The SEOS Project

Science Education through Earth Observation for High Schools

Tutorial 12: Marine Pollution

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Aims of the Tutorial

**Increase awareness** among high school students of the damage done by marine pollution, and what may be done by individuals and society to protect valuable marine environments.
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→ Focus on how remote sensing can help to detect and monitor marine pollution
Marine Pollution Quiz:
Which of these do you think are Marine Pollutants?
And which of them can be detected on a satellite image?

Click on an image to find out
Oil pollution

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Oil spilled at sea can seriously harm marine wildlife such as plankton, sea birds, sea mammals and plants.

Oil can be detected by radar sensors on satellites and with airborne laser sensors. On radar images areas with spilled oil turn out black.

The image below acquired 17 November 2002 shows a double-headed oil spill originating from the stricken Prestige tanker, lying 100 km off the Spanish coast. Image source: ESA

Photo: Partially sunk New Flame vessel in the Strait of Gibraltar in August 2008. David Parody / Marine Photobank
Marine Pollution Quiz:

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The waste heat from electrical generating stations is transferred to cooling water obtained from local water bodies such as a river, lake, or ocean. The water is subsequently returned to the water body with a temperature higher than the ambient water temperature. A thermal shock to aquatic organisms can be the result.

Water temperatures can be detected with space- or airborne thermal infrared sensors.

The image below shows a thermal plume of cooling water which was made visible by an airborne thermal sensor.

Image Source: Geomatics Group, Environment Agency, UK
Marine Pollution Quiz:

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Click on an image to find out
Phytoplankton can form harmful algal blooms that can clearly be detected in the visible bands of satellite images.

The image below shows a so called Red Tide off the Texas Coast in September 2000. Image source: NASA.
Topics of the Marine Pollution Tutorial

(Click on an image to enter a chapter)
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**Introduction**

**Where does marine pollution come from?**

Under the framework of international law, sources of marine pollution are the following:

- Land-based sources and activities,
- Shipping and other sea-based activities such as fishing and aquaculture,
- Dumping,
- Seabed activities, both near and offshore, and
- Atmospheric sources.

(UN Atlas of the Oceans)

Many spillages of harmful substances occur every day all over the world, when filling, emptying and cleaning tanks or pipes, or in the everyday running of factories, pipelines, or oil wells on land. These spills may result from technical failure, negligence, vandalism, accidents or armed conflict. Spillages may occur on the ocean directly into the sea or on land where they are washed into the rivers which eventually end up in the sea.

Many pollutants are discharged from stationary locations or fixed facilities. Examples for these so called **Point Sources** are discharges from the treatment of urban waste water, industry or fish farms.

Discharges from **wastewater treatment** plants and industry cause pollution by oxygen consuming substances, nutrients and hazardous substances. The adverse impacts depend very strongly upon the degree to which (if at all) such discharges are treated before reaching waterways.

Some large cities discharge their wastewater nearly untreated such as Athens, Barcelona, Brighton, Cork and Milan (UN Atlas of the Oceans).

Pollution from unspetific points of discharge is said to originate from offshore.

Exhausts from cars or industry enter the watercycle by evaporation and subsequent condensing with water vapour to form clouds. This **atmospheric discharge** returns to the Earth's surface with rain; either directly into the sea or via streams and rivers.

We can conclude that there are three main transport routes of pollutants into the sea:

1. directly (by release of effluents or by dumping)
2. via rivers (run-off, sewage)
3. via the atmosphere (dust depositon and rain)

Most of the pollutants (about 50-80%, depending on the study) originate from land! However, the major sources of coastal and marine pollution originating from the land vary from country to country.
Introduction

Why is marine pollution an issue?

What probably comes quickly to your mind are animals and plants that live in the oceans, people who live at the seaside or tourists who spend their holidays at the beach. It is obvious that they would be directly affected by polluted water.

And who is responsible?

On the last page you learned that marine pollution is not only caused by substances thrown or spilt directly into the sea.

We are thus responsible for the health of the oceans even if we don't go anywhere near the sea.

The consequences that marine pollution may have on the social and economic welfare of people can be quite serious:

- Increased risk to human health
- Increased cost of human health protection
- Loss of water supplies
- Increased clean up costs
- Loss of tourism or recreational values
- Loss in fisheries
- Loss of property value
- Potential for international conflicts
- Damage to equipment
- Endangerment of species
- Costs of litigation

Thus, marine pollution is a topic that concerns all of us. Although it is on the news mainly when catastrophes like big tanker accidents happen or mass mortality affects the beaches, marine pollution is an issue we should all care about. It is also small amounts of litter or other harmful substances that pollute the marine environment!
Introduction

Detection and monitoring of marine pollution using remote sensing techniques

The means of detecting and monitoring marine pollution very much depends on the type of pollution. The amount of pollutant and its characteristics determine the choice of platform and sensor(s).

Airplane or Satellite?

An obvious way to "take a picture" of the Earth from a distance is to mount a camera on an aircraft. Since planes fly at a relatively low altitude (just a few hundred meters to a few kilometres above the surface), the photographs or data may show many details.

For surveying aircraft to fly, the weather needs to be relatively good, strong winds would, for example, spoil the accuracy of the measurements.

Making pollution visible

Remote sensors work by detecting either of these properties of the sea surface:

- colour
- reflectance
- temperature
- roughness

A pollutant can be detected on the water surface when it modifies one or more of these properties. Oil, for example, dampens surface waves and can therefore be detected as a 'lower roughness' signal in comparison to the sea water around it.

Active and passive sensors

Active sensors send out electromagnetic waves in order to track pollutants in the sea. The signal is changed on the water surface and the reflected signal is detected by the sensor.

Depending on the type of sensor, active systems can be used at night and under 'bad weather' conditions. Radar-based systems can, for example, penetrate clouds and fog.

Passive sensors measure radiation that has been emitted or reflected from the sea surface or the pollutant respectively.

With the possible exception of Microwave Radiometers (which only give up in heavy rain), they are unable to penetrate cloud cover, fog, haze or rain. Their application consequently requires daylight clear skies and is therefore very limited (just imagine a severe oil spill catastrophe that can't be detected because there are clouds all over the image). If weather conditions are suitable optical images may however give valuable information about the extent of pollution.
The oil slick processes are responsible for the break up and dispersion of oil at sea in a chapter about oil weathering.

Directly after the spill, the fresh oil spreads out over the water surface, initially as a single slick. After a few hours, the slick will begin to break up and will then form narrow bands parallel to the wind direction (see photograph below).

![Recent spillage (a few hours old).](image1)

After a few hours up to 1 day, single slick fragments and thicker patches are increasingly noticeable compared to the thin layers which have a rainbow, sheen or metallic appearance.

![Appearance of an oil spill a few days after the spill: an oil slick approaching land, resulting from the Exxon Valdez Oil Spill in March 1989.](image2)

Subsequently, several days after the spill, the thinner films gradually disappear and eventually only patches or stripes of emulsion may remain, especially in a rough sea. Irisescences can however reappear later, even several weeks or months after the spillage, if the sea is very calm and the sun is warming up the spill.

![Irridescent of an oil slick visible on the water's surface above the sunken battleship USS Arizona (BB-39) in Pearl Harbor, Hawaii. The USS Arizona sank on 7th December 1941 after it had been hit by a Japanese](image3)
Weathering of oil on the water surface
- overview -

Oil spilled at sea undergoes a multitude of physical and chemical changes, some of which lead to the disappearance of oil from the sea surface whereas others promote its persistence. These changes are altogether called weathering processes. They may act simultaneously but they also change over time. The weathering processes determine the behaviour of the oil spill, its spread and thickness, as well as its future locations.

The figure below summarises the main processes that cause an oil to weather.

The speed and relative importance of the weathering processes depend on factors such as the quantity and type of oil, the prevailing weather and sea conditions, and whether the oil remains at sea or is washed ashore.

Oil spilt at sea undergoes the following weathering processes (click on a term if you want to learn more about the process):

Physical:
1. Spreading
2. Evaporation
3. Dispersion
4. Sinking/Sedimentation
5. Dissolution
6. Emulsification

Chemical:
7. Photo-Oxidation

Biological:
8. Biodegradation

Weathering of oil on the water surface.
Source: C. Klose after SINTEF
4. Sinking / Sedimentation

Most oils have a density less than that of sea water (see drop down box below). Therefore they don't tend to sink. However, sinking occurs due to the adhesion of particles of sediment or organic matter to the oil. Especially in shallow coastal waters solid particles, such as sand or algae, are abundant providing favourable conditions for sedimentation. Oil that has been washed on the shorelines often becomes mixed with sand. If this mixture is subsequently washed off the beach and back into the sea its density is large enough for it to sink.

Density of sea water and oil ↓

5. Dissolution

The rate and extent to which an oil dissolves in sea water depends upon its composition, spreading, water temperature, turbulence and degree of dispersion. The heavy components of crude oil are virtually insoluble in sea water whereas lighter compounds are slightly soluble. However these compounds are lost rapidly through evaporation. So dissolution does not make an important contribution to the oil left on the sea surface after a spill.

Dissolution of motor oil in water. In the left bottle the oil floats on the water. After approximately 5 minutes of shaking an emulsion has formed (see next page). The milky colour of the water indicates that parts of the oil have dissolved in the water.

Experiment and Photo: Matthias Zech
Oil spill response

While the volatile parts evaporate quickly, the remaining parts of the oil begin to spread and weather immediately after having been spilled.

The main objective of response to an oil spill is to reduce its impact on nature and human health and activities. The appropriate response measures largely depend on a detailed and continuous assessment of the spill conditions. That is the movement of the oil, the extent of the spill, its movement and predicted fate. The decision makers in such a case are assisted by a team of scientific, technical and financial advisory groups. Well trained, equipped and supported teams are mobilised to act on the scene.

The first response to be taken is to try and retain as much oil in the tanks of the vessel in distress as possible before it spills into the sea. For this purpose the vessel is stabilised and the remaining oil is pumped into another tanker.

Once released into the sea, the oil spill must be constantly monitored (see next page). Under normal circumstances (i.e. if the weather conditions allow it), this is done by helicopters.

Every effort is made to collect the oil as close as possible to the source of the spill. Once the spill starts to spread and the heavy parts sink, the oil is very difficult to remove.

If additional risks for humans and the environment can be ruled out or at least be reduced to a minimum, burning the pollutant may be another choice.

Sorbents or herding agents can assist in reducing the spreading and thinning of the oil film prior to its physical removal from the water surface.

Another option is the use of chemical dispersants. When the conditions for the use of dispersants are right, their application has proven to be effective and, on balance, ecologically acceptable (bearing in mind that the alternative might be an oiled beach). Dispersants can be applied by spraying boats and/or aircraft.

The further the spill spreads (due to influence of wind and currents), the thinner the film becomes. Once the film thickness reduces to less than about 1 mm, the physical removal of the oil becomes nearly impossible (see Figure). Once the film thickness is less than about 0.1 mm, the oil will usually be left untreated.
Airborne Maritime Oil Spill Surveillance

Many coastal states worldwide operate maritime surveillance aircraft to monitor their coastal zones. Among other official duties, their task is to prevent the coastal waters from illicit and accidental oil pollution. Taking the North Sea as an example, the estimated discharge of oil in the years from 1980 to 1990 was up to 50,000 tons per year. At that time, newspapers reported almost daily on oil spills that killed seabirds and polluted the beaches. Since then the amount of oil pollution at sea has decreased by more than 50%. This favourable trend has its roots in putting aircraft into operation that are equipped with instruments to detect and quantify oil at sea.

The performance of oil spill instruments is manyfold. Installed aboard aircraft, they can detect spills over distances of more than 20 km. Following spill detection, the type and quantity of substances on the sea surface is analysed at flight altitudes of 300 m, typically. This is the challenge of remote sensing!

Active and passive operation is another distinctive feature of remote sensing instruments. Passive sensors detect signals which are naturally available, e.g., sunlight reflected or thermal radiation emitted from a target. Examples are the multispectral scanner and the microwave radiometer. Active sensors provide their own source of radiation for target illumination and signal detection. Examples are the radar and the laserfluorosensor. Photocameras and video cameras which are also used to keep records of the scene on the ground can be either passive or active, depending on daylight or flashlight use for object illumination.


Source: Dornier Aerospace, Friedrichshafen, Germany, with modifications.

Until the late 1980ies, oil spill analysis was done with visual inspection. Indeed, an experienced oil spill expert has learned to distinguish thick oil layers and thin films on the water surface due to their specific colour appearance. However, quantitative information on the oil film thickness and on the type of oil can be obtained with remote sensing instruments only. Follow the links below to find out more about the instruments used in airborne oil spill monitoring:

- The side-looking airborne radar (SLAR)
- Thermal video and scanners (Thermal IR)
- The optical scanner (UV-VIS-NIR scanner)
Case Study: The Sea Empress Oil Spill

On 15th February 1996 the Sea Empress went aground at St. Anne’s Head near the entrance to Milford Haven in Pembrokeshire in Wales. Over the next 7 days 72,000 tonnes of light crude oil from the Forthies oil field in the North Sea leaked into the sea. The fuel tanks also sprang leak.

The Pembrokeshire coast is highly valued for its wildlife and outstanding natural beauty, and is popular with both tourists and locals. The time of year, the wind direction and effective clean-up at sea reduced the environmental impact, but there were never-the-less adverse effects on fisheries and tourism, as well as on wildlife. Overwintering birds feeding on the mudflats and at sea, were particularly badly affected.

Fate of the oil

About 40% of the light oil evaporated and was carried away by the wind. A further 28% was dispersed naturally by waves and currents. Mechanical recovery was hampered by the strong winds and recovered only about 1-2% of the oil. However, dispersant spraying from aircraft was very successful and resulted in about 24% of the oil being chemically dispersed. The remaining 5-7% of the oil reached the shore, and spread over a 200 km long shoreline. By then the 4.5 thousand tonnes of oil had been transformed into about 11-16 thousand tonnes of water-in-oil emulsion.
Scenario

Maritime surveillance aircraft are operated by many agencies responsible for monitoring of coastal waters in Europe. Oil spills detected during flight missions are reported to authorities for prosecution of polluters.

We are operators of oil spill detection instruments, underway aboard a surveillance aircraft ... 

A maritime surveillance aircraft.
Source: Federal Ministry of Transport, Germany.

... and we happen to detect two oil spills on the sea surface!

During overflight we take pictures with a downward looking photocamera installed aboard the aircraft. There is oil on the water surface which is a hazard for the environment!
directed to the water surface. Water is a good reflector of microwaves, so, waves on the water surface make it possible that part of the radar pulses are reflected back to the aircraft and detected with the SLAR antenna. Oil on the water surface dampens waves, so that a flat water surface reflects the pulses away from the aircraft, just like a mirror, and reflected radar pulses are not detected with the antenna.

A maritime surveillance aircraft with the long bar-shaped SLAR antenna fastened below the aircraft.
Source: Federal Ministry of Transport, Germany.

We are operators of oil spill detection instruments, underway aboard a surveillance aircraft and we have a close look at the image obtained with the SLAR on the screen of the mission computer. At once we observe the image below:

Image of the sea surface to the right of the aircraft, taken with the Side-looking Airborne Radar (SLAR). The aircraft track is parallel to the left edge of the image. Image dimensions on the sea surface are approx. 3000 m along track, 4000 m across track.
Source: The Archimedes 2 Experiment, Joint Research Centre, Ispra Establishment.
Harmful Algal Blooms

How remote sensing can help to detect and follow algal blooms

Monitoring and prediction of algal blooms in the marine environment has become more and more important in the recent years as they are increasingly perceived as a potential threat. Especially in the field of natural resource management and in the public health sector, reliable tools to detect and monitor Harmful Algal Bloom (HAB) events are needed so that mitigation actions can be effectively taken.

Measurements carried out from a research vessel, so-called in-situ (on the spot) data acquisition, is very useful for determining different algal species. However, when it comes to questions concerning the area and movement of an algal bloom, this method is not cost-effective.

Remote sensing thus plays a significant role in the detection, monitoring and prediction of algal blooms in the marine environment.

How does it work?

The main advantages of using remote sensing are a high spatial and temporal resolution, meaning that large areas of algal blooms can be studied and that their movement can be followed by looking at images captured at different times.

By comparing the two images below you can see how the chlorophyll concentration in the sea can change within just one week. The pseudo-coloured images show the relative chlorophyll content of the sea from blue and green (low) to red and yellow (high).

![Image of algal blooms](image)

In coastal areas larger proportions of inorganic matter are suspended and dissolved in the sea water. Here, another method is used that calculates chlorophyll using the red/near infrared ratio.

Remote sensing of algal blooms: requirements and limitation

Optical remote sensing can provide valuable (and beautiful!) images of algal blooms when a certain set of criteria is met. These are
**Harmful Algal Blooms**

**Case Study: Algae invade olympic sailing venue**

As Beijing prepared to host the 2008 Summer Olympics, the city of Qingdao, roughly 550 kilometers (340 miles) to the southeast, prepared its coastal waters for the games' sailing competitions. With the games looming just weeks away, Chinese officials and residents of Qingdao (also known as Tsingtao) struggled with a stubborn adversary: **ALGAE all along the coast!**

A local newspaper reported that on one weekend 11,000 college students had volunteered for **cleanup** duty over the weekend. Several companies had organised teams of employees to help.

In addition to removing algae from the coastal waters, local authorities set up **barriers** to keep the algae away from the sailing venue. One of the most important aspects of coping with the plague was however constant **monitoring**.

**Watching the bloom from space**

Growth and movement of the algal bloom were followed by a ship that sailed around the coastal waters off Qingdao.

The satellite images below show Qingdao and the Bay of Jiaozhou Wan at the beginning of the local cleanup effort. They were captured on 28th June 2008 by the **Moderate Resolution Imaging Spectroradiometer (MODIS)** on NASA's Aqua satellite.

**What happened?**

According to news reports, opinions differed on the cause of the larger-than-normal algal bloom, with some people citing increased rainfall and unusually warm waters in the Yellow Sea. Others blamed wastewater, industrial and agricultural pollution for providing excess nutrients on which the algae could thrive. Many coastal Chinese cities dump untreated sewage into the sea, and rivers and tributaries emptying into coastal waters are often contaminated with high levels of nitrates from agricultural and industrial runoff. These nitrates contribute to the algae that often bloom along sections of China’s coastline.
The most important event in the seasonal cycle in the ecosystem over much of the ocean is the spring bloom. The reproduction of many organisms is timed to coincide with this event and fluctuations between years in its timing may have profound consequences for components of the ecosystem other than phytoplankton.

There are two main factors limiting phytoplankton growth: illumination and nutrients. These factors can be influenced by various environmental conditions, such as temperature, salinity, and nutrients in the water column.

Regional differences

- **In high latitudes** (cold and windy), the winter minimum is more pronounced and the summer minimum is less pronounced.
- **In low latitudes** (warm and less windy), the winter minimum is less pronounced or absent and the summer minimum is more pronounced.

General development of algal blooms

The **duration** of an algal bloom can vary from a few days to more than a month, depending on the environmental conditions.

Its **spatial extent** may range from a few metres to tens of kilometres. During a bloom, one liter of water may contain millions of algae!