Geo-Mar Lett (2003) 23: 140–146
DOI 10.1007/s00367-003-0135-0

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Natural seepage of crude oil into the marine environment

Received: 7 November 2002 / Accepted: 23 June 2003 / Published online: 3 October 2003

Abstract Recent global estimates of crude-oil seepage rates suggest that about 47% of crude oil currently entering the marine environment is from natural seeps, whereas 53% results from leaks and spills during the extraction, transportation, refining, storage, and utilization of petroleum. The amount of natural crude-oil seepage is currently estimated to be 600,000 metric tons per year, with a range of uncertainty of 200,000 to 2,000,000 metric tons per year. Thus, natural oil seeps may be the single most important source of oil that enters the ocean, exceeding each of the various sources of crude oil that enters the ocean through its exploitation by humankind.

Introduction

Crude oil enters the marine environment by two principal processes. One process involves human activities related to the extraction, transportation, refining, storage, and utilization of petroleum (crude oil and natural gas). An example is marine oil spills, caused by failures in human-designed transportation systems such as tankers and pipelines, which are built to move crude oil from one place to another. The second process involves natural oil seepage. The term 'oil seep' is used here to mean naturally occurring seepage of crude oil and tar. Crude-oil seeps are geographically common and have likely been active through much of geologic time (Hunt 1996).

The importance of crude oil entering the marine environment was recognized by the US National Academy of Sciences in a series of three reports (NAS 1975, 1985, 2003). The NAS (1975) report "Petroleum in the Marine Environment" was NAS's first comprehensive attempt to estimate the amount of crude oil that enters the oceans from all known sources. A significant conclusion was that about 10% of crude oil entering the oceans during the early 1980s came from natural oil seeps, whereas about 27% came from oil production, transportation, and refining. The remaining 63% came from atmospheric emissions, municipal and industrial sources, and urban and river runoff.

Crude-oil seeps are natural phenomena over which humankind has little direct control, although oil production probably has reduced oil-seepage rates (Quigley et al. 1999). However, secondary recovery methods using increased formation pressures could possibly cause increased rates of oil seepage. Nevertheless, crude oil that enters naturally into the marine environment does establish a contaminant 'background' against which pollution resulting from human activities (i.e., oil spills) can be measured.

The purpose of this report is to assess the state of knowledge concerning natural seepage of crude oil (liquid petroleum) in the marine environment. The gaseous components of petroleum (natural gas) will not be considered here, because too little is known, especially about rates of gas seepage. Nevertheless, gas seeps are common in the oceans, and gas seeps often entrain oil. In addition, gas resulting from the decomposition of gas hydrate will not be considered. Naturally occurring gases are either lost to the atmosphere or are quickly assimilated by the marine environment, and there is usually little direct, visible evidence of their presence. However, liquid petroleum (crude oil and tar) seeps can have a long-term presence.

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State of knowledge—1975

The estimated input in 1975 of oil from naturally occurring seeps to the marine environment ranged widely from 0.2 to 6.0 million metric tons per year, with a best estimate of 0.6 million metric tons (180 million gallons) per year (NAS 1975). *In the following discussion,* 'metric ton' will be designated as 'tonne' (t; Mt = one million metric tons) and there are about 300 gallons of oil per tonne. These estimated values are contained in a NAS background report by R.D. Wilson, later published as Wilson et al. (1973). These estimates were commonly accepted and widely cited (Bates and Pearson 1975; Frey 1977; Grossling 1977; Koons and Monaghan 1977; Jeffrey 1980; Miller 1992). For comparison, 0.6 Mt oil is about the same amount of oil (0.5 Mt) that escaped during the blowout of the Pemex well, Ixtoc 1, which flowed for about 300 days into the Gulf of Mexico (Patton et al. 1981).

The paper by Wilson et al. (1973) is comprehensive, lists 190 coastline or oceanic seeps, and is the first to estimate natural seepage rates by incorporating extensive geological considerations. They extrapolated the few available seepage rates to estimate the worldwide rate of natural seepage into the oceans. They combined seepage rates on land with information on reported marine seeps and then extrapolated the data to the continental margins, which they classified as areas of potentially high, medium, and low seepage. They incorporated tectonic history, earthquake activity, and sediment thickness in their appraisal. Five basic assumptions were used in their estimates:

1. More seeps exist in offshore basins than have been observed.
2. Factors that determine total seepage in an area (number of seeps per unit area and the daily rate for each seep) are related to the general geological structural type of the area and to the stage of sedimentary basin evolution.
3. Within each structural type, seepage (number of seeps and, to a lesser extent, rate per seep) depends primarily on the area of exposed rock, and not rock volume. The assumption presumes that there is sufficient sediment volume and organic matter for the generation and maturation of petroleum.
4. Most marine seeps occur within continental margins where the thicknesses of sediments exceed a certain minimum.
5. Seepage rates are log-normally distributed, although Kvenvolden and Harbaugh (1983) proposed an exponential distribution as a more realistic model.

The geological relationships and assumptions used by Wilson et al. (1973) and published in condensed form later (Wilson et al. 1974) remain reasonable and seem consistent with observations, although a greater role for tectonics on natural seepage rates has been suggested (Macgregor 1993). To obtain an estimate of worldwide seep rates, Wilson et al. (1973, 1974) had to extrapolate from a few, highly suspect seepage rates for individual seeps. Most estimates at the time were based on rough visual observations, and were probably inaccurate. Another problem is that natural seeps are generally episodic and ephemeral.

State of knowledge—1985

Ten years after publication of "Petroleum in the Marine Environment" (NAS 1975), a second study "Oil in the Sea—Inputs, Fates, and Effects" was issued (NAS 1985). In this later report, natural crude-oil seepage accounted for about 6% of the oil entering the marine environment, whereas the remaining 94% resulted from human activities. For a reassessment of the rates at which crude oil enters the marine environment from natural seeps, the report relied on a paper by Kvenvolden and Harbaugh (1983), prepared for the NAS as a contribution to the 1981 "Petroleum in the Marine Environment/Update Workshop".

Since Wilson et al. (1973, 1974) first made their estimates, little new information had become available that would change their worldwide estimates of marine seepage rates. Only six new marine seep locations had been added to the original compilation of 190 reported seep areas. Estimates of rates of individual seeps had not changed significantly. Therefore, Kvenvolden and Harbaugh (1983) concluded that any change in global seepage rates would depend on factors other than the current knowledge based on direct measurements of seeps and rates. They took an approach much different from Wilson et al. (1973, 1974). It was based on assumptions about the amount of crude oil in the earth that seeps over geologic time. The idea was, in part, originally articulated by Blumer (1972), who estimated an annual seep rate between 1 and 11 Mt. However, he noted that a seep rate of 5 Mt per year (his estimate of the tonnage of oil pollution from human activities) would deplete the ultimate reserves of offshore oil in less than 20,000 years. Thus, he concluded that the seep rate is likely orders of magnitude less, on a worldwide basis, than the oil pollution caused by man.

The average seepage rates over geologic time ultimately depend on the size of the worldwide petroleum resource (Kvenvolden and Harbaugh 1983). Estimates of this resource range widely and depend on the category of petroleum being considered, such as offshore, onshore, total resource, or total reserve. The present estimate is about 400,000 Mt (Ahlbrandt 2002). Kvenvolden and Harbaugh (1983) made comparisons between estimated oil-seep rates and the amount of oil available for seepage in order to assess the maximum geological time that the seep rates could be sustained. Assumed seep rates ranged from 0.02 to 10 Mt per year, whereas, the amounts of oil available for seepage were assumed to range from 10,000 to 100,000,000 Mt. The ranges cover all conceivable seep rates and uncertainties, including the possibility of current oil generation. The ranges depend on the amount of oil that is available for seepage from reservoir and source rocks during geologic time, and that will become available in the future during the lifetimes of the seeps.

Assumptions about worldwide seepage rates and the total quantity of oil available for seepage are closely interdependent. The oil-seepage rate that best seemed to accommodate the requirements of reasonable geologic time and reasonable assumptions concerning availability of oil for seepage was 0.2 Mt per year, with an uncertainty of an order of magnitude. Thus, the average seep rate was estimated to be between 0.02 to 2.0 Mt per year, with a ‘best estimate’ of 0.2 Mt per year. This value is a factor of three lower than the ‘best estimate’ of Wilson et al. (1973, 1974) of 0.6 Mt per year. The lower estimate of 0.2 Mt per year does not mean that seep rates decreased over the intervening ten years between these NAS reports, but rather reflects a difference in methods of making estimations. This lower estimate has been accepted in the Year of the Oceans Discussion paper (NOAA 1998). More recently, GESAMP (1993) adjusted the value to 0.26 Mt per year in an independent study of the impact of oil and related chemicals and wastes on the marine environment.

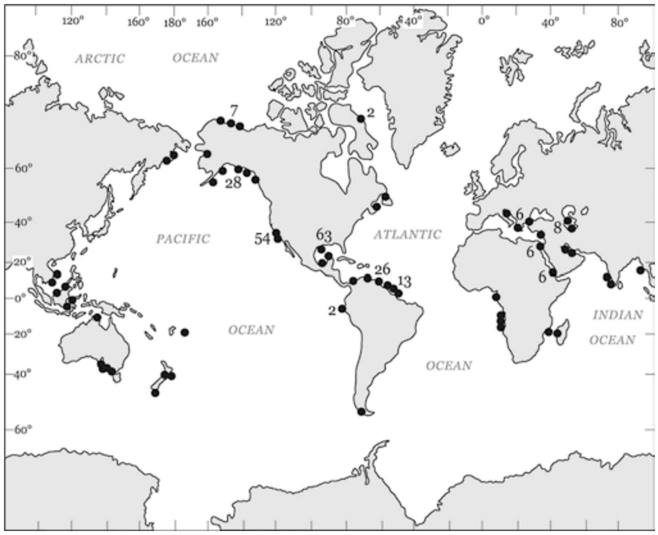

Fig. 1 Locations of naturally occurring crude-oil seeps that impact the marine environment (adapted from Wilson et al. 1973). *Numbers* refer to number of seeps in a given region

State of knowledge—2000

Since the publication of NAS (1985), new information has been acquired, as summarized in NAS (2003) “Oil in the Sea III: Input, Fates, and Effects”. New reports have identified seeps in New Zealand (Cook 1982), Tonga (Sandstrom and Philp 1984), Alaska (Becker and Manen 1988), Greece (Lowe and Doran 1988), Vietnam (Traynor and Sladen 1997), the Amazon River mouth (Miranda et al.1998), and the Gulf of Mexico (MacDonald and Leifer (2002). Thus, more sites or areas can be added to the 196 locations already known (Fig. 1). During this same time period, the estimate of recoverable crude oil in the world changed from about 300,000 Mt (Miller 1992) to about 400,000 Mt (Ahlbrandt 2002). This new information is sufficient to modify the estimates given by NAS (1975, 1985).

During the past 15 years, some new technologies emerged that provide alternative means to estimate seep rates. These developments are summarized here.

1. The number of regions known to have significant seeps has increased based mainly on new information from satellite remote sensing techniques. Methods for detecting seeps by satellite remote sensing have matured, generating much new data from synthetic aperture radar (SAR) on several platforms (RADARSAT, ERS 1&2), and visible band images from Landsat TM and the space shuttle. Areas surveyed include the northern Gulf of Mexico, the Caspian Sea, offshore Indonesia, and the western coast of sub-Saharan Africa.
2. Most recent estimates of crude-oil reserves have not changed much, but confidence in the estimates has increased, largely due to increased quantity and quality of geological data acquired during offshore exploration and production activities.
3. It is now broadly accepted that significant quantities of oil escape from reservoirs and enter the ocean as an ongoing process. Also ongoing oil generation takes place on geologic timescales.
4. High-quality in-situ measurements of seep rates have been made in limited areas, for example, the Coal Oil Point region of California (Hornafius et al. 1999).
5. Geographic information systems (GIS) and powerful computers make it easier to analyze large, complex, remote-sensed datasets in order to establish more exact seepage rates.

Seeps in the northern Gulf of Mexico

Much information on seeps in the Gulf of Mexico has been based on observations of tar residues on beaches and on oily sediment cores recovered during crude-oil exploration. For example, Geyer and Giammona (1980) recognized, based mainly on the occurrence of tar residues on shorelines, that seepage is common in the Gulf of Mexico, but they could not pinpoint areas of seepage or estimate seepage rates. Based on oily cores recovered from the Gulf of Mexico, Anderson et al. (1983) concluded that seeps must be numerous. Kornacki et al. (1994) reported the successful use of seep data to locate commercially viable oilfields in the gulf.

Recent studies suggest that seepage rates in the Gulf of Mexico are much higher than previously assumed in NAS (1975, 1985). MacDonald et al. (1996) used submarines and data from remote sensing to identify at least 63 individual seeps (Fig. 2). Comprehensive remote sensing surveys indicate that there are about 350

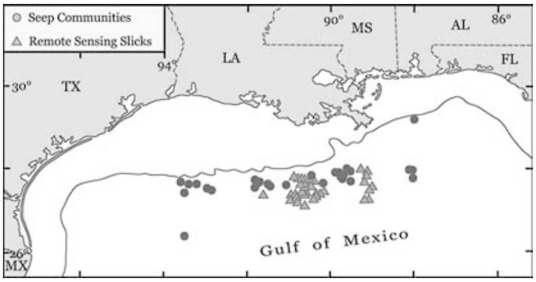

Fig. 2 Map of the Gulf of Mexico showing the locations of 63 natural oil seeps (adapted from Table 3 of MacDonald et al. 1996)

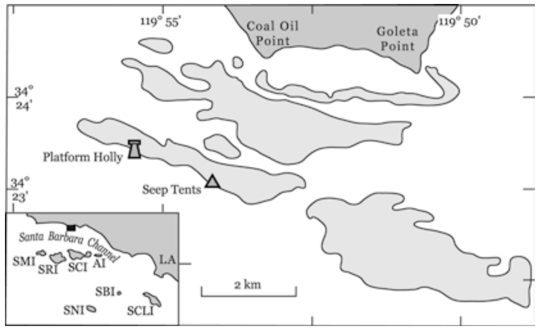

Fig. 3 Map showing areas (*shaded*) of natural oil seeps offshore from Coal Oil Point near Santa Barbara, California. Inset map shows the Channel Islands (*I*) designated *SM* San Miguel, *SR* Santa Rosa, *SC* Santa Cruz, *A* Anacapa, *SN* San Nicholas, *SB* Santa Barbara, and *SCL* Santa Catalina. Seep fields were mapped between 1946 and 1973 (modified from Hornafius et al. 1999)

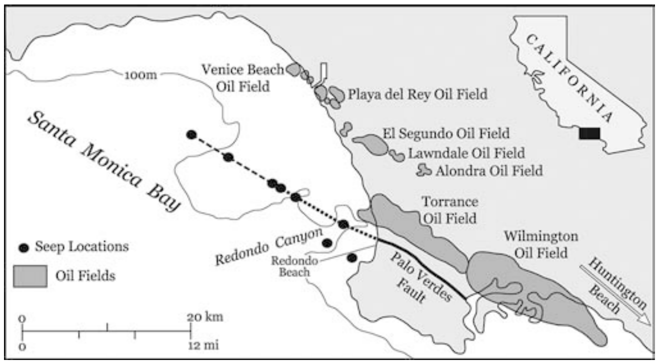

Fig. 4 Map showing locations of natural oil seeps offshore from Santa Monica, California (modified from Wilkinson 1972)

constant seeps in the Gulf of Mexico that produce perennial slicks of oil at consistent locations (MacDonald and Leifer 2002). Using satellite remote sensing to map oil slicks, MacDonald et al. (1993) estimated the total seepage in the gulf to be about 17,000 t per year. Later, however, MacDonald (1998) conservatively estimated a much lower rate of about 4,000 t per year as a minimum value. These different estimates by MacDonald and colleagues emphasize the difficulty in establishing seepage rates.

Commercial enterprises (Earth Satellite Corporation and Unocal Corporation) compiled SAR and other remote sensing data. With the Earth Satellite dataset, Mitchell et al. (1999) estimated, during an aggregate survey of the northern Gulf of Mexico, approximately 1,000 km^2 of floating oil, presumably from natural seeps. Assuming an average oil thickness of 0.1 μm, MacDonald et al. (1993) calculated that 1 km^2 of oiled surface contains about 100 l oil. If the oil persists on the surface for 12 h (before evaporating or spreading to a thickness of less than 0.1 μm), summing over the time the oil slicks are visible results in an estimate of 73,000 t per year for the northern Gulf of Mexico. This value does not include the oil seeping from the prolific Campeche Basin offshore from Mexico in the southern Gulf of Mexico. Assuming the seep scales are proportional to the surface area, a seep rate for the entire gulf is about double the northern gulf estimate, giving a total Gulf of Mexico seep rate of about 140,000 t per year.

Uncertainties with the satellite-derived estimates include:

1. An assumed mean thickness of 0.1 μm for the surface slick thickness. This value is largely based on arguments of MacDonald et al. (1993), who considered threshold thicknesses of 0.1 and 0.01 μm. The slick thickness, of course, affects the total volume estimates.
2. A mean residence time on the surface of 12 h. This value is also based on the work by MacDonald et al. (1993), who noted abrupt changes in wind and slick patterns. They estimate a range of residence time of 8–24 h.
3. The seep rate over a large region is constant in time. MacDonald et al. (1993) and others note that some seeps are episodic and ephemeral. Hence, assuming constant rates is questionable, even when integrated over a large region.

Despite these uncertainties, the new satellite data provide the most direct estimates of seeps and thus represent a major advance over the much less direct methods used in previous estimates (NAS 1975, 1985).

Seeps off southern California

Natural oil seeps have been active offshore southern California throughout recorded history (Weaver 1969; Yerkes et al. 1969), and they are currently widespread (Figs. 3, 4). Early rates were estimated using primitive techniques and gross extrapolations. For example, at Coal Oil Point, early estimates ranged from 520 to 8,300 t per year (Allen et al. 1970; Wilkinson 1971; Mikolaj et al. 1972). Straughan and Abbott (1971) estimated 4,700 t per year (when corrected for a printing error, pointed out in Kvenvolden and Harbaugh 1983). In Santa Monica Bay, seep estimates by Mikolaj et al. (1972) and Wilkinson (1971) range from 100 to 1,000 t per year. Estimates by Fischer (1978), based on mapping of the geographical trends of seeps in the Santa Barbara Channel, range from 2,100 to 35,000 t oil per year.

Recently, more accurate measurements have been made in the Coal Oil Point region by Clester et al. (1996) and Hornafius et al. (1999). They combined information from 'seep tents' (funnel-like structures placed over natural seeps), seep-flux buoys that drifted across the seep region, and 50-kHz sonar data. They concluded that Coal Oil Point seeps about 7,800–8,900 t of oil per year. To account for seeps elsewhere in the Santa Barbara Channel and the offshore Santa Maria and Santa Monica basins, the total oil seepage offshore southern California is estimated to be about twice the seepage at Coal Oil Point, or about 17,000 t annually, rounded to one significant value of 20,000 t of oil per year. This estimate is large but is still less than the upper estimate of Fischer (1978), i.e., 35,000 t per year.

Seepage estimates for the North American offshore

There are four regions offshore North America with known seeps—the Gulf of Mexico, offshore southern California, coastal Alaska, and coastal Baffin Island of Canada. The Gulf of Mexico and offshore southern California have combined annual oil-seep rates estimated at 160,000 t, based on the recent evidence discussed above.

Becker and Manen (1988) identified 29 seeps in the coastal regions of Alaska (Fig. 5). Of the 29 seepage areas, 14 are confirmed as oil seeps, whereas 15 are unconfirmed reports from the shoreline of the Gulf of Alaska. None of the seeps are beneath the water surface. Rather, they lie above the low-tide line or at inland sites, and could influence the marine environment through oil transport in freshwater streams.

Annual rates of oil seepage have been reported for four of the 29 seepage areas in Alaska: Puale Bay (Fig. 5, no. 12), 26–38 t; Oil Bay (Fig. 5, no. 16), 1–2.3 t; Controller Bay (Katalla; Fig. 5, no. 21), 26–52 t; and Samovar Hills (Fig. 5, no. 24), 130 t (Becker and Manen 1988). Using the mean values gives a total of about 360 t annually. Recently, Page et al. (1997) suggested that the total seepage rate from onshore and offshore seep sources into the eastern Gulf of Alaska is much greater than 360–1,200 t per year of oil equivalents, but these values include oil in shales as well as seeps. Although submarine oil seeps offshore from Alaska have been suspected, there are no documented reports (Becker and Manen 1988). Because the seeps of Alaska have not been fully documented, and in order to account for probable undiscovered seeps, the seepage rate for Alaska is conservatively estimated to be a factor of two larger than the total measured rate of 360 t per year, or about 1,000 t annually. NAS (2003) does not address the possibility of undiscovered seeps and reports an estimated annual seepage rate for offshore Alaska of 400 t. Although Alaska is a major source of commercial petroleum, the amount of natural seepage in the marine environment is small compared to the Gulf of Mexico and offshore southern California.

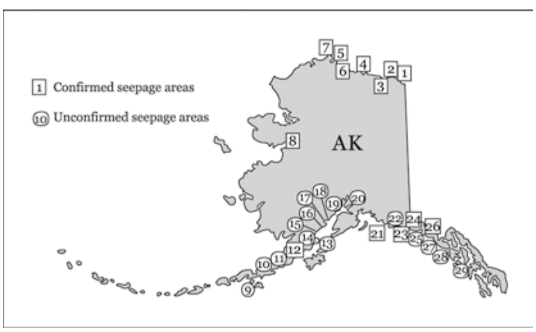

Fig. 5 Locations of Alaskan coastal oil-seepage areas. *Numbers* indicate 29 individual areas identified in Table 1 of Becker and Manen (1988)

In Canada, oil seeps have been found at Scott Inlet (Levy 1978) and Buchan Gulf (Levy and Ehrhardt 1981) on Baffin Island. Although the evidence shows that oil is seeping from the seabed, no rates of oil seepage have been measured or estimated.

The total seepage of crude oil offshore from North America is estimated to be about 161,000 t per year. This new estimate represents approximately one-third of the NAS (1975) mean global estimate of 600,000 t per year. The new estimate seems reasonable given the relative percentage of potential oil-producing area in North America compared with the rest of the world. In addition, recent data from remote sensing suggest that North America is not an exceptional region for seeps.

The new North American estimate of 161,000 t is only 39,000 t less than the NAS (1985) global estimate of 200,000 t per year. As discussed above, methods used for the NAS (1985) estimate were very different from those of the NAS (1975) report. The new North American estimate of about 160,000 t per year strongly suggests that the NAS (1985) global estimate of 200,000 t per year was too small.

Global estimates of oil seepage into the marine environment

Considering that totally different approaches were taken to estimate global oil-seepage rates, it is remarkable that the 'best estimates' obtained by Wilson et al. (1973, 1974) of 600,000 t per year, and by Kvenvolden and Harbaugh (1983) of 200,000 t per year are within a factor of three of each other. Whereas Wilson et al. (1973, 1974) established plausible, but probably inaccurate rates for present seepage, Kvenvolden and Harbaugh (1983) determined possible average rates throughout geologic time and established constraints on these rates based on the availability of oil for seepage. In a sense, the two approaches complement each other; the one establishes reasonable rates and the other, reasonable limits.

Nevertheless, recent and improved data from the northern Gulf of Mexico and from offshore southern California indicate that oil-seepage rates have likely been underestimated. To accommodate the new information, the 'best estimate' of global oil-seepage rate is revised to 600,000 t per year, the original 'best estimate' of NAS (1975). This 'best estimate' can be constrained by the methods of Kvenvolden and Harbaugh (1983) to a lower limit of 200,000 t per year and an upper limit of 2,000,000 t per year. In summary, until better methods are applied and more oil-seep rates are measured, the annual global oil-seepage rate is estimated to be between 0.2 and 2 Mt (60 and 600 million gallons), with a 'best estimate' of 0.6 Mt (180 million gallons). This new 'best estimate' means that 47% of the oil entering the oceans each year is from natural seepage whereas 53% (668,000 t) comes from human activities (NAS 2003). The change in percentage of oil entering the marine environment from natural seepage—from 10% in 1975 to 6% in 1985 to 47% in 2002—is significant and reflects mainly a decrease in the amount of oil entering the marine environment from human activities or unrecognized errors in the assessment of global oil seepage. With reduction in leaks and spills during the extraction, transportation, refining, storage, and utilization of petroleum, natural oil seeps are now believed to be the single most important source of oil to the oceans.

Conclusions

An assessment of the best available data on marine oil seeps suggests that previous estimates of global seepage rates are too low. The annual oil-seepage rate *offshore from North America* is estimated to be about 160,000 tonnes (48 million gallons), whereas the NAS (1985) *global* estimate is only 40,000 tonnes larger. Thus, if the new estimate for North America is correct, then the NAS (1985) global estimate must be too low. However, the new North American estimate is consistent with the NAS (1975) global estimate of 600,000 tonnes per year, given the relative proportion of oil-producing areas offshore from North America and the rest of the world. In addition, recent remote-sensed satellite data suggest that North America is by no means an exceptional region for seeps.

The annual worldwide oil-seepage rate (NAS 2003) is estimated to be between 0.2 and 2 Mt (60 and 600 million gallons), with a 'best estimate' of 0.6 Mt (180 million gallons). These estimates will be better constrained in the future with increased knowledge and better direct and indirect measurements. Remote sensing methods carried by satellite offer the best approach to more accurate estimates. Application of such methods would require a relative modest investment. Given the impact that petroleum has on the marine environment, and especially in light of the potential impact on the carbon cycle and global warming, this investment would be well justified.

Acknowledgments We acknowledge with thanks Bruce Rogers (USGS) for the preparation of the figures.

References

Ahlbrandt TS (2002) Future petroleum energy resources of the world. Int Geol Rev 44:1092–1104

Allen AA, Schlueter RS, Mikolaj PG (1970) Natural oil seepage at Coal Oil Point, Santa Barbara, California. Science 170:974–977

Anderson RK, Scalan RS, Parker PL, Behrens EW (1983) Seep oil and gas in Gulf of Mexico slope sediment. Science 222:619–621

Bates CC, Pearson E (1975) Influx of petroleum hydrocarbons onto the ocean. In: Proc 7th Offshore Technology Conf OTC 2390:535–544

Becker PR, Manen C-A (1988) Natural oil seeps in the Alaskan marine environment. Final Report, Outer Continental Shelf Environmental Assessment Program, US Department of Commerce, Technical Information Service, PB88-235965

Blumer M (1972) Submarine seeps: are they a major source of open ocean oil pollution? Science 176:1257–1258

Clester SM, Hornafius SJ, Scepan U, Estes JE (1996) Quantification of the relationship between natural gas seepage rates and surface oil volume in the Santa Barbara Channel. Trans Am Geophys Union Suppl 77(46), F420

Cook RA (1982) An oil seep at Leask Bay, Stewart Island, New Zealand. N Z J Geol Geophys 25:115–119

Fischer PJ (1978) Natural gas and oil seeps, Santa Barbara Basin, California. The State Land Commission 1977, California Gas, Oil, and Tar Seeps, pp 1–62

Frey MG (1977) Oil in marine waters. In: Proc Offshore Technology Conf OTC 2765:325–330

GESAMP (1993) Impact of oil and related chemicals and wastes on the marine environment. IMO/FAO/UNESCO/WMO/WHO/IAEA/UN/UNEP Joint Group of Experts on the Scientific Aspects of Marine Pollution (GESAMP) Report and Studies no 50

Geyer RA, Giammona CP (1980) Naturally occurring hydrocarbons in the Gulf of Mexico and the Caribbean. In: Geyer RA (ed) Marine environmental pollution, vol 1, Elsevier Oceanographic Series 27A. Elsevier, Amsterdam, pp 37–106

Grossling BF (1977) An estimate of the amounts of oil entering the oceans: sources, effects, and sinks of hydrocarbons in the aquatic environment. Proc Symp American Institute of Biological Sciences, pp 5–36

Hornafius JS, Quigley D, Luyendyk BP (1999) The world's most spectacular marine hydrocarbon seeps (Coal Oil Point, Santa Barbara Channel, California): quantification of emissions. J Geophys Res 104(C9):20703–20711

Hunt JM (1996) Petroleum geochemistry and geology. W.H. Freeman, New York

Jeffrey LM (1980) Petroleum residue in the marine environment. In: Geyer RA (ed) Marine environmental pollution, vol 1, Elsevier Oceanographic Series 27A. Elsevier, Amsterdam, pp 163–179

Koons CB, Monaghan PH (1977) Input of hydrocarbons from seeps and recent biogenic sources: sources, effects, and sinks of hydrocarbons in the aquatic environment. Proc Symp American Institute of Biological Sciences, pp 94–107

Kornacki AS, Kendrick JW, Berry JL (1994) Impact of oil and gas vents and slicks on petroleum exploration in the deepwater Gulf of Mexico. Geo-Mar Lett 14:160–169

Kvenvolden KA, Harbaugh JW (1983) Reassessment of the rates at which oil from natural sources enters the marine environment. Mar Environ Res 10:223–243

Levy EM (1978) Visual and chemical evidence for a natural seep at Scott Inlet, Baffin Island, District of Franklin. Geol Surv Can Curr Res Pap 78-1B:21–26

Levy EM, Ehrhardt M (1981) Natural seepage of petroleum at Buchan Gulf, Baffin Island. Mar Chem 10:355–364

Lowe SP, Doran T (1988) Oil seeps of the Ionian Islands, Western Greece. Am Assoc Petrol Geol Bull 72:1012

MacDonald IR (1998) Natural oil spills. Sci Am 279:56–61

MacDonald IR, Leifer I (2002) Constraining rates of carbon flux from natural seeps on northern Gulf of Mexico Slope. In: Abstr Vol 7th Int Conf Gas in Marine Sediments, 7–12 October 2002, Baku, Azerbaijan. Nafta Press, Baku, p 119

MacDonald IR, Guinasso NL Jr, Ackleson SG, Amos JF, Duckworth R, Sassen R, Brooks JM (1993) Natural oil slicks in the Gulf off Mexico visible from space. J Geophys Res 98(C9):16,351–16,364

MacDonald IR, Reilly JF Jr, Best WE, Venkataramaiah R, Sassen R, Guinasso NL Jr, Amos J (1996) Remote sensing inventory of active oil seeps and chemosynthetic communities in the northern Gulf of Mexico. In: Schumacher D, Abrams MA (eds) Hydrocarbon migration and its near-surface expression. Am Assoc Petrol Geol Mem 66:27–37

Macgregor DS (1993) Relationships between seepage, tectonics and subsurface petroleum reserves. Mar Petrol Geol 10:606–619

Mikolaj PG, Allen AA, Schlueter RS (1972) Investigation of the nature, extent, and fate of natural oil seepage off southern California. In: Proc 4th Offshore Technology Conf OTC 1549:I-367–I-380

Miller RG (1992) The global oil system: the relationship between oil generation, loss, half-life, and the world crude oil resource. Am Assoc Petrol Geol Bull 76:489–500

Miranda FP, Beisl CH, Bentz CM (1998) Application of the Unsupervised Semivariogram Textural Classifier (USTC) for the detection of natural oil seeps using Radarsat-1 data obtained offshore the Amazon River mouth. Am Assoc Petrol Geol Bull 82:1944

Mitchell R, MacDonald IR, Kvenvolden KA (1999) Estimation of total hydrocarbon seepage into the Gulf of Mexico based on satellite remote sensing images. Trans Am Geophys Union 80(49), Ocean Sciences Meet Suppl OS242

NAS (1975) Petroleum in the marine environment. National Academy of Sciences, Washington, DC

NAS (1985) Oil in the sea—inputs, fates, and effects. National Academy of Sciences, National Academy Press, Washington, DC

NAS (2003) Oil in the sea III: inputs, fates, and effects. National Academy of Sciences, National Academy Press, Washington, DC

NOAA (1998) Year of the Oceans. Perspectives on marine environmental quality today. National Oceanographic and Atmospheric Administration (NOAA)

Page D, Boehm PD, Douglas GS, Bence AE, Burns WA, Mankiewicz PJ (1997) An estimate of the annual input of natural petroleum hydrocarbons to seafloor sediments in Prince William Sound, Alaska. Mar Pollut Bull 34:744–749

Patton JS, Rigler MW, Boehm PD, Fiest DL (1981) Ixtoc I oil spill: flaking of surface mousse in the Gulf of Mexico. Nature 290:235–238

Quigley DC, Hornafius JS, Luyendyk BP, Francis RD, Clark J, Washburn L (1999) Decrease in natural marine hydrocarbon seepage near Coal Oil Point, California, associated with offshore oil production. Geology 17:1047–1050

Sandstrom MW, Philp RP (1984) Biological marker analysis and stable carbon isotopic composition of oil seeps from Tonga. Chem Geol 43:167–180

Straughan D, Abbott BC (1971) The Santa Barbara oil spill: ecological changes and natural oil leaks. In: Hepple P (ed) Water pollution by oil. Institute of Petroleum, London, pp 257–262

Traynor JJ, Sladen C (1997) Seepage in Vietnam—onshore and offshore examples. Mar Petrol Geol 14:345–362

Weaver DW (1969) Geology of the northern Channel Islands. Pacific Sect AAPG, SEPM Spec Publ

Wilkinson ER (1971) California offshore oil and gas seeps. California Oil Fields—Summary of Operations 57(1):5–28

Wilkinson ER (1972) California offshore oil and gas seeps. California Division Oil and Gas

Wilson RD, Monaghan PH, Osanik A, Price LC, Rogers MA (1973) Estimate of annual input of petroleum to the marine environment from natural marine seepage Trans Gulf Coast Assoc Geol Soc 23:182–193

Wilson RD, Monaghan PH, Osanik A, Price LC, Rogers MA (1974) Natural marine oil seepage. Science 184:857–865

Yerkes RF, Wagner HC, Yenne KA (1969) Petroleum development in the region of the Santa Barbara Channel. Geology, petroleum development, and seismicity of the Santa Barbara Channel region, California. US Geol Surv Prof Pap 679:13–27