Moreton Bay Oil Spill:
Ecological Impacts and Lessons Learnt

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Introduction

The Incident

On 11 March 2009, 31 containers of ammonium nitrate were lost overboard from the *Pacific Adventurer* approximately 13 kilometres (km) east of Cape Moreton (outside of State waters) (TMS Consulting 2009). This caused damage to the hull and fuel tanks, and resulted in the loss of approximately 270 tonnes (t) of bunker (heavy) fuel oil (AMSA 2009). The oil was transported inshore by a combination of gale-force south-easterly winds and a southerly current, and came ashore later that day and the next along roughly 80 km of coastline (Holzheimer 2009). The eastern beach of Moreton Island, and the rocky shores at Cape Moreton were most heavily affected (AMSA 2009). On Moreton Island, the 8 km area south of Cape Moreton was the most heavily oiled, and the following 17 km were also lightly oiled. North of Cape Moreton, the rocky foreshore area between the cape and North Point was also affected. Smaller quantities of oil also impacted the eastern beaches of Bribie Island and beaches on the Sunshine Coast from Kawana to Marcoola (TMS Consulting 2009).

Therefore, exposed sandy beaches were the predominant habitat impacted by the spill; however smaller areas of rocky shore and wetland habitat (e.g. sedge-dominated wetlands in Spitfire and Eagers creeks on Moreton Island, and mangrove wetlands on the Sunshine Coast) were also impacted (NERG 2009).

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Physical and Chemical Properties of Oils

The environmental impact caused by spilt oil is related to the volume spilt, the physical and chemical properties of the oil, the period of exposure to the oil, and the sensitivity of the receiving environment (Gelin et al. 2003; AMSA 2000; Raaymakers 1994). Some oil products have been demonstrated to be more toxic than others (Van Gelder-Ottway 1976), while the damage of heavier oils has been related to their persistence in the marine environment (Nicodem et al. 1997; Burns et al. 1993). The toxicity of oil also decreases rapidly when it is exposed to water and air, a process termed 'weathering' (Duke & Burns 1999).

Heavy fuel oil is a viscous oil with a density only marginally less than that of seawater (EC 2005). That is, in a relatively still environment, heavy fuel oil would form a layer above seawater, though it would be expected that a fraction of the oil would sink and settle on the seafloor. Several laboratory studies have concluded that 'heavier' oils are considerably less toxic to marine organisms than more refined products such as kerosene (see Van Gelder-Ottway 1976). A greater risk from heavy fuel oil exists in its physical persistence if allowed to reach the shore, and its capacity to form stable water-in-oil emulsions. Water-in-oil emulsions are formed through a combination of weathering and physical disturbance (via wind and currents) of highly viscous oils, and can be difficult to chemically disperse and to mechanically remove (White & Baker 1998; Nicodem et al. 1997).

Diesel is a refined oil product that is less dense and more volatile that heavy fuel oil (EC 2005). As a consequence, spilt diesel oil is likely to form a layer on the surface of the water. The volatility of diesel contributes to substantial evaporative loss, while it is unlikely to form water-in-oil emulsions due to its low viscosity. Though considered comparatively more toxic than the other oils (Van Gelder-Ottway 1976), spilt diesel may be effectively contained using surface booms. Chemical dispersants are also effective in accelerating the weathering and biological breakdown of diesel in seawater (AMSA 2004).

Lubricating oils, of the kind used in diesel engines and gearing, are of a relatively similar density to diesel oils (EC 2005). As such, lubricants would be expected to behave in a similar fashion to diesel oil, and form a surface layer. Lubricants are much less volatile, however, and thus would not evaporate as rapidly. Given substantial wave action and weathering, water-in-oil emulsions are possible.

Potential Impacts of Spilt Oil on the Marine Environment

Oils and fuels are occasionally spilt into the sea, coastal and inland waters in large volumes, as a consequence of infrastructure and transportation failures. These hydrocarbons can cause significant damage to aquatic ecosystems and particularly those within the intertidal zone and benthic sediments (Duke & Burns 1999).

Concentrations of dissolved fuel below 0.01 parts per million (ppm) have not been shown to have adverse effects on any marine organism either in the short or long term, at any stage of development or at a cellular or sub-cellular level. Between 0.01 ppm and 0.1 ppm, some adult animals show sub-lethal behaviour and physiological disturbance, while developmental stages may show retarded growth or increased abnormalities. In the medium term, motile populations, such as adult fish and prawns, are less likely to be significantly directly impacted, as they are capable of avoiding localised areas polluted by fuel. However, any impacts on other invertebrate communities (such as benthic in-fauna) may pass along the food chain to fish and birds. Diatoms have been shown to be sensitive to kerosene at concentrations from 100 ppm (Mironov & Lanskaja 1967, cited in van Gelder-Ottway 1976).

There have been several large spills with major environmental impacts that have occurred as a result of vessels spilling oil in coastal waters. For example, the grounding of the *Exxon Valdez* released 37 000 t of crude oil into Prince William Sound, Alaska and severely affected seagrass, benthos and sea bird communities. The grounding of the *Amoco Cadiz* also led to major environmental harm. When the vessel ran aground off the coast of Brittany, 223 000 t of light crude oil were spilt and caused severe damage to saltmarsh, benthic invertebrate, seabird and fish communities. However, the environmental impacts of these incidents appear to have been relatively short term. Many of the degraded communities in Brittany recovered within a year of the *Amoco Cadiz* spill (Spooner 1978 & NOAA 1992 in White & Baker 1999) and virtually all of the impacted communities in Prince William Sound recovered within two years of the *Exxon Valdez* incident (Dean et al. 1998; Feder & Blanchard 1998; Weins et al. 1996).

Spilt oil can affect marine organisms via several pathways, such as: the physical coating of organisms; penetration and persistence of component petroleum hydrocarbons in the sediments; and the uptake of petroleum hydrocarbons by both plants and animals leading to both lethal and sub-lethal toxicity (Duke & Burns 1999).

Sandy Beach Habitat

In Australia, ocean-exposed, high-energy sandy beaches stretch for over 10 000 km and cover approximately 49% of the coastline (Short 1998). However, little is known about the impacts of oil contamination on these ecosystems, the exception being the two studies on the *Prestige* oil spill incident in Galicia, Spain (de la Huz et al. 2005; Junoy et al. 2005). Beaches may even be considered to be 'resilient' to spills, exemplified by disaster responses where oil is directed onto beaches in order for physical removal of contamination to take place more easily (Fingas 2000). Indeed in the case of the *Pacific Adventurer* spill, an independent review into the environmental effectiveness of the oil spill response, it was noted that (from Raaymakers 2009a):

"While dark oil on white beaches may "appear" to "look bad" environmentally, it is of (relatively) limited ecological consequence and is (relatively) easy to clean-up, compared to oiled mangroves, seagrasses or coral reefs. Additionally, the seaward surf beaches and rocky shores of Moreton Island are very high-energy environments, with (relatively) low biological diversity and productivity, and will "self-clean" due to wave action and other natural processes."

Such claims effectively ignore the ecological values and ecosystem services that high energy sandy beaches provide (Holzheimer 2009), such as supporting coastal food webs and nutrient cycling (Schlacher et al. 2008). These ecosystem services are primarily attributable to the benthic invertebrate fauna inhabiting the sediments of sandy beaches (and similarly other soft-sediment habitat). In south-east Queensland, sandy beach habitat not affected by oil spills can support around 150 benthic invertebrates per m^2 (Holzheimer 2009).

Sedentary benthic animals are more likely to be directly impacted if they are exposed to toxic concentrations of fuels than motile organisms. High concentrations of hydrocarbons in the sediment are likely to cause mortality of benthic infaunal communities. Crude and bunker oils caused mass mortality of epi- and infauna within 2 days of exposure, with crustacean such as amphipods, crabs, mud lobsters and prawns being notably vulnerable (Gesteira & Dauvin 2005; Duke & Burns 1999; Dauvin 1998; Dauvin 1989; Dauvin 1988). Concentrations of crude oil exceeding 500 ppm resulted in mortality of oysters (*Crassostrea gigas*) (Daka & Ekweozor 2004). Shifts in the abundance and community composition of benthic invertebrate and microbe communities are expected after oil spills on soft-sediment habitat (Junoy et al. 2005; Lindstrom et al. 1991).

Rocky Shore Habitat

Expected impacts of oil spills on rocky shore environments are expected to be similar to those of other benthic fauna communities, i.e. acute mortality, and a shift in abundance and community composition. Often, oil removal by wave action is thought to be effective on exposed rocky shores and headlands (Kingston 2002), and intervention may not be required in these habitats. However, a study in Hong Kong found that while the use of dispersants resulted in acute mortality of gastropods, the long-term impacts of the oil spill were most significant at a heavily affected site where dispersants were not used (Stirling 1977). Reports of full recovery occurring within three to four years are not uncommon for rocky shores, while saltmarsh and subtidal ecosystems may take as long as 15 years to recover (see below; Culbertson et al. 2008; Kingston 2002; Burns et al. 2000).

Wetlands

Both petroleum and petroleum by-products are harmful to mangroves (Odum & Johaness 1975). Oil spills may result in acute morbidity and mortality of mangroves, attributable to fresh oil and particularly aromatic hydrocarbon components which can cause mechanical damage by blocking the pores in the pneumatophores and affecting respiration, photosynthesis and translocation (Mackey & Smail 1995). Oiling of roots and sediment may result in tree death, or may depress growth of surviving trees as well as affecting seedling recruitment (Duke & Burns 1999). The chronic effects of weathered oil being incorporated into the sediment can also cause sub-lethal effects, such as: the loss of canopy and less vigorous propagules; inhibition of the growth of seedlings and mature plants; and inhibition of the recolonisation of epi- and in-fauna (Duke & Watkinson 2002; Duke et al. 1997; Nicodem et al. 1997; Volkmann et al. 1994). For example in affected mangrove habitat, crabs returned to the mangroves after one month, but with significantly reduced activity for at least 22 months. Little recovery of in fauna was observed after 22 months (Duke & Burns 1999).

Mangrove seedlings are significantly more vulnerable than mature trees (Grant et al. 1993). Exposure to crude and bunker oils resulted in mortality of grey mangrove (*Avicennia marina*) seedlings within 1 – 2 months; whilst surviving trees showed a significant reduction in canopy biomass (density) between 2 and 22 months after exposure (Duke & Burns 1999); exposure to crude oils resulting in significant defoliation of *Avicennia marina* was also reported by Wardrop et al. (1987). Mature trees exposed to crude and bunker oils typically recover (Duke et al. 1997; Wardrop et al. 1998). Sublethal exposure has been linked to genetic damage resulting the production of non-viable propagules by grey mangroves (Duke & Watkinson 2002).

Coastal oil spills have resulted in persistent or permanent loss of mangrove habitat: 10 t of diesel fuel, released to the east of Cape Flattery in 1991, led to the permanent loss of approximately 3 hectares (ha) of mangroves (Duke and Burns 1999); whilst mangroves in the Parramatta River (Sydney), impacted by crude oil in 1992, still showed a reduction in leaves and small branches three years after the incident. However, such enduring impacts appear to be the 'exception' rather than the 'rule'. The release of 450 t of fuel oil from the bulk ore carrier *Sir Alexander Glen* in 1988, led to heavy oiling of mangroves at Cape Lambert, Western Australia, but no deforestation or death of mangroves resulted (Duke & Burns 1999). Similarly no impact was observed in 1994, when 61 t of waste oil was dumped into mangroves at Yorkeys Knob in Queensland (Duke & Burns 1999). Other small coastal spills in Western Australia, such as the discharges from the Woodside onshore Treatment Plan in Withnell Bay in 1987 and in Johns Creek Boat Harbour in 1994 & 1997, led to the short-term (< 2 years) defoliation of small areas of mangroves (< 1 ha) (Duke & Burns 1999).

Similar to mangroves, saltmarsh habitat is also adversely affected by oil spills. Two common saltmarsh species (*Sarcocornia quinqueflora* and *Sporobolus virginicus*) died rapidly after experimental contamination with crude oil and diesel (Clarke & Ward 1993). Recolonisation of *S. virginicus* from rhizomes outside of the plots occurred, but growth was inhibited; and there was no colonisation of the plots by seedlings of any species during the 17 month study (Clarke & Ward 1993). Initial mortality of gastropods in the plots was also high, however migrations of gastropods from surrounding unaffected areas led to a recovery of gastropod density within a few months (Clarke & Ward 1993).

Marine Vertebrates

Impacts to mobile species such as fish, sharks and marine mammals are most likely to occur due to the flow-on effects of impacts to their habitat and food sources. However, direct contact with oil can result in direct impacts to the animal, due to toxic effects if ingested, damage to lungs when inhaled at the surface, and damage to the skin and associated functions such as thermoregulation (AMSA 2010). For example, waterbirds are particularly susceptible to impacts from oil spills, as if the birds come into contact with the oil, the hydrophobic nature of hydrocarbons can cause reduced waterproofing in waterbird plumage, insulation and buoyancy of the plumage if the animal comes into direct contact with spilt fuel (Wiese et al. 2001). This may cause death due to hypothermia, starvation or exhaustion (Wiese et al. 2001). Toxicity associated with principally the aromatic components may also contribute to morbidity and mortality (AMSA 2000).

Oil Spill Response and Recovery

In general, oil spills that occur in close proximity to infrastructure, such as ports with response equipment, are usually rapidly contained using equipment such as floating containment booms, and often have little environmental impact. Queensland's largest oil spill provides a good example of how the proximity of a spill to infrastructure can aid containment and prevent major environmental damage. When the Santos pipeline ruptured in Lytton near the mouth of the Brisbane River, releasing 1 900 t of light crude oil, all oil was contained within drainage channels and reclaimed riverside land and prevented from entering the Brisbane River and Moreton Bay: ecological impacts were limited to a minor fish kill and some mangrove dieback (AMSA 2004). Other oil spills, which have occurred within Australian Ports and were rapidly contained or dispersed include, the *Al Qurain*, which discharged 184 t of fuel oil in Portland Victoria, the *Laura D'Amato*, which spilt 300 t of light crude oil in Sydney Harbour and the *Korean Star*, which released 600 t of fuel oil within the Port limits of Canarvon, WA (AMSA 2005). In the case of the *Laura D'Amato*, a rapid reaction by the Sydney Ports Corporation and Shell terminal staff had the vessel surrounded within 20 minutes after the event, minimising the spread of oil and preventing major environmental harm (AMSA 2005). Cleanup activities were able to recover 90 percent of the oil that was not lost with evaporation.

It should be noted that severe weather conditions can significantly hinder the response to an oil spill in coastal waters. Strong winds and currents act together to disperse oil and limit the effectiveness of containment booms and scoops. This was the situation during the *Era* pollution incident in Port Bonython, South Australia. Strong winds and tidal currents at the time prevented containment of the 300 t of discharged bunker fuel and caused the oil to drift into mangrove communities (AMSA 2005). Approximately 75 – 100 ha of mangrove habitat were oiled. The oil was left to degrade naturally in mangroves, which led to the death or defoliation of approximately 2.3 hectares of grey mangrove, loss of intertidal seagrass and significant loss of birdlife (Duke & Burns 1999; AMSA 2005).

Natural cleaning (removal of oil from the water surface through natural dispersion and biodegradation) timescales for open water range from half a day for light, volatile oils such as kerosene, to seven days or more for heavy fuel oils (Baker 1999; Nicodem et al. 1997). Oil removal by wave action is thought to be effective on exposed rocky shores and headlands (Kingston 2002), and manual clean up may not be necessary in these environments (Gundlach & Hayes 1978). For low molecular weight volatile components, evaporation or desorption from water followed by photooxidation in the air is thought to be the dominant process (Mantoura et al., cited in Nicodem et al. 1997). Non-volatile components are removed by both microbial consumption and photochemical degradation, which is of particular importance where nutrient availability limits microbial activity (Ehrhardt et al. 1992; Bongiovanni et al. 1989, both cited in Nicodem et al. 1997). Some residual organic matter supports microbial growth, aiding biodegradation (Nicodem et al. 1997). A lag of 1 – 2 months is typical before seeing the onset of microbial degradation (Burns et al. 2000).

Shoreline sediments are capable of retaining oil contaminants for the greatest period of time, from several months to over 20 years (Baker 1999; Burns et al. 1994). Visible oil may disappear long before sediments are depleted of toxic hydrocarbons (Boehm et al. 1987; Burns & Yelle 1992). Once incorporated into the sediment, the degradation of oil is significantly slowed (Boehm et al. 1987; Struck et al. 1993, both cited in Nicodem et al. 1997). Anaerobic conditions (as provided by the sediments the airport drain system) further slow the degradation process (Oudot & Dutrieux 1989; Swannell et al. 1995, both cited in Burns et al. 2000; Burns et al. 1999). Research has shown that wave action, together with fine particles that adhere to stranded oil, provides an effective 'natural' cleaning action which can be accelerated through relocating oiled sediments into the wave-action zone (Owens 1999).

Manual clean-up of oil is a good option for removal of oil from sandy beaches (Gundlach & Hayes 1978). However caution should be taken to wait until all of the oil is on the beach; to not repeated drive over the oiled areas, and to only remove the minimum amount of sand required (Gundlach & Hayes 1978).

Several chemical dispersants have been proven effective on heavy fuel oils, diesel and lubricating oil (in temperatures > 24°C) (AMSA 2004). Dispersants accelerate the weathering and biological breakdown of oil, and have also been used successfully in cleaning shorelines (e.g. Edgar & Barrett 2000).

Flushing can also contribute to the significant diminution of remnant oil concentrations. Trials on crude and bunker oils revealed that higher molecular weight components were most resistant: alkanes were more than 50% degraded after 13 months, whilst the more toxic (Nicodem et al. 1997) aromatics (such as xylene) were approximately 30% degraded after this period (Duke & Burns 1999).

Ecological Impacts of the *Pacific Adventurer* Spill in Moreton Bay

The Clean Up Response

Dispersants were available for use to attempt to disperse the oil at sea before it reached the coastline. However, this was not done due to the adverse weather conditions at the time, a decision that was supported in an independent review of the incident (Raaymakers 2009b).

Once the spill reached the coast, the clean-up strategy was mostly straight-forward, as cleaning an oil spill from sandy beaches (as was predominantly the case in this incident) is relatively simple when compared to cleaning oil from coral reefs or mangroves (TMS Consulting 2009). In this case, low-impact manual clean up methods were used to remove the oiled sand and dispose of it in a managed oily waste stream set-up on the Island. Management of this process was assessed to have been in accordance with current best practice (Raaymakers 2009a).

It was decided to leave oil deposited on the rocky shore to naturally disperse and degrade over time due to wave action and breakdown, due to the low biodiversity noted on unimpated areas of the rocky shoreline, and due to health and safety issues associated with this high-energy environment. However, cleaning trials were done on the rocky shores of Honeymoon Bay, though this was based on social and amenity factors rather than ecological ones (Raaymakers 2009a; NERG 2009).

However, the following were identified as areas where management of the clean-up could have been improved:

- Clean-up priorities were focused on high visibility areas (beaches), which may have been driven by media reporting and public opinion (TMS Consulting 2009). In contrast, very high clean-up priority should have been given to Spitfire and Eagers creeks and their associated wetlands (Raaymakers 2009a). Clean-up trials of the wetlands subsequently began in these wetlands.
- There was urgency around the cleanup (in response to media reports of inaction) that did not align with accepted practice (TMS Consulting 2009), which recommends that clean-up is not started until all of the oil has reached the beach, to minimise disturbance (Gundlach & Hayes 1978). This resulted in re-cleaning some areas of beach as more oil was deposited.

Ecological Impacts and Recovery… Or Ongoing Impact?

At face value, the clean-up of the spill appeared to be a success. Beaches on the Sunshine Coast and Bribie Island were declared clean on 28 April 2009, and beaches on Moreton Island were declared clean in May 2009 (NERG 2009). Cleaning trials continued at the affected wetlands and rocky headlands on Moreton Island after this date.

That is, after the clean-up, there was little visible sign of any ongoing impact. In addition, impacts from the oiling of seabirds and other wildlife appeared to have been relatively minimal (Raaymakers 2009a).

A Scientific Advisory Panel (SAP) was established to provide support and advice to DERM during the assessment and recovery phases of the spill, and initial impact assessments were completed for the impacted habitats (NERG 2009). However, it is difficult to find any published information regarding the nature of: the initial ecological impacts found in the short-term at each of the affected coastal habitats; ongoing monitoring works being completed; or the progress of recovery of ecological ecosystems.

Impacts to Sandy Beach Communities on Moreton Island

Andrew Holzheimer of undertook a study into the impact and subsequent recovery of benthic invertebrate communities on the affected sandy beaches of Moreton Island for his Honours thesis at the University of the Sunshine Coast. Six heavily affected sites on the eastern beaches of Moreton Island were studied, along with six comparative sites outside of the spill areas to the north and south of Moreton Island. The beaches were sampled twice: one week after the oil spill (18 - 27 March 2009) and three months post the spill (19 – 28 June 2009). Replicate samples were collected from three zones (lower, middle and upper shore) at each site for analysis of benthic infauna communities, particle size distribution and oil content in the sand (Holzheimer 2009).

Concentrations of heavy fuel oil in the sediment were highest at the sites closest to Cape Moreton, with mean values of up to 1.03 ± 0.38 mg/g. Interestingly, sites closer to the southern tip of Moreton Island had mean concentrations of heavy fuel oil of up to 0.04 ± 0.01 mg/g one week after the spill (in contrast, no oil was detected in the sediments of the comparative beaches), even though they had been assessed as “oil-free” by Maritime Safety Queensland (Holzheimer 2009). Most oil was found above the drift line on the middle and upper shore. No heavy fuel oil was detected in any sediment samples three months post the spill.

Benthic invertebrate communities on the lower shore of beaches impacted by heavy fuel oil had significantly lower total abundance, species density and species diversity, and corresponding distinct shifts in assemblage structure, compared to beaches that were free from oil contamination. One week after the spill, abundance and species density were approximately one-third of that at the comparative sites. In contrast, the mid and upper shore levels demonstrated little detectable biological change (Holzheimer 2009).

Abundance was lower at all sites during the winter sampling event (three months after the spill), presumably due to seasonal factors. However there was no reduction in the size of the contrast between impact and comparative sites on the lower shore, despite no hydrocarbons being detected in the sediment of any beaches, indicating a lack of recovery in the short term (Holzheimer 2009). In fact, the difference in the abundance and diversity of benthic fauna at impacted sites compared with the unimpacted sites was greater in June 2009 than it was immediately after the spill (Holzheimer 2009).

The effect of the heavy fuel oil on benthic invertebrate communities on the lower shore is in marked contrast with the observed distribution of the majority of visible oil and oil residues: these were seen mainly above the drift line, having been deposited high on the beach due to heavy weather and high tides at the time of the incident (Holzheimer 2009). This is the material that was removed in the manual cleanup operations. This visible oil was likely to have already been weathered and was likely less toxic due to the evaporation of the volatile components (Kaplan et al. 1996; Lee & Page 1997; Kingston 2002). Invertebrates living on the middle and upper shore can actively burrow or escape from contaminated areas providing that they have not been asphyxiated by oil (Holzheimer 2009).

Holzheimer (2009) suggests that when the oil made contact with the shoreline, it was likely to have been less weathered and more toxic (Kaplan et al. 1996; Lee & Page 1997; Kingston 2002). These toxic compounds could have suspended in the water column and impacted the fauna on the lower shore and swash zone directly (Holzheimer 2009). Toxic compounds could have also percolated through the sand into the underlying water table, resulting in a release of toxic compounds at the lower shore near the effluent line, where the greatest biological impacts were detected (Holzheimer 2009). These fractions are highly mobile, not visibly obvious, and not amenable to manual removal (Holzheimer 2009). Organisms that live on the lower shore and in the swash zone are not as mobile as those on the upper shore, and are unable to escape from toxic compounds that are suspended in the water (Holzheimer 2009).

Further sampling to determine whether the communities have recovered since the June 2009 surveys has not been undertaken to our knowledge. Impacts of the Prestige spill on sandy beaches were still detected after 8 months (de la Huz et al. 2005).

Conclusions and Lessons Learnt

- Prioritisation of areas for clean-up should be based on the sensitivity of each ecosystem to impacts from spilt oil; in this case clean-up of Spitfire and Eagers creeks and associated wetlands should have been a very high priority (Raaymakers 2009a).
- Beaches at the southern end of Moreton Island, which were initially assessed as 'oil-free' by Maritime Safety Queensland, were in fact contaminated with heavy fuel oil, albeit in smaller quantities when compared to the beaches further north (Holzheimer 2009). This illustrates the importance of collecting sediment/water samples rather than relying on visual inspection alone to determine the contamination status of an area (Holzheimer 2009).
- Rigorous scientific studies into the impact of such events, including monitoring of ongoing impacts and recovery is required. Public perceptions were that there is no longer a biological impact on the eastern beach of Moreton Island simply because surface oil is no longer visible. In contrast, studies by Holzheimer (2009) found that there was a delayed and persistent toxic effect of the oil on sandy beach invertebrates on the lower shore, with no recovery within a three month timeframe. The design of such studies must be tailored to the impact being monitored.
- The impacts of small and medium oil spills in tropical and subtropical environments are relatively poorly studied, and are biased towards studies of large spills. The results of impact assessments and ongoing monitoring of the Pacific Adventurer spill could be used to gain insight into the best management measures for future incidents. For example, clean-up activities on the sandy beaches of Moreton Island focussed on the visible oil on the upper shore, yet impacts were seen on the lower shore (Holzheimer 2009). How could this impact be minimised in the future? Does this highlight the importance of using dispersants at sea to minimise the amount of oil reaching the coast where conditions allow?

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