NUMBERS OF SEABIRDS KILLED OR DEBILITATED IN THE 1986 *APEX HOUSTON* OIL SPILL IN CENTRAL CALIFORNIA

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Abstract. We developed models describing carcass deposition on beaches and carcass loss at sea in order to estimate the number of birds killed by the February 1986 *Apex Houston* oil spill along the central California coast. A carcass deposition model was used to estimate the total number of beached carcasses by integrating single censuses of dead birds on 51 beaches at the time of the spill, estimated daily proportions of total numbers of carcasses depositing on shore, and a daily rate of beached carcass persistence. A carcass trajectory model was used to estimate the number of birds killed by oil that did not reach shore by integrating simulated slicks arising along the path of the *Apex Houston,* the distribution and abundance of birds at sea, and a daily at-sea carcass loss rate.

The *Apex Houston* spill killed thousands of seabirds along the central California coast. At least 3364 debilitated live oiled birds, primarily Common Murres (*Uria aalge*), were collected from beaches for cleaning and rehabilitation. An estimated additional 5880 dead oiled birds, primarily Common Murres and Rhinoceros Auklets (*Cerorhinca monocerata*), washed ashore. Only 87.1% of 7488 Common Murres, 78.6% of 1566 Rhinoceros Auklets, and 82.8% of 169 Cassin's Auklets (*Ptychoramphus aleuticus*) debilitated or killed by oil were determined to have reached shore. Overall, at least 10,577 birds of 26 species were debilitated or killed including in addition to the above: 276 loons (*Gavia* spp.), 115 small grebes, 468 *Aechmophorus* grebes, 19 unidentified grebes, 283 scoters (*Melanitta* spp.), 37 auklets or murrelets, and 156 birds that were unidentified or of other taxa. Limitations of the models are discussed and future research for refining them is suggested.

Key Words: Seabirds; oil spill; California, *Apex Houston*; Common Murre; Rhinoceros Auklet; Cassin's Auklet.

Despite extensive documentation of large seabird mortalities during marine oil spills (reviews in Stowe 1982, Evans and Nettleship 1985), little has been published on methods of estimating the extent of mortality. Reported numbers of casualties have tended to be guesses, usually simple multiples of the number of carcasses or debilitated birds, or both, found along shorelines (e.g., Greenwood and Keddie 1968, Hope Jones et al. 1970, Bibby and Lloyd 1977, Heubeck and Richardson 1980). More accurate estimates are required for examining the short- and long-term impacts of oil spill mortality on seabirds or preparing the damage assessments used to recover costs from the party responsible for the spill (Dunnet 1987, Ford et al. 1987).

We developed new methods for estimating seabird mortality from a spill of San Joaquin Valley Crude oil, which caused thousands of birds to beach suddenly in February 1986 along the central California coast. The California Regional Water Quality Control Board (CRWQCB) concluded that the tank barge *Apex Houston* probably was the source of the spill. After being towed from the Shell Oil refinery at Martinez, California, to Long Beach, California, between 28 January and 1 February, the *Apex Houston* was missing 616 barrels (25,800 gallons) of oil, had lost a hatch cover, and had visible signs of oil outflow near the hatch opening (CRWQCB 1986).

We developed a model that used tallies of live birds taken to rehabilitation centers and carcass counts on beaches to estimate the number of oiled birds that beached along 355 km of shoreline between Salmon Creek, Sonoma County, and Point Lobos, Monterey County. By subdividing the bird tallies for six coastal regions (Fig. 1), we accounted for differences in beached bird deposition in relation to distance from the spill and variation in the distribution of birds at sea. An aerial census of birds at sea was used in an oil and carcass trajectory model to estimate the number of dead oiled birds that never reached shore. Our methods can be applied elsewhere to alcids and other diving marine birds that tend to be heavily affected by marine oil spills.

METHODS

Point Reyes Bird Observatory (PRBO) is experienced in conducting beached bird censuses (Page et al. 1982, Stenzel et al. 1988) and has estimated the mortality of seabirds in two oil spills—the 1971 San Francisco oil spill (Smail et al. 1972) and the 1984 *Puerto Rican* oil spill (PRBO 1985). Oiled birds from the *Apex Houston* spill first came ashore on 1 February. PRBO began beached bird censuses in Marin County on 3 and 4 February, expanding coverage southwards on 5 February after learning that government agencies were not counting dead birds. The late start, due to our lack of knowledge of the incident, and a limited availability of personnel created three major problems: 1) due to

the long length of coastline with oiled birds, we could only cover a sample of beaches and extrapolate for uncovered areas; 2) since we could cover most beaches only once, it was necessary to estimate the numbers of birds beaching before and after censuses began; and 3) the public had removed most live oiled birds from beaches before we could count them.

Rehabilitation center data

Live oiled birds were recovered from beaches and taken to collection centers for further transport to rehabilitation centers or were transported directly to rehabilitation centers during a large scale rescue effort by government agencies, private organizations, and concerned individuals. Not all collection centers kept complete records. Rehabilitation centers usually made an accession record which included all or part of: date, number of birds of each species, presence or absence of oil, and location found (Carter et al. 1987). We used the accession records of rehabilitation centers to determine the number of live oiled birds removed from beaches, substituting collection center records for incomplete rehabilitation center records when necessary and possible. Despite laborious comparisons, we probably missed hundreds of birds that had been sent to rehabilitation centers. Incomplete records permitted the breakdown of total birds either by taxa or by date and recovery area, but not by all three variables simultaneously.

Beached bird censuses

PRBO conducted 86 carcass counts on 51 beach segments from Point Reyes, Marin County, to Del Monte, Monterey County, between 2 and 11 February 1986. The number of birds of each species with and without oiled plumage, the degree of carcass decomposition, date, beach length, and beach type were recorded for each census. Carcasses were marked or removed to prevent them from being recounted on future censuses. Beaches were typed as: 1) *dune*, sandy with a dune backshore; 2) *bluff*, sandy with a cliff or bluff backshore; 3) *pocket*, short sandy beach at a river or creek mouth; 4) *rocky*, rock or cobble beach with a cliff or bluff backshore; and 5) *protected harbor*, one beach (Princeton Harbor) largely cut off from the ocean by breakwaters.

Once beached, carcasses remain visible for varying amounts of time depending on decomposition, scavenging, burial in sand, and whether or not they are washed back out to sea (Tanis and Morzer-Bruijns 1962, Alexandersen and Lamberg 1971). On 6, 7, and 8 February, the daily rate of carcass persistence was measured on 6.8 km of shoreline at Half Moon Bay and on 5.7 km of shoreline from Pomponio State Beach to north of San Gregorio State Beach. The toes of carcasses were clipped in different patterns to separate birds by date and beach section and carcasses were left where found.

Survey of birds at sea

One aerial survey was conducted on 5 February 1986 by the University of California, Santa Cruz, using census protocols developed by Briggs et al. (1985a, b; 1987) for marine birds over the California outer continental shelf. All seabirds within 50 m were recorded along 10
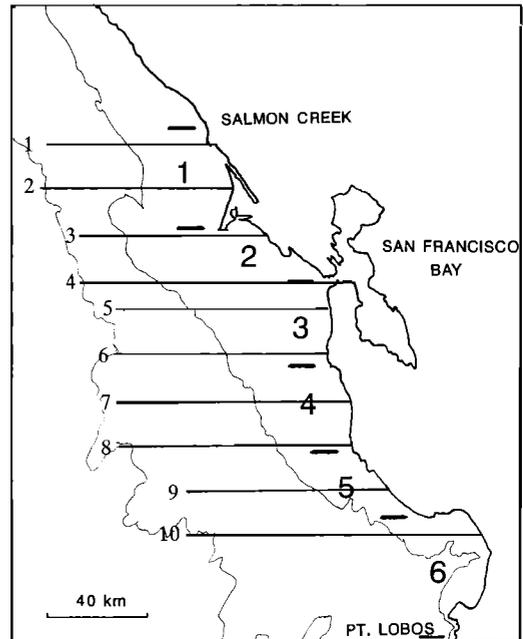

FIGURE 1. Six regions on the central California coast where live and dead oiled birds beached during the *Apex Houston* oil spill, and ten transect lines flown on the 5 February 1986 aerial survey of birds at sea. The 200 m and 3000 m depth contour lines are also shown.

predetermined east-west transects between Bodega and Monterey bays (Fig. 1) during flights at an altitude of 65 m and a speed of 165–185 km/hr. Sightings were converted to densities (birds/km²) by transect and water depth. Shelf waters were <200 m and slope waters 200 to 3000 m deep. Shelf waters were further divided into inner and outer sections by the 100 m depth contour. A total of 40.9 km² was surveyed.

RESULTS

NUMBERS OF OILED BIRDS FOUND ON BEACHES

At least 3858 live oiled birds were sent to rehabilitation centers between 1 February and 31 March (Page and Carter 1986). Live bird beachings peaked between 1–8 February when 3364 birds (or 87.2%) were recovered (Fig. 2). Common Murres (*Uria aalge*) accounted for 86.9% of the total recoveries and over 73% of the recoveries in each region (Tables 1, 2).

The pattern of live bird beachings varied among coastal regions (Fig. 2). Although substantial numbers of birds had been recovered from all regions by 3 February, peak numbers occurred on 3 February in regions 1 to 3, on 4 February in regions 4 and 6, and on 6 February in region 5. In regions 1 to 4, numbers exhibited a sharp peak whereas in regions 5 and 6, they built up and declined more gradually.
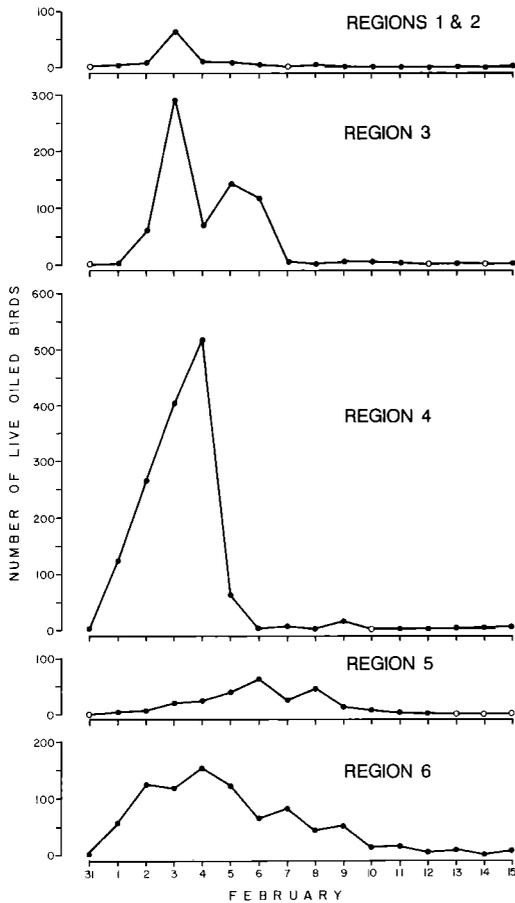
FIGURE 2. Numbers of live oiled birds sent to rehabilitation centers from six coastal regions between 1 and 15 February 1986. Open dots refer to zero counts.

In all, 834 oiled bird carcasses were found on 86 censuses of 51 beach segments between 2 and 11 February (Table 1). Common Murres again accounted for the majority (66.4%) of the oiled carcasses. However, carcasses contained a much higher proportion (15.7%) of Rhinoceros Auklets (*Cerorhinca monocerata*) than did live oiled birds (0.9%).

CARCASS PERSISTENCE

Daily carcass persistence on beaches was determined regardless of when carcasses were deposited. On the day following marking, 69.1% (N = 97) and 72.0% (N = 93) of the carcasses were found on the two beaches. From the second to third day, carcass persistence was 38.1% (N = 97) and 57.2% (N = 138), respectively. Carcass persistence may vary with species, beach type, tide, and time since beaching (Page et al. 1982).
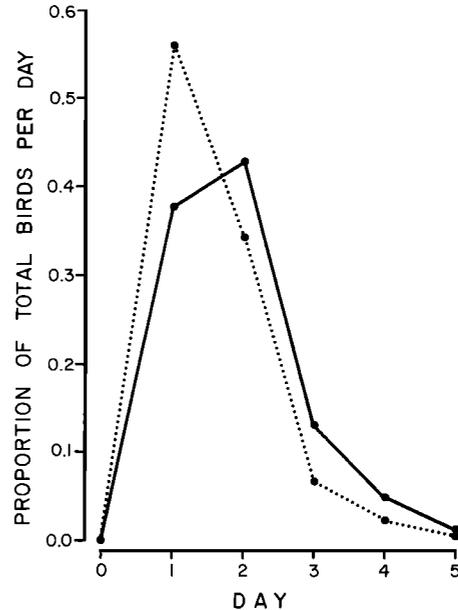

FIGURE 3. Proportions of total live (dotted line) and dead (solid line) oiled birds that reached shore in the Bodega Bay area between 10 November (day 1) and 14 November (day 5), during the 1984 *Puerto Rican* oil spill (N = 298 live and 399 dead oiled birds; PRBO 1985, unpubl. data).

However, our data were insufficient to obtain separate values for any of these categories so we used the mean value of 59.1% (SE = 7.7%, N = 4) in subsequent calculations.

BEACHED BIRD MODEL

We extrapolated for the number of carcasses that washed ashore on a beach over the spill period from the equation:

$$N_t = \frac{O_d}{\sum_{i=1}^{d} S^{d-i} P_i}$$

where:

N_t = total number of carcasses that actually washed onto a beach during the t days of the spill period. In the *Apex Houston* spill, this period was limited to the eight-day peak period of live oiled bird beachings.

O_d = observed number of birds on day d on a single census of a beach.

d = number of days that oiled birds have been depositing on the beach.

S = average daily persistence or survival of carcasses.

TABLE 1. SPECIES COMPOSITION OF LIVE OILED BIRDS TAKEN TO REHABILITATION CENTERS FROM 1–8 FEBRUARY 1986 AND DEAD OILED BIRDS FOUND ON BEACHES FROM 2–11 FEBRUARY 1986 DURING THE *APEX HOUSTON* OIL SPILL. DASHES INDICATE ZEROS

Species	Live oiled		Dead oiled	
	No.	%	No.	%
Common Loon (*Gavia immer*)	27	0.8	—	—
Pacific Loon (*G. arctica*)	25	0.7	7	0.8
Red-throated Loon (*G. stellata*)	18	0.5	6	0.7
Unidentified loon	58	1.7	4	0.5
Aechmophorus grebes	155	4.6	48	5.8
Horned Grebe (*Podiceps auritus*)	3	<0.1	—	—
Eared Grebe (*P. nigricollis*)	2	<0.1	11	1.3
Pied-billed Grebe (*Podilymbus podiceps*)	4	0.1	—	—
Unidentified grebe	19	0.6	—	—
Northern Fulmar (*Fulmarus glacialis*)	1	<0.1	4	0.5
Brandt's Cormorant (*Phalacrocorax penicillatus*)	4	0.1	2	0.2
Unidentified cormorant	3	<0.1	—	—
Black Scoter (*Melanitta nigra*)	—	—	3	0.4
White-winged Scoter (*M. fusca*)	19	0.6	17	2.0
Surf Scoter (*M. perspicillata*)	20	0.6	10	1.2
Unidentified scoter	22	0.7	—	—
Unidentified duck	5	0.1	—	—
Unidentified plover	—	—	1	0.1
Red Phalarope (*Phalaropus fulicaria*)	6	0.2	7	0.8
Sanderling (*Calidris alba*)	1	<0.1	1	0.1
Ring-billed Gull (*Larus delawarensis*)	1	<0.1	—	—
Mew Gull (*L. canus*)	2	<0.1	—	—
California Gull (*L. californicus*)	1	<0.1	—	—
Western Gull (*L. occidentalis*)	1	<0.1	2	0.2
Glaucous-winged Gull (*L. glaucescens*)	2	<0.1	—	—
Unidentified gull	1	<0.1	—	—
Common Murre (*Uria aalge*)	2924	86.9	554	66.4
Marbled Murrelet (*Brachyramphus marmoratus*)	1	<0.1	2	0.2
Ancient Murrelet (*Synthliboramphus antiquus*)	3	<0.1	4	0.5
Cassin's Auklet (*Ptychoramphus aleuticus*)	—	—	17	2.0
Rhinoceros Auklet (*Cerorhinca monocerata*)	30	0.9	131	15.7
Tufted Puffin (*Fratercula cirrhata*)	—	—	1	0.1
Unidentified murrelet	1	<0.1	—	—
Unidentified auklet	4	0.1	—	—
Unidentified birds	1	<0.1	2	0.2
Total	3364	100.0	834	100.0

P_i = proportion of the total number of carcasses coming ashore during the spill period that are expected to be deposited on day i.

i = index variable for day in the summation.

For the *Apex Houston* spill, we calculated N_t values for 46 beaches covered at least once between 3 and 8 February (Page and Carter 1986). For O_d, we used the first census for beaches with more than one count between 3–8 February. S was assigned the value .591, as determined at the time of the spill. Since we lacked actual estimates of the proportion of birds arriving on a given day, we substituted P_i values from data available by region for live birds. We assumed that the proportions of birds that beached daily were similar for live and dead birds during the spill period, but there is little published information on which to evaluate this assumption. However, large numbers of oiled carcasses had reached many beaches by 3 February (see Page and Carter 1986 for details), when live bird numbers began to peak. Thus, the timing of peak deposition for live and dead birds appeared similar. P_i values for live and dead oiled birds also were similar during the *Puerto Rican* spill (Fig. 3; also see Stenzel et al. 1988), but most live birds were reported to beach a few days before most dead ones during the *Hamilton Trader* spill (Hope Jones et al. 1970).

We divided N_t values by the length of the beach in kilometers for the 46 beaches covered and then

TABLE 2. SPECIES COMPOSITION OF LIVE (L) AND DEAD (D) OILED BIRDS FROM SIX COASTAL REGIONS ALONG THE CENTRAL CALIFORNIA COAST DURING THE *APEX HOUSTON* OIL SPILL

Species[2]	Coastal region[1]													
	1		2		3		4		5		6		UNK	
	L	D	L	D	L	D	L	D	L	D	L	D	L	D
Loons	1	—	5	3	6	24	14	23	12	32	50	66	8	—
Small grebes	—	—	—	3	—	12	3	11	—	16	—	64	2	—
Aechmophorus grebes	—	—	10	15	9	79	25	105	45	48	37	66	6	—
Unidentified grebes	—	—	—	—	6	—	9	—	—	—	1	—	3	—
Scoters	6	41	1	—	16	24	11	86	3	48	14	64	10	—
Common Murre	—	—	75	223	327	261	924	1478	181	462	644	1130	87	—
Auklets/murrelets	—	—	—	3	1	—	1	71	—	16	5	78	2	—
Rhinoceros Auklet	—	10	2	3	1	6	7	274	1	64	20	844	1	—
Other species	—	—	—	9	1	24	3	42	5	—	11	52	1	—
Unidentified birds	—	—	—	—	324	—	399	—	1	—	—	—	27	—
Total	7	51	93	259	691	430	1396	2090	248	686	782	2364	147	—

[1] Locations of regions are indicated in Figure 1.
[2] Live bird totals for species groups differ from those in Tables 1 and 3 due to large numbers of unidentified birds by region.

calculated mean values of N for each beach type within each region. Missing values for 6 of the 25 region-beach type combinations were assumed to be similar to those for the same beach type from a neighboring region. We calculated the total length of the different beach types in each of the six regions (from Habel and Armstrong 1978) and multiplied each length by the appropriate mean value of N for each beach type in each region and then summed carcass totals for each region.

ESTIMATED NUMBER OF OILED CARCASSES REACHING SHORE

Using this model, we estimated 5880 beached oiled carcasses, which were broken down into taxa (Tables 2, 3) in direct proportion to numbers of each taxon in each region on carcass counts (Page and Carter 1986). An unknown but presumably small proportion of these birds was likely oiled after death either at sea or on the beach. From 2 to 11 February, 61 carcasses were found without oiled plumage, compared to the 834 with oiled plumage. The 834 moderately- to heavily-oiled carcasses were not so decomposed that we could eliminate oiling as the probable cause of death. Common Murres accounted for 61.1% and Rhinoceros Auklets for 20.4% of the oiled carcasses. *Aechmophorus* grebes and scoters (*Melanitta* spp.) were the next most abundant taxa constituting 5.3% and 3.8%, respectively.

Dead-to-live bird ratios were much greater for Rhinoceros Auklets, auklets/murrelets, and small grebes than for other taxa (Table 3). Rhinoceros Auklets and auklet/murrelets, a category in which Cassin's Auklets (*Ptychoramphus aleuticus*) predominated, were distributed farther from shore and therefore were more likely to die before reaching shore than Common Murres. Loons (*Gavia* spp.) and Common Murres, which had the lowest dead-to-live bird ratios, may have been more likely to swim or fly toward shore after being coated with oil, and because of their larger body size may have required a higher dose of oil before being killed. The high among-species variability in dead-to-live ratios invalidated the use of simply derived multiples of the number of rescued, live oiled birds to estimate the total mortality of birds.

AT-SEA CARCASS LOSS MODEL

Even when numbers of beached live and dead oiled birds are known, a large fraction of the total mortality may remain unmeasured. Winds and currents may carry floating carcasses away from shore where they are never observed (Bibby and Lloyd 1977, Bibby 1981). Many carcasses that are propelled towards shore may not beach because they sink or are scavenged along the way

TABLE 3. ESTIMATED NUMBERS OF BIRDS DEBILITATED OR KILLED DURING THE *APEX HOUSTON* OIL SPILL BETWEEN 1–8 FEBRUARY 1986 FROM SALMON CREEK, SONOMA COUNTY, TO POINT LOBOS, MONTEREY COUNTY. DASHES INDICATE THAT DATA WERE NOT AVAILABLE.

Species	Alive and sent to rehabilitation centers	Dead on beaches	Ratio of dead-to-live on beaches	Lost at Sea (S_j)	Total
Loons	128	148	1.16	—	276
Small grebes	9	106	11.78	—	115
Aechmophorus grebes	155	313	2.02	—	468
Unidentified grebes	19	0	—	—	19
Scoters	61	222	3.64	—	283
Common Murre	2924	3595	1.23	969	7488
Auklets/murrelets	9	168	18.67	29	206
(Cassin's Auklet)	0	(140)	—	(29)	(169)
Rhinoceros Auklet	30	1201	40.03	335	1566
Other species/unid. birds	29	127	4.38	—	156
Total	3364	5880	1.75	1333	10,577

(Page et al. 1982). Our model for estimating numbers of dead oiled birds not reaching shore required: descriptions of the trajectories of the oil and bird carcasses, the rate of carcass loss at sea, the distribution of the birds at sea at the time of the spill, and the numbers of dead oiled birds on beaches. Ecological Consulting prepared a computer model that simulated trajectories of hypothetical oil slicks along the route of the *Apex Houston,* and trajectories of carcasses arising from the hypothetical slicks. Simulated oil slicks were treated as points driven by wind and ocean surface currents. Wind vectors were computed as the wind direction plus a variable deflection angle, D, used to simulate the Ekman effect:

$$D = 25°\exp(-10^{-8}W^3/vg)$$

where: W = wind speed, v = kinematic viscosity of sea water, and g = gravitational acceleration (Samuels et al. 1982, Neumann 1939, Witting 1909). The wind drift factor, or the proportion of the wind velocity imparted to the transported material, was assumed to be 0.035 for oil (Smith et al. 1982) and 0.022 for dead birds (Hope Jones et al. 1970). Real time wind data were obtained from five different central California coastal weather stations: 1) Vandenberg Air Force Base (34.7°N, 120.5°W); 2) Meteorological Buoy 46011 (34.9°N, 120.9°W, Point Sal); 3) Point Pinos (36.6°N, 122.0°W); 4) Meteorological Buoy 46012 (37.4°N, 122.7°W, Half Moon Bay); 5) Meteorological Buoy 46026 (37.8°N, 122.7°W, Gulf of the Farallones). Wind fields were extrapolated linearly between adjacent stations for a smooth transition from one station to the next. Wind vectors at any point were weighted averages of winds from the nearest station to the north and south. Surface current data were based on the characteristic tracing model of Dianalysis of Princeton (Kantha

et al. 1982). Vector fields were discretized into 30-min blocks extending from 21.5° to 49.8°N and from 137.5° to 118.5°W.

Points, representing hypothetical slicks, travelling at 3.5% of wind speed, were launched at three-hr intervals along the track of the *Apex Houston* when it passed by. They were moved at three-hr intervals until contacting shore or until 8 February. Likewise, groups of simulated bird carcasses were launched at each three-hr time step along each slick trajectory and moved at 2.2% of wind speed until they contacted shore or until 8 February (Fig. 4).

An index of the relative number of carcasses that beached in different coastal regions was computed as the number of birds in a one-km² area at the beginning point of a carcass trajectory, decreased by 2.0% at each three-hr time step to account for at-sea loss (derived from Hope Jones et al. 1970). When a group of carcasses beached, it was added to the total beached from all trajectories contacting that region. R_j, the proportion of total beachings predicted in region j, was computed by dividing the number of beached model carcasses in a given region by the total number beaching in all regions:

$$R_j = \frac{L_j}{\sum_{i=1}^{b} L_i}$$

where: L_j = the number of carcasses beaching in region j after accounting for at-sea loss, the denominator is the sum for all regions involved, and b is the total number of regions. R_j values were calculated separately for each species.

P_j, the proportion of carcasses lost before making landfall in region j, was calculated carrying out the same simulation, but without at-sea loss:
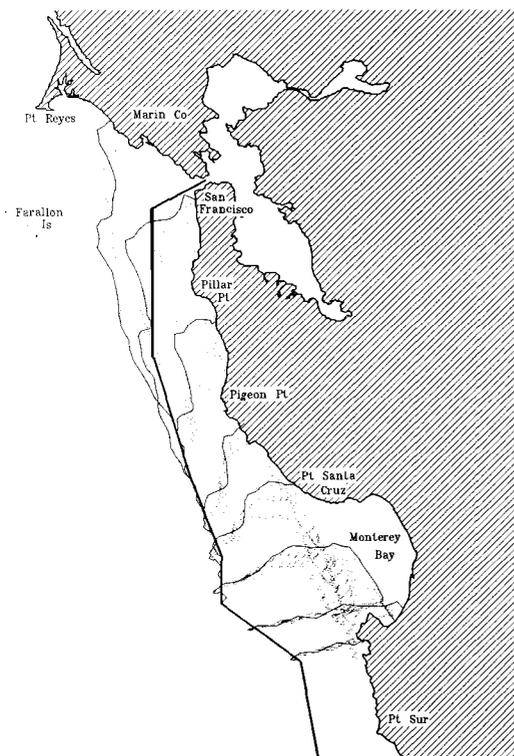
FIGURE 4. Model simulation of the *Apex Houston* oil spill. The heavy line shows the track of the *Apex Houston* and thin lines show oil slick trajectories launched at three-hr intervals from along the vessel's route between Pigeon Point and Point Lobos. Groups of simulated bird carcasses are indicated by dots for each three-hr interval.

$$P_j = 1 - \frac{L_j}{N_j}$$

where: N_j = the number that would have beached in region j without at-sea loss. P_j values were calculated separately for each species.

DISTRIBUTION OF BIRDS AT SEA

A total of 1517 birds of at least 24 species was recorded on the aerial survey. Slope waters were dominated by Red Phalaropes (*Phalaropus fulicaria*), Western Gulls (*Larus occidentalis*), Cassin's Auklets, and Rhinoceros Auklets. Outer shelf waters were dominated by Brandt's Cormorants (*Phalacrocorax penicillatus*), Red Phalaropes, Western Gulls, Herring Gulls (*L. argentatus*), California Gulls (*L. californicus*), Common Murres, Cassin's Auklets and Rhinoceros Auklets. Inner shelf waters were dominated by *Aechmophorus* grebes, Surf Scoters (*Melanitta perspicillata*), Red Phalaropes, and Common

Murres. Densities were not unusual for this time of year in these zones (Page and Carter 1986, Briggs et al. 1987). We chose to determine the numbers of dead oiled birds not reaching shore for Common Murres, Cassin's Auklets, and Rhinoceros Auklets, which were relatively abundant on the survey. We also applied the at-sea loss rate to these species, because it was derived from other data on alcids.

Common Murres. Hypothetical slicks launched between 01:00 and 06:00 hrs (PST) on 29 January off the northern end of Monterey Bay, when the *Apex Houston* encountered heavy seas (Fig. 4), had the greatest potential for contacting large numbers of Common Murres. Slicks passed through a small, very dense aggregation on the inner shelf west of Pigeon Point and moderately dense aggregations in the Gulf of the Farallones (Fig. 5A). The model predicted that 46.2% of carcass beachings between regions 2 and 5 would occur in regions 2 and 3, where only 20.0% were determined to have beached (Table 4). The highest proportion of carcass beachings was predicted accurately in region 4 and proportions were predicted closely in region 5. At-sea loss ranged from 8.6% for carcasses destined for region 5 to 34.1% for region 4.

Rhinoceros Auklets. Rhinoceros Auklets were aggregated in two regions on the outer shelf, northwest of the Farallon Islands and due west of Pigeon Point (Fig. 5B). Slicks bypassed the aggregation in the Gulf of the Farallones but passed through the one west of Pigeon Point. Birds affected there should have beached in region 4, where most carcasses were predicted and many found during beached bird censuses (Table 4). At-sea loss of carcasses ranged from 20.9% to 59.2% among regions 3–5.

Cassin's Auklets. Cassin's Auklets were aggregated northwest of the Farallon Islands and on the slope west of Half Moon Bay (Fig. 5C). Slicks did not pass through these high density aggregations but did pass through low densities on the inner shelf due west of Pigeon Point and off Monterey Bay. Cassin's Auklets oiled in these areas should have beached in regions 4 and 5. Model predictions were fairly accurate for three of four regions examined (Table 4). However, 30.9% of the carcasses were predicted in region 3 where none was found. At-sea loss ranged from 14.5% to 55.4% among regions 2–5.

ESTIMATED NUMBERS OF OILED CARCASSES NOT REACHING SHORE

The number of birds lost at sea was only calculated for regions 2 to 5, because there were insufficient data on the densities of birds at sea for the model to predict at-sea loss for region 6, and the model failed to show birds beaching in

region 1. The number of dead birds lost at sea was estimated separately for the three alcid species as follows:

$$N_j = \frac{M_j}{1 - P_j}$$

where:

N_j = the number of carcasses expected to wash onto region j given no carcass loss at sea.

M_j = the number of carcasses that reached region j (estimated for regions 2 to 5 in Table 2).

P_j = the proportion of carcasses that did not reach region j (derived for regions 2 to 5 in Table 4).

The number of carcasses lost at sea (S_j) was estimated as: $S_j = N_j - M_j$. S_j values were summed over the four regions for each alcid species to give minimal estimates of at-sea carcass loss of 969 Common Murres, 29 Cassin's Auklets, and 335 Rhinoceros Auklets (Table 3). These estimates would have been substantially higher if it had been possible to obtain an estimate for region 6 (Monterey Bay).

DISCUSSION

TOTAL NUMBER OF BIRDS DEBILITATED OR KILLED

By adding live and dead oiled birds on beaches to those lost at sea, we estimated a minimum of 10,577 birds debilitated or killed in the *Apex Houston* oil spill (Table 3). In fact, a few thousand additional birds met a similar fate because: 1) numbers of live oiled birds were underestimated because of incomplete rehabilitation center records (Page and Carter 1986, Carter et al. 1987); 2) numbers of dead birds lost at sea were underestimated because there was no estimate for region 6 (Table 4) and at-sea loss was estimated for only 3 of the 26 species affected; and 3) numbers of beached birds and birds lost at sea were estimated only for the area and time of peak beachings. In fact, an additional 494 live oiled
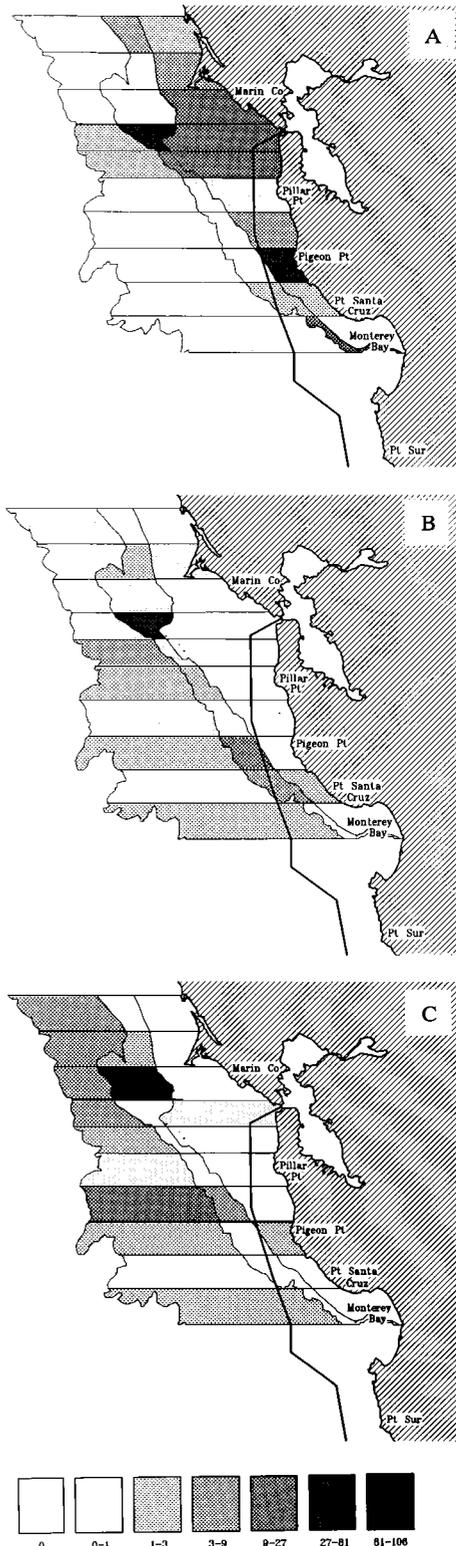
$\longrightarrow$

FIGURE 5. At-sea densities of (A) Common Murres, (B) Rhinoceros Auklets, and (C) Cassin's Auklets based on transects flown on 5 February 1986. Density blocks are defined in an east-west direction by bathymetry: 0–100 m, inner shelf; 100–200 m, outer shelf; and 200–3000 m, slope. North-south divisions were constructed so that each block contained one transect line. Intensity of stipling indicates bird densities per km², as shown in the key. The dark line starting at the entrance of San Francisco Bay is the track of the *Apex Houston*.

TABLE 4.   PERCENT OF COMMON MURRE, RHINOCEROS AUKLET, AND CASSIN'S AUKLET CARCASSES LOST AT SEA.
MODEL BEACHED CARCASS INDICES ARE PROPORTIONS OF HYPOTHETICAL CARCASS BEACHINGS IN REGIONS 2–5
AND ESTIMATED BEACH CARCASS INDICES ARE PROPORTIONS OF 2424 COMMON MURRES, 347 RHINOCEROS AUKLETS,
AND 62 CASSIN'S AUKLETS THAT BEACHED IN REGIONS 2–5, RESPECTIVELY

Coastal region	Predicted time of carcass arrival	Model beached carcass index (R_j)	Percent carcasses lost at sea (P_j)	Estimated beached carcasses (see Table 2)	Estimated beached carcass index
Common Murre					
2	2–3 Feb	0.234	26.1	223	0.092
3	3–4 Feb	0.228	23.9	261	0.108
4	3–4 Feb	0.393	34.1	1478	0.610
5	2–3 Feb	0.145	8.6	462	0.191
Rhinoceros Auklet					
2	—	0.000	0.0	3	0.009
3	3–4 Feb	0.208	59.2	6	0.017
4	3–4 Feb	0.663	53.0	274	0.790
5	2–3 Feb	0.129	20.9	64	0.184
Cassin's Auklet					
2	2–3 Feb	0.078	21.5	3	0.048
3	3–4 Feb	0.309	55.4	0	0.000
4	3 Feb	0.450	37.0	43	0.694
5	2–3 Feb	0.162	14.5	16	0.258

birds were sent to rehabilitation centers between 9 February and mid-March, 510 dead oiled birds were found on 23 carcass counts on 19 beaches between 20–27 February, and a few hundred oiled birds were reported from south of Point Lobos (Page and Carter 1986).

Had PRBO not developed the beached bird model and Ecological Consulting the at-sea carcass loss model, only the approximately 3000 oiled birds sent to rehabilitation centers would have been documented as casualties from the spill. Our study results show that beached carcass counts and aerial surveys of birds at sea must be incorporated into oilspill contingency plans if the total extent of mortality is to be fully appreciated (see Carter and Page 1989).

Although the *Apex Houston* spill involved only about 26,000 gallons of oil, the extent of seabird mortality rivaled some of the worst known incidents (Evans and Nettleship 1985) and far exceeded that of the highly publicized *Puerto Rican* oil spill (PRBO 1985, Dobbin et al. 1986). Casual observers were surprised that such a small spill killed so many birds. However, the *Apex Houston* spill coincided with the period of peak abundance of wintering birds in central California (Briggs et al. 1987) and oil slicks passed through dense aggregations of seabirds.

The long-term impact of the mortality on Common Murres remains unknown. In central California, the murre population declined by over 50% between 1982 and 1986, mostly due to gill-net mortality (see Atkins and Heneman 1987; Takekawa et al. 1990). The *Apex Houston* and

Puerto Rican oil spills, which together killed over 9500 murres, contributed to this crash, but it is not known what portion of murres killed belonged to the resident breeding population. Probably most of the Rhinoceros Auklets affected were from breeding populations farther north (Briggs et al. 1987), because only small numbers breed in central California (Sowls et al. 1980), and because breeding at the Farallon Islands continued to increase in 1986 and 1987 (PRBO, unpubl. data). The Marbled Murrelets (*Brachyramphus marmoratus*) that were killed represented 1% to 5% of the central California breeding population (see Carter and Erickson 1988).

FUTURE RESEARCH

It is not necessary to use our beached bird model when beached birds can be counted accurately through daily counts (PRBO 1985). However, such situations seldom occur, and large numbers of birds usually have beached over several days before any attempt is made to count them, as in the *Apex Houston* spill. It would be valuable to improve the beached bird model by considering the following points:

1. Single censuses should be conducted on as many beaches as possible, because they provide the independent values for carcass numbers on which means for each region-beach type combination are based, and because the species composition of the carcasses is derived directly from these censuses (Carter and Page 1989).

2. We used mean carcass persistence (S) over

two days on two beaches (N = 4) at the time of the spill in the model. Carcass persistence could vary with carcass type, location, and tidal condition. Page et al. (1982) provide evidence that beach type affects carcass persistence. Further research should determine which variables affect carcass persistence the most, so that these could be considered when sampling for S. Predetermined values of S could be used if these would not bias the outcome in the model.

3. The proportion of the carcasses beaching each day (P_i) was assumed to be similar to live birds in the *Apex Houston* spill, but this assumption would not apply to all situations (e.g., Hope Jones et al. 1970). A lag in the beachings of dead oiled birds could be incorporated into the model, although it would be preferable to obtain actual values of P_i for carcasses at the time of the spill. P_i values will vary substantially between spills, between coastal regions and possibly also with beach type. P_i values must be determined from data collected during the spill and at minimum for several regions for large spills.

4. Our method should be applied separately for each abundantly occurring species within each region. This was not possible during the *Apex Houston* spill because large numbers of live oiled birds attributed to some regions were not categorized by species at rehabilitation centers (see Tables 1, 2).

5. Error estimates for each of the variables in the beached bird model and for the total estimate of beached carcasses should be developed. Sensitivity analyses should be used to identify which variables most affect the overall accuracy of the estimates.

In contrast to the beached bird model, an at-sea loss model should always be used because there is no other way to determine the number of dead oiled birds that do not reach shore. Depending on how far from shore a spill occurs, the extent of onshore transport of oil and carcasses, and the abundance and distribution of birds at sea, carcasses lost at sea may or may not account for a large proportion of the overall seabird mortality. Our model was derived from a more detailed model, which also accounted for turnover of birds within slick areas at sea (Dobbin et al. 1986, Ford et al. 1987). Our model required less information about slicks at sea and fewer assumptions about seabird behavior at sea. At-sea loss models should be refined by considering the following points:

1. We modeled oil and carcass trajectories based mainly on wind speed and direction. While this seemed reasonable for floating carcasses, trajectories did not take into account movements by oiled birds before death or the effects of strong nearshore surface currents. Such modelling

omissions may have caused inconsistencies such as the appearance of small numbers of live and dead oiled birds at the Farallon Islands and in region 1 (north of Point Reyes), where our model predicted neither slicks nor carcasses. Detailed on-scene descriptions of slicks at sea would alleviate some problems, as in the *Puerto Rican* spill when at times slicks moved opposite to the direction predicted by winds alone.

2. We used a constant at-sea carcass loss rate of 15% per day based on one prior study in which oiled alcid carcasses were launched at sea (Hope Jones et al. 1970). As Ford et al. (1987) point out, the actual rate may not be a constant and may not be the same for all species and all spills.

3. We assumed only three fates for birds: they die at first contact with oil, survive until rescued on shore, or survive at sea until after the spill. The daily at-sea loss rate was applied only to the first group. If birds survived beyond the moment of impact and moved toward shore, estimates of the time required for carcasses to reach shore would be longer than actual values, resulting in an overestimate of the number of carcasses lost at sea.

4. Ford et al. (1987) discuss the merits and drawbacks of aerial surveys used during the *Apex Houston* and *Puerto Rican* spills. Spatial and temporal persistence of seabird aggregations at sea must be studied to evaluate the appropriateness of a single survey some time after the spill for use in models. Better techniques are required for surveying coastal areas within a few kilometers of shore where large numbers of birds often aggregate.

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