Oil-leakages on the Øvre Romerike aquifer, Southern Norway

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Two leakages of, respectively 20 m^3 and < 10 m^3 of fuel oil have been investigated at Trandum and Sessvollmoen, on Norway's Øvre Romerike aquifer. The hydrocarbon content of the unsaturated and saturated sediments, and the hydrocarbon content of groundwater at both sites have been investigated. At Trandum, where the unsaturated zone consists largely of coarse sands, the oil appears to have migrated rapidly down towards the water table, and high dissolved hydrocarbon concentrations (0.6 - 1.6 mg/l) have been observed in groundwater from scavenger wells. At Sessvollmoen, the unsaturated zone consists of finer sediments, and the oil appears to have been retained at a relatively shallow depth, allowing only minor downwashing of soluble components to the water table. The scavenged groundwater contains around 0.05 mg/l hydrocarbon.

The contrast between the two case studies illustrates the importance of the type of sediment in the unsaturated zone, and thus its retention capacity, when assessing the impact of oil spills on aquifers.

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Introduction

The Øvre Romerike aquifer is Norway's largest discrete aquifer. It has a total area of some 105 km^2 (Davidsen 1990) and is composed of Quaternary deposits, largely of glaciofluvial origin. At present, the aquifer is only lightly exploited, but it has been the focus of much recent attention because of several pollution threats. Authorities have placed emphasis on protecting the quality of the groundwater in the aquifer from «potentially polluting activities», as it represents a possible future water resource for municipalities in the Romerike area (Østlandskonsult et al. 1991).

The area was the subject of one of Norway's earliest attempts at environmental «Geoplan» mapping, where various user-interests, including groundwater interests, were considered in the context of future areal planning (Wolden & Erichsen 1990).

It was in such a context that two oil leakages at Trandum (20 m^3) and Sessvollmoen (<10m^3) were discovered. These attracted much attention from the local and national media. The polluter (the Norwegian Defence Construction Service) was ordered by the State Pollution Prevention Agency (SFT) to undertake extensive investigations and to produce plans for remedial action. It is the results of these investigations that this paper addresses.

Areal use and potential pollution sources

The Romerike aquifer is not urbanised, but nevertheless is the host to several military bases, a military airstrip, a civil airport (Gardermoen), and diverse military exercises. The area is also intensively worked for sand and gravel. The Romerike deposit is believed to contain 150-200 million m^3 of good quality sand and gravel (Wolden & Erichsen 1990). The aquifer contains Norway's largest discrete reserve of fresh groundwater, although at present it is only lightly exploited, supplying the military bases and the local municipality's needs. Authorities have, however, emphasised the need to preserve the quality of the aquifer's groundwater for more extensive potential future use in supplying the municipalities of the Romerike area. Wolden & Erichsen (1990) have compiled «Geoplan» maps illustrating the various sand and gravel, groundwater and geological conservation interests which should be preserved in the area.

There are at present several potential pollution threats to the aquifer:

(a) the existing civil & military airport at Gardermoen, and the proposed removal of Oslo's main airport thither (Davidsen 1990). Propylene glycol and urea are used as de-icing agents,

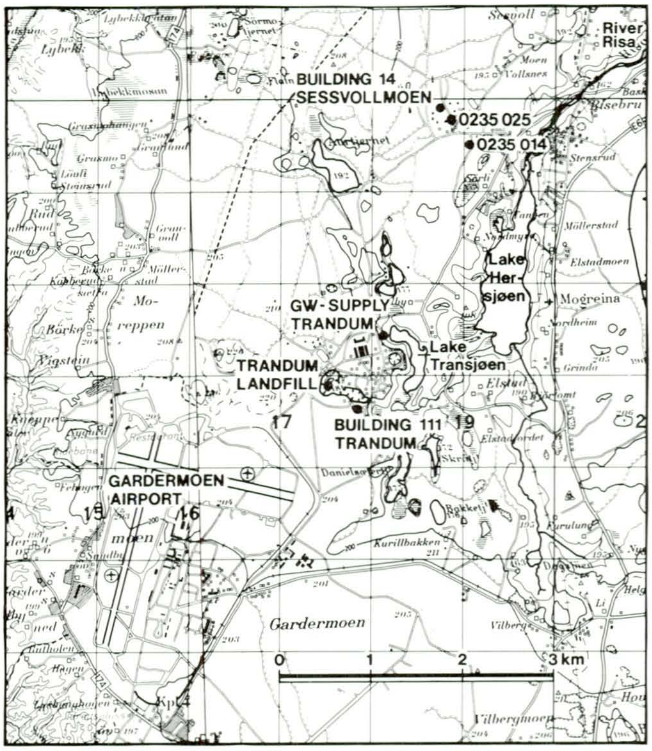


Fig. 1. Map of Trandum/Sessvollmoen area, showing hydrogeological features and various possible pollution threats. 0235-numbers refer to localities in Morland et al. (1990).

and there is also the threat of major spillages of oil or kerosene.
(b) the numerous military bases & training grounds on the aquifer. At these large amounts of oil and diesel are used for heating purposes and for refuelling vehicles. The possibility cannot be excluded that diesel has also been used for 'washing-down' of vehicles.
(c) the recent national hazardous waste survey (Misund et al. 1991a,b) identified several potentially serious landfills and instances of contaminated ground (Morland et al. 1990).
(d) the discovery, in the latter part of 1990, of two separate incidents involving the leakage of fuel oil from storage tanks, at Trandum and Sessvollmoen military bases (Storrø 1991, Banks 1991).

The locations of these pollution hazards are shown on Fig.1.

Geology and hydrogeology

The geology of the area is described in detail by Longva (1987). The Romerike aquifer consists of a 105 km^2 expanse of Quaternary ice-marginal delta sediments built up to the marine limit. The upper part of the aquifer consists of dominantly glaciofluvial sand and gravel deposits, with areas of aeolian sand and glaciolacustrine sands and silts. These are underlain by glaciomarine/marine silts and clays. The upper, coarser part of the deposit exceeds 30-40 m thickness in some areas, while the total depth to bedrock (including marine silts and clays) may be as much as 100 m (Østmo 1976, Jørgensen & Østmo 1990).

The main surface water drainage of the aquifer consists of the northwards-flowing River Risa and Hersjøen Lake. The River and Lake are almost entirely groundwater-fed (Jørgensen & Østmo 1990).

There has been intense hydrogeological and hydrochemical investigation of the aquifer due to its selection as a study area for the International Hydrological Decade (Falkenmark 1972, Norwegian National Committee for IHD 1973, 1975). This has resulted in the publication of a hydrogeological map (Østmo 1976), and descriptions of the hydrogeology (Jørgensen & Østmo 1990) and hydrochemistry (Jørgensen et al. 1991). The aquifer is entirely fed by recharge from precipitation. Østmo's (1976) map

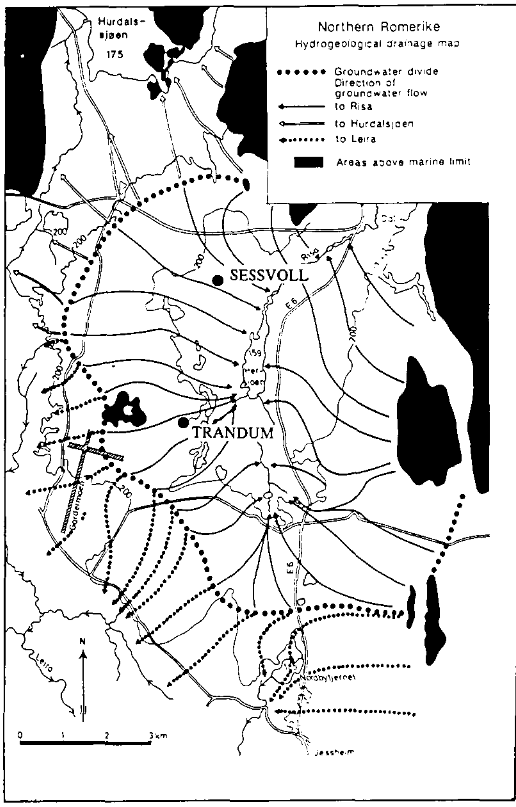


Fig. 2. Regional groundwater flow pattern within the Øvre-Romerike aquifer - after Østmo (1976), Jørgensen & Østmo (1990).

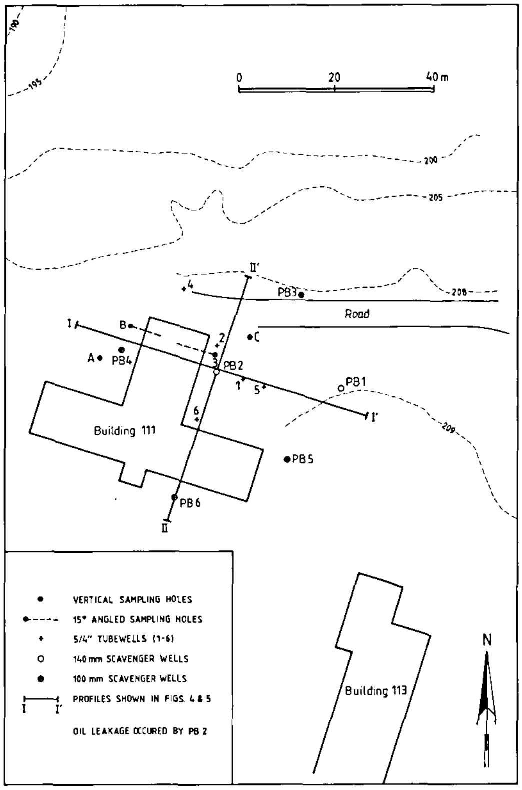


Fig. 3. Summary map of leakage area at Trandum. Profiles I-I' and II-II' refer to Figs.4 & 5. The leakage occurred by PB2.

(Fig.2) indicates that the major central part of the aquifer drains towards Hersjøen and the River Risa. The average discharge in the River Risa (in the period 1967-74) was 0.85 m^3/s (Jørgensen & Østmo 1990). The marginal parts of the aquifer drain outwards towards springs in the periphery of the delta. Hydraulic and hydrochemical balances for the aquifer have been calculated. The permeability within the aquifer is believed to range between 5 m/d for coarse sands to 0.06 m/d for silts on the basis of particle-size distributions (Jørgensen & Østmo 1990).

The Trandum oil-leakage

Introduction

The location of the Trandum base is shown on Fig.1. It lies on the central part of the Øvre-Romerike aquifer, ca. 1-2 km SW of Hersjøen. Groundwater flow drains towards Hersjøen. On October 12^{th}, 1990, an acute leakage of light fuel-oil (consisting mainly of C_{10} - C_{20} hydrocarbons, and with a density of 845 kg/m^3 at 15°C) was discovered at an underground storage tank adjacent to Building 111 at Trandum (Fig.3). The entire contents of the tank (20,000 l) had drained rapidly out into the ground. On excavation of the tank, the leakage was found to have occured through a discrete hole of c. 2 cm diameter. It is believed that the hole was caused by a sharp stone puncturing the (possibly corrosion-weakened) tank under loading. The incident was reported immediately and the Geological Survey og Norway (NGU) were requested to undertake further investigations and immediate remedial action. The results of these investigations are reported in detail by Storrø (1991).

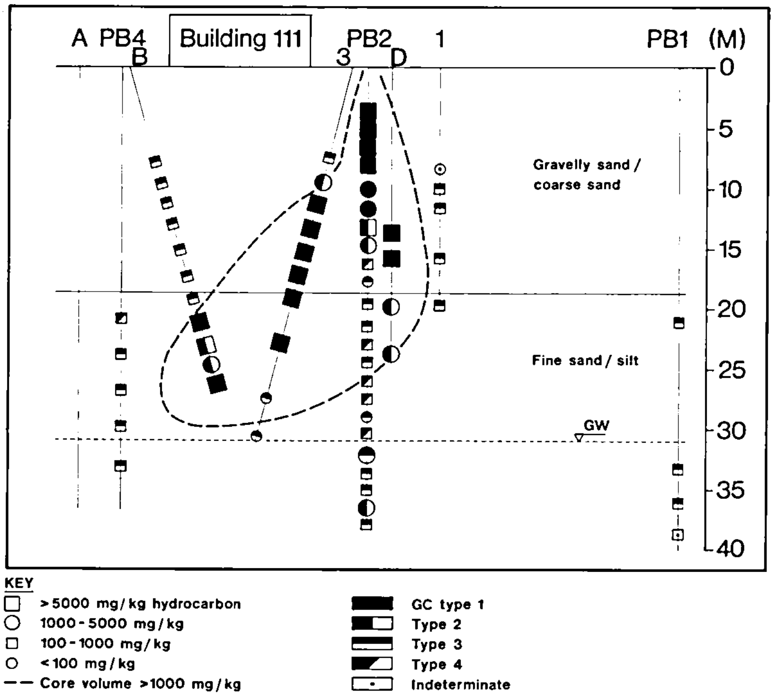


Fig. 4. Profile I - I' (Fig.3) through leakage area at Trandum, showing THC content of sediment and gas-chromatogram type. Drilling dates: PB1 = 17-20/10/90; PB2 = 23-26/10/90; 3 = 27/10/90; B = 7/11/90; PB4 & D = 8/11/90. Assessment of «core volume» is based on situation as determined on November 8th, 1990.

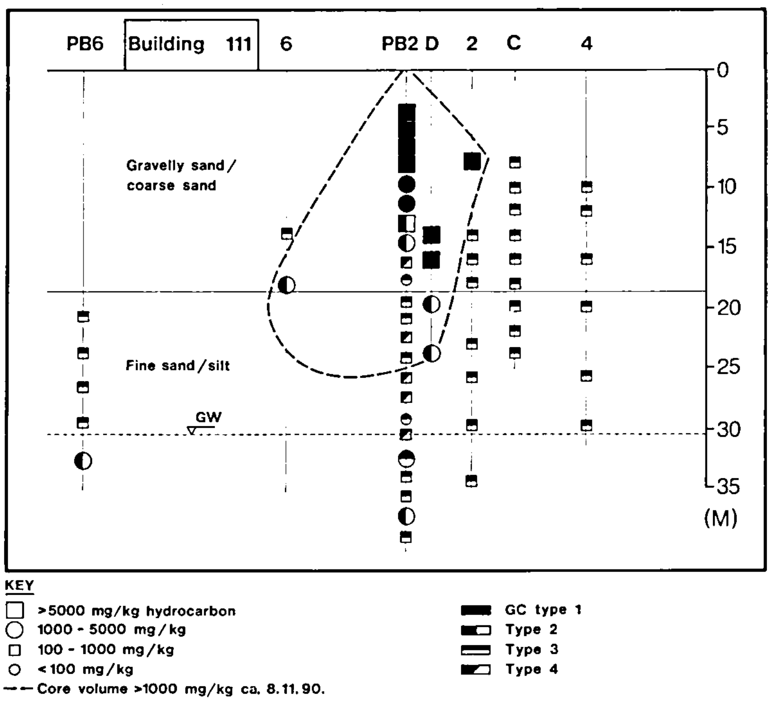


Fig. 5. Profile II - II' (Fig.3) through leakage area at Trandum, showing THC content of sediment and gas-chromatogram type. Drilling dates: PB2 = 23-26/10/90; 2 = 26/10/90; C, D & 6 = 8/11/90; PB6 = 9/11/90. Assessment of «core volume» is based on situation as determined on November 8th, 1990.

Investigations

A plan of the boreholes constructed to investigate the leakage is shown in Fig. 3. The scavenger borehole PB1 was established immediately after the leakage was reported. Sediment and water samples were taken from PB1 to establish the extent of contamination. It was planned to pump the borehole continuously to scavenge contaminated water from the aquifer, but in the event, neither seriously contaminated sediment nor contaminated water was discovered in PB1.

A new scavenger borehole PB2 was thus established on the site of the oil tank, and several trial holes were drilled in the surrounding area. In these, oil contamination was found in the unsaturated zone down to c. 25 m under ground level. The mineral oil content (total hydrocarbon content, THC) in the sediments was determined by gas-chromatography, and the results of the analyses are shown in Figs. 4 & 5. Parallel with sediment-sampling, observation boreholes were established for monitoring of groundwater level and hydraulic gradient.

Stratigraphy

The sediments sampled in the various investigation boreholes gave the following stratigraphy:

0 - 19 m: layered sediments, comprising mainly gravelly sand with individual pure sand or gravel layers.
19 - 31 m: fine sand/silty sand with gravelly layers.
31 - ? m: finesand, silty sand, silt.

It is worth noting here that the stratigraphy at Sessvollmoen was the opposite of that at Trandum, i.e. fine-grained sediments in the unsaturated zone, with coarser sediments beneath the water table.

Hydrogeology

The water table in the Trandum leakage-area, in November 1990, was found to be 31-32 m below ground surface. Contours on the water table (under non-pumping conditions) are shown in Fig. 6. The maximum water table level in the Øvre Romerike aquifer normally occurs around the beginning of July, at the end of the snow-melting period. The increase in groundwater level during the thaw period is normally less than 1 m.

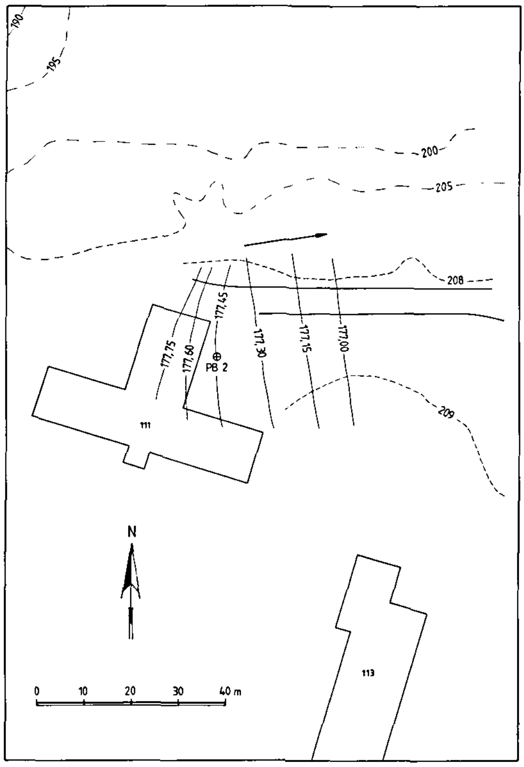


Fig. 6. Groundwater contours (non-pumping) at leakage area, Trandum, 1st November 1990. Dashed lines show topographical contours. Contours are in m above sea level.

A pumping test performed on PB2 yielded a transmissivity coefficient of c. 3 m^2/d, and a hydraulic conductivity of around 0.4 m/d (in the coarser aquifer at Sessvollmoen, the transmissivity was calculated as c. 100 m^2/d). Using a water table gradient of 0.012 - 0.018, and an assumed effective porosity of 10 - 20 %, one obtains a natural average groundwater velocity of some 0.04 - 0.08 m/d. Jørgensen & Østmo (1990) have reported velocities of up to 0.14 m/d in the Øvre Romerike aquifer.

The downward percolation velocity of groundwater recharge in the unsaturated zone has not been investigated during this project. Jørgensen & Østmo (1990), however, report velocities of up to 0.2 m/d during snow-melting.

Oil contamination within the sediments

Borehole 3 was drilled on October 27th , 15 days after the leakage occurred. Significant

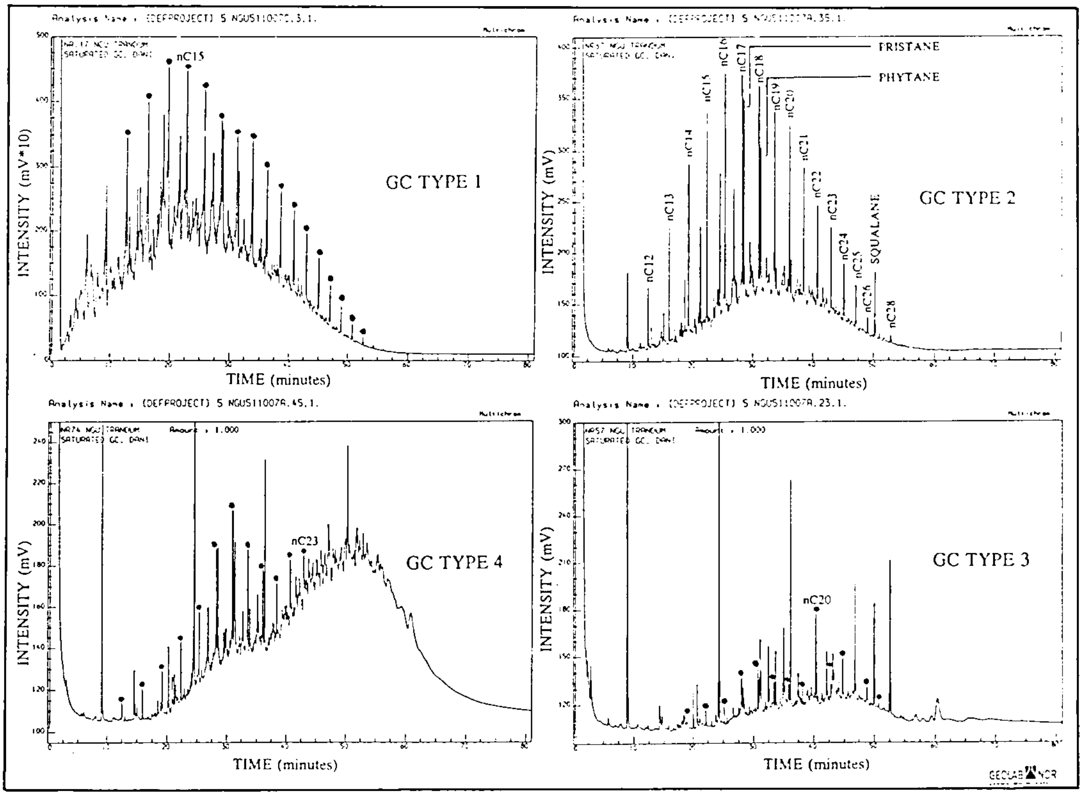


Fig. 7. Qualitative assessment of mineral oil in sediment samples. The figure shows the four main types of gas-chromatogram observed during investigations at Sessvollmoen & Trandum. See text and Figs. 4, 5, 12 & 13 for further explanation.

oil contamination was discovered down to 23 m depth in the sediments in borehole 3. Thus, the initial phase of downward movement of the oil-body during the leakage from the Trandum oil-tank appears to have occurred at around 1.5 m/day. Borehole PB2 was drilled on October 26th, and borehole D was drilled on November 8th at the same location. The 'core' of oil contamination extended to over 24 m deep in borehole D, as opposed to 15 m deep in PB2. Thus, in this later phase, the vertical seepage velocity was at least 0.7 m/day.

The assessed extent of the oil contamination in the unsaturated zone (as of November 8th) is shown in Figs.4 & 5. It has been chosen to define the contamination's 'core volume' as that volume of the sediments exhibiting THC values in excess of 1000 mg/kg (the Dutch B-value for soils). The core-volume appears to extend in a coniform manner from the tank area (PB2), and under Building 111 in a westerly and southerly direction. The core-volume is calculated to be around 940 m^3. With a leakage of 20 m^3 oil, this represents an average concentration of 21 l oil/m^3 sediment, or 10.4 g/kg (dry weight) assuming a dry density of 1700 kg/m^3. This agrees well with figures given in the literature (15-25 l/m^3) for oil-retention capacity in this type of sediment (Kristiansen 1983, Snekkerbakken 1988).

The core volume does not appear to have encountered the water table by November 8th. However, the calculated downward percolation velocities indicate that, although a major proportion of the oil has been retained in the unsaturated zone, the core volume is likely to have reached the water table shortly after that date. The lack of recovered oil phase (see next section) in the scavenger wells indicates, however, either that any floating oil-phase on top of the water table is of very limited extent, or that the oil is completely dissolving in the saturated zone's groundwater.

Gas-chromatography is a useful tool for the qualitative assessment of the hydrocarbon content in various parts of the contaminated area. Fig.7 shows the four main types of chromatogram resulting from the analyses. The prominent peaks in the chromatograms represent the n-alkane components with increasing numbers of carbon atoms in the chain. The chromatograms for the samples with the highest oil concentrations (>5000 mg/kg) show fresh oil (GC type 1), with a GC maximum around C_{14}. Samples with an oil content 1000 - 5000 mg/kg yield chromatograms where the maximum is displaced a little to the right, typically up to C_{17}, due to evaporation of lighter components as the oil seeps down into the unsaturated zone (GC type 2). GC type 3 is typical of the 'natural background' signal occurring in uncontaminated soil due to naturally occurring hydrocarbons. Here the chromatogram maximum is broad and occurs far to the right, typically around C_{22} - C_{25}. Components of GC type 3 could be observed in less contaminated samples (< 1000 mg/kg). GC type 4 is characteristic of oil strongly enriched in heavier components, due to extensive evaporation or biodegradation of lighter components (biodegradation may, in addition to the end products CO_2 and water, also produce heavy, long-chain by-products, thus emphasising the right-hand end of the chromatogram even more (Ståle Johnsen *pers.comm.* 1991)). The GC type 4 maximum may lie as far to the right as C_{27}. GC type 4 is typical of heavily evaporated/degraded fuel oil or of relatively fresh lubrication oil (i.e. possible contamination during drilling). The chromatogram types observed in the samples from Trandum are shown in Figs.4 & 5.

Oil contamination of groundwater

Groundwater samples were analysed for both total hydrocarbon content (THC) by gas-chromatography, and total organic carbon (TOC). The results indicate a clear increase in the groundwater THC from the first sampling date (7/11/90) to the more recent samples (Fig.14). By 20/12/90 all the scavenger wells (PB1 - PB6) exhibited THC in the range 0.6 to 1.6 mg/l, i.e. higher than the Dutch C-value. It is thus concluded that the incident at Trandum base led to local contamination of groundwater in the immediate vicinity of the leakage, although no distinct oil-phase, nor any taste or smell of oil, has hitherto been observed in the water scavenged from the site. The lack of oily taste or smell may conceivably be due to the lighter, taste-causing, oil components being evaporated or biodegraded during their passage through the unsaturated zone (Storrø 1991). It should be noted that samples taken from the scavenger well in January 1992, and analysed by another laboratory, appear to indicate a significant reduction in the hydrocarbon content of the groundwater one year after NGU's investigation (SIFF 1992), probably in part due to bioremediation attempts.

Reference samples were taken from a supply borehole at the Trandum military base some 800 m NNE of the tank-leakage (Fig. 1). The groundwater from this borehole contained clear traces of mineral oil. Subsequent samples have been taken for detailed analysis. These analyses show partially dissolved organic carbon in concentrations higher than the Norwegian drinking water standards permit (TOC < 3 mg/l - SIFF 1987). The geometry of the situation appears to preclude the oil-tank leakage as a possible source. It is therefore suggested that there may exist other sources of oil contamination to groundwater in the area. It should, however, be noted that a later sampling round (SIFF 1992), early in 1992, failed to detected significant hydrocarbon contamination in the supply borehole.

The inorganic chemical composition of Øvre Romerike's groundwater is documented by Jørgensen et al. (1991), and analyses from the Trandum military base show good agreement with the results in their paper. It should however be noted that the groundwater at Building 111 contains significantly higher concentrations of nitrate (2 mg NO_3^--N/l) than that which is typical for the aquifer. This nitrate could be derived from oil decomposition, or from other local pollution sources such as Trandum landfill (Misund & Sæther 1991, Sæther et al. 1992).

Remediation strategy

Scavenger well PB2 is operated continuously to prevent further spreading of oil contamination in the saturated zone away from the site. Scavenger wells PB1 & PB3-6 are equipped with submersible pumps, and can be brought into operation immediately should the situation deteriorate.

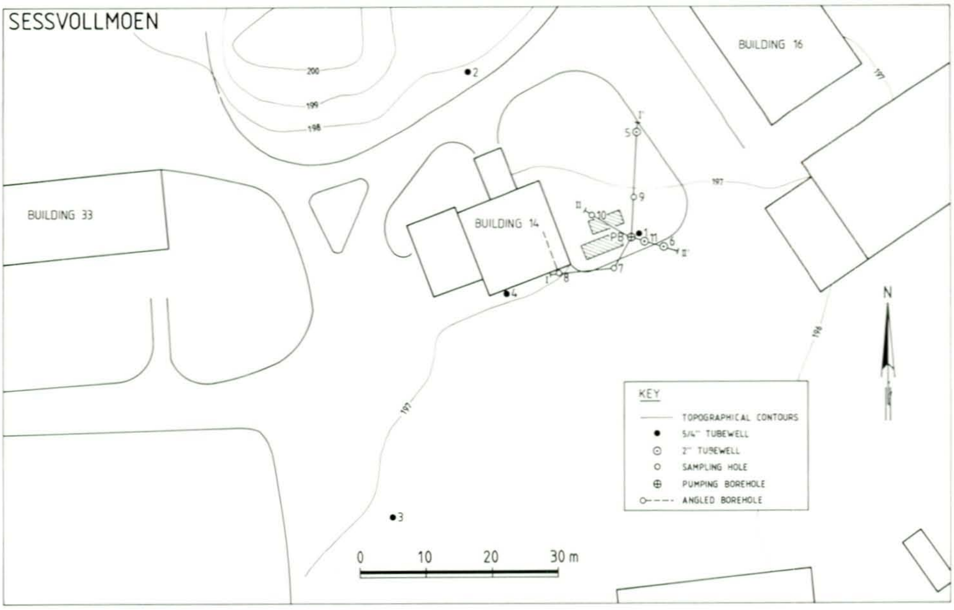


Fig. 8. Summary map of leakage area at Sessvollmoen. Profiles I-I' and II-II' refer to Figs. 12 & 13.

The interested parties in the tank-leakage incident are agreed on a strategy of in-situ bioremediation for the contaminated area. The remediation has been planned by the Norwegian Geotechnical Institute (Hauge 1990), and a pilot project is currently underway (Breedveld et al. 1991).

The Sessvollmoen oil-leakage

Introduction

As a result of the Trandum leakage, awareness of potential leakage problems was undoubtedly increased within the military authorities. As a result, it was not long before a second suspected leak was reported, at Sessvollmoen base (Fig.1), which lies a little to the NW of the central part of the aquifer. According to Østmo's (1976) map, groundwater drainage in this area is ESE towards the River Risa. On November 2nd, 1990, the underground fuel tanks adjacent to Building 14 (Fig.8) were routinely inspected, without any indication of a leakage. Reinspection occurred on December 13th, 1990, and calculations of consumption revealed that a volume of up to 10,000 l of light fuel oil appeared to have been lost through leakage. It is assumed that the leakage occurred near the entry pipe to the return tank, and was due to excavation work in the vicinity. The leakage was reported to the pollution authorities, and NGU was again invited to investigate the leakage. A scavenger well was sunk to 24 m at point PB (Fig.8), about 6 m from the assumed point of leakage. The well was completed on December 19th, 1990. The scavenger well was continuously pumped at 1800 l/hr, such that pump sat in the pumping water level at a depth of 19.65 m in order to recover any oil phase floating on the water table.

Investigations

These consisted of:

(a) drilling sampling boreholes and piezometers to investigate stratigraphy and hydrogeology

(b) sampling the sediments in these boreholes and analysing them for hydrocarbon content.

(c) taking regular water samples from the scavenger well for THC, TOC and inorganic analyses

Stratigraphy

Sediment samples were taken in the pumping borehole (down to 24 m) and several investigation boreholes (down to 20 m). The sediments encountered were mostly fine sand and silt above the water table. In the pumping borehole, where sampling intervals were more frequent than in the other holes, a c. 4 m thick layer of relatively well-sorted medium sand was encountered at around 8 m depth. A similar, thinner layer was also found at around 15 m depth. The water table was encountered at c. 17 m. Below the water table, fine sand and silt continued down to c. 20 m, below which coarser sediments (poorly sorted medium-grained sands) were found again. The base of this coarse layer was not encountered in the 24 m deep pumping hole. The aquifer thus appears to be a layered aquifer, with alternating higher and lower permeability layers. Vertical flow between layers in response to pumping is likely to be important.

It will be noted that the situation at Sessvollmoen is stratigraphically the opposite of the situation at Trandum, where coarse grained sediments in the unsaturated zone overlie finer sediments below the water table.

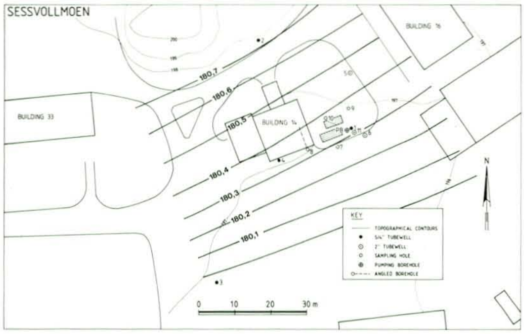


Fig. 9. Estimated groundwater contours (non-pumping) at leakage area, Sessvollmoen, 11th April 1991. Contours are in m above sea level.

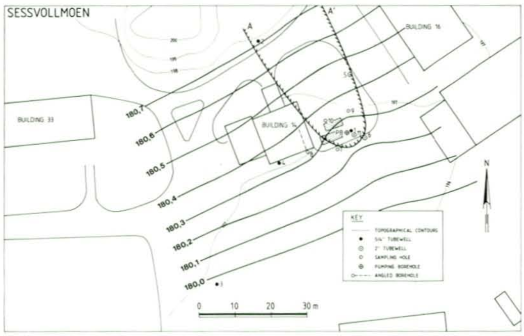


Fig. 10. Groundwater contours (pumping from borehole PB) at leakage area, Sessvollmoen, 11th April 1991. Contours are in m above sea level. A-A' is the catchment area of the pumping borehole.

Hydrogeology

The pumping well was installed to 24 m (with slotted screen from 12 - 24 m) and is thus believed to have drawn its water largely from the coarse-grained layer. All piezometers were, on the contrary, installed to 20 m (with the exception of piezometer 11, installed towards the end of the project) and so measured conditions near the base of the finer layer.

The rapid establishment of the scavenger well and the requirement to keep it continuously pumping permitted only limited hydraulic testing in the form of recovery tests of up to one hour's duration. The configuration of the tests was such that many of the assumptions of common aquifer test methods were not fulfilled, allowing only an approximate estimate of the aquifer's apparent transmissivity (T). Using the Jacob approximation on the pumping well, and piezometers 1 and 6, and also by applying the Theim method (Krusemann & DeRidder 1989), T was estimated as c.100 m^2/d. Assuming an aquifer thickness of several tens of metres, this implies an average permeability of a few m/d, agreeing well with Jørgensen & Østmo's (1990) estimates.

Due to the immediate operation of the scavenger well it was not possible to document the aquifer's rest condition. However, by observing the behaviour of piezometers during the recovery tests, it was possible to estimate the rest condition with a fair degree of accuracy (Fig.9). The natural groundwater gradient was found to be towards SSE rather than ESE as indicated by Østmo (1976). It was thus possible to calculate the drawdown caused by pumping. It appeared that only two of the observation boreholes experienced a drawdown of greater than 2 cm during pumping (compare Figs.9 & 10), namely piezometers 6 (5 m from pumping well, drawdown 5 cm) and 1 (1 m from pumping well, drawdown c.30 cm). From this information one can construct the scavenger well's catchment area either empirically by superimposing the cone of drawdown upon the natural groundwater gradient (Fig.11) or analytically by using the following formulae (Mutch 1989):

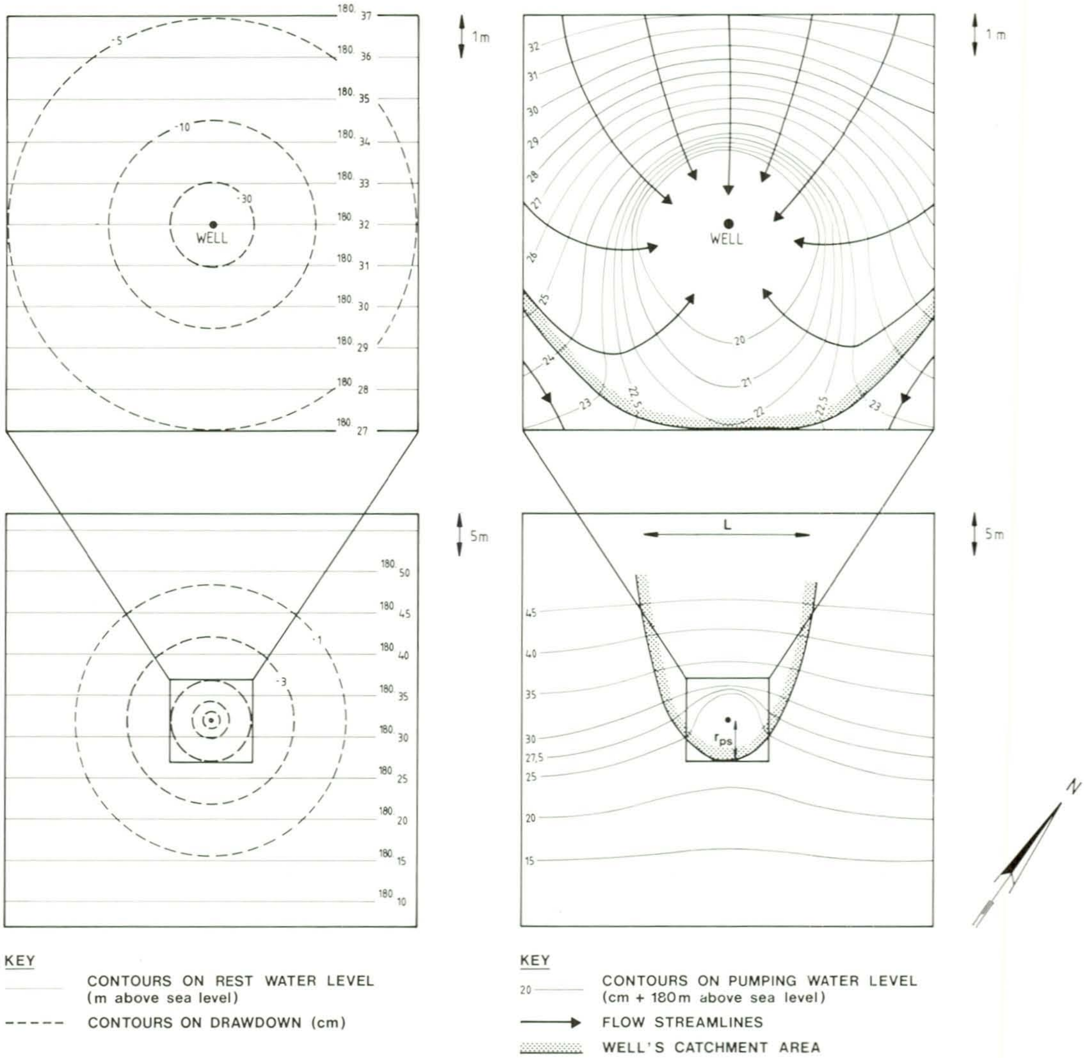


Fig. 11. Empirical calculation of scavenger borehole's catchment area, by superimposing cone of depression onto the natural groundwater gradient. See text for further explanation.

$$L = \frac{Q}{T^{*}i}$$

and $$r_{ps} = \frac{L}{2^{*}\pi}$$

where L = maximum breadth of catchment area upgradient of pumping well

r_{ps} = extent of catchment area downgradient of pumping well

T = transmissivity

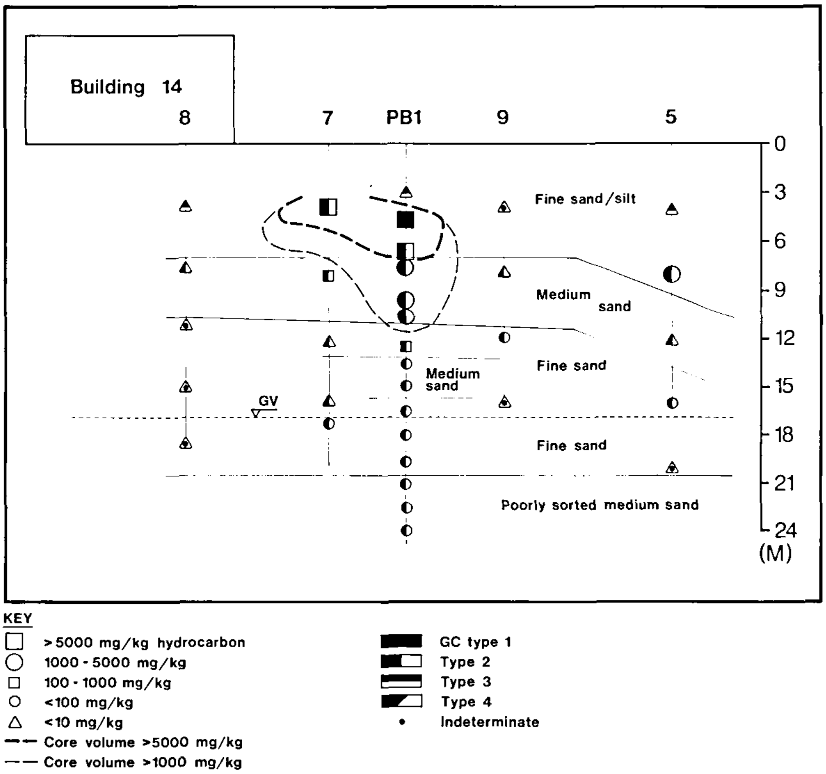
i = natural groundwater gradient

and Q = pumping rate.

There was found to be good agreement between the two methods, although the analytical method obviously depends on having a reliable value of transmissivity. The empirical method gave a catchment area as shown on Fig. 10 with L = c. 25 m and r_{ps} = c. 5 m. The existing catchment area cannot be regarded as totally satisfactory, particularly when one considers that an oil body will spread horizontally during its passage through the unsaturated zone. The boiler house, pipes and part of the tanks lie outside the catchment area.

Unfortunately, the deep piezometer, no.11,

Fig. 12. Profile I - I' (Fig.8) through leakage area at Sessvollmoen, showing THC content of sediment and gas-chromatogram type. Drilling dates: PB = 17-19/12/90, boreholes 5-10 = 19-21/3/91.



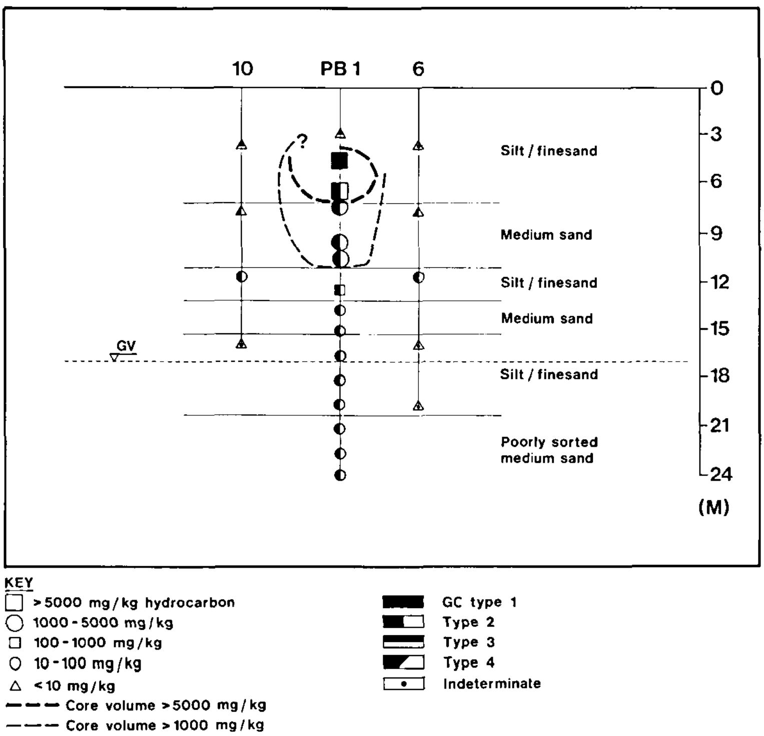


Fig. 13. Profile II - II' (fig.8) through leakage area at Sessvollmoen, showing THC content of sediment and gas-chromatogram type. Drilling dates: PB = 17-19/12/90, boreholes 5-10 = 19-21/3/91.

was not installed when the recovery testing was carried out. It was later shown, however, to respond much faster, and to a greater extent, than piezometer 1 to changes in pumping rate, indicating a considerably higher permeability in sediments below 20 m than in those above. Vertical flows between the aquifer layers may thus be important, but within the scope of the project it was not possible to investigate these further. As any oil contamination which reaches the water table is likely to be largely confined to the vicinity of the water table (i.e. to the finer layer) due to its lower density relative to water, the calculation of the scavenger well's catchment area on the basis of piezometers in the finer layer is defensible for practical purposes.

Oil contamination within the sediments

Sediment samples were extracted from the pumping hole and from investigation holes 5, 6, 7, 8, 9 and 10 using a suitable throughflow sampling device. The holes were bored by the ODEX method using only air as a drilling fluid, and soya oil where lubrication of the bit was necessary (this does not affect analysis results for mineral oils). The samples were analysed for Total Hydrocarbon Content (THC) by gas chromatography. The results of the THC analyses are presented in Figs. 12 & 13. As has been described above, the chromatogram types were identified, and these are also indicated on Figs. 12 & 13.

As can be seen from Figs.12 & 13, serious oil contamination was only found in the scavenger well (PB) and investigation hole 7. The sample from 3 m in the scavenger well yielded no trace of mineral oil contamination, while the sample at 4.5 m contained c.14 g/kg[1]. This indicates that oil has spread rapidly horizontally from the leakage point. During drilling a 5-10 cm thick clayey layer was encountered at 4.5 m, and it seems likely that the oil has spread extensively on top of and within that layer. Within the sediments recovered from the pumping well, the oil content had declined to under 5000 mg/kg by c.7 m deep, to under 1000 mg/kg by c.11 m and to under 100 mg/kg by c. 13 m deep. Even under 13 m deep the oil concentration appears to decline steadily with depth down to the water table (23 mg/kg), indicating a small but finite downwashing of oil components to the water table. Below the water table slightly higher values were found; c. 80 mg/kg down to c. 20 m, and lower values of 23-76 mg/kg[1] down to 24 m confirming the earlier assumption that the majority of downwashed oil remained in the upper, finer layer of the saturated aquifer.

One spurious value was obtained, 2400 mg/kg at 8m deep in borehole 5. This, by the situation's geometry, is unlikely to be due to the leakage under investigation. Although it is not believed to have been a major problem with the sampling programme, contamination during drilling could conceivably have led to this anomalously high value. It could also be due to pollution from another source.

In summary, the core of highly contaminated sediment is relatively limited, being located in the upper part of the unsaturated zone (Figs. 12 & 13). As it was not possible to drill boreholes in the exact vicinity of the suspected leakage, the core volume's areal extent to the west is to some degree unknown. By assuming, however, that the core volume has a double cone shape, it has been possible to estimate that c. 350 m^3 of sediment are contaminated to over 5000 mg/kg, and c.600 m^3 to over 1000 mg/kg. Assuming that the leakage was a maximum of 10 m^3 of oil, the mean oil content in the c.600 m^3 of sediment would be 16.6 l/m^3 or 8 g/kg dry weight. With an assumed porosity of 0.36, this is equivalent to 4.6 % saturation with oil.

The concept of a retention capacity (i.e. that a sediment will have a capacity to retain a certain content of oil in relatively immobile form due to adsorption, capillary retention etc) has been widely used. CONCAWE (1976) and Testa & Paczkowski (1989) give the retention capacity for fuel oil in unsaturated finesand and silt as between 40 (kerosene) and 80 (more viscous oils) l/m^3. Testa & Paczkowski also relate that the API uses a retention capacity of 15% of available porespace. The figures deduced for Sessvollmoen are about one third of these values. This indicates that the majority of the sediment within the core-volume contains a content of oil lower than the theoretical retention capacity. The volume of sediment saturated with oil to retention capacity

[1]Trials using sediment samples with a known content of hydrocarbon indicated that it was only possible to extract (using methanol/n-pentane and dichloromethane) c. 90% of THC for analysis (Johnsen, 1991). Measured values are quoted in the text, but in Figs. 4, 5, 12 & 13 sediment analysis results have been multiplied by 1.11 to give a «corrected» THC.

is thus probably limited to a relatively small volume immediately under the leakage area.

The fact that the average oil content of the core-volume appears to be considerably less than the sediment's theoretical retention capacity bodes well for the potential pollution threat from the site. There would appear to be little danger of further substantial downward movement of the oil phase through the sediment.

Oil contamination of groundwater

In the water recovered from the scavenger borehole, there has been observed neither smell, taste nor film of oil. Gas chromatography has also indicated that the oil found in the water from the borehole consists only of soluble, and not oil-phase, components. This is consistent with the majority of the oil-phase contamination being retained in the unsaturated zone, with a limited degree of downwashing of water-soluble oil components in percolating recharge-water. The THC and TOC contents of the abstracted water from the scavenger borehole are shown in Fig.14. A very high oil content of 2.4 mg/l was observed in January 1991. This could conceivably be due to contamination of the sample with oily material from the unsaturated zone during boring. Since January, the oil content of the water has declined steadily with time, until by April it was 0.045 mg/l, only a little over the Dutch A-value (0.02 mg/l). The decline in oil content with time is thought to be due to the progressive drawing in of less contaminated groundwater from the NW, and from deeper levels in the aquifer (the borehole only being partially penetrating) with time. A water sample taken from peizometer 6 on April 15th, 1991 had a rather high THC value of 0.62 mg/l. Penetrating only just below the water table, having been pumped for only a short time prior to sampling, and lying outside the scavenger borehole's catchment area, the sample probably represents the content of hydrocarbons concentrated near the top of the saturated zone in a relatively undisturbed part of the aquifer.

The lack of existing groundwater abstractions in the vicinity of the leakage, the limited size of the incident and the apparent capacity of the unsaturated sediment to retain the majority of the oil contamination argue against the establishment of costly aquifer remediation

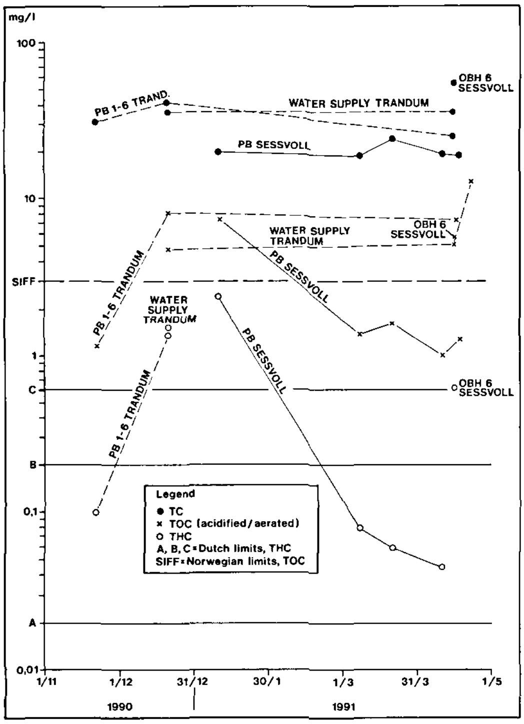


Fig. 14. Variation of THC and TOC in groundwater from Trandum and Sessvollmoen with time. «Water supply borehole» = Supply borehole for Trandum military base, situated at NW end of lake Transjøen (Fig. 1). ● = TC = total carbon (measured prior to acidification and aeration of sample), X = TOC = measured after acidification and aeration (total organic carbon, less some of the more volatile hydrocarbon components), o = THC = total hydrocarbon content. OBH 6 = piezometer 6, Sessvollmoen.

procedures such as active biorestoration. Provided that the scavenger well is relocated such that its catchment area encompasses the entire contaminated area, there will be little danger of contaminated groundwater spreading from the site. Passive rehabilitation of the aquifer (i.e. allowing the oil to naturally be broken down in-situ by microorganisms) is thought to be satisfactory.

Conclusions

Two leakages of, respectively 20 m^3 and <10 m^3 of fuel oil have been investigated on Norway's largest discrete aquifer, the Øvre Romerike aquifer. The first leakage, of 20 m^3, occurred where the unsaturated zone consists largely of coarse sand, with finer sediments below the water table. Despite an average oil retention of 21 l/m³ in the unsaturated zone, the oil appears to have migrated downwards relatively fast (up to 1.5 m/day) during the leakage's initial phase. Hitherto, no distinct oil phase has been observed in the installed scavenger boreholes. Dissolved mineral oil concentrations of around 0.6 - 1.6 mg/l have been observed in the pumped water, and these showed no signs of decreasing with time during the period of NGU's study (although subsequent measurements in early 1992 do indicate some decline).

In contrast, the second leakage (< 10 m³) occurred where the unsaturated zone consists largely of fine sand and silt, with coarser, poorly sorted medium sands under the water table. In this case the oil body is retained at a relatively high level in the unsaturated zone, with only very small (< 100 mg/kg) concentrations of hydrocarbon being observed lower in the unsaturated zone. Despite initially high (2.4 mg/l) hydrocarbon concentrations in the scavenged groundwater, these have substantially decreased during the study period to 0.045 mg/l. This is consistent with the bulk of oil being retained in the unsaturated zone, with only minimal downwashing of dissolved hydrocarbons in recharge water.

Both studies are open to criticism on several grounds. It would have been desirable to drill a more extensive sampling network at both sites. This was not possible due to both economic and logistical constraints (e.g. avoidance of cables, pipes and underground tanks). The latter precluded intensive sampling of the area under Building 111 at Trandum, and the area immediately around the tanks at Sessvollmoen. It would also have been highly desirable to take further time-series of sediment samples, to monitor the downward seepage of oil at Trandum, and to verify the retention of the oil's core volume at Sessvollmoen. Sampling and analysis procedures appear to have been reliable, particularly at Sessvollmoen where there was little indication of contamination during or after sampling, and where a consistent picture of decreasing oil concentations through the unsaturated zone down to < 100 mg/kg was obtained.

Neither oil leakage produced consequences remotely approaching the «doomsday scenarios» predicted by the media. In both cases, groundwater contamination appears to be local and controllable by appropriately sited scavenger wells. In the case of Sessvollmoen, the degree of groundwater contamination is minor. The contrast between the two case studies illustrates the importance of the type of sediment in the unsaturated zone, and thus its retention capacity, when assessing the impact of oil spills on aquifers.

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References

Banks, D. 1991: Kartlegging av oljeforurenset grunn/grunnvann ved bygning 14, Sessvollmoen militærleir. *Nor. geol.unders. report 91.190.* 148 pp.

Breedveld, G.D., Kolstad, P., Hauge, A., Briseid, T. & Brønstad, B. 1991: In situ bioremediation of oil pollution in the unsaturated zone. *NATO/CCMS, Pilot study, 5th International Conference, Washington, 18-22 Nov.1991.*

CONCAWE 1979: *Protection of groundwater from oil pollution - CONCAWE's Spesial Task Force No. 11*, CONCAWE, Den Haag, April 1979.

Davidsen, F. 1990: Gardermoen og vannforurensende aktiviteter. *Vann, 3,* 216-225.

Falkenmark, M. (ed.) 1972: *Hydrological data - Norden. Representative basins, introductory volume.* National Committees for the International Hydrological Decade in Denmark, Finland, Iceland, Norway & Sweden.

Hauge, A. 1990: Plan for rensing av oljeforurenset grunn på Trandum. *N.G.I. (Norges geotekniske institutt) report 902542-01.*

Kristiansen, H. 1983: Virkning av oljeforurensning i grunnen. *NIVA (Norsk Institutt for Vannforskning) report O-82112.*

Johnsen, S. 1991: Analyse av hydrokarboner i jord. *IKU - SINTEF group report no. 22.1885.34/01/91.*

Johnsen, S. 1991, *pers.comm.*: Ståle Johnsen, *IKU (Norwegian Continental Shelf and Petroleum Technology Research Institute), Trondheim*, to David Banks, 1991.

Jørgensen, P. & Østmo, S.R. 1990: Hydrogeology in the Romerike area, Southern Norway. *Nor. geol. unders. 418,* 19-26.

Jørgensen, P., Stuanes, A.O. & Østmo, S.R. 1991: Aqueous geochemistry of the Romerike area, Southern Norway. *Nor. geol. unders. 420,* 57-67.

Kruseman, G.P. & De Ridder, N.A. 1989. *Analysis and evaluation of pumping test data. 2nd edn.* International Institute for Land Reclamation and Improvement/ILRI Publication 47. Wageningen, Netherlands. 377 pp.

Longva, O. 1987: Ullensaker 1915 II. Beskrivelse til kvartærgeologisk kart M 1:50 000. *Nor.geol.unders.Skr. 76,* 39 pp with map.

Misund, A., Banks, D., Morland, G., Brunstad, H. 1991a: Norwegian national survey of hazardous waste in landfills and contaminated ground. *Waste Management Today (News J.), 4, No.8,* 30-35.

Misund, A., Morland, G., Brunstad, H., Banks, D. 1991b: Kartlegging av spesialavfall i deponier og forurenset grunn - Sluttrapport. *Statens forurensningstilsyn report 91/01,* 53 pp.

Misund, A. & Sæther, O.M. 1991: Undersøkelse av forurenset grunn og grunnvann ved Trandum militærleir. *Nor. geol. unders. report 91.228,* 137 pp.

Morland, G., Folkestad, B., Hauge, A., Kolstad, P., & Forsberg, C.F. 1990: Kartlegging av spesialavfall i deponier og forurenset grunn i Akershus fylke. *Nor. geol. unders. report 90.084.* 170 pp.

Mutch, R.D. 1989: Aquifer restoration: basic principles. *Proc. course - «Clean-up of waste-disposal sites», 13-15 nov. 1989,* Centre for Professional Enhancement, Den Haag.

Norwegian National Committee for the IHD 1973. *Hydrological data - Norden. Representative basins; Romerike, Norway. Data 1965-71.* Norwegian National Committee for the International Hydrological Decade, Oslo, 1973.

Norwegian National Committee for the IHD 1975. *Hydrological data - Norden. Representative basins; Romerike, Norway. Data 1972-74.* Norwegian National Committee for the International Hydrological Decade, Oslo, 1975.

SIFF 1987: Kvalitetsnormer for drikkevann. *SIFF (Statens Institutt for Folkehelse) guide «Drikkevann G2».*

SIFF 1992: Trandum - analyse av vannprøver. *Letter from Statens Institutt for Folkehelse to Forsvarets bygningstjeneste, Hamar,* 24th February, 1992.

Snekkerbakken, A.M. 1988: Forprosjekt om sikring av grunnvannsressursene på Gardermosletta. *VIAK AB report, 15th October 1988,* Karlstad, Sweden. 48pp.

Storrø, G. 1991: Kartlegging av oljeforurenset grunn/grunnvann ved bygning 111, Trandum militærleir. *Nor.geol. unders. report 91.155.* 71 pp.

Sæther, O.M., Misund, A., Ødegård, M., Andreassen, B.Th. & Voss, A. 1992. Groundwater contamination from a landfill at Trandum, Southeastern Norway. *Nor.geol. unders. 422 (this volume).*

Testa, S.M. & Paczkowski, M.T. 1989: Volume determination and recoverability of free hydrocarbon. *Groundwater Monitoring Review, Winter 1989,* 120-128.

Wolden, K. & Erichsen, E. 1990: Compilation of geological data for use in local planning and administration. *Engineering geol., 29,* 333-338.

Østlandskonsult A/S, Geofuturum A/S, Akershus fylkeskommune & Luftfartsverket 1991: *Hovedflyplass Gardermoen; grunnvannet som drikkevannskilde; en utredning av grunnvannet som aktuell drikkevannskilde for Romerike.*

Østmo, S. R. 1976: Hydrogeologisk kart over Øvre Romerike, M 1:20.000. *Nor. geol. unders.*

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