Oil spills can be difficult to manage, with reporting frequently delayed. Too often, by the time responders arrive at the scene, the slick has moved, dissolved, dispersed or sunk. This Oil Spill Monitoring Handbook provides practical advice on what information is likely required following the accidental release of oil or other petroleum-based products into the marine environment.

The book focuses on response phase monitoring for maritime spills, otherwise known as Type I or operational monitoring. Response phase monitoring tries to address the questions – what? where? when? how? how much? – that assist responders to find, track, predict and clean up spills, and to assess their efforts. Oil spills often occur in remote, sensitive and logistically difficult locations, often in adverse weather, and the oil can change character and location over time. An effective response requires robust information provided by monitoring, observation, sampling and science.

The Oil Spill Monitoring Handbook completely updates the Australian Maritime Safety Authority’s 2003 edition of the same name, taking into account the latest scientific advances in physical, chemical and biological monitoring, many of which have evolved as a consequence of major oil spill disasters in the last decade. It includes sections on the chemical properties of oil, the toxicological impacts of oil exposure, and the impacts of oil exposure on different marine habitats with relevance to Australia and elsewhere. An overview is provided on how monitoring integrates with the oil spill response process, the response organisation, the use of decision-support tools such as net environmental benefit analysis, and some of the most commonly used response technologies. Throughout the text, examples are given of lessons learned from previous oil spill incidents and responses, both local and international.

General guidance of spill monitoring approaches and technologies is augmented with in-depth discussion on both response phase and post-response phase monitoring design and delivery. Finally, a set of appendices delivers detailed standard operating procedures for practical observation, sample and data collection.
Editors: Sharon Hook, Graeme Batley, Michael Holloway, Paul Irving and Andrew Ross
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Editors: Sharon Hook, Graeme Batley, Michael Holloway, Paul Irving and Andrew Ross
Foreword

Oil spill response requires significant amounts of high-value, robust information to allow decision makers and responders to do the best job possible. The public, through recent tragic experience here and internationally, has raised their expectations that responders can and will clean up spills successfully.

Much of what guides spill response are the deceptively simple questions of:

- What happened, where, and how much oil is in the ocean?
- What will happen to the oil, where will it go and what will it affect?
- How much of the pollution can be cleaned up, and by what means?
- What happens to oil not removed from the ocean or shoreline?
- How do we know if the response is working?

The answers to these questions may seem reasonably straightforward. In reality, oil spills often occur in remote, sensitive and logistically difficult locations, in adverse weather and with oil that weathers and changes character over time. All of this requires robust information provided by monitoring, observation, sampling and science.

The Australian National Plan for Maritime Environmental Emergencies first produced an Oil Spill Monitoring Handbook in 2003 that has been extensively applied and referenced worldwide. However, response requirements, as well as the science and monitoring available to assist the response, have changed dramatically over recent years. The stakes are ever greater.

The 2016 Oil Spill Monitoring Handbook has been produced by the CSIRO at the request of AMSA to assist all people responsible for responding to oil spills to have access to the most up-to-date monitoring science and methods. CSIRO is an independent, trusted science adviser to the National Plan. This CSIRO edition of the Handbook has been designed to be a current reference and to contribute to the better understanding of spills, response and monitoring into the future. Although designed for Australian use, this Handbook should also assist worldwide. The contributions of the Australian National Plan Environment, Science and Technical Network, and their CSIRO science colleagues in producing this Handbook are recognised and commended.

Toby Stone
General Manager, Marine Environment
Maritime Emergency Response Commander
Australian Maritime Safety Authority

Ken Lee
Director
CSIRO Oceans and Atmosphere
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This Handbook was written to provide advice to the Australian maritime sector (ports, shipping and terminals) to assist in determining the monitoring that needs to be undertaken following the accidental release of oil or other petroleum-based products into the marine environment. It updates the Australian Maritime Safety Authority’s 2003 *Oil Spill Monitoring Handbook*, taking into account the latest scientific advances in physical, chemical and biological monitoring, many of which have evolved as a consequence of major oil spill disasters in the last decade, in particular the *Deepwater Horizon* wellhead blowout in the Gulf of Mexico in 2010.

Sections of this Handbook may also be of interest to other sectors, including the offshore petroleum industry, when planning for or responding to their own oil or chemical spills.

Background information is provided on the chemical properties and fate of oil in marine waters and on its toxicity to a full range of receptor organisms, in sufficient detail that readers with a minimum of scientific training can appreciate the reasons underpinning the recommended monitoring strategy. Initial information on the nature of the incident is supplemented by chemical monitoring and the identification of likely biological receptors is used in evaluating a response assessment, which begins with a net environmental benefit analysis. This leads to the selection of an appropriate response option, which may include the use of chemical dispersants, mechanical collection and beach cleaning, among others.

Practical guidance is provided for all aspects of oil spill response, although the primary focus is on response phase monitoring. Responses to oil spills (and other accidental releases of hazardous chemicals) are a complex series of events where responders must balance competing stakeholder interests and priorities to both mitigate any environmental damage (from an ecological, socioeconomic and amenity standpoint) and to minimise any long-term impacts of the release of oil on sensitive ecosystems. Its focus is on the types of receptor organisms and environments that might be encountered in all areas of Australia’s coastal tropical and temperate waters, but the advice provided is readily applicable to oil spill events in other parts of the world, where local guidance may not be available.

Recovery phase monitoring should be applied in the recovery phase to determine the impacts of the spill and the response. For best effect, this should be initiated in parallel to the oil spill response. Details are provided of standard operating procedures for collecting the samples that would inform both the response and recovery phases of the monitoring. Throughout the text, examples are provided of lessons learned from previous oil spill incidents, both local and international. The incorporation of state-of-the-art monitoring approaches should improve contingency plans for future responses to oil spills both in Australia and elsewhere.
Sharon Hook is a Senior Ecotoxicologist with CSIRO Oceans and Atmosphere, Sydney. Sharon has over 20 years of experience in aquatic ecotoxicology and oceanography. Her research interests include applying modern omics-based approaches to environmental problems, determining the impacts of low-level, long-term toxic responses, and the design and implementation of toxicity testing. She has been involved in the risk assessments following several oil spills, including the Exxon Valdez, the Selendag Ayu spills (both before joining CSIRO) and the Montara well release. She is involved in ongoing projects for BP and Chevron characterising the Great Australian Bight. Sharon has authored over 60 scientific publications.

Graeme Batley is a Chief Research Scientist with the CSIRO Land and Water Flagship and past Director of the Centre for Environmental Contaminants Research based in Sydney. He is one of Australia’s leading researchers of trace contaminants in aquatic systems, actively researching this area for over 40 years. He was a lead author of the water and sediment quality guidelines for Australia and New Zealand in 2000 and of the Australian Guidelines for Water Quality Monitoring and Reporting, and has recently led the updating of toxicant guidelines for both waters and sediments. Graeme is author of over 400 scientific publications.

Michael Holloway is Environment and Scientific Coordinator for marine oil spill preparedness and response for the Victorian Government. He trained in marine ecology with a quantitative experimental focus, and has worked at the interface between marine science and management for much of his career. His breadth of interests has led to publications on a range of marine topics including invasive species impacts, ecosystem-based management and risk assessment methods, the national policy on aquatic biosecurity and management of environmental monitoring programs in Port Phillip Bay, Victoria. He is currently interested in the application of decision analytic techniques to the complex environmental problems encountered during oil spill response.
Paul Irving is Scientific Coordinator at the Australian Maritime Safety Authority, responsible for marine environment protection and maritime spill response science and advice. A diverse 30-year background across many aspects of marine and coastal science, conservation and management, from tropical to Antarctic, provides a unique perspective on Australasian and Pacific marine pollution response. As a firm believer in collaboration and partnership to provide practical solutions, Paul spends much of his considerable energies looking for ways to incorporate new science and research knowledge into spill planning, so that communities (social and ecological) affected by maritime pollution get the effective response they deserve.

Andrew Ross is a research scientist with CSIRO. He leads research projects focused on hydrocarbon seeps, the development of new hydrocarbon sensor devices and baseline and oil spill monitoring. He and his team were involved in the Gulf of Mexico MC252 spill response, spending 4 months monitoring surface waters in 2010 and undertaking hydrocarbon seep surveys close to the MC252 incident location in 2011. More recently he has commenced a series of research projects to characterise the baseline hydrocarbon concentrations and geology of the Great Australian Bight. Andrew joined CSIRO in 2004 and has qualifications in marine biology, oceanography and petroleum geoscience.
About the authors

Andrew Revill is a senior research scientist with CSIRO Oceans and Atmosphere, Hobart. He has over 20 years of experience in hydrocarbon analysis including surveys around North Sea platforms and projects relating to the petroleum prospectivity of onshore Tasmania and the persistence of spilled oil from the Iron Barron incident. He provided geochemistry expertise in relation to the Deep Water Horizon spill and is currently involved in ongoing projects for BP and Chevron characterising the Great Australian Bight. Andy has previously been involved in major reviews of the possible environmental impacts of the oil and gas industry and contaminants on Australia’s North West Shelf.

David Griffin is a Principal Research Scientist at CSIRO Oceans and Atmosphere. He is a Physical Oceanographer who has focused on the mesoscale phenomena of the ocean since gaining his PhD in 1986. Much of his career has been devoted to the creation of an analogous forecasting capability for ocean currents. In 2012 he was awarded the Australian Marine Science Association’s Jubilee Award for his development of the OceanCurrent website and for many other applications of physical oceanography. In 2014, he served on the Drift Working Group convened during the search for missing flight MH370.

Xiubin Qi obtained her BSc and MSc in Physical Chemistry from Nanjing University (China) and her PhD in Analytical Chemistry from the University of California, Davis (USA) in 2007. She is currently a research scientist at CSIRO Energy, working on research and development of hydrocarbon detection systems for both environmental monitoring and oil exploration, through integration of multidisciplinary techniques that involve material science, instrument programming, system automation and statistical analysis. She worked as a chief scientist during the 2-month oil spill response survey in the Gulf of Mexico and led the project, co-funded by AMSA and CSIRO, to develop an integrated system for oil dispersant efficacy monitoring.
Charlotte Stalvies is a Senior Experimental Scientist with CSIRO. With a background in geology and geochemistry, her first foray into the world of oil spill response came in the form of two 30-day deployments at sea during the 2010 Deepwater Horizon incident in the Gulf of Mexico. Since then, Charlotte’s work has focused on establishing best-practice approaches to hydrocarbon sampling in marine environments investigating natural hydrocarbon seepage as well as oil spill preparedness, response and monitoring. As a result, Charlotte has led the design and implementation of sampling campaigns in the Gulf of Mexico, Perth Basin, Timor Sea and Great Australian Bight.
Disclaimer

This Oil Spill Monitoring Handbook provides general advice and is not a substitute for locally specific spill-response plans or monitoring plans required by state, territory or Commonwealth regulators. Although it may contain information that is of interest to the offshore petroleum industry, it is designed for use following a release of oil from the sea surface, not a sub-sea release.
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Introduction to oil spill monitoring

Paul Irving, Sharon Hook and Andrew Ross

Australia’s increasing economic activity (imports, exports and petroleum production) has increased shipping traffic and the need for more ports. Australia is already the fifth largest shipping nation globally, and relies on shipping for almost all of its imports and exports (AMSA 2014a), with ship-based commodity exports expected to increase (Lubulwa et al. 2008). Unfortunately, increased exploitation of Australia’s oil and gas resources coupled with increased shipping traffic suggests that another significant oil spill is highly likely. Smaller spills, often measured in litres, are still reasonably frequent events, most often associated with ports and similar maritime facilities, as shown in Fig. 1.1. However, that frequency has been diminishing over recent years, as Australia applies more stringent environmental and maritime laws.

Following a maritime spill of oil and other hazardous or noxious chemicals, information is rapidly required to determine the:

- **amount** and concentration of oil in the environment (i.e. how much is released?)
- **fate** of the oil (how will it weather/change over time?)
- **movement** of oil in the environment (where is it headed?)
- **resources** it will encounter or impact (what sensitive resources are likely to be effected and how?)
- **impacts** of the oil spill (what damage could be caused, even after successful clean-up or response?).

However, it is only through monitoring (field observation, sampling, remote sensing, etc.) that each of these factors can be addressed with sufficient certainty. Even high-quality modelling requires verification and validation. The decision to undertake monitoring will be dependent on the factors listed above, often expressed as an initial risk assessment.

An oil spill response relies on timely and quality information about the nature of the incident, the spill, the receiving environment, likely or actual effects and the effectiveness of treatments. This information is generally one of three types:

- **baseline information** prepared in advance (e.g. risk and threat assessments, resource and environmental knowledge bases, contingency plans, trained expertise and experience)
• **predictive modelling** based on baseline knowledge and delivered in real-time from established sources and systems about location, process and outcomes (such as from weather services or fate and trajectory modelling contractors)
• **field information** about real-time events, actions and effects, obtained using various forms of field observation, sampling, sensing and monitoring capabilities.

The combination of these informs:

• **situational awareness** (what is going on and is there a real risk or threat?)
• **planning** (what response is possible, where and how?)
• **response actions** (what to do, where, when and how much?)
• **termination** (what is a sufficient or a suitable response?)
• **effects assessment** (did either the incident or the response cause ecological or socioeconomic changes?).

In total, these inform the response organisation’s ability to make sense of the incident and its ability to plan and execute the response.

Assuming that all of the necessary information can be obtained, and/or verified (or presumed, as sometimes the mere threat of environmental impact is enough), these all lead to the question: ‘Is there a real risk or threat, and can a meaningful response be mounted?’

Without appropriate, timely and accurate information, any response will likely be ineffective. Without estimating or assessing the uncertainty associated with the information provided (observations, sampling, analysis) both pre-spill and post-spill risk assessment and contingency planning may be compromised and lead to poorer decision making.
Understanding and planning for the various information gathering and communication functions should be a key function in pre-spill contingency preparedness and planning. Experience has shown that, without preparation for monitoring, activities can be constrained. Some of the logistical concerns that may prove to be confounding factors at the time of an impact include:

- **safety of personnel** (always the highest priority, responders, the public and field staff)
- **access to sites** – location, hazards and other physical factors can limit access
- **ambient conditions** – tides, weather and sea state
- **expertise, equipment and capacity** – the spill, the response and the effects will require diverse and often scarce expertise
- **contracts, funding and licenses** – some or all of these may be uncertain if not planned and established in advance.

All of these factors can be anticipated and should be documented in contingency plans (Chapter 4). If these are adequate and sufficiently flexible to a range of options for tackling logistical challenges, a knowledge-based response can proceed.

In 2009, Australia experienced its largest oil spill to date with the blowout from the Montara wellhead platform in the Timor Sea, off the northern coast of Western Australia. The Australian Maritime Safety Authority (AMSA) was required to become the lead response agency. The Australian Government’s Montara Commission of Inquiry (Borthwick 2010) concluded that certain aspects of the response to this incident were considered inadequate. Shortcomings included a failure to initiate scientific (environmental effects) monitoring in a timely manner and a failure to measure the distribution of dispersed oil and dispersants throughout the water column instead of only at the surface. The Commission concluded that ‘it is unlikely that the full extent of environmental damage from the Montara oil spill will ever be established’. The Commission recommended the development of ‘off the shelf’ monitoring programs that could be quickly implemented in the event of another uncontrolled release of oil.

Although the Borthwick Commission primarily focused on the monitoring shortcomings of the offshore petroleum sector, AMSA also took the position that it was time to provide more modern and complete monitoring advice for maritime oil spills.

This Handbook provides guidance on how to prepare for and implement such monitoring programs. It has been prepared at the request of AMSA to provide guidance for response phase monitoring specifically for the shipping industry, although some portions of it may be of interest to the offshore oil and gas sector.

The primary focus of the Handbook is on the accidental release of petroleum (oil, including refined products and condensate). Petroleum spills are important because the increased development of ports and exploitation of petroleum resources makes the probability of such an event much more likely. The toxicity of oil to marine and coastal life means that oil spills have the potential to create severe to catastrophic effects on local and wider ecosystems and to the socioeconomic activities dependent on these resources, as has been recently demonstrated in many incidents worldwide.

There is a very large number of chemical compounds that are transported and could lead to a maritime incident, but this also adds to the complexity of any response and/or monitoring. Some of the guidance that is contained within this document will also provide insight into the response to and management of other chemical spills. The sections on
contingency planning will be most broadly applicable, but other sections may also be helpful, depending on the physical properties and toxicity of the chemical that is spilled.

This Handbook incorporates current best practice and lessons learned from previous spills. It provides guidance to the maritime sector – whose responsibilities include spills from activities associated with shipping, ports and terminals – on how to respond to an accidental release of oil. Hence, it focuses primarily on what is referred to as ‘response phase monitoring’ (see Chapters 3 and 6), because this reflects the mandated responsibilities of the control agencies (and jurisdictions) under the Australian National Plan for Maritime Environmental Emergencies (AMSA 2014b) (see Box 1.1). Response phase monitoring has also traditionally been referred to as ‘Type I’ or ‘operational’ monitoring, but these names do not adequately describe the requirements.

The Handbook also provides guidance on how recovery phase monitoring can be conducted alongside response phase monitoring. Recovery monitoring has been referred to as ‘effects’ or ‘scientific’ monitoring, but neither of these terms adequately covers the breadth or nature of what may need to be monitored after the response is completed.

The Handbook does not aim to be prescriptive but presents a series of options for oil spill response to be chosen by weighing the, at times, conflicting needs (Law et al. 2011) for:

- **speed** – because a fast response may be required for response options such as dispersant use, and to permit the pre-impact and time of impact data collection
- **cost effectiveness** – to ensure value for money and resources committed, both before and during the response
- **effective science** through best use of available scientific and technical expertise
- **best practice integration** with lessons learned from previous spills, both in Australia and internationally
- **coordination and integration** among different agencies stakeholders, functions and responsibilities.

It also provides idealised advice that would have to be modified to suit the conditions on the day. This Handbook does not provide guidance on seafood safety, such as when to close and how to re-open fisheries and aquaculture facilities with due consideration of public health, public perception and socioeconomic factors. AMSA and the Australian Fisheries Management Authority (AMFA) are currently revising their guidelines regarding seafood safety, and updated guidance will be published separately.

Note that this Handbook provides general advice and is not a substitute for locally specific spill-response plans or monitoring plans required by state, territory or Commonwealth regulators. While it may contain information that is of interest to the offshore petroleum industry, it is designed for use following a release of oil from the sea surface, not a sub-sea release.

### 1.1 Stages of a spill response

Following the notification of a spill, the response that is initiated follows a series of stages as illustrated in Fig. 1.2. Each of these stages has associated information gathering and monitoring actions that are further elaborated on in Chapter 4.

The Handbook follows this logical sequence of spill, response and monitoring.

This chapter and Chapters 2 and 3 provide background information, comprising an introduction and, in Chapter 2, an overview of the chemical properties of oil, the toxicological
Box 1.1. The Australian National Plan for Maritime Environmental Emergencies

The Australian National Plan for Maritime Environmental Emergencies (the National Plan) (AMSA 2014b) is Australia’s strategic framework for organising spill prevention, preparedness, response and recovery. It provides a single, national, comprehensive and integrated response arrangement to minimise the effects of marine pollution and other environmental impacts arising from a maritime casualty. The source could be from vessel casualties or offshore petroleum facilities. Although this Handbook is presented as a guidance document to support the National Plan, its relevance and application is expected to be much wider.

AMSA works with a wide range of Australian Commonwealth, state and territory governments, the shipping, ports, oil, salvage, exploration and chemical industries, and with emergency services. The National Plan is less a contingency plan and more a strategy that sets out national arrangements, policies and principles for the management of maritime environmental emergencies. It provides policy and guidance to ensure national consistency on the following key elements:

- governance and strategic management
- casualty prevention
- planning for incident response
- response plans, systems and processes
- recovery and community support
- cost recovery and financial arrangements

The guidance and policy within the National Plan builds on eight important principles, common to all forms of emergency response:

- protect the community, environment and maritime industries
- act on to relevant international conventions
- integrate with the Australian emergency management arrangements
- provide a comprehensive management arrangement
- provide a single integrated response arrangement
- implement a risk-management approach
- implement the polluter pays principles
- provide for stakeholder engagement

The objectives of the National Plan are to have:

- a detailed national, state, local and industry plans and communications arrangements for responding to an oil or chemical pollution incident
- an appropriate level of emergency towage capability around the Australian coastline
- a single national decision maker to coordinate a response to a maritime casualty
- an adequate level of pre-positioned spill-combating equipment, commensurate with the risk involved
- a comprehensive competency-based national training program, complemented by exercises.

National Plan arrangements are implemented within the states and the Northern Territory (NT) through their contingency plans. Several of these plans are directly linked to state/NT emergency management arrangements, which assign specific roles and responsibilities to government agencies.
impacts of oil exposure, the impacts of oil exposure on different marine habitats with relevance to Australia, and an overview of some of the most commonly used response technologies. Chapter 3 gives general guidance on oil spill monitoring.

Chapters 4 and 5 provide insight into the oil spill response process and structure, how monitoring is integrated into this, and the application of decision frameworks for a net environmental benefit analysis (frequently referred to as NEBA).

More detail on response phase and recovery phase monitoring is provided in Chapters 6 and 7, respectively.

A set of appendices contain detailed standard operating procedures (SOPs) for sample collection. These are not intended to be prescriptive, and will not be appropriate for all scenarios, but nevertheless give useful practical guidance.

1.2 Scale of the oil spill and the response strategy

In this Handbook, the guidance provided is based on a ‘worst case’ scenario, namely a large spill resulting from a shipping or maritime facility incident. The National Plan (AMSA 2014b) recognises that most of Australian spills are small and can be easily and successfully dealt with by the spiller, or a single local control agency.

Table 1.1 shows parameters for the classification of incidents into different scales. In this scenario, the control agency would select the subsections of the Handbook relevant to their situation. The overall approach to spill response, as outlined in Fig. 1.2, is the same regardless of the size, but the scale of the response, the number of stakeholders involved

![Fig. 1.2. An overview of the stages of an oil spill response and the general information needs and monitoring actions for each stage](image-url)
and the number of sensitive receptors potentially impacted would be expected to be fewer for smaller spills. As a consequence, a NEBA will often determine that the best response will be not to employ any response technology, but instead to monitor the situation. The NEBA can help to determine the best response options for the incident.

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<td></td>
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</tbody>
</table>

Table 1.1. Guidance for incident classification as provided by the National Plan (AMSA 2014b)
2.1 Properties of oils
Petroleum-based crude oil and its refined products are complex mixtures, primarily of hydrocarbons. Saturated hydrocarbons that are linear, branched or cyclic arrangements of carbon and hydrogen are referred to as alkanes. Cyclic compounds having unsaturated bonds are referred to as aromatic hydrocarbons (as shown in Fig. 2.1). Polycyclic aromatic hydrocarbons (PAHs) have two or more rings in their structures. Oil can also contain some more polar compounds, which include sulfur, nitrogen and oxygen in their structures (Killops and Killops 1993). The overall relative composition of an oil determines its properties and subsequently how it will behave if spilled in the environment.

Each oil type has specific characteristics, which influence its behaviour when spilled and its toxicological effects in water and in sediment, as well as the efficacy of any response and clean-up operations. In order to better understand the properties of spilled oil and how it may interact with its receiving environment, the basic chemical and physical properties of petroleum are briefly reviewed below.

2.1.1 Specific gravity (or relative density)
Specific gravity is the ratio of the weight of a substance, such as an oil, to the weight of an equal volume of water. The specific gravity of most crude oils and refined petroleum products is less than 1.0 g/mL, and therefore these substances generally float on both fresh and salt water (the specific gravities of fresh water and sea water are 1.0 and 1.025 g/mL, respectively).

The American Petroleum Institute (API) gravity scale is a specific measure used to describe oils and petroleum products using the formula:

°API = (141.5/specific gravity) – 131.5

This API gravity is frequently used because it also provides a general indicator to other properties of the oil; for example, in general, the lower the API, the heavier the oil, and the higher the API the lower the viscosity and the higher the relative amount of volatiles
Typically group 1 or light oils have an API gravity greater than 45; group 2 light–medium oils have an API gravity between 35 and 45; group 3 or medium oils have API between 17.5 and 35, while heavy or group 4 oils have an API gravity less than 17.5 (ITOPF 2012).

2.1.2 Viscosity
Viscosity is the measure (usually in centistokes, cSt, at a particular ambient temperature) of how much a fluid (gas or liquid) tends to resist a change in shape, or movement in response to an applied force or shear stress. It denotes opposition to flow and may be thought of as an internal friction between the molecules in a fluid. Tar, for example, is very viscous when compared with gasoline. The viscosity of liquids decreases with an increase in temperature and so is related to pour point, as discussed below. In an oil spill clean-up, the viscosity of an oil determines its ability to penetrate shoreline substrates, its ability to be pumped and its ability to be chemically dispersed. Oils are often classified by the oil industry using the viscosity at 50°C, so oils may be more viscous at ambient temperatures during a spill.

2.1.3 Surface tension
Surface tension is the force of attraction between the surface molecules of a liquid such as oil. It affects the rate at which spilled oil will spread over a land or water surface, or into the ground. Oils with low surface tensions, and therefore faster spreading rates, are likely to be oils with low specific gravities and high API gravities. Generally, surface tension is measured in a laboratory at a particular standard temperature because it is the measurement of force per unit length, generally expressed as N/m (or dynes/cm). In an oil spill response, it
is not the absolute surface tension but rather the difference in surface tension between the oil and the water (for dissolving) or air (for evaporating), and the change in the surface tension of the oil over time.

2.1.4 Adhesion or stickiness
This is a complex property of oil that is hard to define without reference to the oil viscosity and surface tension, the ambient temperature and the surface characteristics of the material to which the oil is stuck. Stickiness is very difficult to measure and describe in absolute terms, but is still used to distinguish one type of oil from another. Most people are able to describe and understand it in relative terms, based on the amount of effort required to clean something. The stickiness of oil can also influence the efficacy of skimmers and shoreline clean-up methods.

2.1.5 Pour point
Pour point is the temperature at which the oil viscosity increases at a greater rate with small temperature decreases. If the ambient temperature is much below the pour point, the oil will essentially behave as a solid. Often viscosity increases as the oil temperature decreases towards its pour point. An oil’s pour point will be related to the wax content of the oil as well as the proportion of heavy compounds, such as asphaltenes.

2.1.6 Volatility
Spilled oil can evaporate into the environment or air when its surface tension is low or its boiling point is reached. Because the oil is a mixture of many different chemicals, each component will evaporate (or become volatile) at different temperatures. The evaporated gases can be very flammable and dangerous.

2.1.7 Asphaltene content
Asphaltenes are among the largest and heaviest components in a crude oil. They tend to be complex mixtures containing hundreds, or even thousands, of individual chemicals, and so are not described with a specific chemical formula. They also tend to stick together in solution. Their importance to spill response is that high asphaltene oils are very susceptible to creating water-in-oil emulsions or mousses. An oil with an asphaltene content greater than 0.5% is likely to form emulsions.

Some examples of the physical properties of different oils are provided in Table 2.1. Many oils are sufficiently well tested, measured and described that predictive models of their character, behaviour and fate have been developed to assist responders. One of these is the ADIOS tool from National Oceanic and Atmospheric Administration (NOAA) (http://response.restoration.noaa.gov/adios).

Oils with a high API gravity will not evaporate to the same degree as oils with a lower API gravity. Oils with a low viscosity will spread rapidly (almost instantly) resulting in thin films more prone to dispersion, but as water temperature approaches the oil’s pour point (the temperature at which an oil will flow freely) viscosity will increase significantly, changing the character and behaviour of the oil.

The refining of oils also changes their characteristics (Table 2.2), but it is important to remember that this process may also result in some of the toxic components becoming more concentrated; for example, the more acutely toxic, lighter aromatic compounds will be concentrated within the lighter refined products such as gasoline and diesel.
2.2 Fate of oils in the environment

2.2.1 Weathering

As soon as an oil is spilled, its chemical and physical properties begin to change through a process known as weathering. The processes contributing to weathering and the fate of spilled oil are best depicted in a conceptual model (Fig. 2.2) and include evaporation, emulsification and microbial degradation. The process of oil weathering has been reviewed recently (RSC 2015), but nonetheless will be briefly summarised here. The timescales of these processes are shown in Fig. 2.3. Weathering changes the suitability of some response options, as discussed further in Section 2.5.

Spreading

Spilled oil immediately begins to spread, but the rate at which this occurs will depend on the volume of oil, its viscosity, and environmental parameters such as wind and

Table 2.1. Physical properties for some example oils

<table>
<thead>
<tr>
<th>Oil</th>
<th>API (°)</th>
<th>Pour point (°C)</th>
<th>Viscosity @ 10–20°C (cSt)</th>
<th>% Mass with BP &lt;200°C</th>
<th>% Mass with BP &gt;370°C</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Condensate</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Angel (WA, NWS)ᵇᶜ</td>
<td>63</td>
<td>−60</td>
<td>0.68</td>
<td>&gt;80</td>
<td>0</td>
</tr>
<tr>
<td>Automotive gasoline</td>
<td>60</td>
<td>−18</td>
<td>&lt;1.0</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td><strong>Light</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gippsland (Vic)ᵇ</td>
<td>52</td>
<td>−13</td>
<td>63</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Gippsland (Vic)ᵇ</td>
<td>46</td>
<td>6</td>
<td>46</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>Kerosene</td>
<td>45</td>
<td>−55</td>
<td>2</td>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td>Curlew (North Sea)</td>
<td>47</td>
<td>−13</td>
<td>2</td>
<td>57</td>
<td>17</td>
</tr>
<tr>
<td><strong>Medium</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tapis (Malaysia)</td>
<td>43</td>
<td>16</td>
<td>30</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Beatrice (North Sea)</td>
<td>38</td>
<td>18</td>
<td>32</td>
<td>25</td>
<td>35</td>
</tr>
<tr>
<td>Automotive diesel</td>
<td>38</td>
<td>−36</td>
<td>4</td>
<td>29</td>
<td>0</td>
</tr>
<tr>
<td>Arabian Extra Light</td>
<td>38</td>
<td>−30</td>
<td>3</td>
<td>26</td>
<td>39</td>
</tr>
<tr>
<td>Barrow Island (WA, NWS)ᵇᶜ</td>
<td>37</td>
<td>−65</td>
<td>3</td>
<td>37</td>
<td>16</td>
</tr>
<tr>
<td><strong>Heavy</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alaska North Slope</td>
<td>28</td>
<td>−18</td>
<td>32</td>
<td>32</td>
<td>41</td>
</tr>
<tr>
<td>Arabian Light</td>
<td>33</td>
<td>−40</td>
<td>14</td>
<td>25</td>
<td>45</td>
</tr>
<tr>
<td>Arabian Heavy</td>
<td>28</td>
<td>−40</td>
<td>55</td>
<td>21</td>
<td>56</td>
</tr>
<tr>
<td>Minas (Indonesia)</td>
<td>35</td>
<td>18</td>
<td>SS</td>
<td>15</td>
<td>58</td>
</tr>
<tr>
<td><strong>Extra heavy</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tia Juana Pesado (Venezuela)</td>
<td>12</td>
<td>−16</td>
<td>SS</td>
<td>3</td>
<td>78</td>
</tr>
<tr>
<td>Boscan (Venezuela)</td>
<td>10</td>
<td>7</td>
<td>SS</td>
<td>4</td>
<td>80</td>
</tr>
<tr>
<td>Bachaquero 17 (Venezuela)</td>
<td>16</td>
<td>−29</td>
<td>5000</td>
<td>10</td>
<td>60</td>
</tr>
<tr>
<td>Bunker C</td>
<td>13</td>
<td>7</td>
<td>SS</td>
<td>2</td>
<td>80</td>
</tr>
<tr>
<td>Wandoo (WA, NWS)ᵇᶜ</td>
<td>19</td>
<td>−39</td>
<td>170</td>
<td>7</td>
<td>50</td>
</tr>
</tbody>
</table>

ᵃCondensate data from Oil and Gas Journal, 1 July 2013, Bunker C data from http://www.labo-analytika.com/html/bunker_c_spec.html; other data adapted from ITOPF (2012) and Volkman et al. (1994). Indicative classification light to extra heavy-extra heavy is based on API gravity. Other classifications based on location. Specific oils may give different groups
ᵇAustralian crude and fuels from the NOAA database used in the ADIOS2 application
ᶜNWS = North West Shelf
Note: SS = semi-solid; BP = boiling point
### Table 2.2. Example of how physical parameters of Tapis crude change with refining

<table>
<thead>
<tr>
<th>Cut volume (%)</th>
<th>API (°)</th>
<th>Specific gravity</th>
<th>Pour point (°C)</th>
<th>Viscosity at 20°C (CSt)</th>
<th>Viscosity at 40°C (CSt)</th>
<th>Viscosity at 50°C (CSt)</th>
<th>Nickel (mg/L)</th>
<th>Vanadium (mg/L)</th>
<th>Paraffins (%)</th>
<th>Naphthenes (%)</th>
<th>Aromatics (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole crude</td>
<td>100</td>
<td>43</td>
<td>0.81</td>
<td>43</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>Butane and lighter</td>
<td>2</td>
<td>123</td>
<td>0.56</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td>100</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light naphtha</td>
<td>7</td>
<td>83</td>
<td>0.66</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td>92</td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heavy naphtha</td>
<td>19</td>
<td>54</td>
<td>0.76</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
<td>56</td>
<td>30</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Kerosene</td>
<td>20</td>
<td>45</td>
<td>0.80</td>
<td>-66</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>59</td>
<td>25</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Diesel</td>
<td>23</td>
<td>38</td>
<td>0.83</td>
<td>19</td>
<td>3</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>60</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>Vacuum gas oil</td>
<td>23</td>
<td>32</td>
<td>0.86</td>
<td>101</td>
<td>18</td>
<td>13</td>
<td>0</td>
<td>0</td>
<td>57</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>Vacuum residue</td>
<td>5</td>
<td>9</td>
<td>1.00</td>
<td>105</td>
<td>20 000 000</td>
<td>700 000</td>
<td>170 000</td>
<td>24</td>
<td>2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*aSource: ExxonMobil, USA (http://www.exxonmobil.com/crudeoil/about_crudes_tapis.aspx)
bCSt = centistokes, unit of kinematic viscosity. 1 centistoke = 1 square millimetre per second
cVolume per cent
A low-viscosity oil, such as diesel, will spread much quicker than a highly viscous bunker fuel, which may remain as a series of patches rather than creating a continuous film (ITOPF 2012). Similarly, a viscous oil will spread quicker in warmer temperatures than cold. Low-viscosity oils will likely spread to a point where they are visible as a sub-micrometre thick sheen on the surface, often appearing as a ‘rainbow’, whereas a more viscous oil may remain in thicker less continuous layers. The degree and speed that spilled oil spreads can affect other weathering processes, such as evaporation and dissolution, which will occur more rapidly for thin films (NRC 2003).

**Evaporation**

In many oil spills, evaporation can be the most important weathering process leading to the loss of significant volumes of the spilled oil (as discussed further in Box 2.1). Up to 75%
of a light crude, 40% of a medium crude oil and up to 100% of a light refined product such as gasoline can be lost through this process (Fig. 2.4), but heavy or residual fuel oils may lose only 10% at most. Components of oil with a boiling point less than ~200°C will evaporate in temperate conditions (ITOPF 2012), leaving the higher molecular weight components, as shown in Fig. 2.5. Predicting evaporation rates can be problematic. Oils are a complex mixture and the proportion of relatively volatile components is not always known, though refined products are better characterised. Elevated ambient temperature, higher wind speeds and higher mixing energy from waves, and a greater rate of spreading will all enhance evaporation rates (NRC 2003). Residues remaining after significant evaporation have an increased viscosity and density, which will affect subsequent behaviour and weathering processes.

**Natural dispersion**

Natural dispersion is the break-up of oil slicks, by wave, currents and wind energy, into microscopic, neutrally buoyant droplets and the distribution of these through the water column, both vertically and horizontally. Low viscosity oils tend to be more readily amenable to dispersion, with water turbulence (e.g. wave and wind energy) playing a large role in the process (SINTEF 2011). As an oil slick is broken up, there will be a range of droplet sizes formed, with small droplets less than ~70 μm being neutrally buoyant and remaining

---

**Fig. 2.4.** Examples of relative evaporation rates of different spilled oil fractions at 15°C water temperature (Source: NRC 2003)

**Fig. 2.5.** Gas chromatograms showing the effect of evaporation on hydrocarbons in a crude oil (Source: Yang et al. 2015). Note the removal of lighter compounds to the left close to the solvent front.
in suspension. These also separate through dilution, and so are less likely to re-coalesce underwater to form larger, more buoyant droplets. Any large droplets will likely rise back to the surface to reform slicks. Over time, this process can disperse significant quantities of an amenable oil and this can be enhanced by the use of chemical dispersants (see Section 2.5.2). Dispersed oil is more amenable to other weathering processes such as biodegradation, dissolution and sedimentation, but may also be more available for uptake by biota (NRC 2003; SINTEF 2011; ITOPF 2012).

### Dissolution

The solubility of different oils varies greatly, as shown in Table 2.3. The degree to which oil will dissolve in water is highly dependent on its chemical constituents and a variety of environmental factors, such as water temperature, turbulence (e.g. wind and wave energy) and physical dispersion within the water column (NRC 2003; ITOPF 2012). Under most conditions found in the environment, the majority of oil components are regarded as having very low solubility, as shown in Table 2.4. Lighter components, and particularly aromatic and polar compounds, have some degree of solubility but these are also some of the components most rapidly lost by evaporation. Evaporation of oil spilled on the sea surface is typically 10–1000 times faster than loss by dissolution (ITOPF 2012). However, dissolution of aromatic hydrocarbons such as benzene, toluene, ethylbenzene and xylenes (known as BTEX compounds) is relevant to the environmental impact of oil because these are some of the most acutely toxic constituents. Dissolution is enhanced by an increased

<table>
<thead>
<tr>
<th>Oil</th>
<th>Solubility (mg/L)</th>
<th>Temperature (°C)</th>
<th>Salinity (%o)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prudhoe Bay</td>
<td>29</td>
<td>22</td>
<td>0 (distilled water)</td>
</tr>
<tr>
<td>Lago Media</td>
<td>24</td>
<td>22</td>
<td>0</td>
</tr>
<tr>
<td>Lago Media</td>
<td>16.5</td>
<td>22</td>
<td>33</td>
</tr>
<tr>
<td>Diesel fuel</td>
<td>3</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>Diesel fuel</td>
<td>2.5</td>
<td>25</td>
<td>33</td>
</tr>
<tr>
<td>Bunker C</td>
<td>6</td>
<td>22</td>
<td>0</td>
</tr>
<tr>
<td>Gasoline</td>
<td>98</td>
<td>22</td>
<td>0</td>
</tr>
</tbody>
</table>

**Table 2.4.** Indicative solubility in sea water of individual compounds found in spilled oil

<table>
<thead>
<tr>
<th>Compound</th>
<th>Solubility (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pentane</td>
<td>40</td>
</tr>
<tr>
<td>Hexane</td>
<td>9.5</td>
</tr>
<tr>
<td>Benzene</td>
<td>1700</td>
</tr>
<tr>
<td>Toluene</td>
<td>530</td>
</tr>
<tr>
<td>Ethylbenzene</td>
<td>170</td>
</tr>
<tr>
<td>Xylene</td>
<td>150</td>
</tr>
<tr>
<td>Naphthalene</td>
<td>30</td>
</tr>
<tr>
<td>Phenanthrene</td>
<td>1</td>
</tr>
</tbody>
</table>
sea state. Sea state is a combination of wind waves and swell with wind speed measured in knots (kn) (10 kn = 18.5 km/h) which will result in increased dispersion of oil droplets within the water column, thereby increasing the surface area of oil available for dissolution.

**Biodegradation**

Biodegradation is the process by which microorganisms (primarily bacteria, but also some fungi and microalgae), oxidise hydrocarbons. The degree to which this can occur will depend on the oil, the microbial population, temperature and the availability of nutrients and oxygen. The rate at which biodegradation will occur can be difficult to predict and is generally considered to be a longer term, but more effective, removal mechanism compared with others such as evaporation and dissolution (see Fig. 2.3). Straight-chain hydrocarbons (alkanes) tend to be more readily degraded than those with branches and the more complex the branching, the more recalcitrant a compound will be. In addition, shorter chain, low molecular weight components will be degraded before longer chains. Similarly, aromatic hydrocarbons tend to be less readily biodegraded than alkanes (see Volkman et al. 1994 and references therein). Thus the effects of biodegradation can appear similar to those of evaporation, with the more rapid removal of low molecular weight components. In addition, since the most easily broken down compounds are also often removed by other weathering processes, highly weathered oil may not be responsive to bioremediation because the compounds remaining may not be efficiently used by bacteria. A detailed analysis and interpretation might be required to determine the dominant removal mechanism.

The terminal products of biodegradation of any organic compound are carbon dioxide and water, but, in order to achieve this, microbes initially introduce oxygen functional groups to the molecule, which has the effect of changing its chemical properties. Parent compounds are biodegraded to secondary products that can be more toxic because of the addition of these reactive functional groups (e.g. phenolic or carboxylic acid groups). One consequence is that these products can be more water soluble and more bioavailable. They are also more reactive with intracellular macromolecules (see Section 2.3.6). Highly degraded oils often exhibit a prominent feature when analysed via gas chromatography-mass spectrometry (GC-MS) referred to as the unresolved complex mixture (UCM) (Fig. 2.6), composed of a mixture of highly branched aliphatic and aromatic compounds that are highly resistant to microbial degradation and may exhibit some toxic effects (Gough and Rowland 1990; Gough et al. 1992; Booth et al. 2008).

![Gas chromatograms illustrating the effect of biodegradation on hydrocarbons in ASMB crude oil (Source: Yang et al. 2015). Note the complete removal of aliphatic hydrocarbons with only the branched internal standard remaining (left). The majority of aromatic compounds are also removed but some are more resistant to degradation (right).](image-url)
Photooxidation

Photooxidation is the abiotic incorporation of oxygen into aromatic petroleum compounds through the generation of reactive oxygen radicals mediated by sunlight as depicted in Fig. 2.7. Photooxidation is determined by incident light levels, water clarity and oil composition. There may also be a requirement for some form of catalyst to be present, such as clay particles or hydrogen peroxide or titanium (McConkey et al. 2002). Photooxidation can lead to a broader range of oxygenated products than biodegradation, which in turn may lead to smaller, more-water-soluble compounds or to larger, stable products through polymerisation reactions, which in turn can form a protective barrier inhibiting any further degradation. It is generally thought that photooxidation plays only a minor role in oil weathering from a mass balance perspective, but several products of these reactions may be acutely toxic (NRC 2003), which could be an important consideration in regions with high light intensity.

Emulsification

Emulsification is the opposite of dispersion in that water is entrained within the slick to form a water-in-oil emulsion, often termed a ‘chocolate mousse’ due to its appearance (Fig. 2.8). Mousse formation tends to occur most readily in oils with lower viscosities (Killops and Killops 1993) with higher (at least 5%) asphaltene content and a high wax content. The basic mechanism is that the asphaltene molecules, aided by resins (if present), encase water droplets in high-strength asphaltene films. Formation of the emulsion is accelerated by sea states greater than around 7–10 kn. Stable emulsions can contain 70–80% water, increasing the volume of oil in a surface slick up to five times. This process leads to a highly viscous, almost solid, product and impedes other weathering processes such as dispersion, evaporation and biodegradation (NRC 2003; ITOPF 2012).

Sedimentation

Most oils have a specific gravity less than that of sea water (1.025) and so float. Incorporation of oil into sediments can obviously occur if oil becomes stranded on the shoreline, but
processes such as evaporation and dissolution can increase the density of oil particles and dispersion can bring these particles into contact with suspended sediments, subsequently leading to sedimentation while the oil is still in open water. Burning of oil at sea can also lead to an increase in density of the residue, increasing the likelihood of sedimentation (ITOPF 2012). Incorporation of oil into sediments can reduce the effectiveness of biodegradation and also provide a pathway for incorporation into biota (see Section 2.3).

Sinking and over-washing

If the oil is, or becomes, more dense than surface waters, it can sink or float neutrally buoyant just below the surface. Some oils have a naturally high specific gravity or density and so do this immediately when spilled. Others lose components during weathering due to evaporation and/or dissolution to become relatively heavier. Some also emulsify, adding enough water that they become close to the density of water. Conditions can also arise where sediments become entrained in the oil and add to its density. In most cases where this occurs it will be due to a combination of these effects. The result is that the oil has very little freeboard (surface slick) during light weather, with most of its volume below the surface.

As the sea-state increases, the slick can break up into smaller patches, with much of the oil remaining below the surface allowing water to easily wash over it, often making it very difficult to observe. This is exacerbated by swell and waves where the oil tends to ‘sit’ at the bottom of the trough. Such a slick can disappear and re-appear depending on weather, wind and wave state (Fingas 2011a). For example, the Cape Upstart spill near Townsville in July 2015 ‘disappeared’ for some days due to sinking, patch creation and over-washing before reappearing as patties and tar balls on local beaches (see Box 6.1).

2.2.2 Summary

When considering the possible fate of spilled oil, it is necessary to assess the likelihood of each removal mechanism based on the properties of the oil in question. One way to do this is through a matrix similar to that shown in Table 2.5. It is then possible to monitor what is...
Actually happening through incorporation of scientific monitoring within the spill response.

Although it is difficult to generalise, some guidance on the likely weathering behaviour of oils is as follows:

- If the asphaltene content is >0.5%, oil is likely to form an oil-in-water (mousse) emulsion.
- Oil components with boiling point below 200°C will tend to evaporate in temperate conditions.
- Oil droplets <70 µm will be neutrally buoyant and remain in suspension.
- Chemical dispersability is significantly decreased at viscosities around and above 2000 cSt.
- A stable emulsion can be 70–80% water, which is four to five times the volume of the oily waste.
- Marine diesel over time will eventually evaporate and disperse into the water column, but rates differ with both water and air temperature, more so with wind speed (and wave energy) (see Table 2.6).

### 2.3 Bioaccumulation and toxicity of oil

Oil is a complex mixture of thousands of chemicals and has a composition that changes with exposure to light and air, and as a result of microbial degradation. The interactions of oil with aquatic organisms are complex, involving bioaccumulation, distribution in the organism, metabolism and elimination. Different compounds within oil are accumulated and metabolised differently depending on their chemical properties. These processes determine the toxic impacts of the oil. There are also large differences between biological taxa in their metabolising capacities. The toxicity of oil has been reviewed recently (RSC 2015), but is summarised briefly here to provide a rationale for the subsequent monitoring guidance.

The impacts that the processes involved in oil weathering have on toxicity are currently unknown, and are the subject of scientific debate. Weathering has been reported to decrease toxicity because it decreases the relative proportion of volatile compounds that cause toxicity via narcosis (Di Toro et al. 2007). Other reports state that weathering increases toxicity because it increases the proportion of PAHs (Carls et al. 1999), which

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**Table 2.5. Example of an expected fate matrix for different spilled oils**

<table>
<thead>
<tr>
<th>Fate process</th>
<th>Light</th>
<th>Medium</th>
<th>Heavy</th>
<th>Extra heavy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spreading</td>
<td>Rapid</td>
<td>Rapid</td>
<td>Moderate-rapid</td>
<td>Slow-moderate</td>
</tr>
<tr>
<td>Evaporation</td>
<td>High</td>
<td>Moderate</td>
<td>Moderate-low</td>
<td>Low-none</td>
</tr>
<tr>
<td>Dissolution</td>
<td>Slight</td>
<td>Slight</td>
<td>Slight</td>
<td>Little</td>
</tr>
<tr>
<td>Dispersion</td>
<td>High</td>
<td>Moderate–high</td>
<td>Moderate–slow</td>
<td>Very slow</td>
</tr>
<tr>
<td>Emulsification</td>
<td>Slight</td>
<td>Moderate</td>
<td>Moderate–high</td>
<td>High</td>
</tr>
<tr>
<td>Sedimentation</td>
<td>Low</td>
<td>Little</td>
<td>Moderate–little</td>
<td>Moderate</td>
</tr>
<tr>
<td>Biodegradation[^a]</td>
<td>Not important</td>
<td>Potentially</td>
<td>Potentially</td>
<td>Important</td>
</tr>
<tr>
<td></td>
<td></td>
<td>important</td>
<td>important</td>
<td></td>
</tr>
<tr>
<td>Photooxidation</td>
<td>Little</td>
<td>Little</td>
<td>Little</td>
<td>Little</td>
</tr>
</tbody>
</table>

[^a]: Long-term process – see also Fig. 2.3
Table 2.6. Examples of obvious or significant weathering and response-related characteristics of different spilled oils

<table>
<thead>
<tr>
<th>Water temperature (°C)</th>
<th>12</th>
<th>15</th>
<th>25</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind speed (kn)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oil type</td>
<td>Diesel</td>
<td>IFO</td>
<td>Diesel</td>
<td>IFO</td>
</tr>
<tr>
<td>Time (h)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>98</td>
<td>99</td>
<td>59</td>
<td>96</td>
</tr>
<tr>
<td>6</td>
<td>87</td>
<td>95</td>
<td>8</td>
<td>89</td>
</tr>
<tr>
<td>12</td>
<td>75</td>
<td>90</td>
<td>0</td>
<td>85</td>
</tr>
<tr>
<td>24</td>
<td>62</td>
<td>86</td>
<td>0</td>
<td>81</td>
</tr>
<tr>
<td>48</td>
<td>51</td>
<td>83</td>
<td>0</td>
<td>78</td>
</tr>
<tr>
<td>72</td>
<td>46</td>
<td>81</td>
<td>0</td>
<td>77</td>
</tr>
<tr>
<td>96</td>
<td>44</td>
<td>79</td>
<td>0</td>
<td>76</td>
</tr>
</tbody>
</table>

*This example is for 1 tonne marine diesel (API = 38°) or marine IFO 180 (API = 14.7°) spilled into the sea (offshore, so no beach stranding), with percentages remaining at defined times for different water temps (°C) and wind speed (kn), based on ADIOS2 Model outputs*
Box 2.1. The influence of oil composition on its environmental fate

An example of the effect of oil type and location on the longevity of a spill is the comparison between the Exxon Valdez and Deepwater Horizon spills (Atlas and Hazen 2011). The Exxon Valdez in 1989 spilled ~40 million litres of Prudhoe Bay crude oil (API = 27°) into the cold water of Prince William Sound, a relatively enclosed inlet with extensive rocky shoreline. In contrast, the Deepwater Horizon spill in 2010 released ~20 times that amount of light Louisiana crude (API = 35.2°) into the warm offshore waters of the Gulf of Mexico. It has been estimated that up to 20% of Exxon Valdez oil may have evaporated, while around 40% was stranded and subsequently relied on physical removal and biodegradation for remediation (Table 2.7) (Wolfe et al. 1994). It is still possible to find relatively fresh oil buried in sediments today reflecting the lack of conditions conducive to natural removal.

Table 2.7. Provisional mass balance for Exxon Valdez oil after 3 years

<table>
<thead>
<tr>
<th>Fate</th>
<th>Estimate</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subtidal sediments</td>
<td>0.13</td>
<td>0.08</td>
<td>0.16</td>
</tr>
<tr>
<td>Floating</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Beached</td>
<td>0.02</td>
<td>0.001</td>
<td>0.04</td>
</tr>
<tr>
<td>Recovered</td>
<td>0.14</td>
<td>0.12</td>
<td>0.18</td>
</tr>
<tr>
<td>Dispersed</td>
<td>&lt;0.01</td>
<td>0</td>
<td>0.01</td>
</tr>
<tr>
<td>Water column oxidation</td>
<td>0.5</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>Evaporation</td>
<td>0.2</td>
<td>0.18</td>
<td>0.25</td>
</tr>
</tbody>
</table>

*From Wolfe et al. (1994)

Fig. 2.9. Estimates for the initial fate of oil spilled from the Deepwater Horizon based on an estimated release of 4.9 million barrels of oil (Source: adapted from Lubchenco et al. 2010). Residual oil includes oil that is just below the surface as light sheen and weathered tar balls that have been washed ashore or been collected from the shore, or is buried in sand and sediments.
In contrast, the *Deepwater Horizon* spill experienced greater levels of evaporation and dispersion (both natural and chemical – no chemical dispersants were used in the *Exxon Valdez* spill), as well as rapid biodegradation due to more favourable conditions and a pre-adapted microbial population due to significant numbers of natural hydrocarbon seeps in the area (Atlas and Hazen 2011; Lubchenco *et al.* 2010). Long-term studies into the persistence of *Deepwater Horizon* oil are yet to be published, but from initial estimates of the spill budget, it would appear less than 26% ultimately became stranded (Fig. 2.9). Subsequently there have been strandings of *Deepwater Horizon* oil, mostly in the form of tar balls (Hayworth *et al.* 2015).

Oil from both spills was subjected to evaporation, dispersion and biodegradation, but the rates at which these occurred was very different. In the case of the *Exxon Valdez*, the large amount of stranded oil and its heavy nature meant it became incorporated into sediments and, coupled with cold temperatures and a less adapted micro-fauna, this resulted in slow rates of biodegradation. In contrast, following the *Deepwater Horizon* spill, the type of oil, offshore nature of the spill, warm water, high level of dispersion and a pre-adapted microbial population led to high rates of natural attenuation, such that within 2–3 weeks, water column concentrations of hydrocarbons were largely diminished (Atlas and Hazen 2011). Thus the fate and persistence of an oil spill will not just be a result of the volume spilled but will be influenced by a range of factors such as type of oil, the environment in which it is spilled and prevailing conditions at the time.

have been associated with toxic effects that occur via other modes of action and human carcinogenesis. Recent studies have shown that UV interactions with PAHs can dramatically increase toxicity to translucent embryos and larvae (Alloy *et al.* 2015), and that the oxygenated PAHs can cause developmental toxicity (Barron *et al.* 2003; Adams *et al.* 2014; Lin *et al.* 2015). The impacts of photoactivated and oxygenated PAHs on other life stages and organisms, including corals, are currently unknown.

The accumulation of various compounds from oil is determined by their solubility in water, the chemical composition and phase of the oil, as well as by the uptake and exposure pathways of the organism. Behavioural responses such as contaminant avoidance may also limit exposure. All parameters that contribute to accumulation and toxicity should be considered in the recovery phase monitoring program.

If oil coats the tissues of an organism (e.g. when a bird crosses the air:water interface or when intertidal organisms are coated by a receding tide), there is typically greater uptake because the constituents of oil do not have to be water soluble, nor does the water act as a diffusive barrier. Compounds are taken directly into the tissue of the organism, often causing overt toxicity. Also, the oil coating can prevent gas exchange, effectively smothering the organism. Following spills of heavy oils, such as in the *Erika* and the *Prestige* events, smothering was thought to have a greater deleterious impact than overt toxicity, especially for birds at sea and on shorelines (F.X. Merlin *pers. comm.*).

Weathered oil may cause fewer effects via toxicity because the more water-soluble components are removed (Di Toro *et al.* 2007), but it could cause greater impacts via smothering because the viscosity of the oil increases and, as a consequence, the likelihood that it will form a sticky, gas-impermeable coating also increases (e.g. Michel and Rutherford 2014). Because of the uncertainty regarding the impacts of weathering on oil toxicity, a monitoring program should be undertaken if oil impacts are anticipated.
2.3.1 Narcotic toxicity

Many constituents of oil, including the aromatic compounds, behave as narcotic compounds. Narcosis has been defined as non-specific reversible disturbance of the functioning of a cell membrane, caused by the accumulation of the pollutants in hydrophobic lipid phases within the organism (van Wezel and Opperhuizen 1995). Many compounds associated with oil are primarily taken up by diffusion across gills in larger organisms or across the cutaneous layer in smaller organisms (Escher and Hermens 2002), especially after short exposure periods. These compounds rapidly accumulate into organisms until they reach an equilibrium predicted by their physical properties. Bioaccumulation of petroleum hydrocarbons, most notably PAHs, is influenced by the rate at which the organisms can metabolise and detoxify the chemicals. At high PAH concentrations, organisms with efficient xenobiotic metabolism, including fish, can succumb to narcosis. The bioavailability and, as a consequence, the narcosis-derived toxicity of oil-associated compounds has been estimated from the solubility of the compound in water and its octanol:water partition coefficient, log $K_{ow}$ (the degree to which the compound partitions to octanol over water) (Di Toro et al. 2007). For some organisms, such as amphipods, the narcosis-based toxicity of PAHs is well predicted by critical body residues (or body burdens) (Landrum et al. 2003; Meador 2006). Typically, smaller organisms reach equilibrium with their environment more quickly, meaning that they are most likely to succumb to the effects of narcotic chemicals (Escher and Hermens 2002). Furthermore, measuring the body burdens of sessile filter-feeding invertebrates (such as bivalves and sponges) is an effective way to integrate water column concentrations and has been used in this way in previous spills (see Box 2.2) (Boehm et al. 2007; Batista et al. 2013). Importantly, the uptake of narcotic compounds is reversible, and compounds causing narcosis are quickly lost once organisms are in clean water (Escher and Hermens 2002).

The results of accumulation of narcotic compounds can include altered behaviour, slowed movement, morbidity and death. These compounds are most likely to be low molecular weight aromatics (Di Toro et al. 2000), which are most prevalent in unweathered oil and refined petroleum products (NRC 2005). These impacts will be most acute for plankton and other organisms that have high surface area to volume ratios. It is these impacts that are typically measured in acute toxicity tests and are easily modelled (Di Toro et al. 2000, 2007), and would be anticipated to occur within hours of an oil spill.

2.3.2 Developmental impacts

Some components of petroleum, including tricyclic PAHs and some other aromatic compounds, have been shown to disrupt normal developmental processes in fish (Fig. 2.10) (Colavecchia et al. 2004; Incardona et al. 2004, 2013, 2014). Exposure to oil can alter the normal formation of the heart in fish embryos exposed to less than 1 µg/L of PAHs in weathered oil dominated by tricyclic and alkyl PAHs (Jung et al. 2013; Incardona et al. 2014). These impacts would be expected to occur following short exposures (Greer et al. 2012), but the mortality associated with impact may not occur immediately and may instead occur post-hatching (Ingvarsdotir et al. 2012). Other changes in heart function occur in juvenile and adult fish exposed to concentrations of oil in the µg/L range (Mager et al. 2014). Most of the work that has investigated these cardiac-mediated developmental impacts has focused on vertebrates. It is not known whether invertebrates are equally sensitive to oil exposure as embryos, but laboratory tests suggest that they are less sensitive, with higher EC$_{50}$ values (concentrations that impact 50% of the population) (e.g. Negri and Heyward 2000; Rial et al. 2014).
2.3.3 Phototoxicity

Many PAHs and the unresolved compounds in residual fuel oil are activated by UV light (e.g. Hatlen et al. 2010, Incardona et al. 2012b, Alloy et al. 2015), which greatly increases their toxicity. For example, fish embryos exposed to fuels oils (but not crude oil) and sunlight experience rapid tissue damage via a cell destruction mechanism that was not observed in exposures in the dark (Hatlen et al. 2010). As discussed previously, the very high levels of mortality observed following the Cosco Busan oil spill in San Francisco Bay were attributed to photoactivation of the residual components within bunker fuel oil (Incardona et al. 2012b). Also, fish embryos exposed to petroleum hydrocarbons via produced formation waters did not produce pigments normally (Meier et al. 2010), meaning that exposure to petroleum and UV light would not have to be concurrent to cause deleterious effects. Since this increased toxicity is a function of both the PAHs and the intensity of UV irradiance, this may have particular relevance for tropical areas of Australia, as well as Antarctica.

Exposure of other oil components to photoactivation seems to cause a different suite of developmental impacts. For example, following the 2007 Cosco Busan oil spill in San Francisco Bay, oil was deposited on the shorelines, which are a spawning habitat for Pacific herring (Incardona et al. 2012a). Traditional oedema and cardiac toxicity was observed, along with elevated rates of tissue necrosis (injury resulting in premature death of cells). The authors hypothesised that the tissue necrosis was a results of exposure to the ‘residual’ component of oil that is elevated in Bunker fuel oil (Incardona et al. 2012a). In laboratory exposures, both exposure to weathered bunker fuel oil and UV-mediated photoactivation were required to generate similar morphological impacts (Incardona et al. 2012b). These impacts would be expected to occur more often with weathered oil.

2.3.4 Metabolism of oil

The degree to which components of oil are stored in an organism’s tissues depends on the organism’s capacity to break down the components within oil. Most vertebrates have a highly efficient capacity to metabolise oil (Whyte et al. 2000). Once accumulated, PAHs and other water-insoluble compounds are rapidly excreted following metabolism to more water-soluble compounds, by the addition of oxygen and other functional groups that make these compounds water soluble, and able to be eliminated. This process is carried out by a variety of different phase I and phase II enzymes (Livingstone 1991).

As a consequence of their capacity to metabolise oil, vertebrates rarely have elevated body burdens (concentrations of the contaminant within tissues) of oil, and exposure can
be best estimated instead by measuring the concentrations of biliary metabolites (see Section 7.4). For vertebrates that metabolise PAHs, the amount of PAHs accumulated in the organism’s tissues does not predict toxic impact (Meador 2006).

Marine invertebrates have a lower capacity to metabolise accumulated PAHs (Snyder 2000), and this can vary greatly, even between closely related organisms (Lotufo 1998). However, those invertebrates that metabolise PAHs can also excrete them rapidly (Lotufo 1998). Although recent advances in molecular biology have identified many of the enzymes involved in metabolising organic compounds, in numerous different taxa of marine invertebrates, these enzymes break down a broad spectrum of compounds, including naturally occurring steroid hormones and fatty acids. The function, inducibility and efficiency of these recently identified enzymes are unknown (Rewitz et al. 2006). Because many invertebrates do not metabolise oil efficiently, the body burdens of poor metabolisers can be used to integrate water column PAH concentrations, as described in Box 2.2.

2.3.5 Trophic transfer of oil
Compounds within oil can also be accumulated with food via trophic transfer (i.e. from lower trophic level organisms to ones higher up the food chain). Because oil can be rapidly metabolised by fish and other vertebrates, it does not biomagnify in the manner of methylmercury and other persistent organic pollutants. It can be accumulated via trophic transfer, however, and large animals that consume lots of invertebrates (e.g. tuna that ingest squid) could potentially get doses of PAHs via trophic transfer. For example, once oil is accumulated in algae it is passed to the microzooplankton that prey on them (Wolfe et al. 1998b). Zooplankton have been shown to ingest oil droplets and accumulate PAHs from them (Almeda et al. 2013, 2014c). Deposit-feeding invertebrates can also accumulate PAHs from the sediment they ingest (e.g. Rust et al. 2004). PAH metabolites have also been shown to be passed between trophic levels in invertebrates (Carrasco Navarro et al. 2013). Trophic transfer has been shown to be an important source of oil to bird populations, (Velando et al. 2010), and could presumably be important for other carnivores that ingest sediment-dwelling invertebrates.

2.3.6 Chronic toxicity of oil
Since PAH metabolites can bind to DNA and other macromolecules within a biological cell, PAH metabolism can increase the potential for deleterious effects. A schematic diagram of this process is shown in Fig. 2.11. For instance, following the grounding of the Sea Empress in Milford Haven, Wales, UK, DNA adducts were measured in several fish species, as well as in a suspension-feeding sponge (Halichondria panicea) and the filter-feeding mussel Mytilus edulis (Harvey et al. 1999). Although the invertebrates would have been expected to accumulate oil, only the vertebrates showed elevated concentrations of adducts formed with DNA (Harvey et al. 1999). However, invertebrates do have some capacity to metabolise oil (Trisciani et al. 2012) and have shown elevated concentrations of DNA adducts in other scenarios (Bocquene et al. 2004).

The impacts of ongoing exposure of fish to petroleum-derived hydrocarbons has been reviewed recently by Collier et al. (2013) and will be only briefly discussed here. Most of the long-term impacts of PAHs on fish health arise from the metabolism of PAHs and the formation of reactive metabolites, as described above. Exposure to these reactive intermediates over time can have a myriad of health consequences that could potentially impact fish populations. Fish exposed to PAHs over prolonged periods experience increased neoplasia and tumour incidence resulting from damage to DNA and other macromolecules,
decreased reproductive success and immune capacity, as well as decreased growth rates and lipid stores (reviewed in Collier et al. 2013). Some examples of long-term health effects include increased incidence of tumours and other lesions, which are most often found in fish exposed to contaminated sediments in urbanised environments, such as winter flounder in the US or European flounder (Moore et al. 1996). Decreased potential for reproductive success was shown by reduced gonadal development, and markers for ovarian maturation were reduced in killifish from urbanised environments with elevated PAH concentrations in sediments (Pait and Nelson 2009; Bugel et al. 2010). Metabolism of these compounds may come at a metabolic cost. Fish collected from contaminated estuaries (Amara et al. 2007) or from areas contaminated by the Erika oil spill (Gilliers et al. 2006) had decreased condition factors and lipid stores. Fish exposed to heavy fuel oil in laboratory studies had reduced expression of immune system genes (Nakayama et al. 2008) and increased susceptibility to pathogens (Bravo et al. 2011). There is also emerging evidence that the changes caused by PAH exposure may be inherited (e.g. Fang et al. 2010).

Since the bioavailability and toxicity of oil changes as it is exposed to air and light, the weathering of a crude oil may decrease its toxicity because the most water-soluble (and hence most bioavailable) compounds are quickly volatilised (as discussed in Section 2.3.1) (Di Toro et al. 2007). Alternatively, weathering of crude oil may increase its toxicity because of the creation of highly reactive and thereby toxic, oxygenated PAHs (e.g. Kang et al. 2014). These oxygenated PAHs would cause toxicity by the same mode of action as depicted in Fig. 2.11 for PAH metabolites.

### 2.3.7 Indirect effects

There can be indirect impacts of oil release on dissolved oxygen concentrations in waters. As described in detail in Section 2.2 (and in Box 7.5), components of oil are rapidly
metabolised by aerobic bacteria. This metabolism can cause local oxygen depletion (Hazen et al. 2010) and, as a consequence, indirect toxic effects. These impacts would be seen in both water and sediment and are most likely to occur with fresh oil, because it is the alkanes and low molecular weight aromatic compounds that are rapidly degraded.

There may also be indirect effects of oil on marine ecosystems where the spilled oil changes normal trophic dynamics. If the release of oil kills zooplankton, for example, there may be an increase in phytoplankton populations, or an increased risk of starvation for larval fishes and other meroplankton (organisms that have one planktonic life stage) (reviewed by Fleeger et al. 2003).

### 2.3.8 Summary
The complex mixture of constituents in crude oil may cause toxicity, or a decline in the health of aquatic organisms following their exposure. There is debate in the literature as to the primary causative agent(s) of toxicity, with some authors claiming that acute

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**Box 2.2. Using bivalve body burdens to predict water column oil concentrations**

Taking spot water column samples for TPH and PAH analysis can be problematic because oil concentrations can be patchy in both time and space (Durell et al. 2006). Semi-permeable membrane devices (SPMDs) are commonly used to concentrate contaminants out of the water column for chemical analysis, but these can contain detectable levels of naphthalene and other low molecular weight PAH contaminants before they are deployed into the field, making field detection of low levels of these contaminants difficult (Durell et al. 2006).

Because bivalves accumulate oil from the water column and from particles without metabolising it, the oil body burdens of mussels have been used as part of oil monitoring programs to detect exposure to produced waters during routine operations (Widdows et al. 1995; Durell et al. 2006) and to estimate water-column oil concentrations following spills (Neff and Burns 1996; Boehm et al. 2007; Payne et al. 2008). Bivalves can be used as monitors in parallel with SPMDs because their uptake proportionally integrates water column contaminant concentrations over an exposure period.

Following the 1989 Exxon Valdez oil spill, concentrations of PAHs in the water column were extrapolated from concentrations of hydrocarbons measured in mussels, using the lipid concentration of the organism and the log $K_{ow}$ of each PAH (Neff and Burns 1996; Boehm et al. 2007; Payne et al. 2008). Based on the mussel body burdens, initial water column concentrations were on average 3.4 µg/L of total PAHs (TPAHs), but were expected to be highly variable (Boehm et al. 2007). These concentrations were also found to decrease within a year to values comparable to those found at un-oiled sites (Boehm et al. 2007). Long-term ecological monitoring of Prince William Sound (Alaska, USA), used concentrations of oil in mussel tissues to predict that minimal exposure to dissolved oil would occur from 1998 onwards (Payne et al. 2008). From this point onward, all oil concentrations were low and changes in TPAHs occurred at the same time across the Sound, including in areas that were not impacted by the spill, showing a return of the system to baseline concentrations. However, in the Port of Valdez, the influence of input from treated ballast water from the Alyeska marine terminal was discernible using the mussel body burdens. It was also possible to identify two small-scale diesel spills by examining bivalve tissue concentrations.
responses can be predicted by the PAH composition (e.g. Di Toro et al. 2000), and others claiming that the concentrations of total petroleum hydrocarbons are a better predictor of acute effects (Barron et al. 1999). The toxic effects will also vary depending on the type of oil spilled. Lighter oils or refined products, with a higher proportion of volatiles, will be more likely to cause narcotic or baseline toxicity and less likely to coat surfaces (Martinez Gomez et al. 2010). Heavy, denser oils are more likely to coat surfaces and to sink, and to cause long-term damage to ecosystems (Martinez Gomez et al. 2010). The toxic impact of oils is also likely to be dose-dependent, with narcosis occurring at high concentrations, and reproductive and developmental impairment and other chronic impacts occurring at lower doses (Meador 2006). In addition to these direct toxic impacts, there could be indirect effects associated with oxygen depletion or trophic cascade effects where recruitment is affected by a reduced abundance of prey available at a critical time period.

2.4 Effects of oil in marine habitats

More specific guidance on the sensitivity of Australian marine habitats and the organisms they contain to the toxicological impacts of oil is provided below. Where possible, this guidance has focused on either field-scale release of oil or previous oil spills, and is provided for representative habitat types. The summary below does not, however, precisely match the Australian environment since it is derived largely from previous spills, and in some cases, the environmental conditions are quite different.

2.4.1 Organisms in open ocean environments

Oceanic waters

Open waters, the areas most likely to be impacted by an oil spill, are habitats for a diverse array of marine organisms. These organisms include plankton (organisms that cannot propel themselves against currents and tides) as well as fish, reptiles, and mammals. The impacts of oil on the wildlife that inhabit oceanic waters are discussed in subsequent sections, while the potential hazards of water-borne oil exposures to different types of plankton, as well as to fish, are discussed in the paragraphs below.

Phytoplankton

Phytoplankton (including microalgae) are photosynthetic organisms, consisting mainly of free-floating algae, protists and cyanobacteria. They are an ancient and extremely diverse group, and are a composite group based on functional similarity as opposed to taxonomic relatedness. This is an extremely important group from an ecological standpoint, because phytoplankton not only comprise the base of the marine food chain but they also produce 45% of global oxygen (Falkowski et al. 2004). Phytoplankton abundance is typically limited by light and nutrient availability. Different species have different growth rates, but these can be very rapid (Falkowski et al. 2004; Parker et al. 2008).

Typically, phytoplankton are not sensitive to the impacts of oil (Hook and Osborn 2012; Echeveste et al. 2010), but they may be sensitive to the response strategy used, such as dispersants (Hook and Osborn 2012). Furthermore, phytoplankton would be expected to respond rapidly to any nutrients added as part of a bioremediation response (which is why nutrient amendment to the water column is typically considered to be ineffective (Prince et al. 2013)). Although phytoplankton are not sensitive to oil, they do accumulate it rapidly because of their small size and high surface area to volume ratio, and can pass oil onto the animals that consume them (Wolfe et al. 1998a,b).
Zooplankton

Zooplankton are also a diverse array of different taxonomic groups, including ciliates, rotifers and microcrustaceans. These can include organisms that are planktonic for their entire life history or for just one life stage. Typically, zooplankton eat either phytoplankton or other zooplankton, but can be a food source for a myriad of organisms, including the early life stages of fish, some adult fish, as well as larger organisms including whale sharks and baleen whales (Mauchline 1998). Copepods (microcrustaceans) are planktonic for their entire life history and are among the most abundant animals on Earth. They are biogeochemically important because they are primary consumers, and transport carbon from the surface waters to the deep sea via their fecal pellets (Mauchline 1998).

As a result of their small size and high surface to volume ratio, most zooplankton will rapidly accumulate oil from the water column via diffusion. Some zooplankton (especially those in Antarctic regions) have a high lipid content, meaning that they will accumulate comparatively high amounts of oil. Zooplankton can also accumulate oil via ingestion of phytoplankton (Wolfe et al. 2001) or dispersed oil droplets (Almeda et al. 2013). However, consumption of zooplankton by fish does not appear to be an efficient means of trophic transfer, perhaps because of the metabolism of oil constituents (Wolfe et al. 2001).

Copepods and microbial eukaryotes (membrane-bound cells containing a nucleus), such as ciliates and rotifers, are all sensitive to the impacts of oil exposure (Hansen et al. 2012; Almeda et al. 2014a). Exposure can cause immediate mortality, as well as lethality that occurs after exposure has ended and the animal has been transferred to clean water (Olsen et al. 2013). Declines in egg production and hatching rates, as well as swimming speeds, have also been reported (Hansen et al. 2015; Cohen et al. 2014).

Planktonic eggs

Some corals, fish and other marine organisms are broadcast spawners, meaning they release eggs into the water column to be fertilised. These eggs then stay in the upper layers of the water column while the embryo develops (Tanaka and Franks 2008). Although eggs are positively buoyant (meaning that they float), they do not stay at the sea surface micro-layer. Instead, they are mixed into the water column above the thermocline by wind, waves and currents (Tanaka and Franks 2008). The size of these eggs, their lipid content, and the amount of time that they stay in the water column before hatching can vary dramatically, even between closely related species. Eggs would not be expected to be in the water column all year round, so, ideally, baseline monitoring would identify when important species are spawning, and when their eggs would be encountered in surface waters. This seasonal information could be used to inform risk analysis. Recent model predictions of oil spill scenarios in Norway estimated that between 0.5 and 10% of Arctic cod embryos would be exposed to potentially lethal concentrations of PAHs, depending on the time and location of the spill (Vikebo et al. 2014).

Because of their small size and high lipid content, eggs accumulate petroleum hydrocarbons from the dissolved phase very rapidly. These compounds can then have profound impacts on embryo development. Fish embryos in particular are very sensitive to dissolved oil, with lethal impacts occurring at TPAH concentrations as low as 0.5 µg/L (Incardona et al. 2014). Impacts may occur during exposure, or may occur following transfer to clean water (Ingvarsdottr et al. 2012). Impacts have been shown to occur following hours of exposure (Greer et al. 2012). Furthermore, since the exposure alters the formation of the heart in vertebrates, even following transfer to clean water, the physiology of the organism may be permanently impacted. Fish that survive the initial oiling had decreased swim-
ming speeds and a decreased ability to capture prey and escape from predators (Hicken et al. 2011). This altered heart morphology may have contributed to the decreased returns of pink salmon from oiled spawning areas following the Exxon Valdez spill (Heintz et al. 2000).

The eggs of invertebrates (which can have a different heart morphology or no heart at all) have also been shown to be sensitive to exposure to PAHs (Bellas et al. 2008). For example, Negri and Heyward (2000) showed decreased fertilisation and metamorphosis in coral embryos exposed to oil. Fertilisation success in sea urchins has also shown to be inhibited by exposure to oil (Rial et al. 2014).

Exposure to UV light may exacerbate the impacts to all classes of plankton. Some Australian waters receive high amounts of UV radiation, and in low nutrient waters (and hence low particle content) the UV radiation may penetrate beyond the upper few metres. As noted earlier (Section 2.2.3), UV irradiation has been shown to increase the toxicity of some PAHs and other aromatic compounds via a process known as photoenhanced toxicity. This can increase the toxicity of PAHs by as much as an order of magnitude for meroplankton, such as crab larvae (Alloy et al. 2015), and for fish embryos (Hatlen et al. 2010).

**Meroplankton**

Meroplankton are animals such as coral, sea urchins, decapods crustaceans and some worms that are planktonic for one stage (typically larvae) of their life history. These can include larvae of economically important species such as coral trout, pearl oyster or rock lobster. Like other zooplankton, meroplankton will take up oil from the water column via passive diffusion, or ingest oil with their foods or by ingesting oil droplets directly (Almeda et al. 2014b). These larval stages can be very sensitive to oil. In laboratory studies, exposure to 1 µg/L concentrations of PAHs has been shown to inhibit settlement of sponge larvae (Cebrian and Uriz 2007).

Assessment of the pre- and post-impact planktonic community should best be done as described in Appendix N.

**Fish**

Fish are an economically and ecologically important component of marine systems. Following a marine incident, there will also be a great deal of concern about whether fish caught from the impacted area are safe to eat, and for the potential loss of revenue from fishing (both commercial and recreational). In addition, decreased tourism from recreational fishing can contribute to the socioeconomic impacts of an oil spill (Fitzgerald and Gohlke 2014). For example, polls conducted after the Deepwater Horizon wellhead blowout found that about half of the people surveyed had reduced the amount of Gulf-caught seafood they were consuming. However, once the fisheries had reopened, few samples of fish were found to contain harmful concentrations of PAHs, and any elevated concentrations were shown to have originated from pyrogenic (combustion) not petrogenic (oil spill-related) sources (Fitzgerald and Gohlke 2014).

Fish can accumulate components of oil either via diffusion across their gills or via trophic transfer. Comparatively high concentrations of dissolved petroleum hydrocarbons are required to cause outright mortality of fish. No reports of oil spills in open water systems causing fish kills (e.g. mass fish mortality events attributable to oiling) could be found, although deaths of aquaculture salmon (in high densities of animals confined to pens) have been reported (Law and Kelly 2004). Exposure to oil in the field may have other impacts, as briefly discussed below. Also, once oil is accumulated by vertebrates, it is
rapidly metabolised and excreted, meaning that body burden is an unreliable means of estimating exposure to oil. Responders are instead encouraged to use biomarkers of physiological change (discussed in more detail in Section 7.4).

Fish that accumulate oil via trophic transfer may also experience compromised health. This may be best illustrated using laboratory studies, because in field-based studies, the exposure route to the fish is uncertain. Salmon exposed to PAHs in their diet had decreased levels of plasma triglycerides and lipase when exposed to low PAH concentrations and reduced total body lipids and triglycerol at higher levels (Meador et al. 2006). Rainbow trout that accumulated PAHs via their laboratory diet had a reduced capacity to withstand a disease challenge (Bravo et al. 2011).

Although organisms in oceanic waters are sensitive to oil, effects in these environments could be limited. Even following a large release of oil, dissolved exposures are expected to be transient because that oil will be mixed into the water column by wind, waves and currents and dissipate within a period of hours to days. Most plankton have fast growth rates and a widespread distribution, so recruitment back into these populations would be expected to be rapid. Fish may also avoid oiled areas (Rooker et al. 2013).

Because of density-dependent recruitment, although fish embryos are very sensitive to oil in the laboratory, effects on populations as a whole are difficult to quantify, especially when coupled with natural variability and other oceanographic variables (Rooker et al. 2013; Fodrie et al. 2014). As a consequence, open-water habitats are considered to have low sensitivity to oil and clean-up technologies, although there may be lasting impacts from short exposures, especially during reproductive phases. Sub-lethal impacts from 24-h exposure of fish to petroleum via the water column included changes in cardiac performance (Mager et al. 2014), which could affect predator:prey interactions. Depletion of zooplankton could also affect early life-stage mortality of fish (e.g. Letcher et al. 1996). Potential changes in the abundance of zooplankton and changes to recruitment of fisheries species should be carefully monitored following a large-scale release of oil in open ocean waters.

Impacts of oil exposure on fish as food items can be assessed as described in Appendix L. Sub-lethal impacts could be described as assessed in Appendix M.

Deep-sea sediments

Because of the vast scale of oceanic waters and the dilution that would be expected to occur, very little oil would be expected to be deposited in deep-sea sediments following a surface spill. However, as oil particles (either chemically or naturally dispersed) get heavier as alkanes and aromatics contained within the oil degrade, some oil would be expected to sink and be deposited in the deep sea. The amount of oil deposited in sediments, however, would be much smaller than in surface waters. Oil is transported into deep-sea sediments via sedimentation of droplets (which adhere to other particles), direct sinking and transport via fecal pellets (Montagna et al. 2013; NRC 2014; Gong et al. 2014; Sørensen et al. 2014). This amount would be greater for a deep-sea wellhead blowout than for a surface spill. For example, there were reports of oil being deposited in deep-sea sediments following the Deepwater Horizon blowout (Valentine et al. 2014; Chanton et al. 2015), but the contribution of natural seeps in the area was uncertain. Oil deposited in the deep sea may have detrimental impacts on deep-sea marine life (Fisher et al. 2014). Following the Deepwater Horizon blowout, a loss of biodiversity was measured in deep-sea sediments around the wellhead. The most severe losses occurred within 3 km of the wellhead, but reported losses in biodiversity associated with elevated TPHs and PAHs were measurable as distant
as 17 km (Montagna et al. 2013). However, active seeps were measured in the study area (JAG 2010), and any contribution of these natural petroleum inputs towards differences in biodiversity is not known. These losses could be correlated with TPH and TPAH concentrations in the sediments. In addition, surveys conducted in the Gulf of Mexico in 2011 found an increased incidence of skin lesions in bottom-dwelling fish (Murawski et al. 2014). This increased prevalence of lesions correlated with an increased incidence of biliary PAH metabolites, but not to temperature, salinity or any known disease outbreak. The incidence of disease had returned to normal by 2012 (Murawski et al. 2014).

Although the amount of oil transported into deep-sea sediments from a surface spill is likely to be small, recovery times in the deep sea are likely to be slow because of slow growth of biota and low levels of recruitment (Montagna et al. 2013). Deep-sea environments would be considered highly sensitive but unlikely to be impacted by a surface spill, such as would occur from a typical shipping accident. Following the Exxon Valdez oil spill, impacts on biota living in waters deeper to 40 m were expected to be negligible (O’Clair et al. 1996).

Impacts in sub-sea habitats could be assessed as described in Appendix P.

**2.4.2 Organisms in nearshore environments**

**Subtidal habitats**

As a generalisation, subtidal habitats are generally less susceptible to the impacts of oil than intertidal habitats, because they are physically separated from the sources of oil at the sea surface and oil does not strand in them, as it does for intertidal and coastal habitats. Nevertheless, oil particles may sediment out and sink, transferring the material to the deep sea (Gong et al. 2014; Montagna et al. 2013; NRC 2014; Sørensen et al. 2014). In shallow water (less than 30 m deep), depending on surface slick volumes, wave energy and water column exchange rates, dissolved or dispersed oil or chemically dispersed oil may form initial concentrations sufficient to cause an impact. However, dilution rapidly resolves this over hours (Lee et al. 2013). Oil may also be washed from intertidal to subtidal environments during shoreline clean-up operations. Guidance is provided on the sensitivity of different nearshore subtidal environments in the sections below. The impacts of oil exposure on the plankton and fish that inhabit these environments has been provided earlier. All of these environments could be surveyed as described in methods for sampling the intertidal and subtidal benthos.

**Toxic effects of oil on benthic marine invertebrates**

Benthic marine invertebrates are an extremely diverse group, comprised of many different taxonomic groups, with different life histories and ecological niches. These organisms could take up oil via diffusion from the dissolved phase, ingestion of contaminated food items, and contact with contaminated sediments. Although marine invertebrates are distributed throughout the ocean floor, they would not be likely to be exposed to appreciable amounts of oil from a surface spill except in nearshore environments, which is why the guidance on toxicological impacts is given here. This guidance is focused primarily on bivalves and crustaceans – the best studied taxa – and additional guidance on coral is provided in the sub-section on coral reefs.

Small invertebrates (micro- and meiofauna) will be very susceptible to the narcotic effects of oil because of their high surface area to volume ratio. As a consequence, disappearance of benthic crustaceans from sediments is often considered an indicator of impact (Gomez Gesteria and Dauvin 2005). These narcotic impacts can not only cause outright mortality of organisms, but also decreases in rates of reproduction (Hook et al. 2014b).
As discussed in Section 2.2.4, although the capacity of invertebrates to break down organic contaminants is less than that of vertebrates, they do have some capacity to metabolise PAHs (Trisciani et al. 2012), and as a consequence do accumulate PAH adducts and result in oxidative damage to macromolecules from chronic exposure to oil. For instance, following the Erika oil spill (which occurred offshore of Brittany, France in December 1999), increases in DNA damage and changes in oxidative-stress markers were measured in mussels collected from the coast in the few months following the event (Bocquene et al. 2004). In addition, mussels chronically exposed to PAHs in estuarine sediments showed elevations in a variety of oxidative-stress markers (Shaw et al. 2011).

As with fish, prolonged exposure to PAHs may have a metabolic cost. For instance, amphipods exposed to the water-accommodated fraction of fuel oil have altered lipid ratios (Olsen et al. 2007). These changes may not only affect the health of the benthic invertebrates exposed to oil, but if the lipid levels of benthic invertebrates are altered, they are then not as good a food item for higher trophic level organisms that prey on them.

Exposure to oil will also have deleterious consequences for developing embryos. These effects have been reviewed previously for broadcast spawners, but exposure can also impair embryo development in organisms that brood their young. For example, the grass shrimp *Paleomonetes pugio* broods its young under its abdomen. Grass shrimp embryos exposed to sediments with elevated PAHs from highway runoff had higher incidences of DNA damage and lower hatching rates than controls (Lee et al. 2004).

### Impacts of oil on subtidal communities

Subtidal communities host a variety of algae, invertebrates and fish. The density and productivity of the communities will depend on the light and nutrients available in the area. These areas are less likely to be oiled than either surface waters or intertidal areas, and, in areas with hard substrate, oil is unlikely to be retained (Law et al. 2011). Oil may, however, be transported into deep subtidal areas by local currents. Fine sediments may retain oil, and dispersed oil may be accumulated by filter-feeding organisms at the seabed (Law et al. 2011). Amphipods, filter-feeding bivalves and urchins are thought to be among the most sensitive organisms to oil contamination in these habitats. Following oil deposition into benthic sediments, the community structure changes via the following pattern: (i) oil sensitive species (such as amphipods) are killed following exposure to oil; (ii) there is a period of low numbers of abundance and richness; (iii) biomass increases as opportunistic taxa, such as polychaetes, colonise the disturbed area; and (iv) the opportunistic species are gradually replaced by the original, oil-sensitive species (reviewed by Gomez Gesteria and Dauvin 2005). Impacts of oil exposure would be expected to be greatest in nearshore communities and in areas where recirculation is restricted, because exposure is likely to be highest.

Following the November 2002 Prestige oil spill off the Spanish coast, benthic communities along the continental shelf were surveyed (Serrano et al. 2006). Although the authors found that depth, sediment grain size, and sediment organic carbon content influenced community attributes such as richness, biomass and diversity, they did not measure any correlation with tar-ball aggregates or hydrocarbon concentrations in the sediment. However, they did note a decrease in the abundance of flatfishes, crabs and other taxa in 2003, followed by an apparent recovery in 2004.

By contrast, a survey taken after the grounding of the Aegean Sea offshore of the Galician coast in 1992 did measure changes in the benthic community structure (Gomez Gesteria and Dauvin 2005) in an embayment. This survey was conducted in shallow water (10–15 m depth, in contrast to the 70–300 m depth in the Serrano et al. (2006) study), in an
embayment as opposed to the continental shelf. The authors measured a decrease in oil-sensitive crustaceans, followed by increased recruitment of oligochaete and polychaete worms at one of the study sites (Gomez Gesteria and Dauvin 2005). They also measured decreased species abundance and a change in species composition that persisted for up to 4 years following the spill. They found that the abundance of amphipods in particular was a good indicator of oil exposure and recovery in soft-bottom subtidal communities.

Impacts of oil deposition may be greatest in subtidal areas where circulation is restricted, such as in shoals and lagoons. Shoals, or shallow areas where sediment has been deposited, often support macroalgal communities, as well as sponges and other macroinvertebrates and can be highly productive (Cohen 2012). Because water over shoals is comparably shallow, organisms here have a greater chance of being exposed to dissolved constituents than in deeper water (where these constituents will be diluted to a greater extent). Also, because shoals form where particles naturally aggregate and sediments collect, and the shallow water will slow the flow of water in this area, organisms in shoals will have a greater chance of being exposed to any sinking oil.

Lagoons can be described as shallow bodies of water separated from the ocean by a reef or island. As a consequence, lagoons tend to be low energy and have reduced circulation. If oil were to penetrate into these areas, it is likely to be persistent because of the reduced circulation, fine-grained sediments and low energy of the environment. Because lagoons are typically small, shallow and have reduced water volume for dilution, organisms in these environments would likely be exposed to high concentrations of oil. These areas can (and should) be protected from oil by damming or booming.

Guidance is provided below for specialised subtidal communities in which key biota such as kelp, seagrass, and corals contribute significantly to community structure.

Kelp forests
Kelp forests are high density areas of brown macroalgae (in Australia these are mainly *Macrocystis pyrifera* or *M. angustifolia*), notable for large leaf-like fronds. Other species include the common kelp *Ecklonia radiata*. Kelp forests are found on hard substrates in temperate and sub-polar waters of Southern Australia. These systems are typically highly productive and important nurseries for fish and shellfish.

Kelp is typically relatively resistant to oil (Dean *et al.* 1996a), but the fauna associated with it may be more sensitive. For instance, following the *Exxon Valdez* oil spill, the abundance of some macrobenthic invertebrates associated with the kelp forests declined in the year following the spill, even though the macroalgae were unchanged (Dean *et al.* 1996b). These environments would be considered moderately sensitive to oil.

Seagrasses
Seagrass meadows are dominated by at least one of 60 different flowering plant species and are typically found in shallow, sandy habitats (Edgar 2008). These form important nursery and feeding areas for many marine animals, including invertebrates, many fish, sea turtles and dugongs (Cohen 2012). Seagrass beds typically occur in areas with reduced wave energy, so oil deposited here may be persistent. Seagrasses are sensitive to oil exposure leading to decreased growth rates, smothering of leaves, changes in the chlorophyll content of leaves and reduced photosynthetic ability (Peters *et al.* 1997). Furthermore, the infauna associated with seagrass meadows may be more sensitive to oil. A 1986 oil spill at Bahia Las Minas, Panama, killed all of the infauna associated with seagrass meadows there. Only those species with high reproduction rates or a planktonic life stage recovered
quickly (Peters et al. 1997). Macroalgae were also slow to recolonise the Panamanian spill site. Following the Exxon Valdez oil spill, the abundances of epibenthic invertebrates, including crabs and sea stars, decreased in shallow subtidal environments throughout the sound (Dean et al. 1996b). They had recovered by 1991 at all habitats except the eelgrass, which showed complete recovery by 1993.

Coral reefs

Coral reefs are highly diverse marine habitats formed by the secretion of calcium carbonate structures by corals. These physical structures slow wave energy and create habitats for fish, sponges, molluscs, crustaceans and a variety of other organisms. Because of the abundance and diversity of marine life supported by these systems, they are often important for tourism and fisheries. Australia is home to two iconic UNESCO World Heritage-listed marine reefs: the Great Barrier Reef (which covers an area of 344 400 km² with several shipping corridors transecting it), and Ningaloo Reef in north-western Australia (7050 km²).

Many corals are broadcast spawners (i.e. they release their gametes and larvae into the water column) and this life stage may be especially vulnerable to spilled oil. The larvae may be directly impacted, or the chemical communication necessary for mass spawning may be interrupted (Peters et al. 1997). Corals are very sensitive to changes in water temperature, salinity and nutrients, and are typically thought of as being at risk ecosystems worldwide, due to the influence of non-oil-related pressures.

Coral that is exposed to oil may experience toxic impacts resulting from coating or smothering, as well as from exposure to dissolved oil. The health of corals may also be compromised by light reduction (which will affect the coral’s algal symbionts) from either surface slicks or as a result of increased turbidity as a consequence of clean-up efforts. Corals efficiently accumulate oil from the water column (Pie et al. 2015). Once accumulated, petroleum hydrocarbons can be persistent in corals and biologically available to the fish and other organisms that graze on them (Peters et al. 1997). Following a fuel oil spill in Micronesia, protein biomarkers of oil exposure were still elevated in coral tissue 3 months after the event, showing retention of oil for at least that period of time (Downs et al. 2006). Corals exposed to oil can show mortality as well as decreased growth rates, decreased lipid content, decreased survival of larvae, decreased gonadal development and increased bleaching (Peters et al. 1997).

Factors influencing the likely exposure of corals to spilled oil include the morphology of the coral (with branching corals being most likely exposed), the depth of the reef (with shallow reefs being most exposed to a shipping accident or other surface spill) and seasonal influences such as temperature, light intensity and reproduction (NRC 2005; Yender and Michel 2010). Following the 1986 Bahia Las Minas spill in Panama, a large decrease in total coral cover was recorded, with an increased percentage of coral colonies with recent injuries 2 years after the spill (Guzman et al. 1991). Decreased growth rates were also measured in some species, with large branching coral (which had the greatest surface area) being the most affected (Guzman et al. 1991).

Once injured, coral reefs may be very slow to recover (Guzman et al. 1994). Injured corals can be overgrown by algae or other taxa, changing the species composition in the area. Oil-exposed corals also lose their resilience (Guzman et al. 1994), making them more susceptible to the impacts of other stressors, including climate change and predation.

Corals are also believed to be especially sensitive to dispersants. Studies with coral larvae have shown greater impacts from chemically dispersed oil than from oil alone on a TPH basis (Negri and Heyward 2000; Goodbody-Gringley et al. 2013). Fertilisation and metamorphosis
were inhibited at concentrations as low as 0.1 mg/L of TPHs in chemically dispersed oil (Negri and Heyward 2000). Other studies have measured morphological changes in coral larvae exposed to dispersed oil and dispersants, but not to crude oil (Epstein et al. 2000).

As a consequence of their ecological and economic importance, their sensitivity to oil and dispersant and their slow recovery rates, coral reefs would be considered among the most sensitive of all Australian ecosystems.

**Coastal environments**

Oil will often be transported into intertidal environments by wind and currents where it can accumulate in sediments. Depending on the sediment grain size and wave energy of the environment, and as a consequence the retention of oil, it can be a chronic stressor and exert impacts over a timeframe of years (Bejarano and Michel 2010).

**Rocky shores**

Rocky shoreline habitats host many organisms, including macroalgae, intertidal corals, sponges, bivalves and crustaceans. They can also have associated larger animals such as fish, marine mammals and birds. Slow-growing lichen populations inhabit the ‘splash zone’. These may be especially sensitive to the impacts of oil. Rocky shores are typically high wind and wave energy environments and oil can be deposited there. Once deposited, the oil can be stranded by receding tides, such that it coats the substrate. However, this oil may be quickly removed by an incoming tide (Law et al. 2011) and, as a consequence, rocky shorelines are not considered sensitive environments. Although the organisms in these environments are sensitive to oil, they can be much more sensitive to attempts to clean them. For instance, early dispersants (which were little more than industrial cleaners) applied to oiled shorelines, delayed recovery to greater than 10 years beyond that which would have been seen with natural attenuation alone (typically 3 years) (Southward and Southward 1978). High-pressure, high-temperature washing of oiled surfaces following the Exxon Valdez oil spill had more deleterious consequences than the oiling alone, with recovery times of 6–12 years, in contrast to 3 years for sites that were not treated with high-temperature, high-pressure washing (Driskell et al. 1996; 2001) (see Box 5.1).

**Beaches**

Beaches are defined by intertidal sediments ranging from muds finer than 0.06 mm diameter to pebbles and cobbles larger than 200 mm diameter. Where the grain size is between 2 and 64 mm, these beaches are not considered to be especially sensitive to the impacts of oil spills because they are regularly cleaned by wave action and have low sediment total organic carbon (TOC), and consequently, low abundances of marine life (Law et al. 2011). This low concentration of TOC and large particle size suggests that any oil that is deposited on beaches would not be retained. Nevertheless, they are often socioeconomically important (used for recreation and tourism), and can be habitats for marine mammals, so that during an event they may attract attention that is disproportionate to their sensitivity. Oil and any dispersant used can coat sand, become entrained in beaches, such that nesting sea turtles, seals, seabirds, infaunal invertebrates or fish nurseries may be at risk of exposure (Cohen 2012). Results of exposure to oil may be acute (e.g. die off of amphipods and replacement by more tolerant species such as worms) or chronic (e.g. gradual accumulation of oil and genetic damage leading to increased prevalence of tumours).

Oil will be deposited along the high-water mark or strandline (limited by the raised strip of land or berm in Fig. 2.12), and the highest hydrocarbon concentrations and impacts
would be expected there. Impacts may also be expected from any response technologies used, (shoreline cleaners or high-temperature washing) especially if sediments are moved. Sensitive organisms include small crustaceans, such as amphipods, as well as sediment meiofauna (Law et al. 2011). Organisms living in the sediments (infaunal) may also be sensitive to clean-up methods, especially to high-pressure washing that dislodges the sediment that they depend on (Driskell et al. 1996).

When it is projected that oil will make contact with shorelines, monitoring should be carried out as described in Appendix T.

**Tidal flats**

Tidal flats, also referred to as mud flats, are coastal wetlands that form in sheltered areas of bays, lagoons and estuaries through sediment deposition by tides and rivers. These can be an important habitat for invertebrates and migratory birds. Sediments in these areas often have a small grain size and are high in TOC and, as a consequence, they are frequently anoxic. Any oil that is deposited into these areas is likely to be persistent, due to low wave energy and slow rates of biodegradation. For example, a survey of intertidal areas in Kuwait and Saudi Arabia conducted 12 years after the Gulf War oil spill found that oil was most persistent in tidal flat areas, with half of all samples taken still causing risk for environmental toxicity due to elevated PAH concentrations (Bejarano and Michel 2010).

Sedimentary infauna may be sensitive to oil. Previous studies have identified that small crustaceans (such as amphipods and crabs), some bivalves, and surface-grazing snails are sensitive to oil toxicity, whereas other taxa, such as capitelid polychaete worms, may have an opportunistic increase in abundance (Law et al. 2011). These species may also be sensitive to any clean-up efforts, especially those that translocate sediments. Oil that is present in these environments may be accumulated by sediment invertebrates, and pose a risk to feeding migratory shorebirds (Velando et al. 2010).

**Salt marshes**

Salt marshes are tidally inundated grassland habitats found in low-energy coastal environments. These areas typically provide nursery areas for many commercially important fish
and invertebrate species. Salt marshes typically consist of fine grain, often anoxic, sediments, held in place by the rhizomes of plants. Damage to or die back of the plants often causes erosion of the habitat as a whole (Law et al. 2011).

Damage to salt marshes is usually most severe in the areas closest to the shoreline. Following the Deepwater Horizon oil spill, aerial images were used to assess the oiling and consequent damage to salt marsh plants in Barataria Bay, Louisiana (Khanna et al. 2013). Oiling and plant stress were both highest within 14 m of tidally inundated areas. Recovery was under way 1 year after the spill, but was proceeding most slowly in the areas closest to the shoreline (Khanna et al. 2013).

Once oil is deposited into salt marsh habitats, it is very persistent. The low energy of the environment means that stranded oil is not readily washed away, and oil does not degrade quickly in anoxic environments. Following the Deepwater Horizon spill, oil that was deposited into oxic marsh sediments was rapidly degraded (within 18 months, even at sites with very high levels of oiling) (Mahmoudi et al. 2013), whereas oil was expected to persist for decades in anoxic sediments (Turner et al. 2014). An earlier study described the recovery of a salt marsh in Buzzard’s Bay, Massachusetts, USA, following the grounding of a barge containing No. 2 fuel oil (a home heating oil) in 1974 (Hampson and Moul 1978). Three years after the spill, elevated concentrations of petroleum hydrocarbons were persistent in the marsh sediments. The impacted marsh had 24-fold greater rates of erosion and reduced infaunal biomass and diversity relative to control sites.

The invertebrates, in particular, that inhabit salt-marsh environments may be very susceptible to oil, and there may be a loss of species and productivity in oiled environments. Foraminifera (a group of shelled organisms living mainly on or in sediments) had a decreased abundance and activity in oiled Louisiana marshes relative to unoiled marshes, following the Deepwater Horizon wellhead blowout (Brunner et al. 2013). Mass mortality of crabs, spiders and other terrestrial invertebrates was also measured in oiled areas of salt marshes in Louisiana and Mississippi in 2010, while plants and snails were unaffected (McCall and Pennings 2012), with populations seemingly recovered by 2011. However, no spill-related changes in larval abundances of fish and macroinvertebrates were apparent in tidal creeks of salt marshes affected by the Deepwater Horizon spill (Moody et al. 2013).

Salt-marsh environments are also easily damaged by clean-up technologies, with anything that damages the root structure of the plants causing erosion of the habitat as a whole (Law et al. 2011). Damage to salt-marsh plants can be monitored as described in Appendix P.

Mangroves

Mangrove ecosystems are dominated by flowering trees that are specially adapted to marine and estuarine conditions (Duke et al. 2000). Mangrove ecosystems are ecologically important, because intact mangroves can decrease the severity of storm impact, prevent sediment from reaching coral reefs and act as a nursery for fish (Peters et al. 1997). These systems provide habitat for both aquatic and terrestrial organisms, and, consequently, a variety of fish and invertebrate species would likely be exposed to oil if it were entrained in mangrove sediments. Mangrove ecosystems can be exposed to oil when it is carried into the system via waves or currents and is stranded by receding tides. This oil then covers the pneumatophores of some types of mangrove trees, smothering them, and reducing oxygen flow to the roots of the plant (Lewis et al. 2011). Oil also inhibits germination of seedlings, increases rates of defoliation, leaf senescence and wilting, reduces numbers of pneumatophores, increases mutation rate and reduces photosynthetic efficiency (Naidoo et al. 2010;
Lewis et al. (2011). Oil also deposits into the sediments, where it can be a source of exposure to infaunal organisms. Mangrove ecosystems typically have fine sediment grain sizes and low wave energy, meaning that oil stranded in these areas is likely to be persistent. These sediments are also anoxic, which means the degradation of oil within the sediments is likely to be slow (Peters et al. 1997). Mangrove forests do not recover quickly from spills, with effects having been measured over decades (Peters et al. 1997). The mortality that occurs as a result of the oiling can be delayed (Naidoo et al. 2010). As a consequence of the sensitivity of mangroves to oil exposure and the long recovery times, mangrove ecosystems are considered among the most sensitive to oiling (Duke et al. 2000). Because mangrove habitat is being lost as a consequence of coastal development worldwide (Lewis et al. 2011), the consequences of oiling may be especially deleterious to conservation efforts.

Oil entrained within mangrove sediments can be available to invertebrates and fish inhabiting these systems, causing toxic impacts and changes in community structure. Following a crude oil spill in the Niger Delta, the biomass of some species was reduced by 81%, whereas the abundance of capitellid polychaete worms increased seven fold (Zabbey and Uyi 2014). Because oil retention in mangroves is expected to be persistent, exposure and impacts to the communities that use mangroves as habitats as well as those that depend on fisheries resources may be persistent as well.

Mangrove systems treated with dispersants or other shoreline cleaners have been shown to recover more quickly than those left untreated. In field trials, mangrove forests that were treated with both oil and dispersants had higher rates of crustacean mortality and decreased worm biomass, but decreased rate of tree mortality, suggesting a quicker system recovery (Duke et al. 2000).

A long-term study (the TROPICS study) of two large tropical systems was conducted in Panama (DeMicco et al. 2011). Both systems contained mangroves, intertidal seagrasses and submerged coral. One was treated with oil and dispersants, the other was only treated with oil. Oil was less persistent at the dispersed oil site relative to the undispersed site. Although the systems treated with dispersed oil initially had higher coral mortality, they recovered quicker in the dispersed oil site. There was also a permanent change to the system in the undispersed site, whereas the system exposed to dispersed oil recovered in 10 years (DeMicco et al. 2011). Damage to mangroves can be monitored as described in Appendix P.

Wildlife

For most of the guidance on sensitive receptors above, the focus has been on habitats and populations of organisms. Marine wildlife (defined as marine mammals, reptiles and birds that use marine and coastal resources, as well as large sharks and rays), are treated differently in this section. Marine wildlife are highly valued by the public and may be specially protected by national or international law. Welfare legislation (e.g. the Queensland Animal Care and Protection Act 2001) also requires that impacted animals be responded to under duty of care arrangements during maritime environmental emergencies. The conservation status and welfare requirements of large and conspicuous animals can lead to members of this group being treated as individuals, whereas for most other organisms (e.g. fish, invertebrates and plankton), the primary concern is for impacts on populations. In addition, the size, large home range and ethical considerations make these animals very difficult to study, especially in a laboratory setting, so most of what is known about their sensitivity to oil has been learned from spills in other regions. Furthermore, the impact of oil spills on wildlife populations may be difficult to estimate. The total population sizes and long-term trends in population dynamics are often not known (Williams et al. 2011). Impacts are often estimated by using the numbers of carcasses recovered, which likely underestimates
the total mortality and does not account for long-term decreases in health (Williams et al. 2011). For some animals, very little is known about their sensitivity to oil, impeding risk assessment. The specific information available regarding the sensitivity of marine wildlife to spilled oil is provided in sections below. Generalised guidance on monitoring of marine wildlife is provided in Appendix R.

**Cetaceans (whales, dolphins)**

Air-breathing marine mammals that do not come ashore, such as whales and dolphins, are typically highly valued by the community. Although the potential plight of these animals will be of great concern, there is little information to suggest that they are particularly vulnerable to oil exposure in the open ocean following spills (Law et al. 2011). There is some indication that they may avoid oil (reviewed in Geraci and St Aubin 1988), but some recent accounts dispute this (Fig. 2.13) (T. Collier *pers. comm.*). Some accounts have dolphins avoiding emulsified and oil slicks, but not sheen oil, and report that avoidance behaviour was inconsistent (Smultea and Wursig 1995). Monitoring of cetacean behaviour during oil spills may be important during the response phase, to ascertain the threat or risk of the incident to this wildlife group.

Whales and dolphins can be exposed to oil via dermal contact (especially as they cross the air:water interface to breathe), via aspiration of oil at the surface and via ingestion of contaminated food items. Animals that consume a high amount of invertebrates as part of their diet may have increased vulnerability to chronic exposure relative to those that consume mainly fish. There are some reports of declines in health of individual pods of killer whales (orcas), though not the population as a whole, in Prince William Sound after the *Exxon Valdez* spill (Matkin et al. 2008).

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**Fig. 2.13.** Atlantic bottlenose dolphins (*Tursiops truncates*) exposed to oil during the *Deepwater Horizon* wellhead release (Photo credit: National Marine Fisheries Service)
Cetaceans, if exposed to oil at the sea surface, may be especially vulnerable to exposure to oil via aspiration. Dolphins and porpoises in particular have a large lung capacity relative to their total body volume, and have a much higher exchange of total lung volume than other mammalian species (Butler and Jones 1997, Piscitelli et al. 2013).

Dolphin populations from Barataria Bay, Louisiana, USA, which received prolonged and continuous oiling from the Deepwater Horizon spill, had higher incidences of lung and kidney disease than those in other urbanised environments (Schwacke et al. 2014). There is also concern that the spill may have contributed to unusually high perinatal mortality in bottlenose dolphins, along with cold weather and a large freshwater discharge into the Gulf of Mexico (Carmichael et al. 2012; Venn-Watson et al. 2015).

Large sharks and rays
Cartilaginous fish are not as well studied from a toxicological standpoint as bony fish, and the impact of oil exposure on these organisms is largely unknown. Sharks are subject to intense fishing pressure worldwide and, as a consequence, many have protected status. Large sharks and rays would either be exposed to oil via transport of material across the gills or skin, or ingestion of contaminated food items, which is especially important for organisms that eat a large amount of invertebrates. Large fish have been shown to avoid oiled areas (Rooker et al. 2013), but it is not known whether sharks and rays would exhibit the same behaviour.

Dugongs
No studies could be found specifically dealing with the impact of oil on dugong populations, but risk assessments for manatees (a related organism found in the Americas) do exist (Geraci and St Aubin 1988). Wildlife response plans specific to dugongs were developed following the Great Barrier Reef Marine Park grounding incidents of the MV Peacock (1996) on Piper Reef, MV Bunga Teratai Satu (2000) on Sudbury Reef and the MV Doric Chariot (2002) also on Piper Reef (M. Short pers. comm.). Dugongs can be exposed to oil via dermal contact (especially as they cross the air:water interface to breathe), via aspiration of oil at the surface, and via ingestion of contaminated seagrass. They may also ingest oil from sediments as they forage for seagrass.

Pinnipeds (seals and sea lions)
Like the other marine mammals, pinnipeds can be exposed to oil via dermal contact either as they cross the air:water interface to breathe, or from oiled substrate as they come ashore to rest, via aspiration of oil at the surface, and via ingestion of contaminated food items, especially for those species that consume large numbers of invertebrates (Geraci and St Aubin 1988). Seals appear not to be very sensitive to contact with oil, but instead to toxic impact from the inhalation of volatile components (Law et al. 2011). There are anecdotal accounts of seals being coated with oil with no discernible impacts, although one spill that occurred when pups were being born resulted in pups with low birthweights (Geraci and St Aubin 1988). However, nearly 5000 two- to three-month old South American fur seal pups were oiled as a result of a spill of 5000 tonne of crude oil near Punta del Este, Uruguay in 1997, when over 4000 died from either direct toxicity, hypothermia or starvation as a consequence of disruption of normal nursing behaviour (Mearns et al. 1999).

Exposure to dispersant or dispersed oil may cause fur-bearing mammals to lose their waterproofing and either drown or succumb to hypothermia (Lipscomb et al. 1993), so seals may be more sensitive to the response technologies than to the oil itself.
Reptiles (turtles, sea snakes and crocodiles)

Very few studies on the impact of oil on marine reptiles exist, although reptiles have been exposed to oil in previous spills and should be accounted for in oil spill management plans. For example, two sea snakes were exposed to oil following the MV Pacific Adventurer oil spill (2000) near Moreton Island in Queensland, Australia. One was successfully rehabilitated and the other perished (M. Short pers. comm.).

Wildlife response plans specific to crocodiles were developed following the grounding incidents of the MV Peacock (1996) and the MV Doric Chariot (2002), both on Piper Reef in the Great Barrier Reef Marine Park (M. Short pers. comm.). Reptiles would be exposed to oil via ingestion of contaminated food items, inhalation or dermal exposure. Turtle nests may be susceptible to oiling if either: (i) toxic components from the oil were absorbed into the developing embryos; or (ii) an oil coating prevented normal gas exchange, smothering the eggs. Turtles may also ingest oil with sediments as they forage for prey, and may acquire toxicologically relevant doses from the invertebrates they ingest. The eggs may also be crushed by clean-up activities, especially if heavy machinery is used. Following the Deepwater Horizon oil spill, there were accounts of visibly oiled sea turtles, but it is uncertain what impact this oiling had on the health of the organism and the populations (USFWS 2011).

Birds (including penguins)

Shorebirds and seabirds are especially sensitive to the impacts of oiling, with most major spills resulting in reports of a high number of causalities. It is estimated that several hundred thousand marine birds were killed in the immediate aftermath of the Exxon Valdez oil spill (Iverson and Esler 2010). This vulnerability arises from birds crossing the air:water interface to feed, as well as from oiling of their shoreline habitats. The life history characteristics will determine to vulnerability of each species and life stage. Seasonal conditions may also affect the vulnerability (e.g. birds may be most vulnerable following the winter when their energy reserves are low or following moulting) (reviewed in Law et al. 2011).

Oiling can also impair navigation and flight performance. ‘Preening’ of feathers to remove oil can be a major source of exposure via ingestion. Populations will be most vulnerable when a large number of individuals are aggregated, such as for breeding or predatory purposes. Birds can be exposed to oil via absorption across skin, inhalation and ingestion of contaminated food items. Bird feathers may be disrupted by exposure to either oil or dispersants, causing the birds to lose their weatherproofing and drown or succumb to hypothermia (Law et al. 2011). Oiling can also impair navigation and flight performance. Seabirds may also be susceptible to chronic exposure to PAHs and other oil constituents accumulated through trophic transfer because they are long-lived upper trophic level consumers (Velando et al. 2010), which can cause delayed mortality. Bird nests may also be susceptible to oiling, and eggs may be crushed by clean-up activities. Generalised advice for monitoring bird populations is given in Appendix Q.

Judging whether bird populations have been exposed to oil can be problematic. The number of birds carcasses recovered on the shoreline is expected to be a small fraction of the number of casualties, as dead birds may sink or be eaten (Williams et al. 2011). In addition, birds that die due to other causes (e.g. shearwaters in a storm) may be coated in oil, causing ‘false positives’. Alternatively, birds that are coated in oil may ‘preen’ and ingest the oil, so that their apparent exposure is less. Depending on the colouration of the plumage, oiling may not always be visible.

Penguins may be especially vulnerable to oil spills because they spend a greater portion of their time in the water than other birds and readily lose insulation and buoyancy if their
Oil Spill Monitoring Handbook

feathers are oiled (Goldsworthy et al. 2000a). As a consequence, they can be severely impacted by even small spills. For example, the 1995 Iron Baron spill of 325 tonnes of bunker fuel may have caused the deaths of as many as 20 000 penguins (Goldsworthy et al. 2000a). Oiled, rehabilitated birds which only had a 50% survival rate (Goldsworthy et al. 2000b), and oiled birds were less likely to successfully rear chicks in the next breeding season (Giese et al. 2000), though whether this is a consequence of altered behaviour, decreased available energy resources or toxic impacts is uncertain.

Penguins may be successfully rehabilitated following oil spills. On 23 June 2000, the bulk ore carrier MV Treasure sank off western South Africa between Dassen and Robben Islands, which currently support the largest and third largest colonies, respectively, of African penguins, Spheniscus demersus. Subsequently, more than 19 000 penguins were oiled and were collected for cleaning and care and ~150 oiled adults died in the wild. Some 19 500 unoiled penguins were also caught at Dassen and Robben Islands and relocated to Port Elizabeth, 800 km to the east, to remove them from waters affected by the oil. Of all penguins caught, amounting to 20% of the total species population, less than 2000 (~10%) died within the first month. The breeding success of these birds was compared with unoiled birds and the fledgling success averaged 61% for the non-oiled birds and 43% in birds oiled during the Treasure spill (Wolfaardt et al. 2008).

2.5 Oil spill response options

There are numerous strategies used to mitigate the impact of an oil spill (e.g. RSC 2015), and these are described in the sections below. Following an oil spill, response personnel must decide what response, if any, they are going to use to lessen the impact of the oil in the environment. A response to the spill should be carried out when it is logistically feasible and is of net environmental benefit (both ecologically and socioeconomically); that is, it represents a reasonable benefit for the cost incurred. If this is not the case, monitoring of the situation and allowing for natural recovery may be the most appropriate response. Any of the strategies described below can be used in isolation or in combination.

2.5.1 Recovery at the source: ship lightering

If possible, ship lightering (i.e. removing the petroleum cargo from the damaged ship) is the preferred response if it prevents the further release of petroleum into the environment.

2.5.2 At-sea response options

Mechanical recovery

Where feasible, collecting the oil from the sea surface, using either skimming, pumps, grabbing or nets, should be considered next. The success of this response option will depend on the selectivity of the device for oil and the type and weathering state of the spilled oil. This response option is probably most appropriate for small spills, because the low oil encounter rate (the proportion of the oil that is encountered by the response technology relative to the size of the spill) may prevent appreciable collection of oil from very large spills. However, following the Prestige oil spill, as much as 50 000 tonnes of emulsified fuel oil were recovered from the sea surface (F.X. Merlin pers. comm.), showing that mechanical recovery may be an option for even large spills. Weather conditions will also greatly influence the success of mechanical recovery of oil, with operations being most successful in calm sea states.
Booms

Booms are floating barriers that act on the sea surface (Fig. 2.14). In an oil spill, they are used to:

(i) concentrate oil to permit its collection
(ii) divert the oil to a point where it can be collected
(iii) protect sensitive habitats (to be discussed in more detail in the section on shoreline clean-up).

There are different types of booms, including curtain booms, fenced booms and moored booms, that have been designed for specific scenarios and current speeds (ITOPF 2012). Booms may be moored into place (e.g. to protect an estuary) or may be towed behind ships. A boom is made up of the following parts: (i) a membrane that forms a barrier between an oil slick and an uncontaminated area; (ii) flotation, which keeps the upper edge of the membrane at or above the water’s surface; (iii) ballast, which is attached to the lower edge of the membrane to keep the structure stable and upright in the water; and (iv) tension members to give the boom strength (Tedeschi 1999). Booms are less effective with wind, waves and current, so can only be used in calm weather conditions and on smaller spills. Although there are booms that have been specifically designed to be effective in currents, most booms cannot withstand current speeds greater than 1 kn. Booms may be submerged in high currents or by high waves (ITOPF 2012).

Skimmers

Skimmers are used for the mechanical recovery of oil (ITOPF 2012). There is a variety of different designs, but all are based on the principle of collecting oil from the water’s surface, and may be used in tandem with booms. Different types of skimmers can include
adhesion (or oelophilic) skimmers, which move through the oil slick. After the oil adheres to the skimmer, the skimmer is pulled out of the water and the oil is scraped off. Weir skimmers use a pump to remove water from underneath the oil-water interface. Suction skimmers, belt skimmers and oil skimmers are also used. The type of skimmer employed should be chosen based on the oil type and sea state for which it is effective. Skimmers are often much more effective on oil that has not yet formed an emulsion (Nordvik 1999; ITOPF 2012).

There are some important limitations to mechanical recovery. These include:

- **Encounter rate** – the likelihood that the device will be able to come into contact with a significant fraction of the oil. These approaches are more successful with oil that has not spread or for small spills.
- **Sea state** – neither technology performs optimally in high sea states.
- **The logistics of storing and disposing of any collected oil need to be considered in advance of using the approach** (ITOPF 2012).

**In situ burning**

Oil can also be gathered in booms and burned at the sea surface (Fig. 2.15). The technique is very effective because it can remove up to 90% of the oil collected into the booms and generates no chemical waste. However, burning is only possible with fresh oil, and generates serious safety concerns due to the potential for inhalation of the smoke produced. Also, because oil must be in a layer greater than 1 mm thick, the approach requires the use of a fire-proof boom. The equipment and trained personnel to carry out in situ burning are not presently available in Australia, so it is generally not considered a viable response option here.

![Fig. 2.15. In situ burning](Photo credit: U.S. Coast Guard)
Oil dispersants

Oil dispersants are a mixture of surfactants and solvents used to break up oil slicks into droplets that are then mixed into the water column via wind and wave energy (NRC 2005). As shown during the Deepwater Horizon response, they can also be injected into subsurface plumes to achieve the same result. Their use can prevent oil from being washed into nearshore environments and onto coastlines (Fig. 2.16), and can also protect marine mammals and birds that have to cross the air:water interface to breathe. They accelerate the process of oil degradation, by increasing the surface area by which bacteria can access the more labile fractions of the oil. However, using dispersants distributes oil into the water column where it can cause deleterious impacts to planktonic life stages of organisms that live in the water column. Dispersant use may make other oil spill response options, including the use of sorbents and skimmers, less effective.

There are constraints on the use of oil dispersants. They can only be used when it is logistically feasible and where the spilled oil can be effectively dispersed. The factors that change dispersant efficacy have been reviewed by the US National Research Council (NRC 2005), and are briefly summarised here. It is important to note that oil dispersants whose behaviour has been validated in laboratory testing may not be effective under field conditions.

The efficacy of dispersants decreases with increased oil viscosity, which is why oil is only thought of as being dispersible early in the weathering process. Some highly viscous oils are difficult to disperse even when fresh (NRC 2005). There also needs to be a certain minimum wave energy at the time to ensure that the oil slick breaks into small droplets, but if the wave energy is too high, there is increased probability that the dispersant will be carried ‘off target’ by washing or wind drift. Under very high wave energies, the use of chemical oil dispersants may not be necessary at all, because the mechanical energy in the waves themselves may be sufficient to disperse the oil (NRC 2005). Alternatively, depending on wind and wave conditions, a foamy ‘mousse’ can form, and these emulsions are not easily dispersed. Salinity, temperature and oil composition (in particular the amount of saturated hydrocarbons) can also influence dispersant efficacy (Fingas 2011b). As a consequence, the use of chemical oil dispersants is only recommended in circumstances where they are likely to be effective. Their efficacy under real world conditions must be monitored, as described below and in Appendix F.

Dispersant use generally requires NEBA to show that their use is likely to minimise the overall environmental damage relative to other response options, including allowing natural attenuation alone (NRC 2005) (discussed in more detail in Section 5.1). Modern dispersants are toxic to marine organisms, but their toxicity is typically much less than that of dispersed oil (Adams et al. 2014). However, if dispersants are effective and used appropriately, dispersed oil may not be sufficiently concentrated for very long before it is diluted by currents and waves. Nevertheless, deleterious impacts of dispersed oil may occur even after very short exposures (Greer et al. 2012). These impacts may be greatest on embryonic life stages, which are both very sensitive to oil and unable to avoid exposures (discussed in more detail in Section 2.3.2).

Although dispersing oil increases the rate at which it is degraded, not all fractions of oil are degraded equally. Simple alkanes and aromatics are degraded rather quickly, but the polar fraction of oil is typically more recalcitrant and degrades much more slowly. This heavier portion of oil can flocculate and sink, depositing into the deep sea. Following the Deepwater Horizon blowout, some studies claimed that oil was deposited in the deep sea where it damaged coral colonies (Fisher et al. 2014). However, there were active seeps in the area and it was not certain to what extent the presence of deep-sea oil could be attributed to natural sources.
Other oil spill chemical counter-measures

Chemical counter-measures can be added to oil slicks to change the physical properties of the oil to make it easier to contain, collect and recover. They include: (i) herding agents, which make oil slick thicker and easier to recover; (ii) emulsion-treating chemicals, which either prevent the formation of emulsions or separate the emulsion back into oil and water; and (iii) solidifiers, including gelling agents, which make the oil a solid mass without changing its specific gravity. These substances will only be briefly discussed as there is little scientific literature available, and their use is often not recommended (Walker et al. 1999; Fingas 2011c).

Herding agents are most effective in calm water with little wind or currents and where there is a dock or similar hard structure against which the oil can collect. Multiple applications may be required before the product is successful. As a consequence, these are best used on small spills in nearshore environments.

Gelling agents and other solidifiers are designed to make oil into a solid compound. Solidifying oil will make it easier to collect via nets or other mechanical means. However, the oil can no longer be collected by skimmers and could sink, making it extremely difficult to recover at sea. Solidified oil also could potentially smother organisms with which it comes into contact. A large amount of solidifying agent is also needed to treat even a small spill, making its use impractical. Also, as the agent works, the solidified oil acts as a barrier, preventing the chemical countermeasure from reaching the oil underneath. For these reasons, solidifiers have not been used in oil spill response.

Emulsion inhibitors or breakers are used to prevent the formation of oil and water emulsions. Low doses of dispersants can also act as emulsion breakers. Comparatively few emulsion breakers have been used in oil spill response because of concerns about their efficacy or toxicity (Fingas 2011c).

Natural attenuation

Once released into the environment, given sufficient time, oil will break down through weathering and be ultimately biodegraded. The amount of time that this takes depends on environmental factors. For example, in North Atlantic sea water, after 14 days, concentrations of the relatively light *Macando* crude oil had decreased by half (Prince *et al.* 2013). By contrast, once oil is deposited in anoxic sediments, it can persist for decades (Peacock *et al.* 2005; Short *et al.* 2007). Persistent oil can cause toxic effects and can also limit the socio-economic uses of an area. Also, oil stains can be visually unappealing and can limit the amenity uses of an area.
2.5.3 Shoreline response options

Before an area is oiled, there are steps that can be taken to minimise the impact and simplify any clean-up that is required. Where possible, sensitive species such as farmed bivalves or shore-nesting birds should be removed from the area. In addition, debris should be removed from a shoreline pre-impact to reduce the amount of oiled material that will have to be removed and to simplify any subsequent clean-up operations.

Deploying booms for shoreline protection

Booms can be deployed to prevent the oiling of a sensitive area (e.g. across the mouth of a lagoon), but care must be taken in deciding to deploy booms, because they are only effective in calm seas. During storms, booms may break apart and cause mechanical damage to sensitive habitats, as well as pushing oil onto the shoreline. Any oil that does cross the boom line as a result of wave action can be trapped in a sensitive habitat by the boom. When booms fail, they are often left in place to prevent oil from spreading and impacting other areas.

Shoreline clean-up

Clean-up efforts are meant to return the habitat to pre-spill conditions without causing additional harm or jeopardising sensitive resources. A secondary goal of shoreline clean-up is to remove oil so that it is not remobilised and spread on the next tide. Removing most of the oil from a contaminated shoreline may not be the most appropriate metric for deciding which shoreline clean-up response to use. Aggressive clean-up techniques can exacerbate damage, so natural recovery or less invasive clean-up strategies are often preferable (Yender and Michel 2010). In fact, shoreline clean-up has been consistently found to not enhance ecological recovery of oiled coastlines (Sell et al. 1995).

Recovery has been said to take place in three steps: (i) the breakdown of oil; (ii) initial colonisation by biota; and (iii) return of the community and age structure of the biota to pre-impact levels. This process was found to take 3 years on average for rocky coastlines and 5 years for salt marshes, regardless of the clean-up strategy used. Aggressive clean-up was found to be detrimental for ecosystem recovery because of sterilisation of the system (e.g. removal of the biofilms that encourage larval settlement). In addition, intensive shoreline clean-up was found to retard the recovery of marshes (Michel and Rutherford 2014). For vegetated areas, recovery will be faster if the spill happens outside of the growing season. Because clean-up was found to have at best a marginal impact, using clean-up technologies was recommended only where there were thick, potentially smothering oil deposits or extensive penetration of oil to deep sediment layers (Sell et al. 1995).

In salt marshes that were heavily oiled following the Deepwater Horizon wellhead blowout, the most rapid recovery was found in marshes that received manual treatment and forward planting to retard shoreline erosion. Mechanical clean-up was found to mix oil deeper into the sediments, where it was more persistent and, as a consequence, slowed recovery relative to natural attenuation. There was, however, a greater cost (due to the need for personnel) and a slower pace when manual treatment was used (Zengel et al. 2015).

Because shoreline clean-up (as an oil spill response) has been found to have at best minimal effectiveness, natural attenuation of the oil on the shoreline should be considered. Factors that alter the rates of natural attenuation are outlined in Table 2.8. Although clean-up of shoreline resources may not accelerate the recovery of the intertidal area, it may protect other resources in the area, such as birds, marine mammals or subtidal habitats including coral reefs or fish farms. In addition, shoreline clean-up can be justified, even if it is of no ecological value, if there is sufficient socioeconomic justification (Baker 1999).
There is no ‘best’ shoreline cleaning method, and selection will depend on situational factors, with the efficacy of any method chosen counter-balanced with operational feasibility (Baker 1999). Selection of response strategy should also consider plans for the storage, transportation and disposal of oiled waste (ITOPF 2012).

After a habitat is oiled, the area should be surveyed repeatedly. The first survey is meant to assess the damage caused by the oil and the extent of oiling, and subsequent surveys will evaluate the efficacy of the treatment, or the progress of natural recovery, so that the need to change methodology, provide additional treatment, or adjust the strategy to new constraints can be evaluated (Yender and Michel 2010).

There are numerous options for shoreline clean-up, including barriers and berms (artificial embankments), manual cleaning, mechanical oil removing, sorbents, vacuum, vegetation cutting and removal, sediment reworking low pressure flushing, high-pressure cleaning, and nutrient enrichment (Michel and Rutherford 2014). These approaches can be used alone or in concert. More commonly used techniques are summarised below.

### Mechanical recovery at the shoreline

The primary goal of shoreline clean-up should be to remove bulk or free oil that could be deposited elsewhere with the next high tide or storm event, hence adding to the overall level of contamination. Oil can be recovered at a contaminated shoreline by similar processes to those that occur at sea. In this case, the oil is collected behind booms or dams and removed by pumps or skimmers. Oil can also be removed from shorelines by flushing with high-pressure hoses (see Box 5.1).

As a secondary response, oil that has been incorporated into sediments can also be removed. One option for this is surf washing (Fig. 2.17), which involves transport of oiled material into the surf zone, where the sediment is washed by wave action. Although this process is obviously very disruptive to sedimentary infauna, it is effective at removing oil, especially from beach sand. Piled rocks or other man-made shoreline armour should be disassembled, cleaned and re-installed. Other clean-up options that could be considered include high-pressure and high-temperature washing (but see Box 5.1), sieving and removal.

<table>
<thead>
<tr>
<th>Physical factor</th>
<th>Slow natural clean up</th>
<th>Fast natural clean up</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposure to wave energy</td>
<td>Low wave energy</td>
<td>High wave energy</td>
</tr>
<tr>
<td>Localised exposure</td>
<td>Cracks, cervices, spaces under boulders</td>
<td>Smooth surfaces</td>
</tr>
<tr>
<td>Slope of shore profile</td>
<td>Gentle slopes</td>
<td>Steep slopes</td>
</tr>
<tr>
<td>Substrate (alters depth of oil penetration)</td>
<td>Shingle, gravel, some sand</td>
<td>Fine sediments (oil is unlikely to penetrate waterlogged sediments); rock face</td>
</tr>
<tr>
<td>Oil flocculation with clay</td>
<td>Minimal</td>
<td>Extensive (this prevents oil from adhering to substrates)</td>
</tr>
<tr>
<td>Height of stranded oil</td>
<td>Supratidal zone</td>
<td>Middle and lower shore</td>
</tr>
<tr>
<td>Oil type</td>
<td>More viscous</td>
<td>Less viscous</td>
</tr>
<tr>
<td>Loading of oil</td>
<td>Heavy</td>
<td>Light</td>
</tr>
<tr>
<td>Temperature</td>
<td>Cold climate</td>
<td>Warm climate</td>
</tr>
</tbody>
</table>

Table 2.8. Physical factors that influence the rates of natural attenuation of oil on coastlines (adapted from Baker (1999) and Michel and Rutherford (2014))
of fine sediment, and manual cleaning. If surf washing and high pressure cleaning are considered, the shoreline gradient will have to be maintained to prevent erosion. A protocol for doing this is provided in Appendix U.

**Sorbents**

Sorbents are any of a range of materials that preferentially concentrate oil from water (ITOPF 2012). They are most appropriately used during shoreline clean-up to collect small pools of oil, and are not appropriate for open water use because of the difficulty in retrieving the sorbents once released. They are also frequently used in conjunction with shoreline washing to collect oil that is released by the washing processes, but large-scale use of sorbents should be discouraged because it increases the volume of waste to be disposed of. The logistical issues of transport, storage and disposal of oiled sorbents should be considered in advance of their use. Their use may also interfere with the actions of dispersants or skimmers.

**Shoreline cleaners**

Shoreline cleaners comprise surfactants that remove oil from oiled coastlines. They differ from dispersants in that, instead of dispersing oil, they make oil float so that it can be more easily collected (Fingas and Fieldhouse 2011). Typically, shoreline cleaners are sprayed on an oiled area at low tide, then washed into a boomed collection area where the oil can be recovered by some mechanical means, such as skimmers (Fingas 2011c). Shoreline cleaners

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Fig. 2.17. Surf-washing undertaken at Flying Fish Cove on Christmas Island to remove oil from the MV Tycoon that penetrated coral beach sediments for more than 1 m (Photo credit: Paul Irving, AMSA)
cleaning agents may themselves be toxic, as with the shoreline clean-up following the *Torrey Canyon* spill (Southward and Southward 1978). Modern use shoreline cleaners are much less toxic (Fingas 2011b).

**Bioremediation**

Bioremediation is a means of enhancing the natural attenuation of oil spill residuals by accelerating the growth of oil-degrading microorganisms. Microbial degradation is the primary route of oil degradation in the marine environment (Atlas 1995; Head *et al.* 2006). Hydrocarbon-utilising bacteria typically make up 1% of the microbial population in pristine environments and can increase to greater than 10% in oil-contaminated environments. Following an oil spill, an increase in the number and activity of oil-degrading bacteria is rapid and sustained. The rates of oil degradation are influenced by the physical composition of oil, temperature, nutrient availability, salinity, pressure and the surface area to volume ratio of the oil. Although oil degradation occurs at all of the temperatures at which it has been tested, it occurs most rapidly at warmer temperatures (Atlas 1981).

Bioremediation, or the addition of nutrients and oxygen to accelerate the growth and activity of oil-degrading bacteria, may be effective in increasing the rates of natural recovery (Atlas 1981). This process is relatively ineffective in sea water because mixing and dilution make it difficult to sustain high nutrient concentrations (Lee and Merlin 1999). However, the process has been effective on a variety of shorelines with different substrate types (Lee and Merlin 1999). Because bacteria and fungi are present in the environment before a spill occurs, ‘seeding’ by adding additional microbes is unnecessary (Atlas 1995). The *Exxon Valdez* spill was among the first field tests of bioremediation (Bragg *et al.* 1993). Adding nutrients to oiled shorelines accelerated the rates of oil degradation by 3–5 times relative to unfertilised areas, although areas that had already been remediated did not benefit from the additional application of nutrients (Bragg *et al.* 1993). This process should be carefully monitored to ensure that the rates of oil degradation are being accelerated, the residual oil is amenable to biodegradation, that toxic concentrations of nutrients are not present (Lee and Merlin 1999), and that the population levels of hydrocarbon-degrading bacteria are amplified (as opposed to the abundance of nuisance species of algae and bacteria being increased). This is best done using the molecular methods outlined later in Section 7.4 and Box 7.5.
Preparing for oil spill monitoring

Paul Irving, Michael Holloway, Sharon Hook, Andrew Ross and Charlotte Stalvies

In advance of any spill event, it is essential that those responsible for monitoring are fully familiar with how to design an oil spill monitoring program, so that this can be readily adapted for rapid implementation to any incident, regardless of size or circumstances. This chapter deals with these requirements.

Following an oil spill, there are two types of monitoring that need to be run in parallel. These are response phase monitoring and recovery phase monitoring.

**Response phase monitoring** relates directly to the objectives of the response and the spill clean-up operations, including planning, execution, assessment and termination. Response phase monitoring (previously termed ‘operational’ or ‘Type I’ monitoring) should be designed to:

1. improve situational awareness
2. enhance information available to response advisors and decision makers
3. determine and assess response endpoints
4. assess the efficacy of the response in mitigating spill effects
5. assess any impacts of the response on sensitive resources.

The response phase monitoring comprises multiple, interdependent parts.

**Initial response phase monitoring** involves rapid data gathering for situational awareness, commencing within the first few hours of the response. The primary aim is to determine the location and size of the spill and the contaminated area to inform the response. This can include using aerial surveys and remote-sensing techniques for spill detection, gathering information to inform trajectory modelling and accessing pre-prepared spatial data on the distribution of sensitive receptors (see Section 4.3.2). This phase of monitoring may be characterised as qualitative (or semi-quantitative), non-probabilistic and observational. Once basic situational awareness is established, the decision may be made to initiate more advanced response phase monitoring.

**Advanced response phase monitoring** includes measuring the composition and concentration of spilled oil along the trajectory in the water, in the sediments and along the shoreline, as well as monitoring any treatment used and the efficacy of that response (Radovic et al. 2012). To meet these objectives, monitoring is usually quantitative, probabilistic and may use inferential statistical methods. This information is often needed to justify and response actions taken or, alternatively, to explain why no mitigation was pursued as part of the legal record of the spill.
Recovery phase monitoring (previously known as ‘scientific’ or ‘Type II’ monitoring) includes short- and long-term damage assessments, environmental recovery assessment following an oil spill response, scientific studies on affected resources and all other monitoring activities not directly related to mitigating the environmental impacts of an oil spill. The term ‘recovery’ can be, and has been, used to mean many things in spill response including collecting oil off the water, rehabilitation of the environment, return to normal socioeconomic conditions, and being reimbursed for costs incurred. This Handbook will use the term in relation to recovery in an environmental context. The socioeconomic aspects of recovery are outside of the scope of this work and will not be discussed further.

In most jurisdictions around Australia, for maritime spills, recovery phase monitoring is the responsibility of the environmental quality compliance or territorial or resource management agencies; that is, the Environment Protection Authorities (EPAs). The agencies, legal requirements and capabilities can vary across jurisdictions, but, in general, jurisdictional spill response control agencies, such as AMSA, do not have a direct responsibility for undertaking recovery phase monitoring. Further information about study design for recovery phase monitoring is provided in Chapter 7.

It is critical that response phase monitoring be conducted in parallel with recovery phase monitoring. Some key data used for recovery phase monitoring and analysis can only be collected during the initial phase of the oil spill response – namely baseline data and time-of-impact data – because response actions or elapsed time may degrade or destroy information. This means that such monitoring needs to also be dealt with in this Handbook. The rationale behind the collection of these data is outlined below.

The overlap between these types of monitoring is described further in Chapter 7. A weight-of-evidence approach to recovery phase monitoring would provide the most robust data for impact assessment, where measured hydrocarbon concentrations in the environment, their toxicity in standardised laboratory tests, exposure of organisms in the field to oil (either through biomarkers or bioaccumulation) and changes in community structure are all considered.

3.1 Designing a monitoring program

The basic frameworks for the design of a monitoring program have been defined by the Australian Guidelines for Water Quality Monitoring and Reporting (ANZECC/ARM-CANZ 2000a). These are easily applied to oil spill monitoring. The overall framework is defined in Fig. 3.1. During response phase monitoring, timelines for these activities are often highly compressed and occur over the period of hours to days in order to contribute to the situational awareness required during an incident.

3.1.1 Setting objectives

As each oil spill will have its unique circumstances and environmental conditions, each monitoring program will be different, depending on the objectives of the program and the needs for both response and recovery. Some guidelines to help frame the approach to monitoring, examples of when each would be used, and the design considerations are provided in Table 3.1.

The setting of objectives depends on a system understanding and this is often facilitated by the use of a conceptual process model. A generalised fate model is shown in Fig. 2.2, and a model including receptors is shown in Fig. 3.2.
**Table 3.1.** Summary of key monitoring questions, methods, data requirements timeframes and purpose at different stages in a response

<table>
<thead>
<tr>
<th>Question</th>
<th>Monitoring design and methods</th>
<th>Data characteristics and analytical requirements</th>
<th>Purpose</th>
<th>Timeframe</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Initial response phase monitoring – rapid descriptive data gathering</strong></td>
<td>• Where is oil? • How much oil is there? • Where is it heading? • What is in its path? • How is the oil likely to change/weather?</td>
<td>• Remote sensing (6.3.2) • Aerial survey (6.3.2) • SCAT surveys (5.2, App. O) • Fate/trajectory modelling (6.2) • Reference data (e.g. OSRA – 4.3.2)</td>
<td>• Primarily descriptive • Observational/visual assessment • Summarise data • No estimate of precision • Non-probabilistic sampling (e.g. authoritative sampling) • Predictive modelling</td>
<td>• Situational awareness • Response planning • Inputs for oil fate and trajectory modelling • Preliminary impact/risk assessment • Preliminary NEBA</td>
</tr>
<tr>
<td><strong>Advanced response phase monitoring – quantitative data collection</strong></td>
<td>• What is the level of exposure to oil? • What is the toxicity of oil in the environment? • What is the fate of the oil? • What is the current state of some variable?</td>
<td>• Field data/sample collection (3.2.2) • Chemical analysis of water/sediment/tissue (6.5) • Biomarker analysis (7.4) • Toxicity testing (7.3) • Hazard assessment (6.6)</td>
<td>• Probabilistic sampling • Inferential data analysis (use samples to make inference about population) • Replicate sampling units (water bottles, quadrats)</td>
<td>• Prioritise response activities • Assess likely impact of spill and response • Assess efficacy of response methods • Assess whether clean-up end-points reached • Time-of-impact data for recovery phase</td>
</tr>
<tr>
<td><strong>Recovery phase monitoring – impact and recovery monitoring</strong></td>
<td>• What has changed since spill/response? • What is the impact of oil/response? • Is the system recovering?</td>
<td>• Reference/gradient/BACI design (7.1) • Field data collection (7.1) • Measurement of ecological variables (7.4) • Incorporation of baseline data if available (7.5)</td>
<td>• Causal data analysis • Baseline data (if available) • Probabilistic sampling • Control/reference sites • Replication at scale of spill • Random site selection • Statistical power analysis</td>
<td>• Determine impact of the spill or clean-up • Determine whether recovery is occurring</td>
</tr>
</tbody>
</table>
Fig. 3.1. Framework for an oil spill monitoring program (Source: adapted from ANZECC/ARMCANZ 2000a)

Fig. 3.2. Conceptual process model of an oil spill dispersion. Sources are in black italics, habitats in orange and receptors in purple.
There are key differences in the objectives of response phase and recovery phase monitoring programs, as well as with different aspects of each type of monitoring. These significantly influence the monitoring methods likely to be used, and the scope of studies, logistics and costs of any agreed program. While both types of monitoring should be undertaken in parallel during a spill response, the type of monitoring largely determines who has responsibility for determining the appropriate scale and design of the study.

Setting objectives is the first (and arguably most important) step in defining what any monitoring activity, study or program needs to deliver. It can be as simple as a statement of what the monitoring seeks to measure (e.g. descriptive, measurement of change, determination of cause and effect), and defines the parameters to include in monitoring.

For response phase monitoring programs, the primary objectives will generally be determined by response intelligence (situational awareness), planning or operational needs. The specific question will likely come from the contingency plan, the developing incident action plan, and the Incident Controller (IC) or another nominated person within the Incident Management Team (IMT).

When setting objectives, it is important to understand how monitoring information will be used in the decision-making process (Table 3.1). In the initial stage of the response, monitoring objectives will most likely focus on determining the source and location of the spilled oil and where it is likely to have an impact. Data will also be assembled on the oil properties, environmental conditions and sensitivities within the potential impact area. This information is used to prepare a NEBA, select appropriate response strategies and plan the response operation. For some spills this may be sufficient to meet the needs of the response, particularly if the impact is small or sensitive resources are not at risk.

In larger spills, more detailed quantitative information on the oil in the environment may be needed to inform the response. The objectives would focus on quantifying toxicity, exposure gradients, and weathering and fate of oil, for example. This information would be used to refine the NEBA, prioritise clean-up activities, assess efficacy of response strategies and assess potential impacts of the response. Monitoring design may need to take into account secondary objectives for the data, such as effectiveness versus efficiency, rates of recovery, oil budgets and overall cost (e.g. clean-up as well as waste disposal costs).

For recovery phase monitoring, objectives will focus on determining the environmental impacts of the spill and the progress of recovery. While not the primary focus of this handbook, monitoring for these objectives should commence as early as possible in the response, with data collection planned in conjunction with response phase monitoring. Meeting the objectives of recovery phase monitoring requires careful study design, monitoring at multiple control sites and continuation of monitoring (sometimes for many years) after the response.

Some key aspects to consider when setting objectives are:

- What specific question(s) needs to be answered?
- Have knowledge gaps been identified and addressed?
- Have the limitations of not having information been evaluated?
- Will the information gathered consider major stakeholders’ needs?
- How will the information be managed and communicated?
- Do specific objectives:
  - clearly and concisely communicate the purpose of monitoring?
  - specify what the monitoring will achieve?
  - indicate when the monitoring is complete?
3.2 Study design for environmental monitoring

Having set objectives, the next task is to design how the information will be collected, transmitted and stored in a cost-effective manner (Fig. 3.3).

For any monitoring program, it is also vital to have good design, specified outcomes, and defined methods of data acquisition, transfer and assessment. Without these in place before the program is implemented, monitoring is unlikely to provide satisfactory answers, meet responder or stakeholder expectations or be cost-effective.

Examples of the importance of good design in relation to oil spill response have been provided in several publications (Gilfillan et al. 1996; Green and Montagn 1996; Paine et al. 1996; Robertson 2001; Peterson et al. 2001). Several others provide a comprehensive overview of study design issues (e.g. AMSA 2003; Zhu et al. 2001).

A checklist of considerations in the design of a monitoring study is given in Table 3.2.

3.2.1 Determining the scale and location of the monitoring

Monitoring must reflect the scope (scale, spatial boundaries and duration) and potential effects of the spill, and deal with key environment issues relevant to the spill. Several factors must be taken into account when defining monitoring requirements, but primarily:

- the size of the spill
- the characteristics of the oil (or chemical)
- the type of discharge (single or continuous release)
- dispersion and dilution rates
- the characteristics of the receiving environment.

The appropriate scale for a program will be determined largely by its specific objectives.

Fig. 3.3. Framework for designing an oil spill monitoring study (Source: adapted from ANZECC/ARMCANZ 2000a)
In the initial response phase, where a key objective is to delineate the area affected by the spill, the monitoring will encompass a large geographic area, but at a relatively coarse resolution using methods such as aerial surveys, ground surveys and remote sensing. Observations are limited to the distribution of oil that can be detected visually or by remote sensing. If required, detailed observations and chemical analysis may then be used to determine toxicity, exposure, weathering and fate. This necessitates sampling of the environment, which then introduces considerations such as choice of sampling units, sample size and selection of sites (see discussion below). Where variability is high, to precisely characterise oil concentration or reliably detect an impact may require a large monitoring effort in both time and resources. The need for such effort must then consider whether the objective of the study is of sufficient importance to justify the monitoring needed; that is, the time and resources required may be considered ‘unreasonable’ unless the objective of the study is of high importance or relevance to the response effort.

The spatial boundaries of a monitoring study will depend primarily on the actual or potential area affected by the spill, and should be sufficient to meet monitoring objectives. The study area or location is usually focused on determining impacted areas and the level of effects, linking effects to the spill source, and supporting decisions on clean-up strategies.

The boundaries should also be sufficient to cover representative areas of each:

- type of substrate
- ecological community
- shoreline energy level
- degree of oiling
- clean-up method employed
- reference site.

### Table 3.2. Checklist of factors to be considered in the design of a monitoring program

<table>
<thead>
<tr>
<th>Item</th>
</tr>
</thead>
<tbody>
<tr>
<td>What resources or sensitive receptors are present in the area?</td>
</tr>
<tr>
<td>- Have they been exposed to oil or other chemicals?</td>
</tr>
<tr>
<td>What is the spatial and temporal scale of the survey?</td>
</tr>
<tr>
<td>A balance must be made between being feasible (i.e. fast and cost effective) and being thorough (taking many samples over a large time scale and fine spatial gradient to produce the best possible data package)</td>
</tr>
<tr>
<td>- Should the survey be subdivided into sections where the most oiled areas are surveyed most intensively and most often, and less intensively at less impacted sites?</td>
</tr>
<tr>
<td>Are there baseline data available?</td>
</tr>
<tr>
<td>- Are the baseline data seasonally appropriate?</td>
</tr>
<tr>
<td>- Is the methodology used comparable with what would be implemented in subsequent studies?</td>
</tr>
<tr>
<td>- What level of variability was recorded in the baseline data?</td>
</tr>
<tr>
<td>What study design are you using (e.g. BACI, references sites, a combination)?</td>
</tr>
<tr>
<td>How many control and impacted sites will you measure?</td>
</tr>
<tr>
<td>Is there (will there be) an obvious gradient along the impact?</td>
</tr>
<tr>
<td>What are the trigger points for the initiation and cessation of monitoring?</td>
</tr>
<tr>
<td>What parameters are to be monitored?</td>
</tr>
<tr>
<td>What methodology will you use?</td>
</tr>
<tr>
<td>What are the methods for data analysis?</td>
</tr>
<tr>
<td>How will you track samples and analysis?</td>
</tr>
<tr>
<td>What forms and databases will you use?</td>
</tr>
</tbody>
</table>

In the initial response phase, where a key objective is to delineate the area affected by the spill, the monitoring will encompass a large geographic area, but at a relatively coarse resolution using methods such as aerial surveys, ground surveys and remote sensing. Observations are limited to the distribution of oil that can be detected visually or by remote sensing. If required, detailed observations and chemical analysis may then be used to determine toxicity, exposure, weathering and fate. This necessitates sampling of the environment, which then introduces considerations such as choice of sampling units, sample size and selection of sites (see discussion below). Where variability is high, to precisely characterise oil concentration or reliably detect an impact may require a large monitoring effort in both time and resources. The need for such effort must then consider whether the objective of the study is of sufficient importance to justify the monitoring needed; that is, the time and resources required may be considered ‘unreasonable’ unless the objective of the study is of high importance or relevance to the response effort.

The spatial boundaries of a monitoring study will depend primarily on the actual or potential area affected by the spill, and should be sufficient to meet monitoring objectives. The study area or location is usually focused on determining impacted areas and the level of effects, linking effects to the spill source, and supporting decisions on clean-up strategies.

The boundaries should also be sufficient to cover representative areas of each:
3.2.2 Critical sampling design considerations

Critical sampling design considerations include the selection of monitoring sites, required precision, sampling frequency and monitoring targets (Fig. 3.2). In the initial response phase, when monitoring involves observations of the entire geographic area of the spill, these considerations may not be relevant. In later monitoring stages, when sampling is required, these questions become critical.

Selecting monitoring sites

Generally, it is not possible to sample the entire area affected by a spill, so, for practical reasons, effort is allocated to smaller areas or sites within the affected area. Within a site, sample data are collected for the variables of interest.

The degree of oiling is likely to be patchy, even at a site that seemingly has uniform physical characteristics. Choosing sites and locations within sites to sample can influence the level of impact that is measured. The choice of sampling location will depend on the objective of the monitoring program. Some commonly used methods for selecting sampling locations are:

- **Authoritative or selective sampling.** In this case, expert judgement is used to bias sampling deliberately in favour of a particular subset of the population (e.g. the most heavily oiled sites). This allows for a small number of samples, but samples are not representative of the broader area and are not amenable to statistical inference.

- **Random sampling.** This is more likely to provide a representative sample and therefore allows conclusions about the broader area. It may require a larger number of sample locations to achieve a given level of precision. For monitoring that may be legally challenged, or scientifically scrutinised, this method is recommended. This is unusual for response phase monitoring though. Haphazard sampling (as described in Quinn and Keough 2002) may be a less laborious way to achieve the same result.

- **Systematic sampling.** This sampling uses a grid or consistent pattern across the defined area. This approach is most suitable when looking for locations that are not obviously contaminated, such as sub-surface oil.

In determining the sampling method, personnel should also consider the need for repeated sampling or measurements. If sampling is non-destructive (e.g. counts of sessile invertebrates) then each location can be recorded and re-used. This reduces the chance variation over time but requires that careful consideration be given to whether each location is really representative of the site (if this is required, of course), and the fact that repeated measurements may not be independent of one another.

When attempting to detect impacts or compare areas, it is important to account for pre-existing influences on the environment.

Stratification of sites

Wherever possible, monitoring sites should be selected on the basis of one (or more) defined strata such as a single substrate type (cobble beaches, rock platforms), defined tidal elevation or range, or a homogeneous area of biological importance (e.g. seagrass beds). This ‘stratification’ minimises non-spill related variance and allows sites to be directly compared where the key difference is the impact of the spill or clean-up method used, rather than a range across a local variable (such as wave exposure or habitat type).

Selection of control sites

When comparing impacted sites with unimpacted sites, the latter should be as similar as possible to impacted sites, should be representative of wider areas, and be free from obvi-
ous sources of confounding influences unrelated to the spill. In particular, key physical factors (i.e. temperature, salinity, currents, aspect, habitat type, shore profile and substrate) should not differ significantly between sites. Multiple sites are usually required to account for natural variability between control and impact sites.

Sampling sites can also include areas that have been impacted by the spill and are left to recover naturally. These sites are used to assess the effects of clean-up options, and/or natural recovery. It is often difficult to convince people that leaving impacted sites uncleaned is an appropriate thing to do.

**Spatial variability – spatial replication**

Some monitoring variables, particularly ecological ones, can display considerable variability both within and among sites, and may display different temporal trajectories even between sites that are relatively close together. This variability may exist completely independent of oiling, and can reduce the precision of sampling and potentially confound interpretation of results. To manage this, monitoring must provide an estimate of the natural variability (and therefore the precision of sampling) by taking replicate observations at the relevant spatial scales. Replicate samples within sites provide an estimate of variation within sites, while replication of study sites is required to account for natural variability between control and impact sites.

**Frequency – temporal replication**

The timing and frequency of sampling is dictated by the objectives. For example, in monitoring to support shoreline operations, the degree of oiling could be determined once before the clean-up commenced, then once more when the clean-up was completed, to ensure that the endpoint had been reached. In contrast, longer-term ecological monitoring (recovery phase) may require sampling over several years in order to distinguish between impact or recovery and natural temporal variability. Selection of sampling times may be random or, more usually, would be stratified according to the expected degree of temporal variability. For example, variables that fluctuate seasonally might be sampled in the same season each year (Keough and Mapstone 1995).

**Precision**

Natural variation of local or spill impact parameters can reduce the precision of sampling, which reduces the reliability of sample results and limits the size of effect that can be detected statistically. The required level of precision will depend entirely on the objective of each monitoring study and the end-use of the data. The sampling effort required to obtain a specified level of precision can be calculated fairly simply (Sokal and Rohlf 2011), but determining the degree of precision required is a matter of judgement. The precision of sampling becomes important when inferring differences between two or more samples, when it is necessary to distinguish between an actual difference and an apparent difference due to imprecise sampling. Generally, detection of small changes will require more sampling and replication than detection of gross changes. The level of sampling effort to detect a change of specified size can be calculated using statistical power analysis (Section 7.1.3). It is important to note, however, that during operational phase monitoring, other constraints may limit the size of the monitoring program.

**Selecting monitoring targets**

The choice of which variables to monitor may be specified in the program objectives or, in some cases, may be determined by the personnel doing the monitoring. Various monitoring targets have various advantages and disadvantages (Table 3.3).
Table 3.3. Potential targets for each level of monitoring

<table>
<thead>
<tr>
<th>Option</th>
<th>Suitable habitat</th>
<th>Advantages and disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Initial response phase – Has this area been in contact with oil?</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| Remote sensing                                   | Sea surface, shoreline    | • Wide area covered  
• Data obtained can be coarse  
• Data must be interpreted correctly (Section 6.2)  
• Image availability may be an issue  |
| Deploy field teams                               | Sea surface, shoreline    | • Accurate information can be obtained  
• Detailed information can be obtained (e.g. amount of oil coverage on leaves and roots)  
• Can be combined with other levels of monitoring  
• Logistical constraints  |
| Observer accounts                                | Sea surface, shorelines   | • Wide area covered  
• Reliability of information may be an issue  |
| **Advanced response phase – Is the oiling in the area likely to cause an impact? What is the spatial or temporal extent of oiling?** |                           |                                                                                                                                                                                                                            |
| Chemical analysis of environmental samples       | All                       | • Clear information about the concentrations, weathering state, and potentially the source of oil  
• Can be difficult to extrapolate from concentrations to effects, especially for chronic exposure  
• Does not account for bioavailability  
• May only be a snapshot – does not integrate over time  
• May not account for multiple stressors, response technology  
• Samples collected from areas with pre-existing impacts  |
| Collection of samples for toxicity testing       | Waters, sediment          | • Clear information about the potential for oil concentrations to cause impacts  
• Can be difficult to extrapolate from laboratory effects to field effects, especially for chronic exposure  
• Toxicity tests cannot be performed on all taxa (notably few tests for corals, seagrasses, mangroves)  
• May only be a snapshot – does not integrate over time  
• May not account for non-chemical stressors  
• Samples collected from areas with pre-existing impacts  |
| Biliary FACs in fish bile                         | Any environment where fish are present | • Well-established marker for oil exposure  
• Shows exposure to pharmacologically relevant oil concentrations only, not effects  
• May not be appropriate for all types of oil – will be a better indicator for heavier products  
• May not account for multiple stressors, response technology  
• Need to sample fish with a confined home range  |
### Preparation for Oil Spill Monitoring

<table>
<thead>
<tr>
<th>Option</th>
<th>Suitable habitat</th>
<th>Advantages and disadvantages</th>
</tr>
</thead>
</table>
| Accumulation of oil in sessile invertebrates, deployed bivalves or SPMDs | Any environment where bivalves are present or can be deployed | • Well-established marker  
• Integrates concentrations over time  
• Need to choose animals that do not metabolise oil  
• The same organisms need to be sampled at multiple sites for comparison  
• Seasonal variation due to spawning can confound results  
• May not account for multiple stressors  
• Samples collected from areas with pre-existing impacts can be difficult to interpret |
| Increased abundance of hydrocarbon-degrading bacteria                   | Waters, sediments                                    | • Clear indication of the bioavailability of labile hydrocarbons  
• Bacteria may not respond to the same fractions of oil that are causing toxicity |
| Recovery phase – What is the impact of exposure to oil or the response technology? Has the area recovered from these impacts? | Any                                                   | • Clear indication of impacts and recovery  
• Often need to select appropriate indicator taxa  
• Labour intensive, need trained personnel  
• Need suitable reference sites  
• Baseline data preferable  
• Natural variability and multiple stressors can confound the data |
| Change in abundance or community composition of resident organisms (e.g. decreased abundance of plankton/eggs/embryos; changes in per cent coral cover, die-off of plants) Can be done via traditional or molecular methods | Any                                                   | • Clear indication of a diseased state  
• Needs suitably trained personnel  
• Species-specific, not ecosystem wide, information is obtained |
| Copepod to nematode ratios                                             | Soft-bottomed sediment where both copepods and nematodes are normally abundant | • Well-established and sensitive indicator for adverse effects  
• Less labour- and knowledge-intensive than total community abundance  
• Need suitable reference sites  
• Baseline data preferable  
• Natural variability and multiple stressors can confound the data |
| Histology in fish or other invertebrates                               | Any environment where fish are present               | • Good health indicator in difficult-to-survey organisms  
• Need specialised equipment, trained personnel  
• Species-specific, not ecosystem wide, information is obtained |
| Decreased photosynthetic ability                                        | Mangroves, salt marshes, seagrasses                  | • Sensitive indicator of health  
• Increasingly used in the literature  
• Need highly trained personnel  
• Can be difficult to interpret the data  
• Species-specific, not ecosystem wide, information is obtained |
| Molecular markers of exposure and effects in organism                   | Any organism                                          |                                                                                             |
Key components to consider when deciding what parameters to include in monitoring include:

- Are human, equipment and other required resources available?
- Are selected parameters able to detect changes/trends?
- Can parameters be measured in a reliable, reproducible and cost-effective way?
- Are parameters appropriate for the time and spatial scales of the study?
- Are appropriate field techniques available?

More guidance on selecting appropriate monitoring targets for the protection of Australian habitats is provided in Section 7.5.1 and in Table 3.3.

During the initial response phase, factors that could lead to termination of the monitoring include:

- The spill is a comparatively small size.
- The product spilled is light and easily weathered.
- The spill is entirely in deep water, offshore areas for the purposes of informing the response.
- The spill is effectively contained using booms and mechanical clean-up.

Factors that could lead to escalation of monitoring:

- a comparatively large spill
- a heavy oil
- a spill that could impact a nearshore area or socioeconomically important resource
- a spill for which a controversial response technology is used.

As outlined in Section 1.2, this Handbook covers a wide range of potential spill scenarios from small to very large. In any given scenario, however, the monitoring program needs to be tailored to meet the needs of the IMT managing the response, and should be proportional to the size and expected impacts of the spill. An example of where a smaller monitoring effort was chosen, and the rationale for the smaller response, is provided in Box 3.1. By contrast, a description of an exercise that, if real, would have triggered an extensive monitoring program, is provided in Box 3.2.

### 3.3 Field sampling program

With the basic outline of a sampling program determined, the next stage involves the implementation of this in the field. This will include: (i) initial reconnaissance; (ii) the selection of sample collection methods for water, biota, sediments and particular requirements for oil in these matrices (e.g. oil on surface waters); (iii) identification of any field measurements needed; (iv) determining sample container requirements for identified analytes; and (v) determining sample preservation and storage requirements (ANZECC/ARMCANZ 2000a). Considerations need also to be given to QA/QC and occupational health and safety issues associated with these measurements.

#### 3.3.1 Initial reconnaissance

For any spill, response intelligence needs mean it is always necessary to collect basic information on the type and volume of the spill, its trajectory and the likely receiving environment. This information can assist in identifying key design elements of a monitoring program and areas where further information is required. Without knowledge about
Box 3.1. Response phase monitoring for the Golden Beach mystery spill

A mystery spill near the town of Golden Beach, on Ninety Mile Beach in Victoria in March 2014, resulted in oiling of ~23 km of shoreline with crude oil in the form of weathered waxy granules up to 1 cm in diameter. Surveillance showed evidence of additional oil deposition during the initial phases of the response. The clean-up effort focused on priority amenity areas of beach in the vicinity of the town and camping grounds. Since the threshold for potential ecological harm was not thought to be exceeded during the spill because of the weathered state of the oil and the very low concentration of the oil, as discussed further below, clean-up efforts were primarily focused on amenity values. A clean-up endpoint based on amenity values was discussed and agreed with local community representatives.

Response phase monitoring was initiated to inform operations in conjunction with the shoreline clean-up. Because the source of the oil was unknown, a key consideration for monitoring was the possibility of additional oil coming ashore during the operation and after clean-up ceased. Trajectory modelling was initiated (reverse modelling to determine possible sources and forward modelling conducted to predict the movement of fresh oil) and monitoring consisted of both aerial and on-ground surveillance. Aerial surveillance was conducted daily during the operation with the objectives of:

- identifying the source of the oil
- determining the presence of oil at sea that could result in additional stranding
- determining the spatial extent of shoreline oiling.

Aerial surveillance was conducted from fixed-wing aircraft by a trained oil spill observer. The flight path was recorded by GPS and geo-located photographs were mapped against the flight path to generate a visual record. Helicopters also contributed to aerial surveillance, including after clean-up operations had ceased.

Daily land-based surveillance (on foot and by an all-terrain vehicle) was undertaken to:

- determine the density of oil granules
- monitor the natural weathering and dispersion of existing oil
- look for evidence of fresh oil or redistribution of existing oil
- determine when clean-up endpoints were reached.

Following clean-up, an additional monitoring program was implemented to detect any additional oil stranding, or redistribution of oil that could result in the need for further clean-up.

The situation called for a design that could be undertaken by personnel with minimal training in monitoring, within a reasonable timeframe (i.e. a complete survey in 1 day). The shoreline was sampled using quadrats (25 × 25 cm) placed within the oiled band at ~50 m intervals along a 200 m stretch of beach at each of six locations within the initial 23 km oiled area. At each point, a 20 cm trench was dug across the oiled band to look for evidence of buried oil. Quadrats and trenches were photographed to retain a visual record of the fate of the oil on the shoreline (Fig. 3.4).

The extent of oiling was assessed in the field by comparison of surface cover with a set of photographs of quadrats that were below the acceptable termination criteria.
Monitoring personnel were instructed to alert the IC in the event of either a greater cover oil than shown in the photos, or the appearance of fresh oil.

Monitoring was scheduled daily for the week following the termination of clean-up, then twice-weekly for 2 weeks, and then monthly for 3 months, because it was considered that the likelihood of further oiling from the original source would decrease over time.

Several other considerations informed the monitoring program for Golden Beach:
• The environment team considered the need for water sampling, but, since aerial surveillance found no evidence of an oil slick at sea and levels of oiling on the shoreline were low, water sampling was not considered warranted.
• Due to the relatively low density of oil on the shoreline, and the weathered nature of the oil (which made it unlikely to penetrate sediments), sediment analysis was not warranted (monitoring found no evidence of buried oil).
• There was no evidence of oiled biota and no slick observed at sea, therefore sampling of biota was not done.
• Through the use of sensitivity maps, a potential risk of disturbance of endangered shorebirds (hooded plover) by shoreline clean-up operations was identified, but local wildlife authorities advised that the species was not present in the area at the time.
• Investigations were unable to trace the oil back to a source.

This monitoring program was relatively modest in size and relied mainly on visual assessments rather than quantitative analysis. Nevertheless, the program met all of the operational requirements of the response, and the size of the program was considered commensurate with the level of risk assessed at the time of the incident.

**Fig. 3.4.** Quadrat (25 cm × 25 cm) with light cover of weathered oil granules on Golden Beach, 21 March 2014 (Photo credit: Michael Holloway). This level of oiling was well below the agreed threshold for ecological harm, and clean-up primarily focused on ensuring amenity objectives were met.
Box 3.2. Exercise Westwind monitoring planning example, 8–12 June 2015

As part of the National Plan for Maritime Environmental Emergencies, Australia regularly undertakes oil spill response drills to make sure that our readiness is sufficient. One of these recent drills, Exercise Westwind, serves as a good case study for an oil spill scenario that would have had rapid escalation in the scale of the response if it had been an actual event instead of a drill. The exercise simulated an integrated multi-sectoral (e.g. industry, CSIRO and government response agencies) response to a Level 3 maritime environmental emergency (see Table 1.1). The exercise brought together both government department and agencies (state and federal) as well as the offshore oil and gas industry in Australia.

The deployment exercise comprised an IMT based in Perth, WA, with tactical operations carried out in Exmouth, WA.

Tactical operations included:
- simulated well intervention, including sub-sea remotely operated vehicle (ROV) operations
- fixed-wing aerial dispersant deployment
- offshore, nearshore, shoreline and oiled wildlife response.

During the exercise, several monitoring requirements were considered for the simulated incident, with monitoring requirements evolving throughout the exercise. Although no monitoring personnel were deployed to the field, the exercise tested preparedness planning within CSIRO to the point of deployment in the field.

Fig. 3.5 outlines the decisions that were taken within the IMT by the environment unit during the exercise, the questions that needed to be answered and the monitoring actions to be undertaken to answer these questions. The schematic also details some of the considerations associated with each monitoring/response action, which can be critical impediments to the deployment of an effective and timely monitoring response that informs situational awareness. Due to the exercise being simulated over a compressed period, no timing elements have been included.

At the beginning of the exercise, aerial surveillance and oil spill trajectory modelling was initiated through the National Plan arrangements using pre-existing contracts and trained personnel. During an actual incident, collection of spilled materials would also be critical to understanding oil behaviour, weathering and toxicity, and would have to be performed in concert with the aerial surveillance and trajectory modelling if the oil characteristics were unknown.

Due to the location of the simulated spill in open waters, an early decision was made to disperse the slick to reduce the possibility of the oil at the sea surface collecting on beaches or impacting other sensitive receptors in the area. If dispersants are to be used, monitoring their efficacy will inform the response on the validity of the combat approach. Dispersant efficacy monitoring is discussed elsewhere in this book, but can take a variety of forms and is independent of the dispersant used. Planning for the deployment of dispersant efficacy monitoring equipment, combined with opportunistic sampling to validate water column dispersion and hydrocarbon loadings, was undertaken.

As the exercise scenario evolved, spill trajectory modelling suggested that shorelines in the region would be oiled. This required monitoring teams to be deployed
### Decision point

- **Incident**
  - Determine nature and magnitude of incident
  - Where is the oil? Spatial extent on surface
  - Where is the oil likely to go? On surface and below
  - What is the oil and how will it change?

- **Dispersant application**
  - NEBA process determines dispersant use and offers best environmental outcomes
  - Are the dispersants working as predicted?
  - Can shorelines be assessed pre-oiling?
  - What is the nature of the oiling?

- **Shoreline impact predicted**
  - NEBA process identifies sensitive nearshore receptors
  - What is the baseline condition of the nearshore receptors?

- **Sensitive receptors identified**
  - NEBA process identifies sensitive nearshore receptors
  - What is the baseline condition of the nearshore receptors?

### Data required

- Where is the oil? Spatial extent on surface
- Where is the oil likely to go? On surface and below
- What is the oil and how will it change?

### Monitoring/assessment requirements

- Initiate spill modelling
- Collection of spilled materials
- NEBA process suggests possible shoreline oiling
- Shoreline assessment and technique

### Considerations

- Contract and expertise to initiate activities?
- Understanding of input parameters and their impact on outputs?
- Ability to integrate and interpret products into response situational awareness framework?

- Is a field sampling kit available to be very rapidly deployed?
- Are trained responders available locally and do they have the correct PPE (e.g., gas masks)?
- Is a vessel (or other) able to travel to the location immediately?
- Has the logistics chain and sample receiving laboratory been tested?

- Is a field monitoring kit available to be very rapidly deployed?
- Are trained responders available and do they have the correct PPE?
- Is a vessel (or other) able to travel to the location on arrival of the monitoring team to port?
- Is it suitable to carry out the activities?
- Does the vessel have suitable sample storage? Is specialist deployment equipment required?
- Has the logistics chain and sample receiving laboratory been tested? Are there sufficient consumables for a prolonged campaign?

- Is field monitoring logging equipment available to be very rapidly deployed?
- Are trained responders available and do they have the correct PPE?
- Are there up-to-date infrastructure and sensitive receptor maps available?
- How do the responders get to the field? Is transport available? What is their accommodation?

- Is field monitoring equipment available to be rapidly deployed?
- Are trained responders available and do they have the correct PPE?
- Is a nearshore waters vessel (or other) able to be deployed to the location. Is it suitable to carry out the activities? Is diving required?
- Does the vessel have suitable sample storage? Is specialist deployment equipment required?
- Has the logistics chain and sample receiving laboratory been tested?

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**Fig. 3.5.** Examples of monitoring requirements during Exercise Westwind in June 2015
to collect data on the extent of oiling, as well as to assess sensitive receptors and logistics concerns. This was anticipated to follow augmented shoreline assessment and clean-up technique methods. Planning for team and equipment mobilisation and survey areas was undertaken ready for deployment.

In addition, the impacts within the region on other sensitive shoreline receptors (corals and associated habitats considered at risk of being affected as the incident scenario evolved) were identified. To enhance the understanding of what sensitive receptors were present and their baseline condition, a monitoring team was mobilised. A pre-emptive assessment strategy was rapidly planned, which included sampling and collection of data in areas that had already been previously studied.

Although monitoring teams were not deployed to the field during this exercise to complete the monitoring objectives, the exercise was invaluable in testing the operational requirements of oil spill monitoring, which are often overlooked in the oil spill planning process. Preparedness of oil spill monitoring, as with oil spill operational response, is critical if meaningful monitoring is to be undertaken, which enhances situational awareness and understanding of the efficacy of combat operations.

where a spill is likely to end up, it is difficult to select monitoring sites or sampling and analysis methods.

In most spill situations, information on the spill trajectory can be assessed by direct spill tracking (e.g. visual observations and remote sensing), or estimated using wind and current data (manual or computer calculations).

- **Aerial surveillance** provides a reliable and rapid method for defining the overall extent of a spill area, and identifying oiled shorelines and those at threat from the spill. Photographs, video, mapping and verbal feedback all provide basic information that can be used to define information needs and response priorities.

- **Ground surveys** permit more detailed observations of shoreline conditions including the physical structure, ecological character and human use of shorelines. This monitoring approach can provide comprehensive detail on the resources and activities likely to be affected by a spill, the potential extent of oiling and level of impact, likely recovery, and logistical considerations for different response methods.

- **Remote sensing** includes a wide range of techniques to detect spills using equipment such as infrared (IR) thermal imaging, side-looking airborne radar, and satellite images. These techniques are not always available or suitable, but can provide very useful data in some situations.

Most methods, including biological sampling, require expert input and this should be sought early in the development of a program if there is any doubt about the appropriateness of a technique, or there are questions about whether the selected method can provide the type of information required.

When selecting monitoring methods, the following questions cover some of the key aspects that must be considered:

- Can sampling be undertaken safely (see Section 4.2.3)?
- Can appropriate data be obtained by field measurements?
- Does the design account for spatial and temporal variability?
• Will the study provide meaningful information in a relevant timeframe?
• Will samples need to be collected?
• Will sampling devices collect representative samples?
• Will sampling devices contaminate or affect the sample?
• Will samples contaminate or affect the sampling devices?
• How many samples are required?
• Will samples need to be preserved before analysis?
• Are procedures in place to track samples and field data?
• Can potential sampling error be minimised (e.g. sampling protocols, training)?
• Can potential sampling errors be managed?
• Can data be analysed and accessed in a timely manner?
• What resources are needed and are available for the monitoring program? Do logistical concerns impede their deployment (i.e. can they get to the spill location in enough time to be effective)?

Some suggestions as to which monitoring data could be collected at different time points during the spill are provided in Box 3.3.

### 3.3.2 Sampling of waters, sediments and biota

Because oil spill monitoring, even following relatively small incidents, will require numerous sampling campaigns where different types of samples are taken by different people in different locations at different times, standardised operating procedures (SOPs) for the collection of these samples or for the collection of biological data must be followed. This ensures that the samples and resulting data are of sufficient quality to be used in monitoring and also that samples collected across the entire campaign are comparable. Examples of generalised SOPs that could be modified for monitoring efforts are provided in the appendices of this volume, as outlined in Table 3.4. These SOPs, or alternatives that may be more appropriate for a given circumstance, should be used in the planning process to ensure that the necessary equipment and trained personnel are available at the time of an incident.

The sampling of waters can involve sampling of the bulk water column, as well as the surface microlayer where the oil will be concentrated. The surface film can be collected using a Teflon® mesh or an expanded polytetrafluoroethylene (ePTFE) absorbent membrane sampler. In sampling the water column for dissolved hydrocarbons, any of the traditional sampling methods can be used, provided that they avoid collecting the surface film (e.g. Appendix B). In some instances (e.g. Appendix A), grab samples are collected that deliberately include surface oil.

Because the concern is for hydrophobic organic compounds, glass sample containers are preferred to minimise adsorptive losses. A pole sampler containing a plastic (polyethylene) sample bottle can be used to rapidly transfer surface water samples to a glass jar. For depth sampling (>1 m), conventional Niskin bottles (grey PVC) are adequate, but samples should be transferred as soon as possible to amber glass bottles. All samples should be stored at 4°C in the dark.

Most of the standard sediment sampling protocols are applicable to oil spill contaminants. These include grab samples, shoreline samples using PVC or Perspex® push corers or for deeper areas larger cores collected by divers or multicorer rosette samplers operated from a boat. Sediment samples should be stored frozen to avoid losses. These can be partially thawed and sub-sectioned before analysis if depth profiles are being measured.
Box 3.3. What monitoring steps need to be taken when?

Before an incident occurs
Environmental baseline data, including the presence of sensitive receptors in the spill area, should be collated. These are available as geospatial data, such as the oil spill response atlas (an example is provided in Fig. 3.6). More information may be available from baseline surveys conducted in areas that would be impacted if a spill were to occur as a result of oil and gas exploration.

As soon as an incident occurs, but before sensitive areas are impacted
Spill responders should, wherever possible, obtain pre-spill data on the parameters to be monitored. Once areas expected to be impacted by oil are known, baseline data can be collected. If the area is well studied, this may be as simple as assembling previously collected monitoring data. Custodians of relevant baseline data should be consulted to determine data availability and suitability. These custodians may include, for example, offshore petroleum industry titleholders, state government agencies or research agencies. However, if a shipping accident occurs outside these areas, samples of pre-existing conditions may be required. Depending on the size of the spill and expected impacts, these samples may include water and sediment for analysis of hydrocarbon chemistry (Appendices A–I), plankton tows for community structure analysis (Appendix N), sediment cores for microbial community structure analysis.
The collection of biological samples for oil contaminant analyses follow standard procedures, and specific SOPs are provided in the Appendices.

3.3.3 Collection of baseline data

In some locations, as part of the oil spill management emergency or contingency plans prepared by the maritime, or oil and gas industry, baseline data will already exist for the region likely to be impacted and will not need to be collected at the time of the spill. However, in the case of a shipping accident (which could, in theory, occur anywhere in Australian maritime waters, not just in areas monitored for the potential impacts of oil production), there may be little, if any, baseline data to assess the environmental impacts of the spill. Jurisdictions may hold information about existing baseline data, which could be assessed for compatibility with monitoring needs.

Once an impact occurs, but before any response begins

An additional set of samples (e.g. water and sediment chemistry, planktonic and shoreline samples, tissue samples) may be taken once oil has made contact with the receptors in question, but before the response to oiling occurs. These samples will help to demonstrate that any ecosystem damage relates to the oil exposure and not to the response, which may be important in subsequent litigation.

During the response phase

Samples will need to be collected during the response phase to assess the efficacy of the response. Some of these samples could also be used to determine when the response phase has ceased and how to transition to the recovery phase.

During the recovery

Samples for the recovery phase of the operation should be taken as specified in any pre-existing monitoring plan. However, the samples taken during earlier phases should act as a foundation for determining the impact of the spill and recovery from that impact. For large spills where recovery is expected to take place over a period of years or over a large spatial scale, monitoring for recovery may need to take place using an adaptive management framework.
If data do not exist or are not suitable, urgent just-in-time samples will have to be collected from areas likely to be in the oil trajectory before oil actually makes contact, as well as from potential reference sites outside the spill zone. The nature of these samples should be predicated on hypotheses about the sorts of impacts that may be reasonably expected, and may include:

1. Water, biological tissue and sediment samples to permit accurate determination of hydrocarbon concentrations and composition
   (a) These samples are especially important in urbanised areas, areas with high shipping traffic, areas with offshore production, or any other areas that may have pre-existing concentrations of petrogenic or pyrogenic hydrocarbons. This is described further in Section 7.2.

2. Data on the ‘normal’ aquatic species composition in the area to be impacted
   (a) These may include the occurrence of rare or threatened and endangered species that may be ‘patchy’ or episodic users of an ecosystem
      (i) Responders will have to counterbalance the high degree of public interest in these organisms (and the high degree of scrutiny these data will receive) with the fact that rare species are unlikely to reveal useful trends and the possibility that resources may be better used elsewhere.
      (b) Responders will have to strike a balance between thorough documentation and efficiency (for both time and cost) and are encouraged to focus on the habitats outlined in the sections on specific Australian marine ecosystems (described in Section 2.3)

### Table 3.4. SOPs for sample collection, discussed in the Appendices

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<td>Wide-mouth jars</td>
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<td>Volatile organic compounds analysis</td>
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<td>Surface oils analysis</td>
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<td>Sediment</td>
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<td>Non-avian wildlife</td>
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Molecular analysis of microbial and planktonic species composition may assist in assessing the system (described in more detail in Box 7.5). These samples should be collected even if there are no immediate plans to analyse them. If bioremediation is being considered, samples documenting the normal abundance of bacteria and algae (which are normally nutrient-limited) will be invaluable in determining the impact of the response efforts.

(c) Because the opportunity to collect pre-impact baseline data, if they do not exist already, will be limited by logistical constraints and the ability to distinguish between changes that are caused by natural variation and seasonal impacts (as well as any changes related to global climate change) and those that are caused by oil, responders should keep this in mind when designing their monitoring studies.

3. For any area where the response is likely to involve heavy equipment, samples to document the ‘normal’ sediment grain size distribution and geomorphology should be taken before the response commences and after it is completed.

4. If biomarkers are to be used to help establish cause and effect relationships (see Section 7.4), ‘reference’ tissue should be archived. Because these analyses are often invaluable in the attribution of any changes observed in community structure or organism health to the oil exposure, responders should consider archiving samples even if there are no immediate plans to analyse them.

A checklist of considerations for pre-impact baseline data collection is given in Table 3.5.

### 3.3.4 Time-of-impact data

As counter-intuitive as it sounds, it can often be difficult to conclusively prove that an oil spill actually had a negative impact in a system. Although oil is highly toxic in laboratory studies, a myriad of factors, including natural ‘patchiness’ of organisms in ecosystems,
density-dependent recruitment, multiple stressors and the impacts of the oil spill response, can make the impact of the spill difficult to measure (Fodrie et al. 2014). Time-of-impact samples are especially valuable where an oil spill response technology is used, because that response may cause more or additional deleterious impacts than the oiling itself (see Box 5.1). The samples that could be taken at the time of impact are similar to those described above.

A checklist of considerations for time-of-impact samples is given in Table 3.6.

### 3.3.5 Monitoring QA/QC

Information collected during the response to a spill may become part of a legal record. It is possible that there may only be one chance to collect the samples that become the permanent record of what happened before, or at, the time of impact. Due to the importance of the samples from a scientific and legal standpoint, the influence that the samples will have on the decision-making process during the response, and the often considerable expense that goes into collecting them (from both a resources and human capital standpoint), it is important that appropriate quality assurance and quality control (QA/QC) protocols be followed to ensure that the samples and subsequent monitoring data can be used for maximum value (ANZECC/ARMCANZ 2000a). General guidance is provided on QA/QC. Each procedure in the response and recovery phase will have its own QA/QC requirements, and it is important that users are aware of these before the onset of sample collection. A more detailed description of QA/QC is provided in Section 3.5.

#### Standard operating procedures

During an oil spill response monitoring survey, especially following a major spill, it is very likely that multiple survey aircraft vessels, and shoreline teams will collect complementary data and samples. Since this information will be used by the IMT both for response planning and for assessment of the environmental damage, it is very important to develop SOPs to be used by all monitoring teams. These may include (but are not limited to):

- oil and sea state classification
- visual observation protocol
• sample collection procedure
• scheme used in numbering samples (e.g. Fig. 3.7)
• sensors to be deployed in field monitoring
• sensor maintenance and calibration method
• report template
• data QC procedures
• data interpretation workflow.

Operators collecting the same or similar data types should be operating from the same SOPs to ensure that the data are compatible. If the SOP is altered for logistical or safety reasons, a record of that change should be available to and adopted by all operators. This is especially important for teams working at different times, in different locations or on different vessels.

Replication
A single sample may be anomalous. Replicate samples should be taken (or repeated-measurements collected for features such as the oil spill trajectory that cannot be repeated) to account for the variability in both the feature being measured as well as the measurement technique. There are numerous statistical treatises on power analysis that deal with the sample numbers required to significantly distinguish an effect from mere chance (e.g. Quinn and Keough 2002), but, in most operational responses, the need for precision will be counter-balanced against logistical concerns, as well as ethical concerns for animal samples. At a minimum, three replicates are suggested for samples with low variability and five replicates for more highly variable samples if repeated measures are not used (e.g. as in hydrocarbon sampling).
Record keeping

To be able to use a sample after it has been collected, it is necessary to have information regarding where the sample was collected from, by whom, when, by what method and for what purpose. This information is referred to as the sample metadata and should be stored in a sample data sheet. An example of a sample data sheet is given in Appendix S. The same sample collection guidelines should be followed for each of the sample types. Any anomalous observation or issues that occurred at the time of sampling should be recorded because this can be critical information for assessing sample quality. Upon collection, the operator should also prepare a chain-of-custody form (Fig. 3.8) to provide evidence that the SOP for sample collection and processing has proceeded normally, or to document any exceptions from the normal SOP. Where possible, sample metadata should be logged electronically to avoid transcription errors and permit rapid transfer of data from the field.

Storage

Once collected, samples need to be stored appropriately to prevent contamination and decay. There are recommended holding times for water, sediment and biota samples beyond which the reliability of chemical, ecotoxicological and other testing results cannot be guaranteed. For example, PAH analysis in waters should be undertaken within 14 days from collection. For operational and legal reasons, it is important that samples for such analyses, wherever possible, are in compliance with the recommendations. When it is not possible to adhere to these holding times (e.g. as a consequence of remote locations or logistical challenges), these holding times may be extended through the processing of samples in the field (e.g. water extractions with solvents). However, these mitigation approaches do create additional potential points of contamination, may not be possible with the field facilities or may pose unacceptable logistical and safety risks. If holding times and in-field processing and analysis are not possible, inclusion of spiked samples using standards with known compositions and concentrations in the sample sets could help assess the decay of samples.

A key consideration in the storage of samples is whether the samples need to be stored at ambient conditions, refrigerated or frozen, either at −20°C or −80°C. Storage and shipping of samples, especially those frozen is often overlooked in planning and execution.
of monitoring plans and if not contemplated sufficiently early within the monitoring activity can lead to significant delays and the loss of samples through incorrect shipping.

Precise information regarding how each sample type should be stored, and for how long, will be provided in the SOPs. The chain-of-custody form is used to ensure that correct handling and storage of materials occurs throughout the transfer of samples from sampler to courier to receiving laboratory. In addition, the form can be used to identify individuals who may be helpful in resolving any questions about sample quality. Any observations that the samples appear to have been contaminated or stored improperly should be noted on the form. In some cases, especially where litigation is anticipated, a tamper-evident seal is attached to the samples to ensure they are received by the processing laboratory without alteration. Another consideration when shipping samples is one of permits. Do samples need quarantine permits to be shipped interstate? Do the receiving laboratories also need permits?

Contamination

A sample that is contaminated (e.g. with oil from the response vessel that is collecting samples, or with extraneous microbial material) cannot be used for operational, scientific or legal purposes. As a consequence, great care must be taken to avoid cross contamination. Sample contamination can arise from the monitoring vessel itself, improperly cleaned sampling equipment or lubricants used in the equipment, as well as from sunscreens, personal care products or cigarette smoke. Examples of precautions that could be taken include:

- changing gloves and other disposable gear between samples
- using a plastic sheet to avoid sample contact with dust and debris
- decontaminating sampling equipment before use by flushing equipment with clean sea water
- sampling from the middle of sediment cores
- collecting samples away from the vessel bilges or diesel generators.

An example of a pre-sampling cleaning protocol is given in Appendix J. Check SOPs to determine the best way to avoid contamination of individual sample types before sampling commences. Additional guidance is provided in the Australian Guidelines for Water Quality Monitoring and Reporting (ANZECC/ARMCANZ 2000a).

Blanks

Sample blanks are collected whereby the sampling procedure is mimicked without actually taking a sample, in an attempt to quantify the degree of cross contamination (from both the sampling and sample handling procedures) (ANZECC/ARMCANZ 2000a). Blank samples can be critically important, especially if complete decontamination is impossible, because they will allow differentiation between ‘signal’ and ‘background’. Some methodological blanks should be incorporated into the sample collection to determine background levels of contamination and sample carryover to be quantified or eliminated.

For water samples, for example, blanks might include: (i) field blanks, designed to detect contamination by dust and atmospheric fallout during opening sample container sand manipulating samples; (ii) container blanks to determine contamination from sample containers; (iii) equipment blanks to detect contamination from sampling equipment; (iv) filter blanks to detect contamination introduced during filtration; and (v) trip blanks where uncontaminated containers are transported along with samples to determine the contribution of the shipping process to hydrocarbon concentrations.
Spikes
Standard additions, or spikes of a known quantity of an analyte to a field-collected sample, is a common approach for demonstrating the efficiency of the measurement approach. This spike is typically a known standard that is not one of the analytes of interest but exhibits similar behaviours, including evaporative losses. Typically these recovery standards comprise deuterated versions of the analytes of interest. It is also a means of accurately measuring the amounts of material in a matrix if the values are anticipated to be near the limits of detection.

3.4 Laboratory analyses
The design of an appropriate laboratory chemical analysis program to deliver accurate and precise data, with required detection limits for identified analytes, is beyond the scope of this document. Analyses should be prioritised based on analyte stability and should be undertaken with appropriate laboratory QA/QC. It is important that those involved with chemical and ecotoxicological testing and ecological assessments are consulted with respect to sampling protocols (e.g. Appendix P) and sample size requirements and desirably have input into the sampling program.

For any analyte, the laboratory detection limit or limit of reporting (LOR), should be considered in relation to the level of sensitivity and precision required in the resultant data. Reports of analytical data produced by a laboratory should, for each analyte, include an indication of the method used, LOR, and any notes or comments that the analyst may feel should be recorded. These might include that sample sizes are too small, observations or indications of constituents present that were not requested for determination, indication that the sample has not been properly stored or transported, inappropriate sample container, and so on.

3.5 Data handling and management
During response phase monitoring, data may be transferred between sampling teams in the form of:

- imagery such as satellite imagery to show the location and distribution of the slick
- GIS layers such as GIS shapefiles to provide updated versions of oil spill trajectory modelling predictions of likely zones of impact to direct vessel response activities
- photography of the slick, samples collected, evidence of marine fauna or other wildlife
- GPS location data
- situational reports.

As such, large data volumes may be generated from multiple types of data. During large-scale response operations the use of a centralised database may be recommended through a formal data management plan, to act as a central data store. A data repository such as this can help track the data generated, can remove or reduce the reliance of recording information and observations on paper or one computer, and can enable data quality control and quality assurance measures to be applied to all data equally.

Data collected in the field should be backed up throughout any period of deployment, on a frequent and regular basis. Automatic data back-up is recommended for routine activities. Due to the vast scale of Australia’s national marine territory, a maritime oil-pollution incident could literally occur anywhere. As such, immediate transmission of
Data gathered in the field to the IMT may be unreliable or not possible. In these cases, duplication of records is imperative. Depending on the location of the oil spill response operation, a data sharing and telemetry channel could be set up and tested. Typically, if complete data records cannot be transmitted, then duplicate data records (in the form of hard drives) will be returned to the IMT as soon as possible (e.g. vessel return to port) or at a pre-agreed schedule.

Data security is important, to ensure that access to data is controlled and any data leaving the IMT should be authorised and interpretation/meaning/context provided.
Responding to an oil spill: initial assessment

Paul Irving, Xiubin Qi and Sharon Hook

4.1 Functions, roles and structures

Prior to any oil spill, there should be a clear plan for responding to that spill and for making an initial assessment. The structure for these plans and how they are implemented upon incident notification to inform situation awareness and the initial elements of the response are outlined in this chapter.

The Australian National Plan for Maritime Environmental Emergencies (AMSA 2014b) reflects the mandated responsibilities of the control agencies (and jurisdictions) (Box 1.1). This is consistent with the Australian Interservice Incident Management System (AIIMS), which is a doctrinal approach to response organisation structure very similar to equivalent systems used worldwide. Information management is critical to effective response and so the AIIMS model identifies many functions involved in obtaining, managing, processing and using information, which include the design and implementation of monitoring programs. Below is a brief introduction to a generic IMT organisational structure and functions (Fig. 4.1), showing where various types of monitoring functions are likely to located. This structure assumes a response large enough to require extensive deployment.

Most information management is undertaken in the planning and intelligence functional areas. These functions are closely linked. Planning requires intelligence on which to base options analysis and risk management. Intelligence is the process of collecting, evaluating and analysing information on the incident and provides the resultant information to the IMT. Intelligence can either be provided by an Intelligence Section for more complex incidents, or be a unit within the planning section for smaller less-complex incidents. Both can be combined within planning, depending on incident size. Monitoring design and delivery sits within an expanded intelligence function as shown below in Fig. 4.2.

4.2 Preparedness and contingency planning

Arrangements for monitoring should be understood and integrated into the incident management arrangements established within specific contingency plans. This may also include relevant legislative delegations, with certain powers and functions only being able to be undertaken or implemented by agencies or individuals. Marine Pollution Contingency Plan guidance can be found in AMSA’s Technical Guideline for the Preparation of Marine Pollution Contingency Plans for Marine and Coastal Facilities (AMSA 2015a).
PLANNING

Plans
Development and documentation of the IAP and supporting plans.

Resources

Communication planning
Response communications systems and logistics planning.

Management support
Administration services, document management, and communications management and delivery.

INTELLIGENCE

Environment

Mapping
Resources and response mapping, spatial and geographical information.

Modelling and predictions
Collection, analysis and presentation of situation information, through creation and maintenance of Common Operation Picture (COP) and Situation Reports. Weather information. Air observers.

Situation and analysis
Risk assessments, predictions of incident behaviour, contingency planning and development of most likely and worst-case scenarios.

Technical advice
All other response-related technical and scientific advice.

Monitoring advice
All monitoring-related design and delivery.

Fig. 4.2. The location of a monitoring responsibility and role within the intelligence functional area
In brief, the overall contingency plan should provide:

- **Risk assessment**: An assessment of the reasons for, and effects of, potential marine pollution associated with a particular facility or operational activity, including:
  - identification of expected monitoring requirements (objectives, expectations, techniques, methods, etc.) based on the possible spill and response scenarios
  - advance identification of resources that could be impacted, their sensitivity and value
  - conditions under which impact could occur
  - potential effects of the pollution and the significance of those effects to both ecological and socioeconomic resources.

- **Strategies**: The response options and strategies likely be deployed during an incident will be described in the contingency plan, but each may require specific planning regarding monitoring.

- **Capability/logistics**: The identification and provision of the necessary resources, equipment and trained personnel to design and implement the monitoring. Plans for the logistical arrangements needed to get people, equipment and resources to remote sites quickly, if necessary.

- **Documentation**: The development of clear and agreed documentation of incident management systems, organisation and procedures.

- **Maintenance**: The development and implementation of a system for the ongoing maintenance of monitoring capability (physical and human resources).

The good practice for contingency planning outlined in the Technical Guideline is also applicable to planning for monitoring. The process is summarised below in five steps:

1. **Establish the context.** The person responsible for monitoring operations should define the scope, regulatory, administrative and organisational context of any monitoring functions and roles, considering the:
   - Regulatory environment, including applicable legislation and regulation, permit conditions and relevant international conventions and agreements
   - Administrative arrangements, including the relevant state/territory/Commonwealth marine oil spill or disaster management arrangements and any other associated contingency plans
   - Organisational environment, including decision-making structures, approval processes, and procurement requirements
   - Stakeholders, including government agencies (local, state and Commonwealth), community groups and response support agencies.

2. **Risk assessment.** Using the material provided in the overall contingency plan, the monitoring team use the type of incidents likely and how monitoring could determine response needs, including:
   - What incidents are possible?
   - What contaminants could be released – crude oil, condensate, liquid chemicals, gases, lubricants, etc.?
   - What spill volumes are possible?
   - Identification of the area over which environmental impacts will potentially occur for each spill scenario, referred to as the zone of potential impact (ZPI).
   - Assessing the likely impacts to environmental and socio-economic resources resulting from each spill scenario.
3. **Response capability/logistics.** To determine what response strategies can be used within each response scenario:
   - Identify what response operations should occur where.
   - Evaluate each of the response strategies to determine specific monitoring needs.
   - Identify the monitoring resources required.
   - Procure and maintain any resources that can be arranged in advance, and establish systems/arrangements for any that can be established on the day.
   - Identify any common resources able to be leveraged or likely to be in short supply due to response activities.
   - Establish training and exercising arrangements to support the response capability.

4. **Documentation.** The monitoring capability should be documented within both the contingency plan and any associated standard operating procedures. It should include:
   - a description of the incident management arrangements, including command and control
   - monitoring procedures and processes, including activation and notification arrangement, planning processes, reporting and operational management
   - resources, including equipment listings, etc.

5. **Review and audit.** A process for review of the monitoring plan and capability should include:
   - regular auditing of capability
   - review of need
   - supporting or holding after-action reviews following exercises or incidents.

### 4.2.1 Field monitoring capability readiness

An important component of readiness is having personnel who could be deployed to field sites on very short notice to respond to an event. This component of readiness may require contracts with external agencies. The oil spill monitoring staff/team should know for which role they could be required, be capable and ready to respond, know with whom they will be working within the response structure, be knowledgeable of the SOPs and protocols required, but still sufficiently flexible and creative to complete the tasks.

Potential members of any field monitoring team should maintain a complete record reflecting training courses required for team members, renewal frequency, training provider information and current team members’ certificate status. In addition, automatic reminders should be set up for team members to renew certificates before their expiration date.

Table 4.1 lists some of the components of readiness that would enable a field monitoring team to complete its tasks at short notice. The exact list will vary according to context, response, task and organisational requirements.

### 4.2.2 Team roles and qualifications

The team leader should be clear on staffing requirements and each team member’s role and responsibilities. The role assignment can be critical to ensuring smooth field operations and team coordination. Table 4.2 presents one possible team composition, qualifications required and each member’s major role and responsibilities. Team composition will very much depend on the type of incident, response and monitoring expected and being planned for.

An example, based on the steps involved in the deployment of the CSIRO dispersant efficacy monitoring team, is provided in Fig. 4.3. Further examples of the information that would be required upon team deployment are provided in Appendix V.
Table 4.1. Different components of readiness that need to be maintained in case of an oil spill

<table>
<thead>
<tr>
<th>Personnel</th>
<th>Preparedness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Roles clearly assigned</td>
</tr>
<tr>
<td></td>
<td>Personal protective equipment (PPE) kit/grab bag is complete</td>
</tr>
<tr>
<td></td>
<td>Mandatory training certificates up to date</td>
</tr>
<tr>
<td></td>
<td>Contingency plan in place for back-up/replacements</td>
</tr>
<tr>
<td>Equipment</td>
<td>Monitoring equipment well maintained and serviced</td>
</tr>
<tr>
<td></td>
<td>Sensors routinely calibrated</td>
</tr>
<tr>
<td></td>
<td>Consumables maintained in adequate stock</td>
</tr>
<tr>
<td></td>
<td>Tool box and accessories checked</td>
</tr>
<tr>
<td></td>
<td>Contingency plan in place to deal with field equipment failure</td>
</tr>
<tr>
<td></td>
<td>Laptop/software, instrument data acquisition/communication tested</td>
</tr>
<tr>
<td></td>
<td>Equipment in an accessible location for deployed personnel to obtain</td>
</tr>
<tr>
<td></td>
<td>Logistics requirements known and shipping providers identified</td>
</tr>
<tr>
<td>Documents</td>
<td>Staffing requirement/team role assignment sheet</td>
</tr>
<tr>
<td></td>
<td>Equipment packing manifest with weight and dimension estimate</td>
</tr>
<tr>
<td></td>
<td>Field operation flow chart</td>
</tr>
<tr>
<td></td>
<td>Field monitoring recording form</td>
</tr>
<tr>
<td></td>
<td>Tool box instruction sheet</td>
</tr>
<tr>
<td></td>
<td>Equipment/software user manual</td>
</tr>
<tr>
<td></td>
<td>File sharing and communication plan</td>
</tr>
</tbody>
</table>

Incident occurs

IC considers dispersant

CSIRO scientific advice sought

IC agrees on dispersant use

Field team notified

Ops/Aerial applies dispersant

Field team activated

Ops/Plans assesses dispersant efficacy

Field team deployed

Plans/Env verifies dispersant efficacy

Field team active

IC agrees dispersant use ceases

Field team reports

Fig. 4.3. The process of field deployment used by CSIRO’s dispersant efficacy monitoring team
4.2.3 Health and safety considerations

The safety of responders and those involved in monitoring efforts is paramount. Numerous, up-to-date resources for health and safety will be available from the responder’s organisation, as well as from the IPIECA JIP Oil Spill Responder H&S Guide (http://www.ipieca.org/publication/oil-spill-responder-health-and-safety), the US National Institute of Environmental Health Sciences (http://tools.niehs.nih.gov/wetp/index.cfm?id = 2495) and

Table 4.2. An example of the possible composition of an oil spill monitoring team

<table>
<thead>
<tr>
<th>Team</th>
<th>Team composition</th>
<th>Qualification required</th>
<th>Roles/activity</th>
</tr>
</thead>
</table>
| Field team | Field team leader | Comprehensive understanding of all components of monitoring program | • Plan monitoring activities and resolve major issues during field monitoring  
• Communicate with and report to IMT office  
• Liaison with field operations team, office support team  
• Coordinate with field team members to conduct field monitoring to generate quality data and record  
• Choose the most appropriate sampling plan with regard to the data type and the spill situation in order to accurately represent the local characteristics  
• Engages with contractors, consultants and laboratories |
| Observer/data processing | | Trained with SOP for open water oil observation, data entry and data processing | • Observe and record observation/activities/photographs  
• Data entry, processing, back up and transfer |
| Field operator | | Trained with equipment maintenance and operation, preferably with instrumentation background  
Familiar with operating vessel facilities | • Conduct field monitoring  
• Maintain and service instruments and equipment  
• Understand QA/QC procedures  
• Understand SOPs and monitoring methods |
| Vessel crew | | | • Support field monitoring operation |
| Office support team | Office team leader | Comprehensive knowledge of all components of monitoring program  
GIS/database qualifications  
Familiar with travel, transport and logistics practices | • Communicate with and report to IMT office  
• Liaison with field team, coordinate with office team members for activity planning and formal report generation  
• Adjunct and liaison with intelligence unit mapping team to assist with activity planning and final report generation  
• Provide logistics support on travel ticket/accommodation booking, and shipping of equipment and chemicals |
### Table 4.3. Checklist of hazards associated with the response that response workers need to be aware of

- Are there hazards associated with the contaminant?
  - Oil only?
  - Oil and response agent?
  - Was a different chemical spilled?
  - Are there vapours or volatiles?
  - How should workers avoid skin contact and ingestion?
  - Is a copy of a safety data sheet (SDS) available?

- Are there hazards associated with the physical environment?
  - Does site access have the potential for slips, trips and falls?
  - Will access be constrained by tides? Is high tide known?
  - Are there currents, rips, eddies and waves that workers need to be aware of?
  - Will the work be in or near deep water and carry the risk of drowning?
  - Are there reefs or other marine hazards?
  - Does the weather pose hazards? These may include:
    - Storms?
    - Heat? (heat exhaustion/heat stroke)
    - Cold? (hypothermia)
    - Exposure? (sunburn/frost bite)
    - Strong winds/cyclones?
  - Are there slippery or loose surfaces?
  - Cliffs?
  - Mudflats with the risk of getting stuck?

- Are there hazards associated with the biological environment?
  - Risks from inappropriate handling of oiled wildlife (e.g. eye injuries from birds)?
  - Risks from potentially venomous wildlife?
    - Corals, jellyfish, snakes, spiders?
  - Risks from aggressive wildlife?
    - Crocodiles, sea lions, seals?

- Are there hazards associated with the clean-up?
  - Could there be injuries from the machinery?
    - Burns/scalds?
    - Entanglement?
    - Crushed or broken hands, limbs?
    - Noise?
  - Could there be injuries associated with vehicle use?
  - Could there be injuries resulting from buoys, booms, anchor cables (tripping)?
  - Could there be injuries associated with manual handling (back or lifting injuries)?

- Could there be hazards associated with the personnel?
  - Stress/fatigue?
  - Drug and alcohol use?
  - Pre-existing medical conditions?
    - Heart attacks?
    - Epileptic seizures?

---

Safety & Health Awareness for Oil Spill Clean-up Workers (https://www.osha.gov/Publications/Oil_Spill_Booklet_05.11_v4.pdf).

In addition, any extra health and safety considerations for field or remote work (e.g. on a vessel or at a shoreline) need to be highlighted, as discussed in the checklist in Table 4.3. All potential members of any field deployment teams should be aware of the process involved in their deployment and be prepared and trained to deal with emergencies, including first aid. It is critical that the teams deployed in the field are familiar with the...
safety regime and legislative requirements being applied during the response and with the organisational HSE system being used. It is prudent to employ best practice methods in order to assess and minimise risks. If risks are high and cannot be effectively and safely managed, then the activity should not be undertaken. Pre-prepared safety documentation and checklists can help in assessing and managing risks but each activity must be assessed based on the situation. Active safety management when undertaking activities in the field is strongly encouraged. This can include daily safety briefings, toolbox meetings to assess new risks, and take-5 meetings to assess risks during routine/daily activities.

Worker safety (response or monitoring) is the responsibility of the response agency and the incident controller. Responders and/or monitoring staff should be responsible for the safety of themselves and their colleagues.

4.2.4 Logistical requirements
The field team leader should be able to provide clear description of logistical requirements for field deployment. Clearly defined requirements will facilitate the IMT’s planning department to arrange appropriate survey vessels or support appropriate to shoreline deployments that enable execution of the specific monitoring program. Some prompts for thinking about logistics of deployments are provided in the checklists in Tables 4.4 (for shorelines) and 4.5 (for vessels).

4.3 The spill response process
The primary objective in any oil spill response is to minimise the damage. A typical spill response follows the stages shown in Fig. 1.2. Each stage requires information to inform the assessments and decisions required. The right-hand column identifies some of the myriad of data, information and knowledge required to successfully progress the response.

Although these steps are presented as a linear progression, oil spills (and responses) are dynamic and often complex. As circumstances change, information gathering and assessment may need to be repeated. This may be based on operational needs (i.e. weather conditions or oil weathering changing response tactics) or changes in ambient conditions (sea or wind conditions changing the projected spill trajectory).

Contingency plans should contain very detailed statements of what will happen once an incident occurs, what baseline information is available, how this information can be applied and how further information should be obtained. As well as the preparatory work, once the incident has occurred, the spill contingency plan should include a process for incident notification and evaluation (depicted in Fig. 4.4), the initial assessment and vulnerability analysis (Fig. 4.5), the risk analysis and response assessment that is used in deciding which response (if any) to use is depicted in Fig. 4.6.

Good monitoring design will likely include pre-spill baseline information collection as part of preparedness. This should be collected and available well in advance as part of the development of the contingency plan for a specific risk. Good design and implementation may involve recovery phase monitoring being activated and undertaken in parallel with response phase monitoring, for efficiency and effectiveness purposes, as discussed elsewhere in this Handbook.

4.3.1 Spill notification and developing situational awareness
Spill notification and reporting is probably the stage least dependent on formal monitoring information, because incidents may be reported by members of the public as well as by those involved in the incident directly. It is the beginning of developing situation
Table 4.4. Checklist for deployment to remote sites

- Can the necessary monitoring equipment be transported?
  - Sampling equipment?
    - Is there a way to keep samples collected at the proper temperatures?
- Can the site accommodate the response team?
  - Can people be transported there?
  - Is there accommodation?
  - Is there catering and a water supply?
  - Are there decontamination or washing facilities?
  - Are there shade or rest areas?
  - Can fuel be obtained?
  - Where will equipment be stored and maintained?
- Can the site be accessed?
  - What are road conditions?
  - Can the site be accessed by boat?
  - Are there airstrips?
  - Is the area of Indigenous cultural significance?
  - Is there vegetation, coral, or other significant habitats?
  - Does the site have any inherent hazards?
- Is there a communications plan?
- Is there a waste management plan?
  - Can hazardous waste be shipped offsite?
  - Are there any quarantine requirements?
- Is there a first aid or medical evacuation plan?
  - Are sufficient people trained in first aid?

Table 4.5. Checklist for deployment to vessels

- Can the necessary monitoring and response equipment be accommodated?
  - Does the vessel have a power supply? What volts/frequency?
  - Is there a winch? Is there a crane? Is there a means of securing deployed equipment?
  - Is there a water supply or other means of decontaminating equipment?
- What working area is available?
  - Is there enough space for the team to operate their equipment?
  - Is there a dry work space for laptops?
- What storage is available?
  - Can samples be stored at the appropriate temperature?
  - Can cases for laptops and other equipment be stored dry?
  - Is there storage for chemicals that may be required?
  - Is there storage for any waste that may be generated?
- Can the vessel accommodate the response team?
  - Are there berths, or will the team be deployed for daytime or local work only?
  - Is there catering and a water supply?
  - Are there decontamination or washing facilities?
  - Are there shade or rest areas?
  - Are there toilets?
  - Where will equipment be stored and maintained?
- Is there a communications plan?
In most cases this information is in a standard report form or template and requires virtually no formal monitoring. It may need verification or validation, if only to ensure that the reported facts are correct.

It is important to note that the reported information may be incomplete or inaccurate, and often experience with previous events or inference is used to make assumptions about what might be occurring. This is particularly so when the spill has unknown origins (a mystery spill, such as described in Boxes 3.1 and 6.1) and/or where the observer is unable to directly validate the reports of spilled oil (e.g. by aircraft observation or remotely sensed observation, such as from a satellite). Fig. 4.4 provides a list of information types, and presents them as equally important – not as a progressive list. All of the elements are interrelated to provide a comprehensive assessment of the unfolding incident.

**Location**

Knowing the location of the oil permits an initial assessment of its movement and fate, and determination of the appropriately responsible jurisdiction (state or Commonwealth). It also permits assessment of the potential severity of the incident and the nature of any possible or required response. Normalised geospatial references (latitude/longitude, etc.) are the most informative local information, but general descriptor information is acceptable where there are definitive landmarks.

The time of reporting and time of incident (if the latter is different and known) are crucial for initial assessments of weathering, movement, interaction with adjacent sensitive receptors (shorelines, wildlife areas, etc.) and logistics of response.

Location also provides an initial prediction of response (and perhaps compliance) jurisdiction and responsibility for future actions (monitoring, response and recovery).

**Oil spill character**

The character and impact of the oil spill will be dependent on the type of oil released. The type of information provided here can be highly variable, depending on the skill, experience, role and proximity of the observer. Spill response texts (such as the ITOPF Technical Information Papers) cover a range of descriptors for oil. Knowing the exact nature or name of the oil can open up a wide range of relevant, associated information. Sections 2.1 and 2.2 describe oil character, behaviour and fate in detail. However, it is also valuable to know the
source (see Incident below), the volume spilled (size matters), and the rate and duration of the release (instantaneous, over time, variable, ongoing). These all influence weathering. Finally, sometimes all that is available is the spatial extent of a slick of a particular description (sheen, black or coloured). Even this can provide valuable intelligence about the incident and response required.

**Oil classification**

Although the petroleum industry often characterises crude oils according to their geographical source, because each oil has its own unique chemical and physical properties, this classification is not always useful in a spill. Responders require more specific information that is not a primary consideration for refining purposes (e.g. toxicity, physical state, and changes that occur with time and weathering). The following classifications based on the specific gravity (or API) and other environmentally relevant properties are more useful in a response scenario. A brief summary of the character, expected behaviour and environmental impacts of different oil types is provided in Table 4.6 below. Note that this information is based on North American research, and oil weathering may be very different under tropical conditions.

**Nature of the incident**

The nature of the spill source also informs jurisdiction and responsibility. Maritime spills include those from ships, ports, terminals and shore-side facilities, whereas the offshore petroleum sector has responsibility for spills from its activities and facilities, including rigs and pipelines. Responsibility for the incident is important in determining who has responsibility for the response and, as a consequence, for any monitoring. Severity has many criteria, including some of those listed above, but normally focuses on spill or response size, extent, likelihood and extent of impact, and visibility to stakeholders, among other factors. Initial proximity to or likely imminent interaction with sensitive receptors, or effects on sensitive receptors of response actions, are also important factors to be determined, but initially these may be inferred rather than directly observed.

**Ambient conditions**

Spilled oils respond to ambient conditions (see weathering explanation in Section 2.2). At the time that the report is made, it is most useful to obtain as much real-time information as possible about the local conditions. Local conditions will inform early decisions about response options. The three major sources of this information will be personal knowledge, local knowledge (the reporter or other local sources) or commercial (or other) weather forecasting services (now casting or synoptics). The biggest source of uncertainty will be the resolution and applicability of the information available through the predictive services for the locations in question, because most operate for general public use, including maritime weather forecasts over extended areas. If more resolved or detailed information is required, the Bureau of Meteorology can provide this, requiring a prior agreement for interpretation and delivery.

Sources of information also include local hydrographic charts and topographic maps (if close to land). These can provide a great deal of information about gross ambient conditions (bathymetry, currents and tidal streams, bottom type, local features, etc.) and should be readily accessible online.

**Observer information**

This provides two key pieces of information: contact details in order to seek more or more detailed information (photographs, etc.) from the reporter of the incident if need be; and
Table 4.6. An overview of different oil types and their expected behaviours in the environment (Source: adapted from Boehm et al. (2013))

<table>
<thead>
<tr>
<th>Oil type</th>
<th>Very light</th>
<th>Light</th>
<th>Medium</th>
<th>Heavy</th>
<th>Very heavy</th>
</tr>
</thead>
<tbody>
<tr>
<td>API gravity</td>
<td>&gt;45°</td>
<td>31–45°</td>
<td>23.3–31°</td>
<td>10–23.3°</td>
<td>&lt;10°</td>
</tr>
<tr>
<td>Examples</td>
<td>Jet fuels, gasoline, condensates</td>
<td>Diesel, some fuel oils, light crude oils</td>
<td>Most crude oils</td>
<td>Bunker fuel oil, heavy crude oil</td>
<td>Asphalt, or emulsion</td>
</tr>
<tr>
<td>General description</td>
<td>Clear, highly viscous, spreads rapidly, strong odour</td>
<td>Light in colour, brown or black</td>
<td>Increasingly viscous, brown or black</td>
<td>Increasingly viscous, brown or black</td>
<td>Tar-like and sticky, brown or black</td>
</tr>
<tr>
<td>Evaporation</td>
<td>Very quickly</td>
<td>Quickly</td>
<td>Somewhat</td>
<td>Very slowly</td>
<td>Not appreciably</td>
</tr>
<tr>
<td>Penetration of porous surfaces?</td>
<td>Yes</td>
<td>At high temperatures</td>
<td>Limited</td>
<td>Only when heated</td>
<td>Not appreciably</td>
</tr>
<tr>
<td>Relative water solubility</td>
<td>Very water soluble</td>
<td>Water soluble</td>
<td>Some components are water soluble</td>
<td>Limited water solubility</td>
<td>Not appreciably</td>
</tr>
<tr>
<td>Emulsification</td>
<td>Does not form mousses or other emulsions</td>
<td>Forms mousses or other emulsions</td>
<td>Forms mousses or other emulsions</td>
<td>Form mousses or other emulsions</td>
<td>Formation of mousses or other emulsions is possible</td>
</tr>
<tr>
<td>Amenability to chemical dispersants?</td>
<td>No</td>
<td>Not recommended</td>
<td>Yes</td>
<td>Often ineffective</td>
<td>No</td>
</tr>
<tr>
<td>Toxic effects</td>
<td>Acute toxicity based on narcosis</td>
<td>Multiple modes of action</td>
<td>Multiple modes of action</td>
<td>Multiple modes of action</td>
<td>Typically occurs as a consequence of smothering</td>
</tr>
<tr>
<td>Persistence in the environment</td>
<td>Short</td>
<td>Potential for long-term contamination</td>
<td>Long-term contamination expected</td>
<td>Long-term contamination expected</td>
<td>Long-term contamination expected</td>
</tr>
</tbody>
</table>
an assessment of the ability (expertise, experience, skill, proximity, etc.) of the reporter to provide accurate and complete information.

4.3.2 Initial assessment

Assuming that the initial report identifies a real incident for which response may be required, the initial assessment becomes the verification of information in the event notification, and lays the foundations for establishing a response. As described in more detail in Section 2.5, the size, tactics and intensity of response option used will depend on many factors. Most of these decisions are informed by the developing situational awareness and decision processes such as the initial (and recurring) NEBA (described in Section 5.1). Hence, the response progression from notification to initial assessment to response assessment often appears seamless, and transition points may be defined by apparently arbitrary triggers, (i.e. contingency plan processes, response decision points, functional or organisational appointments), as shown in Fig. 4.5.

The following stages rely heavily on pre-prepared arrangements for observation, remote sensing and monitoring. These observation processes can have the multiple benefits of:

- **Providing verification** – giving greater certainty about the incident and response ahead
- **Informing response decisions** – providing the information required for initial decisions on response options, tactics and logistics
- **Creating a baseline** – provides the first data points (observations and/or samples) in a time series for recovery phase monitoring

Further, future possible monitoring activities should not be ignored during the initial assessment. This phase offers the opportunity to ready or ‘push forward’ further monitor-

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**Fig. 4.5.** Initial assessment where the spill and response becomes information intensive and complex
ing capability but not fully activate or ‘stand up’ the capability. This readiness will enable subsequent monitoring activities to commence more rapidly, once activated, to the benefit of the response. During this initial assessment, readying the further monitoring capability permits the assessment of resources that are available as well as timeframes of deployment. Readiness will also help determine the scope and design of the monitoring program.

**Predictive modelling and verification**

Predictive modelling normally encompasses spill or slick movement (trajectory), weathering (fate), weather and oceanographic models, as are described in more detail in Chapters 2 and 6. Normally, planning and preparedness are required to make most effective and efficient use of professional or commercial services for modelling because they are often first required very early in the assessment, and may be required many times during the response.

Models are only as good as the data provided, so feedback, verification and validation of the spill trajectory and condition will increase utility of the model predictions and reduce uncertainty regarding the model output.

**Geospatial data and receptor identification**

Modern emergency management requires geospatial data and information. A Geographic Information System (GIS) can provide a mechanism to centralise and visually display all data relevant to an oil spill in a geographic context (NAPSGF 2009). Hazards such as oil spill trajectories can be analysed alongside other map data such as boom locations, sensitive species locations, critical facilities, census information, and archaeological and other culturally important sites. Potential areas of impact can also be calculated to improve managers’ ability to understand risks and responses. Graphical data, displayed as maps, charts, graphs, reports or websites, enable more effective data dissemination and understanding (NAPSGF 2009).

In Australia, this visual display has often been referred to as the Oil Spill Response Atlas or OSRA, but this only refers to the data layers. The modern approach is to reference the entire capability – people skills, datasets or layers, and the electronic software systems.

Each GIS data layer is stored as an individual file and can be displayed with other files to provide a sense of spatial relationship. Oil spill relevant data can include pre-prepared datasets such as:

- environmentally sensitive areas/sensitivity index
- roads/infrastructure (including boat launches and mooring locations)
- population data (census)
- land use/land cover
- place names and borders
- managed areas (reserves, conservation areas, etc.)
- species/populations areas and locations

As the incident and response unfolds, data regarding locally available information can be added, including:

- oil spill source location and trajectory
- oil spill trajectory model outputs
- ambient conditions (weather, sea state, tides, currents, hazards)
- health hazards (volatile clouds, work hazards areas)
• response resource locations (booms, skimmers, waste reception areas, operating bases)
• response activity areas (dispersant application, shoreline clean-up)
• impacted areas (economic, environmental, amenity resources)

These data can be integrated on a map to show: which sensitive species habitats will be affected by the slick’s movement; the ambient weather and sea conditions that will influence the movement of the oil and the ability of responders to work; the best locations to deploy equipment, and response teams; and to plan, execute and record monitoring.

Because this geospatial capability is now so crucial to all phases of spill response planning and action, and in particular monitoring efforts, preparation are all important. Suggestions for preparedness include:

• understanding that GIS can be used for more than contingency and/or response planning
• having a GIS team identified and trained for spill response work before the incident
• providing technical capacity and resources for them to operate (data, internet connectivity, servers, printers/plotters, supplies and IT staff support)
• forming partnerships with the GIS team before an incident to identify what they can do and what you need them to do
• integrating GIS into standard operating procedures
• embedding the GIS staff into the response management structure, even if not co-located
• providing an incident management organisational chart to the GIS team so they can know who does what and who needs what
• providing regular training and exercising that includes the GIS team
• providing a space or role in the Incident Control Centre for the GIS team or their liaison to better encourage collaboration and communication
• designating a GIS liaison.

GIS personnel are unlikely to be exposed to pollutants in their roles, but nonetheless consider having them trained spill response and safety, as are all other responders.

4.3.3 Contingency plan activation
A contingency plan can be activated based on the information provided in the initial event notification. Alternatively, verification of key information through an initial assessment may provide the trigger for the implementation of the contingency plan. Regardless, the contingency plan should start to become a key source of pre-prepared services or capabilities in:

• baseline information – for example, local sensitive receptor or logistics information held in geospatial databases
• observation/remote sensing – for example, reconnaissance from shore, vessel or aircraft, and/or remote sensing from satellite or aircraft
• predictive modelling – for example, weather, currents, spill trajectory (e.g. OilMap), spill fate (e.g. ADIOS).

Monitoring initiation
The information collected as part of the initial incident assessment and verification is used to initiate the processes of monitoring and response, as shown in Fig. 4.6. This information
needs to be current and accurate to provide sufficient information for responders to make good decisions about how to deploy monitoring teams and equipment, as well as to inform the NEBA process, as described in more detail in Chapter 5.

### 4.3.4 Response decisions

Much of the information to be input into the response assessment are the factors that are incorporated into the initial incident assessment, as discussed in Section 4.2. The remaining factors – the response options and logistical constraints – are discussed in Section 5.2.
Response option assessment

Sharon Hook, Paul Irving and Andrew Ross

5.1 Evaluating response options: net environmental benefit analysis

Once the initial information from an incident report has been collected and an initial assessment undertaken – including verification that a spill occurred and its location, oil type, and predicted trajectory, as well as the receptors that the oil may come into contact with, (as described in Chapter 4) – an initial risk analysis is conducted to determine the potential consequences of the oil spill and what (if any) response options can be used to lessen the consequences. Oil spill response options are described in more detail in Section 2.5. The goal of an oil spill response is to minimise the damage (both ecological and socioeconomic) and to hasten recovery of any affected resources (Davies and Hope 2015). Before a response option is considered, the following questions must be answered (NRC 2005):

1. Is there a need to respond?
   (a) Does the oil spill pose a risk to the system from either an ecological or a socioeconomic standpoint?

2. Will the response strategy work on the type of oil spilled?
   (a) Refer to Table 5.2

3. Is the response strategy operationally feasible?
   (a) Can response personnel get to the site in time? Do the environmental conditions make it unsafe for them to work?
   (b) Is there sufficient booms/dispersant/etc. available?

4. What are the environmental consequences of the response option?

Damage, from both an ecological and socioeconomic standpoint, can occur from both the response to the oil spill as well as from exposure to spilled oil (Davies and Hope 2015), so the fourth question above is assessed by weighing the net environmental benefits.

Net environmental benefits have been defined as ‘gains in value of environmental services or other ecological properties minus the value of adverse environmental effects caused by those actions’ (Efroymson et al. 2004). As discussed earlier, NEBA is commonly used to weigh competing stakeholder interests in the events such as oil spills (Davies and Hope 2015; AMSA 2014b). It is the environmental risk assessment protocol typically used for the selection of oil spill counter-measures, including the use of chemical oil dispersants, shoreline clean-up and other oil spill counter-measures. In this context, ‘environmental benefit’ includes both ecological and socioeconomic consequences of the oil spill.
An oil spill response technology may cause greater impacts to one portion of a system (e.g. dispersants increase the risk of oil exposure to plankton), but may benefit the system as a whole (i.e. they are of net environmental benefit) (IMO 2014). Any oil spill response should only be undertaken when there is thought to be a net benefit to the environment (weighing both ecological and socioeconomic interests) relative to natural recovery and other spill response options (see Box 5.1). The NEBA process is especially helpful when multiple response options have merit, but the best choice for the system as a whole is not clearly apparent (Efroymson et al. 2004). The decision criteria for choosing response options should include the likelihood of a reduction in the overall damage (from both an environmental and economic standpoint), the feasibility of the response option, and whether the cost is reasonable when compared with the perceived benefit. In general, it is important to remember that oil spills that are treated in the open sea are thought to have fewer environmental consequences than those that enter nearshore environments (IMO 2014).

Ecological risk assessments differ from NEBA in that they can be done in advance of a spill. These ecological risk assessments can include identification of high-priority resources, from either a socioeconomic or ecological standpoint, and identification of areas that would be at high risk for a spill (e.g. an area with high shipping traffic or a port where petroleum resources were loaded onto ships) (NRC 2005). In these cases, resource managers should identify potential spill responses that might alleviate any environmental consequences of spilled oil. As discussed in Chapter 4, these risk assessments form an important part of contingency planning. However, this process differs from a NEBA because it cannot, in advance, anticipate the environmental conditions on the day of the spill nor the type and weathering state of the spilled oil (NRC 2005).

Because each spill has unique circumstances that will change the response options as described in Section 2.5, unfortunately, the NEBA process cannot be undertaken in advance (NRC 2005). Response options will need to be flexible and adaptable to account for specific contaminants, location, ambient conditions, sensitive receptors and human uses of a given location (Davies and Hope 2015). The NEBA process comprises the following steps that should be taken at the time of the spill and as situational awareness unfolds:

1. Determine the physical characteristics, sensitive receptors and human resources of the area to be mitigated.
2. Incorporate ‘lessons learned’ from previous spills in similar areas where the considered response option was used.
3. Predict the ecological and socioeconomic costs of the response options including natural attenuation (Baker 1999).

This process needs to be undertaken quickly once the initial information about the spill has been collected, as some response options are only valid for a short operational period (Davies and Hope 2015). For the initial NEBA, the spill location, size and oil type, as well as any information about weather (to inform logistics) and known sensitive receptors in the area would be used as inputs, as outlined in Fig. 4.6. The NEBA process will need to be repeated as new data are collected and the efficacy of any response option is evaluated, as depicted in Fig. 5.1 (IMO 2014). This process, and the inputs that inform this process, should be well documented, because there will be considerable interest from stakeholders in why a response option was taken, or why natural attenuation was chosen instead (NRC 2005). A summary of the response options described in Section 2.5. The circumstances under which they are effective, and their constraints, are provided in Table 5.1.
### Table 5.1. Summary table for different at sea response technologies for dealing with an oil spill

<table>
<thead>
<tr>
<th>Response option</th>
<th>More effective if:</th>
<th>Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical recovery</td>
<td>• the spill is small</td>
<td>• Availability of equipment</td>
</tr>
<tr>
<td></td>
<td>• the oil has not been chemically dispersed</td>
<td>• Oil encounter rate</td>
</tr>
<tr>
<td></td>
<td>• the weather conditions are calm</td>
<td>• Weather conditions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Storage and disposal of any oil collected</td>
</tr>
<tr>
<td>In situ burning</td>
<td>• the spill is small</td>
<td>• Not previously used in Australia</td>
</tr>
<tr>
<td></td>
<td>• the oil is fresh</td>
<td>• Oil must be collected in fireproof booms</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Safety concerns for inhalation</td>
</tr>
<tr>
<td>Chemical oil dispersants</td>
<td>• the oil is fresh</td>
<td>• Environmental concerns</td>
</tr>
<tr>
<td></td>
<td>• the oil is neither too heavy nor too light</td>
<td>• Only unweathered oil is dispersible; not all oil types are dispersible</td>
</tr>
<tr>
<td>Non-dispersant chemical treatments</td>
<td></td>
<td>• Efficacy is uncertain</td>
</tr>
<tr>
<td>Natural attenuation</td>
<td>• small spills</td>
<td>• Oil can be transported to sensitive areas requiring additional clean-up</td>
</tr>
<tr>
<td></td>
<td>• very light oil or refined products</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• spill is unlikely to contact a sensitive area</td>
<td></td>
</tr>
</tbody>
</table>

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**Fig. 5.1.** Example of the continuous process for NEBA used to assess and choose between response options (Source: https://www.amsa.gov.au/forms-and-publications/Publications/Protocol-for-OSCA-approval.pdf)
5.2 Decision making for shoreline clean-up and assessment

If a shoreline is oiled, the responders will have to decide whether to remove the oil from the impacted habitat. Detailed guidance for shoreline assessment is provided by NOAA, such as their shoreline clean-up and assessment technique (SCAT) (http://response.restoration.noaa.gov/oil-and-chemical-spills/oil-spills/resources/shoreline-assessment-manual.html). An idealised workflow for shoreline assessment is provided in Appendix T. Factors to consider in determining the shoreline clean-up strategy include:

- whether there is a potential for people to be exposed, either via direct contact with oil or by ingestion of contaminated seafood
- the potential for oil to be remobilised and to affect other nearby resources
- the degree of environmental damage and the persistence of that if the oil is not removed
- environmental damage that could be caused by clean-up techniques
- natural attenuation and recovery rates (Yender and Michel 2010).

Following an oil spill event, there will often be significant public pressure to remove oil from an area and restore wildlife and other resources (Burger 2010), but different stakeholders can have different goals and metrics for shoreline clean-up, which can include:

- petroleum concentrations that are equivalent to background levels
- petroleum concentrations that are lower than regulatory guidelines
- petroleum concentrations that are below the predicted no effect concentrations for either lethal of sub-lethal toxicity
- oil does not accumulate in food organisms
- oil contamination does not alter ecosystem function
- oil has no aesthetic impact
- human use (either commercial or recreational) of an area is not changed by the pollution event (adapted from Baker 1999).

Extensive guidance on selecting among different options is provided by NOAA (2013) and is briefly summarised in Table 5.2. Responders are cautioned that shoreline clean-up can have substantial negative consequences, as outlined in Box 5.1.

Box 5.1. Shoreline clean-up and the Exxon Valdez

The goal of shoreline clean-up is to remove the maximum amount of oil with the least amount of injury to ensure maximum recovery. Numerous factors are involved in the decision to clean shorelines, including aesthetics, bioaccumulation of oil into food organisms, and potential exposure to birds and marine mammals, in addition to shoreline ecology (Mearns 1996). The following criteria to assess shoreline clean-up were recommended:

- What methods were used?
- What criteria were used to select the methods?
- How effective was the treatment?
- What was the impact of the treatment?
- How do the effects of the treatment compare with the effects of oil?
The *Exxon Valdez* tanker spilled an estimated 42 million litres of oil into Prince William Sound, with an estimated 10–20% of the oil being deposited on shorelines (Driskell *et al.* 2001). This oil was removed initially by manual cleaning, then later by high-pressure, high-temperature shoreline washing (Mearns 1996) as shown in Fig. 5.3. The water used was heated to above 60°C, the pour-point of the oil. It was intended that this oil would then be collected by booms and skimmers (Mearns 1996). By some estimates, the high-pressure, high-temperature washing caused more damage to shoreline ecosystems than the oiling (Driskell *et al.* 1996). Some organisms (macroalgae in particular) survived the initial oiling, even after a month of heavy exposure, but were killed by the high-temperature clean-up (Houghton *et al.* 1996).

The exact impacts of the treatments are uncertain because of lack of documentation. Pre-impact conditions were often not available, treated shorelines received different degrees of treatment and were oiled to different levels. Although aggressive washing was effective at removing oil, it also completely destroyed the algae and marine invertebrates, in that as much as 90% of the populations may have been lost. Also, no studies directly compared the effects of oil with the effects of the clean-up, so while the cost of the aggressive clean-up was apparent, the benefits are unknown. This high-pressure washing also resulted in oil being transported offshore in sediment plumes. Transporting oil from the shoreline where it was exposed to sunlight and air in the subtidal zone may have slowed natural weathering processes and photolysis (Mearns 1996).

![High-pressure washing with deluge, to remove oil stranded following the *Exxon Valdez* oil spill (Photo credit: E.R. Gundlach, http://www.oil-spill-info.com/Spill_ExxonValdez.html)]
Some post-hoc studies compared low-pressure, warm-water washing with high-pressure, hot-water washing and two different shoreline cleaning agents to see how this changed the abundance of dominant taxa. Although all treatments had negative impacts on abundance and diversity, high-pressure, high-temperature washing had the most negative impacts, which persisted through 1995. Interestingly, the two Corexit (dispersant) formulations were more toxic than would have been predicted from laboratory studies alone, suggesting that exposure to shoreline cleaners for even a brief period may cause injury (Lees et al. 1996).

Another post-hoc study compared growth and survivorship in a predatory whelk that experienced high mortality during the spill. Snails were tagged and released in (northern hemisphere) summer 1991, then surveyed in September 1991 and July 1992. Growth was equivalent at oiled only and oiled and washed sites. Both were lower than control. Survivorship was lowest at oiled sites, intermediate at oiled and washed sites, and highest in the control. With the exception of one site, decreased growth rates could be correlated with PAH concentrations in the sediment (Ebert and Lees 1996).

This high-pressure washing also removed much of the fine-grained sediment. This removal impacted organisms that depend on this substrate, such as little neck clams, and made them slower to recover at sites where this washing occurred (Fukuyama et al. 2014). Recovery is defined as a return to a state within the boundaries of natural variability (Houghton et al. 1996). Additional studies examined recovery from the oiling and the clean-up effort (e.g. Driskell et al. 1996). In assessing recovery, researchers first had to assess what the impacts were and to determine whether the systems had returned to normal following these impacts. The resources that were assessed in this effort were infauna on lower intertidal gravel or sand-silt beaches. The impacts that were being examined included mortality, decreased size or biomass, and reduced reproduction. The recovery being assessed was from the damage caused by high-pressure washing, where beach biota were killed from the thermal shock, fine sediment and small infauna were washed out of the system, fauna were dislodged from their rocks, sessile fauna were buried, and oil was moved into the deep intertidal waters. Sites that had just been oiled had seemingly recovered by 1992, but oiled and washed sites had not. The high degree of inter-annual variability in the system was masking both impact and recovery, but bivalves, which are dependent on fine grained sediment, were recovering slowest (Driskell et al. 1996).

Another study examined the recovery of intertidal organisms from the oiling and the clean-up. It monitored primarily for the abundance of dominant taxa, including mussels, snails, limpets, barnacles, hermit crabs and algae. It was found that washing greatly reduced the epifaunal cover. Some opportunistic algal species recovered quickly, but that, overall, the system had big changes in dominance and dramatic die-offs because the age/class structure was out of balance (Houghton et al. 1996).

The recovery of these shorelines is also complicated by the fact that all organisms at the site are a single cohort, and as a consequence go through synchronous boom and bust cycles (Driskell et al. 2001). Depending on the species, recovery at the oiled and treated sites was complete after 6–12 years (Fukuyama et al. 2014).

The lessons learned from the shoreline clean-up following the Exxon Valdez spill (Houghton et al. 1996) were:

(i) Do not necessarily remove all oil, but instead, remove oil that is expected to re-float and coat other parts of the system or just oil that forms asphalts and pavements.

(ii) Perform shoreline clean-up with the net environmental benefit principles in mind.
5.3 Response evaluation

Before a response can be terminated, the efficacy of that response needs to be evaluated against criteria determined via monitoring (discussed in Chapter 6). The efficacy of any chosen oil spill response measure will need to be demonstrated by one or more criteria, as shown in Fig. 5.2.

The National Plan guidance on Response, Assessment and Termination of Cleaning for Oil Contaminated Foreshores (AMSA 2015b) will provide more detailed information on how and when to terminate a response. Field monitoring will be required to inform this process. When additional response will not lead to additional environmental benefit (at least in proportion to the cost), the response is terminated, but recovery phase monitoring (described in Chapter 7) continues.

Table 5.3 contains a checklist of factors to consider in evaluating the response.
Table 5.2. Examples of shoreline clean-up techniques recommended for different habitat types (Source: adapted from NOAA 2013)

<table>
<thead>
<tr>
<th>Clean-up technique</th>
<th>Exposed rocky shores</th>
<th>Exposed man-made shorelines</th>
<th>Exposed wave cut platforms</th>
<th>Sand beaches</th>
<th>Sand and gravel beaches</th>
<th>Gravel beaches</th>
<th>Rip rap</th>
<th>Exposed tidal flats</th>
<th>Sheltered rocky shores</th>
<th>Sheltered man-made structures</th>
<th>Peat shores</th>
<th>Sheltered tidal flats</th>
<th>Salt/brackish marshes</th>
<th>Mangroves</th>
<th>Coral reefs</th>
<th>Sea grasses</th>
<th>Kelp forests</th>
<th>Soft bottom</th>
<th>Mixed and hard bottom</th>
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<tbody>
<tr>
<td>Natural recovery</td>
<td>A</td>
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<td>Barriers/berms</td>
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<td>Manual oil removal/cleaning</td>
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<td>Mechanical oil removal</td>
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<td>Debris removal</td>
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<td>Vegetation cutting/removal</td>
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<td>Flooding</td>
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<td>Low pressure/ambient water flushing</td>
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Techniques that have fewer ecological consequences are blue, and those that have more consequences are red, with intensity of shading signifying degree to which the approach is recommended or not. Grey shading denotes insufficient data to support recommendations, black shading denotes inconclusive advice, and tan shading denotes that the approach is inappropriate for the habitat type. Purple shading denotes conflicting recommendations for different oil types, with the specific recommendation:

A – Natural recovery is preferred for lighter oils on sand beaches; B – Flooding is preferred for lighter oils on beaches; C – Nutrient enrichment is preferred for lighter oils on sheltered cliffs; D – Natural recovery is preferred for lighter oils on sand/gravel beaches; E – Flooding is preferred for lighter oils on gravel/sand beaches and gravel beaches; F – Manual/mechanical removal is preferred for heavier oils on gravel beaches; G – Flooding and manual/mechanical removal is preferred for lighter oils on gravel beaches; H – Sorbents are preferred for lighter oils; I – High pressure, ambient temperature washing is preferred for mid-weight and heavy oils; J – Flooding is preferred for heavier oils on peat shores.
Table 5.3. Checklist for demonstrating the efficacy of an oil spill response

- Has the oil spill trajectory been altered?
  - Examples: photographic or remote-sensing evidence showing that an oil slick has been contained by a boom or effectively broken up by dispersants

- Have the oil concentrations in an area changed?
  - Water samples?
  - Sediment samples?
  - Tissue samples?
  - Real-time monitoring data?
  - Other?

- Has the thickness of oil on the sea surface or shoreline changed?
  - Visual observation?
  - Remote-sensing data?
  - Other?

- Has the shoreline been altered by the approach?
  - What is the slope of the shoreline? Has it changed?
  - What is the sediment grain size? Has it changed?
  - What is the per cent covered with vegetation? Macrofaunal communities? Have these changed?

- Has the response affected the biological communities?
  - Has there been a change in the species composition? Is this due to the oiling or the response?
  - Are the organisms in the area in good health? How will this be determined?
  - Has there been a change to the use patterns by wildlife? Is this due to the oiling or the response?
Response phase monitoring

Andrew Ross, Andrew Revill, Xiubin Qi, Charlotte Stalvies, David Griffin and Sharon Hook

6.1 Introduction

Once a response has commenced, monitoring should also be initiated. This monitoring should include information on the position and trajectory of the oil slick, its weathering state and concentration, and whether it has impacted any sensitive receptors. The information gathered via the monitoring process informs the ongoing need for the response, the efficacy of the response and ongoing environmental effects assessment, as discussed in the sections below, and shown graphically in Fig. 6.1.

Fig. 6.1. An overview of the different aspects of response phase monitoring – how it can validate existing knowledge, inform situational awareness, and assess and evaluate operational success.
6.2 Oil spill trajectory modelling

Once an oil spill occurs, or a mystery slick is detected, it is necessary to understand where the oil could move, spread, break up or change through natural weathering processes. This information is needed to:

- gain an understanding of what resources may be affected and when it could occur
- determine the appropriate response and monitoring actions
- determine the time available for these actions.

Otherwise, it may be a waste of time and resources to deploy equipment or conduct sampling in the wrong locations, or at the wrong times. The response could also become focused on the more immediate and visible threats at the expense of future threats.

Although mapping of the present location of surface oil may be possible using surveillance aircraft or vessels, these generally require daylight hours and suitable weather conditions. Satellite observations are constrained by return times and sensor resolution. The capacity to observe the distribution of submerged oil is also limited. It is also necessary to calculate, or forecast, the future movement of the oil.

To assist quick response, very basic ‘rules of thumb’ have been developed and applied to predict the gross movement of surface oil over the open sea. One example of this is the often-quoted rule for net oil-slick movement of 3% of the wind speed and 97% of the current speed. However, such simple calculations are often very inaccurate, because wind, currents and tides can vary significantly over time and space, and the ‘rule’ takes no account of oil weathering.

Advanced oil spill trajectory models (OSTMs) consider these limitations by calculating all of the significant fate and movement processes, including:

- movement of oil due to varying wind and current conditions
- fracture and spreading of oil patches
- evaporation of volatile components to the atmosphere
- physical mixing and submergence (entrainment) of oil into the water due to wave action
- the formation of water-in-oil emulsions
- decay through biological and sun action
- shoreline stranding behaviour.

The more advanced trajectory models are three-dimensional, and can represent discharges of oil and gas from underwater as well as the movement of oil at depth.

Trajectory models are used in different modes to suit these different applications. **Stochastic (or probabilistic) modelling** involves running trajectories for the spill event many times, often changing only one or a small number of variables, such as the simulation start date, hence varying the sequence of winds and currents that are used to force the movement of the oil spill each time. Then the distribution of outcomes is randomly subsampling to produce a probability map of outcomes. This approach is most commonly applied to a known source of a spill, such as a terminal or offshore facility, and is used to estimate the risk of oil exposure to surrounding resources, under specified conditions (e.g. for a defined periods of time) when planning for hypothetical spill events. Analysis of the many results will indicate the probability of particular outcomes – showing both those that are more likely and less likely.

The results of stochastic modelling can be used to guide contingency planning, such as what outcomes need to be planned for and where response equipment may be required.
Results can also be used to guide the oil spill monitoring planning to determine the most likely locations to set up monitoring.

**Forecast trajectory modelling** is usually applied to predict the future movement and weathering of oil during an actual spill event. The starting point would typically be the distribution of oil at the present time, which might be a discrete point source for the leak or the present location of slicks on/in the water. The forecast trajectory modelling would use the best available current and wind forecast data and would forecast forward in time from that starting time. The outcome would predict where oil will be at some future time, what the character, concentrations and volumes of oil are likely to be, and what shorelines or sensitive receptors may be impacted. This provides guidance on when and where assets should be deployed or monitoring should be undertaken.

Forecast models can also be used to test contingencies, such as what would happen if particular circumstances arose, or to gauge the effect of particular response actions, such as the effect of spraying dispersant onto oil slicks, or the placement of booms at a particular location in a particular configuration. These approaches are commonly used in a NEBA. Forecast models can also be used to assist in directing monitoring, based on the predicted locations of the oil.

Model forecasts allow the response or monitoring team to view the spill scenario as a whole, identifying a range of likely impacts, which helps to prevent target bias, where one particular impact (e.g. oil coming ashore on one shoreline) may be given the full attention of the responding/monitoring team over other potential impacts (e.g. oil travelling over time to impact a different area).

**Reverse trajectory modelling** uses the model run backwards in time to determine the possible source or origin of oil from a more recent sighting location. Generally, the observed distribution of the oil, which might extend over a large area, would be mapped and the trajectory of each portion of the present slick would be calculated in reverse order. The trajectory model would use the best available information on the wind and current over the past period of interest.

Reverse trajectory modelling is commonly used to identify where oil may be coming from, or to differentiate between suspected sources, and will usually be used in concert with other evidence, such as the path of shipping traffic, and estimates of the weathering state (age) of the oil.

**Hindcast trajectory modelling** is used to determine where oil might have reached once the response is concluded. There will often be a requirement to assess which locations were exposed to oil over the event (incident and response) history. It will generally involve using updated wind and current data, oil properties, incident details and observations.

Like all models, OSTMs rely on the accuracy of the information supplied and so remain subject to potential uncertainties. Good practice can reduce the level of uncertainty, including accounting for variability in parameters such as current and wind data, and oil type or volume. Often, this simply means multiple model runs or, where possible, using variable parameter ranges.

Good forecasting modelling practice recommends that spill forecasts are only produced for relatively short durations (12–24 h into the future) to inform response decisions, and that feedback loops are set up between the model operator and field surveillance to improve accuracy. Wind and current forecasts will generally be most accurate over shorter durations, because the models that produce these forecasts use observations of the current and wind to self-correct every 12–24 h. Forecasts extending to 48 h (or longer) ahead will provide a longer range forecast, but with highest confidence on the shorter forecasts (i.e. up to 24 h) only.
Daily 24-h modelling forecasts, updated each morning during a response, will have suitable duration to guide field surveillance and response monitoring over a daily operational cycle and will be suitably long enough to forecast the oil movement during nighttime when surveillance is hindered. Field surveillance is used to confirm the predicted location of oil or identify discrepancies in the model forecasts and will be incorporated into the next model forecast iteration. This prevents compounding of errors and allows refinement of the model forecasts for the specific situation based on actual observations.

Models configured to use more than one independent forecast for the wind and current, sourced from different oceanographic and atmospheric models, can be used to check the ‘consensus’ between the model forecasts. High consensus (agreement among the model forecasts) indicates that there can be more confidence in the prediction. Low consensus (disagreement among the forecasts) indicates the need for more caution and checking by field surveillance.

Past observations of the wind and current, are not normally directly useful for slick movement predictions. However, local observations of wind and current can be used to validate and fine-tune modelled wind and current data, to identify any consistent errors in the wind and current forecasts.

Table 6.1 provides a summary of mitigation strategies to make best use of models, given their limitations, in the operational and scientific monitoring plan (OSMP) process.

### 6.2.1 Support to oil spill monitoring

Oil spill trajectory models can be used throughout the process of developing, maintaining and executing monitoring plans. The OSTM results can be used for briefings and to guide sampling and post-spill (recovery phase) impact assessments. Typically, the OSTM results are used to identify areas of impacted sites (those exposed to oil) and control sites (those that were not exposed). Impact assessments may want to consider all possible exposure pathways, not just the water surface, intertidal habitats, but also submerged habitats and fauna that could have been exposed to oil that entered the water column. Hence, more detailed trajectory calculations would be made with a three-dimensional model that calculates for entrained and dissolved oil concentrations involved and how long exposure persisted.

An example of how oil spill trajectory modelling can be used to allocate resources for monitoring is provided in Box 6.1.

An oil spill modelling support arrangement is in place in Australia through AMSA to support spill response and monitoring at a national, state and local area level. The oil spill trajectory model (OILMAP) is coupled with an environmental data server (EDS) that provides real-time forecasts of the wind and currents. The EDS contains forecast wind and current data from various sources that covers both coastal and offshore waters for the whole of Australia. Appendix V outlines the inputs required and process for requesting oil spill trajectory modelling, as well as information on how to interpret model output, and the various formats that it may be supplied in.

### 6.3 Physical monitoring

#### 6.3.1 Verification of spill trajectory

When a report of oil on the water is received from an unknown source, it is necessary to first confirm that the report is correct. Many natural phenomena may be anomalously identified as oil slicks, including stable patches of wind ruffles on the water surface set up by local wind shadows, algal blooms, coral spawn, the interface between coastal and ocean
waters, discoloured river discharges, sediment plumes, seeps of tannins or natural oils, and rafts of detritus, and so on (Fingas 2011a).

For spills occurring in densely trafficked, areas such as harbours, shipping lanes or the inner continental shelf generally, the location of the spill is likely to be associated with the original report, or subsequent sightings. For nearshore regions, there is probably no better source of information on local ocean currents than local fishermen and other mariners who frequent the region. Harbour pilots, the harbour master, water police or other authorities should be contacted. Steps should also be taken immediately to gather on-scene information.

Having confirmed that oil is definitely present, it is then necessary to gather initial information on the distribution and nature of the oil involved. An overview of the present distribution and nature of the oil will be the starting point for forecasting the movement of existing oil slicks into the future and will provide the guidance for initial planning and preparations.

At this early stage, these observations can be limited to gauging the overall length, width and shape of the surface slick, the positional bounds occupied by slicks, as well as

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**Table 6.1. OSTM limitations and mitigation strategies**

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<tr>
<th>Limitation</th>
<th>Mitigation strategies</th>
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<tr>
<td>Models are only as accurate as the data that are provided to them.</td>
<td>Provide the OSTM models with the most up-to-date input data from reliable sources. Check consensus using wind and current data from alternative forecast providers. Revise forecasts frequently using feedback from field observations when new information becomes available.</td>
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<td>Model results are based on weather and ocean forecasts – the further ahead the prediction, the less reliable the result.</td>
<td>Apply the OSTM model to predict 12–24 h ahead so that they will use more reliable wind and current forecasts. Revise forecasts frequently when updated wind and current data is available.</td>
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<td>Model results are very dependent on input assumptions – conservative input, gives conservative results, and vice versa.</td>
<td>Ensure the model inputs are as close to the actual values as possible. Run alternative forecasts, adjusting the assumptions to determine the effect of the sensitivity of the forecast to the assumptions.</td>
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<tr>
<td>Model results may be misinterpreted. Model outputs are only as effective as those interpreting them.</td>
<td>Make sure the model results are communicated effectively to all parties of interest. Confirm that the persons interpreting the model results and making decisions based on the results are well versed in model interpretation. Seek guidance on the interpretation of the forecasts and the level of confidence that can be applied from the model operator.</td>
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<td>Models can give a range of ‘likely’ or possible outcomes</td>
<td>Run consensus forecasting to provide a range of potential outcomes to understand the sensitivity to uncertainties. Do not interpret the results as the only single actual outcome, use as an indication of potential outcomes. Verify the model output with independent observations to determine which more closely represents reality. Establish a feedback mechanism between the field observations and the model operators so that the model can be refined for the situation.</td>
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general observations of the oil that is involved and how it is behaving (e.g. are the slicks composed of heavy viscous oil sitting low in the water, is the oil emulsified, or are they thin sheens?). This information is important because it will indicate how the slicks will tend to move and weather, as well as the risks that the slicks may pose.

Early gathering of supporting information on the prevailing currents and wind will assist forecasting by providing a check of model forecasted conditions. Information on the expected movement of the oil, based on local patterns of wind and current, should also be sought from mariners experienced with the area, but care should be taken as the actual conditions at the time may not match the ‘typical’ or perceived patterns (such as what happened during a previous incident). Wind and current patterns tend to be too highly variable to assume set conditions and it will be more reliable to support these opinions with local observations of prevailing current and wind over the area.

On-scene information on prevailing wind might be gained from wind gauges or observations of sea state (see Section 6.4.3 for guidance) and more reliability will be gained if observations are made at several locations.

The most effective way of gathering this information is probably to deploy several ‘self-locating datum marker buoys’ (SLDMBs) such as the ones deployed by AMSA when they assume responsibility for a search, or simple dan buoys (used by fishermen to monitor drift) if SLDMBs are not available. The buoys may diverge from the contaminated water but will still help to monitor the general sense of the movement. Predictions of tidal currents are available for some locations around Australia, but there are not many locations where these predictions are accurate enough to add value to the trajectory calculation. The motion of the buoys will soon reveal if tidal currents are moving the spill back and forth.

The design of the marker buoys should also be carefully considered as to whether they will better indicate the net movement of oil slicks floating on water, or the movement of water beneath the water surface. Floating markers that are designed to sit at the surface, such as purpose-designed oil spill tracking buoys, or even make-shift options such as oranges or dan-buoys, will move due to the combination of wind and current drag that acts on them. The current that is exerted on surface floats, being within centimetres of the surface, will also tend to be more wind-dominated than will occur in deeper layers. This will be more likely the case under higher wind speeds that will tend to push the surface layer downwind and set up wind waves that shunt the markers downwind. The movement of these surface marker buoys will be a better indication of the movement of oil slicks due to the combined action of the wind and current. Depending on their specific shape and design, such drifters may experience a different balance of wind effects (leeway) compared with the particular oil involved in the incident, causing them to diverge from the slicks over time.

In addition to wind and current drag, objects adrift in the sea will be subject to random, or dispersive, turbulent movements. These will add random variability in the movement of oil slicks and will also add variability to the movement of marker buoys over time. Consequently, even if the marker buoys are perfectly tuned to the movement of slicks of the particular oil type, the trajectory of a single buoy may not be a good indication of the path of the oil slicks over an extended time. It is therefore recommended that two or more marker buoys are released simultaneously from a common location and tracked to indicate the variability that is being exerted by dispersive forces.

Fig. 6.2a shows where strong tidal currents might be expected to occur. At the entrances to enclosed bodies of water, the tidal current is obviously related to the rise and fall of sea level. The relationship at other places, however, is much more complex and generally elliptical rather than back and forth.
For spills occurring in water deeper than 30 m, the reliability of information on currents over the continental shelf or beyond diminishes. The exceptions are those areas that are covered by the five ocean current radar systems of Australia’s Integrated Marine Observing System (IMOS). These are off Perth, Adelaide, Coffs Harbour and the southern Great Barrier Reef (Fig. 6.2b). If skies are clear (as in Fig. 6.2b), it is often possible to infer the direction of the currents from the satellite thermal imagery. For many areas around Australia, the IMOS maps of ocean currents derived from satellite altimeter maps of sea level can be used to estimate the current speed as well. This is particularly true off Sydney (Fig. 6.2b), where there are strong current velocities associated with the East Australian Current and its eddies.

The IMOS observations may help explain the past trajectory of the oil, but they are less suited to the task of predicting the future trajectory. This is especially true at times and places where the ocean current is changing rapidly, which is more often the case over the continental shelf than seaward of it. This occurs because winds are more effective at driving ocean currents over the continental shelf than they are in the deep ocean. Over the shelf, the wind can drive strong flows that are generally aligned with the coast. This component of the flow is quite well predicted by the large-scale ocean current predictions issued by the Bureau of Meteorology. Digital access to these forecasts can be obtained by registering with the Bureau.

Details regarding of the eReefs project are available from http://www.ereefs.org.au/.

6.3.2 Remote-sensing surveillance

Oil spill trajectory modelling has inherent assumptions and uncertainties that can become amplified over long distances and time, and in areas where currents are variable or poorly represented. The path of released oil therefore requires assessment by other methods, often through the use of remote sensing. Remote sensing is the science and technology of obtaining information about objects or areas from a distance, typically from aircraft or satellites. As discussed in Section 4.1, plans for accessing remote-sensing information and specialist guidance on interpreting it should be put into place before an event occurs. In
Box 6.1. Oil spill trajectory modelling following a ‘mystery spill’

On 16 July 2015, fishermen reported seeing an oil slick while travelling from the Burdekin River to the outer reef. When word of the incident reached the Great Barrier Reef Marine Park Authority the next day, an oil spill trajectory model was ordered, with the goal of identifying sensitive resources in the area that could be at risk. The output of the model is shown in Fig. 6.3:

Trajectory modelling on Friday 17 October 2015 was undertaken with two specific objectives in mind:

- short-term prediction to assist with focussing the following day’s aerial and other surveillance efforts
- longer-term predictions of whether and where any oil might eventually impact shorelines.

Spill response decision-support staff produced several versions of the trajectory model over the first few days of the response.

Fig. 6.3. The 5-day forward prediction of oil slick movement obtained from the oil spill trajectory model. The estimated extent of the oiling is illustrated in black; the darker blue area shows the predicted trajectory of the oil over time (Photo credit: GBRMPA)
There were several challenges in tracking this oil slick that the trajectory modelling helped with. First, there was an apparent delay in reporting initial observations from members of the public to response agencies. This was overcome by having several runs with different starting locations and times, to see whether this had any material effect on the outcomes. The model scenarios were not greatly impacted by these changes. Second, there was initial uncertainty about the type of oil spilled and the effects of weather and sea conditions on this oil. Several credible oil types were modelled, including bilge waste (another heavy oil mixture) and lighter fuels. The results quickly suggested that lighter fuels would weather rapidly in the conditions and the bilge waste would react similarly to heavy fuel oil. Given the ambient weather, wash-over was expected and modelled for. Modelling therefore focused on heavier oils, and the informed wait and see approach was adopted, with some confidence about the areas to monitor and when.

In addition, surveillance activities between Saturday 18 July and Thursday 23 July were unable to locate the oil, although search areas included both the modelled areas and beyond. As the suspected spill was later confirmed as heavy fuel oil, this was not an unexpected result, albeit frustrating. Heavy fuels oils generally have a high specific gravity and so ‘float’ very low on the sea surface. They also don’t degrade readily in the sea, and once spilled are known to increase their specific gravity through slight evaporation and dispersion, and water-in-oil emulsification. This means the oil can travel at or slightly below the water surface. Depending on sea state (it was variously up to 35 kn over the following days), the oil effectively became invisible to aerial and vessel observation, including special infrared and UV sensors, and to satellite sensors. Because first-hand sightings of oil had ceased, the immediate response was scaled back and the public was asked to report sightings to local authorities. Based on the longer-term trajectory modelling, which predicted oil beginning to strand on northern islands and coast later in the week, a shoreline assessment and further aerial surveillance was planned, in case oil came ashore. Again, the value of the modelling as a planning tool was effectively vindicated. The predicted path of the oil was similar to reality, as was the timing. The oil stranded generally where and when predicted, on the shorelines of the Palm Island Group, Hinchinbrook Island and the mainland between Orient Creek and Lucinda.

This example demonstrates the value of the responder–modeller relationship. The responders and science advisers used their experience and expertise to assess the likely oil source and likely type and its likely weathering in the ambient conditions. The modellers asked questions about reasonable variables, options and uncertainty testing, including the influences of currents and winds in the area. This is not to say that alternative means to track the slick, such as tracking buoys, might not have assisted responders. In the end, the trajectory and weathering modelling provided the opportunity to prepare responders, advise stakeholders, and pre-position additional shoreline response equipment.

combination with oil spill trajectory modelling, timely remote sensing is a powerful tool to inform situational awareness.

In an oil spill response, remote-sensing methods are used to survey large areas of open ocean and provide images of the extent of oil slicks, the trajectories of the oil slick movement and even the thickness of the slicks (Kachelriess et al. 2014; Partington 2014). As such, this information enhances situational awareness and is critical for planning and directing resources to operational response elements such as oil clean-up and
environmental effects monitoring. The measured oil-slick trajectories are also a valuable validation of computer-based oil spill trajectory models and facilitate the development of more accurate predictions of trajectories (Liu et al. 2015).

Despite its many uses, remote sensing does have some limitations. The disadvantages include a requirement for specialised training in image analysis and, potentially high operational costs, depending on the approach taken (especially when observations are based on aerial observation methods). Cloud cover, wind conditions and other environmental factors can complicate the interpretation of remote-sensing data, and the data processing can be time and resource intensive. In addition, previous studies have had limited success in estimating the thickness of oil slicks, and therefore volumes, on the surface (Wettle et al. 2009).

Remote sensing can also be used to:

- locate oil slicks to be treated with dispersant
- provide evidence of successful dispersant application
- dispatch the personnel and equipment on impacted shorelines in order to remove the stranded oil quickly before it is be remobilised by the tide to other sites.

Remote-sensing equipment comprises two major components: sensors and platforms on which these sensors are mounted. The choice of sensor determines the image-based information that is obtained, and the platform determines the scale of the response, as outlined below.

### 6.3.3 Sensors

Sensors used to detect oil spills cover a wide range of the electromagnetic spectrum from radio waves, microwaves and the IR to UV-visible spectral range. They are generally classified as passive or active remote sensors. Passive sensors detect naturally transmitted radiation such as IR, visible, thermal and microwave radiation. Active remote sensors, on the other hand, transmit radiation to the target and receive radiation coming from the target. The different types of sensors, the means by which they operate, their advantages, disadvantages, and operational limits are summarised in Table 6.2.

### 6.3.4 Platforms

Sensors used for remote sensing can be mounted in aircraft (manned or unmanned) or satellites (Brekke and Solberg 2005). Satellite-borne remote sensors have a much larger beam width (swath) (several tens of kilometres) than airborne remote sensors. Satellite-borne synthetic aperture radar (SAR) systems or far-range airborne radar systems are generally used for initial surveillance of large areas for oil spill detection. Near-range airborne remote-sensing systems (300–1000 m of swathing range), with integrated multiple optical sensors, are used for further investigation of suspicious features detected by SAR systems to determine thickness and type classification of oil slicks.

### 6.3.5 Wide-area coverage

Among the methods listed above, SAR is still the most applicable and efficient method for oil spill detection and monitoring due to global and frequent coverage, large spatial extents that can be captured in each capture, high resolution and ability to operate day/night in all weather conditions (Fan et al. 2015; Tian et al. 2015). Wind speed can, however, significantly affect oil slick visibility to SAR. Back-scattered radar from oil slicks are only visible at a limited range of 3–10 m/s. When wind speed is higher than 7–10 m/s, only
thicker oil is detectable, while when wind speed is lower than 3 m/s, SAR cannot differentiate background sea state from oil slicks. Additionally, SAR is also susceptible to interferences from false positives (such as low wind areas and algal blooms) and cannot identify pollutant types, because any pollutant (ship discharges, organic plumes) that can dampen the sea-surface capillary waves is displayed as dark features in SAR images. These lookalikes can be eliminated using data-processing techniques, expert interpreters or local image confirmation. Despite the limitations on its use, SAR is a powerful and very rapidly deployable tool to enhance situational awareness. Due its availability overnight, it is often collected during the hours of darkness in order to plan daylight operations. Several new SAR platforms and data transmission facilities (e.g. ESA Sentinel constellation) are being launched with mission objectives of data delivery within 20 min of image capture. This quasi-realtime data delivery will offer significant enhancements to situational awareness during and incident.

Collection of visual data, typically from satellite platforms, is another powerful method of rapidly collecting information on the extent of slicks over large areas. A rapidly growing number of providers are able to supply high-quality rapid visual data at various scales and resolutions. As noted above, the collection of visual data from satellite platforms is limited by cloud cover and darkness, but many captures can be acquired during each day, reducing the effects of cloud cover.

Collection of satellite data during an oil spill would typically involve the collection and analysis of both visual and SAR data to develop a time series of slick extents that could be used to inform not only the spill response but also provide valuable inputs to help refine spill response models.

### 6.3.6 Localised coverage

Finer scale analysis is typically performed using optical sensors. These techniques typically have greater sensitivity than SAR. Compared with other remote sensors, laser fluorosensors offer high selectivity for oil slicks over other objects or features (Fingas and Brown 2014). Spectra obtained using this method can be processed to generate oil type and oil thickness information. IR/UV scanners have become standard tools for oil spill response monitoring for both detection and determining the thickness of oil slicks. UV sensors alone are very sensitive to thin oil sheens, while IR sensors can detect thicker oil slicks and also extend the operation to night-time (although with lower sensitivity). The operation of optical sensors (such as IR, UV and fluorosensors) is generally restricted by weather conditions and natural illumination. The interferences for IR and UV sensors are also often different.

Since no single sensor can provide identification of oil slicks with a high level of confidence due to interferences from environmental factors as well as operational constraints, an integrated approach that employs multiple sensor technologies to make full use of complementary information generated from different sensors will be the most accurate. Commercial systems such as MEDUSA and the MSS 6000 already incorporate several sensor technologies, such as laser fluorosensors, IR/UV line scanners, forward-looking IR sensors, microwave radiometers, side-looking airborne radar systems and camera systems.

In addition to requiring a good knowledge of the advantages and limitations of various remote-sensing methods, data interpretation of the images gained from remote sensing will be most accurate if the operators have complete situational awareness and have chosen sensors that best suit the monitoring objectives. Table 6.3 summarises remote sensor suitability for various components of oil spill response.
Table 6.2. Summary of the different types of sensors that can be applied to the remote sensing of oil spills

<table>
<thead>
<tr>
<th>Method</th>
<th>Mechanism to differentiate oil and water</th>
<th>Advantages</th>
<th>Intrinsic disadvantages/major false positives</th>
<th>Operational limitations</th>
<th>Sensitivity to weather condition</th>
<th>Data processing</th>
<th>Cost</th>
<th>Supplier</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual observation/photography and videos</td>
<td>Higher reflectance of oil slicks, color difference</td>
<td>Minimum data processing</td>
<td>Sun glint, wind sheens, surface algae</td>
<td>Day</td>
<td>Cloud, fog, sun glitter</td>
<td>Low</td>
<td>Economical</td>
<td>Very large number of vendors and free data providers, including but not limited to Modis, Landsat, Quick bird, etc.</td>
<td>Documentation of spills</td>
</tr>
<tr>
<td>UV sensors (passive)</td>
<td>Higher reflectance of oil slicks</td>
<td>High sensitivity to thin oil sheens</td>
<td>Wind slicks, sun glints and biogenic material</td>
<td>Day/night</td>
<td>Cloud and fog</td>
<td>Moderate data processing</td>
<td>Inexpensive</td>
<td>HRC Photon MWIR NIIRS 7.1 UV-IR line scanner from Optimare</td>
<td>Thin oil sheen to be combined with IR images</td>
</tr>
<tr>
<td>IR sensors (passive)</td>
<td>IR light adsorption associated with hydrocarbons in oil slicks</td>
<td>Day/night operation</td>
<td>Difficulty in detecting oil emulsion</td>
<td>Day/night (lower contrast)</td>
<td>Cloud and fog</td>
<td>Moderate data processing, can be difficult to interpret</td>
<td>Inexpensive</td>
<td>UV/IR scanners are now standard tools for oil spill response Commonly used for oil slick detection Relative thickness info can be used to direct oil clean-up operation</td>
<td></td>
</tr>
<tr>
<td>Laser fluoroscope (active)</td>
<td>Sensor irradiates UV light on target and detects fluorescent light emitted from oil slick</td>
<td>High sensitivity and selectivity to oil slick, minimum interference</td>
<td>Limited coverage (narrow beam and low altitude)</td>
<td>Day/night</td>
<td>Cloud, fog</td>
<td>Moderate data processing</td>
<td>$300–1000 per capture</td>
<td>Optimare</td>
<td>Oil detection, oil type identification and oil slick thickness determination (when combined with water Raman signal)</td>
</tr>
<tr>
<td>Method</td>
<td>Mechanism to differentiate oil and water</td>
<td>Advantages</td>
<td>Intrinsic disadvantages/major false positives</td>
<td>Operational limitations</td>
<td>Cost</td>
<td>Supplier</td>
<td>Application</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------------------------------</td>
<td>------------------------------------------------------------------------------------------------------------</td>
<td>---------------------------------------------------------------------------</td>
<td>-----------------------------------------------</td>
<td>----------------------------------------------------------------------------------------</td>
<td>-----------------------</td>
<td>------------------------------------------------------</td>
<td>------------------------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hyperspectral sensors (passive)</td>
<td>Sample a very large number of spectral wavelengths across the optical part of the electromagnetic spectrum</td>
<td>High data rates, extensive data processing, specialist skills required</td>
<td>Sun glints, white wave caps</td>
<td>Day</td>
<td>Cloud, fog and rain</td>
<td>Extensive data processing</td>
<td>Unknown Hyvista, AVIRIS, SpecTIR ProSpec TIR VIS, AisaHAWK</td>
<td>Oil type classification Oil thickness mapping</td>
<td></td>
</tr>
<tr>
<td>SAR (active)</td>
<td>Oil slick dampens sea capillary waves</td>
<td>Can operate on all weather conditions</td>
<td>Sensitive to wind speed</td>
<td>Day/night</td>
<td>No</td>
<td>Extensive data processing</td>
<td>$1200–8000 per capture TerraSARx CosmoSkymed, Radarsat, RISAT</td>
<td>The most applicable and efficient method for oil spill detection and monitoring</td>
<td></td>
</tr>
</tbody>
</table>
6.3.7 Other factors to consider when choosing a remote-sensing method

Accurate tracking of an oil-slick trajectory and changes to the oil requires multiple images of an incident site (or of the moving slick) to be collected in a short period of time. Some satellites (typically multispectral) can allow for multiple image captures per day, while other satellite systems, such as SAR, may take much longer to be in an appropriate location for image capture and this should be taken into consideration when choosing a remote-sensing approach.

The other factor to consider is data-processing time (Acker et al. 2014; Brekke et al. 2014; Brekke and Solberg 2005). Many remote-sensing methods require extensive data processing to extract oil-slick features and eliminate false positives and may cause significant delays in OSR operational programs waiting for information feeds from the surveillance.

Remote-sensing technologies have been deployed in several major oil spill incidents. A wide spectrum of remote-sensing technologies were used during the Deepwater Horizon oil spill to aid both oil spill situational awareness and impact-monitoring response (Kokaly et al. 2013; Leifer et al. 2012). Because there was no time to assess and validate a system still in development, relatively mature remote-sensing systems, such as the satellite-borne MODIS (Moderate Resolution Imaging Spectroradiometer), MERIS sensors and SAR systems were most useful and were actively employed to provide oil extent and migration information to facilitate informed operational decision making. Airborne remote-sensing systems such as AVIRIS airborne visible/IR imaging spectrometer) generated hyperspectral data that enabled quantitative mapping of oil-slick thickness, which was critical information input for oil clean-up operation. Integration of the hardware system with reliable and robust data-processing software with rapid data-processing capability is mandatory.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Support for clean-up</th>
<th>Night and fog operation</th>
<th>Detection of oil with debris</th>
<th>Oiled shoreline survey</th>
<th>Spill mapping</th>
<th>Ship discharge surveillance</th>
<th>Enforcement and prosecution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Still camera</td>
<td>2</td>
<td>n/a</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Video</td>
<td>2</td>
<td>n/a</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Night vision camera</td>
<td>3</td>
<td>4</td>
<td>1</td>
<td>n/a</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>IR camera (8–14 µm)</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>n/a</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>UV camera</td>
<td>2</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>UV/IR scanner</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>n/a</td>
<td>4</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Multispectral scanner</td>
<td>1</td>
<td>n/a</td>
<td>n/a</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Radar</td>
<td>n/a</td>
<td>4</td>
<td>n/a</td>
<td>n/a</td>
<td>4</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Microwave radiometer</td>
<td>1</td>
<td>3</td>
<td>n/a</td>
<td>n/a</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Laser fluorosensor</td>
<td>4</td>
<td>3</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

*n/a = not applicable; numbers represent a scale from 1 = poorly suited to 5 = ideally suited
Source: adapted from Fingas 2012
during oil spill response. A multispectral expert system that employs a neural network algorithm is a successful application example.

During the Montara oil spill incident, AMSA adopted UV/IR remote-sensing technologies for mapping the distribution of oil slicks by mounting an Argon ST IR/UV scanner on the AMSA Dornier 328–120 (Ball and Young 2010). The deployments had some success identifying oil slicks close to the Montara oil rig. The images collected were susceptible to various interferences and were subjected to data quality control. Clouds introduced false positives as they tended to show cooler features relative to sea surface, similar to oil slicks. Inconsistent image qualities, such as alternation of scanner gain setting during operation and interferences from operating conditions, complicated the data preprocessing. ENVI, a software for advanced georeferenced image processing, was used to convert collected digital images to thematic maps and extract features potentially related to oil slicks and gas plumes.

Starting from 2013, AMSA have used SAR for maritime monitoring and marine surveillance to detect oil spills in Australian waters. SAR data are delivered to AMSA by KSAT (Kongsberg Satellite Service), a Norwegian commercial company that obtains and analyses radar and optical remote-sensor data from multiple satellite sources and delivers to customers including oil and gas companies and government organisations. This approach is a common way of accessing satellite data, when they are required, from multiple platforms or from different sensor types, and there are several providers offering this service.

6.4 Vessel-based surveillance

Vessel-based surveillance is used to verify remotely sensed (satellite and airborne) and model predictions of potential surface oiling (as described previously in Sections 6.1 and 6.2) with in-field observational data to enhance situational awareness and decision support during the response phase of an oil spill. Deployment of monitoring systems from vessels is also typically the only mechanism by which entrained hydrocarbons within the water column can be assessed (e.g. after dispersant use, or from sub-surface release of hydrocarbons). In addition to providing data on location, distribution and type of slicks on the sea surface or entrained oil within the water column, vessel-based surveillance can also guide sampling activities in order to verify the occurrence and properties of hydrocarbons and collect biological samples. Vessel-based monitoring of the oil spill should commence immediately after incident notification. The location to which the ships are deployed will be informed by the oil spill trajectory modelling and ideally will be verified by remote sensing.

Vessel-based surveillance can range from qualitative visual assessments through to detailed chemical characterisation. The level of complexity in the surveillance and monitoring required will be determined by the monitoring objectives and particular spill scenario. If multiple vessels are employed, there may also be a range of monitoring techniques employed from vessel-to-vessel, depending on the particular component of the monitoring plan objective that they are tasked to undertake.

The utility of vessel-based observations diminishes rapidly with time, so observation-based data need to be rapidly incorporated into mapping products (such as GIS) used by incident controllers to aid rapid decision making. This may require verbal transmittal of observation data or electronic transmission of the data from the field. Failing this, the visual-observation data collected during daylight hours need to be incorporated into situational maps overnight. In addition, vessels should be updated regularly with the latest
predictions based on the latest remote-sensing data and model outputs in order to permit adaptive design of vessel areas of operation.

6.4.1 Generic vessel operational considerations

When operating vessel-based monitoring, regardless of the objectives, it is important to consider several aspects of general logistics and how information will be integrated into the larger dataset of information:

**Vessel type** – Surveillance can take place from most vessels, however, they must be suitable for the location and anticipated extent of the incident. Vessels with communications infrastructure are preferred, particularly those with an ability to electronically transmit data.

- Vessel-based surveillance requires entering oiled areas. In order to reduce contamination of non-oiled areas, vessel hull decontamination should be considered where practical.

**Surveillance equipment** – The minimum equipment requirements typically include binoculars, note pads, and cameras with embedded GPS geotagging capabilities, however, with more complex approaches, the requirements are increased.

**Personnel** – Personnel undertaking the vessel-based surveillance require basic training in the methods being used. In addition, reference guides and standardised logging sheets are required.

- Personnel involved in vessel-based surveillance should be qualified in basic survival and first aid techniques and be provided all pertinent PPE.
- Visual observation methods require a constant watch to be kept, typically on the bridge, and require more than one observer.

**Safety** – Where the release is large and from a point source and vessel-based surveillance necessitates entering in close proximity to the incident site, volatile hydrocarbon monitoring should be undertaken, and fitted respirators used with appropriate filters.

Vessel-based surveillance is capable of providing more detailed information if suitable equipment is available. This can involve a range of activities from sample collection for subsequent laboratory analysis, rapid real-time flow-through sensors (see Box 6.2), which will provide some quantitative information about oil in the water column, but limited compositional information, through to shipboard detailed geochemical analyses (Fig. 6.4), which can provide information on oil type and weathering state (see Section 2.2).

6.4.2 Visual observations

Where vessel-based visual observations are employed, the data produced are generally basic, qualitative and restricted to daylight. In their simplest form, visual observations provide presence/absence data throughout the expected impact area, but visual observation of oil on the sea surface can also be used to:

- estimate the quantity and geographic distribution of oil at various locations
- make qualitative judgments of the nature of oil release
- assess weathering or break-up/dispersion of the oil
- identify at risk resources (e.g. wildlife)
- determine the geographic distribution of surface slicks and compare those with predicted sea-surface locations
- determine the success of oil spill countermeasures.
Descriptions of surface conditions should be augmented with photographic evidence wherever possible.

### 6.4.3 Sea state

Hydrodynamic conditions (such as waves and currents) can play a critical role in oil dispersion. Sea state conditions should be recorded at the time of monitoring. Keep in mind that forecasts cannot always replace local observation of weather conditions, which can reflect microclimates.

To minimise subjective assessment, it is suggested that a standard sea-state code be adopted when taking records, as shown in Table 6.4. The table relates wind speed with observed sea state and can give an approximate and concise estimate of sea state.

<table>
<thead>
<tr>
<th>Beaufort wind scale</th>
<th>Description of winds</th>
<th>Description of sea state</th>
<th>Wind speed (km/h)</th>
<th>Wind speed (kn)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Calm</td>
<td>Flat</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1–3</td>
<td>Light winds</td>
<td>Small wavelets, ripples</td>
<td>&lt;19</td>
<td>&lt;10</td>
</tr>
<tr>
<td>4</td>
<td>Moderate winds</td>
<td>Small waves</td>
<td>20–29</td>
<td>11–16</td>
</tr>
<tr>
<td>5</td>
<td>Fresh winds</td>
<td>Moderate waves</td>
<td>30–39</td>
<td>17–21</td>
</tr>
<tr>
<td>6</td>
<td>Strong winds</td>
<td>Large waves</td>
<td>40–50</td>
<td>22–27</td>
</tr>
<tr>
<td>7</td>
<td>Near gale</td>
<td>Breaking waves with spray in the direction of the wind</td>
<td>51–62</td>
<td>28–33</td>
</tr>
<tr>
<td>8</td>
<td>Gale</td>
<td>High breaking waves</td>
<td>63–75</td>
<td>34–40</td>
</tr>
<tr>
<td>9</td>
<td>Strong gale</td>
<td>High breaking waves, dense streaking foam, spray may affect visibility</td>
<td>76–87</td>
<td>41–47</td>
</tr>
<tr>
<td>10</td>
<td>Storm</td>
<td>Very high waves, long overhanging crests, sea surface may appear white</td>
<td>88–102</td>
<td>48–55</td>
</tr>
<tr>
<td>11</td>
<td>Violent storm</td>
<td>Exceptionally high seas, edges of waves cannot be discerned from foam</td>
<td>103–117</td>
<td>56–63</td>
</tr>
<tr>
<td>12</td>
<td>Hurricane</td>
<td>Air is filled with spray and foam, very limited visibility, sea appears completely white</td>
<td>&gt;118</td>
<td>&gt;64</td>
</tr>
</tbody>
</table>


### 6.4.4 Oil identification and volume estimation

Based on its appearance, oil can generally be classified as black oil, brown oil, mousse, sheen (light sheen, rainbow sheen and silver sheen), streamer and tar ball. These characteristic appearances are detailed in several field guides such as the dispersant application observer job aid published by AMSA (2014c).

Aerial surveillance observer aids can be effectively employed during vessel surveillance of oil slicks and can provide the following information:

- state of oil
- area covered
- estimate of oil thickness
• per cent cover
• estimate of amount of oil, based on oil thickness and area covered.

The oil thickness estimate can follow the Bonn Agreement Oil Appearance Code (BAOAC) (Table 6.5), which provides an estimate of oil thickness and concentration for oil slicks at sheen, rainbow, metallic, transitional dark and dark colour states. To minimise subjective assessment and inconsistent standards or criteria, it is suggested that aerial observers obtain training and follow standard protocols such as the dispersant application observer job aid published by NOAA.

The identification of oil-on-water for even experienced seafarers is not straightforward, but as oil spreads on water some assessment of film thickness can be made by colour (e.g. BAAOH 2012) which potentially allows an estimate of total volume to be calculated.

Visual assessment can be subjective and the ramifications for estimating the volume of a slick by assigning the wrong description can be quite large. Thus, in order to obtain comparable and robust data it is recommended that:

• basic observer training is undertaken
• a field identification guide is used
• standard observation classification approaches are used throughout the response.

In addition, it is recommended that photographic records are acquired in order to permit shore-based personnel to assess classifications made in the field (Fig. 6.4). Observational data can be recorded in several ways including log sheets, spreadsheets and integrated logging systems. It is critical that logged data adhere to strict spatial recording standards, which allow integration with information acquired via alternative methods.

### 6.4.5 Vessel-based surface slick identification systems

Several remote-sensing techniques can be employed on vessels in order to identify surface slicks. Many of the technologies that can be employed have been discussed within Section 6.2.2 but are designed specifically for vessel applications rather than aerial or satellite platforms.

Two examples of technologies employed include X-band radar and thermal imaging systems. X-band radar operates using the same principles of SAR, detecting the surface dampening of millimetre scale waves by surface sheens and slicks. Several studies have successfully demonstrated the utility of these systems (Crooke et al. 2015; Noest and Egset 2006). For instance, Fig. 6.5 shows an X-band radar display terminal image of a surface slick caused by a natural seep in the Gulf of Mexico. This image clearly distinguishes a

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
<th>Layer thickness interval (µm)</th>
<th>L/km²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sheen (silvery/grey)</td>
<td>0.04–0.30</td>
<td>40–300</td>
</tr>
<tr>
<td>2</td>
<td>Rainbow</td>
<td>0.30–5.0</td>
<td>300–5000</td>
</tr>
<tr>
<td>3</td>
<td>Metallic</td>
<td>5.0–50</td>
<td>50 000–50 000</td>
</tr>
<tr>
<td>4</td>
<td>Discontinuous true oil colour</td>
<td>50–200</td>
<td>50 000–200 000</td>
</tr>
<tr>
<td>5</td>
<td>Continuous true oil colour</td>
<td>&gt;200</td>
<td>&gt;200 000</td>
</tr>
</tbody>
</table>

Table 6.5. Relationship between amount of spilled oil and the appearance of the slick according to the Bonn Agreement oil appearance code

dark feature running north to south, which is comprised rainbow to silver sheens. As with the SAR techniques, X-band radar is highly sensitive but can be prone to the same false positives and has similar operational constraints, such as wind speed and waves. In this context, false positives are less problematic than in remote sensing because the vessel is in close proximity and anomalies can be directly investigated.

IR systems operate similarly to those mounted on surveillance aircraft and seek to detect differences in surface temperatures between the ocean and oil slick due to their differing thermal properties. Consequently, IR detection requires that slicks have sufficient surface thickness so that they can have a different thermal signature to the surrounding water mass. The slicks that are detected by IR systems are inherently thicker than those detected by X-band radar, which can detect very thin sheens that would have no thermal contrast to the surrounding waters. The IR systems are, in theory, less affected by wind speed so can augment X-band radar measurements. The use of the system requires a camera operator to guide the IR camera and locations of features are determined by triangulation, which with increased range can reduce locational accuracy. Combination X-band radar and IR could be used to determine relative thickness of the surface slicks.

Both of these systems (or combined systems) should ideally be available either pre-installed on dedicated response vessels or locally available to be installed on a suitable vessel in the event of an incident, as procurement and shipping would require a lead time that may be unfeasible during a response. Many vessels already have installed X-band radar systems so may only need the installation of a dedicated terminal, which can also be integrated with ship-based information such as wind, compass, ship automatic identification system (AIS) and GPS. Careful consideration must be made before installation because the oil spill detection system must not interfere with the radar-based navigation systems.
on the vessel. Vendors of the equipment also provide complete radar systems inclusive of both the radar antenna and terminal.

Some of the benefits of the use of these types of system include:

- They are typically more quantitative than visual observations alone.
- The data outputs include images as well as shape files that can be readily imported into GIS systems and readily integrated with other spatial data (Fig. 6.6). With X-band radar and integration with other ships systems, both the wind and wave field in the vicinity of the vessel can be determined – a valuable input into spill models.
- The detection range is greater. X-band radar provides 360° view (if mounted above superstructure) 100 m to ~7 km. For IR systems, the range is typically several hundred metres.
- These systems are independent of light and therefore permit day and night operations.

The installation of these systems is increasing, especially in high-latitude areas where there are prolonged periods of darkness that would inhibit oil spill response operations.

### 6.4.6 Vessel-based water column monitoring

While surface slicks are the visible manifestation of an oil spill, the collection of information in the near surface and deeper in the water column is critical to understanding entrained and dissolved oil within the water column. Entrained oils can take different

---

**Fig. 6.5.** Example of an X-band radar terminal image capture showing surface slick (dark), which visual observation confirmed comprised silver and rainbow sheens.
trajectories to surface slicks and affect different areas. Although there are few combat actions that can be taken to prevent impacts associated with these entrained hydrocarbons, understanding their location may permit more effective decision management decisions in those areas, such as determining fisheries closure thresholds and prioritising the deployment of oiled wildlife teams. Understanding water-column-entrained hydrocarbons also informs the understanding of fate and effects of the oil spill, which is important during recovery phase monitoring. The assessment of entrained oil within the water column is often intimately, but not exclusively, linked to the use of dispersants, which also need to be monitored to determine if the dispersant is effective in dispersing oils (Section 6.4.2).

Water-column monitoring of entrained oils comprises two components. The first is *in-situ* measurements of physical and chemical properties of the water column to determine the presence and nature of the entrained materials. The second component is the collection of samples for subsequent analysis, either in the field or at a shore-based laboratory. The latter approach is discussed in Section 6.5. Typically, these activities occur in tandem combined with the collection of other sample types (e.g. microbiological samples).

*In-situ* measurement can employ several different sensors, a selection of which are detailed in Table 6.6. A key consideration in the use of any of the sensors is that they are regularly calibrated and maintained. Without calibration, semi-quantitation is not possible and the data are therefore of limited value. Once the data are collected, robust QA/QC data processing should be applied in order to ensure that the data are reliable and comparable with other datasets. The QA/QC process should use accepted methods from reputable sources such as IMOS (in Australia) and NOAA. Once the data have been processed, they still require detailed interpretation in order to discriminate between entrained

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Fig. 6.6. A map of the Biloxi Dome survey area of the Gulf of Mexico showing bathymetry, water column acoustic anomalies, photography, wind directions, SAR and X-band data integrated to provide a situational awareness picture (Source: Crooke et al. 2015)
Table 6.6. Summary of the different types of sensors that can be used for water column monitoring during oil spills

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Purpose</th>
<th>Detection mechanism</th>
<th>Operational considerations</th>
<th>Availability</th>
</tr>
</thead>
</table>
| Polycyclic aromatic hydrocarbon fluorimeter | Measures polycyclic aromatic hydrocarbon response as a proxy for hydrocarbon/oil concentration | Fluorescence                 | • Calibration required for quantitation and sensor drift  
• Data QC/QA required  
• Expertise required to interpret data | Several commercial suppliers  
Each instrument has different specifications which should be considered before purchase |
| Particle analyser                      | Measures particle size distribution in water column and distinguishes between existing particles and entrained oils | Laser scattering or underwater microscope | • Calibration required for quantitation and sensor drift  
• Data QC/QA required  
• Expertise required to interpret data | Several commercial suppliers once again with different specifications |
| Turbidity meter/nephelometer           | Measures turbidity of waters; can be used to distinguish changes in particle/droplet loadings | Light scattering             | • Calibration required for quantitation and sensor drift  
• Data QC/QA required  
• Expertise required to interpret data | Widely available multiple suppliers |
| Coloured dissolved organic matter fluorimeter | Measures coloured dissolved organic matter, which can overlap with PAH sensor response. Used to eliminate false positives | Fluorescence                 | • Calibration required for quantitation and sensor drift  
• Data QC/QA required  
• Expertise required to interpret data | Widely available, multiple suppliers |
| Chlorophyll fluorimeter                | Measures chlorophyll content of waters, which can be used to determine if other fluorimeter and turbidity responses are due to algae in water column. | Fluorescence                 | • Calibration required for quantitation and sensor drift  
• Data QC/QA required  
• Expertise required to interpret data | Widely available, multiple suppliers |
| Dissolved oxygen                       | Measures dissolved oxygen content as a proxy for hydrocarbon biodegradation in water column | Clarke electrode Optode      | • Calibration required for quantitation and sensor drift  
• Data QC/QA required  
• Expertise required to interpret data | Several commercial suppliers once again with different specifications |
<table>
<thead>
<tr>
<th>Sensor</th>
<th>Purpose</th>
<th>Detection mechanism</th>
<th>Operational considerations</th>
<th>Availability</th>
</tr>
</thead>
</table>
| Salinity    | Measures physical water properties, and can indicate different water masses stratified intervals | Conductivity measurement electrode | • Calibration required for quantitation and sensor drift  
• Data QC/QA required  
• Expertise required to interpret data | • Widely available multiple suppliers  
• Standard component of conductivity temperature depth sensors used in oceanography |
| Temperature | Measures physical water properties, and can indicate different water masses stratified intervals | Thermistor                | • Calibration required for quantitation and sensor drift  
• Data QC/QA required  
• Expertise required to interpret data | • Widely available multiple suppliers  
• Standard component of conductivity temperature depth sensors used in oceanography |
| Pressure/depth | Determines depth of measurements                                         | Pressure sensor           | • Calibration required for quantitation and sensor drift  
• Data QC/QA required | • Widely available, multiple suppliers  
• Standard component of conductivity temperature depth sensors used in oceanography |
hydrocarbons and interferands. This requires trained, and preferably experienced interpreters, but the data interpreters do not necessarily need to be based in the field.

Deployment of monitoring instrumentation for water-column measurements of entrained oil can take several forms. Typically, instrumentation and water sampling equipment is ‘cast’ vertically through the water column. The deployment using this approach ranges from hand deployment of light-weight sensors and water sampling equipment in shallow waters, through to deployment of large conductivity, temperature, depth (CTD) profiler sensor packages incorporating a water sampling Niskin bottle rosette (Fig. 6.7).

With any approach used, the type of instrumentation required should be balanced against the infrastructure needs of the deployment vessel. A hand-deployed system needs virtually no vessel infrastructure. A large CTD profiler requires a vessel with winches and an A-frame. With any method used, there is a high probability that equipment will become contaminated by surface oils. To avoid surface contamination, typically an area free from surface oils is created by using the vessel to create a wash-swept area through which water column profiling equipment is deployed. This approach minimises contamination, but, in addition, detergents should be used to clean equipment, as well as small amounts of solvent (e.g. ethanol) to clean optical windows, and so on between each deployment.

Consideration must also be given as to whether data are to be recorded and displayed in real-time during the profiling. If this is required – for example, in order to collect waters at particular depths where there are anomalies – then this process requires a conductive cable, a winch fitted with a slip-ring and deck unit to communicate with the device underwater through the cable. Furthermore, if a large number of sensors are deployed then battery systems or specialised cabling will be required to power the sensor package. This is a non-trivial undertaking. Sensor power consumption and battery discharge voltages over time need to be understood and a suitable pressure housing needs to be used. It is crucial that a full suite of spares should be included when considering deployment of the equipment. This may include spare sensors.

Fig. 6.7. CSIRO augmented CTD water column profiler incorporating many of the sensors described above integrated with water sampling Niskin bottle rosette
Noting the considerations above, the use of CTD profilers augmented with other sensor payloads can be used effectively to identify entrained oil. The approach was used successfully in the Macondo incident allowing the sub-surface entrained oils to be tracked over time (Fig. 6.8) (NRC 2013).

In addition, the sensors have also been integrated into near-surface water monitoring platforms, such as unmanned surface vehicles and vessel-based flow-through systems, both of which have been demonstrated during recent incidents. Several of the sensors detailed above have also been incorporated into other water column measurement

![Graphs showing water-column profiles of coloured dissolved organic matter (CDOM) and dissolved oxygen with depth during the Macondo Gulf of Mexico oil spill showing water column anomalies due to entrained oils (Source: Kenneth Lee, CSIRO, pers. comm.)](image)

Fig. 6.8. Water-column profiles of coloured dissolved organic matter (CDOM) and dissolved oxygen with depth during the Macondo Gulf of Mexico oil spill showing water column anomalies due to entrained oils (Source: Kenneth Lee, CSIRO, pers. comm.)
platforms, such as Slocum gliders and towed profilers. To our knowledge, neither of these platforms has been trialled during an incident, but, with the rapid development towards smaller, lower power, but higher sensitivity instruments, the number of data collection approaches will continue to grow. When considering the deployment of in situ sensors, either in combination with water column sampling or not, it is important that expert advice is sought early in order to maximise monitoring outcomes.

6.5 Chemical monitoring

As discussed in the sections above, visual and remote-sensing operations primarily provide qualitative information on oil at the sea surface, with some degree of broad-scale quantitation possible. However, as discussed in Section 2.2, the composition of an oil determines its properties, and consequently how it will behave in the environment. Because the concentrations and composition of oil are dynamic in the environment, and cannot be predicted accurately by models, they must be measured directly (Fig. 6.9). The hydrocarbon sample types collected during response phase monitoring include surface waters, surface oil, and sediment samples. Fig. 6.10 shows how the weathering processes discussed in Section 2.2 affect the distribution of oil in the environment and, as a consequence, which environmental media should be collected for chemical analysis.

6.5.1 Sampling

The collection of physical samples, whether they are oil, water or sediment, can help guide response activities by providing:

- descriptions of the distribution of oil in the water column to verify oil spill trajectory model predictions (discussed in Section 6.1) about the locations and distribution of the oil
  > This will inform the NEBA process and environmental risk assessment by indicating which environmental receptors are at risk.

![Real-time shipboard geochemical analysis](image-url)
information about the physical and chemical properties of the spilled oil, including some measure of the weathering processes occurring
  ➤ This information will determine the response options that are available (e.g. Is this oil able to be dispersed? Can the oil still be collected in booms?).

• information about the concentration of oil to inform the hazard assessment
  ➤ Weathering will change the toxicological properties of the oil (e.g. How likely is it to smother benthic organisms?).
  ➤ If evaporation or dissolution has brought the concentration of oil in the water column below the threshold that is hazardous to aquatic life, response phase operations could be terminated.

• evidence that may later be required to establish a link between the spill and potential source(s) (i.e. proof of pollution) (OSPAR Commission 2010), such as via hydrocarbon source analysis as discussed in Section 7.2.

During different phases of the spill response, chemical monitoring samples are collected with different goals in mind. For instance, at locations where baseline monitoring has not previously been carried out, samples can be collected before any potential oiling occurs. Ideally, baseline data to ascertain the background hydrocarbon concentrations and compositions in an area should be collected to provide some measure of the state of the environment before being impacted by oil (discussed further in Section 7.1). Where baseline samples are required, they should be of the same types and be collected using the same methodologies as those collected during response phase activities. This consistency of sampling will allow comparable data to be generated for use in recovery estimations and impact assessments.

Sampling during response phase monitoring can provide a wealth of information about the changes in composition and distribution of spilled oil, as well as the effectiveness of the operational response (discussed in Chapter 5). This combined information can help responders understand when response phase operations are complete.

Ongoing monitoring may be required to determine the impacts of the spill, as well as the impacts of the response itself, even after the response has been completed (Chapter 7). Studies may be short-, medium- or long-term. Samples for chemical analysis should be

Fig. 6.10. Relationship between sample types and weathering processes acting on oil spills (Source: adapted from Lehr 2001). Processes are in black, the types of oil and where it is deposited are in coloured type.
collected during the response phase to support this. Concentration data may also be used to assess the hydrocarbon concentrations for comparison with those that are expected to cause acute toxicity (Bejarano et al. 2014).

It is essential when collecting samples that, wherever possible, good quality control procedures are used (e.g. elimination of contamination through the use of clean glassware and PPE) and standard chemical laboratory practices are followed, such as the inclusion of blanks (as described in Section 3.2). On-board sampling and analysis can also be used to assess the efficacy of the response techniques and technologies being used to combat the spill, particularly when dispersants are being considered or used, and some options for how this might be conducted are discussed below.

### 6.5.2 Dispersant efficacy monitoring

If the application of a chemical oil dispersant (either via a plane or a ship) is used as a response option, the efficacy of the dispersant on spilled oil under the environmental conditions at the time of the incident should be assessed (described in Appendix F). Field monitoring of dispersant effectiveness is required:

- to ensure that the response option is an appropriate use of resources (e.g. Is the dispersant working? Is further dispersant application required to enhance oil dispersion?)
- to ensure that the shoreline or other ecological resources identified via the NEBA process as requiring protection are no longer at risk from oil exposure
- to enable ecotoxicological risk assessment of both the dispersant itself and of the increased partitioning of dispersed oil into the water column. Effectiveness monitoring is especially important for the planning authorities to decide if the same dispersant can be used for treating more oil slicks and/or if more dispersant should be applied as part of the same spill response.

Effective use of dispersants effectively ‘hides’ the oil, causing a high need for monitoring of the actual environmental consequences of dispersant use.

As with all monitoring approaches, there are several options available for monitoring dispersant efficacy, ranging from simple visual observation to a more rigorous approach where several sensing technologies are used. Because of the limited timeframes for using dispersants and the logistical constraints that are often involved in deploying field crews, visual observation of dispersant efficacy may be the most practical, if not the most precise, monitoring option. In this case, the dispersant can be considered to be effectively dispersing oil, if upon addition of dispersant, the surface oil disperses into the water column forming a cloud-like suspension. This visual approach does not provide any details on particle sizes (required to understand the stability of the suspension) nor does it indicate the overall loadings of oils into the water column (an indicator of both efficacy and the likelihood of toxic impacts).

The use of sensor devices offers an opportunity to gain greater insights into dispersant efficacy, which could be crucial in the continuation of dispersant operations or decisions on which formulations to use during an incident.

### Sensing technologies and sensor selection

Sensing technologies developed for oil-in-water detection are based on the intrinsic properties of oil and its dispersion state in water. Crude oil is a complex mixture of hydrocarbons and other chemicals: aliphatics, aromatics, asphaltenes, resins and some trace elements (S,
N and metals), as described in Section 2.1. Among these components, PAHs can fluoresce when exposed to UV light. The emitted fluorescence can be easily detected by a fluorometer with proper excitation and emission filter settings. Fluorometric methods can detect concentrations of oil in water as low as µg/L to ng/L due to their high sensitivity.

The two images in Fig. 6.11 show the difference between naturally and chemically dispersed oil.

When oil is naturally dispersed, it tends to form large oil droplets that, at low concentrations, are distributed close to the water surface. When chemically dispersed, it tends to form high concentrations of generally smaller oil droplets that penetrate deeper into the water column. A variety of sensors, such as particle analysers or turbidity meters, can capture some features of the changes of dispersed oil droplets. Several approaches to the deployment of sensors for dispersant efficacy monitoring are discussed in Box 6.2. The use of these sensors is discussed further in Appendix F.

Monitoring program design and implementation

The recommended steps for the dispersant monitoring program are:

1. Ideally, obtain oil and water samples from the field to use in laboratory pre-screening, as described below. However, during an incident, the speed of oil weathering may require that dispersants are used within a restricted time window, negating the ability to perform laboratory testing.
2. If time permits, incident-specific pre-screening should be undertaken before dispersants are applied, to ensure that the chosen dispersant is effective against the oil that was spilled (see Appendix X). If all dispersants are ineffective in field trials, the IMT may want to consider other response options (NRC 2005).
3. Aerial observation and field monitoring using instruments should be conducted immediately after dispersant application, as described in Appendix F. Results from all monitoring should be transmitted to the IMT office to assist in planning further dispersant application operations.

Dispersant effectiveness monitoring should ideally be conducted 15 min after dispersant application and should continue for 2–3 h. This is necessary because:

- For thick oil slicks, it takes time for dispersant to penetrate through the oil and take effect on the developing oil plume.
- It takes a longer time to chemically disperse emulsified oil, weathered oil and some heavy oil than lighter products.
• The resulting plume of dispersed oil may be directly below the oil slick and not initially visible from a plane. Over time, the oil slick may drift away from the oil plume as a result of the surface wind.
• Suspended oil droplets may coalesce and gradually resurface.

Laboratory pre-screening-test
If possible and time permits, a laboratory screening test should be performed before dispersant application. Laboratory screening has few logistic requirements and the result will assist decision makers to set dispersant application priorities to be implemented in the field. It should, however, be noted that these laboratory tests are not definitive because they do not simulate real field conditions so results should be treated with some caution and field measurements are still required.

There are several laboratory-based dispersant effectiveness methods that have been developed, such as the swirling flask (SFT) method and the Mackay method. Though taking different forms, the principles of these methods are quite similar. They all involve a similar workflow:

1. Load a fixed amount of sample oil onto the surface of water in a container.
2. Treat the oil with a specific ratio of oil to dispersant.
3. Introduce a consistent mixing energy to facilitate oil dispersion.
4. Allow the mixture to settle for consistent amount of time before quantification of oil in dispersed in the water phase.

6.6 Hazard assessment following an oil spill
The goal of hazard assessment, discussed in more detail in Section 7.3, is to determine the potential of the source oil or its form in water and sediments, to cause toxicological effects (Radovic et al. 2012). A hazard assessment of the spilled material (and any chemical response technologies) will be an essential part of the risk assessment (Martinez-Gomez et al. 2010). These assessments can be conducted at multiple levels of biological organisation, either by looking at hydrocarbon concentrations that cause toxicity or molecular changes in response to oil exposure (biomarkers), by examining bioaccumulation of oil in invertebrates, or by measuring ecological changes in species diversity and abundance. The most robust assessment will use multiple lines of evidence. Crude assessments can be performed using published water quality guidelines. These are derived from sub-lethal ecotoxicity test data for a range of receptor species (typically more than eight species from at least four different taxonomic groups) plotted in a species sensitivity distribution (SSD). The potential for impact on a given percentage of species (typically 95%) (or to a particular species) can be read off the plots as a contaminant concentration (discussed in more detail in Section 7.3).

Because oil is a complex mixture that may change with time and environmental conditions, it is possible that no two oil spills will cause the same toxic impacts because of differences in the source oil, as well as differences in the environmental conditions at the times of the spill. Similarly, the toxic impacts of spilled oil are likely to change with time as the oil weathers.

Ideally, a hazard assessment of spilled oil would be undertaken with water or sediment samples collected during the spill response (Radovic et al. 2012). Examples of the types of bioassays that could be performed are given in Table 6.7. Many commercial laboratories across Australia perform these assays routinely. Water and sediment samples for these assessments should be taken as previously described for chemical analysis. One possible
Box 6.2. Equipment for dispersant efficacy monitoring

Once chemical dispersants are applied, their ‘real world’ efficacy (i.e. the dispersant effectiveness against the spilled oil in its current weathering state under the existing environmental conditions) needs to be determined, both to ensure that the response approach will adequately protect resources and to inform environmental risk assessment to dispersed oil. Although there are numerous approaches to measure dispersant efficacy in the laboratory, including the swirling flask method, the Mackay method and wave tank trials (Li et al. 2008, 2009a,b), there are comparatively few approaches to obtain real time, in situ information about dispersant efficacy.

Submersible chemical sensors can provide real-time or near real-time semi-quantitative concentrations of dispersed hydrocarbons in water compared with conventional chemical analysis of water samples (Conmy et al. 2014). This capability has been applied in the field of dispersant effectiveness monitoring for timely informed decision making of dispersant selection and application. The commonly used SMART (Special Monitoring Applied Response Technologies) kit, was developed for this purpose. It was previously deployed after the Montara and Deep Water Horizon incidents (Tan 2011). It comprises a Turner C3 fluorometer targeting crude oils and relies on its response increase to give a qualitative indication of oil dispersion. However, when the amount of surface oil slick is unknown, the amplitude of enhanced fluorometer response cannot be relied upon to rank the dispersant effectiveness. Additional property information of dispersed oil can be indispensable in evaluating the dispersion effectiveness. In 2014, CSIRO developed a new monitoring kit (the Oilfish, Fig. 6.12) that contains a multi-channel fluorometer and a particle analyser (Qi et al. 2015). It is capable of providing in situ monitoring of changes in the properties of chemically dispersed oil in addition to the overall increase in dispersed oil in water, and therefore can yield more quantitative assessment of oil dispersant efficacy. The towed platform on which the sensors are mounted has the flexibility to be deployed in two different modes – for fixed depth (~1 m) sub-surface water monitoring and water column profiling, respectively. This technology is unique in that it permits simultaneous, real-time measurement of both oil droplet size and number, as well as oil concentration.

Fig. 6.12. The Oilfish, an optical sensor array developed to monitor dispersed oil
criterion for response termination could include field-collected samples no longer causing toxic effects in laboratory assays. So, when field concentrations of oil are no longer shown to be acutely toxic to indicator species, ceasing spill response actions could be considered. Monitoring for ecological recovery would then commence. For smaller spills with more limited resources, hydrocarbon concentrations in environmental samples could be com-

<table>
<thead>
<tr>
<th>Taxonomic group</th>
<th>Species name</th>
<th>Region</th>
<th>Endpoint</th>
<th>Test type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crustacean</td>
<td><em>Penaeus monodon</em> (tiger prawn)</td>
<td>Tropical</td>
<td>96-h survival</td>
<td>Lethal</td>
</tr>
<tr>
<td></td>
<td><em>Allocheistes compressa</em> (amphipod)</td>
<td>Temperate</td>
<td>96-h survival</td>
<td>Lethal</td>
</tr>
<tr>
<td></td>
<td><em>Melita plumulosa</em> (amphipod)</td>
<td>Temperate</td>
<td>96-h survival</td>
<td>Lethal</td>
</tr>
<tr>
<td>Fish larvae</td>
<td><em>Pleuronectes platessa</em> (pink snapper)</td>
<td>Temperate/Tropical</td>
<td>96-h fish imbalance</td>
<td>Lethal</td>
</tr>
<tr>
<td></td>
<td><em>Serolia lalandi</em> (yellowtail kingfish)</td>
<td>Temperate/Tropical</td>
<td>96-h fish imbalance</td>
<td>Lethal</td>
</tr>
<tr>
<td></td>
<td><em>Lates calcarifer</em> (barramundi)</td>
<td>Temperate</td>
<td>96-h fish imbalance</td>
<td>Lethal</td>
</tr>
<tr>
<td></td>
<td><em>Macquaria novemaculeata</em> (Australian bass)</td>
<td>Temperate</td>
<td>96-h fish imbalance</td>
<td>Lethal</td>
</tr>
<tr>
<td></td>
<td><em>Acanthopagrus butcheri</em> (black bream)</td>
<td>Temperate</td>
<td>96-h fish imbalance</td>
<td>Lethal</td>
</tr>
<tr>
<td></td>
<td><em>Acanthochromis polycanthus</em> (damsel fish)</td>
<td>Temperate</td>
<td>96-h fish imbalance</td>
<td>Lethal</td>
</tr>
<tr>
<td>Algae/phytoplankton</td>
<td><em>Nitzschia closterium</em> (diatom)</td>
<td>Temperate</td>
<td>72-h growth inhibition</td>
<td>Sub-lethal</td>
</tr>
<tr>
<td></td>
<td><em>Isochrysis galbana</em> (flagellate)</td>
<td>Tropical</td>
<td>72-h growth inhibition</td>
<td>Sub-lethal</td>
</tr>
<tr>
<td>Macroalgae/seaweeds</td>
<td><em>Ecklonia radiata</em> (kelp)</td>
<td>Temperate</td>
<td>72-h germination</td>
<td>Sub-lethal</td>
</tr>
<tr>
<td></td>
<td><em>Hormosira banksii</em> (Neptune’s necklace)</td>
<td>Temperate</td>
<td>72-h germination</td>
<td>Sub-lethal</td>
</tr>
<tr>
<td>Bivalve larvae</td>
<td><em>Mimachlamys asperrima</em> (doughboy scallop)</td>
<td>Temperate</td>
<td>48-h larval development</td>
<td>Sub-lethal</td>
</tr>
<tr>
<td>Sea urchin larvae</td>
<td><em>Heliocidaris tuberculata</em> (sea urchin)</td>
<td>Temperate</td>
<td>72-h larval development or 1-h fertilisation success</td>
<td>Sub-lethal</td>
</tr>
<tr>
<td>Benthic amphipod</td>
<td><em>Melita plumulosa</em></td>
<td>Temperate</td>
<td>10-day survival or 10-day reproduction</td>
<td>Lethal and sub-lethal</td>
</tr>
<tr>
<td>Benthic copepod</td>
<td><em>Nitocra spinipes</em></td>
<td>Temperate</td>
<td>10-day reproduction</td>
<td>Sub-lethal</td>
</tr>
<tr>
<td>Benthic clam</td>
<td><em>Tellina deltoidalis</em></td>
<td>Temperate</td>
<td>10-day survival or 30-day survival and growth</td>
<td>Lethal and sub-lethal</td>
</tr>
</tbody>
</table>
pared with SSDs identifying acutely toxic oil concentrations obtained from the literature, but because of the variability in hydrocarbon composition and the uncertain impacts this has on toxic impact, the results obtained from these analyses will not be as robust as for assessments performed on samples collected at the time of the spill.

Neither ecotoxicity tests nor monitoring of biomarkers (biochemical or physiological endpoints used to detect an impact of exposure to oil or another biological stressor) (reviewed in Hook et al. 2014a) are a substitute for environmental monitoring because neither is predictive of general ecological impacts (Martinez-Gomez et al. 2010). However, both can provide ‘cause and effect’ evidence linking oil and changes in species structure. Given that ecosystems are dynamic and that pre-impact data may not exist, ecotoxicity tests and biomarker-based studies can be invaluable lines of evidence. The use of ecotoxicity tests and biomarkers can provide spill responders with information pertaining to three questions (Martinez-Gomez et al. 2010):

1. How hazardous is the spilled oil (as well as any dispersants or other counter-measures used) to marine organisms?
2. What area is affected by the spill?
3. How long do the effects of the spill persist?

### 6.7 Habitat monitoring

#### 6.7.1 Identification of potential receptors

Once there are predictions of where oil released in the environment is likely to be transported to, as described in Section 6.1, as well as what state the oil is in (described in Section 2.2), the sensitivity of receptors in that environment to oil and response technologies should be considered. Since it is impossible to assess the impacts of oil on every possible marine organism, this assessment is typically done instead by using the sensitivity of different marine habitats. The environmental sensitivity of each habitat is determined based on the persistence of oil in a given environment in the absence of any clean-up measures, as well as on the sensitivity of organisms within that environment to the effects of oil (Scott et al. 2013). Oil spill response atlases, which contain these environmental sensitivity analyses, should be developed for specific areas well in advance of any potential spill, but in the absence of that information, a general environmental sensitivity analysis is provided below in Table 6.8. Note that this analysis is for the impacts of oiling in the absence of any response measures and does not consider the potential impacts of dispersants, cleaners or nutrient amendment.

The environmental sensitivity is not the same as organism sensitivity. Although, zooplankton, for example, are very sensitive to oil, their habitat (planktonic communities) has a lower rating on an environmental sensitivity index, because oil is not expected to persist for the long term.

<table>
<thead>
<tr>
<th>Habitat</th>
<th>Recovery time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planktonic communities</td>
<td>Days–weeks</td>
</tr>
<tr>
<td>Rocky shores</td>
<td>2–5 years</td>
</tr>
<tr>
<td>Tidal flats</td>
<td>5–10 years</td>
</tr>
<tr>
<td>Coral reefs</td>
<td>10–50 years</td>
</tr>
<tr>
<td>Mangroves</td>
<td>25–80 years</td>
</tr>
</tbody>
</table>

*Adapted from ExxonMobil (2008)
in the water column for very long and their populations are expected to recover quickly. Even in the case of embryonic (planktonic) stages, the worst-case scenario would be that recruitment is severely curtailed (depending on the spatial scale of the spill) for one cohort. At the other end of the spectrum, coral reefs and mangroves are very sensitive to oil. Both retain oil and are expected to have slow recovery times because of their slow growth rates. In general, open ocean environments would be less sensitive than nearshore environments, hard substrate would be less sensitive than soft substrate, and high-energy environments would be less sensitive than low-energy environments, largely because of the capacity for oil to be diluted in these environments and its persistence once there. These differences in sensitivity inform decisions to disperse oil. Guidelines for developing an environmental sensitivity index are provided by NOAA (Petersen et al. 2002) and are available at: http://response.restoration.noaa.gov/sites/default/files/ESI_Guidelines.pdf.

Other factors, in addition to the environmental sensitivity, such as the presence of marine mammals and other high-value species, economically important areas (e.g. tourism or population centres), and the distribution of fisheries resources can be used along with the environmental sensitivity index in assessing management responses to oil spills (Singkran 2014). Initial response phase monitoring (observation and/or sampling) can used to determine if any sensitive resources have been in contact with the spilled oil. This can trigger more intense monitoring to determine more precisely the extent and intensity of any effects. Also, this monitoring can be used as a trigger to intensify specific recovery phase monitoring.
Recovery phase monitoring

Sharon Hook, Andrew Revill and Michael Holloway

Recovery phase environmental monitoring and impact assessment (previously known as scientific or Type II monitoring) should be a key part of any integrated and effective marine spill incident response. For maritime spills, it may not be the primary focus or responsibility of the control (response) agency, but will almost certainly be the responsibility of an associated resource management, environmental protection, science or regulatory compliance agency. For the offshore petroleum sector, recovery monitoring is the responsibility of titleholders. However, many countries have no pre-considered and agreed process for the conduct and coordination of post-spill monitoring. Australia provides guidance for the offshore petroleum sector through NOPSEMA (2014), and the UK PREMIAM project (Law et al. 2011) now also provides specific post-spill monitoring guidance. Any recovery phase monitoring program will need to consider three key elements: (i) appropriate science (e.g. chemical analysis, ecotoxicology and ecological impact surveys); (ii) suitable logistics (e.g. transport, chain of custody and storage of samples); and (iii) overall management, reporting and coordination of any program (including how it integrates with existing response or compliance actions).

In Australia, there is no single equivalent guidance document for recovery phase monitoring of maritime oil spills, because responsibility varies across sector (maritime and petroleum), jurisdiction (Commonwealth, state and territory) and agencies. Arising out of the recommendations of the Montara incident, the new offshore petroleum sector regulator, NOPSEMA (2014), has provided an information paper to titleholders on operational and recovery phase monitoring. Although not directly applicable to maritime spill recovery phase monitoring, it nonetheless provides a valuable starting point.

Recovery phase monitoring is different from response phase monitoring because the purpose is to assess the impact of an incident and to determine when recovery of the impacted environment has occurred. Because the recovery phase monitoring should ideally be conducted in parallel with the response phase monitoring, some samples for the recovery phase monitoring need to be taken before impact and at the time of impact, and the monitoring program needs to be designed such that the impact of the oiling and the impact of the response can be differentiated. These monitoring activities will likely be conducted in parallel, and during the same period, and in the same places that the response is occurring, as depicted in Fig. 7.1.

Despite the public perceptions of impact, conclusively demonstrating that an impact has occurred and that it was a result of the oil, as opposed to the response or natural vari-
ability, is a scientific challenge. To demonstrate that an ecosystem has been impacted, a weight-of-evidence approach is recommended, in cases where it is demonstrated that:

1. Hydrocarbon concentrations are elevated in an area (and their composition is similar to either the source oil or to weathered source oil, i.e. are spill-derived).
2. Environmental samples (water or sediment) cause deleterious impacts in standardised toxicity tests.
3. There are indicators of exposure to oil or impacts of oil (elevated tissue concentrations or biomarkers) in organisms collected from the area.
4. There is a change in species abundance and/or community structure following the oiling.

Incidents such as oil spills are often subject to intense scrutiny and litigation (Picou et al. 2004). Good data for any one of the criteria above may not stand alone in litigation. Without the impacts information, the hydrocarbon elevations can be argued to have been too transient to have had an effect. It can be argued that organisms can avoid oiled water or sediment and, consequently, standardised toxicity tests will over-estimate impacts. Physiological changes are not easily linked to ecological impact, and changes in community structure could be due to natural variability or a result of the response effort. Taken together, there could be strong evidence of an oil-related impact; for example, if there were elevated concentrations of oil in an area that were sufficient to cause harm in laboratory tests and oils accumulated by organisms at the site (evidence could be biomarkers or tissue
concentrations) and there were changes in the health and abundance of organisms at the sites. In addition, robust monitoring data can be used to differentiate between the impacts of the oil spill from previous (or subsequent) disturbance, or from ongoing pressures such as fishing and climate change.

7.1 Monitoring designs to detect impacts and recovery

Monitoring to detect impact and recovery aims to detect changes in ecological receptors caused by an oil spill or response technology. This type of monitoring is done:

- as a trigger for action to deal with the impact, should it be detected
- to make a case for compensation, penalties or other action
- to gain scientific knowledge about how spills impact the environment, in order to inform the response to future spills.

The intent is to demonstrate a causal relationship between the spill and/or response activity and the measured ecological change. The main challenge here is to separate the effect of natural spatial and temporal variation from that of the spill. Different designs do this with varying degrees of success, as discussed below.

This type of monitoring will generally target an ecological endpoint at the species or community level (e.g. reproductive success, population density or community structure). Other variables such as exposure to contaminants or tissue concentrations may be quantified to support interpretation of results, but are not the primary focus.

The various study designs and their associated analytical techniques have their roots in classical experimental design, and therefore require:

- replication of treatments at the appropriate scale – for an oil spill, the ‘treatment’ is the oil spill itself
- appropriate controls – experimental units (sites) that are otherwise similar to oiled sites, except for exposure to oil. The impact of oil is then inferred from the difference between control and oiled sites.
- random assignment of treatments (oiled versus not oiled) to experimental units (sites) – this guards against potential biases in the assignment of treatments. The assumption in an oil spill is that the oiled and unoiled sites are part of the same population of possible sites.
- representative, unbiased sampling – in order to avoid sampling artefacts
- sufficient statistical power to detect an impact, should one be present.

In an oil spill, these requirements often cannot be met (Parker et al. 2013). Therefore, monitoring personnel need to be aware of the extent to which these requirements are met, and temper conclusions accordingly.

7.1.1 Control-impact or reference studies

In these studies there are no baseline data. Impacts are inferred by comparing an impacted site with control or reference sites. Sampling is repeated through time at ecologically relevant intervals (e.g. seasonally or annually to reduce the confounding effects of natural population fluctuations (Keough and Mapstone 1995)). Replication at the appropriate spatial scale is achieved by using more than one control site (and impact site, if possible) to obtain an estimate of natural site-to-site variability.

The lack of baseline data means that control-impact studies require careful interpretation. Attributing differences between sites to the spill assumes they were similar to begin with (i.e.
assumption of spatial equilibrium *sensu* Parker *et al.* 2013). Differences may, however, simply represent a pre-existing difference and not the result of oiling. This can be a particular issue in an unplanned event such as an oil spill because of non-random assignment of treatments (oil) to experimental units (sites). For example, along a particular stretch of coastline, locations that are more exposed to wave action may be more prone to oiling than sheltered areas (Herkül and Kotta 2012). Here, oiled sites would have a high degree of exposure to wave action and control sites would have a lower exposure, driving other differences in the natural biota unrelated to the oil, confounding the study. In such cases, it might be necessary to go further afield to find control sites that are have a similar degree of exposure to oiled sites. Alternatively, Wiens and Parker (1995) suggested that variables such as exposure could be included as covariates in the monitoring design in order to account for such effects.

Control-impact studies have also been used to monitor recovery of impacted areas by invoking the concept of parallelism (Parker *et al.* 2013). This concept recognizes that control and oiled sites are likely to be different before a spill occurs (i.e. there is no assumption of spatial equilibrium). Recovery is considered to have occurred when sites vary in parallel with each other (but are not necessarily the same). This approach assumes that biological communities at the sites respond similarly over time to large-scale influences such as oceanic regime and climatic shifts (Fukuyama *et al.* 2014). Local temporal fluctuations may disrupt this assumption.

### 7.1.2 Gradient designs

Gradient designs have been used to detect ecological impacts where a contaminant disperses from a point source (Ellis and Schneider 1997). Variables are measured at a range of distances from the source and analysed by linear regression. A significant relationship is taken as evidence of an impact.

To implement a gradient design, the spatial extent of the exposure gradient needs to be correctly identified. Sampling of environmental contaminant levels or biomarkers may be used to confirm the presence and extent of an exposure gradient.

While intuitively appealing, gradient designs do not provide a way to eliminate potential confounding by pre-existing gradients, natural or otherwise. For example, some point sources may exhibit a pre-existing impact gradient as a result of chronic discharge over a long period. Furthermore, parameters such as depth, sediment size and turbidity all exhibit natural gradients, which could confound the results. Monitoring designs must account for these factors as far as possible.

### 7.1.3 BACI design

Before-after-control-impact (BACI) designs were developed to overcome confounding issues due to natural spatial and temporal variability. They have been used successfully to evaluate the impacts of a range of human activities. They may also be used for unplanned impacts such as oil spills, provided that certain conditions are met (see discussion below). Where feasible, properly replicated BACI designs are the best way of detecting ecological impacts with a high degree of confidence. Box 7.1 provides an example of where a BACI design has been implemented to measure long-term ecological impacts.

**The logic of BACI designs**

BACI monitoring designs test the hypothesis that there is a change in the difference between the mean of the variable at impact and control sites from before to after the spill (Green 1979). In statistical terms, an impact is represented by a significant interaction between the treatment (impact versus control) and time (before versus after). A simplified, theoretical example of a BACI design is shown in Fig. 7.2.
The figure depicts an unreplicated BACI design, where the apparent interaction could also be caused by independent natural variability between sites (Fig. 7.2b). As with the control-impact design described above, sampling (both pre- and post-spill) should be repeated through time to reduce the influence of random variation within sites (e.g. Stewart-Oaten).

**Box 7.1. Long-term ecological monitoring informs the impact assessment from the Prestige spill**

Barros *et al.* (2014) provided an example of how long-term monitoring data can be used opportunistically to study the impact of an oil spill. Their study on the annual reproductive success of colonies of the European shag in the north-west Iberian Peninsula commenced in 1994. In 2002, one of their study sites was heavily oiled during the *Prestige* oil spill, while three others remained unaffected. This situation lent itself to a BACI study to examine the impact of the spill.

The study showed that the bird’s reproductive success did not differ between oiled and un-oiled sites before the spill. In the 10 years after the spill, reproductive success decreased by an average of 45% at the oiled site, but remained unchanged at the unoiled sites. The study was expanded to include several additional oiled and un-oiled sites after the spill. Analysis of those post-spill data showed long-term differences among the oiled and unoiled sites, consistent with those for the sites with pre-spill data. It was argued that the study showed a clear impact of the spill on the long-term reproductive success of this species.

A potential confounding source in this study was that the oiled and un-oiled colonies occurred in different regions of the coast, with oiled colonies all on the west coast of the peninsula while un-oiled colonies were on the north coast. This lack of interspersion could mean that some other, regional scale environmental change could also be responsible for the observed pattern. The authors drew on various sources of data to show that environmental conditions did not differ. This study demonstrates the incorporation of existing monitoring into a long-term oil spill study. It contributes to knowledge of oil spill impacts by showing that seabirds can suffer long-term, indirect effects for many years after a spill.
et al. 1986). Similarly, replication at the appropriate spatial scale should be included by having multiple control sites sampled before and after the spill (Underwood 1991). Control sites would ideally be selected from a larger pool of ecologically similar sites.

Elaborations of a replicated BACI design to include spatially and temporally nested sampling schemes capable of detecting different types of impacts (e.g. pulse versus press or changes in natural variability) have been proposed. The mechanics of these designs and their analysis have been described by various authors (Underwood 1991, 1992; Keough and Mapstone 1995).

**Monitoring designs and statistical power**

The power of a monitoring design refers to the probability that it will detect an effect of a specified size, if that effect occurred. There is little point in investing in a monitoring program that is not capable of detecting an impact; indeed, such a program could be misleading. In monitoring designs, power is a function of the degree of natural variability, the sample size, the size of effect that needs to be detected and the chosen type one error rate. Power therefore can, and should be, calculated as part of the design of the program, and this will assist greatly in determining the required number of control sites and replicate samples. An example of how a BACI design has been successfully used in an oil spill setting is given in Box 7.1.

### 7.2 Oil concentration and composition in the environment

Identification of spilled oil immediately following the spill event is relatively straightforward. However, as weathering and clean-up processes progress, it becomes increasingly important to be able to distinguish and quantify the spilled oil from any other natural or anthropogenic sources as part of the recovery phase monitoring process. Since there are numerous sources of hydrocarbons in the marine environment, measuring the composition of the petroleum is used not only in identifying the entity responsible for a marine incident but also to differentiate between spill-sourced oil and oil from other sources of environmental contamination. Because very few environments are truly pristine, the recovery can be considered complete when the spill-sourced hydrocarbons are below a pre-determined threshold, even if analytical results indicate the presence of other petroleum products in the environment.

There are numerous analytical techniques available to identify petroleum hydrocarbons in environmental matrices (Wang and Fingas 2003a), but none of the most commonly used approaches measure all hydrocarbon fractions. The technique that provides greatest information is high resolution gas chromatography, especially when coupled with mass spectrometry (GC-MS) (Volkman et al. 1997) because this allows targeting of specific compound classes that can be used to quantify and identify sources (Volkman et al. 1997; Wang and Fingas 2003a).

#### 7.2.1 Hydrocarbon source identification

**General hydrocarbon distributions**

Gas chromatograms of hydrocarbon extracts typically exhibit a range of resolved and unresolved compounds. These are predominantly straight-chain and branched alkanes, which in themselves provide little source information (Volkman et al. 1997), but their general distribution can often be used to distinguish between oil types and petroleum and naturally derived hydrocarbons (Fig. 7.3 (Volkman et al. 1997; Wang and Fingas 2003a).

The variety of weathering processes that occurs once an oil is spilled can blur these differences over time (see Section 2.2). It is also important to remember that sediments often
contain significant quantities of naturally occurring hydrocarbons and these need to be distinguished from any anthropogenic contamination (Fig. 7.4).

**Aromatic hydrocarbons**

Individual aromatic hydrocarbons, particularly those with alkyl side-chains, can be useful in distinguishing between oils (Volkman *et al.* 1997) but this is best done using the specificity of GC-MS and monitoring target ions, although again the susceptibility of these compounds to weathering, particularly evaporation, water washing and photooxidation, limit their use in long-term monitoring.

**7.2.2 Hydrocarbon biomarkers**

In the context of oil spill source identification, the term biomarker is used to refer to a suite of compounds which can be identified in oils and traced back to compounds that occur within living organisms. These can be thought of as chemical fossils and are widely used...
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by petroleum geochemists to identify oils and the environment in which they were deposited (Peters and Moldowan 1993) and, as a group, contain a large number of individual compounds with each one potentially providing information (Table 7.1).

The advantage of using the biomarker compounds is that they are relatively high molecular weight (Fig. 7.5) and as such are relatively unaffected by weathering processes. However, this also means that their usefulness is limited when dealing with refined products, such as diesel, which have a low boiling point range. The most common compounds, and those briefly outlined here, are the steranes and hopanes (Peters and Moldowan 1993). Steranes are a group of compounds derived from sterols that are contained in living organisms (e.g. such as cholesterol) and are routinely used to fingerprint oils (Volkman et al. 1997). A predominance of C_{29} steranes as found in Bass Strait oils is generally indicative of organic matter derived from higher plants, while C_{27} compounds will dominate in oils derived from marine algal material, such as those found in the Middle East (Peters and Moldowan 1993).

The second group of compounds most commonly used in oil identification are the hopanes. These are compounds derived from functional compounds primarily contained within bacteria and cyanobacteria (Peters and Moldowan 1993; Volkman et al. 1997)). These compounds are generally monitored using the m/z 191 ion and again can be used to distinguish oils from different regions, such as oils from carbonate environments such as the Middle East tend to have a high abundance of the C_{29} compound. As with the steranes, it is possible to use the ratios of these different compounds to assign semi-quantitative contributions to mixtures of hydrocarbons often found in sediments, but there can be large differences in concentrations in oils, which means the profile of one oil can mask the other, even when present in roughly equal proportions.
In approaching the identification of a spilled oil, a tiered approach is often recommended so that only the most detailed analyses are conducted on those samples that require them (Fig. 7.4). Where possible, saturated hydrocarbon profiles, requiring only gas chromatography, will be employed (this can provide information on some biomarkers such as pristane and phytane). Where this provides insufficient clarity, either due to oils being too similar or alteration due to weathering, then gas-chromatographic analysis of other markers is warranted (Fig. 7.6). An example of hydrocarbon source identification is provided in Box 7.2.
Fig. 7.5. Example of a biomarker analysis of an oil sample (Note: * = n-C_{17}, numbers refer to carbon number, S and R refer to stereochemistry at carbon 22 for hopanes and carbon 20 for steranes; α and β refer to hydrogen stereochemistry at carbons 5, 14 and 17; D = diasteranes.)

Fig. 7.6. Oil spill identification protocol (Source: Wang and Fingas 2003b)
Box 7.2. Use of hydrocarbon source identification for an unlawful discharge

An oil slick was identified from an aeroplane near Hayman Island (in the Whitsunday Island group) on 25 December 2002. Oil samples were collected from the water and local beaches, and from ships known to have transited the area over previous days, including vessels that went to other countries. One ship that had been in the region and then sailed directly to New Zealand was the *Pacific Quest*. In New Zealand, local

![Graph](image1)

**Fig. 7.7.** Biomarker (triterpane) analysis of the oil slick identified off the Whitsundays (a) compared with the sludge tank of the *Pacific Quest* (b). Note the very close matching of virtually all peaks within the samples.

![Graph](image2)

**Fig. 7.8.** Gas chromatograms comparing the unweathered oil in the sludge tank of the *Pacific Quest* (upper plot) with the weathered slick identified off the Whitsundays (lower plot). In the lower plot, the light oil components have been lost due to weathering (most likely dissolving and evaporating).
inspectors took samples that were freighted back to Australia under security (to ensure chain-of-custody) for analysis. The chemical composition of the Whitsunday samples was used to determine which of the vessels had illegally discharged the oil. Targeted analysis was used to examine and determine specific oil components (chemical composition and biomarkers) that could be used to indicate the source. The biomarker ratios from the samples collected at the spill site showed a near perfect match for the oil in the sludge tank of the Pacific Quest (as shown in the Fig. 7.7). Further analysis using gas chromatography compared unweathered oil from the one of the vessel’s sludge tanks with slick samples. Again there is a near perfect match, allowing for weathering of the light fractions from the field samples (Fig. 7.8). This information, coupled with satellite imagery, the vessel’s electronic route record, and other records on the vessel, eventually led to the successful prosecution of the Pacific Quest for the oil spill under the Australian Protection of the Sea (Prevention of Pollution from Ships) Act 1983.

7.3 Direct laboratory toxicity assessment of environmental samples

Often, the risk to organisms posed by exposure to contaminants is estimated using standardised toxicity tests. Although these tests are not intended to mimic environmental conditions, they are meant to provide a standardised approach to ranking and comparing the risks posed by different environmental conditions. There are numerous standardised toxicity tests available, including those that measure acute (short-term) and chronic (long-term or continuous) exposures, and measure lethal (mortality-based) or sub-lethal (changes in physiological processes, growth, reproduction, development, etc.) endpoints (Radovic et al. 2012; Martinez-Gomez et al. 2010). These tests typically use species that are common to the area, sensitive to contaminants, robust (meaning the controls in the tests do not vary much) and reliable (meaning the tests can be repeated by different operators and laboratories). Table 6.5 provides information about the range of tests available in Australia. These tests can use water or sediment samples collected from the environment. Alternatively, environmental contaminants such as the source oil or weathered source oil can be spiked into the test media to determine impacts.

Currently, Australian and New Zealand water quality guidelines require the use of species sensitivity distributions (SSDs), as described briefly in Section 6.5, to assess the risk of an environmental contaminant or the risk posed by a contaminated sample (ANZECC/ARMCANZ 2000b). The rationale behind this requirement is that one toxicity test is unlikely to assess the impacts on all organisms in the environment, but that by evaluating the cumulative distribution from the results of tests using at least eight species from four or more different taxonomic groups, environmental complexity is more likely to be accurately assessed. The SSD is then used to predict a concentration or dilution that is protective of a given percentage of species (typically 95% for moderately disturbed ecosystems, but 99% for undisturbed areas of high conservation value). By coupling these predictions with measurements of oil concentrations, it is possible to predict whether the spill plume (or chemical dispersion of the spill plume) is likely to have acute or chronic impacts (e.g. Bejarano and Mearns 2015). Recent literature also recommends the use of SSDs in oil spill responses (Barron et al. 2013; Bejarano et al. 2014). An example SSD is provided in Fig. 7.9 for naphthalene in marine waters.

As described in more detail in Section 2.2, the composition and the toxicity of each oil is different, and likely to change with weathering. Therefore, although SSDs are available
for standard oils, they are going to be more useful if obtained for the oil spilled and for the current weathering state of that oil, and even more accurate for field-collected water or sediment samples.

In the immediate aftermath of a spill, environmental water and sediment samples are collected to determine (as described in an Appendices A–I) whether exposure to these media are likely to impact organisms in the environment. These results are then used as part of the risk analysis following an oil spill to estimate the spatial and temporal extent of impact, as well as what proportion of species were likely to have been impacted.

### 7.4 Molecular biomarkers

Biomarkers, defined as a measurable physiological change in an organism, can be used as to determine the spatial and temporal scale of the impact of released oil and to attribute impacts to oil, as opposed to other stressors (Hook *et al.* 2014a). There are different types of biomarkers; some indicate exposure to oil (such as EROD induction/CYP1A transcription or an increase in biliary PAH metabolites), while others indicate impacts of oil or other contaminants (including any changes in oxidative stress metrics or an increase in DNA damage). These are described in more detail in Boxes 7.3 and 7.4. Although there is difficulty in directly linking these physiological metrics to population level impacts, biomarkers do demonstrate exposure to a pharmacologically relevant dose of oil, and are the first step in the adverse outcome pathways leading to oil impacts (Ankley *et al.* 2010).

Because changes in biomarkers often provide insight into impacts that are otherwise difficult to quantify, they have been key evidence in previous spills to show both when an impact occurred and when it has abated to a negligible level (see Box 7.4). Biomarker levels are known to fluctuate with seasonal factors and individual variability, so if these endpoints are to be used, it is essential that samples are taken at the time of impact (when

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![Figure 7.9](image_url)

**Fig. 7.9.** An example of a species sensitivity distribution of chronic toxicity data for exposure in marine waters to the PAH, naphthalene. The 95% species protection concentration is denoted by the dashed lines.
Box 7.3. Different types of biomarkers, and how you would use them

The most common biomarkers for oil exposure exploit the xenobiotic metabolism and detoxification systems that vertebrates possess. Although, as discussed in Box 7.4, a biomarker-based approach has been used with invertebrates, for the purposes of this illustration, the test organism is assumed to be a single fish.

PAH metabolites
As the components of oil are broken down to be excreted from the body, the metabolites are stored in the bile. Biliary PAH metabolites are one of the most direct indications that a fish has been exposed to oil. These are specific to oil, and would persist for only a short time (days to weeks) after exposure. To measure PAH metabolites, the gall bladder is excised, frozen, then metabolites are extracted with methanol and analysed fluorometrically. There are specific metabolites for different PAHs within an oil.

EROD induction
Cytochrome p450 1A (CYP 1A) is the first enzyme in the pathway that breaks down PAHs. Ethoxyresorufin-o-deethylase (EROD) activity correlates with this pathway, and is one of the most commonly used biomarkers for oil exposure, and can be used for different oil types, as shown in Fig. 7.10. EROD is most commonly measured in teleost fish, different invertebrates have varying capacities to induce this protein (and as a consequence, to break down oil). Also, only high molecular weight PAHs have been shown to induce EROD (Lee and Anderson 2005). EROD levels are typically elevated for days after exposure. To measure EROD activity, liver or gill must be excised immediately after the organism is euthanised and stored immediately at –80°C.

CYP1A transcripts
Increasing, transcript levels (or mRNA copy numbers) for CYP1A have been used to indicate exposure to CYP1A. This approach has several advantages over EROD activity.

Fig. 7.10. EROD induction levels in fish exposed to different petroleum products (Source: Hook et al. unpublished results)
One advantage is that transcripts of CYP1A may be increased by more types of oil than just high molecular weight PAHs (Hook et al. 2010; Holth et al. 2014). Also, if samples are immediately preserved in RNAlater® (Life Technologies) or similar preservative, they can be stored at room (or elevated) temperatures for hours, and at 4°C for days. Transcript levels can offer a snapshot of contaminants that the organism has been exposed to. They can be elevated for hours to days after exposure, but would be expected to return to background quickly.

**Effects biomarkers**

A variety of other endpoints, including oxidative-stress enzymes (e.g. catalase, glutathione peroxidase, glutathione S-transferase), markers for DNA damage, or markers of condition, are used as markers for the effects of oil. Although these markers are sufficient to show that an organism’s physiology has changed, it is often uncertain whether the organism is able to compensate for the toxicological insult without changing its physiology. Also, these markers are not specific to oil and may indicate non-contaminant stressors.

Impact is greatest, to allow for a point of comparison for ‘return to baseline’ analyses. Samples should also be taken with a BACI or reference design, so that ‘normal’ versus ‘impacted’ comparisons can be made. If a reference design is being used, samples need to be taken within 2 weeks of each other to ensure that seasonal variability does not confound data interpretation. Although samples should be collected (ideally) before and at the time of impact, once collected, they can be archived indefinitely.

Digestive fluids, blood, and other bodily fluids will break down biomarkers, so whole organisms should not be stored, and instead the tissues of interest should be dissected out (except where organisms are so small that dissection is impractical). Biomarkers degrade (sometimes within minutes) of organism death, so great care must be taken to harvest tissues immediately after the organism has been sacrificed. Also, facilities should be available to ensure that tissues are stored at the proper temperature (often –20 or –80°C). Commercial laboratories do not offer biomarker analyses, so samples should be processed at government or academic laboratories with experience in this area. Ideally, before a spill occurs, there will be a plan in place that identifies what types of biomarkers will be collected in each organism, and detailed information regarding sampling protocols specific to these biomarkers will be provided. However, in the absence of the plans, generic advice is provided in Appendix M, so that the necessary samples can be taken in the absence of any specific guidance.

### 7.5 Community structure analysis

In recent years, concern about oil impacts has shifted away from being focused on individual species (e.g. a natural resources damage assessment approach) towards a focus on habitats and ecological functions (NRC 2013). Modern analyses focus on the ‘goods and services’, such as nursery areas for fisheries, amenity areas for recreation, provided by ecosystems instead of just the species present within the areas. As a consequence, recovery phase monitoring should focus on indices of community health and resilience, such as the index of biological integrity (King and Richardson 2003), as well as those that tie any...
Box 7.4. How biomarker data have been used in previous spills

The changes in levels of biomarkers following an oil spill have been well documented for decades (e.g. Stegeman 1978; Lee et al. 1981), so they would no longer be considered as research tools. Instead, as demonstrated in the examples below, biomarkers are commonly used in the assessment of the spatial and temporal impact of oil spills to identify boundaries. Since many of the most commonly used biomarkers reflect exposure only, they are used to focus resources at particular locations and timescales for recovery phase monitoring. They are being included in this Handbook because samples should be taken at time of impact to accurately assess the duration of potential effects.

Biomarker-type responses were extensively used to assess the impacts of the 1989 Exxon Valdez oil spill (EVOS) in Prince William Sound, Alaska, USA. Aryl hydrocarbon hydroxylase levels (a xenobiotic metabolising enzyme) were measured in Dolly Varden trout (Salvelinus malma) 120 and 460 days after the spill. Enzyme levels were elevated in fish collected from a heavily oiled site relative to those collected from a reference site at both time periods, suggesting continuous exposure to oil (Collier et al. 1996). However, several years later, the oil-response biomarkers were no longer elevated. Huggett et al. (2003) measured oil exposure biomarkers (EROD induction immunohistochemistry, and bile PAH metabolites) in nearshore and offshore fish species. No significant difference in the levels of the biomarkers were measured between sites in the EVOS path and other regions in the Gulf of Alaska. The data were used to argue that there was no ongoing exposure of fish to Exxon Valdez oil in Prince William Sound occurring in 1999 (Huggett et al. 2003). A similar study was carried out in 2004, looking at the transcript levels of biomarker genes in the gills and livers or caged coho salmon (Oncorhynchus kisutch) (Roberts et al. 2006). Again, no differences between spill-path and non-spill-path sites were observed, suggesting that there was no ongoing exposure to Exxon Valdez oil in fish (Roberts et al. 2006).

Following the 1999 Erika oil spill (Brittany, France), biomarker levels in the blue mussel, Mytilus edulis, were followed for 3 years to determine the time that oil impact lasted (Bocquene et al. 2004). Levels of acetylcholine esterase, glutathione S-transferase, catalase, malondialdehyde and DNA adducts were measured. Glutathione S-transferase and catalase levels did not change, but malondialdehyde and DNA adduct levels were elevated for 6 months following the spill, whereas acetylcholinesterase levels were suppressed (inferred to be a generalised stress response) for a year after the oil spill. From this, it was concluded that the effects of the oil spill lasted for at most 1 year.

Biomarker levels in demersal fish were also used to determine the spatial and temporal scales of oil impact following the Prestige oil spill (Galician coast, 2002–2003) (Martinez Gomez et al. 2006, 2009). Hepatic levels of EROD, glutathione S-transferase, glutathione reductase and catalase were elevated at levels that correlated with the trajectory of spilled oil 5 months after the spill; however, these levels were lower both 2 and 3 years after the spill (Martinez Gomez et al. 2009). Similar results were observed in mussels (Fernandez et al. 2010). Two years after the spill, both PAH concentrations and oxidative stress markers in the mussels had returned to background levels.

Another recent study compared changes in biomarker levels (EROD and biliary PAH metabolites) in the impacted area, downstream locations, and a reference site following
changes in composition, abundance, and function to oil exposure. Frequently, these changes are measured via community structure analysis.

Community structure analysis is used to quantify the abundance, diversity and condition of different taxonomic groups in a given area. Typically, this is done by surveying the abundance of different organisms. The age, size class, sex and condition of organisms can also be recorded. This surveying can be done at different scales (e.g. to the level of species, to taxa or just to amount of overall biomass). The latter approach is not recommended because opportunistic species can colonise an area following a disturbance, and these species would not have the same function in the ecosystem as those they replaced. In previous spills, changes in the community structure have been used to demonstrate impact (e.g. Baguley et al. 2015), and a return to a baseline state has been used to demonstrate recovery (e.g. Fukuyama et al. 2014).

This section discusses monitoring programs that attempt to determine causality; that is, to detect changes actually caused by the spill, against a background of natural variability. These changes may not be attributable to the oil exposure, but may instead result from response activities, increased traffic and human disturbance, or altered trophic interactions.

7.5.1 Ecological variables

The choice of which variables to monitor is fundamental to the design of the program. Ecological variables can be at the individual level (e.g. physiological or pathological responses) or population level (e.g. abundance or diversity). Indices of community structure or species diversity may also be used as a variable in a univariate (e.g. just the impacts of oil) analysis, and there are also examples of multivariate (e.g. the impacts of the oil and the response strategy used) BACI designs (e.g. Martin et al. 2012).

A common approach in environmental monitoring is to use indicator variables – measures that are indicative of more general ecological change, or changes in a single parameter that represent the community as a whole. Indices of community structure or species diversity may also be used in place of indicator variables (e.g. Martin et al. 2012). For example, the concentration of chlorophyll $a$ is often used as an indicator of the impact of nutrient enrichment (e.g. Biggs 2000); similarly, altered abundance of copepods relative to polychaetes is a commonly used indicator of exposure to oil (Baguley et al. 2015). Indicator variables should ideally have the following features (Keough and Quinn 1991):
• There is an established link between exposure to oil (or response element used) and changes in the variable, based on laboratory or field studies.
• They should be indicative of broader ecological changes, demonstrated through field experiments.
• They should be moderately sensitive to oiling at the expected exposure level, but not over or under-sensitive.
• They should be reasonably common at control and impact sites.
• They should be cost effective to sample.

Alternatively, monitoring programs may concentrate on particular species of concern such as marine mammals, irrespective of any knowledge about their sensitivity, due to public concern or legislative requirements, even though these organisms are typically harder to monitor and do not align as well with BACI and other statistical designs.

Changes in the community structure of an area exposed to oil would seemingly be a clear impact of an oil spill, because presumably the toxic impacts of oil would cause a decrease in organism abundance. Typical changes in community structure following an oil spill may include disappearance of sensitive taxa (e.g. a decrease in the number and abundance of crustaceans and an increase in polychaetes, as reviewed by Gomez Gesteria and Dauvin 2005), or an increase in hydrocarbon-degrading bacteria and fungi (Bik et al. 2012). However, populations of organisms change with seasons, due to other stressors, and perhaps due to the response, so care must be taken to be able to unequivocally attribute these changes to the oiling. For example, animal populations in a given area may fluctuate seasonally, or annually due to variation in reproductive cycles, or on longer time scales due to climatic factors (e.g. El Nino). Populations may vary from place to place and, furthermore, fluctuations may occur within locations independently of what is happening elsewhere. All of this background variability can confound interpretation of monitoring results, making it impossible to distinguish natural changes from changes caused by some impact, such as an oil spill (Table 7.2).

Analysing the changes in abundance in hydrocarbon-degrading microbes may augment the interpretation of community structure database on macrofauna. Hydrocarbon-degrading bacteria follow clear successional patterns and can show the temporal scale of impacts of oil (see Box 7.5), and can be used to demonstrate the presence of labile petroleum-based hydrocarbons.

### 7.6 Ecosystem recovery

The National Plan (AMSA 2014b) defines recovery as recovery of costs, rehabilitation of the environment, and return to normal socioeconomic conditions. Although measuring

<table>
<thead>
<tr>
<th>Source of variability</th>
<th>Confounds interpretation of:</th>
<th>Result</th>
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<tr>
<td>Through time (e.g. seasonal, climatic)</td>
<td>Differences at a site from before to after a spill</td>
<td>Creates the appearance of impact when there is none or, conversely, masks the presence of an impact when one exists.</td>
</tr>
<tr>
<td>Between locations</td>
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<tr>
<td>Within locations over time</td>
<td>A divergence (or convergence) of a variable at a single control and impact site from before to after the impact (i.e. unreplicated)</td>
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</table>
Box 7.5. Changes in microbial structure and function during the Deepwater Horizon oil spill

The numerous studies done in the wake of the Deepwater Horizon oil spill demonstrate how changes in the community structure of bacteria can be used to show the spatial and temporal degree of oil impact (Kimes et al. 2014). MC252 oil is a light crude, consisting mainly of alkanes, and as a consequence would be expected to be readily biodegraded. The microbial response to the spill was ‘rapid and robust’, especially in the water column, where oil was degraded aerobically, with measured activation of conserved pathways to break down low molecular weight aliphatic and aromatic hydrocarbons (Kimes et al. 2014). These changes can also be used to show the metabolic capacity of indigenous microbes, and the degree to which remaining oil could be expected to be degraded by bioremediation. Changes in the microbial community structure can also be used to show the impact of clean-up efforts.

Microbial communities in the water column

In general, the release of oil into the water column caused local increases in the microbial biomass, and changed the species composition and function (Kimes et al. 2014). The community inside the hydrocarbon plume was less diverse both functionally and phylogenetically than the community outside the plume (Rivers et al. 2013). Multiple modes of hydrocarbon metabolism were occurring simultaneously, but the relative proportion of each changed, depending on the available petroleum components (Dubinsky et al. 2013). These changes in species composition followed a predictable succession of dominant bacteria, depending on the available hydrocarbons (Kimes et al. 2014). Samples collected between 25 May and 2 June 2010, indicated an increase in gamma proteobacteria, notably from the genus Oceanospillaralles, which correlated with the depth distribution of hydrocarbons and the oxygen anomaly (Hazen et al. 2010). This was followed by an increase in Cycloclasticus and Colwellia, then by an increase in methanotrophs and methyltrophs (Chakraborty et al. 2012). Functional analysis performed with the GeoChip (Lu et al. 2011) also indicated that there was an increase in genes involved in BTEX, alkanes, cycloalkanes and PAH degradation, carbon metabolism, sulfate reduction, nitrate assimilation and metal resistance (Hazen et al. 2010; Lu et al. 2011; Chakraborty et al. 2012). There was also an increase in the abundance of methane-oxidising bacteria (as determined by abundance of a key methane-oxidising gene) following the spill, which peaked in May and early June, and declined sharply after that (Crespo-Medina et al. 2014). By September and October 2010, the population of hydrocarbon-degrading bacteria had decreased to 1–5% of the total microbial biomass (Yang et al. 2014). The hydrocarbon composition in the water column had a greater influence of the microbial population than depth (and temperature) or nutrient availability (Dubinsky et al. 2013). The biodegradation of the more labile compounds led to an enrichment of recalcitrant compounds and oxygenated hydrocarbons (Kimes et al. 2014).

Microbial communities in deep-sea sediments

Oil degradation in the sediment occurs via both aerobic and anaerobic processes, and would be expected to proceed much more slowly. Kimes et al. (2014) used metagenomic analysis to profile the activity of deep-sea microorganisms from sites 0.5, 2.7 and 127 km from the Deepwater Horizon wellhead. They identified a microbial community capable of aerobically degrading hydrocarbons in all samples, and an
enrichment of functional genes associated with anaerobic hydrocarbon degradation and delta proteobacteria closer to the wellhead blowout site.

**Microbial communities in marsh sediment**
The bacterial community in salt marshes inundated with petroleum from the Deepwater Horizon spill shifted towards known hydrocarbon-degrading taxa, including Proteobacteria, Bactroides and Actinobacteria, but returned to a normal composition once the petroleum components had decreased below detection (Beazley et al. 2012).

**Microbial communities in beach sands**
Successional changes in the bacterial community structure following shoreline stranding of oil in Grand Isle, Louisiana, USA at three time points in June 2010 were measured using 16S gene sequences, and changes in the functions of those communities were surveyed using metatranscriptomics (Lamendella et al. 2014). Bacterial numbers increased at the most highly contaminated sites. Known hydrocarbon-degrading bacteria were identified, including Oceanospirales initially and Colwellia and Cycloclasticus at later sampling dates, which matched successional patterns observed in the water column. Functional gene associated with hydrocarbon degradation were also detected and matched patterns of oil degradation, as transcripts that could be mapped to PAH degradation were most abundant when PAHs were being lost from the sediment.

A similar study conducted following shoreline stranding of oil in Pensacola, Florida, USA in July and September 2010 also found predictable successional changes (Kostka et al. 2011). This study used analysis of cultures of bacteria isolated from beaches where oil had been deposited and enriched by growing cultures with oil as the sole carbon source. They observed an increase in the abundance of gamma proteobacteria, and a high proportion of the alkane degrader Alcanivorax in early samples. Changes in community structure could be correlated with time since oil stranding and with amounts of oil deposited.

Studies have also shown that beach sands were enriched in oxyhydrocarbons, suggesting that physical weathering may be more important in those environments (Kimes et al. 2014).

**How clean-up efforts can affect microbial communities**
Changes in the microbial community can also be used to examine the impacts of the response effort. For instance, following oiling in Grand Isle, Louisiana and Dauphin Island, Alabama, the beach was washed with oceanic water and the sand was tilled. Prior to oiling, the beach sands were enriched with enteric bacteria. The remediation efforts led to an introduction of oceanic bacteria, including hydrocarbon-degrading bacteria. These may have caused a permanent ‘regime change’ in the microbial community of these beaches (Engel and Gupta 2014).

the recovery, is outside the scope of the response phase monitoring and is discussed elsewhere (NOPSEMA 2014), a brief overview of how you would tell if an ecosystem is recovered is provided because it informs the samples that need to be collected before contact with oil and at time of impact.
As for the assessment of ecosystem impact, a weight-of-evidence approach is recommended. An ecosystem would be considered to have recovered if:

1. hydrocarbon concentrations are similar to pre-impact and reference areas. The source of these hydrocarbon is the combustion of fossil fuels (i.e. atmospheric deposition and boat traffic) or natural seeps.
2. environmental samples no longer cause deleterious impacts in standardised toxicity tests
3. oil body burdens/biomarker levels no longer suggest exposure to oil
4. community structure has returned to baseline or is changing in parallel to reference areas.

Examples from previous incidents of how it was determined that the impacts of previous spills had ceased are given in Boxes 2.2, 7.4 and 7.5. If impacts are expected to occur over a large spatial area or over a multi-year time scale, community structure may change in the system as a whole (e.g. in impacted and un-impacted areas) due to other stressors, such as fishing pressure, introduced species or climate change. As a consequence, an adaptive monitoring framework may be appropriate.
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These appendices provide examples of SOPs that will not necessarily be ‘fit for purpose’, but can easily be amended in the planning phases to suit a responder’s needs and the local environment. These SOPs are typically for sample collection only, and any guidance received by the analytical laboratory or the data analysts will supersede the guidance in the following pages. These are also deliberately general so that they can be applied to as many different scenarios as possible. A key to the appendices is provided in the table below:

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Many of the SOPs listed above will also be suitable for the collection of water and sediment samples for laboratory-based ecotoxicology analysis. Appendices T and U provide an overview of shoreline assessment and determining the shoreline gradient. Examples of some commonly used forms are also provided, including sample data sheets (Appendix S), and the activation proforma used for team deployment (Appendix W).
Appendix A. Standard operating procedure for shipboard collection of surface waters using wide-mouth jars

A1 Purpose and scope
This appendix describes the procedure for collecting surface waters for analysis of dissolved hydrocarbons, or whole oil (if sampling is conducted in an area of slick). The collection of samples from the sea surface microlayer has yielded useful data in previous spill scenarios. Please note that this SOP is written for sample collection from a large vessel, but could be modified to be used from a smaller vessel or even a dock.

A2 Equipment
- wide-mouth amber glass jar, minimum volume 350 mL, with Teflon®-lined lid
- extendable sampling pole, or if not available, a boat hook
- hose clamps
- screwdriver
- aluminium foil (to wrap clear glass jar if amber glass is not available)
- nitrile gloves
- thin foam
- adhesive tape
- zip-lock bags large enough to contain jar

A3 Special instructions
The collection of surface waters using wide-mouth glass jars is conducted from a suitable position on the vessel deck, as far away from potential sources of contamination as possible (such as the vessel stack, bilge or outlets). Ideally, the sampling position will be as close to the sea surface as possible, to minimise reaching over the side of the vessel to collect a sample. The following criteria must be met before sample collection:

- The Master or Officer on Watch must sanction deployment.
- A minimum of two operators is required. Each person must put on personal protective equipment before going out onto the work deck areas (as a minimum, head protection, safety boots/shoes, coveralls and work vests). Operators involved in the deployment of the equipment over the side of the ship should additionally wear a life jacket.
• Survey operators must consult with the Officer on Watch with regard to any local hazards, such as weather conditions, nearby ship or fishing activity and structures. Equipment will not be deployed if conditions are unsafe.

• A toolbox meeting should be held on the Bridge before deployment, involving all crew involved with operations. Ensure that the Bridge is informed of intended deployment and that the Bridge is instructed to inform operators of any intended ship manoeuvres in good time. The toolbox meeting will cover all aspects of the deployment, including what is to be achieved, an overview of all safety aspects involved in the deployment and each person’s role within the process. Only when all parties are satisfied will deployment commence.

• It should also be noted that the final decision as to whether a deployment will commence ultimately lies with the Captain. However, if at any point any person feels it is unsafe (e.g. due to adverse swell conditions), then operations will immediately stop and the situation reviewed.

A4 Sample collection procedure

• Ensure sample handlers are wearing clean nitrile gloves.

• Equipment should be deployed with the ship maintaining station. The work area must be adequately illuminated and clear of personnel excess to requirements (unless observing from a safe distance).

• Check voice communications between the Bridge and deck via hand-held VHF radio. It must be possible to maintain radio contact between the Bridge and sampling team throughout the operation.

• Attach a clean wide-mouth glass jar to a sampling pole using hose clamps.

• Ensuring appropriate personal protective equipment (PPE) is being worn, stand at the selected sampling location, ensuring it is safe to do so.

• Once the surface water is accessible, inform the Bridge by VHF that sample collection is about to commence. Sample collection will only proceed with authorisation from the Bridge.

• Extend the sampling pole over the surface of the water, and scoop water from the top of the sea surface into the glass jar. Do not fill the jar completely, because, if present, hydrocarbons on the sea surface can be collected at the meniscus of the water in the jar, and so it is important to preserve this.

• When sampling is complete, pull the sampling pole back on-board carefully, being sure not to tip water out of the jar.

• Remove the jar from the sampling pole.

• Cap the jar and ensure it is tightly screwed on.

• Record the appropriate sample information on the sample label:
  ➤ date and time in UTC – this may be the most important information because track information may allow the sample to be relocated at a later date.
  ➤ station/site number or if an unplanned site is being sampled, a suitable identifier must be used
  ➤ sampler’s initials or name
  ➤ any comments about sampling (e.g. half of water lost during retrieval of jar, possible biological material recovered in jar).
• Put the samples in a secure location while the work area is reinstated, with barrier chains replaced across duckboard. The sampling pole and other equipment must be stowed away to avoid creating trip hazards.

• Inform the Bridge that sampling operations are complete.

• Wrap a strip of thin foam around each sample jar and secure with tape. This is to provide a layer of cushioning between the jars to try to reduce the chances of breakage caused by the glass jars knocking into each other in the refrigerator.

• Place each foam-wrapped jar in a small zip-lock bag and store at the correct temperature. If breakage does occur, the glass and sediment should be contained by the zip-lock bag.

• Store samples at 4°C.
Appendix B. Standard operating procedure for Niskin bottle collection at depth of waters for dissolved hydrocarbon analysis

B1 Standard operating procedure for the operation of a CTD sensor rosette array to collect water samples at depth

B1.1 Purpose and scope
A CTD sensor records conductivity, temperature and depth. It is often coupled in a rosette array that incorporates Niskin bottles, allowing the capture of a water sample at a precise depth. These water samples can then be filtered for microbial or planktonic analysis, or used for hydrocarbon analysis.

B1.2 Special instructions
- Make note of the depth rating on the instrument and do not use instruments at depths greater than their ratings
- Maintain communications with the Officer on Watch to ensure that vessel movements are coordinated and that any cable is clear of the vessel.
- Monitor metocean (wind, wave and climate) conditions before and during deployment to maintain safe working environment; consider aborting operations if conditions are marginal.

Protocol before CTD deployment
- Prepare the CTD profiler on deck and check all systems are operating correctly; check all cables, plugs and shackles for wear, defects, etc. Prepare the CTD for launch (e.g. remove stoppers from tubing).
- Ensure with the Vessel Master that GPS tracks for deployment are accurate and the order of sampling is communicated among relevant personnel.
- Check the weather forecast and make weather observations to ensure the sea state is acceptable.
- The Vessel Master must approve each deployment and communicate to the crew before launch.
- A risk assessment should always be completed before deployment of equipment to ensure the operation can be completed safely; always take a precautionary approach.
- Make sure all personnel understand their roles through conducting a review of HSE documentation and/or toolbox talk that should incorporate the risk assessment.
- Ensure all participants have appropriate personal protective equipment (hard hats, steel-capped boots, safety glasses, work gloves and personal flotation device (PFD).
• Ensure only essential personnel participate in the preparation and deployment.
• Move the CTD to the deployment staging area (most likely the hydrographic winch door)

Protocol for CTD deployment and retrieval

• The Vessel Master should approach and hold station at a waypoint with the CTD drop area facing into the sun.
• Confirm water depth at station.
• Open the hydrographic winch door (if required).
• Following the signal to deploy from the Vessel Master, deploy CTD using winch controls into the water (winch to be operated by vessel or authorised crew only).
• Minimise the time taken from when the CTD is let out of reach to when it is lowered in the water, so as to reduce potential swing and impact against vessel.
• Check for cable loops or problems at the surface while the CTD is lowered into the water before losing sight below the waterline.
• Pause just below the surface for 2 min to activate the CTD logging (offline logging mode) or to confirm data collection and CTD systems are operational and functioning as expected.
• Lower the CTD at maximum 1 m/s to the target depth or to 10 m of sea floor, using an altimeter if fitted to monitor depth. Slowly winch the spool out towards the sea floor to avoid collision.
• When the target depth is reached, record the waypoint.
• Pause for 2 min at the maximum/target depth. Review the downcast data to identify the sampling depths through the water column if coaxial cable or real-time data display is being used.
• Advise the Vessel Master of the intention to retrieve CTD to the surface.
• Proceed with upcast at a maximum of 1 m/s and pause at water sampling depths, where appropriate; Vessel Master continues to adequately hold vessel in position.
• Watch for approach of the CTD to near the surface and pause just below the surface for 2 min.
• Ensure only required personnel are near the staging area.
• Use winch controls to guide the CTD back onto the deck smoothly and quickly (winch to be operated by the vessel or authorised crew only).
• Ensure that crew grab hold of the CTD frame as soon as it is safe to do (use boat hooks or other implements where required in order reduce risks of man-over-board), so that when the frame leaves the water, it can be guided safely away from the side of the vessel.
• Lower and land the CTD on the deck.
• Close the hydrographic winch door and secure the CTD.

Protocol for completion of operations

• Prior to any vessel movement or engine start-up, operators should check that:
  ➢ all equipment is clear of the water
  ➢ all gear is safely stowed and powered down where appropriate
  ➢ any servicing that requires the vessel to be stationary is completed.
• When the CTD team is satisfied that it is safe for the vessel to move on, give an ‘all clear to move’ command to the Vessel Master.
• Commence sampling operations.
Download and store data (if internal logger used).
• Rinse and clean the CTD ready for the next deployment. Clean sensors where appropriate (refer to the particular safe work instruction for the sensor).
• Data collected from previous CTD deployment should be checked for integrity before deploying on further surveys.
• Water samples collected may then be filtered onto glass fibre filters (for chlorophyll $a$ analysis), onto $0.2 \, \mu m$ filters (for microbial analysis) or other sized filters. Alternatively, water samples may be stored at $4^\circ C$ in the dark and filtered in the laboratory.

**B2 Standard operating procedure for collection of waters for dissolved hydrocarbon analysis**

**B2.1 Purpose and scope**
This document describes the procedure for the collection of water samples for dissolved hydrocarbon analysis (PAHs and TPHs). Waters will be sub-sampled from Niskin bottles following field sample collection.

**B2.2 Equipment**
- certified clean 1 L amber glass bottle with Teflon®-lined cap
- nitrile gloves

**B2.3 Special instructions**
Prior to sampling, ensure the area is clean and free from potential sources of hydrocarbon contamination (e.g. oil or smoke from vessel stack or cigarettes, or contamination from previous sampling activities).

**B2.4 Sample collection procedure**
This is protocol describes collection of a single sample, and can be scaled to accommodate your needs for replication and storage capacity.
- Wear a pair of clean nitrile gloves.
- First, open tap of Niskin bottle so that water flows.
- Take a new 1 L amber glass bottle, and fill for several seconds under the flow of water from the Niskin bottle so that the bottle is about one fifth to one quarter full.
- Close the tap on the Niskin bottle and cap the amber glass bottle.
- Shake the water in the bottle to ensure that the entire surface of the bottle is washed.
- Uncap the amber glass bottle and empty out the water.
- Open the tap on the Niskin bottle and repeat the process twice more so that the bottle is rinsed a total of three times.
- Once clean, return the 1 L bottle to the flow of water from the Niskin bottle and fill the bottle.
- Cap the bottle and record the depth from which the water came (e.g. 10 m from bottom, 5 m from surface).
- Repeat sampling process for samples from other depths.
- Record appropriate sample information on the sample label:
• date and time in UTC – this may be the most important information because track information may allow the sample to be relocated from the track information at a later date.
• station/site number or if an unplanned site is being sampled, a suitable identifier must be used
• sampler’s initials or name
• record any comments about sampling from the Niskin, (e.g. only two rinses of bottle achieved, not three).
• Record any comments about overall sampling event (e.g. Niskin bottle misfire, sample collected in vicinity of high sensor readings, potential contamination issues).
• Store all samples at 4°C.
Appendix C. Standard operating procedure for the collection of waters for volatile organic compound (BTEX) analysis

C1 Purpose and scope
This appendix describes procedure for the collection of water samples for the group of volatile organic compounds known as BTEX (benzene, toluene, ethylbenzenes and xylenes). Waters are sub-sampled from Niskin bottles used for field sampling.

C2 Equipment
- pre-acidified (hydrochloric acid), 40 mL volatile organic analyte (VOA) vial (if using preservative)
- nitrile gloves
- vial rack to ensure vials are stored upright.

C3 Special instructions
Prior to sampling, ensure the area is clean and free from potential sources of hydrocarbon contamination (e.g. oil or smoke from vessel stack or cigarettes, or contamination from previous sampling activities).

C4 Sample collection procedure
- Wear a pair of clean nitrile gloves.
- When the Niskin bottle sampler is retrieved from the water, open the tap so that water flows.
- Reduce the flow of water from the tap on the Niskin bottle to ensure water is flowing gently.
- Take a pre-acidified 40 mL VOA vial and fill from the stream of water. The vial contains hydrochloric acid, and therefore the water must not be allowed to overflow the vial, but must be filled so that no headspace remains when the lid is screwed down.
- Cap the vial, then invert several times to mix in the acid preservative.
- Repeat with second vial so that two samples are collected.
- Close the tap on the Niskin bottle.
• Record the depth from which the water came (e.g. 10 m from bottom, 5 m from surface).
• Repeat the sampling process for samples from other depths.
• Record appropriate sample information on the sample label:
  ➤ date and time in UTC – this may be the most important information because track information may allow the sample to be relocated from the track information at a later date.
  ➤ station/site number or if an unplanned site is being sampled, a suitable identifier must be used
  ➤ sampler’s initials or name
  ➤ record any comments about sampling (e.g. water overflowed VOA vial losing some portion of the acid preservative; small bubble noted in vial after inverting).
• Samples from the same depth will have the same information recorded because they are considered splits of the same sample.
• Record any comments about the overall sampling event (e.g. Niskin bottle misfire, sample collected in vicinity of high sensor readings, potential contamination issues).
• Store all samples at 4°C.
Appendix D. Standard operating procedure for shipboard collection of surface oil using Teflon® nets

D1 Purpose and scope
This document describes the procedure for the collection of hydrocarbon samples using Teflon® nets, supplied by General Oceanics Inc. (Miami, FL, USA) (GO). The nets have been shown to have a high affinity for oil, meaning that a reliable sample can be collected, even from very thin slicks and sheens. Please note that this SOP is written for sample collection from a large vessel, but could be modified to be used from a smaller vessel or even a dock.

D2 Equipment
- Teflon® nets (typically 150 µm mesh)
- wide-mouth amber glass jar, minimum volume 350 mL, with a Teflon®-lined lid
- extendable sampling pole, or if not available, a boat hook
- hose clamps
- screwdriver
- aluminium foil
- nitrile gloves
- thin foam
- adhesive tape
- zip-lock bags large enough to contain jar.

D3 Special instructions
The collection of surface oil using GO nets is conducted from a suitable position on the vessel deck, as far away from potential sources of contamination as possible (such as the vessel stack and bilge outlets). Ideally, the sampling position will be as close to the sea surface as possible, to minimise reaching over the side of the vessel to collect a sample. The following criteria must be met before deployment of the GO nets:

- The Master or Officer on Watch must sanction deployment.
- A minimum of two operators is required. Each person must put on PPE before going out onto the work deck areas. As a minimum, head protection, safety boots/shoes, coveralls and work vests. Operators involved in the deployment of the equipment over the side of the ship should additionally wear a life jacket.
• Survey operators must consult with the Officer on Watch with regard to any local hazards (e.g. weather conditions, nearby ship or fishing activity and structures). Equipment will not be deployed if conditions are unsafe.

• A toolbox meeting should be held on the Bridge before deployment, involving all crew involved with operations. Ensure that the Bridge is informed of intended deployment and that the Bridge is instructed to inform operators of any intended ship manoeuvres in good time. The toolbox meeting will cover all aspects of the deployment, including what is to be achieved, an overview of all safety aspects involved in the deployment and each person’s role within the process. Only when all parties are satisfied will deployment commence.

• It should also be noted that the final decision as to whether a deployment will commence ultimately lies with the Captain. However, if at any point any person feels it is unsafe (e.g. due to adverse swell conditions) then operations will immediately stop and the situation reviewed.

D4 Deployment and recovery procedure

When using GO nets, before sampling ensure the area is clean and free from potential sources of hydrocarbon contamination, particularly airborne contamination such as volatile organic compounds (VOCs), smoke from the vessel stack, galley exhaust fumes or cigarette smoke because the nets will pick up these contaminants. Where possible, use pre-cleaned nets (GO nets should be cleaned on land and transported already cleaned, to avoid the use of chemicals at sea. If pre-cleaned nets are not available, new, pre-packaged nets should be used and any background signal accounted for during analysis.) All pre-cleaned nets should be stored wrapped in clean aluminium foil until required. Once a slick or sheen has been observed, the following procedure will apply:

• Equipment should be deployed with the ship maintaining station; the work area must be adequately illuminated and clear of personnel excess to requirements (unless observing from a safe distance).

• Check voice communications between the Bridge and deck via hand-held VHF radio. It must be possible to maintain radio contact between the Bridge and sampling team throughout the operation.

• If the on-board sampling location allows, employ two slick samplers to collect samples simultaneously, with an additional person to act as both buddy and timer, and to maintain radio contact with the Bridge. If not, one sampler will collect two consecutive samples.

• Attach a pre-cleaned foil-wrapped GO net to a sampling pole using hose clamps.

• Ensuring appropriate personal protective equipment (PPE) is being worn, stand at the selected sampling location, ensuring it is safe to do so.

• Once the surface target is within reach, inform the Bridge by VHF radio that deployment is about to commence. Deployment will only proceed with authorisation from the Bridge.

• Just before deployment, don a pair of clean nitrile gloves and remove the foil cover from the GO net. Avoid contamination of hands and net with extraneous surfaces.

• Deploy the nets onto the slick or sheen, moving each net through the oil for a period of 2 min, or as long as is practicable.
• When sampling is complete, pull the sampling pole back on-board and retrieve the net by loosening the hose clamps. Touch only the handle of the nylon net ring, and avoid contact with the oil-covered net.

• The work buddy will be required to help remove the nets, and therefore must be wearing clean nitrile gloves.

• Remove the nets from each pole using clean aluminium foil to hold the net.

• Unclip the net ring so that the net can be slid off the net ring, and transferred, using clean aluminium foil, into a clean wide-mouth glass jar.

• Cap the jar by covering the inside of the jar cap with foil and ensuring it is tightly screwed on.

• Record appropriate sample information on the sample label:
  ➤ date and time in UTC – this may be most important information because track information may allow the sample to be relocated from the track information at a later date.
  ➤ station/site number or, if an unplanned site is being sampled, a suitable identifier must be used
  ➤ whether the sample is A or B (to denote the repeats)
  ➤ sampler’s initials or name
  ➤ record any comments are sampling (e.g. slick or sheen just beyond reach of net, sheen dissipated before collection, possible biological material recovered in net).

• Put the samples in a secure location while the work area is reinstated – barrier chains replaced across duckboard, the sampling pole and other equipment must be stowed away to avoid creating trip hazards.

• Inform the Bridge that sampling operations are complete.

• Wrap a strip of thin foam around each sample jar and secure with tape. This is to provide a layer of cushioning between the jars to try to reduce the chances of breakage caused by the glass jars knocking into each other in the refrigerator.

• Place each foam-wrapped jar in a small zip-lock bag and store at the correct temperature. If breakage does occur, the glass and sediment should be contained by the zip-lock bag.

• Store samples at 4°C.
Appendix E. Standard operating procedure for the collection of thin sheens using slick samplers

E1 Purpose and scope
This document describes procedure for collecting surface oil slicks with AGI slick samplers (Amplified Geochemical Imaging LLC, Newark, DE, USA). The slick samplers are engineered to be hydrophobic and collect a variety of volatile inorganic and organic compounds. The pores are large enough to provide transparent passage of the volatile molecules through a GORE-TEX® membrane, while being small enough to eliminate water contact. These sampling modules have been found to be particularly effective in sampling thin sheens by providing low molecular weight compound information.

E2 Equipment
- slick samplers (identified by serial number)
- aluminium foil
- nitrile gloves
- fishing line
- fishing pole
- floats
- dichloromethane (requires material safety data sheet)
- cardboard box/case (for isolation storage after sampling).

E3 Special instructions
- Store the samplers under ambient conditions before and after use. After use, the samplers containing slick oil must be stored in darkness to prevent degradation of any hydrocarbons present. Do not refrigerate or freeze due to potential contamination issues.
- Samplers should not be handled by smokers, owing to the sensitivity of the device. Chemicals in cigarette smoke and on smokers’ hands and clothing are potential sources of contamination, despite the use of gloves.
- Remove samplers from their jars just before sampling, not earlier. Potential contaminants in the ambient air from diesel fuel and paint fumes or other solvents could compromise samplers.
E4 Preparation procedure

- Make a note of the serial numbers for the devices to be prepared and used. Also see the field-laboratory air blank needed below. This blank must be prepared at the same time as sampling takes place.
- Prepare the sampler in a room without noticeable VOCs or fumes (using a fume hood if possible). Wear clean nitrile gloves. Place a layer of clean aluminium foil over the work space before preparing the sampler.
- Thread the fishing line through the two line holes on the fishing pole and pull through to ensure that at least 1 m of line is available. Two samplers will be attached to the end of the line.
- Open the first sampler. The protected part nearest the lid with the metal clip attached must be the only part that comes in physical contact with anything during set up.
- Leave the sampler in the jar as much as possible. Make a loop in the fishing line, pass it through the protected sampler loop, and lift out the sampler to pass it through the loop in the line. Return the sampler to jar and replace the lid. Keep the sampler in the jar until needed. The lid of the jar will close even when the sampler is tied on.
- Attach the float to line, ~60 cm from the first slick sampler. Pass the line through the hooks at both ends so that the float will lay horizontally in the water.
- Near the opposite end of the line, attach the second slick sampler by the same method as the first. With less line available, it may be easier to tie a secure knot rather than using the loop to connect it to the line. Keep this sampler in the jar with the lid on.

E5 Sampling procedure

- Once a slick is identified, remove the samplers from the jars and recap the jars straight away to prevent contaminants from entering. Cast the samplers into the water with the help of the fishing pole. Once the samplers are in the slick/sheen, begin timing and collect for 2 min. Move the samplers across the surface of the water, re-casting across the target area if necessary. Sea state and height above the surface (vessel freeboard) may make this difficult.
- At the end of the sampling period, retrieve the samplers and direct the unprotected ends into the jars. Recap immediately. Take care to replace each sampler into the same jar they originally came from.
- For decontamination, discard the float and 1 m of extra line (or longer if oil has contaminated the line) to ensure no contamination between sampling instances. Clean the eyes of the fishing pole with a few drops of dichloromethane to remove any potential contaminants arising from the slick.
- Wearing clean nitrile gloves, feed new line through the eyes on the fishing pole for the next set of samples and wrap in foil to protect from contaminants.
- Unscrew the caps and cut the remaining line from the samplers. Replace the caps tightly and discard the line responsibly.
- Store the used samplers in a closed box at ambient temperature.
- Record the serial numbers in the sample list and log books (and in the sampling database, if available). Include all relevant data including date, time, latitude, longitude, sea state, wind speed and direction, and a description of the slick/sheen sampled. Document the slick with photographs and make a note of which samplers pertain to which slick.
E6 Blank procedure
In addition to the slick samples, several types of blanks must be collected:

- **Air blanks**: Expose the sampler to the air on the deck at the point of sampling for 2 min. Collect this blank at a baseline station at the beginning and end of the sampling cruise to determine background air contamination. The baseline station should be offshore but away from known slicks, seeps and surface pollution.

- **Water blanks**: Using the same procedure for collecting slick samples, cast the samplers into the water for 2 min in an area where no slick is observed. Collect this blank at a baseline station at the beginning and end of the sampling cruise to determine background water contamination.

- **Field-laboratory air blanks**: Expose the sampler to the air for 2 min in the field laboratory area where the samplers were prepared, to collect field laboratory background contamination.

- **Trip blanks**: Send one unopened sampler to AGI to check for potential contamination due to transportation and storage on board.

Store samples in a closed box at ambient temperature.
Appendix F. Use of sensors for oil spill monitoring

F1 Standard operating procedure for hydrocarbon sensor calibration and maintenance

F1.1 Purpose and scope
Calibration of the various optical sensors used to measure the chemical and physical properties of dispersed oil in situ is required for the following reasons:
- to convert instrument counts into more meaningful physical or chemical information such as temperature in degrees or chemical concentration in mg/L.
- to correct error attributable to sensor signal decay and drift
- to ensure sensor data collected at different times or by different teams are comparable.

F1.2 Special considerations
- The calibration container should be chosen to minimise stray light, light reflection and adhesion of the analyte to the container.
- The calibration set up should be able to closely mimic the actual sensor mounting configuration when deployed and taking measurements in the field.
- Operational conditions should be clearly documented, including:
  - temperature
  - chemicals and solvent used (manufacture, purity)
  - stirring speed of stirrer bars
- Some ethanol solvent may contain low concentration of impurities that trigger a PAH fluorometric response and therefore should be avoided or the calibration curve should be corrected to account for this interference.

F1.3 Sensor calibration and maintenance procedure
- All sensors should be pre-calibrated before field deployment.
  - Standard chemicals (as recommended by the manufacturer) should be used.
  - Ensure that standard’s excitation and emission spectra are supposed to have high overlap with the fluorometer’s filter setting.
  - The calibration information should be fully documented and calibration conditions should have documented reproducibility.
- To obtain a calibration curve for the spilled oil, determine the sensor’s sensitivity (slope of the calibration plot) by comparing the ratio between the manufacturer’s recommended standard and the actual spilled oil when a sample of the target oil can be obtained.
• Once in the field, the calibration should be checked daily. A one-point check may be sufficient.
  ➤ Where possible, use a solid standard.
  ➤ Ensure that the standard is stored protected from light, dust and heat.
  ➤ Compare the solid standard against a liquid (as recommended by the manufacturer) upon return to the laboratory.
• To maintain sensor performance in the field, regularly:
  ➤ maintain a complete record of sensor ID, specification sheet and sensor calibration record
  ➤ ensure all cables, software, data acquisition unit are complete, up to date and stored properly
  ➤ inspect housing, pin and sensor window for noticeable faulty signs.
• Post-survey calibration using both liquid standard and solid standard should be conducted (either locally or by third licenced party) to correct major sensor drift during surveys.
• Ideally, all sensor information should be stored and managed in an inventory database system.

F2 Standard operating procedures dispersant efficacy monitoring
F2.1 Purpose and scope
Once a decision is made to disperse oil, the response approach needs to be continually monitored to ensure that oil dispersion is effective, to determine if another response tool should be considered, if the dispersant needs to be applied again and to estimate the ecological consequences of the dispersant application. There are several previous guides used previously to monitor oil spill dispersant efficacy; these include the SMART and NRT protocols. Each of these approaches have advantage and disadvantages in their application.

F2.2 Special instructions
There are two in-situ dispersant effectiveness assessment methods: (i) visual observation of the oil slick and (ii) field monitoring of oil particles in the water column. The two methods can provide complementary information for assessing dispersant effectiveness. Table F1 briefly summarises the changes of oil following an effective chemical dispersion and recommended monitoring techniques to detect these changes. It also describes how multiple techniques will provide complementary information. Visual observation of the oil dispersant effectiveness should be conducted both from a plane and helicopter (if the response team has access to them) and surface vessels by experienced or trained personnel. In addition, photographic or video evidence should also be collected that can be also interpreted by shore-based personnel. Each technique in the table is described in more detail in the sections below.

F2.4 Equipment
• a means of visualising the slick (this can be aerial or vessel-based)
• particle analyser or fluorometer to measure dispersed oil.
F2.5 Data collection procedure

Visual observation (either aerial and/or vessel-based)

- At predetermined intervals, observers document both:
  - a reduction of a surface oil slick
  - the formation of a plume of dispersed oil under the oil slick
- Observers need to account for potential interference, including
  - herding (the ‘pushing together’ of a slick)
  - algal blooms
  - lacing (where dispersant cause holes to appear in the slick)
- Precise information is given in the dispersant application job aid.

Sensor-based dispersed oil measurement

In this Handbook, the use of a multi-channel fluorometer and a particle analyser is recommended to capture both concentration increases and particle size reductions expected
during effective dispersant of oil. The use of sensor systems provides a semi-quantitative method of collection of dispersant efficacy data and augments visual methods. A protocol for its use is given below.

The suggested design criteria for the deployment platform include the following requirements:

1. The platform should keep the mounted sensors away from the bow wave to minimise interference caused by bubbles and turbulence and to avoid introducing artificial mixing energy to the oil dispersion.
2. The platform should allow the mounted sensors that are continuously monitoring water to either be at a constant depth or variable depth below the sea surface.
3. The platform should be lightweight, easy to handle, and able to be disassembled for transport by air, if required.
4. The platform should be readily able to be deployed on and from small vessels, with minimal requirements on vessel infrastructure, such as a boom or crane.

**Survey track design**

The vessel monitoring the dispersant efficacy should follow the path of the surface and sub-surface oil. There are several options to map the dispersant monitoring transect. These are listed in order of preference:

1. Guiding the transect of the monitoring vessel by an aerial surveillance platform, if available.
2. Using buoys to track the sub-surface plume (Davis drifters) and the remaining surface oil (Orion buoys).
3. Manually estimating the trajectory of surface and sub-surface oil, based on the speed and direction of wind and current.
4. Visual observation from the monitoring vessel.

If all the first three options are not available, it is necessary to rely on visual observation on board the monitoring vessel to locate the oil slick and dispersed plume. This method is the least reliable due to the limited observation ranges.

**F2.6 Interpretation of results**

There are a variety of factors that may affect oil’s dispersion state following treatment with chemical oil dispersants. These include:

- operational factors: how well the dispersant is applied and incorporated into oil
- environmental conditions at the time of dispersant application and oil dispersion: wind, sea state (wave and current), water salinity, temperature and humidity
- properties (viscosity, density and pouring point) and state (weathering and emulsification states) of the oil
- type of dispersant
- dispersant-to-oil ratio

Field teams need to record these properties and factors in order to aid in the interpretation of dispersant efficacy.

A specialist at the IMT planning office is required to integrate reports submitted from various field teams and conclude on the effectiveness of dispersant effectiveness to advise on further field operations. The use of the Vroom-Yetton-Jago decision model is recommended to process multiple sources of information and evaluate dispersant effectiveness,
as shown in Fig. F1. The decision tree will guide the incorporation of information from multiple field teams and conclusions on dispersant effectiveness.

In the decision tree, green circles represent positive observations and red circles represent negative observations associated with the dispersant pre-test, operational performance of the dispersant application, sea state, visual assessment and field monitoring respectively, as explained in Table F2. These positive and negative inputs are integrated as shown in Fig. F1.

**Table F2. Indications of effective use of dispersants**

<table>
<thead>
<tr>
<th>Dispersant pre-test result</th>
<th>Positive</th>
<th>Negative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dispersant pre-test result</td>
<td>Indication of high dispersant effectiveness</td>
<td>Indication of low dispersant effectiveness</td>
</tr>
<tr>
<td>Operational performance of dispersant application</td>
<td>Effective and successful dispersant application</td>
<td>Ineffective dispersant application (strong wind or missing oil slick target)</td>
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<tr>
<td>Sea state</td>
<td>Wave provides high mixing energy</td>
<td>Wave provides low mixing energy</td>
</tr>
<tr>
<td>Visual assessment</td>
<td>Indication of high dispersant effectiveness</td>
<td>Indication of low dispersant effectiveness</td>
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<tr>
<td>Field monitoring</td>
<td>Indication of high dispersant effectiveness</td>
<td>Indication of low dispersant effectiveness</td>
</tr>
</tbody>
</table>

**Fig. F1. (opposite)** Decision tree for dispersant effectiveness assessment. The numbers refer to the code list of derived conclusions based on above the Vroom-Yetton-Jago decision model:

1. Dispersant is effective under current conditions.
2. Dispersant is unlikely to be effective under current conditions. Visual observation might be a false positive.
3. Dispersant effectiveness is uncertain (A false negative of visual observation due to plume directly under oil slick or a false positive of field monitoring due to CDOM, plankton?)
4. Dispersant is unlikely to be effective under current conditions, possibly due to oil weathering or emulsification.
5. Dispersant is likely to be effective under current conditions, though mixing energy is low.
6. Dispersant is unlikely to be effective under current conditions, possibly due to low mixing energy. Visual observation may be a false positive.
7. Unlikely to happen. (A false positive of field monitoring due to CDOM, plankton?)
8. Dispersant is unlikely to be effective under current conditions, possibly due to low mixing energy.
9. Dispersant is likely to be effective under current conditions.
10. Dispersant is unlikely to be effective under current conditions, possibly due to dispersant application performance.
11. Dispersant effectiveness is uncertain: false negative visual observation, possibly due to a plume directly under the oil slick or false positive of field monitoring due to CDOM, plankton?
12. Dispersant is unlikely to be effective under current conditions, possibly due to oil weathering or emulsification or dispersant application performance.
13. Dispersant is unlikely to be effective under current conditions, possibly due to oil weathering or emulsification or dispersant application performance.
14. Dispersant is unlikely to be effective under current conditions, possibly due to oil weathering or emulsification or dispersant application performance or low mixing energy.
15. Dispersant effectiveness is uncertain: A false negative visual observation due to the plume directly under the oil slick or false positive of field monitoring due to CDOM, plankton?
16. Dispersant is unlikely to be effective under current conditions due to multiple or combined reasons.
17. Dispersant is unlikely to be effective.
## Decision Tree for Dispersant Effectiveness

<table>
<thead>
<tr>
<th>Conclusion</th>
<th>Field monitoring</th>
<th>Visual assessment</th>
<th>Sea state</th>
<th>Performance of dispersant application</th>
<th>Pretest result</th>
</tr>
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<tbody>
<tr>
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Appendix G. Standard operating procedure for grab sample collection of sediments for PAH, biomarker and TOC analyses

G1 Purpose and scope
This document describes the procedures for the collection of sediments from a grab. Sediments will be analysed for polycyclic aromatic hydrocarbons (PAHs), total petroleum hydrocarbons (TPHs) and hydrocarbon biomarkers.

G2 Equipment
- Smith-McIntyre grab
- Certified clean 250 mL glass jars with lids
- Pre-cleaned metal scoop
- Nitrile gloves
- Aluminium foil
- Thin foam
- Adhesive tape
- Zip-lock bags large enough to contain jars

G3 Special instructions
Prior to sampling, ensure the area is clean and free from potential sources of hydrocarbon contamination (e.g. oil or smoke from vessel stack or cigarettes, or contamination from previous sampling activities.

G4 Sample collection procedure
- Wear a pair of clean nitrile gloves.
- Open the lid on the Smith-McIntyre grab to allow access to collected sediment in buckets.
- Using a pre-cleaned metal scoop, transfer sediment to a clean glass jar, and fill the jar ⅔ full. (Note that if the sediments appear to have high concentrations of hydrocarbons such as gas hydrates or visible oil staining), collect two samples; similarly, if the grab sample was collected in the vicinity of high sensor readings or acoustic flares. Samples should be labelled as A and B.)
- Ensure the lid is firmly sealed.
• Record appropriate sample information on the sample label:
  ➤ date and time in UTC – this may be the most important information because track information may allow the sample to be relocated at a later date.
  ➤ station/site number or if an unplanned site is being sampled, a suitable identifier must be used
  ➤ sampler’s initials or name
• Record any comments about sampling (e.g. unconsolidated material, any potential contamination issues, nature of the sediment (stony, shelly, sandy, etc.)).
• Wrap a strip of thin foam around each sample jar and secure with tape. This is to provide a layer of cushioning between the jars to try to reduce the chances of breakage caused by the glass jars knocking into each other in the freezer.
• Place each foam-wrapped jar in a small zip-lock bag and store at the correct temperature. If breakage does occur, the glass and sediment should be contained by the zip-lock bag.
• Store sediment samples frozen at ~20°C.
Appendix H. Standard operating procedure for collection of overlying waters plus sediment from corers for PAH and biomarker analyses

H1 Purpose and scope
This appendix describes the procedures for the collection of overlying waters and sediments from multicorers (Fig. H1). Water samples will be analysed for dissolved hydrocarbons (PAHs and TPHs), and the sediments analysed for PAHs and biomarkers.

H2 Equipment
- clean 350 mL amber glass wide-mouth jars with lids or clean 1 L amber glass bottles with lids
- certified clean 250 mL glass jars with lids
- core extruder
- siphon
- palette knife or other flat metal blade
- nitrile gloves
- aluminium foil
- thin foam
- adhesive tape
- zip-lock bags large enough to contain jars

H3 Special instructions
Prior to sampling, ensure the area is clean and free from potential sources of hydrocarbon contamination (e.g. oil or smoke from vessel stack or cigarettes, or contamination from previous sampling activities).

H4 Sample collection procedure
- Record the number of liner from which the core samples are collected.
- Put on clean nitrile gloves.
- Siphon off the overlying water using vinyl tubing.
- This water can be collected in a 1 L amber glass bottle or a 350 mL wide-mouth jar, depending on the volume of water and how easy it is to collect the sample. Once the overlying water has been collected, stand the core vertically on the core extruder.
• Extrude the core from the bottom using the metal core extruder to push from the bottom of the core. Continue extruding until the only part of the core remaining in the liner is 8 cm from the base of the core.
• Slice off the extruded sediment above the 8 cm mark using a suitable, clean utensil.
• Continue extruding until a 5 cm section of sediment has been extruded.
• Slice off the sediment using a pre-cleaned palette knife or other suitable (cleaned) utensil.
• If sufficiently consolidated, lay the disc of sediment flat and slice in half across the maximum diameter to give two equal semi-circular discs, each 5 cm thick.
• If the sediment is consolidated enough, cover with clean aluminium foil and transfer to a pre-washed empty 250 mL clear glass jar. If the core material is unconsolidated, divide the sediment into two halves and transfer half to a pre-washed empty 250 mL clear glass jar using a cleaned metal scoop. The core is divided to ensure that if the material is consolidated, the core section will fit through the neck of the jar. If the material is unconsolidated, a greater volume of material may be able to be scooped into the jar. If this occurs, please record this information.
• If the core appears to have high concentrations of hydrocarbons, replicate samples should be collected, as should occur if the core was collected in the vicinity of high sensor readings or acoustic flares. Cap the samples by covering the inside of the jar cap with foil and ensuring that the cap is tightly screwed on.
• Record appropriate sample information on the sample label:
  ➤ date and time in UTC) – this may be the most important information because track information may allow the sample to be relocated at a later date
• station/site number or if an unplanned site is being sampled, a suitable identifier must be used
• sampler’s initials or name

• Record any comments about sampling (e.g. unconsolidated material, any potential contamination issues).
• Collect the sample for headspace gas analysis according to the standard operating procedure for that sample type.
• Wrap a strip of thin foam around each sample jar and secure with tape. This is to provide a layer of cushioning between the jars to try to reduce the chances of breakage caused by the glass jars knocking into each other in the freezer.
• Place each foam-wrapped jar in a small zip-lock bag and store at the correct temperature (store water samples at 4°C and sediment samples frozen at –20°C).
Appendix I. Standard operating procedure for shoreline sediment sampling with a manual push corer

I1 Purpose and scope
This Appendix describes how to collect sediments from the shoreline (e.g. no vessel to support a multi-corer or a grab sampler). This procedure only covers sample collection – transfer of samples into jars should proceed as outlined in Appendices F and G.

I2 Equipment
- clean 350 mL amber glass wide-mouth jars with lids or clean 1 L amber glass bottles with lids
- certified clean 250 mL glass jars with lids
- corer – PVC or Perspex® tube typically 2 or 5 cm diameter, chosen to accommodate the volume of sediment required
- core (this can be two halves of PVC pipe, split along the length)
- siphon
- palette knife or other flat metal blade
- nitrile gloves
- aluminium foil
- thin foam
- adhesive tape
- zip-lock bags large enough to contain jars
- a metal perimeter (a metal box with no top or bottom)

I3 Procedure to collect sediment from the shoreline
- If the interest is in sub-surface oil, scrape the surface of the sediment clean before sampling. If surface oil, omit this step.
- Push the core into the sediment to be sampled.
  ➤ The depth of sampling should not be greater than ⅔ of the height of the tube
- Seal the top of the core and pull the core out of the sediment.
  ➤ It may be necessary to twist the core, but do not bend it.
  ➤ Wet or loose sediments may require you to dig to the bottom of the tube and block the opening.
- Transfer the contents to a pre-cleaned glass jar, as described in Appendices F and G.
• Alternatively, a metal perimeter (a metal box with no top or bottom) can be used and sub-sampled: push the perimeter into the sediment.
• Leaving the perimeter in place (so that surface sediments do not fall in and contaminate deeper sediments), extract the sediment, either with a pre-cleaned spade or with minicorers.
• Immediately transfer to pre-cleaned glass jars as per Appendices F and G.
Appendix J. Standard operating procedure for pre-cleaning of equipment prior to sampling for headspace gas and organic geochemistry

J1 Purpose and scope
In order to reduce the chances of introducing contamination to the sediment and water samples (described in Appendices A–I) to be sent for headspace gas and organic geochemical analysis, steps must be taken to ensure that the sampling equipment is clean before use. This appendix describes the procedure for pre-cleaning of sampling equipment on-board a vessel.

J2 Equipment
- aluminium foil
- nitrile gloves
- dispenser suitable for use with organic solvents
- 20 L carboy of Milli-Q deionised water
- 4 L Winchester of methanol
- deep plastic tray
- eye protection
- 1 L plastic jug
- plastic funnel
- 20 L carboy for waste solvent

J3 Special instructions
It is important not to sample next to direct sources of contamination, such as the vessel stack, where hydrocarbons or hydrocarbon-based products are stored, or in the vicinity of smoking. Clean nitrile gloves should always be worn and, as an absolute minimum, gloves should be changed between sampling sites. When sampling for headspace gas or organic geochemistry, it is important to use clean aluminium foil, and metal utensils, which can be cleaned according to the method given below.

J4 Cleaning procedure
- Set up the dispenser in a bottle of methanol so that 10–15 mL of methanol can be dispensed with each pump.
• Ensure that the bottle of 20 L carboy of Milli-Q deionised water and the supply of methanol are within a comfortable working distance of each other to reduce the chances of spillages. When working with methanol, ensure that work is not carried out in a location where there is a risk of inhaling fumes. Wear two pairs of gloves, as well as eye protection and other personal protective equipment.

• After core sampling has occurred, the sediment adhering to the tools used to cut the core and transfer sediment into sampling containers can be washed off using the ship’s water supply.

• Following this, rinse the ship’s water off with Milli-Q water from the carboy. Continue until the surface has been washed.

• Next, holding the tool being washed over the deep plastic tray, pump methanol over the surface of the tool, so that the water is removed from the surface. The methanol run-off should be collected in the tray.

• Lay the clean tool on a clean piece of aluminium foil in a location where it is unlikely to become contaminated while the solvent dries.

• Continue this washing process until all metal utensils have been washed.

• If, during the cleaning process, methanol comes into contact with gloves, change gloves because methanol may seep through with prolonged contact.

• To dispose of the waste solvent in the plastic tray, using the corner of the tray, pour the liquid into a plastic jug.

• Using the funnel, if required, empty the jug into a carboy for waste solvent.

• Once the utensils are dry, wrap in clean aluminium foil and store until next required.
Appendix K. Standard operating procedure for the collection of sediments for molecular microbial analysis

K1 Purpose and scope
This appendix provides instructions for how to collect sediment samples aseptically so that they may be analysed for microbial community structure.

K2 Equipment
- disposable gloves
- corer and mini corers (can be PVC or Perspex®, diameter chosen to accommodate the volume of sediment required for downstream analyses).
- 4–7% bleach solution for sterilising equipment
- sterile 50 mL plastic centrifuge tubes

K3 Special instructions
- It is critical that the samples be handled aseptically to avoid introducing bacteria from other samples and from your hands, equipment, etc.

K4 Sample collection procedure
- Prior to use, soak all equipment overnight in 4–7% bleach, and have enough sterile mini corers to sample without having to reuse them.
- Once sterilised, handle equipment only with sterile gloves.
- Collect the sediment core, then use sterile mini-cores to sub-sample it.
  - Syringes with the ends cut off or disposable centrifuge tubes with the conical ends removed can act as mini-corers.
- Cut off the upper few centimetres of the core (assuming that the depth of bioturbation is only a few centimetres) with tools that have been cleaned in dilute bleach.
- Discard the part of the core that is below the bioturbated depth.
- Cut the upper layer of the sediment core in half, longitudinally.
  - To avoid cross contamination, remove sediment from the inner section of the core (that has not been in contact with the outer core and the sediment core) with a sterilised disposable spoon or similar.
  - Freeze three replicate samples of ~50 mL in DNA-free polycarbonate tubes.
- Place the polycarbonate tube into a zip-lock bag to avoid cross contamination of samples.
- Store samples at –20 or –80°C.
- Between stations, soak the corer in dilute bleach, and clean your tools.
Appendix L. Standard operating procedure for collection of seafood samples for the analysis of taint

L1 Purpose and scope
The contamination of seafood is a major public health concern and will attract media and public attention. Following a spill, the potential for contamination should be evaluated.

L2 Equipment
- disposable gloves
- a dissection kit appropriate for the samples being taken
- glass vials – ideally amber, with PTFE lids,
- aluminium foil
- zip-lock bags.

L3 Special instructions
- Plastics can contaminate samples with hydrocarbons, so use metal tools, wrap samples in aluminium foil or store in glass jars, and avoid contact with plastic wherever practicable.
- Guidance is given for a variety of taxa, but care should be taken to sample food organisms used by all members of the community, including Indigenous and immigrant groups.
- Take care in dissecting tissues because stomach contents or bile may contaminate samples and create the appearance of taint where none exists.
- Samples should be analysed at an accredited facility. Guidance is given here on their collection and proper storage only.

L4 Sample collection
Fish
For human health concerns, collect muscle tissue:
- Excise the fillets, double wrap in aluminium foil, store in a zip-lock bag at –20°C.
- To determine if the fish are being exposed to oil, collect the bile.
- Collect the gall bladder and store in an amber or foil-wrapped vial at –20°C.
Bivalves
- Excise the shell, double wrap the soft parts in aluminium foil, and store in a zip lock bag at –20°C.

Crustaceans
- Remove the carapace, then take a sample of muscle and hepatopancreas, and store separately, double-wrapped in aluminium foil at –20°C.

Other invertebrates
- Dissect out a section of muscle, taking care to avoid the gut, then store double-wrapped in aluminium foil at –20°C.
Appendix M. Standard operating procedure for the collection and archiving of tissue samples for biomarker analysis

M1 Purpose and scope
This protocol provides general guidance for the collection of tissues for biomarker analysis (e.g. to measure physiological changes in an organism that has been identified in response to oil exposure). It assumes that a qualified laboratory will collect the samples, and that it is known which analyses will be undertaken. For the purposes of illustration, fish tissues are described, but the guidance can be adapted to any animal.

M2 Equipment
- 70% ethanol and paper towels/tissues (Kimwipes) for cleaning
- a dissection kit appropriate for the samples you will be collecting
- sample data sheet and a pencil (pen can blur easily)
- appropriately labelled tubes (unique sample ID, replicate number, date). If you are freezing the samples in liquid nitrogen, these must be cryotubes.
- cutting board or similar work surface, often covered with aluminium foil
- for RNA samples only: RNAlater® or similar tissue preservative
- for protein samples, or RNA samples if no preservative is to be used: liquid nitrogen filled dry shipper or other means of flash freezing samples
- for vertebrates: tub of sea water and clove oil (to kill the fish)
- for invertebrates: tub of ice (to kill invertebrates)
- disposable nitrile gloves

M3 Special instructions
- An animal ethics permit may be required for work with vertebrates.
- Samples must be taken and tissues archived within minutes of the organisms death.
- Great care must be taken to avoid cross contamination of samples.
- Individuals sampled should be the same species.
- Ten individuals of each species are typically suitable for analysis. Because the amount of tissue required for most analyses is quite small, it is often wise (where possible) to subdivide tissues into multiple aliquots to allow for multiple analyses.
**M4 Preparation procedure**

- Prepare a sample data sheet:
  - For each sample, record (at the time of sampling):
    - unique sample ID
    - date
    - time
    - location of sampling (use GPS coordinates if possible)
    - species and sex (if apparent)
    - length or weight (both if feasible)
    - general condition (e.g. Does this look like a healthy fish? Is the specimen visibly oiled?)
    - the number of aliquots of each tissue that are taken (the priority would be: liver, gall bladder, gill, brain)
  - initials of the operator
  - initials of a witness.

- Label the tubes.
  - Each tissue aliquot will require its own tube.
  - Tubes should have the unique sample ID, date, replicate number.
  - Tubes should be labelled with a ethanol proof marker, or printed labels should be secured and encapsulated in sticky tape.
  - Label more tubes than you think you will need! Because work must be done quickly in the field, there will not be sufficient time to accurately label tubes then.

- Fill the dry shipper with liquid nitrogen, or fill the tubes with RNAlater®.

- Immediately before starting, clean your workspace and dissecting tools. Cover the cutting board with aluminium foil. Put on gloves.

**M5 Sampling procedure**

- Record the size and appearance of the animal, then euthanise it.
- Once the fish is euthanised (and it has stopped ‘gilling’ and no longer responds to touch, use cervical dislocation at this point if you are not certain), quickly harvest the tissues. Tissue samples ~6–7 mm in size (about the size of a fresh green pea) are suitable for RNA analysis, and samples 8–9 mm in diameter (the size of a chick pea) are sufficient for protein. Take care not to rupture the gall bladder while collecting it for metabolite analysis, because biliary fluid will contaminate other tissues. Use paper tissues (Kimwipes or similar) to keep your samples free of blood, digestive fluids, etc.
- Once sample tissues are harvested, immediately (within seconds) preserve samples – either immerse them in RNAlater®, closing and inverting the tubes, or put them in the dry shipper. Ensure that there is sufficient space in the shipper that tubes can be frozen instantaneously.
- Update the sample data sheet.
- Clean the apparatus thoroughly with ethanol, inspect the aluminium foil for tears (replace if necessary), check the integrity of gloves (replace if necessary).
- Repeat.
**M6 Archiving procedure**

- Organise the samples into containers for long-term storage, working quickly to ensure that frozen samples do not begin to thaw.
- Scan the sample data sheets.
- Prepare chain of custody forms for the samples. If different aliquots are being sent to different laboratories, a chain of custody form will be needed for each set of samples.
Appendix N. Standard operating procedure for sampling plankton community structure and biomass

N1 Purpose and scope
This protocol describes the collection of data to characterise the zooplankton community, including holoplankton, early life stages of fish and invertebrates, in terms of their horizontal, vertical and diel distribution, abundance, biomass and composition, and the collection of specimens for hydrocarbon contact/content.

N2 Equipment
- Neuston net (Fig. N1) – for the surface layer
- bongo net (Fig. N2) – to determine the distribution of plankton over a given depth
- multinet (Fig. N3) – to obtain vertically stratified samples of zooplankton
- 100 µm mesh size and a dull grey colour (so that macroplankton do not avoid the net) is recommended
- sample jars
- preservatives (recipes follow)
- flowmeter (calibrated so that you know the number of revolutions per litre it tows)

N3 Special instructions
Sampling of zooplankton needs to be done at the same approximate time of the day to avoid confounding related to diurnal migration (e.g. zooplankton typically perform vertical migration and spend the night closer to the surface than daytime). Sampling 2 h before or after sunset or sundown is to be avoided because it is a time of active migration. Daytime is defined as from 2 h after sunrise to 2 h before sunset and night is defined as 2 h after sunset to 2 h before sunrise at each location. If nets are deployed at night, non-essential lights should be switched off.

N4 Sample collection procedure
- Choose a net that is appropriate for the type of sample to be undertaken.
- Measurement of biomass or abundance and quantifying live/dead zooplankton requires separate hauls at the same station.
- Record the flowmeter reading, and position the flowmeter halfway through the mouth of the net. (Note – Neuston nets do not require flowmeters because they are towed half submerged and are not quantitative as a consequence.)
• Neuston net
  ➢ Deploy on either side of the vessel so that it veers away from the ship to minimise the interference from bow waves.
  ➢ Visually monitor to ensure that the mouth remains at the sea surface.
• Bongo net – lower the net at 1 m/s until the net is 1 m from the bottom.
• Connect nets to a conducting cable to enable observation and control of the net position in the water column in real time, observation of filtering efficiency and stopping the tow if efficiency drops.
• Tow nets at a speed of 1 m/s to avoid damaging the animals.
• The tow time for biomass/abundance is 10 to 15 min.
  ➢ Shorten time if the net becomes clogged with jellyfish, seaweed or flotsam.
• At the end of the tow for biomass and abundance, pull net back on board and rinse on the outside with sea water.
  ➢ Pull the net quickly out of the water, so the organisms in it will be concentrated into the bucket.
  ➢ The water jet should remove the organisms from net material but not damage them.
• The tow time for quantifying live/dead zooplankton should be kept as short as possible, around 5–10 min.
  ➢ The net should not be hosed down following live/dead assays because this may kill the animals and inflate the numbers of dead zooplankton.
- Transfer the content of the cod end (the trailing end where the organisms are caught) to a sample storage jar.
- Between samples, rinse the net out thoroughly after the transfer of the cod end content to a sample storage jar to avoid carryover of animals from earlier tows.

**N5 Staining and preservation**
- Preserve samples for enumeration and biomass are preserved in 5% borax-buffered formaldehyde solution in sea water.
  - Containers should be filled completely to avoid sloshing of organisms.
- Transfer samples for quantifying live/dead organism to a staining jar and add neutral red stock solution (recipe in Section N7) (1.5 mL per 1000 mL of sample; aiming for a bright red colour, not pink).
- After 15 min, briefly rinse sample with filtered sea water to remove excess stain and store sample in Petri dishes at –20°C until further processing in the laboratory by appropriately trained taxonomists. Live animals are stained bright red (dead are unstained).

**N6 Biomass and size structure estimation**
- Samples can be fractionated into sizes by sieving, for example:
  - >1000 µm (fish larvae, gelatinous plankton)
  - 1000–355 µm (large adult copepods, chaetognaths (arrow worms), fish eggs, some invertebrate eggs and larvae)

*Fig. N2.* Example of a bongo net (Photo credit: Joanna Strzelecki)
➤ 355–250 µm (medium adult copepods, some invertebrate eggs and larvae)
➤ 250 µm or less (small adult copepods, juvenile stages of copepods, copepod and invertebrate eggs).

• Alternatively use video image analysis (FlowCam and Zooscan) to obtain more accurate characterisation of size structure of zooplankton assemblage.

**N7 Reagents**

**Borax buffered formalin:**

- Add 30 g of sodium tetraborate to 1 L of analytical reagent grade formalin (40%).
- This is added to sample for final concentration of 5% solution of formalin in sea water.

**Neutral red stock solution:**

- Add 0.1 g neutral red powder (high purity biological stain) to every 10 mL deionised water and slowly stir the solution under dim light overnight to completely dissolve the powder.
- After preparation, store the stock solution in the dark at room temperature in a sealed amber borosilicate glass vial.
- The shelf life is ~1 month (when stored in dark and not exposed to excessive heat).
Appendix O. Collecting samples for sediment infaunal analysis

O1 Purpose and scope
This appendix describes how to collect samples for sediment infaunal analysis (i.e. to measure the composition and abundance of animals that live within the sediment). This protocol was adapted from Chariton et al. (2016). This monitoring assumes that samples of macrofauna will be collected in the field and shipped to a laboratory, where they will be identified by a trained taxonomist. Alternatively, samples can be analysed by their DNA content, as described in Appendix J.

O2 Equipment
In addition to the equipment required to collect the sediment core (see Appendices G–I), this procedure requires:
- disposable gloves
- sieves
- sea water wash bottles
- wide-mouth glass jars
- 10% buffered formalin or 70% ethanol
- pencil or ethanol-proof ink for labelling jars

O3 Special instructions
- Formalin exposure has been associated with long-term health problems, including cancer. Consult the material safety data sheet and develop a risk plan before using it, and always use it wearing gloves, in a well ventilated area. Ethanol is flammable, and should be shipped as a hazardous good.
- Choose sieves that will capture animals of the size required (e.g. 1, 0.5 or 0.1 mm).

O4 Procedure
- Obtain a sediment sample (see Appendices G–I), ideally of 10 cm depth.
  - The sediment sample can be used for collecting infauna if:
    - sediment has not been pushed out or flowed out from the sampler
    - there is still water in the sampler (i.e. it stayed closed after the sample was collected)
- the surface of the sediment is even
- enough sediment was collected – a depth of 4–5 cm in medium–coarse sand, 6–7 cm in fine sands, and >10 cm in silty sediments.

- Gently sieve the sediment sample to remove the animals. If you want to collect animals from different size classes, you will need to use multiple sieves.
- Use the wash bottle to transfer the animals to a glass jar. Fill the jar with diluted the preservative. The sample (including rinse water) should not make up more than 10% of the total volume of the jar.
- Label the jar with pencil, because formalin or ethanol will remove most ink
Appendix P. Standard operating procedure for sampling intertidal and subtidal areas for community composition

P1 Purpose and scope
The goals in monitoring intertidal and subtidal benthic communities, both animals and plants, are to: (i) document the normal patterns of organism distribution, and how these have been impacted by the spill; (ii) document the exposure to oil or impact of response technologies; and (iii) determine any lethal or sub-lethal impacts from exposure to oil.

P2 Equipment
- GPS
- camera
- data sheets and pencil or waterproof pen
- equipment for delineating sampling units (e.g. quadrats, transect lines)

P3 Special considerations
Monitoring should include quantitative surveys to document the distribution, abundance and distribution of benthic communities, ideally along a contamination gradient. This monitoring effort should document:

- the distribution and extent of critical habitats within the impacted areas
- relevant variables such as the per cent cover, density, size or age structure of target organisms in the response area
- the apparent condition and level of oiling of those organisms
- leaf and frond damage in plants
- the presence of grazers in plant communities
- tissue samples taken to assess the oil or dispersant body burden within the organism
- tissue samples collected for molecular biomarker-based analysis (described in Appendix M) of physiological processes (such as growth and reproduction) necessary for fitness.

Although intertidal and subtidal benthic communities encompass a wide array of communities in Australian maritime jurisdictions, all can be approached by replicate surveys of the most abundant taxa.
Sampling units such as quadrats should be appropriate to the distribution of the biota being measured. For example, quadrats should be large enough that the majority of quadrats contain at least one individual, but small enough that the sampling can be conducted within a reasonable timeframe.

Study design should consider the appropriate scale of replication and power of the study:

- If the objective is to determine the difference between sites that have been treated differently (e.g. cleaned versus left to self-clean), then replicate sites are required for each treatment.
- If the objective is to determine the impact of the spill, the design will compare the area affected by the spill (impact site) with replicate similar areas not affected by the spill (control sites).
- The power of such studies will generally be most strongly influenced by the number of replicate sites rather than the sample size within each site.

**P4 Sample collection procedure**

- Monitoring sites with similar physical characteristics as well as taxonomic representation should be in accordance with the chosen study design.
- Each site should either be subdivided into replicate areas or replicate sites – see Chapter 3 for more discussion of monitoring design
  - Replicate sites should have similar physical and biological characteristics as well as similar degrees of oiling and similar response strategy and intensity should be selected.
  - Ideally, some oiled sites will be left uncleared to assess the impacts of the response strategy.
- At each site, take precise coordinates, along with a physical description of the site, the weather conditions, and the apparent degree of oiling.
- Collect water and sediment samples, along with the photographic transects, any samples for microbial community analysis, and any tissue samples.
- Classify organisms to the lowest taxa as possible, but at least to the genus level.
- Collect samples at each site from each habitat type along a contamination gradient. Take enough samples to account for natural variability and to ensure adequate statistical power.
- Determine the community composition by taking a photo-transect or by counting and recording the numbers, condition and taxonomic identification of each individual.
Appendix Q. Standard operating procedure for surveying the impacts of oil spills on bird populations

Q1 Purpose and scope
The aim of this monitoring effort is to determine whether populations of coastal birds and seabirds are injured as a consequence of the oil spill, either from direct contact with oil, ingestion of contaminated food, or via destruction of their habitat. This monitoring should also include the documentation of the numbers of dead birds that are visibly oiled, as well as the identification of surviving oil-exposed individuals to be treated and rehabilitated by properly trained veterinarians and their staff. In addition, this monitoring needs to obtain information on the impacts of the response efforts on the bird populations. Operators should be aware of the likelihood of undercounting carcasses and the difficulty in identifying oiled plumage by visual inspection.

Q2 Special instructions
To carry out this monitoring, the locations of coastal and seabird populations, as well as their critical nesting and feeding habitats, must be known. Background information on their conservation status, migratory behaviour and feeding habits will also be helpful. Some of this information can be obtained from either pre-existing baseline data or from vessel-based surveillance at the time of a spill, and compared with information from the oil spill trajectory modelling or visual observations of the spilled oil. In addition to information about the oil trajectory, information will be needed about the locations and use of any chemical oil dispersants or shoreline cleaners, because surfactants can strip feathers of their waterproofing and cause hypothermia and drowning.

Q3 Data collection procedure
Q3.1 Aerial surveys
- Aerial surveys should be carried out by trained ornithologists, with one on each side of the aircraft.
- Undertake an initial overflight of the area to visualise the degree of oiling in areas of bird habitat and the number and length of detailed surveys that will need to be taken.
- Once the degree of impact has been estimated, take line transects (at a suggested altitude of 80 m, a speed of 185 km/h and at least 2 km apart to avoid double counting) to verify the presence or absence of seabirds in the area.
Presence/absence may not be consistent with baseline data, especially if the response has increased traffic in this or nearby areas.

Observe and record the number of dead and dying birds in oil-impacted areas.

- When birds are observed, record their:
  - approximate number
  - species, age and sex (if apparent)
  - location (descriptive and GPS)
  - proximity to oil
  - condition
  - weather conditions and visibility.
- Take photographic records where possible.

**Q3.2 Ground or vessel-based surveys**

- These surveys should also be carried out by pairs of trained ornithologists, either along transects from the vessel or shoreline transects.

- Document:
  - numbers and types of birds
  - age, and sex (if apparent)
  - condition
  - activity levels
  - descriptive and GPS-based location
  - weather conditions.

- Record the location of any nests.
- Collect some carcasses and plumage from dead individuals for analysis of oil or dispersant residue.
- In addition, record physical descriptions of dead individuals (e.g. oiled, entangled in fishing gear).
- Report information gathered from this monitoring program to the operations command centre as soon as possible to inform future clean-up and response actions.
Appendix R. Standard operating procedure for surveying the impacts of oil spills on non-avian marine wildlife

R1 Purpose and scope
For the purpose of this procedure, non-avian marine wildlife is defined as large sharks, rays and cetaceans (such as whales, dolphins and seals), as well as reptiles including sea turtles, crocodiles and sea snakes. The procedures outlined apply to monitoring to determine the impact of an oil spill and of any response effort on populations of these animals. The monitoring should also include the documentation of the numbers of dead individuals that are visibly oiled, as well as the identification of surviving oil-exposed individuals to be treated and rehabilitated by properly trained veterinarians and their staff. Injured wildlife can be extremely dangerous – responders and volunteers should be warned not to approach any animal that may not be dead.

R2 Special instructions
- The locations of critical habitat and nesting sites (for sea turtles) should be known in advance
  - Compare critical habitat with the models of the oil spill trajectories.
  - Compare critical habitat with the visual observations of spilled oil.
- If baseline data are unavailable, carry out post-spill, pre-oil-contact surveys of critical habitat.
- The following background information for each wildlife species will also assist with the oil response:
  - conservation status
  - migratory behaviour and seasonal usage patterns
  - prey items.

R3 Procedures for aerial or vessel-based surveys
- Whales and large sharks may be best monitored via aerial survey.
- Dugongs and seals may also be monitored using this approach in calm seas.
- Divide the area to be surveyed into zones.
- Traverse these zones using either a saw-tooth or linear transect.
- For each transect, record:
  - the GPS coordinates of the start and end
› the GPS coordinates for any turns
› the weather conditions
› the speed and altitude of the aircraft.
• For each observation of potentially impacted wildlife, record:
  › the GPS coordinates
  › the numbers
  › species and (relative) size
  › if apparent, the condition
  › the direction of travel
  › the activity level.
• Photographs should also be taken.

R4 Procedure for shoreline
• Observers should walk a shoreline transect (or travel by vessel parallel to the shoreline).
• For wildlife observed, including beached or dead animals, record:
  › the location (descriptively as well as by GPS coordinates)
  › the condition of any wildlife observed.
• Photograph all wildlife if it is safe to do so.
• Seek veterinary assistance immediately for any oiled or otherwise distressed wildlife.
  › Responders or volunteers should keep to a safe distance.
  › Photograph seemingly healthy animals, but do not approach them.
• For obviously dead wildlife:
  › Note the condition and age of the carcass.
  › Measure the animal and identify it (to the extent possible) to species.
  › Record the presence of oil or and entangling materials.
  › If feasible, swab the nasal passages or gut for the presence of oil, and collect the carcass.
• Report any information obtained to the operational command to inform future response and clean-up technologies. This is especially critical because dispersant operations may cease if large sharks, rays or whales are in the zone of operations.
Appendix S. Example of sample data sheets

Samples information can be logged into a chain of custody form, as illustrated in Fig. 3.8. Samples can also be logged into a simple spreadsheet database, as shown in Fig. S1. Alternatively, samples can be logged electronically, as illustrated in Fig. S2.

<table>
<thead>
<tr>
<th>Site_ID</th>
<th>Capture_ID</th>
<th>Capture_Date</th>
<th>Site_Name</th>
<th>Fish_Spp</th>
<th>Fish_ID</th>
<th>Total_Length</th>
<th>Weight</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>5</td>
<td>22-Mar-11</td>
<td>Barker Inlet</td>
<td>Platycophalus bassensis</td>
<td>0311103</td>
<td>460</td>
<td>1081</td>
<td>worm like parasite visible</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>22-Mar-11</td>
<td>Barker Inlet</td>
<td>Platycophalus bassensis</td>
<td>0311104</td>
<td>405</td>
<td>737</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>7</td>
<td>22-Mar-11</td>
<td>Barker Inlet</td>
<td>Platycophalus bassensis</td>
<td>0311105</td>
<td>295</td>
<td>286</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>22-Mar-11</td>
<td>Barker Inlet</td>
<td>Platycophalus bassensis</td>
<td>0311106</td>
<td>340</td>
<td>420</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>9</td>
<td>22-Mar-11</td>
<td>Barker Inlet</td>
<td>Platycophalus bassensis</td>
<td>0311107</td>
<td>330</td>
<td>396</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>22-Mar-11</td>
<td>Barker Inlet</td>
<td>Platycophalus bassensis</td>
<td>0311108</td>
<td>345</td>
<td>446</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>11</td>
<td>22-Mar-11</td>
<td>Barker Inlet</td>
<td>Platycophalus bassensis</td>
<td>0311109</td>
<td>330</td>
<td>402</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>12</td>
<td>22-Mar-11</td>
<td>Barker Inlet</td>
<td>Platycophalus bassensis</td>
<td>0311110</td>
<td>335</td>
<td>445</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>13</td>
<td>22-Mar-11</td>
<td>Barker Inlet</td>
<td>Platycophalus bassensis</td>
<td>0311111</td>
<td>355</td>
<td>510</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>14</td>
<td>21-May-11</td>
<td>Cape Jervis</td>
<td>Platycophalus laevigatus</td>
<td>0511320</td>
<td>265</td>
<td>245</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>15</td>
<td>21-May-11</td>
<td>Cape Jervis</td>
<td>Platycophalus laevigatus</td>
<td>0511321</td>
<td>225</td>
<td>155</td>
<td>1 gonad?</td>
</tr>
<tr>
<td>5</td>
<td>16</td>
<td>21-May-11</td>
<td>Cape Jervis</td>
<td>Platycophalus laevigatus</td>
<td>0511322</td>
<td>215</td>
<td>135</td>
<td>1 gonad</td>
</tr>
<tr>
<td>5</td>
<td>17</td>
<td>21-May-11</td>
<td>Cape Jervis</td>
<td>Platycophalus laevigatus</td>
<td>0511323</td>
<td>258</td>
<td>225</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>19</td>
<td>22-May-11</td>
<td>Cape Jervis</td>
<td>Platycophalus laevigatus</td>
<td>0511324</td>
<td>157</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>20</td>
<td>22-May-11</td>
<td>Cape Jervis</td>
<td>Platycophalus laevigatus</td>
<td>0511325</td>
<td>226</td>
<td>165</td>
<td></td>
</tr>
</tbody>
</table>

Fig. S1. Spreadsheet for logging sample data
Fig. S2. Example of electronic sample data recording
Appendix T. Overview of shoreline assessment

T1 Purpose and scope
The goal of a shoreline assessment is to provide quantitative data for the assessment of the impacts of oiling, as well as any response employed on shoreline habitats and commonly occurring organisms within those habitats. To accurately assess these potential impacts, the operator must know what ecosystems/habitats are present, the most abundant organisms present within these habitats, as well as the oil exposure that occurred and the response strategy used. Extensive information on shoreline assessment is available from other sources (e.g. NOAA 2013; ITOPF 2012). Some of that information is briefly summarised here.

T2 Special instructions
The baseline information required for shoreline assessment includes background petroleum hydrocarbon concentrations for both the water and sediment. Background tissue contaminant concentrations for sessile invertebrates, such as bivalves, or oil-exposure biomarker concentrations would also be helpful. If possible, additional baseline samples should be collected post spill, pre-shoreline oiling. Where these samples should be taken should be informed by the oil spill trajectory modelling (Section 6.2) and visual observations of oil (Section 6.4.2).

T3 Data collection procedure
An example of the forms that could be used in shoreline assessment is provided by the Western Australian Department of Transport at: http://www.transport.wa.gov.au/media-Files/marine/MAC_F_OS01_Shoreline_Assessment_Form.pdf
- Describe the characteristics of the shoreline, including:
  - assessment of the use of the shoreline as an ecological habitat (e.g. what lives there)
  - length and width of the shoreline
  - the wind/wave energy (see Table T1)
  - geomorphological processes that are ongoing (e.g. does sand accrete or erode from the area?)
  - the shoreline substrate size and type (see Table T2)
  - the degree of anthropogenic influence.
- This assessment can be carried out via:
  - helicopter
Appendix T

- video and still photographic analysis with collection of simultaneous GPS coordinates
- high-resolution satellite imagery of the area
- deployment of field teams to the area.

- Document the degree of shoreline oiling, including the surface and sub-surface distribution of oil, as well as the evenness or patchiness of coverage.

- To document surface oil:
  - Divide the shoreline into sectors.
  - For each sector record the length and width of any oiled bands, as well as the per cent cover of oil, as shown in Fig. T1.
  - Also record the thickness of oil (Table T3).

- To document sub-surface oil:
  - Divide the shoreline into sectors.
  - For each sector, record GPS coordinates, and dig a pit.

Table T1. General indicators of shoreline energy

<table>
<thead>
<tr>
<th>Energy</th>
<th>Lowest</th>
<th>Increasing</th>
<th>Highest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate</td>
<td>Mud</td>
<td>Sand</td>
<td>Pebble</td>
</tr>
<tr>
<td>Form</td>
<td>Swamps/flats</td>
<td>Beach</td>
<td>Reefs</td>
</tr>
<tr>
<td>Gradient/slope</td>
<td>Flat</td>
<td>Gentle slope</td>
<td>Steep slope</td>
</tr>
</tbody>
</table>

*Adapted from AMSA (2003)

- Sporadic 1% - 10%
- Patchy 11% - 50%
- Broken 51% - 90%
- Continuous 91% - 100%

* Trace = < 1%

Fig. T1. A visual guideline for the degree of shoreline oiling, the black shading represents oil; (a) for discrete oil deposits such as tar balls; (b) for oil banding and (c) per cent cover in circular sampling quadrats (Source: NOAA 2007)
In this pit, record:

- the substrate type
- the minimum depth of oil penetration
- the maximum depth of oil penetration

- Record the type, weathering state, and thickness of the oil.
- Collect samples of the oil deposited on shorelines for laboratory-based compositional analyses

- Shoreline assessment should be continuously updated to operations to allow for prioritisation of response strategies and clean-up efforts.
- Include GIS coordinates for sensitive habitats or socioeconomically important communities.

### Table T2. Guideline for characterising shoreline substrate

<table>
<thead>
<tr>
<th>Type</th>
<th>Size</th>
<th>Descriptive notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bedrock or rock</td>
<td>One continuous piece</td>
<td>Porous or non-porous? Crevices or no crevices? (Porosity and crevices increase the persistence of oil)</td>
</tr>
<tr>
<td>Boulder</td>
<td>&gt;256 mm diameter</td>
<td>Porous or non porous? Crevices or no crevices? (Porosity and crevices increase the persistence of oil)</td>
</tr>
<tr>
<td>Cobble</td>
<td>64–256 mm diameter</td>
<td>Porous or non-porous?</td>
</tr>
<tr>
<td>Pebble</td>
<td>4–64 mm diameter</td>
<td>Use ‘shingle’ if flattened</td>
</tr>
<tr>
<td>Gravel or granules</td>
<td>2–4 mm diameter</td>
<td>Rounded or flat?</td>
</tr>
<tr>
<td>Sand</td>
<td>0.06–2 mm diameter</td>
<td>Fine to coarse in size</td>
</tr>
<tr>
<td>Mud/silt/clay</td>
<td>&lt;0.06 mm diameter</td>
<td>Note the presence of organic matter Is it consolidated or loose? Is it dry? (mud cliffs)</td>
</tr>
<tr>
<td>Earth/soil</td>
<td></td>
<td>Usually only cliffs or sea walls</td>
</tr>
<tr>
<td>Ice</td>
<td></td>
<td>Most likely only in the Antarctic territories</td>
</tr>
<tr>
<td>Shell grit</td>
<td></td>
<td>Wet/dry Likely to occur with sand</td>
</tr>
<tr>
<td>Coral</td>
<td></td>
<td>Can be rubble, cobble or boulder size Note if it is living or dead</td>
</tr>
<tr>
<td>Concrete</td>
<td></td>
<td>Artificial substrate Rubble or rip-rap (rock armour or rubble)</td>
</tr>
<tr>
<td>Wood</td>
<td></td>
<td>Can be artificial substrate or debris overlaying other substrate</td>
</tr>
<tr>
<td>Metal</td>
<td></td>
<td>Artificial substrate</td>
</tr>
</tbody>
</table>

*Adapted from AMSA (2003)*

### Table T3. Descriptors of different oil thicknesses

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pooled oil</td>
<td>Pooled oil – mm to cm thick</td>
</tr>
<tr>
<td>Oil cover</td>
<td>Measurable in mm</td>
</tr>
<tr>
<td>Oil coat</td>
<td>Can be scratched off and will obscure the underlying substrate</td>
</tr>
<tr>
<td>Oil stain</td>
<td>Cannot be scratched off, texture is visible through the rock</td>
</tr>
<tr>
<td>Oil film or sheen</td>
<td>Transparent coating</td>
</tr>
</tbody>
</table>
Appendix U. Standard operating procedure for monitoring a shoreline gradient

U1 Purpose and scope
Shoreline clean-up methods may change the gradient and slope of the substrate, leaving the beach susceptible to erosion. The shoreline gradient should be monitored during the response, especially if heavy machinery is to be used.

U2 Equipment
- stakes and a hammer
- measuring tape
- compass or theodolite
- tall pole

U3 Procedure
Using marker stakes (suitable for low energy shores with minimal physical disturbance) (Fig. U1):
- Before the response begins, determine how many profiles you will need along the stretch of coast you are dealing with.
- At each profile location, hammer a back stake into the substrate in the supratidal zone (i.e. above the high tide mark) and more along a known line (compass bearing) towards the foreshore at several tidal elevations. The number of intermediate stakes will depend on the length and variability of the shoreline profile.

Fig. U1. The use of marker stakes to determine shoreline gradient (Source: AMSA 2003)
• The back stakes are the key and must remain undisturbed from natural processes (tides and storms) and response work. This process should still work even if the lower elevation stakes are disturbed or removed. They can be reinstated because their known location (a measured distance along the known compass bearing from the back stake).
• Measure the distance (H) between the top of each stake and the sediment surface (H = height of the stake off the surface).
• If using a theodolite (Fig. U2), use the telescope to see the heights on the marked pole to determine the height of the pole from the substrate at each set point along the transect.
• Where possible, also record the profile using a drawing in notebook and take horizontal (in profile) pictures using the camera.
• Use the profile to determine the areas where most care (if any) needs to be taken to prevent or reduce erosion – this is normally the erosion face closest to the base of the beach berm or dune face.
• During response activities, monitor the heights (H) at each profile and advise responders if any changes in activity or process need to be actioned.
• After response activities have ceased, re-measure the profile(s) to determine if the heights (i.e. beach profiles) have changed after the response (Figs U3 and U4).

Fig. U2. Using a theodolite to determine shoreline gradient (Source: AMSA)

Fig. U3. The use of marker stakes to determine shoreline gradient change where beach has accreted before response (Source: AMSA)
Appendix U

H(t₁) (constant)

Graduated pole

Surface oil patches

D = distance along the transect

Theodolite

Fig. U4. The use of marker stakes to determine shoreline gradient change where beach has eroded due to response or natural erosion (Source: AMSA)
**Appendix V. Example of an activation proforma to be used in event notification**

Table V1 is an example of the types of information that needs to be communicated in either activating field monitoring teams or placing them on standby. This information can be essential during an incident to clarify roles and expectations, and also to provide the necessary authority for subsequent actions.

![Table V1. Generic activation proforma](image)

<table>
<thead>
<tr>
<th>Generic activation template and check list</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Activation and expectations</strong></td>
</tr>
<tr>
<td>Activation level required (Check)</td>
</tr>
<tr>
<td>Is this a change in activation level? (check)</td>
</tr>
<tr>
<td>Is this oral or formal written activation?</td>
</tr>
<tr>
<td>Change to activation status?</td>
</tr>
<tr>
<td>Urgency</td>
</tr>
<tr>
<td>Date/time of request and</td>
</tr>
<tr>
<td>Date/time of expected response</td>
</tr>
<tr>
<td>Requester name and authority to make request</td>
</tr>
<tr>
<td>Response (output) expectation based on conversation and testing by monitoring group of need, activation level, timing and costs</td>
</tr>
<tr>
<td>Incident details</td>
</tr>
<tr>
<td>Incident context</td>
</tr>
<tr>
<td>Written situation report (SITREP)</td>
</tr>
<tr>
<td>Date/time when more information will be available</td>
</tr>
<tr>
<td>Monitoring provider contribution</td>
</tr>
<tr>
<td>What specific output or product is expected by the response agency from the monitoring provider?</td>
</tr>
<tr>
<td>Notes of conversation(s) between response agency, duty officer and monitoring provider.</td>
</tr>
</tbody>
</table>
Appendix W. Standard operating procedure for requesting oil spill trajectory modelling

W1 Purpose and scope
This appendix describes the data requirements and procedures for requesting oil spill trajectory modelling, to be used in conjunction with operational oil spill monitoring.

W2 Data requirements
- location of the spill origin or observed location of the slick (latitude and longitude)
- volume (or mass) of the oil spilled
- type of oil spilled (e.g. HFO, diesel, heavy crude)
- spill start time (or time observed slick) and date
- spill duration (over a period of time if continuous, or instantaneous if observed slick)
- type of spill (surface or subsurface release)
- if subsurface release, an indication of the discharge rate is required in simple terms (i.e. low, medium or high-pressure release)
- ambient wind and current conditions (these are usually provided by the latest predicted wind and current forecast models from the EDS)

W3 Special notes
- As part of the National Plan, OSTM capability is available for:
  - response
  - planning
  - exercise purposes
- Requests for modelling and forecasts are available on the AMSA website – through the National Plan links.
- Requests can be made through the AMSA NEMO portal, or emailed to AMSA from the spill pro forma: https://www.amsa.gov.au/environment/maritime-environmental-emergencies/national-plan/General-Information/SPILLREQUEST/index.asp

W4 Oil spill trajectory modelling request procedures
W4.1 Requesting oil spill trajectory modelling
The following outlines the OSTM requesting process:
1. Spill occurs.
2. Spill is reported to the relevant authority.
3. Requester (i.e. MSQ) fills out an OSTM request form and submits it to AMSA for action (through NEMO portal or a filled out OSTM pro forma emailed directly to AMSA).
4. OSTM request form is forwarded by AMSA to the model operator that is on-duty at that time (the duty officer), followed by a call to activate the 24/7 response service.
5. Note that it is very important to identify who the contact persons will be, and include phone numbers and email addresses so effective two-way communication can exist between the duty officer and the requester.
6. The duty officer carries out the required modelling, and forwards the results back to AMSA/the requester by email and FTP (file transfer protocol).
7. The duty officer will call the requester to confirm receipt of the model results and explain any significant findings.
8. (a) If further modelling is required, return to Step 3 and repeat.
   (b) If no further modelling is required, the requester will call the duty officer to confirm stand down.
9. The duty officer will send an email to AMSA/the requester confirming date and time of stand down.

W4.2 Updating the oil spill trajectory model results
For a small, short-term incident, a single set of modelling may be sufficient. However, many incidents will persist over several days, and in this event, additional follow up oil spill modelling forecasts may be required. It is important that the most up-to-date information regarding the incident is conveyed to the duty officer throughout the event. As an incident unfolds, and more refined information becomes available regarding the specifics of the incident, these details should be passed on to the duty officer, to enable them to update the modelling with the new intelligence accordingly. The most up-to-date information that is input into the models results in more accurate forecasts from the models, and thus a better representation of the scenario.

Over the course of a spill event, observations of oil will typically be made by the response and monitoring team. These observations should be provided to the oil spill modellers to calibrate and update the model results, so the most accurate forecasts of the spilled oil can be made.

The revision process is carried out in much the same way that an initial request would be made, following steps 3 to 10 as outlined in Section 4.1 above.

The following list covers some of the details that may be available to update the oil spill modelling:

- Revised estimate of the volume spilled if initial estimates were incorrect.
- Revised date/time of the spill if initial times were not correct.
- Revised oil type if initial oil type was unknown.
- Location (latitude and longitude) and times of visual observation of the slick (from aircraft overflights or vessels in the area).
- Distribution of the oil – Is it patchy, continuous, streaky, etc.?
- Appearance of the oil – What colour is it? Is it a silver-grey sheen, rainbow sheen? Is it thick and true colour? Is it highly weathered, has it emulsified?
- Approximate volumes of oil (able to be calculated from the distribution and appearance using the Bonn Agreement Oil Appearance Code – BAOAC).
- Location and approximate volumes of shoreline contact.
W4.3 Ask the advice of the modeller

At times, modellers will provide you with several different trajectories based on several different current or wind model combinations (e.g. best- and worst-case scenarios). The actual path of the oil/chemical spill will not be a mid-point between these two trajectories. Models are, however, forecasts and, like weather forecasts, although they can provide a high level of accuracy they are predictive in their nature and therefore open to variance. However, they consist of the best available information at the given time.

W 4.4 Interpreting oil spill trajectory modelling results

Sophisticated modelling software is used to predict the fate and trajectory of maritime oil spills and care is needed to correctly understand the output. Output formats include:

**Microsoft PowerPoint presentation – PPT:** The most commonly provided output is a Microsoft PowerPoint presentation as it is readily transferrable, and able to be visualised on a variety of devices without specialist software (providing Microsoft Office is installed). Typically, PowerPoint presentations will contain the scenario specifics (e.g. spill volume, duration of forecast) and snap shots of the forecast spill at set time intervals (e.g. every 2 h). This is a very effective way of sharing and visualising the results.

**Microsoft Word document – DOC:** A detailed Microsoft word report may be provided, which discusses the model inputs including the ambient winds, currents, oil type and weathering characteristics. It will also contain the model results outlining the movement of the oil over time. This is typically more thorough than a PPT, but can take longer to produce and hence may be provided after initial results are delivered as a PPT.

**JPG image file:** JPG is a graphic or image file format that can be displayed by many software packages, including default image viewers installed on most personal computers and portable devices (i.e. tablets). JPG files can be inserted and displayed in Microsoft Word documents or in Microsoft PowerPoint presentations. A single JPG file will show a fixed image showing the distribution of the material at one single point of time. A time-sequence of JPG images can be provided to reveal the change in distribution over time. For example, for a 24-h model run, you may wish to see what is happening to the spill at 2-h steps. Twelve individually date/time-stamped JPG figures would be provided at 2-h intervals. The model results may be output at other time increments, as requested (i.e. hourly or 6-hourly).

**Animation file – AVI:** An AVI file is a movie file that can be viewed with most movie programs, such as Windows Media Player. Separate AVI files can be provided for different information themes (e.g. the concentration of oil on the water, concentrations underwater). AVI files show a sequence of individual time steps captured at defied time intervals (e.g. every hour or every 3 h). In some instances, the AVI file can be very large, so when an AVI is sent it will be in a compressed file, which needs to be un-zipped. Once the file is un-zipped (using WinZip or similar) the AVI can be visualised in Windows Media Player or similar software.

**ArcGIS Shapefile – SHP:** Many GIS users prefer to obtain the shape files to visualise the forecasts of the trajectory models. SHP files provide vector-based visualisation that can be displayed as a layer in GIS software along with other geographic information. It is important to note that the shape files will normally be supplied as a time series of data showing the concentrations or distributions of material at individual time steps. The GIS operator should be aware that the data are a time series and that the GIS software controls must be used to animate the sequence to reveal the progression of the
forecast over time. It could be misleading to display only one time step without those viewing the image knowing that the information relates to that point in time.

In the case of concentrations, the GIS operator will also need to allocate their own symbology or colour key to reveal the distribution of concentrations. It is suggested that in-house skills and methodology for this process should be developed in preparation for a spill model.

**Google Earth file – KMZ:** A Google Earth KMZ file is a fast and simple way of visualising and animating the results of trajectory modelling. KMZ files animate the trajectory/output in Google Earth. Double clicking the KMZ file should automatically open it in Google Earth. Controls for the various layers (points, trackline and surface oil thickness) are contained in the Google Earth legend.

A sample image showing OSTM output is presented in Fig. W1. The figure shows the:

- **Surface swept area** – the white area represents the area that surface oil may have passed over from the beginning of the scenario through to the present time step.
- **Surface oil** – the black area represents the area that surface oil is at the present time step.
- **Shoreline oil** – the red area along the coastline represents the areas where oil has come ashore during the scenario, from the beginning to the present time step.
- **Weathering and fates graph** – shows the fate of the oil across the whole scenario, and indicates the quantity (mass or volume) of oil that is: on the water surface, in the water column, ashore and evaporated as a function of time. The vertical dashed line on the weathering and fates graph indicates the present time in the simulation. In the image above it is 21 h into the 24-h scenario.
Appendix X. Standard operating procedures for testing incident-specific field oil spill dispersant effectiveness

X1 Purpose and scope
If there is time to perform one, a field oil spill dispersant effectiveness test can improve decision making about the potential use of available dispersants on unknown oil, or under marginal conditions. This SOP describes two procedures (a quick test and a semi-quantitative test) and the equipment requirements for each (see Fig. X1).

In most places around Australia the choice of available National Plan dispersants for general maritime incident use will be limited to only one to three Oil Spill Control Agent Register-listed general purpose dispersants. Dispersant use will be restricted by policy, location (proximity to the coast or sensitive resources) and water depth, and a NEBA will be required.

An initial field effectiveness test may, therefore, be less informative than simply applying dispersant and monitoring the results.

Obtaining suitable samples of the oil to be dispersed is likely to be difficult. The slick may be offshore and the time taken to obtain a sample (vessel required) and conduct the test may mean that the result is no longer representative of the state of the oil on the water.

Dispersant effectiveness testing, if used, should be carried out continuously and simultaneously with application, and ideally at the beginning of each operational period. Each dispersant application becomes, in effect, a dispersant effectiveness test.

X2 Preparation for testing
X2.1 Location and equipment requirements
Having decided that the test can be conducted in a timeframe that allows the results to be useful, the safety of testers is paramount. Because this work involves oil and solvents, it is important that all work is carried out in well-lit, well-ventilated location, with a laboratory bench and sink, with running water.

AMSA provides a kit to each jurisdiction able to meet most requirements below, other than that which is generally available from local suppliers (e.g. hardware and stationery).

Specific equipment required for each type of test is provided in Sections X2. (QET) and X3 (SQT).

General equipment (not included in the Test Kit) but required for both tests are:

- waterproof overalls or apron and eye protection.
- 1 box of nitrile gloves (not latex gloves, which are permeable to toxic hydrocarbons).
- 1 box of tissues or paper towels.
Fig. X1. A diagrammatic representation of how the two test procedures and comparisons link together (Source: adapted from https://www.amsa.gov.au/environment/maritime-environmental-emergencies/national-plan/General-Information/documents/QldEHPDispersantChecklist.pdf)

- garbage bags for solid waste and plastic sheet or newspaper to cover workbench
- stand for separation funnels (sturdy cardboard box with cut holes or a retort stand)
- 2 L of solvent for extractions and cleaning (white spirits or turps)
- 10 L plastic bucket for liquid wastes
- 15 mL vials – ~30 (up to 23 may be used)
- mark all vials with a 10 mL line copied from an accurately filled 10 mL reference vial
- fine-point permanent marker to write on vials and labels
- small stick-on pre-prepared labels to mark vials.
- test-tube rack (collapsible) or very small cardboard box with holes cut into it
- Blu Tack to stand vials up for photographs
- plastic teaspoons for stirrers and 1 mL and 15 mL disposable syringes
- safety data sheets for hazardous materials being handled (read carefully).
- dishwashing detergent and bottle brushes.

Tips to improve the set up, test and clean-up process:

- Minimise contact of oil with glassware, to cut down on washing up.
- Add water and solvents directly to graduated glassware to save on using measuring cylinders.
- Label or mark all glassware to avoid confusion.
- Have pre-prepared labels for final photographs with dilutions and dispersant types.
• Use a sheet of white paper taped against a window as a backlit background for sample photos.
• Leave caps on containers to minimise fumes.
• Accurately fill one vial with 10 mL of water and use as a standard to save on measuring cylinders.
• Mark the shaft of the syringe plunger against the top of the barrel at the right volumes before use, because it is difficult to read markings and see the end of the black plunger against the black oil.

**X2.2 Sea water and oil samples**

If dispersant is being considered, then the likely location will be an offshore slick, because dispersant use in shallow coastal water (less than 10 m deep and close to shore) is generally prohibited or inadvisable. This may make obtaining suitable oil samples problematic. A fresh oil sample should be obtained as early as possible after the spill and may need to be acquired using a vessel. If possible, the source of the oil should also be sampled to obtain fresh oil.

The **oil samples** should be in:

• 300 mL screw-top glass or plastic containers labelled with the source of the oil (slick, bunkers, waste tank, etc.) and the location, date and time of sampling.

The amount of sea water required is not large, but a large sample (10 L in a clean bucket) is best to minimise temperature variation during the testing. Label the sea water with source, time and date and temperature.

**X3 Standard operating procedure for the ‘quick dispersant effectiveness test’ (QET)**

**X3.1 Purpose and scope**

This test takes around 20 min. This is a very quick and dirty ‘quick effectiveness test’ that compares an oil and water mixture with an oil and dispersant and water mixture, in a very basic simulation of dispersant operations.

\[
\text{oil + dispersant + water + agitation}
\]

is compared with

\[
\text{oil + water only + agitation}
\]

The comparison is visual. No solvent extraction is done.

**X3.2 QET equipment**

Up to four sets of equipment may be needed for all the tests (i.e. blank plus two to three dispersants). Have sufficient (and spare) disposable items and glassware, and solvent resistant waste bottles.

For three dispersants to be tested you will need at least:

• 1 × 250 mL beaker for measuring sea water (can be used for all)
• 3 × 125 mL separating funnel with caps for simulating ocean mixing
• 3 × 100 mL beakers for mixing dispersant and oil (typically three are needed)
• 3 × 1 mL plastic disposable syringes for adding dispersant
• 3 × 2 mL plastic disposable syringes for dispersant/oil mixture
• 3 × each of 5 mL and/or 10 mL syringes for oil (up to 50 mL may be needed)
• 4 × 15 mL vials – for samples for this test
• 3 × 15 mL vials – for dispersed oil samples held over for use in the following semi-quantitative test.

X3.3 QET procedure
This test prepares an oil and water sample and an oil/dispersant/water test mix. Test mixtures should be at about the same temperature as the water in the environment where the dispersant is to be applied.

Oil/water/dispersant test mix
• Determine the appropriate dispersant-to-oil ratio (DOR) for each available dispersant to add to the oil (normally start with 1 part dispersant to 35 parts oil; DOR 1:35).
• In a 100 mL beaker, add 1 mL dispersant to appropriate volume of oil and mix until dissolved.
• To the separating funnel, with lower valve closed, add 100 mL of sea water.
• To the separating funnel add 2 mL of the dispersant and oil mixture. Replace cap and tighten.
• Carefully rotate the separating funnel and rotating it end-over-end for 2 min at ~4 s per rotation.
• Stand the separating funnel upright in a holder, remove the cap, and allow it to settle for 5 min.
• Drain 10 mL of dispersed oil solution into a labelled calibrated vial.
• Drain 10 mL of dispersed oil solution into a second labelled calibrated vial. Put aside for the semi-quantitative test, if needed.
• Repeat the procedure above for each available dispersant.

Oil/water undispersed reference sample
• Add 2 mL of untreated oil to 100 mL of sea water in the separating funnel (without dispersant). Replace cap and tighten.
• Carefully rotate the separating funnel end-over-end for 2 min at ~4 s per rotation.
• Stand the separating funnel upright in the holder, remove cap and allow it to settle for 5 min.
• Drain 10 mL of the oil and water mix into a 10 mL calibrated, labelled vial as the undispersed reference.

Comparison of dispersed and undispersed oil and reporting
Stand all vials in a row or in a vial holder against a flat white background. Compare and photograph the final set of blank and dispersant test vials. Record results as shown in Table X1.

X4 Standard operating procedure for the ‘semi-quantitative dispersant effectiveness test’ (SQT)
X4.1 Purpose and scope
This test can take up to 60 min. The ‘semi-quantitative test’ is only carried out for those dispersants that are expected to show a significant likelihood of being effective (i.e. succeed in the QET or are otherwise known to have effectiveness against the kind of oil
spilled). It compares a solvent extraction of the dispersed oil with known percentage dilutions of the oil in solvent using a visual comparison of the density/colour.

**X4.2 SQT equipment**

Up to three sets of equipment may be needed for each of the test dispersants. Have plenty of pre-labelled vials and glassware to prevent washing between samples.

For each dispersant to be tested you will need:

- 1 mL plastic syringe for measuring out 0.5 mL of oil
- 6 × 15 mL vials – 100%, 50%, 25%, 12%, 6%, dispersed oil test.
- 1 × 25 mL measuring cylinder for measuring out clean solvent
- 1 × 25 mL measuring cylinder for measuring out standard solutions
- 1 × 250 mL conical flask with cap for preparing solvent extraction sample
- 1 × 250 mL conical flask with cap for mixing standards
- Sticky labels set – 100%, 50%, 25%, 12%, 6%,

**X4.3 SQT procedure**

**Test sample solvent extraction preparation**

This produces the dispersed oil sample for comparison with the known standards. It takes 30 min to complete.

- For each test dispersant, take the 10 mL of dispersed oil prepared in the quick effectiveness test (see Section X3.3 if a new sample is required) and place in a clean 250 mL conical flask.
- Add 100 mL of solvent. Firmly tighten the cap.
- Shake vigorously for 30 s, then loosen the cap and stand for 20 min to allow the solvent and oil to separate from the water.
- Into a calibrated vial, carefully pour 10 mL of the oil plus solvent phase from the top.
- For each dispersant, this is now the test sample to be compared with the known relevant standard set.

**Reference standards preparation**

This produces the set of known standard percentage oil dispersions for comparison with each test sample. This procedure takes around 30 min to complete. Except for the 100% standard, the following steps are serial dilutions.

- **100% standard** – Add 250 mL of solvent to a clean 250 mL conical flask, then add 0.5 mL of oil. Make sure cap is firmly tightened and shake. Allow to stand for 5 min. This standard is not used for comparison because no dispersant is 100% effective. More than 50% will be obvious and deemed successful.
• **50% standard** – Add 25 mL of the 100% standard to a beaker, then add 25 mL of solvent. Pour 10 mL of this into a calibrated vial marked 50%.

• **25% standard** – Add 25 mL of the 50% standard to a beaker, then add 25 mL of solvent. Pour 10 mL of this into a calibrated vial marked 25%.

• **12% standard** – Add 25 mL of the 25% standard to a beaker, then add 25 mL of solvent. Pour 10 mL of this into a calibrated vial marked 12%.

• **6% standard** – Add 25 mL of the 12% standard to a beaker, then add 25 mL of solvent. Pour 10 mL of this into a calibrated vial marked 6%.

Visually compare the relevant dispersed oil extracts with the known concentration standards (50%, 25%, 12%, 6%) against a flat white background, as shown in Fig. X2.

**Comparison of relevant dispersant effectiveness and reporting**

From a visual comparison of the test sample(s) with the solvent standards, an estimate of effectiveness can be made. Where different dispersant-to-oil ratios using the same dispersant are used, these should be well labelled. Where possible, samples from both the quick and semi-quantitative tests should be photographed for inclusion in reports and records.

**X5 Clean-up**

It is important to recondition all equipment and pack away, and clean-up workspaces as soon as possible, to ensure readiness in case additional testing is required.

Wastes, including solvent waste, should be appropriately disposed of. Note, solvent and oil will need to be disposed of as regulated waste, or included in the oily waste stream being cleaned elsewhere.

![Fig. X2. The vials of the reference dispersant extractions together with the two test vials, in this case all Ardrox 6120, in dispersant to oil (DOR) ratios (1:10 and 1:20) (Source: adapted from https://www.amsa.gov.au/environment/maritime-environmental-emergencies/national-plan/General-Information/documents/QldEHPDispersantChecklist.pdf)](image)
Glossary of terms and acronyms

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acute toxicity</td>
<td>An adverse lethal (mortality) or sub-lethal (e.g. bioluminescence inhibition) effect from a toxicant that occurs as a result of an exposure period that is short relative to the organism’s life span</td>
</tr>
<tr>
<td>Adverse outcome pathways</td>
<td>The chain of events, from bioaccumulation, to molecular changes, physiological changes, that result in ecological changes. A way of linking molecular changes to population level impacts.</td>
</tr>
<tr>
<td>Ah receptor</td>
<td>Aryl-hydrocarbon receptor, which induces the synthesis of oil-degrading enzymes in vertebrates when a PAH binds to it</td>
</tr>
<tr>
<td>Algae</td>
<td>Aquatic plants that do not have root structures or flowers. Microalgae (also called phytoplankton) are microscopic. Macroalgae can be seen without magnification.</td>
</tr>
<tr>
<td>Alkanes</td>
<td>Saturated hydrocarbons containing only carbon and hydrogen atoms in linear, branched or cyclic structures, having only single bonds</td>
</tr>
<tr>
<td>Amphipod</td>
<td>A malacostracan crustacean of the order Amphipoda; typically these live in or on sediment</td>
</tr>
<tr>
<td>AMSA</td>
<td>Australian Maritime Safety Authority</td>
</tr>
<tr>
<td>ANZECC</td>
<td>Australian and New Zealand Environment and Conservation Council</td>
</tr>
<tr>
<td>Aromatics</td>
<td>Petroleum compounds with ringed structures</td>
</tr>
<tr>
<td>ARMCanZ</td>
<td>Agriculture and Resource Management Council of Australia and New Zealand</td>
</tr>
<tr>
<td>Asphaltenes</td>
<td>High molecular weight macromolecules containing N, S and O heteroatoms that are found in crude oil</td>
</tr>
<tr>
<td>BACI</td>
<td>Before-after-control-impact</td>
</tr>
<tr>
<td>Baleen whale</td>
<td>Also known as Mysticeti; named for the long plates of baleen that hang in a row (like the teeth of a comb) from their upper jaws and are used for straining and capturing food</td>
</tr>
<tr>
<td>BAOAC</td>
<td>Bonn Agreement Oil Appearance Code</td>
</tr>
<tr>
<td>Bathymetry</td>
<td>Sea floor topography</td>
</tr>
<tr>
<td>Benthic</td>
<td>Referring to organisms living in or on the sediments of aquatic habitats</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
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<td>-------------------------------------</td>
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</tr>
<tr>
<td>Biliary FAC (fluorescent aromatic</td>
<td>PAH metabolites found in bile</td>
</tr>
<tr>
<td>compounds)</td>
<td></td>
</tr>
<tr>
<td>Bioaccumulation</td>
<td>The uptake of a contaminant from the environment into an organism’s tissue</td>
</tr>
<tr>
<td>Bioassay</td>
<td>A test used to evaluate the relative potency of a chemical by measuring its effect on a living organism relative to a control or reference</td>
</tr>
<tr>
<td>Biodegradation</td>
<td>Broken down by bacteria</td>
</tr>
<tr>
<td>Biodiversity</td>
<td>The variety and variability of living organisms and the ecological complexes in which they occur</td>
</tr>
<tr>
<td>Biomarker</td>
<td>(1) A constituent of oil that is resistant to microbial degradation and consequently can be used to identify oil types (2) A biological marker: a measureable indicator of some biological state or condition</td>
</tr>
<tr>
<td>Biofilm</td>
<td>Densely packed communities of microbial cells that grow on living or inert surfaces and surround themselves with secreted polymers</td>
</tr>
<tr>
<td>Biogenic</td>
<td>Created by living things</td>
</tr>
<tr>
<td>Biomagnify</td>
<td>A compound with a higher body burden in higher trophic levels than in lower trophic levels. Typically, these compounds are stored in fat and not excreted efficiently.</td>
</tr>
<tr>
<td>Bitumen</td>
<td>Solid residue that remains when the lighter components of an oil have been removed</td>
</tr>
<tr>
<td>Bivalve</td>
<td>A mollusc with a shell in two parts, hinged together. Examples are clams, oysters and mussels.</td>
</tr>
<tr>
<td>Body burden</td>
<td>The concentration of a contaminant in an organism’s tissue</td>
</tr>
<tr>
<td>BTEX</td>
<td>Benzene, toluene, ethylbenzene and xylene – volatile monoaromatic components of oil</td>
</tr>
<tr>
<td>Carcinogenesis</td>
<td>The formation of a cancer</td>
</tr>
<tr>
<td>Cetaceans</td>
<td>An order of marine mammals that include whales, dolphins and porpoises</td>
</tr>
<tr>
<td>Chemical dispersant</td>
<td>An oil spill response chemical containing a mixture of solvents and surfactants, which, assisted by wave energy, breaks oil slicks into droplets</td>
</tr>
<tr>
<td>Chronic toxicity</td>
<td>Adverse effects over a significant portion of an organism’s life span (e.g. effects on growth and reproduction)</td>
</tr>
<tr>
<td>Ciliate</td>
<td>A type of microzooplankton – a microbial eukaryote</td>
</tr>
<tr>
<td>Condensates</td>
<td>Petroleum products that are gaseous at reservoir temperatures and pressures, but condense once brought to the surface</td>
</tr>
<tr>
<td>Copepod</td>
<td>A small crustacean found in the sea and nearly every freshwater habitat, which can be either planktonic (drifting in sea water) or benthic (living on the sediments)</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
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</tr>
<tr>
<td><strong>CTD</strong></td>
<td>Conductivity, temperature and depth – usually referring to a CTD sensor rosette array</td>
</tr>
<tr>
<td><strong>Cyanobacteria</strong></td>
<td>Bacteria that obtain their energy through photosynthesis</td>
</tr>
<tr>
<td><strong>CYP 1A</strong></td>
<td>Cytochrome p450 1A – an enzyme involved in the metabolism of oil in vertebrates</td>
</tr>
<tr>
<td><strong>Dispersion</strong></td>
<td>Becoming spread out or less concentrated – in this case, mixing into the water column via currents and waves</td>
</tr>
<tr>
<td><strong>Dissolution</strong></td>
<td>Dissolving via mixing into the water</td>
</tr>
<tr>
<td><strong>Ecotoxicology</strong></td>
<td>The science dealing with the adverse effects of chemicals, physical agents and natural products on populations and communities of living organisms</td>
</tr>
<tr>
<td><strong>EDS</strong></td>
<td>Environmental data server</td>
</tr>
<tr>
<td><strong>Emulsification</strong></td>
<td>Water mixing into oil, creating an emulsion or mousse</td>
</tr>
<tr>
<td><strong>EROD</strong></td>
<td>7-ethoxyresorufin-O-deethylase, an enzyme associated with oil metabolism in vertebrates</td>
</tr>
<tr>
<td><strong>Eukaryote</strong></td>
<td>An organism consisting of a cell or cells in which the genetic material is DNA in the form of chromosomes contained within a distinct nucleus. Eukaryotes include all living organisms other than the eubacteria and archaea.</td>
</tr>
<tr>
<td><strong>FAC</strong></td>
<td>Fluorescent aromatic compounds – PAH metabolites measured in fish bile, which are an indicator of recent exposure to oil</td>
</tr>
<tr>
<td><strong>GC-FID</strong></td>
<td>Gas chromatography with flame ionisation detection</td>
</tr>
<tr>
<td><strong>GC-MS</strong></td>
<td>Gas chromatography mass spectrometry</td>
</tr>
<tr>
<td><strong>GIS</strong></td>
<td>Geographic information system</td>
</tr>
<tr>
<td><strong>Glutathione S-transferase</strong></td>
<td>An enzyme involved in the metabolism of oil</td>
</tr>
<tr>
<td><strong>Histology</strong></td>
<td>Finding disease or injury by examining an organism’s tissue.</td>
</tr>
<tr>
<td><strong>Hydrophobic</strong></td>
<td>Less soluble in water than in fat</td>
</tr>
<tr>
<td><strong>IMOS</strong></td>
<td>Integrated Marine Observing System</td>
</tr>
<tr>
<td><strong>IMT</strong></td>
<td>Incident management team</td>
</tr>
<tr>
<td><strong>Infauna</strong></td>
<td>Animals living in the sediments of water bodies</td>
</tr>
<tr>
<td><strong>Irradiance</strong></td>
<td>A measure of radiant energy</td>
</tr>
<tr>
<td><strong>Log Kow</strong></td>
<td>The logarithm of the octanol:water partition coefficient, indicating the degree to which a chemical partitions in octanol over water</td>
</tr>
<tr>
<td><strong>Meiofauna</strong></td>
<td>Small benthic invertebrates (62–500 µm) that live in both marine and freshwater environments.</td>
</tr>
<tr>
<td><strong>Meroplankton</strong></td>
<td>Organisms that are planktonic for only a part of their life cycles, usually the larval stage (e.g. the larvae of sea urchins, sea stars, crustaceans, marine worms, some marine gastropods and most fish)</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
</tr>
<tr>
<td>----------------------</td>
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</tr>
<tr>
<td>Metabolism</td>
<td>All of the chemical reactions involved in maintaining the living state of cells and organisms</td>
</tr>
<tr>
<td>Metabolite</td>
<td>A substance produced during metabolism</td>
</tr>
<tr>
<td>Mode of action</td>
<td>The molecular, biochemical or physiological pathway by which a toxicant causes injury</td>
</tr>
<tr>
<td>Mousse</td>
<td>An oil and water emulsion</td>
</tr>
<tr>
<td>Narcosis</td>
<td>A non-specific reversible disturbance of the functioning of a cell membrane, caused by the accumulation of a narcotic compound in hydrophobic lipid phases within the organism</td>
</tr>
<tr>
<td>Narcotic</td>
<td>A compound that partitions into cell membranes</td>
</tr>
<tr>
<td>NEBA</td>
<td>Net environmental benefit analysis</td>
</tr>
<tr>
<td>Necrosis</td>
<td>Tissue death</td>
</tr>
<tr>
<td>Neoplasia</td>
<td>A type of tissue damage that suggests tumour formation</td>
</tr>
<tr>
<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
</tr>
<tr>
<td>NOPSEMA</td>
<td>The National Offshore Petroleum Safety and Environmental Management Authority</td>
</tr>
<tr>
<td>OSRA</td>
<td>Oil Spill Response Atlas</td>
</tr>
<tr>
<td>OSTM</td>
<td>Oil Spill Trajectory Model</td>
</tr>
<tr>
<td>Oxic</td>
<td>Containing oxygen; an environment, condition or habitat in which oxygen is present</td>
</tr>
<tr>
<td>PAH</td>
<td>Polycyclic aromatic hydrocarbon</td>
</tr>
<tr>
<td>Pathogens</td>
<td>Disease-causing agents</td>
</tr>
<tr>
<td>Pericardial oedema</td>
<td>Accumulation of fluid around the heart in a developing embryo</td>
</tr>
<tr>
<td>Petrogenic</td>
<td>Derived from a petroleum source</td>
</tr>
<tr>
<td>PFD</td>
<td>Personal flotation device</td>
</tr>
<tr>
<td>Photoactivation</td>
<td>Exposure to light: some compounds, including certain PAHs, become more toxic</td>
</tr>
<tr>
<td>Photooxidation</td>
<td>The degradation of a compound in the presence of oxygen that is facilitated by radiant energy such as UV light</td>
</tr>
<tr>
<td>Phytoplankton</td>
<td>Photosynthetic organisms consisting mainly of free-floating algae, protists and cyanobacteria</td>
</tr>
<tr>
<td>Pinnipeds</td>
<td>Any of an order or suborder (Pinnipedia) of aquatic carnivorous mammals (such as a seal or walrus) with all four limbs modified into flippers</td>
</tr>
<tr>
<td>Plankton</td>
<td>Made up of small or microscopic organisms that drift or swim weakly in a body of water, including bacteria, diatoms, jellyfish, and various larvae</td>
</tr>
<tr>
<td>Pneumatophores</td>
<td>Specialised root structures that grow out from the water surface and facilitate the aeration necessary for root respiration in hydrophytic trees such as many mangrove species</td>
</tr>
<tr>
<td><strong>Polycyclic aromatic hydrocarbons</strong></td>
<td>Petroleum compounds with more than one ring in their structure (PAHs)</td>
</tr>
<tr>
<td>-------------------------------------</td>
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</tr>
<tr>
<td><strong>Pour point</strong></td>
<td>The temperature at which an oil loses its flow characteristics and becomes semi-solid</td>
</tr>
<tr>
<td><strong>PPE</strong></td>
<td>Personal protective equipment</td>
</tr>
<tr>
<td><strong>Proteobacteria</strong></td>
<td>A major group of Gram-negative bacteria, including pathogens such as <em>Escherichia</em>, <em>Salmonella</em>, <em>Vibrio</em>, <em>Helicobacter</em> and <em>Yersinia</em></td>
</tr>
<tr>
<td><strong>Protists</strong></td>
<td>Members of an informal grouping of diverse eukaryotic organisms that are not animals, plants or fungi</td>
</tr>
<tr>
<td><strong>Pyrogenic</strong></td>
<td>Arising from the heating or burning of compounds (e.g. fossil fuels)</td>
</tr>
<tr>
<td><strong>QA/QC</strong></td>
<td>Quality assurance/quality control</td>
</tr>
<tr>
<td><strong>Quadrat</strong></td>
<td>A plot used in ecology to isolate a standard unit of area for study of the distribution of an item over a large area. While originally rectangular, they can be rectangular, circular or irregular.</td>
</tr>
<tr>
<td><strong>Quality assurance (QA)</strong></td>
<td>The implementation of checks on the success of quality control (e.g. replicate samples, analysis of samples of known concentration)</td>
</tr>
<tr>
<td><strong>Quality control (QC)</strong></td>
<td>The implementation of procedures to maximise the integrity of monitoring data (e.g. cleaning procedures, contamination avoidance, sample preservation methods)</td>
</tr>
<tr>
<td><strong>SAR</strong></td>
<td>Synthetic aperture radar</td>
</tr>
<tr>
<td><strong>Sea state</strong></td>
<td>The condition of the free surface on a large body of water, influenced by wind waves and swell</td>
</tr>
<tr>
<td><strong>Sedimentation</strong></td>
<td>Oil binding to particles and sinking to the bottom sediments</td>
</tr>
<tr>
<td><strong>Slick</strong></td>
<td>A mass of floating oil covering an area of water</td>
</tr>
<tr>
<td><strong>Specific gravity</strong></td>
<td>The density relative to that of water</td>
</tr>
<tr>
<td><strong>SPMD</strong></td>
<td>Semi-permeable membrane device (for passive sampling of organic contaminants)</td>
</tr>
<tr>
<td><strong>SAR</strong></td>
<td>Satellite-borne synthetic aperture radar</td>
</tr>
<tr>
<td><strong>SSD</strong></td>
<td>Species sensitivity distribution</td>
</tr>
<tr>
<td><strong>Stickiness</strong></td>
<td>The property of adhering to a surface that is touched</td>
</tr>
<tr>
<td><strong>Swath</strong></td>
<td>Beam width of a remote sensor; the mapped area that can be captured in one image</td>
</tr>
<tr>
<td><strong>Taxon (taxa)</strong></td>
<td>Any group(s) of organisms considered sufficiently distinct from other such groups to be treated as a separate unit or units (e.g. species, genera, families)</td>
</tr>
<tr>
<td><strong>Topography</strong></td>
<td>A detailed map of surface features</td>
</tr>
<tr>
<td><strong>TPH</strong></td>
<td>Total petroleum hydrocarbon – all of the ‘oil’ that can be detected in a water or sediment sample</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
</tr>
<tr>
<td>----------------------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Trophic transfer</td>
<td>Dietary bioaccumulation where contaminants are successively taken up by organisms higher up the food chain</td>
</tr>
<tr>
<td>UCM</td>
<td>Unresolved complex mixture</td>
</tr>
<tr>
<td>UV light</td>
<td>Light that is beyond the visible spectrum. This light can damage cells.</td>
</tr>
<tr>
<td>Unsaturated</td>
<td>Containing double bonds</td>
</tr>
<tr>
<td>UTC</td>
<td>Coordinated Universal Time – the primary time standard by which the world regulates clocks and time. UTC is considered interchangeable with Greenwich Mean Time.</td>
</tr>
<tr>
<td>Viscosity</td>
<td>The viscosity of a fluid is a measure of its resistance to gradual deformation by shear stress or tensile stress.</td>
</tr>
<tr>
<td>VOC</td>
<td>Volatile organic compound</td>
</tr>
<tr>
<td>Weathering</td>
<td>Changes in oil following exposure to the environment – includes spreading, evaporation, dispersion, dissolution, emulsification, biodegradation and photooxidation.</td>
</tr>
<tr>
<td>Xenobiotic</td>
<td>A chemical compound that is foreign to a biological system</td>
</tr>
<tr>
<td>Xenobiotic metabolising enzymes</td>
<td>Enzymes that are responsible for the breakdown of xenobiotic aromatic compounds. Examples include cytochrome p450 1A, glutathione S-transferase and mixed function oxidases.</td>
</tr>
<tr>
<td>Zooplankton</td>
<td>Floating or weakly swimming animals that rely on water currents to move any great distance. They are usually larger than phytoplankton.</td>
</tr>
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