prestige oil spill in wild populations of a poor dispersal marine snail from intertidal rocky shores. Marine Pollution Bulletin 56, 270–281.

Prego, R., García, A.C., 2004. Cadmium, copper and lead contamination of the seawater column on the Prestige shipwreck (NE Atlantic Ocean). Analytica Chimica Acta 524, 23–26.

Purnell, K., 2009. Are HNS spills more dangerous than oil spills? In: Conference Proceedings, Interspill, Marseille, May 12–14, 2009.

Ridoux, V., Lafontaine, L., Bustamante, P., Caurant, F., Dabin, W., Delcroix, C., Hassani, S., Meynier, L., Silva, V.P., Simonin, S., Robert, M., Spitz, J., Canneyt, O.V., 2004. The impact of the "Erika" oil spill on pelagic and coastal marine mammals: combining demographic, ecological, trace metals and biomarker evidences. Aquatic Living Resources 17, 379–387.

Salas, N., Ortiz, L., Gilcoto, M., Varela, M., Bayona, J.M., Groom, S., Álvarez-Salgado, X.A., Albaigés, J., 2006. Fingerprinting petroleum hydrocarbons in plankton and surface sediments during the spring and early summer blooms in the Galician coast (NW Spain) after the Prestige oil spill. Marine Environmental Research 6, 388–413.

Sánchez, F., Velasco, F., Cartes, J.E., Olaso, I., Preciado, I., Fanelli, E., Serrano, A., Gutierrez-Zabala, J.L., 2006. Monitoring the Prestige oil spill impacts on some key species of the Northern Iberian shelf. Marine Pollution Bulletin 53, 332–349.

Santos, M.M., Solé, M., Lima, D., Hambach, B., Ferreira, A.M., Reis-Henriques, M.A., 2010. Validating a multi-biomarker approach with the shanny *Lipophrys pholis* to monitor oil spills in European marine ecosystems. Chemosphere 81, 685–691.

SEEEC, 1998. The Environmental Impact of the Sea Empress Oil Spill Final report of the Sea Empress Environmental Evaluation Committee, February 1998. The Stationery Office, London, ISBN 0 11 702156 3.

Serrano, A., Francisco Sanchez, F., Preciado, I., Parra, S., Frutos, I., 2006. Spatial and temporal changes in benthic communities of the Galician continental shelf after the Prestige oil spill. Marine Pollution Bulletin 53, 315–331.

Singhota, G.S., 1995. IMO's role in promoting oil spill preparedness. Spill Science & Technology Bulletin 2, 207–215.

Solé, M., Lobera, G., Lima, D., Reis-Henriques, M.A., Santos, M.M., 2008. Estearases activities and lipid peroxidation levels in muscle tissue of the shanny *Lipophrys pholis* along several sites from the Portuguese Coast. Marine Pollution Bulletin 56, 999–1007.

Tronczynski, J., Munschy, C., Moisan, K., Guiot, N., Truquet, I., Olivier, N., Men, S., Furaut, A., 2004. Contamination of the Bay of Biscay by polycyclic aromatic hydrocarbons (PAHs) following the T/V "Erika" oil spill. Aquatic Living Resouces 17, 243–259.

Varela, M., Bode, A., Lorenzo, J., Álvarez-Ossorio, M.T., Miranda, A., Patrocinio, T., Anadón, R., Viesca, L., Rodríguez, N., Luis Valdés, L., Cabal, J., Urrutia, A., García-Soto, C., Rodríguez, M., Álvarez-Salgado, X.A., Groom, S., 2006. The effect of the "Prestige" oil spill on the plankton of the N-NW Spanish coast. Marine Pollution Bulletin 53, 272–286.

Viñas, L., Franco, M.Á., Soriano, J.A., Garaña, I., Bargiela, J, González, J.J., 2005. Evolution of the PAH content in commercial shellfish from Galicia (NW Spain) after the Prestige oil spill. In: ICES Annual Science Conference, Aberdeen, UK.

Widdows, J., Donkin, P., Staff, F.J., Matthiessen, P., Law, R.J., Allen, Y.T., Thain, J.E., Allchin, C.R., Jones, B.R., 2002. Measurement of stress effects (scope for growth) and contaminant levels in mussels (*Mytilus edulis*) collected from the Irish Sea. Marine Environmental Research 53, 327–356.

Zuberogoitia, I., Martínez, J.A., Agurtzane Iraeta, A.Q., Ainara Azkona, A., Zabala, J., Begona, J., Merino, R., Gómez, G., 2006. Short-term effects of the Prestige oil spill on the peregrine falcon (*Falco peregrinus*). Marine Pollution Bulletin 52, 1176–1181.