PTE 518 Lecture Note 3

Impact of Oil Spill on The Ecology/Eco-System:

The marine environment is a dynamic and diverse network of habitats and species, interwoven by complex physical and ecological processes that interact with humans and their activities at many levels. Marine habitats and their associated communities are often grouped into eco-systems e.g the open ocean, deep-sea, coral reefs, salt marshes, rocky shores etc. Although they are all connected and impacts on one eco-system can affect others. Eco-system structure and function are important features when assessing impacts. The many benefits that humans receive from these habitats and communities are referred to as eco-system services. The more obvious of these are the fish, shellfish, snails, and other foods that we consume and the aesthetic or recreational benefits that we derive from the sea. Additionally, many coastal communities have strong cultural and spiritual ties to the sea. However, there are many other less obvious services.

The marine plankton of the vast areas of open oceans plays a major role in the maintenance of our atmosphere by transferring carbon to the deepsea. The open oceans and deep sea are also home to many of the fish that we catch for food. However, abundance and productivity increase greatly in shallower waters and closer to coastal areas. Coastal wetlands and some shallow water eco-systems including salt-marshes, mangroves, kelp forests and sea grass beds are particularly productive, providing much of the material that feeds neighbouring shallow water eco-system.

Figure 1: Typical Marine Environment and the Potential Benefits

They also provide food and shelter for young fish and many other species; protect our coasts from storms and flooding and capture sediments and organic wastes that runs off the land. Mangroves and coral reefs also provide building materials, while new pharmaceutical products are increasingly being developed from the enormous diversity of marine species.

Biodiversity (i.e the variety of life) is in itself a valuable feature of these ecosystems as it increases the complexity of the food chains and other ecological processes, which in turn increases their resilience to natural and anthropogenic impacts. Most marine food chains include a range of primary producers (i.e plants and algae, including phytoplankton that take their energy from sunlight or organisms that use chemical energy in deep sea vents), bacteria feeding (primarily feeding on dissolved organic carbon), herbivores (zooplankton, seabed invertebrates and some fish), carnivores, scavengers and parasites (a wide range of animals and decomposers (particularly bacteria and fungi). Biodiversity and other ecosystem services are reflected in the national and international regulatory regimes that recognize the need for conservation and protection of important habitats and species. This includes the designation of protected areas.

Mineral oils (i.e petroleum) derive from plant material and animals that originated millions of years ago and have been modified over time by heat and pressure underground. In many locations, these underground reservoirs of oil are connected to the surface by geological features such as faults or salt domes and in some areas natural seeps occur through the seabed. These naturally occurring oil seeps have been present in the world's ocean for millions of years and marine organisms have evolved to develop molecular mechanisms which enable them to biodegrade and detoxify these substances and incorporate them into the food chain. Natural background levels of petrogenic hydrocarbons exist in seawater and seabed sediments and are greater in some areas than others depending on the prevalence of oil seeps. Since the industrial revolution, these natural levels have been added to by aerial emissions, land run-off and inputs from marine transport.

Large oil spills are rare, but can result in significant and long term adverse impacts. The scale of spill impact can range from minimal e.g following spill of lighter oil on Open Ocean with little or no effect lasting few hours to few days as compared to spill of heavy oil on sheltered wetlands with long term effects. Larger spills have the potential to cause greater damage than smaller ones, but the level of impact varies considerably depending on the oil and incident type, local conditions such as season, weather and location and resources present.

With the challenges of pipeline vandalization in the Niger-Delta and the vandalization of other associated oil facilities, oil spill management in Nigeria is a critical issue. It is also important to note that with the development of oil exploration in the polar and deepwater environment, comes a number of challenges to oil spill response and science. Plants and animals in cold water eco-system tend to be longer lived and slower growing than those from warmer climates and the rates of many biological processes is relatively slow. Persistence of oil, a major factor in oil recovery, may also increase with higher latitudes. It is therefore often assumed that recovery from oil spill will take longer, but this depends on many other factors. Studies have shown that microbes present in cold water eco-system can degrade oil rapidly when no other limiting conditions are present.

Oil spill response efforts are designed variously, to remove all contamination, enhance it’s biodegradation and prevent it reaching the more sensitive parts of the eco system but can cause further damage to the environment. In some situations, there is need to consider trade-offs and assess the net environmental benefit of response option. Science underpins environmental risk operations and management of operations including oil spill response decisions. Our knowledge is based on a large body of evidence from studies of past spill and experimental research.

Oil in the Marine Environment:

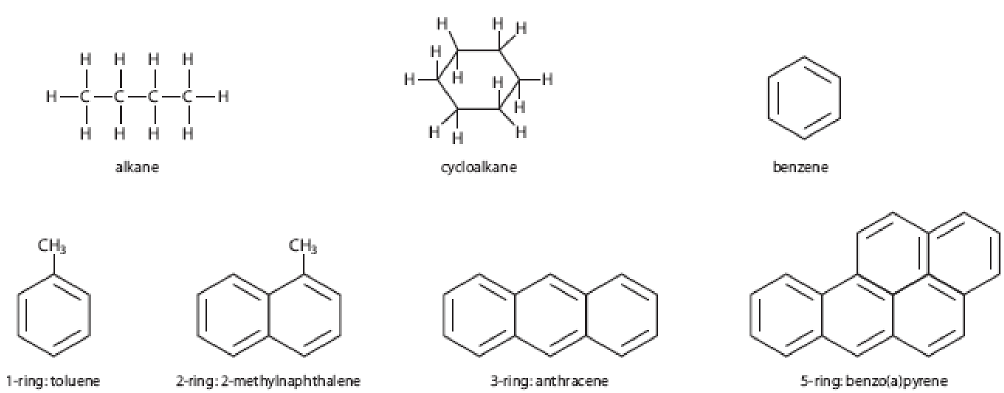
Composition and Characteristics of Oil:

Crude oils are complex mixtures of hydrocarbon with small amounts of compounds such as benzene, toluene, ethylbenzene and xylene (BTEX compounds) especially for Aromatic Hydrocarbons. Crude oils also contain complex elements like sulphur and other trace elements. Refined products from gasoline to bitumen are also composed of mainly hydrocarbon and are produced from crude oil through various refining process to achieve the desired chemical and physical characteristics.

Hydrocarbons can be classified into many different groups based on their chemical structure, but the characteristics that are most relevant to their fate are their molecular weight and boiling points (usually closely related), and their water solubility and bioavailability (also closely related). The compounds with the lowest molecular weight usually have the lowest boiling point and are volatile at low environmental temperatures. Many of these compounds may display acute toxicity, but on the surface of the sea or shore they evaporate so quickly that their contribution to marine impacts is generally small. If released into deep water they have a greater contribution to toxicity, though these low molecular-weight compounds generally biodegrade rapidly. At the other end of the scale, high molecular weight hydrocarbons (e.g asphaltene a major component of bitumen) have a high boiling point, are resistant to biodegradation and are very persistent. They may also be chronically toxic but usually much less biologically available due mainly to their very low solubility in water. Between these two extremes are a wide range of hydrocarbons many of which has the capacity to cause biological impacts.

Assessing the toxicity of hydrocarbon compounds is not straight forward and is influenced by many factors. However, aromatic hydrocarbons particularly PAHs (Polycyclic Aromatic Hydrocarbons) tend to have greater toxicity than other hydrocarbon groups. Their concentrations as (total PAH or individual PAH compounds) are often analysed and monitored in water or sediments as an indicator of toxic contamination. Many low molecular weight aromatics have relatively high water solubility and therefore biological availability, but also low persistence. These can be responsible for most of the narcotic effects that cause acute impacts. Of greater concern are some of the middle molecular weight PAHs that are less soluble but more persistent and so highly toxic that the small amount that become biologically available have the potential to cause longer term chronic impact. Even high molecular weight aromatic compounds such as asphaltenes could cause some chronic effects in an organism if it is closely associated with some tar residue for long enough.

PAHs can enter the marine environment through a number of sources, not just from oil spills. Atmospheric deposition of particles derived from the incomplete combustion of coal, oil and many other materials results in significant inputs of pyrogenic PAHs to natural eco-systems. The properties of a whole oil are a function of its constituent compounds. The key physical properties are density or (specific gravity), viscosity, pour point (The temperature above which it will pour) and the key chemical properties are the aromatic, wax and asphaltene content. Light oil products have low density and viscosity and often high aromatic content, so are often acutely toxic but unlikely to be persistent in most environments. Heavy crudes and fuel oil have a relatively high density and viscosity and are much more likely to be persistent and can still be toxic depending on their composition. These key properties are likely to change, once an oil has been spilled



.

Figure 2: Examples of the Chemical Compounds in Crude Oil

Key terminologies related to toxicology are presented in the section below. However, it is important to note that the main environmental effects from oil spills are typically due to the physical coating or smothering of plants and animals, particularly on shoreline habitats rather than through the oil's toxicity.

Toxicology (Key terminologies):

Vulnerability and sensitivity to oil: Vulnerability describes the likelihood that a resource will be exposed to oil. Sensitivity assumes that the resource is exposed to the oil and describes the relative effect of that exposure. Hence a deepwater coral may be sensitive but not vulnerable to a surface oil spill, while a rocky shore seaweed may be vulnerable but not sensitive.

Toxicity: Toxicity is the potential of a material to have adverse effects on living organisms, aquatic toxicity is the effect of chemicals on aquatic organisms. Since any substance has the potential to be toxic, the specific organism and it's exposure to the substance should always be considered.

Exposure: Exposure is the combination of the duration of exposure to the chemical and the concentration of the chemical.

Exposure Route: Exposure route is the way the organism is exposed to the substance including ingestion, directly or in the food) absorption through the gills or contact with the skin. The magnitude of a toxic effect depends on the sensitivity of an organism to the chemicals.

Acute and Chronic Toxicity: Acute toxicity involves harmful effects in an organism through a single or short-term exposure. Chronic toxicity is the ability of a substance or mixture of substances to have harmful effect over an extended period, usually upon repeated and continuous exposure.

Bioavailability: Bioavailability is the extent to which a chemical is available for uptake into an organism. With respect to oil spill, it is usually closely related to both the display of toxicity and rate of bio-degradation.

Bioaccumulation: Bioaccumulation occurs when an organism absorbs a toxic substance into its tissues at a rate greater than that at which the substance is lost.

The fate of oil – Occurrence of spill:

As soon as oil is spilled into the marine environment, it becomes subject to a number of natural processes known as "weathering", that quickly and progressively change its characteristics and distributes it within the environment. The importance of each process on the fate of oil depends on the environment where the spill occurred.

Oil Weathering Process:

Evaporation: Most fresh oils contain a proportion of low molecular weight hydrocarbon that have a low boiling point (e.g alkanes with less < 12 carbon atoms and BTEX compounds). When released on the sea or shore, evaporation of these hydrocarbons on the sea or shore will begin immediately into the atmosphere, influenced by ambient temperature and air movement. This process progressively influences the viscosity of the spilled oil, but also reduces the volume and acute toxicity of the remaining oil. If the oil remains at the surface for many hours or days, this weathering process can leave a sticky residue. The proportion of oil can vary from almost none to almost all of the oil originally spilled. For instance, 10 gallons of oil spilled in a tropical sea can evaporate within 3 hrs on a calm summer day with sea temperature at (25^0C). While it will take about 6 hours for similar 10 gallons of oil to evaporate from an artic sea of 5^0C. It is also important to note that in the same condition, heavy oil would loose only about 15% or 20% of its volume, in four (4) days.

Spreading and Movement: If oil is spilled onto the sea surface, it will spread even without any movement due to tides or wind. The rate of spread depends on the oil's pour point or viscosity: light oils will spread very quickly at any sea temperature, but heavy oil will spread very slowly and remain thicker over a longer range of period, particularly in colder seas, where this can also reduce the rate of dispersion. Any surface life or animals that need to come to the surface to breathe will be vulnerable to an oil slick and the wind and direction of the tides will influence how far and wide the slick may spread. As most oil spread and move they also rapidly start to fragment, resulting to patchiness and formation of numerous slicks. The oil thickness often becomes very uneven, with scattered areas of thicker oil, separated by large area of very thin oil (sheen) or clear water.

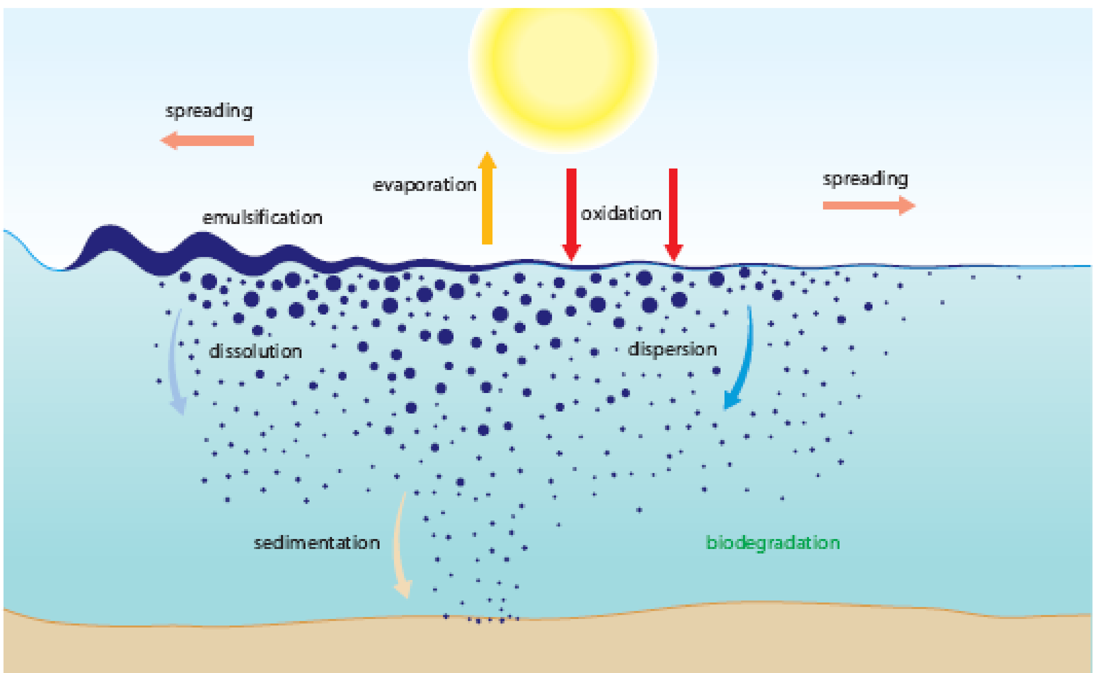


Figure 3: Oil Weathering Process

Dissolution:

While most of the hydrocarbons have such low solubility in water (including seawater) that we can define them as insoluble. Some of the hydrocarbons, especially the aromatic hydrocarbons like Benzene, Toluene are relatively soluble in sea water and hence dissolve in water during oil spill depending on the composition of the oil and the viscosity. This water soluble fraction has a disproportionate impact on marine organisms being more bioavailable than other hydrocarbon and often more acutely toxic. High concentrations of these hydrocarbons are generally limited to the water in the immediate vicinity of the spilled oil and rapid dilution occurs both vertically and laterally. Biodegradation of water soluble hydrocarbons is generally rapid. In Figure 4, a photograph of the effect of dissolution of oil is shown from the case of oil spill during the 1991 Gulf war being spread by wind and tide towards South of Kuwait.

Figure 4: Photo showing oil from 1991 Gulf War Oil Spill Spreading South from Kuwait Under wind and tide effect

Dispersion:

Wave action or other agitation of the oil on (or in) the water will result in the formation of oil droplets that become mixed into the water column; the greater the agitation, the greater the mixing potential. The majority of oil from most spills, whether spilled onto the sea surface, released subsea or deposited onto the shoreline, is eventually dispersed. Larger droplets mixed into the water-column quickly re-surface, but small droplets are less buoyant and do not re-surface; they are mixed horizontally and vertically in the water column. The extent and depth of mixing depends on wave action and water currents. This process can potentially lead to subsurface marine life being exposed to contamination. However, as with the dissolved hydrocarbons, the concentrations of dispersed oil are highest in the immediate vicinity of the release, be it a surface slick or sub-surface rising plume, and reduce rapidly as the oil is dispersed further away from the source. In the case of surface slicks, the buoyancy of the oil droplets means that vertical mixing into deeper water is slower than lateral mixing, and elevated concentrations are generally limited to the upper few metres. Dispersed oil droplets have a large surface and this facilitates biodegradation by microbes. The effectiveness of oil droplet biodegradation is a key benefit of using chemical dispersants to enhance the natural dispersion process.

Emulsification:

Larger droplets of dispersed oil will quickly re-surface and can trap seawater droplets within the surface slick to form a water-in-oil emulsion. Most oils will therefore progressively incorporate water when they are mixed in turbulent conditions (i.e in moderate or rough seas). The greater the mixing effect, the more water is incorporated into the emulsion, hence the emulsion increases; in some circumstances the volume of a water-in-oil emulsion can be up to five times greater than the volume of oil originally spilled.

Emulsions may be stable or unstable, and can have very different physical characteristics to their parent oil. Stable emulsions typically have high water content (sometimes greater than 70%) and are usually highly viscous. They can remain stable for several weeks, and are colloquially referred to as “chocolate mousse” or sometimes just “mouse” due to their consistency and typically reddish-brown colour. The formation of stable mousse can greatly reduce the rate of dispersion and other weathering processes. In calm, warm conditions, e.g after landing on a beach, a mousse may breakdown to its constituent oil and water, but some emulsions are highly persistent.

Sedimentation:

The fate and effects of dispersed oil are greatly influenced by the amount of suspended solids (fine sediments and other particles) present in the water column. Dispersed oil droplets can bind to suspended solids and change their physical characteristics. Chemically-dispersed droplets may be less likely to bind than physically-dispersed droplets until the dispersant is biodegraded. Deposition of these suspended solids to the seabed can occur, where they may be incorporated into muddy seabed areas with active sedimentation or more widely distributed as a loose aggregation (floc) of oiled particles, or a combination of both. In worst-case situations, where concentrations of oil droplets and suspended sediments are both high, heavy deposition of contaminated particles could result in severely oiled seabed sediments where they may persist for years and potentially have long-term effects. A notable example occurred in two estuaries on the north-west coast of France following the 1978 Amoco Cadiz oil spill. Fortunately, such conditions are unusual and most dispersed oil is more widely distributed and biodegraded before it can become incorporated into seabed sediments. However, the presence of loose flocs of oiled particles (i.e flocculent material formed by aggregation of suspended oil and sediment particles) can result in filter-feeding animals on the seabed being exposed to elevated concentrations of hydrocarbons.

Sinking:

Sinking is often discussed along with sedimentation, but from an ecological perspective it is very different because it does not produce plumes or flocs of oiled particles. Sinking occurs if the spilled oil is denser than seawater, and can result in very persistent accumulations that lie on the seabed and sometimes become buried. The impacted area of seabed is typically smaller than that affected by sedimentation of dispersed oil, but sunken oil can cause long term smothering and loss of habitat. Not many oils are this dense even after much weathering. However a few dense oils, can weather to a high density and sink in some circumstances. For instance, wind-blown sand can sometimes be deposited on floating oil causing it to sink, and layers of fresh water on the sea surface near rivers or ice floes can reduce the density of seawater, again allowing the oil to sink. Burnt residues of oil can be heavier than seawater and therefore prone to sinking. While such circumstances are not commonplace, spilled oil often comes ashore on sand beaches and mixes with sand in the surf zone, resulting in the formation of tar balls and tar mats that can sink in the shallow subtidal zone just off the beach.

Figure 5: Instance of Sinking on the Shores of Louisiana during Macondo well incident

Shoreline stranding:

Sinking process described earlier progressively reduce the quantity of oil in a surface slick, so it is possible for an offshore oil spill to result in no oil, or only small amounts of oil, reaching the shore. However, most moderate or large spills result in at least some shoreline oiling, which may then impact the full range of habitats and species present below the high tide level, sometimes above it.

Natural physical and chemical processes will continue to weather the oil and gradually remove it, but the speed of removal varies greatly and depends on a range of factors. Persistence will be greater in places that are sheltered from wave action and water movement, but only small amounts of wave action are required to remove oil. Residues that remain for more than a year or two are generally only found in very sheltered situations or locations where it has been deeply buried.

Photo-oxidation:

Hydrocarbons exposed to ultraviolet (UV) light can be photochemically oxidized to form other compounds. This is often a minor component of the weathering process but PAHs are particularly sensitive. Laboratory studies of some compounds have found that the resulting products can be more toxic than the parent compounds, largely because they are more soluble in water. This increased bioavailability also increases their potential for biodegradation. The extent to which UV light has any effect on whole oils and on overall toxicity in the natural environment is the subject of ongoing investigations.

Biodegradation:

Marine bacteria have evolved to produce enzymes that allow them to utilize hydrocarbons from crude oil as food source. By metabolizing hydrocarbons they grow and multiply, and in turn become a food source for other organisms. It is through this natural process that the majority of the oil from a spill is ultimately biodegraded, and the energy and materials contained within it are returned to the food chain. Degradation requires adequate oxygen, nutrients and trace elements and its rate is primarily dependent on the ratio of surface area to volume of the oil, i.e finely dispersed droplets will degrade rapidly while a thick slick or a patch of oil on a shoreline will degrade slowly. Large hydrocarbon molecules are not readily biodegraded and can persist for many years; these include some PAHs that are potentially toxic but have extremely low solubility in water and therefore have very limited biological availiability. Some of the largest hydrocarbons such as asphaltenes (used for road asphalt), are so resistant to biodegradation that a patch of tar could remain for hundreds of years but is effectively inert. Bacteria that can degrade oil are present everywhere, though not always in large densities, so there can be a time lag before they have multiplied enough that their activity becomes appreciable. Biodegradation rates can be limited by the concentrations of available nutrients that the microbes require to multiply and grow. Lack of oxygen can also be a limiting factor in some situations, particularly within muddy sediments. Cold temperatures reduce the rate of biodegradation, but not necessarily to a great extent. Recent studies of deep water situations in the Gulf of Mexico show that the bacteria are adapted to the stable 5°C conditions and can degrade oil quickly if it is adequately dispersed.

Exposure to oil and mechanisms of effect:

It is important to note that spilled oil may be distributed into a number of different habitats and in different forms. In some rare severe situations, persistent heavy deposits on areas of shoreline or seabed can result in long term loss of natural habitat, but there are many other possible effects of oil exposure. Depending on where and how an organism lives, it may be exposed to the oil in a variety of ways and the mechanism of any effect can also vary. For animals and plants that live or spend time on the surface of the sea or shoreline, the greatest impacts are likely to be due to physical smothering, but they may also be exposed and impacted in other ways. For instance: air-breathing animals may inhale volatile hydrocarbons or ingest oil with their food or when preening; some animals and plants may absorb hydrocarbons through their skin or other surfaces; and many animals have sensitive mucous membranes that will react to direct oil exposure. In water column, dissolved hydrocarbons may be absorbed through gills or other exposed tissues, while dispersed droplets of oil may be captured and swallowed by filter feeding animals. Animals and plants that live on the surface of shallow seabed (epibiota) may also be exposed to dissolved and dispersed oil, but if oil becomes incorporated into the sediment it will become available to a much wider range of sediment-dwelling animals.

Factors that influence oil impacts:

It is clear that the impacts of an oil spill depend hugely on the circumstances. Spill volume is only one factor and not necessarily the most important. Oil source and type, wave action, water depth, the amount of sediment in the water, winds and tides, temperature and how close the spill is to the shore can make the difference between no detectable impact and a severe impact on many resources. The combination of these physical and chemical factors will also determine which habitats are exposed to the oil and in what form e.g a slick oil on the water surface, a cloud of oil droplets in the top few metres of the water column, a floc of oiled particles on the seabed, a plume of oil rising from a subsea release, a coating of oil on a shoreline.

It is a feature of the marine environment that many species tend to aggregate at physical interfaces between land and sea (coastlines), air and water (sea’s surface) or where ice meets water. Oil also tends to concentrate at these interfaces. If the oil reaches the shore, other environmental factors including wave action, slope, substratum type and presence of features that trap oil will also be important. Their influence on the persistence of oil on the shore will be one of the most important considerations for long-term impacts.

Seasonality: Most species go through seasonal stages in their behaviour or biology (e.g migrating, breeding and spawning), particularly in temperature and polar regions. These different stages can greatly affect how vulnerable they are to an oil spill. Seasonality often results in a particular species or life stage being concentrated in a particular area at a particular time of the year.

Lifestyle factors:

There are a number of biological traits that can make a species more or less able to recover quickly from oil spill. These include longevity (lifespan), reproductive strategy and capacity (particularly numbers of offspring), mobility/dispersal potential (e.g planktonic juveniles), growth rate, feeding method and geographic distribution. Hence, if spill impacts a population of species that is long lived, slow growing with very few offspring per year and restricted to a small area, recovery from even a modest impact may be slow. On the other hand, a population of a species with opposite traits is likely to recover quicker, even a large number of such species are killed by the oil.

Lifestyle factors:

Individual organisms, populations and even communities and ecosystems that are already stressed from another cause may be impacted particularly severely by an oil spill. This is the concept of "cumulative impact". Migrating seabirds, for example will be more sensitive to the effects of oiling if they have not recovered from severe weather during their journey. Multiple oil spills in the same location may also progressively reduce the conditions and resilience of communities and eco-system, resulting in longer-term impacts.

Control of Oil Spill

Forces Exerted on Boom:

The use of booms is one key strategy used to contain oil spill. This section of the lecture note considers how the force that acts on the boom in the case of oil spill can be computed. Further details on the use of boom technique to contain spill are contained in the reference paper also added to the course materials.

To estimate the approximate force (Kg) exerted on a boom with a sub-surface area A (m^2) by a current with a velocity (m/s) the following formula can be used:

$F = 100 \times A \times V^2$

Hence, the approximate force acting on a 100m length of boom with a 0.6m skirt (width), in a 0.25 m/s (0.5 knot) current would be:

$F = 100 \times (0.6 \times 100) \times (0.25)^2 = 375$ kg (force).

References:

1. Impact of marine spill on Marine Ecology – Good Practice Guideline for Incident Management and Emergency Response Personnel. (Accessed - 08/03/18).
2. Use of Booms in Oil Pollution Response – Technical Information Paper. (Accessed – 09/03/18)