HENRY HUNTINGTON

POLFOTO (manipulated)

Komi

Exxon Valdez

Petroleum Hydrocarbons

In 1989, television carried scenes of oil-soaked birds and polluted beaches after the tanker *Exxon Valdez* ran aground off the south central coast of Alaska. This subarctic disaster gave an indication of what hydrocarbon pollution can do farther north in the Arctic. In 1994, more television pictures, this time from Usinsk in the Komi Republic of Russia, further turned the world's attention to the environmental impacts of oil development in the Arctic. In one of the largest oil spills ever on land, many thousands of cubic meters of crude oil poured from a ruptured pipeline. Oil from several leaks spread over the surrounding wetlands contributing to large-scale damage to the vegetation and wildlife of the area.

In spite of the concerns raised by the Komi spill, it remains difficult to determine how much damage it actually caused. The land surrounding the pipeline was severely contaminated long before the accident and before television crews started to document environmental damage from the spill. Russian pipelines are old, lack safety valves, and are plagued by constant leaks. Often, the oil is left flowing while repairs are made on a section of the pipe, because the lost oil costs less than putting in a bypass and because stopping the flow might cause the oil sitting in the pipeline to solidify. Accounts of the environment around Russian oil fields also speak of large contaminated areas where oily water and chemicals are stored in wetlands that periodically overflow to nearby river basins.

The Russian experience is not an inevitable result of oil exploitation in the Arctic. Other ventures show that it is possible to limit the environmental impact of most routine operations. But as the exploitation of the huge resources of oil and gas increases, so does the risk of serious accidents. Although more stringent regulation will reduce the frequency of accidents, incidents due to human error and technical deficiencies over recent decades have shown that regulation alone cannot completely prevent spills. Moreover, many features of the Arctic environment make it likely that spills here will have more severe consequences than spills elsewhere.

This chapter discusses risk scenarios for oil spills in marine as well as terrestrial environments, along with the environmental impact of routine releases of contaminants from oil and gas exploration. Special sections of the chapter are devoted to polycyclic aromatic hydrocarbons (PAHs). Of all the contaminants associated with petroleum production, these persistent organic pollutants present the greatest risk to environment and health. PAHs also have several other sources that contribute to their load in the environment.

Sources and levels

The main environmental concern about hydrocarbon pollution stems from the exploitation and transport of oil and gas resources, but operational discharges of oil from ships can also create local damage. Runoff from land, discharges in waste water, and atmospheric deposition contribute to the load on a regional scale. Natural oil seeps are another significant source. Operational discharges from offshore exploitation also contain dissolved oil components.

Oil exploration in the Arctic is expanding

The Arctic may contain some of the world's largest petroleum reserves. These resources are located both on land and on the continental shelves. The map on the opposite page shows some of the major oil and gas fields that are currently used for production and those where exploration activities are underway. The key areas with current production are Norman Wells on Canada's Mackenzie River, the Prudhoe Bay oilfield on Alaska's Beaufort Sea coast, the Nenets Autonomous Okrug and the Yamalo-Nenets Autonomous Okrug in Russia, and two fields on the Norwegian shelf. In addition, off-shore exploration activities are heading toward production in the Barents Sea, off the northwest coast of Russia, on the Norwegian shelf of the Barents Sea, off the west coast of Greenland, and on the North Slope of Alaska. See the table on this page.

Both exploration and production activities can be major sources of petroleum hydrocarbons to the Arctic environment. The environmental impact of routine operations depends to a large extent on practices for handling and transport of oil and gas and for discharging drill cuttings and produced water. Hydrocarbons are not the only concern. Operational discharges contain considerable amounts of other organic contaminants and heavy metals. The table on page 6 summarizes potential impacts from different phases of oil exploitation.

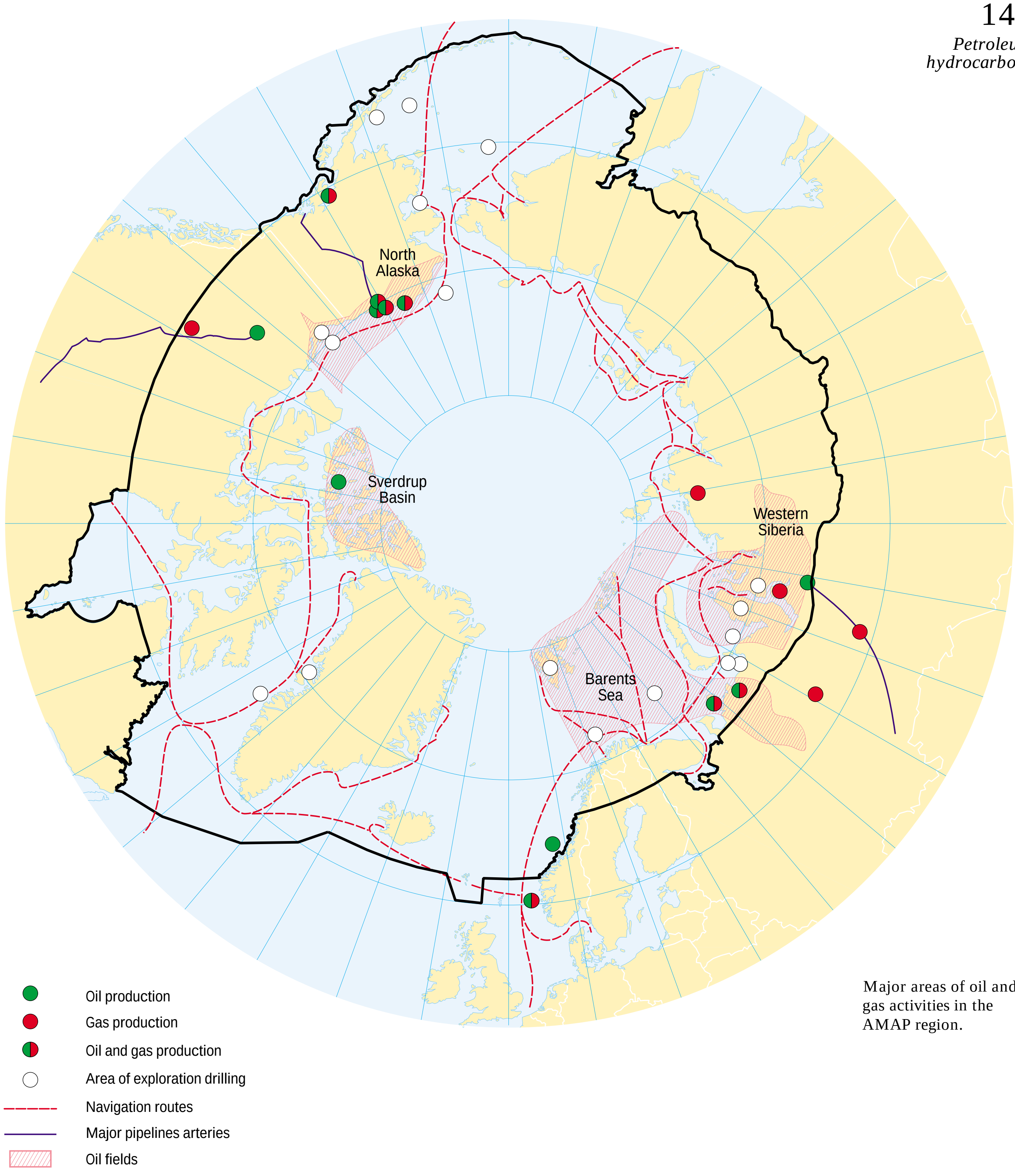
Discharge of drill cuttings causes environmental damage

Drilling muds are used to lubricate the drillbit, to control pressure in the well, to support and seal the walls of the bore hole, and to carry drill cuttings to the surface. At the surface, drill muds are normally separated from the drill cuttings, which have usually been dumped on land or directly in the water near oil rigs. The cuttings usually settle quickly, and in areas with weak circulation, they can create large accumulations around an oil rig.

The muds are made of various mixtures of a dozen substances, including special clays, oils, metals, and other compounds that may be toxic to biota. Water-based muds are most common. In the offshore environment, water-based muds will spread more widely than oil-based muds. Certain situations require use of environmentally threatening oils as the base of the muds. Until the early 1980s, diesel oil was used in such cases, but it has since been replaced by low-aromatic mineral oils in an attempt to reduce environmental impacts. Recently, synthetic oil fluids have partially replaced oil-based fluids, especially in off-shore drilling.

Studies of bottom fauna around oil fields on the Norwegian shelf north of 62°N have shown that changes are local and that harmful biological effects only occur in the vicinity of the discharges. The discharge of water-based muds has been observed to have slight effects on biological communities in an area of about 15 square kilometers around the drilling site. Synthetic oil muds modified the bottom fauna in an area of a couple of square kilometers.

Canada		
Mackenzie Delta and nearshore Beaufort Sea	Reserves	Estimated size: 238-318×10^6 m^3 oil 0.29-0.36×10^{18} m^3 gas
Tar sands at northwest Melville Island, gas on Sabine Peninsula and in offshore Hecla Fields	Reserves	
Norman Wells, Mackenzie River	Production and pipeline to Zama, Alberta	Annual production: 1.3×10^6 m^3 oil
United States		
Prudhoe Bay, Beaufort Sea coast	Trans-Alaska Pipeline connects field to Port Valdez in south-central Alaska	Original size: 3.1×10^9 m^3 oil; still commercially recoverable: 1.2 ×10^9 m^3 oil
Russia		
Nenets Autonomous Okrug, Komi Republic, Yamal-Nenets Autonomous Okrug	Production and network of pipelines linking production sites with national system	Estimated annual production volume from the 18 largest companies: 93×10^6 tonnes oil 742×10^{12} m^3 natural gas 3.4×10^{12} m^3 casing-head gas 2×10^6 tonnes gasoline (total Arctic production may be several times greater)
Shelf areas of Barents, Kara, and Pechora Seas	Exploration for oil and gas	
Norway		
Norwegian Sea	Production in the Draugen and Heidrun fields	Estimated reserves: 330-3330×10^6 m^3oil equivalents of which two-thirds valents of which two-thirds
Barents Sea	Exploration for oil and gas	Estimated reserves: 295-1955×10^6 m^3oil equivalents of which two-thirds is gas
Greenland		
Nuussuaq, Davis Strait	Exploration	



Major areas of oil and gas activities in the AMAP region.

Similar studies in the Beaufort Sea showed that discharges of water-based drilling fluids could alter the abundance of several types of bottom animals, but again only in a relatively limited area.

Land-based wells use similar drilling muds as off-shore drilling activities, but different methods of waste disposal. On land, used muds are often dumped into sumps. The efficiency of containment varies widely, and it is not uncommon that groundwater, vegetation, soil, and biota are contaminated. The damage is usually restricted to an area within a few hundred meters of the sump. In some cases in Russia, the waste is dumped directly into landscape depressions rather than into specially constructed dumps, resulting in environmental damage to larger areas.

Adherence to strict regulations and the use of improved waste management technology are essential to limit the environmental consequences of drill muds and cuttings. New practices, including narrower bore holes and combining exploratory and production wells, also help reduce the amount of waste.

OIL-RELATED ENVIRONMENTAL IMPACT.

Activity	Kind of pollution	Main chemicals	Sites affected	Potential effect targets
Exploration phase				
Rigging	Physical disturbance, noise, physical presence	None	Locally on site and along transport routes	Soils, permafrost stability, bottom sediments, vegetation, fauna, behavioral patterns
Seismics	Physical disturbance, noise	None	Locally on site	Aquatic organisms (e.g. fish larvae)
Exploratory drilling	Discharges of drill cuttings and chemicals	Water-based drilling fluids, anti-corrosion agents, scale inhibitors, cementing agents, completion chemicals, and others	Locally to regionally	Soil and sediment contamination levels, vegetation, bottom and near-bottom fauna, amenities, and other environmental usage
Accidental spills (blowouts)	Oil discharge	Hydrocarbons dispersants	Local (on land) to long-range (rivers, lakes, and sea)	Contamination levels (soils, snow, surface waters, ice, sediments), vegetation and fauna, amenity values, and tourism
Construction phase				
Removal of vegetation	Physical disturbance, noise	None	Locally on site	Habitat diversity, quality, and availability, erosion, permafrost stability (peat removal), animal behavior
Technical installations	Physical disturbance, physical presence	None	Locally on site	Habitat quality and access, permafrost stability
Excavation and infill of soils and sediments	Physical disturbance	None	On-site soils and downstream surface- and groundwater	Water courses and drainage patterns, ground and surface water, soil and sediment organisms
Road/trail construction	Physical disturbance, noise, physical presence	None	Locally	Access, migration routes, erosion, vegetation, animal behavior
Use of helicopters and supply vessels	Noise, exhaust discharge	Combustion products	Along routes	Contamination levels of water, soils and organisms, biotope quality, behavioral patterns
Dredging and construction pipelines	Physical disturbance, noise, physical presence	None	Pipeline trajectory and adjacent areas	Soils, bottom sediments, vegetation, fauna, behavioral patterns (migration)
Production phase				
Well drilling	Discharges of drill cuttings and chemicals	Drilling fluids, anti-corrosion agents, scale inhibitors, cementing agents, completion chemicals, and others	Locally to regionally	Soil and sediment contamination levels, land access, vegetation, bottom and near-bottom fauna
Well production	Discharge of production water and chemicals	Production water, scale inhibitors, flocculant agents, biocides, anti-corrosion agents, gas treatment chemicals	Local soils, local/regional surface- and groundwater, surface- and shallow sea water, possibly sea floor	Contamination level of soil and waters, vegetation, land fauna and marine pelagic organisms
Other operational aqueous waste effluents	Wash and drainage water, ballast water, sanitary outlets, operation spills and leakages	Hydrocarbons, chemicals, sewage	Soils, local watersheds, shallow sea water	Contaminant levels, water vegetation and fauna, waterfowl and seabirds
Flaring, venting and purging, energy production (combustion) fire protection tests, exhaust and dust, loss of fugitive gases	Air emissions	CO_2 and CO, methane, VOC, NO_x, SO_2 and H_2S halons, ozone-depleters	Wide range due to atmospheric transport	Greenhous gas and ozone levels, soil, water, sediment and organism contaminant levels, human health, vegetation and fauna
Use of helicopters and supply vessels	Noise, exhaust discharge	Combustion products	Along routes	Contamination levels of water, soils and organisms, biotope quality, behavioral patterns
Accidental spills (well sites, pipelines, transport vehicles and vessels)	Oil discharge	Hydrocarbons, dispersants	Local (on land) to long-range (rivers, lakes and sea) distribution	Contamination level (soils, snow, surface waters, ice, sediments), vegetation and fauna, amenity values, and tourism
Decommissioning phase				
Technical demobilization	Physical disturbance, noise	None	Locally on site	Soils, permafrost stability, bottom sediments, vegetation, fauna, behavioral patterns

Produced water often has high oil content

Water brought up from wells along with the oil and gas is a major source of the hydrocarbons released by oil exploitation. On the Norwegian shelf this 'produced' water accounted for 76 percent of the total operational and accidental input of hydrocarbons to the sea between 1990 and 1995.

For offshore wells, produced water, including any added chemicals, is usually discharged into the sea. For several United States and North Sea fields, however, this water is reinjected into the reservoir to facilitate the further recovery of petroleum. Before discharge, the produced water has to be treated to comply with regulatory limits that restrict the amount of hydrocarbons in the water. For the United States, regulations stipulate that petroleum hydrocarbons in the water should not exceed 72 milligrams per liter for any one-day period or 40 milligrams per liter as an average over 30 days. Similar limits are in effect on the Norwegian Shelf. However, the methods used to determine the oil concentration do not measure dissolved oil components, which are thus discharged 'unnoticed'.

Accidental spills are rare but can be devastating

Blow-outs, spills, and leakage during production and transport of petroleum pose the largest oil pollution threat to the Arctic environment. In addition, fishing and other ship action may contribute to numerous smaller spills and leaks. Pipeline ruptures and leaks, such as those in Usinsk, Russia in 1994, and tanker accidents such as the *Exxon Valdez* in Alaska in 1989, are examples of massive oil contamination over large areas. The *Exxon Valdez* spilled 35 000 tonnes of oil, while estimates for the Usinsk spill range from 37 000 to 44 000 tonnes of crude oil flooding rivers and lakes. The Usinsk spill was in addition to chronic leakage from the pipeline. The total discharge from the pipeline into the environment has been estimated at 103 000 to 126 000 tonnes of crude oil. Oil blow-outs at production sites, fortunately, have not yet occurred in the Arctic.

Most oil spills are small to insignificant. For instance, the 365 accidents reported in 1994 at Norwegian offshore installations together released only 55 tonnes of oil, and only seven of the incidents discharged more than one cubic meter. Nevertheless, it is the rare, difficult-to-predict large spills that become environmental calamities.

Based on statistics from oil spills in areas outside the Arctic, one can make a rough estimate of the probability of spills over the production period of specified Arctic petroleum reserves. In the Beaufort and Chukchi Seas, such estimates predict between one and eight spills equal to or larger than 1000 barrels of oil (approximately 160 cubic meters). The probability of one or more spills is between 58 and 99 percent. The number of spills exceeding 10 000 barrels (1600 cubic meters) will be between 0.3 and 2.5. The probability of one or more of these large spills is between 24 and 92 percent. The most likely source of these spills is pipelines, followed by tankers and platforms.

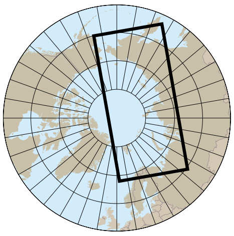
These theoretical risk calculations do not take special Arctic conditions into account. In reality, pressure ridges in the ice or icebergs scouring the bottom could increase the risk for damage to any installation on the sea floor. Arctic conditions may also affect the size of the spill because of difficulties in recovering oil and in drilling relief wells.

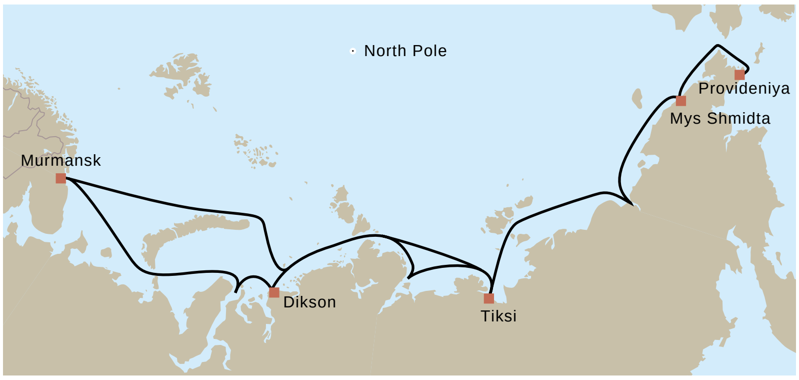
Tanker spills are the largest threat from shipping

The main oil-related threat from shipping is connected to transporting oil in tankers. Most incidents occur at the terminals where tankers load or unload. Even if the discharge is considerable, the damage is usually localized to the immediate area around the port.

Tanker accidents contribute a small percentage of the overall input of oil to the oceans but get public attention because of their potentially large environmental impact, particularly if the tanker is large or the spill occurs close to shore. The groundings of the *Exxon Valdez* off the coast of Alaska in 1989 and the *Braer* near the Shetland Islands in 1993 are two examples.

Increased exploration and development of oil resources in the Arctic will lead to increased tanker traffic. A main focus will be on the Northern Sea Route, a system of sea lanes north of Asia between the straits joining the Barents and Kara Seas in the west and the Bering Strait in the east; see the map below.





The Northern Sea Route.

This route has been important for transporting goods to remote Russian settlements, and opened for international shipping in 1987. Accurate estimates of the amount of ship traffic in these waters are difficult to make, but this route is by far the most active in Arctic waters. With significant prospects for offshore oil and gas in the Kara and Barents Seas, traffic along the Northern Sea Route is likely to increase, as will the risk of accidents. An international program coordinated by Russia, Norway, and Japan is currently assessing the route's overall feasibility.

Other shipping, such as sealifts to isolated communities and industrial facilities, traffic to and from drilling operations, icebreaker support, and research cruises are also potential sources of oil pollution. In some of the marginal seas, there are large fishing fleets as well. Oil pollution from regular shipping is still a problem in some areas, with both legal and illegal discharges of oily ballast and bilge water. There is an increasing number of tourist cruises in the Arctic, with large ships carrying substantial amounts of bunker oil. In addition to sea ice, poor nautical charts of the Arctic increase the risk of accidents.

Many legal instruments are already in place

There are a number of legal instruments to prevent oil pollution of marine waters. Some are aimed at shipping while others specifically address oil and gas exploitation. The Protection of the Arctic Marine Environment (PAME) component of the Arctic Environmental Protection Strategy reviewed these instruments in its 1996 report. PAME has also produced guidelines for offshore oil and gas exploration and production in the Arctic and subarctic. At present, getting compliance with existing legal instruments appears more important than developing new ones.

Poorly maintained pipelines pollute Russian tundra

In addition to marine shipping, large quantities of oil are transported over land via pipelines. During the 1970s and 1980s, Russia built an extensive pipeline network, including six trunk oil pipelines, stretching over 10 000 kilometers across Western Siberia. The network is capable of carrying 400 million tonnes of oil every year. As described in the introduction, many of the pipelines are in poor shape and leaks are frequent. There were 103 large-scale failures at oil and gas pipelines in the Russian Federation in 1991-93, many of them in Arctic and subarctic areas.

In the United States, the Trans-Alaska Pipeline carries oil from the fields in Prudhoe Bay to Port Valdez on a fjord in southern Alaska. Automated shutdown of pump stations and valves in this pipeline are designed to limit spills. At the most, about 0.2 percent of the oil in the line, or 2226 cubic meters, could spill onto the land before the line could be effectively shut down. A Canadian pipeline, connecting oilfields and refineries at Norman Wells on the Mackenzie River with northern Alberta, has similar safety features.

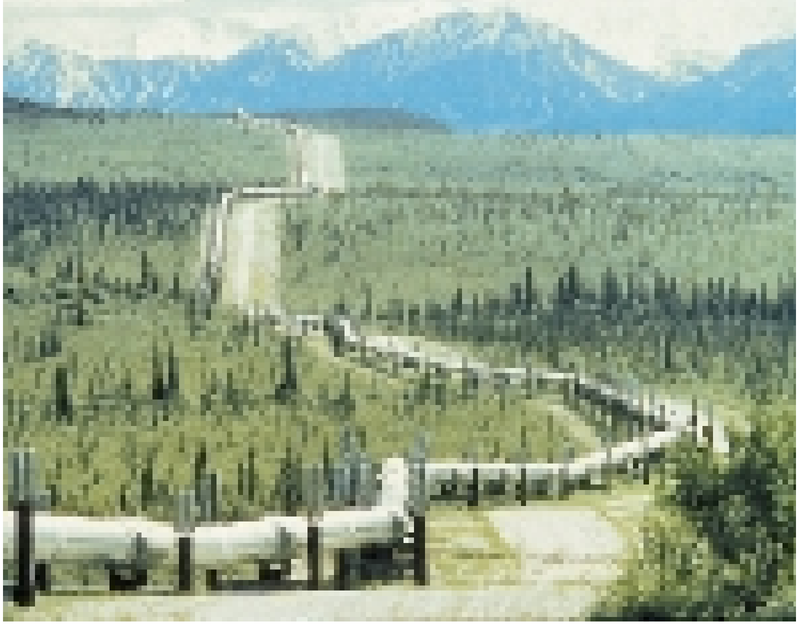
Natural oil seeps add to hydrocarbon load

Natural sources of hydrocarbons add to the load in the environment. For example, some oil seeps in the Arctic have been recognized since prehistoric times and lumps and pebbles of oil shale and seepage tar have been used as fuel by North American Inuit. In many instances, the seeps have led to the discovery of commercially recoverable petroleum reserves. Many of the natural oil seeps originate in north-flowing rivers, such as the Mackenzie and the Ob, which eventually discharge into the Arctic Ocean.

Globally, oil seepage contributes between 0.02 and 2 million tonnes of oil per year to the environment. Of the total entering the marine environment from different sources, at least 15 percent comes from natural oil seeps. There are no estimates for the Arctic region, but the proportion from natural sources is probably greater than the global average. For example, the Mackenzie River in Canada's Arctic contributes the largest quantities of hydrocarbons

Drilling, Norman Wells area, Canada.

Trans-Alaska Pipeline.



GLENN SHAW

UNKNOWN SOURCE

UNKNOWN SOURCE

to the Beaufort Sea region. Oil seeps have also been detected in eight areas of the United States Arctic, seven of which are located along the Beaufort Sea coast. The Barents Sea and locations near Spitsbergen are other regions that have natural oil seeps.

PAHs have many different sources

Polycyclic aromatic hydrocarbons are a group of contaminants related to oil exploration and extraction that also have other sources. In areas of high concentration, such as oil spills, they can be acutely toxic. The main environmental concern is that some of the compounds can cause mutations and cancer at low concentrations.

Spilled petroleum products are the largest single source of PAHs. Crude oils contain up to 10 percent PAHs, while the PAH content of shale oils and coal-derived synthetics can be as high as 15 percent. Incomplete combustion of wood and fossil fuels are important sources, as are incineration of garbage, steel and coke production, coal liquification, and coal gasification. Although most emissions stem from human activities, there are some natural sources such as microorganisms that are known to produce small amounts of PAHs.

Produced water from both oil and gas platforms contains PAHs. Taking into account the large volumes of produced water discharged from oil production, the yearly input of PAHs into the environment, even from a single offshore oil field, may be significant.

Natural gas contributes to climate change

Oil and gas exploration mostly have local or subregional environmental impacts, but one of the pollutants, methane, is of global concern. Methane acts as a greenhouse gas and thus contributes to global warming as discussed in the chapter *Climate change, ozone depletion, and ultraviolet radiation*. It is the main component of natural gas and is released to the atmosphere by gas drilling, from leaky pipelines, and by venting and flaring activities on oil and gas rigs. Globally, these activities are the fourth largest source of methane to the atmosphere.

Burning of fossil fuels is also the main anthropogenic source of the greenhouse gas carbon dioxide.

Air, oceans, and rivers carry hydrocarbons from industrial areas

In addition to contamination from sources within the Arctic, petroleum hydrocarbons are transported from heavily industrialized areas by air currents, ocean currents, and rivers. The main pathway is probably via the atmosphere. Based on models, it has been estimated that atmospheric transport annually adds about 40 000 tonnes of hydrocarbons to the Arctic marine environment and about 40 000 tonnes to the terrestrial environment.

Levels in the marine environment

Different analytical methods to determine total petroleum contamination have been used by different Arctic countries, which makes it difficult to compare levels in the environment around the circumpolar area. So far, assessments using comparable methods can only be made at a subregional level.

Hydrocarbons can be detected in seawater throughout the Arctic. Except for local pollution in harbors, the highest levels occur just off river mouths. Concentrations in the marine waters of the Russian Arctic are generally much higher than those found in North American waters. One explanation might be differences in analytical technique, but oil pollution carried by the large Russian rivers probably contributes. Except for areas affected by spills, anthropogenic input so far is relatively low and does not have any ecological significance.

Seaports are the most polluted marine environments

The most severe cases of pollution occur in areas with intense industrial and military activity. For example, most of the sewage produced at the Murmansk Seaport and Naval Base is discharged untreated into the Kola Fjord. About 40 ships based in this port have no oily-water separators or other procedures to process oil-containing waters. In winter, the Kola Fjord is relatively stagnant, and concentrations of hydrocarbons sometimes exceed the maximum permissible concentration (50 micrograms per liter) by a factor of 150 in surface waters close to Murmansk. In summer, water circulation increases and hydrocarbon concentrations are rarely higher than twice the permissible level.

KNUT BRY

Murmansk Seaport.

Along the Norwegian Arctic coast, measurements from 1994 show that levels of hydrocarbons in sediment vary considerably. In general, they are higher than in other Norwegian harbors. The highest level, 7000 milligrams per kilogram, was found in Hammerfest.

Some estuarine sediments are clearly contaminated

Reflecting input from north-flowing rivers, silt sediments along some coasts are contaminated with hydrocarbons. The highest concentrations occur in the estuaries of the Pechora, Ob, and Yenisey Rivers. The maximum concentration in the Pechora estuary is 250 micrograms per gram. In the Laptev Sea, outside the Lena River, the hydrocarbon concentration in the silt sediment is even higher, over 300 micrograms per gram.

Fish levels indicate marginal contamination of Arctic waters

Measurements of hydrocarbons in fish tissue show that fish from the southern Beaufort Sea are more contaminated than fish from the northeast Pacific Ocean, which is considered a clean environment. The concentrations of hydrocarbons are similar to those in fish from Atlantic waters. Other biota from Alaska also show indications of some contamination with petroleum hydrocarbons.

Oil spills in coastal and marine environments

The impact of oil spills in the marine environment depends to a large extent on whether the oil reaches sensitive animals. Large spills in the open ocean may not have as large an impact as a small spill close to the coast or in the vicinity of large bird colonies. Transport and dispersal of oil therefore become important factors in trying to understand the risks involved in Arctic oil and gas exploitation. The major difference between the Arctic and other areas is the presence of ice. Lessons learned from oil spills in other areas can therefore not be directly applied for the Arctic.

Ice will trap and transport oil

Normally, the lighter fraction of oil spilled at sea evaporates while the rest is dispersed in the water with the help of wind and waves. Ice can effectively limit this natural cleaning potential. Instead, it provides surfaces both above and below the water on which oil can be trapped. The undersurface of sea ice can be very rough, with large pockets in which the oil can remain for as long as the ice stays solid. Some of the oil might even be encapsulated and move with the ice. Oil spilled in winter under landfast ice might thus move only tens of meters from the spill area. On the outer shelf, the edge of the multi-year pack ice can move about 150 kilometers per month in winter. Lack of equipment and methods to contain oil and to clean ice-infested areas increases the potential threat from oil spills in the Arctic.

Shelf seas that produce and export large volumes of ice would be particularly efficient at transporting spilled oil into the interior of the Arctic Ocean, where it would follow the large-scale drift patterns of the pack ice. For example, oil spilled in the Beaufort Sea may circulate within the Beaufort Gyre for five or more years, whereas oil spilled in the Kara and Laptev Seas could exit the Arctic via the Barents Sea and Fram Strait within one or two years. The figure at the top of page 32 describes this large-scale circulation.

Oil encapsulated in the ice will not break down but will instead appear essentially unweathered at the surface when the ice starts to melt. It is released when the ice sheet begins to break up. Because the dark oil absorbs heat, the break-up of oiled ice occurs about two weeks earlier than normal. Once there is open water, the oil slick will behave as it would in an open ocean with ice floes.

The release of oil in spring can be very damaging to wildlife. Biological activity is high and the amount of open water available for birds and marine mammals is relatively limited. The risk of animals congregating in oily areas is therefore relatively high. This is a compelling argument for cleaning up winter oil spills before spring comes.

Sunlight and microbes break down oil

Whether released at sea or on land, petroleum products and oily wastes will change with time. This ‘weathering’, which is especially well studied in the marine environment, is caused by a combination of physical, chemical, and biological factors.

Under temperate conditions, most of the light hydrocarbons evaporate within one or two days of a spill. Computer simulations show that 23 percent of the mass of a hypothetical spill covering 150 000 square meters in the northern Bering Sea would evaporate. After the *Exxon Valdez* oil spill, it was calculated that 20 percent of the oil evaporated. Once the hydrocarbons are in the air, light and oxygen will break them down in photochemical reactions. Low-molecular weight compounds therefore last only a few days. Higher molecular weight compounds appear to have a half-life of about a week. In the High Arctic, however, and especially in ice-infested waters, evaporation will generally be slower.

In ice-covered waters, evaporative loss also depends on the timing of the spill. If it occurs during the initials stages of ice growth, dissolved hydrocarbons may sink toward the bottom with the brine that forms during ice formation. Here they would persist for several months without evaporating. When oil-polluted ice breaks up, waves can very rapidly dissolve the hydrocarbons in the water, increasing concentrations by factors of 300 to 700 in less than one day. The concentrations would gradually decrease over the next six days as the compounds evaporate.

Bacteria and fungi can use hydrocarbons as an energy source and thus help in the final clean-up of an oil spill. However, in the Arctic, the degradation will be slow due to the short season in which temperatures are high enough for bacteria and fungi to be active. In Beaufort Sea sediment, oil degradation was apparent only after eight months, even though the bacterial community could grow at temperatures below freezing. The slow rate of biodegradation, which has also been demonstrated in the Barents Sea, may have been due to a lack of nutrients. Another reason may have been that the physical and chemical characteristics of oil in cold water make it less available for the microbes. In contrast to temperate spills, natural cleaning after a spill in the Arctic may therefore take decades rather than years. This underscores the need for special care to protect sensitive areas against spills.

Effects on animals vary

Oil spills will affect most exposed animals, but the impact will vary greatly depending on species and circumstance. Although zooplankton take up components of the oil, the toxic effects appear to be short-lived. For example, the Potomac spill off West Greenland revealed oil in the gut of copepods and amphipods but found no apparent effects.

Fish eggs and larvae are vulnerable. They often develop near the surface, where they are more likely to be exposed to dissolved oil components. They are also more sensitive to oil toxicity than adult fish.

Adult fish in the Arctic are probably no more sensitive to oil spills than fish in other areas, and the experience so far has been that even large oil spills have had no apparent impact. However, natural variations in fish stocks would make it difficult to prove that any effects were caused by the oil. Fish, in general, are able to detect oil even at extremely low concentrations, and may avoid oil spills by swimming away.

Soiled feathers kill seabirds

Soiled seabirds have become symbols of the environmental threat posed by oil spills. Oil fouls their plumage, taking away their insulation, so they quickly lose heat. The birds also ingest oil when trying to clean their feathers. The oil toxins may impair their ability to reproduce, and soiling of eggs kills embryos.

Seabirds are particularly at risk because huge populations gather in one place. A single

NICO VINK

Cleaning oiled seabird.

Arctic breeding colony may contain a large proportion of the individuals of a certain species, and one spill in the vicinity of such a community could severely harm the worldwide population. The long-term effect of oil spills on bird populations is controversial, and it is uncertain whether observed oil mortalities are substantial in relation to natural mortality.

The damage a spill does to bird populations is related less to its size than to its proximity in time and space to large bird gatherings. When the *Amoco Cadiz* released 250 000 tonnes of oil off the coast of Brittany, France, only about 4500 birds were killed, whereas 35 000 tonnes of oil from the *Exxon Valdez* probably killed 500 000 birds. Also, a nearly inconspicuous spill in 1979 on the east coast of Finnmark, northern Norway, killed between 10 000 and 20 000 birds, primarily guillemots.

Behavioral patterns make some seabirds more sensitive than others to oil spills. Alcids are among the most sensitive, in particular Atlantic puffins, common murres, thick-billed murres, razor-billed auks, and northern gannets. Common eiders are also considered vulnerable.

Some sea mammals are vulnerable to oil-soiling of their fur

Fur seals, sea otters, and polar bears rely on their fur for insulation and also to help them keep afloat. Oil contamination may therefore be particularly damaging to these animals. In the *Exxon Valdez* spill, approximately 2000 to 3000 sea otters in the area were killed directly after the accident and a number probably died later.

Seals and walrus do not rely on their fur for insulation, but may still suffer if oil hinders them when they swim. In these conditions, pups may die from exhaustion. Oil is also known to cause eye lesions.

Whales seem unharmed by contact with oil. One reason might be that oil does not stick to their skin. They may also avoid oil slicks, but several observations suggest that they do not take any notice of them.

Rocky shores recover fairly fast

Shoreline and shallow subtidal communities are the prime focus of concern during most coastal spills. The impact can vary greatly, however, depending to a large extent on whether the physical characteristics of the coast allow waves to wash the oil away, or if sediments retain the contamination for a long time. Several attempts have been made to classify sensitivity. The most sensitive areas are estuarine salt marshes where oil can remain for a decade. Straight, rocky headlands, on the other hand, might be clean after less than one year. Some sensitivity indexes also take biological and human use of the seashore into account.

A thorough investigation of the immediate impact of the *Exxon Valdez* spill showed that members of the four main groups of organisms – sea weed, barnacles, mussels, and periwinkles – survived the spill. A year late, densities were somewhat less than on other shores, but after two years most oiled shorelines appeared healthy and in a state typical of pre-spill communities.

Many organisms, such as barnacles and mussels, close up to avoid drying during low tide, and this behavior may also protect them from light oil contamination. Mobile organisms such as crustaceans may escape by seeking deeper water. However, this escape response may cause the animals to get stuck in the oil and, in general, crustaceans and amphipods are sensitive to oil spills. After the *Amoco Cadiz* spill, it took eight years for the amphipod populations along some of Britanny's shores to return to normal. Scavenging amphipods play a key role in Arctic marine food webs and oil damage may therefore have more severe consequences in the Arctic than in warmer regions.

Macroalgae growing just below the shoreline on rocky shores may be protected by their mucoid surface. However, after a spill of 1000 tonnes of bunker oil off the Arctic coast of Norway in 1981, all macroalgae died in the heavily oiled areas. In lightly oiled areas, the parts of the macroalgae that had been coated with oil showed retarded growth the next spring, but new sprouts appeared healthy.

Sand and mud retain oil and increase biological damage

On sheltered sandy and muddy shores, the effects of oil spills can be pronounced and remain for many years. Two years after an upper-shore spill of diesel oil at Spitsbergen, substantial amounts of oil were still present one half meter down in the shore sediment. In this case, the only species that was present before the spill disappeared. Experiences from experimental and non-Arctic spills vary from no apparent long-term effects to severe impacts with instability in the structure of the biological community up to a decade after the accident. Generally, recovery is probably slower in the Arctic because of slow turn-over rates and long life spans of the organisms.

▶ Containing the oil. Komi spill.

▼ Cleaning up the Komi spill.

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The underside of sea ice may be a vulnerable environment

A unique feature of the Arctic marine environment is the community of plants and animals that live on the underside of the sea ice. Any oil spilled under multi-year ice will remain unchanged until the ice thaws, and plants and animals here will thus be exposed to toxic substances for a long time. Some experimental studies indicate that algae density, biomass, and productivity did not change when a moderate amount of oil was applied under ice. Also, the effects on an ice amphipod were only moderate. However, amphipods are known to be sensitive to oil and to get caught easily in oil film, so spills under ice are likely to trap and smother a substantial number of these animals.

Oil in terrestrial and freshwater environments

Data on hydrocarbons in soil are only available for Russia, where levels away from known spills range from 10 to 40 micrograms per gram. Spills and leaks from pipelines make local levels much higher. For example, after spills from the Vosey Pipeline, as much as 15 percent of the dry weight of soil in a spot close to a pipeline leak was hydrocarbons.

Long-term monitoring of petroleum hydrocarbons in Russian river water indicates high pollution levels in the areas of oil and gas exploration and production. This is especially true in the lower part of the Ob River, where hydrocarbon concentrations often reach several milligrams per liter. Even if local contamination is severe, however, these rivers have a self-purification ability that keeps hydrocarbons from being transported downstream by the flow of the river. For example, during the Komi oil spill, only a minor portion of the spilled oil reached the mouth of the Pechora River, though some tar balls were trapped there and ‘fingerprint’ analysis proved that they originated from the spill area.

The highest values reported for North American river sediments are lower than those in the Russian rivers. Values of about 35 micrograms per gram were found close to the Beaufort Sea coast, and the highest values – up to 148 micrograms per gram – are from Norman Wells, an active oil exploitation area along the Mackenzie River.

Soils, plants, and snow determine how oil spreads on land

Oil spills on land will, in general, be more confined than spills in water. The rate and extent of spreading will depend on plant cover, whether the ground slopes, and how much oil the soil and vegetation will absorb. Mosses, for example, are very efficient in absorbing oil. Waterlogged soils also hinder oil penetration. Cracks in the soil above permafrost, on the other hand, may lead oil down to the permafrost where it can spread horizontally into deeper soil layers.

Snow also affects spreading patterns. Hot oil, such as from a ruptured pipeline, tends to form channels in the snow, transporting the oil along the underlying ground and contaminating relatively large areas.

One terrestrial spill has been well documented. In August 1989, about 50 cubic meters of oil and produced water leaked from a valve in a production pipeline near Prudhoe Bay. The oil spread over half a hectare of Arctic coastal tundra, inundating small lakes and ponds. Most of the oil stayed close to the surface of the water-saturated tundra. Within a year, the concentration of oil in the soil had decreased almost 80 percent, but, after this initial drop, natural clean-up by light and bacteria slowed down considerably. By 1991, thaw settlement of the permafrost had stabilized and plant cover was well on its way to meeting the regulatory criterion for recovery, equal to 30 percent of the mean percentage plant cover in an adjacent unaffected area.

Oil will destroy plant cover

The amount of damage oil spills cause on land varies, but all actively growing plant tissues in wetlands can be completely destroyed. Sedges are known to recover, while mosses can be completely eliminated. If the damage is limited to above-ground parts of the plants, the vegetation can usually recover. Damage to the roots, however, will have effects even in the following growing season. Plants with shallow roots are probably the most sensitive.

Plant damage can have more severe consequences in the Arctic than in other areas. Arctic plant cover is usually extremely vulnerable to surface damage because it is so thin. It also takes longer to grow back because of low temperatures and the lack of nutrients. After a spill, the toxic components of oil are expected to remain in the soil for up to 30 years, further decreasing the chance that vegetation will recover.

Studies after an oil spill along the Trans-Alaska pipeline have shown that it is possible to assist vegetation recovery by applying fertilizer and by tilling the soil.

The effects of oil on terrestrial animals are poorly understood, but animals that rely on their fur for insulation might suffer. For example, a major spill along the St. Lawrence River killed a number of muskrats.

Russian wetlands are polluted from production activities

In Russia, oil and gas extraction poses a serious threat to wetlands in the production areas when oil and other contaminants are discharged directly into landscape depressions. In northwestern Siberia, petroleum concentrations in this discharge can range from 0.5 to 5.2 grams per liter. The depressions are also used for dumping untreated waste water. When wetlands overflow, they serve as secondary sources of hydrocarbons and other chemicals to nearby rivers and lakes, and almost all samples taken from rivers in northwest Siberia exceed the maximum permissible concentrations.

Spills in streams and lakes can taint the fish

If oil gets into streams, ponds, or lakes, it can kill zooplankton, and the remaining oil can prevent recovery for several years. In streams with prolonged seepage, total abundance and species diversity is known to decrease.

Plants in freshwater ecosystems recover fairly quickly, especially in streams where most of the oil gets washed away.

Experiences from areas outside the Arctic show that oil can kill fish, but so far there are no documented cases of this in the Arctic. Tainting of fish, on the other hand, has been an issue. For example, after a spill of diesel oil into a river, people living downstream complained that the fish tasted oily, and laboratory studies showed that the spilled fuel could have been the cause.

Birds that gather by lakes and ponds in the Arctic will be sensitive to oil spills. For example, a large number of ducks, geese, and herons were killed after a spill on the St. Lawrence River. After the *Exxon Valdez* spill, numerous bald eagles nesting in the area died after eating dead, oil-contaminated birds and sea otters.

Levels and effects of PAHs

Polycyclic aromatic hydrocarbons do not dissolve well in water and instead tend to associate with particles. Sediments are thus the most important reservoir in the environment. In cities, PAHs are major components of air pollution. This is especially true in cities on the Kola Peninsula, where PAH levels regularly exceed maximum allowable concentrations.

PAHs are degraded by light, either in the atmosphere or in the upper reaches of a water column. In the Arctic, degradation is generally slower than at lower latitudes because of low temperatures and low light.

Seawater and sediments are clearly contaminated with PAHs

Several areas of the Arctic have elevated levels of PAHs in seawater and marine sediments relative to global background concentrations. The Beaufort Sea is an area with particularly high levels. The main source is probably the Mackenzie River, which flows through regions with known fossil fuel deposits, natural hydrocarbon seepage, and burned-over areas. In five local areas within the Arctic, sediment concentrations exceed environmental guideline limits. These are in the Barents Sea, Spitsbergen, harbors in northern Norway, the Beaufort Sea, and Tuktoyaktuk Harbour in the Northwest Territories, Canada.

The relationship between different PAH compounds can be used to identify their main sources. Alaskan sediments point to petroleum hydrocarbons, while PAHs in the Barents Sea show a greater contribution from combustion sources. The Canadian Beaufort Sea has a mixture of the two sources, which is also the case for Russia's marine environment, though the Russian levels are generally lower. Sediments near Spitsbergen are enriched in PAHs compared with the Russian sediments, which probably reflects contamination from coal particles and petroleum products.

Fish can bioaccumulate PAHs directly from sediment. In general, PAH levels in Arctic marine animals are similar to those reported for background locations outside the Arctic. However, starry flounder from Tuktoyaktuk Harbour had consistently high concentrations, which probably reflects a chronic exposure from polluted water and sediment in the harbor.

Fish are able to break down PAHs, and these compounds do not seem to bioconcentrate or magnify in the food web.

Freshwater and terrestrial PAH levels are also high

The levels of PAHs in freshwater sediments vary greatly, and probably reflect a combination of long-range transport and local industrial and natural sources in the watershed. As with the marine environment, several areas have higher concentrations than the global

Levels of benzo[a]pyrene in the air of Russian cities on the Kola Peninsula; mean (annual average) and maximum (highest concentration during the year over a 20 minute period) levels in 1991 and 1993, in nanograms per cubic meter. The maximum permissible concentration is 1 nanogram per cubic meter.

City/Town	Value	1991	1993
Apatity	Mean	0.5	–
	Maximum	1.4	2.7
Kandalaksha	Mean	2.2	–
	Maximum	5.8	9.5
Kovdor	Mean	0.8	–
	Maximum	2.5	1.8
Monchegorsk	Mean	2.2	–
	Maximum	8.6	8.1
Murmansk	Mean	1.1	–
	Maximum	4.0	3.4
Nikel	Mean	0.5	
	Maximum	2.9	2.2

background. Norwegian peak values reach almost 7000 nanograms per gram of sediment.

Concentrations measured in burbot from Canada, Russia, and Finland are probably below those that would cause observable effects. The highest values are reported for fish caught at Norman Wells in the Northwest Territories, Canada.

In Arctic Russia, only a few analyses of whitefish from major rivers are available. They show that there must be a chronic source of hydrocarbons at most of the sampled locations.

Reindeer and Arctic birds in Russia have relatively low PAH concentrations, while PAHs levels in bird carcasses from Alaska are higher.

Summary

The major anthropogenic source of hydrocarbon contamination in the Arctic is oil and gas development, but several other sources contribute to the load in the environment. These are releases from marine shipping, burning of fossil fuels, long-range transport, and natural oil seeps.

Accidental oil spills and chronic releases from poorly maintained pipelines and from ships pose the greatest threat from petroleum hydrocarbons. Some severe local and regional problems associated with oil and gas exploration, development, and transportation have already occurred.

The Arctic environment is more vulnerable to spills than warmer environments because oil breaks down more slowly under cold, dark conditions and because Arctic plants and animals need a longer time to recover from damage. In addition, remedial measures are difficult due to the extreme conditions of cold, ice cover, and winter darkness.

The environmental threats to the Arctic associated with oil and gas development, production, and transport are primarily local and/or regional and not circumpolar in scale. An important exception is if a large oil spill were to occur coincidentally with large congregations of certain migratory bird and mammal species in Arctic areas. In such cases, a large proportion of a population may suffer.

Petroleum hydrocarbons are also present in areas not directly affected by spills or prolonged chronic releases. However, in background circumpolar environments, concentrations are relatively low and not of ecological significance. The most highly contaminated areas in the Arctic are certain rivers and estuaries in Russia close to human settlements and industrial or military areas, and in terrestrial/freshwater environments where accidental and operational spills have occurred, such as the area affected by the Usinsk pipeline rupture.

Polycyclic aromatic hydrocarbons (PAHs) are widespread in the Arctic environment. They come from a variety of sources, including oil, combustion, and biological activity. Measured levels in the environment are generally below the levels thought to cause observable effects in biota, although certain PAHs do reach levels of concern in marine sediments in limited areas.