PRBO contribution
#368

ESTIMATING MORTALITY OF SEABIRDS FROM OIL SPILLS

R. Glenn Ford
Ecological Consulting
2735 N.E. Weidler Street
Portland, Oregon 97232

Gary W. Page and Harry R. Carter
Point Reyes Bird Observatory
4990 Shoreline Highway
Stinson Beach, California 94970

ABSTRACT: *From an aesthetic and damage assessment standpoint, the loss of seabirds may be one of the more important results of a marine oil spill. Assessment of the actual numbers of seabirds killed is difficult because the bodies of dead or incapacitated seabirds are often never found or recorded. We present a computer methodology that estimates the number of birds that come in contact with an oil spill and partitions these birds among four possible fates: (1) swimming or flying ashore under their own power; (2) carried out to sea by winds and currents; (3) carried inshore, but lost before being beached; and (4) beached by winds and currents. Beached birds are further divided into those that are recovered and those that are not. The accuracy of the methodology is examined using data for two recent spills in central California, each of which resulted in the beachings of large numbers of birds. The methodology also has potential application to real-time emergency response by predicting when and where the greatest numbers of bird beachings will occur.*

Death and injury to seabirds are visible and well-documented effects of marine oil spills.[2,5,9,11,18,20,21] A frequent immediate response to spills is an intensive, concentrated effort to rescue stricken birds. Later, federal and state agencies may attempt to assess damages to those resources under their trusteeship; estimating the total mortality of seabirds is a major component of this procedure. For example, the damage assessment carried out for the 1984 *T/V Puerto Rican* oil spill assigned 77% of the estimated monetary damages to seabird losses.[13]

We describe a procedure for assessing seabird losses in this article, together with its application to two incidents in central California: the 1984 *T/V Puerto Rican* (*TVPR*) incident, and a spill of San Joaquin Valley Crude (SJVC) in 1986.[15,22,25] The procedure estimates the number of birds potentially contacting an oil slick and classifies them into four categories: (1) those oiled, debilitated, and beached alive; (2) those oiled, killed, and beached after death; (3) those oiled, killed, and lost at sea; and (4) those remaining at sea, whether oiled or not, and surviving beyond the period of the spill's peak impact. The number of beached birds, the abundance and distribution of birds at sea at the time of the spill, and the size and path of the slick are entered into a computer model that then classifies birds into the appropriate category. A prototype of this model is described in Ford *et al.*[16]

The modeling procedure provides data for the quantification component of the Type B Natural Resource Damage Assessment procedure under the Comprehensive Environmental Response, Compensation and Liability Act of 1980 (CERCLA). Within CERCLA, the proposed Natural Resource Damage Assessment Model for Coastal and Marine Environments (NRDAM/CME; CERCLA Type A) is inappropriate for damage assessments involving seabirds, because seabirds are not included in the model's biological data base. The NRDAM/CME model also uses resource densities averaged over large geographic regions, an inappropriate approach for seabirds, which are variable and often tightly clumped in their distribution. The Type A damage assessment procedure is specified only for oil spills of less than 10,000 gallons.[14]

Estimating the number of beached birds

Live oiled birds. Information on the numbers of beached birds is critical for assessing seabird mortality following an oil spill. The most obvious method of obtaining this information is to count the oiled birds on beaches at the time of an incident.[24] However, beached bird counts typically exclude many live, oiled birds that already have been removed and sent to rehabilitation centers. In populated areas, many people volunteer to collect live oiled birds following a spill. While these volunteers speed up the rescue of birds, the accurate information obtainable from beached bird counts is decreased. Under such conditions, the most practical method of obtaining counts is for the collection and rehabilitation centers to maintain accurate records. These records should include recovery date, recovery location, and identification of species.

During the *TVPR* incident, an organized beached bird survey effort enabled us to tabulate numbers of live oiled birds as they were collected. In contrast, the only sources of information on live oiled birds during the SJVC spill were collection and rehabilitation center records.

Dead oiled birds. Ideally, carcasses of oiled birds should be counted daily for the duration of an oil spill incident, after high tide, along the entire stretch of coastline potentially affected by the spill. Carcasses should be identified to the nearest recognizable taxon, the pattern of oiling on the plumage described, and the degree of body decomposition noted. They should be either marked or removed from the beach to avoid their inclusion in future counts. This level of organized effort is often impractical. Even adequate personnel cannot census inaccessible coastal areas. For example, during the *TVPR* incident, our analysis predicted that as many as one-third of the carcasses could have come ashore along stretches of coastline consisting of steep rocky cliffs that could not be searched.[15]

Failure to search beaches on a regular basis usually will lead to an underestimation because carcasses do not remain indefinitely on the beach face. Carcasses may wash back out to sea on the rising tide, become covered with sand, or be eaten by scavengers.[3,23] For the SJVC spill, we determined how long carcasses remained on the beach face. The toes of 336 beached carcasses were clipped characteristically and the beaches rechecked daily for the presence of marked bodies. Day-to-day persistence varied from 38% to 72% and averaged 59% over two areas and two days.[22] Thus, a delay of two days in carrying out a beach census could result in the loss of many beached carcasses.

There are two approaches to maximizing the use of limited personnel when estimating the numbers of dead beached birds over a large coastal area. One is to census only areas where the density of carcasses is likely to be greatest. Selection is made according to physical characteristics of the beaches[24,29] or is based on early reports of observers. If data are collected in this way, intervening uncensused coastal areas must be ignored in the final assessment and the estimated number of beached carcasses will inevitably be downwardly biased. This approach has the advantage of simplicity and permits workers to concentrate on doing a thorough job of censusing over a limited area.

A better method for making the most of limited manpower is to census carcasses on a stratified random sample of beaches along the entire length of coastline affected by the spill. Care must be taken to avoid the inclination to go where the greatest number of carcasses are reported. Censused beach segments should be 1 to 3 km in length, although the nature of the shoreline often determines the length. For very long beaches, it is better to sample several widely spaced beach segments instead of few long ones. Carcass deposition rates vary with different coastal segments and different types of beaches, and censuses should include every possible combination of these categories. An estimate of the total number of carcasses along the entire affected coastline is obtained by estimating the average carcass density for each segment/beach type combination, multiplying by the length of that combination in the affected area, and summing the resulting values.

During the SJVC spill, we estimated the density of carcasses on six coastal segments and five beach types over 355 km of coastline. Major geographical features were used to define coastal segments. Beaches were classified as rocky, dune-backed, bluff-backed, protected harbor, or pocket based on experience with collecting beached seabirds.[22] Estimated carcass densities (birds/km) varied by a factor of 55.4 times among coastal segments and 6.7 times among beach types.[22]

Limited manpower may prevent regular rechecking of affected beaches. Since not all carcasses are likely to beach on the same day, and their deposition varies from day to day (usually peaking rapidly and then tapering off), and since carcasses can disappear at a relatively rapid rate, a single count of a given stretch of beach provides a poor estimate of the total number of carcasses. If used without correction, a single count will always underestimate the actual number of carcasses reaching shore. A daily count on a representative sample of beaches to estimate the daily carcass deposition rate is the best way to compensate for this bias.

An alternative is to assume that the daily deposition rate for carcasses follows that for live birds. If this is assumed and the daily persistence of carcasses (S) is known, the total number of carcasses deposited on a given stretch of beach (N) can be extrapolated from those found in a single census (O) on day l by using the formula:

$$N = O / \sum_{i=1}^{l} (S^{l-i} P_i)$$

Where: l = the number of days after birds begin to be deposited
P_i = the proportion of the total expected to be deposited on day l based on the deposition rate of live birds

Daily live and dead bird deposition rates were similar during the *TVPR* spill and could not be shown to be dissimilar in the SJVC spill. In another incident, the beaching of dead birds lagged behind that of live ones;[18] in this case the lag must be factored into the calculations.

Overestimation of the numbers of dead and injured birds is most likely to occur when birds that died from causes other than the oil spill in question are attributed to the spill. Dead seabirds are found on beaches throughout the year, and sometimes natural processes such as severe weather, diminished food supply, or outbreaks of disease lead to sudden large scale die-offs.[1,19] This can cause confusion during oil spills, especially if birds dying of natural causes become oiled near or after death.[17] During the *TVPR* incident, for example, relatively large numbers of dead and dying surf scoters (*Melanitta perspicillata*) and white-winged scoters (*Melanitta fusca*) were found along central California beaches in the area affected by the spill. Although many of these birds were oiled and their deaths initially attributed to the spill, further examination showed them to be emaciated. Biologists familiar with the area knew that die-offs of both species had occurred at this season in the past, and that an unusually high mortality of scoters had been reported immediately before this spill. It was therefore concluded that oil from the *TVPR* spill was not necessarily the primary cause of mortality for these species.[13,25]

Another factor that can lead to overestimation of the numbers of beached birds is the assumption that all oiled birds in an area can be attributed to the same source. In fact, oiled birds are common in some areas due to chronic oil discharge from heavy vessel traffic or industrial activity.[21,24] It is even possible that a ship might choose to discharge oily waste near a known spill site believing that the added discharge would go unnoticed.

This problem should be dealt with by taking oil samples from birds to determine if the chemical fingerprint of the oil matches the known fingerprint of the spilled oil. Since fingerprinting oil is expensive, an efficient practice is to store a large number of samples. Samples can be preserved by removing and refrigerating oil-soaked plumage in clean, air-tight containers that will not contaminate the sample.[12] If the source of oiled birds for a particular time or area is uncertain, the samples can be analyzed as required.

Estimating the number of birds lost at sea

Even when the number of carcasses beached during an incident is known or can be estimated, a large fraction of the total mortality may remain unmeasured. Winds and currents may carry floating carcasses away from shore so that they are never observed.[3,4] Many carcasses that are propelled towards shore may not beach because they sink or are scavenged.[3,4,23] Calculating the extent of at-sea carcass loss for a specific incident requires four pieces of information: (1) a description of the trajectory of the oil; (2) a description of the trajectories of bird carcasses; (3) a rate for at-sea carcass loss; and (4) a description of the distribution of birds at sea in the area affected by the spill. The relationship between this information and the computer model we use for calculations is shown in Figure 1.

Trajectory of the oil. The path and area of an oil slick may be assembled from overflight data from the time of the incident, or by a *post hoc* modeling effort. When overflight data are extensive, a composite picture of the area and path of the slick can be constructed by extrapolating between successive observations, as illustrated for the *TVPR* incident (Figure 2). An alternative approach was used during the SJVC spill in which an oil spill trajectory model simulated the path of the slick using real time, wind, and current data. Either trajectory analysis ultimately provides a description of the position of the slick through time.

Trajectory of carcasses. The trajectories of dead birds can be modeled either by assuming that they followed the same course as the spilled oil, or by carrying out a separate trajectory analysis. Dead birds float passively in the direction dictated by winds and currents, as do oil slicks. The primary difference is that carcasses are subject to more drag than surface slicks. Slicks are typically assumed to move at 3.0% to 3.5%[27] of the wind speed, whereas carcasses have been found to move at 2.2% to 4.0%.[3,4,18] The percentage may vary with the type of seabird; more neutrally buoyant diving birds probably float lower in the water and move at a slower rate than do lighter soaring birds, such as gulls, which may also float with one wing extended upwards in a sail-like fashion.[3,18]

Rate of at-sea carcass loss. The loss of birds at sea probably is caused by the sinking of water-logged carcasses,[18,23] or their consumption by scavengers such as gulls and albatrosses. Carcass recovery rates of from 10% to 100% have been recorded in experiments using gulls (*Larus* spp.), where trajectories seemed to be directed toward shore and where potential beaching areas were searched.[3,23] At-sea loss rates may vary among species, with more neutrally buoy-

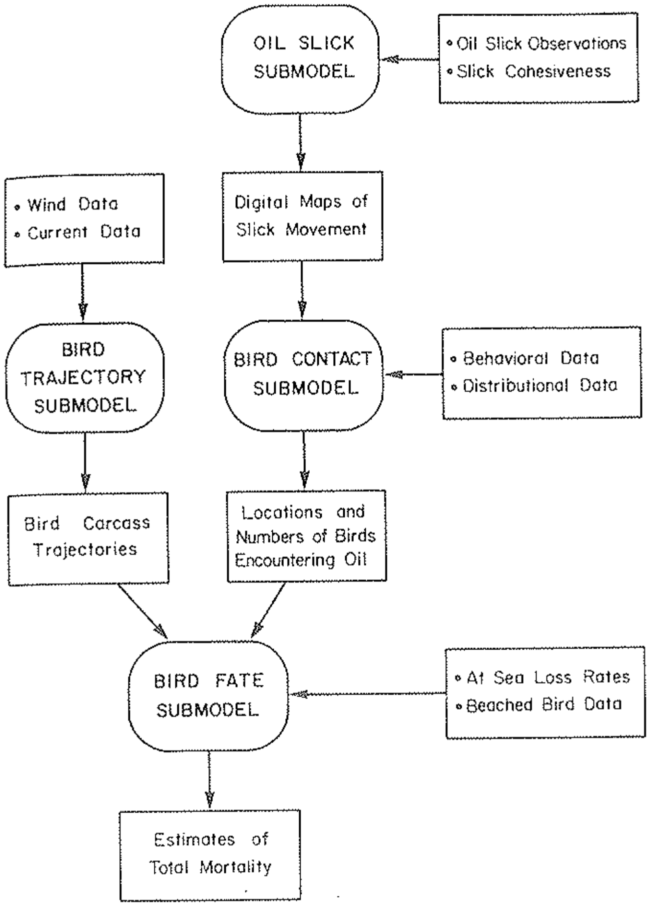

Figure 1. Flow diagram showing the relationships among the four sections of the computer model used to partition seabird mortality during the *T/V Puerto Rican* incident

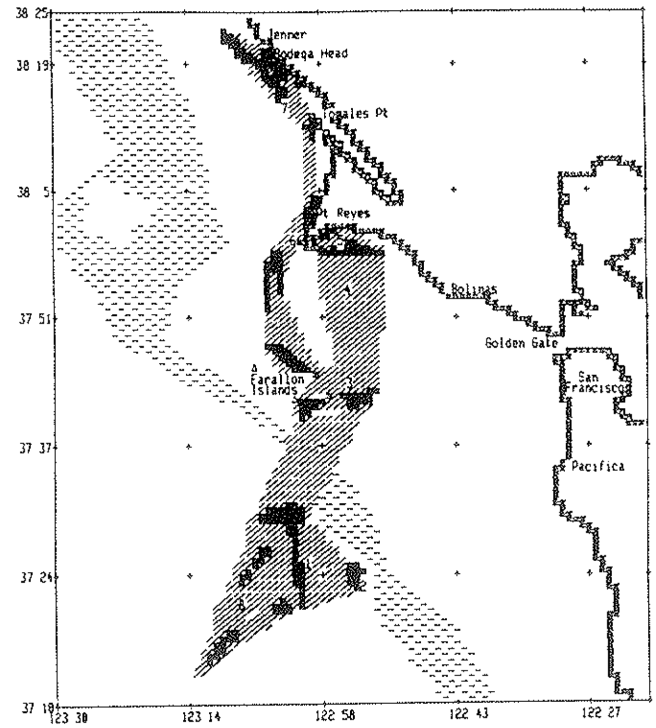

Figure 2. Observed and interpolated positions of the *T/V Puerto Rican* oil slick, November 3–11, 1984—Solid areas are slick observations; stippled areas are interpolated areas where the slick is assumed to have passed. The dashed region shows the 100 to 200 meter depth zone corresponding to the continental shelf break. (From Ford and Page[15])

ant birds such as loons, alcids, and cormorants sinking more quickly than birds such as gulls that float higher in the water.[4,23] Also, smaller species may be more susceptible to scavengers than larger ones.

For analyzing the case histories discussed in this paper, the best available information on at-sea loss is derived from Hope Jones *et al.*[18] Twenty percent of 410 oiled alcid carcasses dropped at varying positions offshore were subsequently recovered on beaches. The majority beached eight to 14 days after release. We assume that 20% were still afloat after 10 days and the other 80% were lost by then. Further, we assume the rate of loss to be constant at 15% per day. Applying this rate to the *TVPR* and SJVC incidents, we calculated at-sea losses for common murres (*Uria aalge*) at 60% (*TVPR*) and 30% (SJVC) of the birds killed.

At-sea carcass loss may not be constant. Instead it may increase between the time of oiling and landfall because of carcass deterioration. We are unaware of empirical studies bearing on this subject. The assumed relationship is important when estimating mortality. If there is a lag between oiling and carcass loss, beached carcass counts of nearshore species such as scoters and grebes could provide a reasonable estimate of dead oiled birds (given trajectories directed toward shore) since most carcasses would reach shore quickly; however, if the loss rate is constant, beached carcass counts would underestimate mortality because carcasses would begin disappearing immediately after the birds' deaths.

Distribution of birds at sea. Little is known about the attraction and avoidance behavior of seabirds toward an oil slick; thus the expected number of contacts between birds and oil can be estimated only by the abundance of birds in the path of the slick.

Since marine birds tend to aggregate in areas where prey are clumped,[8] aerial surveys are the only feasible method to describe such "patchy" bird distributions over large areas. Over the narrow continental shelf where both the *TVPR* and the SJVC spills occurred, the surveys were flown using fixed-width transects perpendicular to shore.[7,10] Many narrowly spaced transects were flown on the same day, providing a "snapshot" of seabird distribution and abundance. Transects used in our studies were flown at 50–100 m altitude, at 150–200 km/hr, and covered a 50-m-wide belt.

Drawbacks of the method are: Flight speed causes inconspicuous and underwater birds to be missed; tight aggregations of birds between transects can be totally missed; flying birds cannot be associated with a specific area of sea surface; birds roosting on land are excluded, even though later when foraging they could contact a slick; and birds aggregating near shore, for example in bays or by promontories, are not effectively sampled. Despite these drawbacks, aerial surveys are the most effective method for quickly covering the spill region.

Aerial surveys should be conducted as soon as possible after the spill. What little is known about the temporal stability of seabird abundance and distribution at sea suggests it may vary among habitats. Aggregations of alcids at shelf fronts may persist from five to 30 days,[6] and those close to shore may persist for months.[26] Given what is known, we suggest aerial censuses should be completed no later than three weeks after an incident. Aerial surveys were made on four dates from eight to 17 days after the *TVPR* spill and on one date about eight days after the SJVC spill.[22,25]

Considering all the sources of error listed above, we expect the reliability of survey data varies from species to species. Reliability may be highest for loons and alcids because their aggregations tend to be looser and more persistent than those of other shelf species. This trait is expected because loons and alcids exploit less temporally and spatially patchy prey than surface feeders such as pelicans and gulls. Loons and alcids also spend less time flying and only visit land in connection with breeding activities.

While better techniques are needed for surveying nearshore species such as grebes and scoters, estimates of at-sea loss are less critical for them than for offshore species. The degree of at-sea loss, which is proportional to the distance between where the bird is oiled and shore, is likely to be relatively low for nearshore, compared with offshore, species.

Overriding all other factors is the fact that at-sea bird abundance is likely always underestimated by post-incident surveys. The degree to which at-sea densities are reduced could vary considerably among incidents. In some instances, large aggregations of birds could be hit so severely that by survey time the aggregations would no longer be detectable. However, at present we know of no cost-effective methodology to overcome this problem.

Model estimation of mortality and survival

The modeling procedure estimates the mortality and survivorship of birds in the path of a slick, based on the assumption that all birds contacting the region of the slick can be categorized as either dead, debilitated, or non-debilitated immediately after the encounter. Integration of the slick path with the distribution of at-sea bird densities identifies the locations and the potential number of contacts between seabirds and the slick. These are put into a carcass trajectory model along with the assumed at-sea carcass loss rate (15% per day) to determine the proportion of birds lost at sea relative to the number of dead oiled birds that beached along a given coastal segment. Working backwards from the number of these beachings, we estimate the proportion of the contacts that were fatal.

As an example, suppose we recover 1,000 oiled seabird carcasses and 750 live oiled birds on a segment of coast. If we determine that 60% of the dead birds were lost at sea, then 2,500 birds actually died and were directed toward that coastal segment. Suppose further that the oil trajectory analyses and bird distribution data indicate that 5,000 birds could have contacted the slick and been directed toward the coastal segment. Then we assume that about 2,500/5,000 or 50% of the contacts between the birds and the slick were fatal and 750/5,000 or 15% were debilitating.

Continuing with the preceding example, suppose we estimate there were an additional 1,500 potential slick/seabird contacts that would have resulted in birds being carried offshore by winds and currents. We would then estimate that 50% or 750 of these birds actually made fatal contact and 15% or 225 were debilitated. We assume these debilitated birds are passively transported out to sea, where they eventually die. Therefore, 975 of 1,500 (65%) of the potential contacts are fatal. Thus, in this hypothetical example, 1,000 seabird carcasses were recovered on the beach, 1,500 carcasses were directed toward the beach but lost at sea, 975 carcasses were carried out to sea, 750 debilitated birds beached and went to rehabilitation centers, and 2,275 birds contacted the slick region and survived.

T/V Puerto Rican incident

On October 31, 1984, two explosions severely damaged the *T/V Puerto Rican* as it was leaving San Francisco Bay. After being towed 18 km southwest of Southeast Farallon Island, it broke in half and released about 35,000 barrels of petroleum hydrocarbons.[13] Following the spill, 1,300 live and dead oiled birds of at least 30 species, including 470 common murres, were recovered on beaches from San Francisco to Mendocino counties.[13,25] Most beachings occurred within an eight-day period.

This incident was characterized by a highly organized response, and the effects were much better documented than is often the case. Personnel from the Point Reyes Bird Observatory were able to compile beached bird data for about 35% of the accessible coastline, including all of the beaches reported to have large numbers of beached birds. It was possible to census many beaches more than once, and to determine accurately the identity and location of live and dead oiled birds. The U.S. Coast Guard carried out extensive overflights during the incident, and their records produced a complete description of the path of the slick (Figure 2). Aerial censuses of seabirds were carried out on four separate occasions by observers from the University of California, Santa Cruz. Bird carcass trajectories were computed by the Hazardous Materials Response Branch of the National Oceanic and Atmospheric Administration using the On-Scene Spill Model.[28]

We concentrated our modeling efforts on estimating the numbers of common murres lost at sea or washed up along inaccessible stretches of coastline, and calculated that about 27% had been recovered alive or dead, 21% had beached along inaccessible portions of the coast, and 52% had been lost at sea.[15] The data base for the *TVPR* incident was complete enough to test the validity of our methodology. The model was able to accurately predict the numbers of murres on a particular stretch of coastline, accounting for 81% of the variation in the numbers of murres found along a coastal segment.

San Joaquin Valley crude incident

During the first week of February 1986, a spill of San Joaquin Valley crude (SVJC) oil polluted beaches in central California. Between February 1 and 8, 3,364 living and 834 dead oiled seabirds were recovered. The State of California Regional Water Quality Control Board, San Francisco Region, after reviewing the available information, concluded that the evidence pointed strongly to a tank barge loaded with SJVC oil en route from Martinez, California, to Long Beach. As part of an assessment of the damage resulting from the spill, we estimated the total seabird mortality based on the assumption that the barge identified by the water quality board was the source of the oil spill.

The amount of information available for this incident was much less than for the *TVPR* incident because the loss of oil occurred during heavy seas, and because the USCG was not alerted to look for the

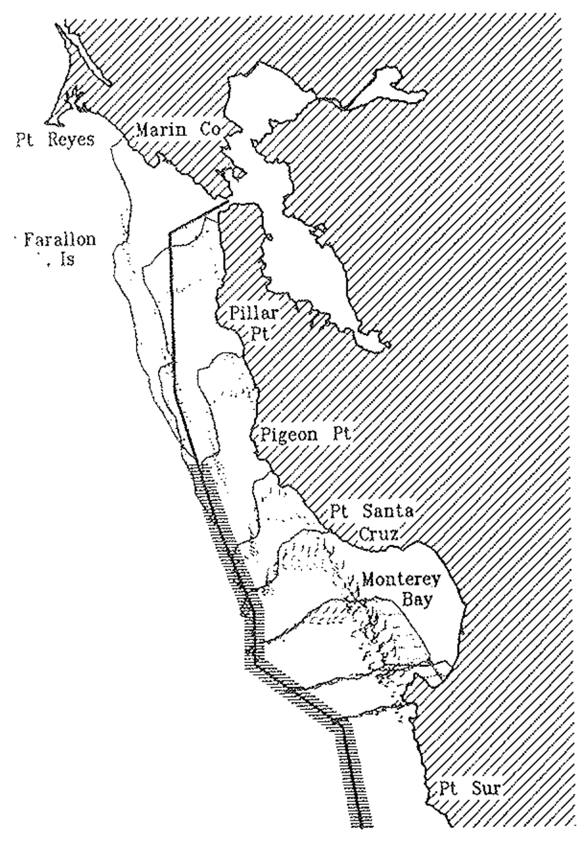

Figure 3. Model simulation of the heavy-weather scenario in which a vessel released San Joaquin Valley crude oil continuously, starting off Pigeon Point—The heavy line shows the presumed track of the vessel. The section of the route that is shaded with horizontal cross-hatching indicates the time when the vessel speed was slowed due to weather conditions. Thin lines are model oil trajectories launched at three-hour intervals along the vessel route. Dots show the positions of simulated groups of bird carcasses at three-hour intervals. Groups of simulated bird carcasses were launched at three-hour intervals along the path of each oil spill trajectory.

slick until oil and birds already had begun to come ashore. As there were few at-sea observations of the slick, modeling efforts were hampered by uncertainty as to exactly where the oil was released. Because the incident went unreported for some time, and because the total length of affected coastline was at least 350 km, many beaches were not searched for carcasses until late in the incident and much of the accessible coastline was not covered. However, we were able to sample a representative set of beach types throughout the affected area at least once and to measure carcass persistence on beaches. Additionally, rehabilitation centers kept adequate records on arrivals of live oiled birds.

We corrected the observed numbers of oiled carcasses for uncensused areas and for carcasses missed because beaches were censused only once. For common murres, the species most severely affected by this spill, we estimated that in addition to the 2,924 live oiled birds and 554 beached carcasses recovered, 3,041 carcasses were beached but not counted.

We used real-time wind data from two coastal weather stations and three offshore buoys, combined with a surface-current vector field (Oil Spill Risk Analysis Model developed for the Minerals Management Service by Dianalysis of Princeton), to model trajectories of both birds and oil (Figure 3). Trajectory analyses indicated that oil released along the track of the barge identified by the water quality board could have resulted in the observed spatial and temporal pattern of beaching of both birds and oil. Model bird carcass trajectories were directed inshore, and few birds beached along stretches of coastline that were not sampled by Point Reyes Bird Observatory personnel. We therefore corrected the beached carcass estimates assuming that at-sea loss occurred on the way to landfall. Our final calculations indicated that 38% of the oiled murres reaching shore were recovered, 41% beached but were not recovered, and 21% were lost to natural processes on the way to shore.

Conclusion

The procedure described in this paper provides a more sound basis for estimating the mortality of seabirds from oil spills than have previous procedures that either guessed at or ignored at-sea losses, or derived them without empirical data.[16,30] Our procedure reduces the assumptions inherent in models by incorporating data collected at the time of the spill. For the first time, we provide estimates of total mortality and survival. Such estimates are central to determining the potential impact of oil spills on seabird breeding populations over time.[30]

References

1. Armstrong, I. H., J. C. Coulson, P. Hawkey, and M. J. Hudson, 1978. Further mass seabird deaths from paralytic shellfish poisoning. *British Birds*, v79, pp58–68
2. Barrett, R. T., 1979. Small oil spill kills 10–20,000 seabirds in north Norway. *Marine Pollution Bulletin*, v10, pp253–255
3. Bibby, C. J., 1981. An experiment on the recovery of dead birds from the North Sea. *Ornis Scandinavia*, v12, pp261–265
4. Bibby, C. J. and C. S. Lloyd, 1977. Experiments to determine the fate of dead birds at sea. *Biological Conservation*, v12, pp295–309
5. Bourne, W. R. P., 1970. Special review—after the *Torrey Canyon* disaster. *Ibis*, v112, pp120–125
6. Briggs, K. T., D. G. Ainley, L. B. Spear, P. B. Adams, and S. M. Smith, in press. Distribution and feeding of two alcids (Cassin's auklet and common murre) in relation to central California upwellings. *Proceedings of the 19th International Ornithological Congress*
7. Briggs, K. T., W. B. Tyler, D. B. Lewis, and K. F. Dettman, 1983. Seabirds of Central and Northern California, 1980–1983: Status, Abundance, and Distribution. Center for Marine Studies Report, University of California, Santa Cruz, California
8. Brown, R. G. B., 1980. Seabirds as marine animals. *in* Behavior of Marine Animals, J. Burger, B. L. Olla, and H. E. Winn, eds. Vol. 4. Marine Birds. Plenum Press, New York, pp1–39
9. Brown, R. G. B., D. I. Gillespie, A. R. Locke, P. A. Pearce, and G. H. Watson, 1973. Bird mortality from oil slicks off eastern Canada, February–April 1970. *Canadian Field Naturalist*, v87, pp225–234
10. Burnham, K. P., D. R. Anderson, and J. L. Laake, 1980. Estimation of Density from Line Transect Sampling of Biological Populations. *Wildlife Monographs*, v72, pp1–202
11. Clark, R. B., 1968. Oil pollution and the conservation of seabirds. *Proceedings of the International Conference on Oil Pollution of the Sea*, Rome, pp76–112
12. Clark, R. C., Jr., and D. W. Brown, 1977. Petroleum: properties and analyses in biotic and abiotic systems. Effects of Petroleum on Arctic and Subarctic Marine Environments and Organisms, D. C. Malins, ed. Vol. 1. Nature and Fate of Petroleum. Academic Press, New York, pp1–89
13. Dobbin, J. A. and H. E. Robertson, 1986. Resource Damage Assessment of the *T/V Puerto Rican* Oil Spill Incident. Report to the National Oceanic and Atmospheric Administration, Contract 50-DGNC-6-00102.
14. Economic Analysis Inc. and Applied Science Associaton, 1986. Measuring Damages to Coastal and Marine Natural Resources: Concepts and Data Relevant for CERCLA Type A Damage Assessments. Vol. 1. Interior Department, CERCLA 301 Project, Washington, D.C.
15. Ford, R. G. and G. W. Page, in preparation. A Model to Assess Seabird Mortality from Oil Spills: The *T/V Puerto Rican* Incident.
16. Ford, R. G., J. A. Wiens, D. Heinemann, and G. L. Hunt, Jr., 1982. Modeling the sensitivity of colonially breeding marine birds to oil perturbation. *Journal of Applied Ecology*, v19, pp1–31
17. Harrington-Tweit, B., 1979. A seabird die-off on the Washington coast in mid-winter 1976. *Western Birds*, v10, pp49–56
18. Hope Jones, P., G. Howells, E. I. S. Rees, and J. Wilson, 1970. Effect of *Hamilton Trader* oil on birds in the Irish Sea in May 1969. *British Birds*, v63, pp97–110
19. Kinsky, F. C., 1968. An unusual seabird mortality in the southern North Island (New Zealand) April 1968. *Notornis*, v15, pp143–155
20. Moffitt, J. and R. T. Orr, 1938. Recent disastrous effects of oil pollution on birds in the San Francisco Bay region. *California Fish and Game*, v24, pp239–244
21. National Research Council, 1985. Effects. *in* Oil in the Sea: Inputs, Fates, and Effects. National Academy Press, Washington, D.C., Chapter 5, pp369–547
22. Page, G. W. and H. R. Carter, 1986. Impacts of the 1986 San Joaquin Valley Crude Oil Spill on Marine Birds in Central California. Special Scientific Report, Point Reyes Bird Observatory, Stinson Beach, California
23. Page, G. W., L. E. Stenzel, and D. G. Ainley, 1982. Beached Bird Carcasses as a Means of Evaluating Natural and Human-caused Seabird Mortality. Report to Department of Energy, Contract DE-AC03-79EV10254
24. Piatt, J. F., R. D. Elliott, and A. MacCharles, 1985. Marine Birds and Oil Pollution in Newfoundland 1951–1974. Newfoundland Institute for Cold Ocean Sciences Report No. 105
25. Point Reyes Bird Observatory, 1985. The Impacts of the *T/V Puerto Rican* Oil Spill on Marine Bird and Mammal Populations in the Gulf of the Farallones, 6–19 November 1984. Special Scientific Report, Point Reyes Bird Observatory, Stinson Beach, California
26. Sealy, S. G., and H. R. Carter, 1984. At-sea distribution and nesting habitat of the marbled murrelet in British Columbia: problems in the conservation of a solitarily nesting seabird. *in* Status and Conservation of the World's Seabirds, J. P. Croxall, P. G. H. Evans, and R. W. Schreiber, eds. International Council for Bird Protection Technical Publication No. 2, pp737–756
27. Smith, R. A., J. R. Slack, T. Wyant, and K. J. Lanfear, 1982. The Oil Spill Risk Analysis Model of the U.S. Geological Survey. Geological Survey Professional Paper 1227, USGS, Washington, D.C.
28. Torgrimson, G. M., 1981. A comprehensive model for oil spill simulation. *Proceedings of the 1981 Oil Spill Conference*, American Petroleum Institute, Washington, D.C., pp423–428
29. Tsouk, E., S. Amir, and V. Goldsmith, 1985. Natural self-cleaning of oil-polluted beaches by waves. *Marine Pollution Bulletin*, v16, pp11–19
30. Wiens, J. A., R. G. Ford, and D. Heinemann, 1984. Information needs and priorities for assessing the sensitivity of marine birds to oil spills. *Biological Conservation*, v28, pp21–49