PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

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A survey of inputs to the North Sea resulting from oil and gas developments

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The annual input of petroleum hydrocarbons to the North Sea has recently been estimated to be between 100 and 170 kt and is derived from a variety of sources.

Although there is uncertainty about the size of inputs from some sources, there is general agreement that the atmosphere, rivers and land run-off (including coastal sewage), and coastal oil industry activities combined with shipping, remain sources of major inputs. However, the size of annual inputs from the offshore oil and gas exploration and exploitation activities has recently increased to about 20 kt and these activities now form one of the major sources of petroleum hydrocarbons to the North Sea. This increase is almost entirely due to the use of oil-based drill-muds and the consequent discharge of drill cuttings contaminated with residual mud.

At present, experience in the United Kingdom has shown that this input of fresh, unweathered oil rapidly enters otherwise uncontaminated offshore sediments, producing strictly local effects around the point-source discharges. The nature and composition of this input differs from the majority of the inputs to coastal waters and sediments, and from the diffuse atmospheric input to offshore waters.

Of the 140 kt of materials other than oil discharged annually to the North Sea from oil and gas developments in the United Kingdom, 98–99% arise from drilling operations, but the vast majority of inputs from this source are biologically inert or derivatives of natural products. Surveys indicate that, of the remaining materials, less than 50 t of the more toxic products (i.e. those with a 96 h LC_{50} to *Crangon crangon* of less than 1 part/10^6) are discharged into United Kingdom waters annually.

The largely uncontaminated offshore North Sea waters and sediments remain little affected by offshore oil and gas developments, but if these activities enter already contaminated estuarine and coastal waters, the contamination and effects from this source will be harder to distinguish.

Introduction

Estimates of the global input of petroleum hydrocarbons to the seas have been provided by the United States National Academy of Sciences (N.A.S. 1975, 1985) but valid estimates of inputs to a particular body of water such as the North Sea require the compilation of detailed local information. This is no easy task, and it is fortunate that recent interest in the sources, fates and effects of oil in the North Sea has led to the gathering of such information, which is made available both by national governments and international regulatory bodies such as the Paris Commission.

Sources of petroleum hydrocarbon inputs to the North Sea

The Eighth Report of the Royal Commission on Environmental Pollution (1981) provided figures for the estimated inputs of petroleum hydrocarbons to United Kingdom waters from various sources (table 1). This table is taken from table 2.2 of that report. At about the same time, Whittle *et al.* (1982) contributed a paper to the Royal Society Discussion Meeting on 'The long-term effects of oil pollution on marine populations, communities and ecosystems',

Table 1. Estimated annual inputs of petroleum hydrocarbons to United Kingdom waters†‡ (kilotonnes) (from Royal Commission on Environmental Pollution (1981))

natural seeps	0.1–0.3
atmosphere	8–9
run-off from land (including urban run-off and inland municipal waste)	5–10§
coastal discharges of municipal wastes (sewage)	7§
coastal refineries	8
other coastal effluent	11
oil terminal operations	0.1
accidental losses from tankers at sea	10
operational discharges from tankers at sea	?
losses from general shipping	?
offshore production	0.5
discharges from ballast water treatment facilities	0.5
rounded totals	50–56‖

† Defined as: the North Sea (west of the median line), the English Channel (full extent), the Celtic Sea (south-west to the 100 fathom¶ line), the Irish Sea (full extent) and Scottish coastal waters (west and north to the 100 fathom line). Total area so defined = 715000 km^2.

‡ Compiled from estimates by the United Kingdom Petroleum Industries Association and Government Departments.

§ Including an unknown proportion of hydrocarbons of biogenic origin.

‖ No data for two items.

¶ 1 fathom = 1.83 m.

which also provided best estimates for such inputs. Table 2 is taken from table 7 of their paper and presents the position in about 1980. Both apply to approximately the same area of United Kingdom waters. There is generally good agreement between the two estimates, the differences being almost entirely due to their different estimates of the atmospheric input and the fact that the Royal Commission on Environmental Pollution report (1981) makes no estimates for operational losses from ships.

More recently the Institute of Offshore Engineering at Heriot-Watt University has conducted a survey of contaminant inputs (I.O.E. 1985) which includes inputs of petroleum hydrocarbons. Table 3 is taken from table 7.6 of their summary and updates the position to about 1982–83. Some idea of the probable relative inputs owing to operational tanker discharges and general shipping losses can be gained from table 4, taken from table 7.5 of the Institute of Offshore Engineering report, but there is much uncertainty about the actual quantities entering the North Sea from these sources. The derivation of the 23 kt of oil from offshore oil and gas production (bottom line of table 3) is shown in table 5 which is taken from table 7.4 of the Institute of Offshore Engineering report. It is difficult to compare in detail these estimated inputs to the whole North Sea, which include those originating from North Sea states other

Table 2. Estimated annual inputs of petroleum hydrocarbons to United Kingdom waters† (kilotonnes)

(After Whittle *et al.* 1982.)

	best estimates	
natural seeps	*< 0.3*	
offshore oil activity	*3.41–3.56*	
formation and production water		0.75–0.9
displacement water		0.05‡
accidental spills		0.1‡
platform runoff		0.01
drill cuttings		2.5
transportation	*7.55–9.0*	
tankers: large spills		1.9–2.2§
small spills		0.5–0.1
non-tanker spills		< 1.0
operational losses from ships		4.0–5.0
shore terminals, refinery terminals, coastal storage depots, crude loading terminals		0.1–0.2
oily water discharges		0.5
refineries	*6.0–6.5*	
municipal and industrial effluents	*15.51–16.91*	
sewage effluent to tidal waters		0.5–1.4
sewage sludge dumped at sea		6.5–7.0
industrial waste dumped at sea		< 0.01
industrial effluent		8.5
urban runoff to tidal waters		
rivers	< 7.5	
atmosphere	30.0‖	
(*dredge spoil*)¶	(2.8)¶	
total	70.3–73.8	

† Area considered for inputs: west and north to 200 m depth, south to latitude 49° N and east to median line, excluding west of Eire. Total area considered approximately 750000 km^2.
‡ Plus large spills from major incidents.
§ Plus massive spills from major incidents.
‖ Maximum estimate 250.
¶ Not included in inputs total, redistribution rather than input.

than the United Kingdom, with those previously presented for United Kingdom waters, because of the different types and sizes of area receiving them. However, given that all the United Kingdom offshore production inputs cited in tables 1 and 2 were to the North Sea, that little of the United Kingdom coastal and atmospheric inputs will enter Celtic Sea and northwest Scottish waters, and that the Institute of Offshore Engineering (1985) assumes that 50% of the total United Kingdom inputs enter the North Sea, two general statements can be made about relative North Sea inputs with time. Firstly, despite differences in estimated size of inputs, it is agreed that the atmosphere, rivers and land run-off (including coastal sewage), and finally coastal oil industry activity combined with losses and discharges from shipping, form three major sources of petroleum hydrocarbons. Secondly, the input from North Sea oil and gas developments has changed from a minor to a major source and this is almost entirely because of the increase in the amounts of oil discharged on drill-cuttings from the use of oil-based drill-muds. This is illustrated by the most recent figures from the United Kingdom Department

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TABLE 3. ESTIMATED ANNUAL INPUTS OF PETROLEUM HYDROCARBONS TO THE NORTH SEA† (KILOTONNES)

(After I.O.E. 1985.)

natural seeps	0.3–0.8‡
atmospheric	19§
rivers, land runoff (including inland municipal waste)	40–80
coastal sewage discharges	3–14
coastal refineries	6.0
oil terminal operations (including reception facilities)	0.8
other coastal industrial effluent	9
accidental losses from tankers at sea	5–12
operational discharges from tankers at sea	?
losses from general shipping	?
offshore production	23
total	107–165

† North Sea defined as waters north of the Strait of Dover, the Skagerrak and the area to 61° N to a line at 4° W.

‡ Estimated for an area of 5.3×10^5 km^2 of continental shelf at 0.5–1.5 t 1000 km^{-}

§ Includes United Kingdom inputs to non-North Sea waters.

TABLE 4. INPUTS OF OIL TO THE NORTH SEA IN 1982 FROM SHIPPING AND TANKER TRANSPORTATION OPERATIONS AS REPORTED TO THE PARIS COMMISSION IN 1983 (KILOTONNES)

(After I.O.E. 1985.)

	U.K.	Norway	Denmark	Netherlands	Germany
losses from tankers	3.0–10.0	0.56	0.0005	1.65	0.32
losses from shipping (including operational discharges from tankers)	?	2.0	1.5	?	0.2
reception facilities	0.5	n.a.	0.002	0.046	0.012
oil terminals	0.5	1.5	0	n.a.	0.29
inland navigation	?	n.a.	0	4.0–9.0	5.7

n.a., Not available.

of Energy showing that the total quantity of oil discharged on cuttings by the United Kingdom has increased from 5.78 kt in 1981 to 19.6 kt in 1985. These also show that the earlier figures for this input in tables 1 and 2 were underestimates.

There are several points to be made about inputs from these four major sources. It is to be expected that coastal waters receive a greater annual deposition of petroleum hydrocarbons from the atmosphere than more distant North Sea waters. This input is diffuse and its composition and environmental effects are largely unknown because of changes brought about by processes such as photolysis and photo-oxidation while in transit. Inputs from rivers to the North Sea can be considered more as point sources and the effects are thought to be restricted to coastal waters. This is because most of their oil load is highly modified, degraded and adsorbed onto suspended solids by the time it reaches the sea and the bulk of this material will sediment out and be trapped in the estuary or be confined to adjacent coastal waters. However, the effects there of river-borne oil are augmented by the many, direct, industrial point sources of oil into estuaries and coastal waters including those from coastal oil industry activity. General land run-off, most shipping losses and operational discharges from shipping may be considered as a diffuse coastal input or as a series of minor, local point sources. The input from offshore

Table 5. Total combined sector North Sea oil inputs from offshore operations by source, 1982–1983 (kilotonnes)

(After I.O.E. 1985.)

production and displacement water	3.0	increasing annually
oil on cuttings	20.0†	reflects annual usage of oil-based muds and drilling activity
drainage	0.1	relatively constant
atmospheric inputs from flaring	0.2–1.0	approximate figure, decreasing
spills	0.4–2.0	highly variable from one year to the next, range makes no allowance for major incidents such as prolonged blowout
total North Sea	23.7–26.1	

† No input from Dutch Sector drilling activity is assumed.

oil and gas developments is very different because it enters the sea almost entirely as unweathered oil attached to particles which pass directly to otherwise uncontaminated offshore sediments around a series of discrete point sources. The low-toxicity alternative base-oils now in common use also differ significantly in composition from the residues of crude, refined and lubricating oils that characterize most of the other inputs because of the absence of higher molecular mass aromatic fractions. They also differ from the fresh crudes and fuel oils typical of large spillages because of a reduced content of lower molecular mass aromatics. Therefore the environmental effects of discharged base-oils in sediments can be expected to differ from those of other oil inputs. If large-scale oil and gas development moves into coastal and estuarine waters this point-source contamination could be added to areas already likely to be under general stress from other oil inputs and other contaminants, such as heavy metals and persistent organohalogens. On the other hand the biological populations in these areas are likely to be more adapted to the presence of oil than those offshore.

A more detailed examination of the sources and nature of the inputs from offshore oil and gas developments to the whole North Sea can be made by considering the United Kingdom sector activity, because these inputs are largely due to drilling activities and the United Kingdom has the greatest number of offshore installations and the largest drilling programme.

United kingdom inputs to the North Sea from offshore oil and gas developments

Sources of information

The pollution control authority for the United Kingdom offshore oil and gas industry is the Petroleum Engineering Division (PED) of the Department of Energy (DEn). A close liaison is maintained between DEn and the two Government fisheries departments, the Department of Agriculture and Fisheries for Scotland (DAFS) and the Ministry of Agriculture, Fisheries and Food (MAFF). The Petroleum Engineering Division of DEn receives information of all discharges of oil from the United Kingdom offshore industry into the marine environment because of its powers under the Prevention of Oil Pollution Act 1971. This Act covers the discharges of oil in produced water and storage displacement water, oil spills and oil on drill cuttings.

There are no statutory regulations covering the discharge of chemicals which are part of normal operations, but surveys of chemicals used offshore during 1982 and 1984 have been carried out and when combined with information from the voluntary 'Notification Scheme for the Selection of Chemicals for Use Offshore' give an indication of the quantities, types and toxicities of chemicals used and discharged in both drilling and production activity.

Growth of offshore oil and gas activity

Before discussing the various discharges we shall briefly consider the growth in the United Kingdom offshore oil and gas activity over the past five years, bearing in mind that gas was first produced offshore in 1967 and oil in 1975. Gas production has risen from 37.4×10^9 m^3 in 1981 to 43.0×10^9 m^3 in 1985 and oil production has risen from 87.7 mt to 127.5 mt over the same period. The great majority of discharges arise from drilling operations and the number of wells drilled annually has increased from 211 to 273. Only a small fraction of the discharges from production activity arises from gas production; the majority is associated with oil production and during the past six years the number of oil production platforms has increased from 26 to 36.

(*a*) *Oil*

Oil from offshore activity enters the marine environment from three sources.

(i) *Oil spills*. Table 6 gives details of offshore oil spills from platforms reported to the Department of Energy from 1981 to 1985. Each year there have been two or three spills in the range of 30–80 t but the majority of spills are in the range of 1–3 t. However, there is no discernible pattern of oil spills and it is not possible to predict their future numbers or sizes.

TABLE 6. OFFSHORE OIL SPILLS FROM INSTALLATIONS REPORTED TO THE DEPARTMENT OF ENERGY 1981–1985

year	number	total amount/t	number of producing platforms
1981	71	104	26
1982	42	162	28
1983	62	186	32
1984	47	130	34
1985	87	310	35

(ii) *Oil associated with produced water and storage displacement water*. When oil is first produced from a geological reservoir the water content is usually low but over the life of any production platform the water content gradually increases. When the water content exceeds a certain level (usually that figure acceptable for transport via a pipeline) water is separated from the oil and discharged offshore. Some offshore installations possess facilities for storing oil in sub-sea cells with an oil–water interface. When oil is transferred to these the displaced storage water is discharged.

Section 3 of the 1971 Prevention of Oil Pollution Act makes it an offence for any offshore installation to discharge any oil or any mixture containing oil. However, it is not practicable to remove oil totally from production water and so installations are exempted from the

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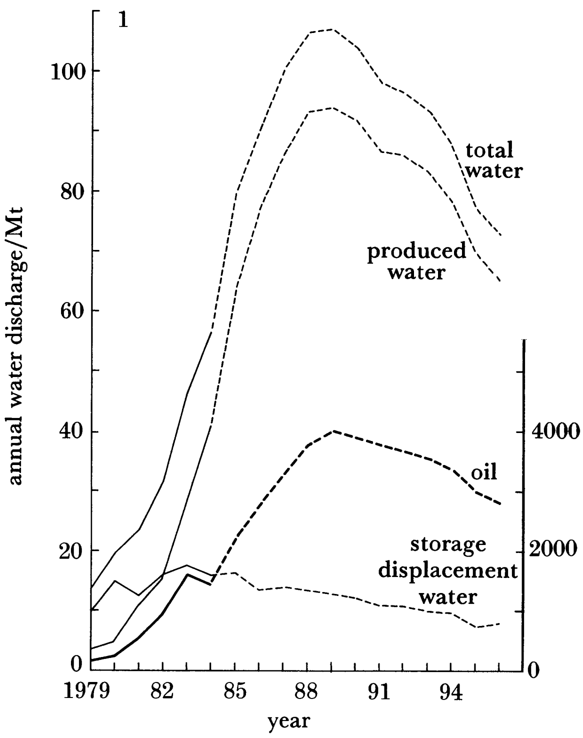
provisions of the 1971 Act under section 23. Each exemption has a schedule attached which sets out the requirements for sampling and analysis of the relevant discharge. Platforms are expected to comply with a monthly average oil in water standard of less than 40 mg l^{-1} and records of analyses for oil water and volumes of water discharged are returned to DEn each month. These returns, combined with a recent survey of projected production water discharges from each platform, enable a picture of past and future discharges to be constructed.

Figure 1 shows this picture for all fields currently in production from 1979 to 1996. Data for 1979 to 1984 are actual recorded figures, for 1985 to 1989 are reliable projections and for 1990 onwards are speculative because of problems in forecasting. New fields not yet in production have not been included.



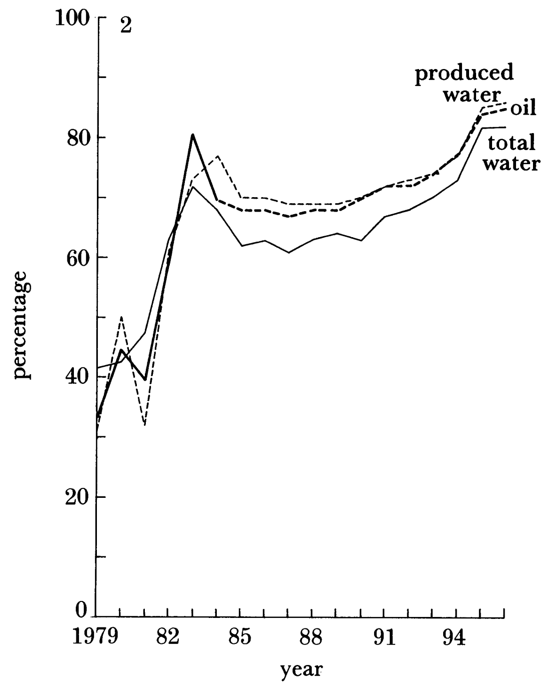


Figure 1. Projection of oil and water discharged from United Kingdom North Sea oil operations.

Figure 2. Projection of United Kingdom East Shetland Basin discharges as a percentage of all United Kingdom North Sea oil production discharges. The left ordinate is the East Shetland Basin discharge as a percentage of total North Sea discharge.

The indications are that water production will peak around 1989–1990 although the tail-off may not be as steep as shown when new platforms come into production. A peak figure of around 110 Mt per year of water can be expected, i.e. around twice the 1984 figure. It should be noted that current installed capacity for water treatment is around 220 Mt per year.

The projected increase in the discharge of oil associated with the water will be larger, rising to a probable figure of around 4 kt per year (about three times the 1984 figure); this is because of the concentration of oil in discharged water increasing as the water flow rate approaches the control equipment design capacity. At present, two thirds of platforms are operating with their control equipment at between 10% and 50% of design capacity, the median figure being

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30 %. It has been assumed that the average concentration will be 40 mg l^{-1} for produced water and 10 mg l^{-1} for storage displacement water. The latter input will decrease slowly from a current annual figure of around 18 mt to around 9 mt.

Within the North Sea, much of the discharged water comes from the East Shetland Basin. This is a well-defined and relatively concentrated area of activity which tends to produce about three times more water per barrel of oil than other areas because of its formation characteristics. Figure 2 summarizes the importance of the East Shetlands area which is now producing around 70 % of water and associated oil and could produce an even higher percentage of discharged oil beyond 1989.

(iii) *Oil on drill cuttings*. In 1984, Section 1 of the 1971 Act was amended such that the definition of oil was changed from 'crude oil, fuel oil, lubricating oil and heavy diesel oil' to 'any oil produced directly or indirectly from crude oil'. This alteration was required to enable the 1971 Act to apply to diesel-oil and refined mineral-oil used in the formulation of oil-based muds (OBM). Drilling muds are traditionally regarded as mixtures of clays, water and chemicals circulated to the drill bit to lubricate the systems, carry away rock cuttings, maintain the required pressure at the bit end and to provide an aid to geological formation evaluation. An important requirement for any drilling mud is that it stabilizes the borehole against collapse. In the North Sea OBMs are necessary owing to the occurrence of claystones, shales and salt formations which can react with water-based muds to produce unstable hole conditions. This can lead to protracted drilling operations, reduced safety and possibly the complete loss of some wells.

The past five years have seen a marked increase in the use of OBM, although this appears now to have levelled off and should in future reflect the general level of drilling activity. In 1981 the main base-oil used to formulate OBM was diesel-oil; concern about the amount of diesel oil being discharged to sea led to the establishment of a working group made up of representatives from DEn, DAFS, MAFF and the offshore oil industry to study the environmental effects around production platforms. As a result, new guidelines were drawn up to control the discharge of oil on cuttings. It was concluded that the discharge of water-based muds did not constitute an environmental problem but that whole, oil-based muds should not be discharged. If diesel-based muds are to be used it is necessary for the installation to be fitted with equipment to remove oil from the cuttings. In practice, since the new regulations came into effect no diesel-based muds have been used. Where an acceptable low toxicity base-oil OBM is to be used the installation and operation of efficient equipment to separate cuttings from mud is considered to be adequate.

Table 7 shows the number of wells drilled using OBM from 1981 to 1985. From 1981 to 1984

TABLE 7. WELLS DRILLED WITH OIL-BASED MUD (OBM) ON THE UNITED KINGDOM SECTOR 1981–1985

year	1981	1982	1983	1984	1985
total wells drilled	211	229	223	290	273
percentage drilled using OBM	36	50	65	76	77
percentage using low toxicity mud	2	15	39	71	77
weight of diesel discharged/t	5500	6000	6200	1400	0
weight of low toxicity oil discharged/t	280	2600	8300	18400	19600
total oil discharged/t	5780	8600	14500	19800	19600
oil per well/t	76	75	100	90	93

an average figure of 177 g oil per kilogram of dry cuttings was assumed and this has been substantiated by the figures for 1985 when an average of 180 g kg^{-1} was recorded. The total quantity of oil discharged on cuttings is determined primarily by the amount of drilling activity and it is not possible to determine what this will be in the future.

(iv) *Total oil inputs from installations*. Total inputs of oil to the North Sea from the United Kingdom sector offshore oil and gas activity are summarized in table 8. It can be seen that the main input of oil (90 %) is from drill cuttings with reported oil spills representing only about 1 % of the oil released into the sea.

TABLE 8. TOTAL INPUTS OF OIL TO THE NORTH SEA FROM UNITED KINGDOM SECTOR OFFSHORE OIL AND GAS ACTIVITY

year	1981	1982	1983	1984	1985
total input/t	*6409*	*9689*	*16386*	*21350*	*22072*
percentage from:					
oil spills	1.6	1.6	1.1	1.0	1.4
produced water	8.2	9.6	10.4	6.7	9.8
drilling	90.2	88.8	88.5	92.3	88.8
total stabilized crude oil produced from offshore fields/mt	*87.7*	*100.1*	*110.5*	*120.8*	*127.5*

(*b*) *Chemicals*

In 1979 the United Kingdom Government established its 'Notification Scheme for the Selection of Chemicals for Use Offshore' (CNS) to monitor and advise on the use and discharge of chemicals from oil and gas activities on the United Kingdom continental shelf. The aim of the voluntary scheme is to prevent damage being caused to the marine environment by discharges other than oil from offshore installations.

Surveys of chemicals used in 1982 and 1984 were carried out to determine the quantities and types of chemicals discharged. An attempt has been made to separate drilling operations from production operations; here production refers to chemicals added after the production manifold (prior to and downstream of phase separation) and also to chemicals added for the treatment of injection water or cooling water.

(i) *Production chemicals*. In 1984, 22 kt of production chemicals were used compared to 9 kt in 1982, the main increase being about 7.5 kt of gas treatment chemicals (mainly monoethylene glycol, triethylene glycol and methanol). Gas platforms were not included in the 1982 survey. Production chemicals constituted only 5–10 % of all chemicals used and typically only one fifth by mass were discharged to the sea. Production chemicals therefore constituted only 1–2 % of all discharges. Table 9 lists the type of products discharged because of offshore production

TABLE 9. PRODUCTS DISCHARGED AS A RESULT OF OFFSHORE PRODUCTION OPERATIONS (TONNES)

year	1982	1984
scale inhibitors	950	1200
corrosion inhibitors	550	220
biocides	180	500
demulsifiers	30	600
oxygen scavengers	30	120
gas treatment	—	520

operations. The main differences between 1982 and 1984 would appear to be the increased discharges of biocides, demulsifiers and oxygen scavengers. However, in the 1982 survey the use of onboard chlorine generators was not covered and this accounts for the majority of the increased discharge of biocides in 1984. The increased discharge of oxygen scavengers and demulsifiers is due to increased rates of water injection and water production.

There has been a marked increase in the proportion of production chemicals used and discharged for which full toxicity data have been made available; this has increased from 33% of the discharged materials by mass in 1982 to 70% in 1984. No toxicity or product composition data have been made available for about 20% of the mass discharged but given that the scheme is voluntary it will be difficult to improve this situation. Nevertheless, from the information received, it seems unlikely that any production chemicals used and discharged had potentially harmful toxic properties (i.e. with a 96 h LC_{50} to brown shrimp, *Crangon crangon*, of less than 1 part/10^6).

It is not possible to predict future discharges of production chemicals other than to say that they can be expected to increase as more treated water is injected into reservoirs and more residually contaminated water is produced with the oil, even though oil production itself is expected to decline.

(ii) *Drilling fluids*. The number of wells drilled increased from 223 in 1982 to 290 in 1984 and the quantity of chemicals used increased by roughly the same proportion. However, the quantity of chemicals discharged remained relatively constant at 133 kt in 1984 compared with 136 kt in 1982, i.e. the percentage of chemicals used which were discharged dropped from 81% to 57%. This reflects the increased use of oil-based muds: from 50% of all wells drilled in 1982 to 76% of all wells drilled in 1984. United Kingdom regulations allow the discharge of whole, water-based muds but not of whole, oil-based muds which have to be returned to the shore for reprocessing. The discharges of the base-oil component were excluded from both surveys because they are covered elsewhere.

Of the other drilling fluid components discharged, 127 kt in 1984 and 131 kt in 1982 are inert or derivatives of natural products and are considered to have little or no environmental impact apart from local effects of physical smothering, sediment grain size alteration and organic enrichment. Note that even the discharge of clean rock cuttings would lead to the first two of these effects and that barites and bentonite, which together account for around 75% by mass of all drilling discharges, are virtually insoluble and inert.

There are no important differences between the types and quantities of drilling fluid chemicals discharged during 1982 and 1984, and table 10 lists the majority of chemicals discharged as a result of offshore drilling operations. Polymeric viscosifiers such as carboxymethyl celluloses and starches are generally biodegradable and have little or no environmental effect beyond organic enrichment. The main lignosulphonate used is ferrochrome lignosulphonate with 3–4% Cr^{3+}. Chromium is strongly adsorbed onto the clay minerals in the drilling mud and probably has little or no effect outside the immediate settlement zone. Of the total 5–6 kt of 'non-inert' materials, full composition and toxicity data are available for about 50% by mass but no information on 25% by mass. However, because of statutory requirements, although toxicity data are not available on all the individual mud components, they are available on the complete mud systems which must have a 96 h LC_{50} to *Crangon* of greater than 6000 parts/10^6. Therefore, although it would be desirable to bring more individual drilling products into the CNS, such an omission is not as serious as it might at first appear

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TABLE 10. PRODUCTS DISCHARGED AS A RESULT OF OFFSHORE DRILLING OPERATIONS (TONNES)

year	1982	1984
weighting agents and inorganic gelling products	*112400*	*111600*
inorganic chemicals	*12560*	*11000*
polymeric viscosifiers	*4280*	*3680*
lignosulphonates, lignites, etc.	*700*	*630*
minor additives:		
surfactants, detergents	250	200
de-foamers	65	400
biocides	150	20
corrosion inhibitors	150	20
drilling lubricants	190	200
oxygen scavengers	160	65
dispersants	30	95
pipe release agents	25	15
scale inhibitors	10	10

in estimating potential environmental damage. From the toxicity data available, it can be predicted that the great majority of the 'non-inert' materials have a 96 h LC_{50} to *Crangon* of greater than 1 part/10^6.

As with the discharge of oil associated with drill cuttings it is not possible to predict future discharges of drilling chemicals, which will be related to overall drilling activity.

One tentative conclusion from the two surveys of production and drilling chemicals is that the quantity of more toxic chemicals (i.e. those with a 96 h LC_{50} to *Crangon* of less than 1 part/10^6) discharged from offshore oil and gas activity on the United Kingdom continental shelf during 1982 and 1984 was less than 50 t per year. Therefore although the quantity of non-oily materials discharged offshore to the United Kingdom continental shelf is large, the effects are expected to be restricted in extent and severity. Similarly, the oil inputs from the United Kingdom offshore oil and gas industry enter North Sea waters and sediments from a series of point-sources and have strictly localized effects compared with coastal inputs. This can be shown by considering the results of surveys carried out by MAFF, monitoring hydrocarbon concentrations in United Kingdom waters and sediments.

HYDROCARBON CONCENTRATIONS IN UNITED KINGDOM WATER AND SEDIMENTS

Water

Hydrocarbon concentrations in uncontaminated offshore water are generally less than 2 μg l^{-1}. Law (1981) found total hydrocarbon concentrations in subsurface waters of 0.7–1.3 μg l^{-1} (mean 0.9 μg l^{-1}) Ekofisk crude oil equivalents near the median line of the North Sea between 55 °N and 57 °N, south of the Auk and Ekofisk oil fields. In a more recent survey in 1985 carried out between Auk, the Forties field and the Norwegian coast, concentrations between 0.7 and 1.3 μg l^{-1} (mean 1.0 μg l^{-1}) were found. All these values were determined by fluorescence spectroscopy and blank-corrected. In the southern North Sea concentrations were somewhat higher, 1.3–2.7 μg l^{-1}, with a mean of 1.7 μg l^{-1} (Law 1981). In coastal areas and around industrialized estuaries higher concentrations are found. A series of transects were sampled during a cruise in 1984 directly out to sea from four east-coast estuaries, those of the rivers Tyne, Tees, Humber and Thames. Concentrations along these transects fell from 9.4 to 0.8 μg l^{-1}, 83 to 0.4 μg l^{-1}, 15 to 0.5 μg l^{-1}, and 11 to 1.5 μg l^{-1} respectively. Concentrations typical of offshore water were not reached within 40 miles of the coast off the Humber, but were established 20 miles off the other three estuaries. By comparison, preliminary results from a study of the dispersion of oily water discharges from a North Sea production platform in 1985 show the maximum hydrocarbon concentration 250 m down-current of the platform to be 60 μg l^{-1} at 10 m depth.

Sediments

In clean, sandy, offshore sediments on the Dogger Bank in the central North Sea total hydrocarbon concentrations are 0.4–2.0 μg g^{-1} dry mass Ekofisk crude-oil equivalents (Law & Fileman 1985). This is similar to the range found found in clean, sandy sediments in water greater than 100 m deep in the Western Approaches of 1.1–2.0 μg g^{-1} dry mass (Law 1981); a general background figure for clean sand would therefore appear to be less than 2 μg g^{-1}. Finer sediments tend to have higher concentrations, and so in muddier deposits background concentrations may reach 5 μg g^{-1}.

Sediment hydrocarbon concentrations vary widely in areas affected by oil pollution. During investigations of a chronic oil pollution problem associated with a refinery discharge Dicks & Iball (1981) found aliphatic hydrocarbon concentrations ranging from 100 to 5620 μg g^{-1} dry mass in an estuarine saltmarsh. Sediment samples collected intertidally from the outer Humber estuary and the north Lincolnshire coast following the *Sivand* oil spill in 1983 ranged from 16 to 1300 μg g^{-1} dry mass Ekofisk crude oil equivalents at sites believed to be unaffected by the spill but subject to chronic low-level input. Discharges of drill cuttings from offshore operations in which oil-based muds are used may lead to very high sediment concentrations close to discharging platforms. Davies *et al.* (1984) reviewed the effects of the use of oil-based drilling muds in the North Sea and compiled results from surveys done by a number of different groups around North Sea installations. They found that hydrocarbon concentrations in sediments within 250 m of a platform could be 1000 times the background concentration, but concentration gradients away from the platform were very steep and normal background concentrations were usually reached 2–3 km from the platform. Very high concentrations could be found beneath and directly alongside platforms: greater than 50000 μg g^{-1} dry mass alongside Beatrice (Davies *et al.* 1984) and 160000 μg g^{-1} dry mass diesel equivalents underneath Murchison (Law *et al.* 1982). Although the effects of such accumulations on benthic animals are obviously very marked, major biological effects occur in only a very limited area, generally within 500 m of the platform (Davies *et al.* 1984).

Most oil and gas developments to date have been in offshore areas largely unaffected by other hydrocarbon inputs. In the future it seems likely that more fields will be developed in coastal and even estuarine environments and it will then be more difficult to link effects and causes than at present.

Coastal areas

Data obtained during two recent pre-development surveys carried out by MAFF will serve to illustrate the greater complexity of sediment hydrocarbon distributions in coastal areas, whether in the North Sea or elsewhere. The first survey was carried out in the English Channel in 1982, south and west of the Isle of Wight. Sediment hydrocarbon concentrations ranged from 0.3 to 370 μg g^{-1} dry mass Ekofisk crude oil equivalents (figure 3).

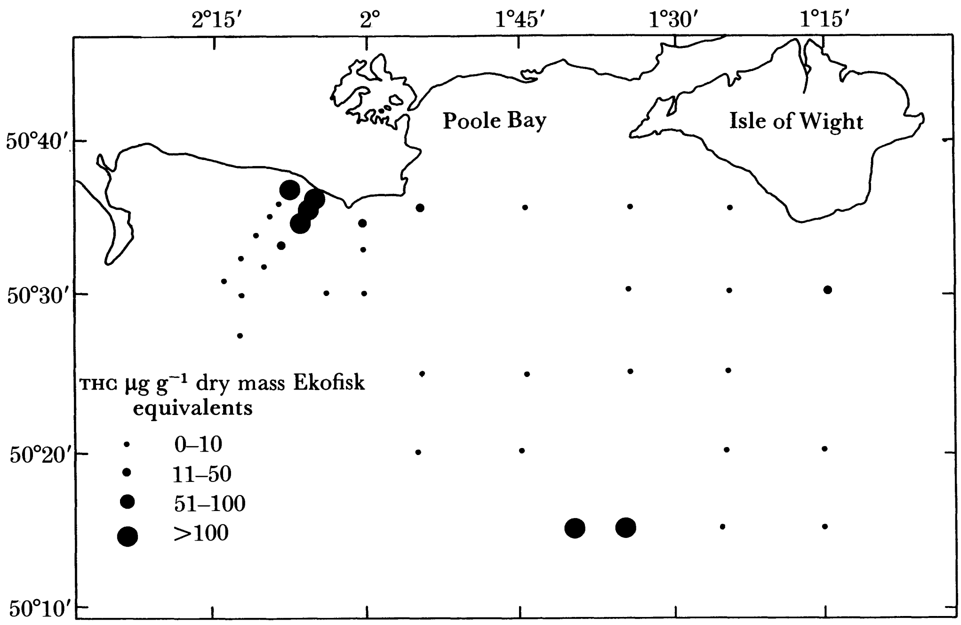

FIGURE 3. Total hydrocarbon concentrations in surface sediments from the English Channel, south and west of the Isle of Wight, in 1982.

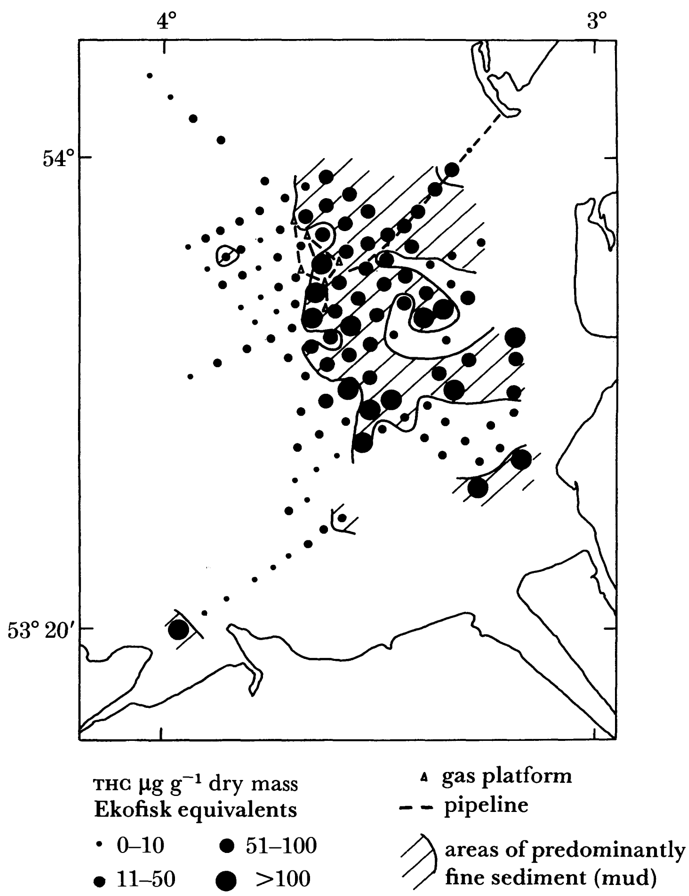

FIGURE 4. Total hydrocarbon concentrations in surface sediments from the eastern Irish Sea in 1982–1983.

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The high concentrations (120–370 μg g^{-1}) found in the northwestern corner of the grid, close to the Dorset coast, result from the presence of oil shale deposits at Kimmeridge and of a shale shelf outcropping into the sea. Similar oil shale deposits in the sediment at the two offshore sites at the bottom of the sampling grid are responsible for the isolated high values there (160 and 280 μg g^{-1}).

The second pre-development survey was done in 1982 and 1983 around the (then) proposed Morecambe Bay gas field. The sediment hydrocarbon distribution is related to the occurrence of fine mud particles as the dominant size fraction of the sediment (figure 4).

The gas field is situated at the western edge of a large mud patch extending down the eastern margin of the eastern Irish Sea, with sandy sediments occurring to the west of the gas field. Concentrations of sediment hydrocarbons ranged from 3.3 to 410 μg g^{-1} dry mass Ekofisk crude oil equivalents. The association between fine sediment and high concentrations of hydrocarbons is evident but the source of the hydrocarbons is more difficult to establish. The eastern Irish Sea is subjected to hydrocarbon inputs from a large number of different sources, including most, if not all, those discussed in the first part of this paper. A large proportion of the hydrocarbons reaching the eastern Irish Sea either enter adsorbed onto particulate material or rapidly become so, and it seems likely that high hydrocarbon concentrations are found in muddy sediments because this is where these are being deposited. The distribution is complex, and interpretation of monitoring data for sites at any distance from the discharge point would be much more difficult in an already contaminated coastal area like the eastern Irish Sea, than in comparatively clean offshore waters.

Conclusion

The inputs of petroleum hydrocarbons to the North Sea arise from a wide variety of sources. Although recent estimates of the size of these inputs varies, it is generally agreed that atmospheric return, rivers and land run-off (including coastal sewage), and coastal oil industry activities combined with shipping, remain major contributors. However, inputs from offshore oil and gas industry activities have recently increased and now form a major source. This increase is almost entirely due to the use of oil-based drill-muds and the consequent discharge of mud residues with rock cuttings. The nature, composition and effects of this input differ from those of inputs from most other sources and the United Kingdom situation is that its effects are restricted to small areas adjacent to the point-source discharges.

Of the materials other than oil discharged to the sea from offshore oil and gas developments in the United Kingdom, 98–99% arise from drilling operations but the vast majority of these are biologically inert or derivatives of natural products. Surveys of the materials used and discharged indicate that less than 50 t per year of the more toxic products are discharged into United Kingdom waters.

The largely uncontaminated offshore waters and sediments of the North Sea remain little affected by offshore oil and gas developments. If such activities move into already contaminated estuarine and coastal waters, contamination and effects from this source will be harder to distinguish from those of other sources.

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Discussion

R. E. Jones (*School of Ocean Sciences, University College of North Wales, Menai Bridge, U.K.*). Do the monitoring techniques record the quantity of short-chained hydrocarbons discharged and is this fraction accurately incorporated in the total hydrocarbon budget?

R. A. A. Blackman. The monitoring techniques used by MAFF to measure total hydrocarbons in water and sediment do not record short chain hydrocarbons. The figures for the budget of total petrogenic hydrocarbons entering the North Sea from the various sources are derived from a wide variety of monitoring methods, very few of which accurately record the short chain hydrocarbons. Such compounds are generally considered to be relatively ephemeral, except under continuous discharge conditions, and of low acute toxicity, although less is known of their chronic and sublethal effects.

J. G. Parker (*Shell Exploration and Production, Aberdeen, U.K.*). There is considerable generation of hydrocarbons in the sea due to planktonic activity. Has there been an assessment of the contribution from this source, and if so, how does it compare with the input from the offshore industry?

R. A. A. Blackman. Whittle *et al.* included estimates for biogenic hydrocarbons in United Kingdom waters in their paper (1982, p. 204). Phytoplanktonic production was then estimated to contribute about 100 kt annually, while total marine biogenic input to United Kingdom waters (from phytoplankton, zooplankton, benthos and fish) was estimated to be about 165 kt annually. These figures are similar to a 'standing stock' of petrogenic hydrocarbons in the North Sea of about 110 kt, based upon a background subsurface water concentration of 2 $\mu g\ l^{-1}$ (Whittle *et al.* 1982, p. 215) but biogenic hydrocarbons consist of a smaller range of, for the most part, simple straight and branched-chain compounds that are easily degradable and exert no toxic effects at these low levels.