American Fisheries Society Symposium 18:167–176, 1996

Intertidal and Supratidal Site Selection Using a Geographical Information System

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Abstract.—A geographical information system (GIS) was employed in the selection of sampling sites for the intertidal and supratidal injury assessment of the *Exxon Valdez* oil spill. The use of GIS was suggested by (1) the large amounts of shoreline (potentially 2,003 kilometers) contaminated by this oil spill, (2) the extreme heterogeneity of shoreline types and degrees of oiling in the *Exxon Valdez* oil spill area, (3) the need to embody the various shoreline habitats and degrees of oiling in the assessment, and (4) the need to make statistical inferences regarding intertidal and supratidal injury to the universe of all oiled shorelines in this oil spill area. The shoreline affected by the *Exxon Valdez* oil spill was stratified into 15 classes based on habitat type and degree of oiling. Potential sampling sites were randomly drawn from the database with probability proportional to size. Field surveys conducted in 1989 to verify shoreline classifications, verify degree of oiling, and locate and mark shoreline segments for subsampling found many misclassified sites. Moderately to heavily oiled sites selected in the stratified random sample were retained and subjectively paired with reference (non-oiled or very lightly oiled) sites. The final quasi-experimental study design for intertidal and supratidal injury assessment consisted of 50 oiled sites paired with 47 reference sites. Randomly selected oiled sites maintained their probability-based selection status for inferences to the entire *Exxon Valdez* oil spill area. Recommendations are made concerning the future use of GIS for intertidal and supratidal injury assessments.

A primary goal of the Coastal Habitat Injury Assessment (CHIA) was to quantify injuries to intertidal and supratidal biota in the *Exxon Valdez* oil spill area. Information from this study was used in the Natural Resource Damage Assessment (NRDA) program conducted under the auspices of the *Exxon Valdez* oil spill trustees. The requirements of this study were dictated by the dual need to test the hypothesis of injury to intertidal and supratidal biota and to determine the nature and degree of injury over the full range of intertidal and supratidal habitats found in the oil spill area. Most oiled shoreline had received one or more types of cleanup treatment before or during this study; however, records were inadequate to determine the amount or type of cleanup activity on most specific study sites. The objective of the study was to assess the confounded effects of oil and cleanup on the shoreline biological community. We refer to the sites as treated, or oiled–cleaned, or oiled.

Geographical information systems (GIS) have the capability to collect, store, process, and display large amounts of spatial data (Burrough 1986). They have been used for a wide range of natural resources applications, including management, environmental planning, and assessment (Webb 1982; Dangermond 1991; Schaller 1992). Geographical information systems have also been used for cumulative environmental impact assessment where it was necessary to analyze empirical relationships between resource loss and overall environmental degradation (Johnston et al. 1988). However, the implementation of a full-scale GIS can be a long and expensive process involving multiple organizations (Antenucci et al. 1991). The need to initiate a rigorous intertidal and supratidal assessment covering a large geographic area required that a full-scale GIS be available within a short time. Fortunately, advanced GIS capabilities existed within state and federal resource agencies in Alaska at the time that the T/V *Exxon Valdez* spilled 42 million liters (11 million gallons) of North Slope crude oil into Prince William Sound on 24 March 1989.

The GIS capabilities used in this study were located in three federal agencies and one state agency. The U.S. Geological Survey (USGS), Earth Resources Observation System (EROS) field office provided primary support with assistance from the U.S. Forest Service, Chugach National Forest; the U.S. Fish and Wildlife Service, Alaska Region; and the Alaska Department of Natural Resources, Lands Records and Information Section. These agencies each developed GIS capabilities using similar hardware and software before 24 March 1989 and had a history of working cooperatively on applications and systems development.

The initial planning for this study was conducted during May and June 1989. During this time it was decided by the Trustee Council management team that intertidal, supratidal, and subtidal study sites would be selected using a probability-based approach that allowed for extrapolation of results to the universe of all treated sites in the *Exxon Valdez* oil spill area. During June 1989 the concept of using a GIS to select sampling sites was approved. A working group comprising the principal investigators and technical support staff undertook the review of available data and GIS capabilities and completed the task of defining user needs and determining the feasibility of a workable solution. By late June 1989 the system was designed, digitizing was underway, and the first test plots were available. In mid-July, a pilot field study was conducted in the Naked Island and northern Knight Island areas in Prince William Sound to test the site evaluation methodology. Following that, full-scale site selection commenced in the Prince William Sound (PWS), Cook Inlet–Kenai Peninsula (CIK), and Kodiak–Alaska Peninsula (KAP) regions. The first phase of site selection was completed in August 1989 concurrent with the first occupation of the sites and subsampling by the supratidal, intertidal, and subtidal study crews under the lead of the University of Alaska-Fairbanks (UAF).

Based on the results of the 1989 site-selection surveys and initial UAF subsampling, many sites were found to be misclassified on either degree of oiling, habitat type, or both. Additional treated and reference sites were selected in 1990 to address the intertidal and supratidal components of the CHIA. The subtidal component of the CHIA adopted a different site-selection strategy in 1990.

Methods

The study area was defined by the universe of all shorelines on USGS 1:63,360-scale topographic quadrangles where any shoreline had been documented as receiving grounded *Exxon Valdez* oil. This approach was intended to ensure a comprehensive sampling of all habitat types and degrees of oiling (ranging from heavy to none) in the spill area. The methodology for site-selection was designed to (1) test the hypothesis that oiling (treatment) had not caused injury to subtidal, intertidal, and supratidal biota; and (2) allow for extrapolation of injury determinations at study sites to the universe of all treated sites in the spill area. The GIS for site-selection "GEO" was constructed from three primary databases using ARC/INFO[1]:

1. The State Shoreline consisted of the approximate mean high water line digitized from the USGS 1:63,360 scale topographic quadrangle series in the spill affected area. The shoreline was modified by interpretation of 1:60,000 scale high-altitude color infrared photographs to add small islands and update post-1964 earthquake shoreline changes.
2. The Environmental Sensitivity Index (ESI) maps classified the shoreline into 19 geomorphologic types following the shoreline classification system described by Gundlach and Hayes (1978) and Hayes et al. (1980). The ESI rates the shoreline from 1 to 10 based on progressively higher sensitivity to oiling. The 1:60,000 scale maps were digitized from five map atlases covering the spill-affected area (RPI 1983a, 1983b, 1985, 1986; M. O. Hayes and C. H. Ruby, Research Planning Institute, unpublished data 1979). The ESI classification scheme was translated to five habitat types (Table 1) for this study.
3. The Oil Spill Impact (OSI) database was maintained by the Alaska Department of Environmental Conservation (ADEC) for the *Exxon Valdez* oil spill area (ADEC, unpublished data, 1989). The OSI classifies the shoreline into five oiling types: heavy, moderate, light, very light, and no observed oil at a nominal scale of 1:63,360. The OSI data were based on cumulative aerial and ground observations made by ADEC personnel using standardized evaluation criteria (Table 2). The OSI classification scheme was condensed to three oiling types for this study: heavy–moderate, light–very light, and no observed oil (reference).

Using GEO, the shoreline was stratified into 15 habitat–oiling classes: five habitat types multiplied

[1]ARC/INFO geographical information system software. Version 5.0. Environmental Systems Research Institute, Redland, California.

TABLE 1.—Translation of Environmental Sensitivity Index (ESI) shoreline types to Coastal Habitat Injury Assessment (CHIA) habitat types.

ESI number	CHIA habitat type	ESI shoreline type
1	Exposed rocky shores	Exposed rocky headlands
1		Exposed rocky shores
2		Wave-cut platforms
2		Exposed wave-cut platforms
3	Fine-textured beaches	Fine–medium-grained sand beaches
3		Fine-grained sand beaches
4		Coarse-grained sand beaches
5	Coarse-textured beaches	Exposed tidal flats
5		Mixed sand and gravel beaches
5		Exposed tidal flats (low biomass)
6		Mixed sand and gravel beaches
6		Gravel beaches
7		Gravel beaches
7		Exposed tidal flats
7A		Exposed tidal flats (moderate biomass)
7		Exposed tidal flats (moderate–high biomass)
8	Sheltered rocky shores	Sheltered rocky shores
9	Sheltered estuarine shores	Sheltered tidal flats
10		Marshes

by three oiling types. Shorelines within these strata were divided into segments ranging in length from 100 to 600 m (corresponding to arcs in the GIS). Arcs less than 100 m were removed from the target universe because they were too small to allow repetitive, destructive subsampling of multiple transects. Multiple visits with destructive subsampling within short shoreline segments could affect recruitment and introduce bias. Arcs were limited to 600 m to ensure that sites could be efficiently subsampled during one low-tide period. Following stratification, each arc was assigned a unique identification number.

Arcs were randomly selected without replacement from each of the 15 habitat–oiling classes with probability (approximately) proportional to size. Selection probabilities are approximate because the sites were randomly selected without replacement and there was no adjustment for the changing size of the stratum. The center points and arc numbers of the first 15 selected sites within each class were color plotted on 1:63,360 scale maps depicting shoreline, habitat–oiling type, upland ownership, and USGS topographic quadrangle boundaries.

TABLE 2.—Alaska Department of Environmental Conservation criteria used for rating Oil Spill Impact (OSI).[a]

OSI type	Rating criteria
Heavy	>6-m-wide band or >50% coverage–penetration
Moderate	3- to 6-m-wide band or 10 to 50% coverage–penetration
Light	1- to 3-m-wide band or 1 to 10% coverage–penetration
Very light	<1-m-wide band or <1% coverage–penetration
No observed oil	No oil observed

[a]Oil spill impacts are evaluated solely on the amount of area covered or penetrated by oil between the mean high tide and mean low tide lines.

Sites were visited in the field to verify mapped data and to locate and mark shoreline segments for subsampling by the CHIA crews. Surveys were performed during low to mid-tide levels. Tides in the study area are mixed semidiurnal. For purposes of this study, the intertidal zone was defined as the zone between mean lower low water and mean higher high water; the supratidal zone was defined by the zone between mean higher high water and extreme higher high water (generally the upper extent of visible oiling on oiled sites); and the subtidal zone was defined as the zone between mean lower low water and the 20-m isobath.

The center point of each arc was located on the shoreline using the GEO maps, USGS topographic maps, visual references, and compass bearings. The end points of each arc were marked and the length measured along the upper intertidal zone (generally above the line of *Fucus gardneri*). Each shoreline segment was surveyed along its entire length to classify and map oiling and habitat types. Sites that could not be safely reached by skiff or where beach slopes were measured with a clinometer to exceed 35 degrees for more than 50% of the shoreline were rejected as inaccessible for intertidal sampling. Sites not matching the mapped habitat–oiling type were reclassified to the most appropriate type, but retained the original probability of selection (weight) for statistical inferences. Reclassification was accomplished by measuring the alongshore length of habitat–oiling units within each arc. The longest unit determined the habitat–oiling classification of the site. In 1989, the goal was to obtain four sampling sites in each of the heavy–moderate oiling strata and three sampling sites in each of the other strata for a total of 150 sites in the three regions.

For 1990, the CHIA was changed to a quasi-experimental design by retaining the randomly selected treated sites and matching each with a subjectively selected "reference" site. In true experiments, the treatment would be randomly assigned to one of the members of the pair, hence the term quasi-experiment is used to indicate that conclusions are limited by the protocol through which reference sites are selected. The objective was to pair each treated site with a reference site on the basis of physical characteristics known to influence intertidal community structure. We also subjectively selected additional paired heavy–moderate treated and reference sites in habitat categories where the sample size was below the target value.

Suitable pairs of reference sites and treated sites were first identified based on 1989 field survey data and site photographs. Treated sites that lacked suitable references from within the group of non-oiled sites sampled in 1989 were matched with new reference sites using the following procedure. Using GEO and other sources, five potential reference sites were identified in closest proximity to each treated site from shorelines classified as non-oiled or very lightly oiled. Reference was made to the 1989 Post-Treatment Shoreline Oiling Assessment (ADEC 1989a, 1990a, 1990b) to determine the oiling history of each potential reference site. Sites classified as having more than very light oiling by any shoreline survey were rejected from consideration as references. Potential reference sites were listed according to their distance from each treated site, with the closest site receiving the highest priority. All other sites classified as light–very light oiling were eliminated from the study in 1990. No damages to intertidal and supratidal biota were to be claimed for injuries to light–very light oiled sites and, as discussed above, some of the very lightly oiled sites were used as references.

Field surveys conducted at treated sites and at potential reference sites determined the closest match of physical and biological characteristics. The physical characteristics of greatest import were (1) substrate composition, (2) wave exposure, (3) beach slope, (4) proximity to sources of fresh water, and (5) nearshore bathymetry. General biological characteristics of the sites were also checked. These were limited to general indicators of community composition including the presence or absence of mussel beds, algal beds, gastropods, and barnacles. Potential reference sites were evaluated in order of priority until a suitable site was found. An attempt was made to measure reference-site lengths equal to the paired treated site, but always a minimum of 100 m of comparable habitat was marked.

Additional paired treated and reference sites were subjectively selected in habitat types that were below the target sample size of the 1989 studies. These sites were selected to test oiling–injury hypotheses and to incorporate some special interest study sites occupied by non-CHIA biologists in 1989. However, these sites were treated as censused subpopulations and were not used to extrapolate injury assessment to other oiled sites.

TABLE 3.—Results of 1989 site selection in the Prince William Sound (PWS), Cook Inlet–Kenai Peninsula (CIK), and Kodiak–Alaska Peninsula (KAP) regions.

Region	Universe	Potential sites	Sites surveyed	Sites reclassed
PWS	4,975	125	63	38
CIK	4,130	164	103	41
KAP	12,257	135	74	40
Total	21,362	424	240	119

Results

From a universe of 21,362 sites encompassing 9,173 km of shoreline, 424 potential sites were plotted on maps using GEO (Table 3). Site visits were conducted in rank order according to selection within strata during 15 July 1989 to 22 August 1989. A total of 240 sites were visited. Initially, it was intended that the three (or four in the case of moderate–heavy oiled strata) highest ranked accessible sites within each strata would be accepted if they were found to fit the GEO classification. However, it became apparent early in the survey that many sites did not fit the GEO classification for either habitat type, degree of oiling, or both. For example in PWS, the first region examined, 38 of 63 sites (60%) were found misclassified. Other regions had lower classification errors.

The selection of reference sites in the original, stratified random sample resulted in unforeseen sampling problems. The control strata were found to be "too large," containing habitat unrepresentative of the oiled strata. For example, in PWS all of the heavy–moderate treated sites were located on islands. Most island shorelines in the path of the *Exxon Valdez* oil spill exhibited some evidence of oiling during site examinations in 1989. Under the 1989 site-selection criteria, any evidence of oil, even one tar ball or tar spot, was cause for rejecting a reference site. With the exception of four sites, all PWS reference sites were located on the mainland. Most reference sites were in bays with more freshwater sources, lower salinity, and greater winter stress (lower temperatures, ice scour). Therefore, standard measurements of biotic health, including species richness, density, biomass, and recruitment, were not directly comparable between many GEO-identified treated sites and reference sites in the absence of oil.

Figures 1 and 2 compare the locations of 1989 and 1990 study sites in the Prince William Sound region. To preserve the statistical validity of the study design and allow statistical inferences to the most important subset of oiled shoreline, we retained all heavy–moderate oiled sites selected by the 1989 protocol, regardless of the initial classification, and subjectively paired them with the closest reference site having similar physical characteristics. We also allowed very lightly oiled shorelines as potential references in 1990. These very lightly oiled sites were interspersed with treated sites on the islands and improved the capability of the study to control extraneous factors and increase the precision and accuracy in measurement of oiling effects. This approach preserved the probability sample of heavy–moderate oiled sites based on the original stratification and database. Three important results were as follows:

1. Selected sites carried their original unequal weights from whatever original strata they were in.
2. The original frame (database and stratification) was retained to extrapolate results to the subset of accessible heavy–moderate treated sites.
3. The target number of sites in some strata was not attained (e.g., in the CIK region no accessible heavy–moderate oiled, exposed rocky shore sites were identified in 1989 among the highest ranked accessible sites within original strata).

In 1990, site-selection was focused on pairing suitable reference sites with treated sites and with purposively selecting treated sites to provide information in habitat categories where there were a deficit of randomly selected sites. The objective was to obtain a minimum of four replicate oiled-reference pairs for each habitat type in each region. Purposively selected sites represented only themselves in the extrapolation of results to the subset of accessible heavy–moderate treated sites within a given habitat type. Table 4 summarizes the results of the 1990 site-selection.

TABLE 4.—Results of 1990 site selection; regions are defined in Table 3. (T) = treated site; (C) = control site.

Region	Sites needed	Potential sites	Sites surveyed	Sites accepted
PWS	3 (T) 14 (C)	3 (T) 69 (C)	3 (T) 47 (C)	1 (T) 12 (C)
CIK	10 (T) 14 (C)	5 (T) 27 (C)	5 (T) 19 (C)	4 (T) 8 (C)
KAP	7 (T) 12 (C)	6 (T) 41 (C)	5 (T) 22 (C)	5 (T) 9 (C)
Total	20 (T) 40 (C)	14 (T) 137 (C)	13 (T) 88 (C)	10 (T) 29 (C)

Following the pairing of suitable 1989 reference sites with treated sites, an additional 20 treated and 40 reference sites were sought in 1990. Using GEO and other sources, 14 treated sites and 137 potential reference sites were identified for ground truthing. An insufficient number of heavy–moderate treated sites in some habitat types, most notably sheltered estuarine shores and exposed rocky shores in the CIK region, made it impossible to reach the desired goal of four treated sites per habitat type called for in the study plan.

Field surveys conducted during low tide series from 23 April 1990 to 11 June 1990 resulted in 101 sites being ground-truthed and 39 additional sites being accepted into the study. In three cases, it was necessary for a reference site to be "paired" (i.e., grouped) with more than one treated site. The final array of intertidal and supratidal study sites consisted of 50 treated sites paired with 47 reference sites. The numbers of sites for some habitat types including coarse-textured beaches, were larger than planned, whereas sample sizes for other habitat types, including sheltered estuarine shores, were smaller than planned. The randomly selected treated sites maintained their probability-based selection status for making statistical inferences within the resulting quasi-experimental design. Further details concerning the basis for statistical analyses are reported in McDonald et al. (1995). The results of subsampling of the sites are reported in Highsmith et al. (1996, this volume) and Stekoll et al. (1996, this volume).

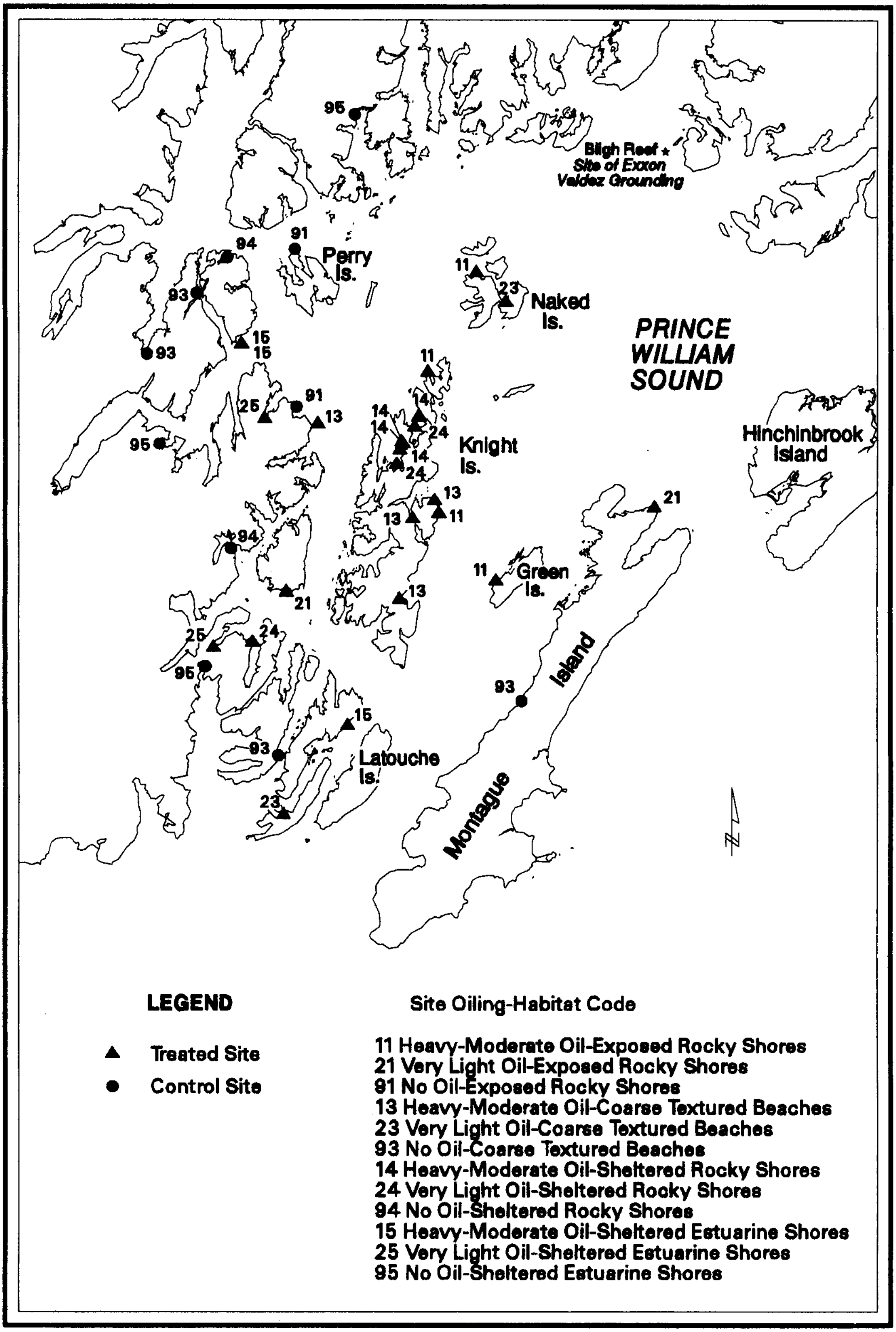

FIGURE 1.—1989 Coastal Habitat Injury Assessment (CHIA) study sites, Prince William Sound region. Map was produced by the Alaska Department of Natural Resources.

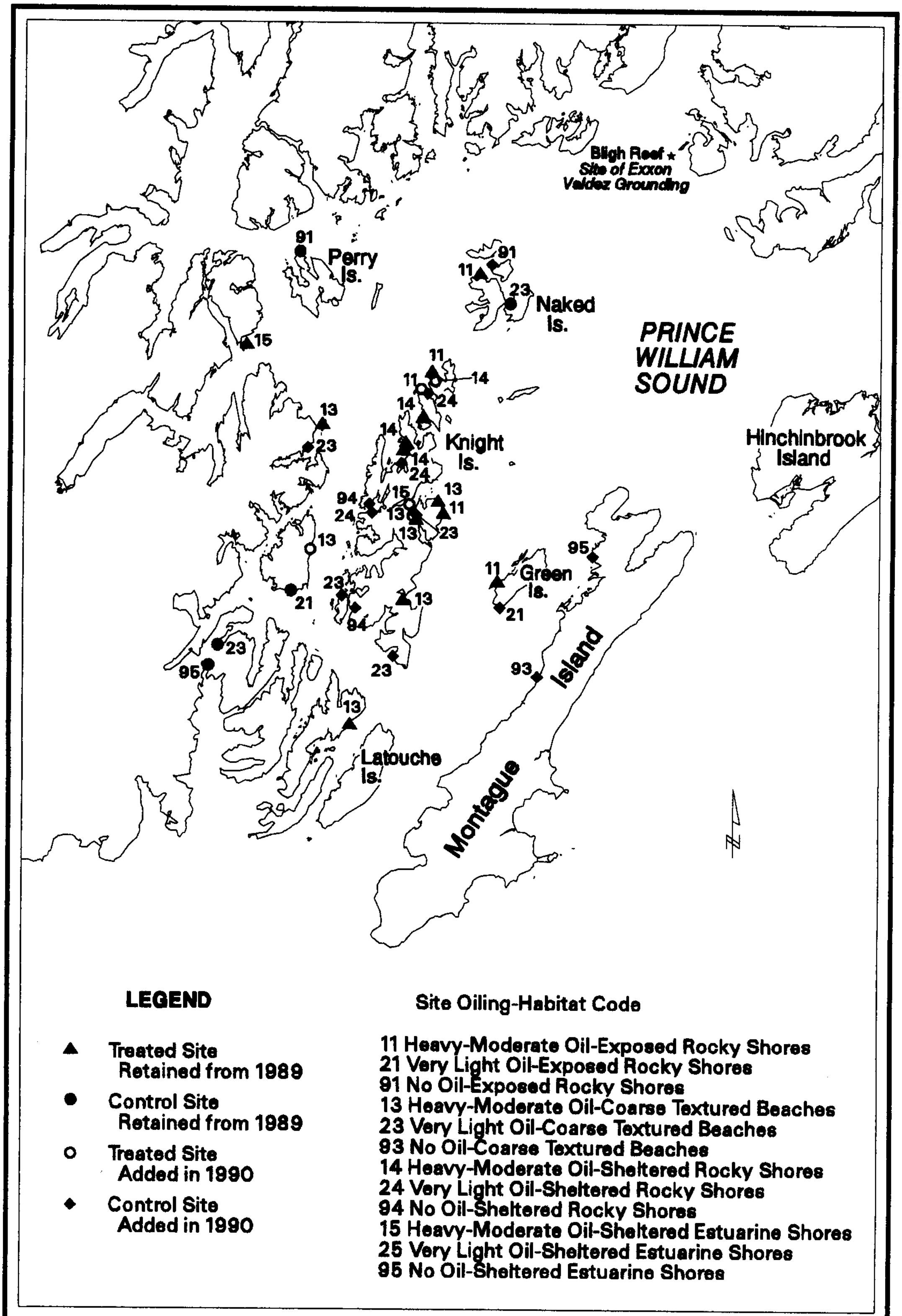

FIGURE 2.—1990 Coastal Habitat Injury Assessment (CHIA) study sites, Prince William Sound region. Map was produced by the Alaska Department of Natural Resources.

Discussion

The *Exxon Valdez* oil spill potentially contaminated 2,003 km of shoreline consisting of 501 km in PWS, 161 km in CIK, and 1,341 km in KAP (ADEC 1989b). The task of quantitating spill injuries to intertidal and supratidal biota presented a formidable challenge. In the spill area there were very little preexisting biological baseline data that could be used for assessment of intertidal and supratidal injury. Most of the existing baseline data were not in a form that could be used for Natural Resource Damage Assessment (NRDA) studies and occurred at sites that were not significantly oiled. These facts eliminated the possibility of conducting a classical "Before-After-Control-Impact" (BACI) design (Stewart-Oaten et al. 1986).

The use of a GIS to identify potential intertidal and supratidal study sites within a stratified random sample of treated and reference sites was suggested by (1) the extraordinary amount of shoreline and associated habitat potentially affected by the spill, (2) the extreme heterogeneity of shoreline types and oiling impacts in the *Exxon Valdez* oil spill area, and (3) the need to make inferences from intertidal and supratidal sampling to the universe of all spill-affected shorelines. The availability of shoreline sensitivity and oiling impact information for the spill area and the existence of in-place GIS capabilities and skilled GIS technicians enabled the rapid development of the programs and databases needed to construct a workable GIS.

Oil spills induce short-term and long-term effects on shoreline biota and there is great urgency to carry out damage assessment studies at the earliest time. During the *Exxon Valdez* oil spill there was neither sufficient time nor resources to independently validate existing complex data sets, including the State Shoreline, the ESI classification scheme, and the OSI database before implementing the Coastal Habitat Injury Assessment (CHIA) study plan. This study showed the need to validate data sets that will be used for damage assessment before implementing a study plan. Many misclassifications could be attributed to (1) the strong dependence on aerial overflight information in the ESI and OSI databases that was often inconsistent with characteristics that we observed in the intertidal zone during ground surveys, (2) the lag time of 2 to 4 months between shoreline oiling information in the OSI database and our site-selection surveys, (3) collapsing the 19 ESI types into five habitat types, and (4) digitizing errors, including one that misclassified 20 potential sites into the wrong habitat category.

The large number of sites misclassified in the GEO database initially appeared to threaten the validity of the study plan. This problem was averted by restricting the sample to heavy–moderate treated sites in the top 50 accessible sites in each region (40 in PWS) ranked according to order of selection within the original strata. However, reclassifying the sites and restricting the sample size resulted in more than the target number of sites in some categories and less than the target number of sites in others. This problem was rectified by randomly eliminating the surplus sites and filling in deficient categories with purposively selected, treated sites. Each selected heavy–moderate treated site was then subjectively matched with a reference site from either non-oiled shoreline or very lightly oiled shoreline in a quasi-experimental design. Reference sites were interspersed with the treated sites because of the spotty nature of contact of oil with the shoreline, resulting in improved capability of the study design to control extraneous factors and increase the precision and accuracy in measurement of oiling-cleanup effects. Subsampling results from the purposively selected sites represented only themselves and were not used to extrapolate results to the other treated shorelines. Final unequal weights of the accessible heavy–moderate treated sites for statistical analysis within the quasi-experimental design were obtained by Monte Carlo-simulated sampling from the original frame (database and stratification) using estimates of the misclassification rates (McDonald et al. 1995).

Using hindsight, what changes would the authors make in the design of the CHIA in response to the *Exxon Valdez* oil spill? A complete discussion of all alternatives would include most of modern field ecology, marine science, and statistical theory, but we will attempt to address several important points as they relate to our basic design and logistical constraints.

1. It is now known that a straight stratified random sample (same number of study sites with no problems of misclassification) would probably not have sufficient statistical power to detect important adverse effects in the universe of oiled shoreline. Scientists conducting independent studies for Exxon Corp. used within-site sampling variance (i.e., pseudoreplication) to artificially increase statistical power in tests of hypotheses (Gilfillan et al. 1995; Page et al. 1995). This practice increases the likelihood that ad-

verse effects will be declared statistically significant and is an excellent conservative approach from their point of view to help them meet their objective of 80% power to detect 20% effects. However, in NRDA cases, the trustees are charged with proving adverse effects. Use of pseudoreplication to artificially increase the power is unacceptable in presentation of results from the trustees' studies. The paired site quasi-experimental design with randomly selected treated sites and subjectively selected reference sites is one of the few designs that had sufficient power to "prove" effects by the usual scientific method. Of course, we did not know whether sufficient power existed when the study was being redesigned during 1989 to 1990. Also, in any experiment, the conclusions must be referenced to the protocol for selection of reference sites and measurement of variables.

2. We recommend equal size units with equal probability of selection within strata to simplify data recording, analyses, and future uses of the data.
3. Fewer misclassifications in the original database would be desirable. If we had known the high rate of misclassifications in the database, we probably would have selected a simple random sample from equal size units. Sites would then be visited in the rank order of selection until the desired number of sites were classified into the subpopulations (domains) of interest.
4. We would allow for very lightly oiled shorelines, including those with occasional tar balls or tar spots, to qualify as potential reference sites. The net result would have been better interspersion of reference sites and treated sites. Use of very lightly oiled shoreline as reference should yield conservative estimates of the effects of oil-cleanup on heavy–moderate treated sites.
5. At all sites, we would measure more quantified "covariates"; that is, uncontrolled extraneous physical factors (e.g., proximity to sources of fresh water, wave exposure) that influence the biological community.
6. We would devise unique sampling procedures for discrete biological communities of special interest, such as mussel beds.
7. Finally, with the growing use of GIS for oil spill response (Harper et al. 1991), database standards should be established to require ground truthing and estimates of classification errors. This would improve the application of GIS to future subtidal, intertidal, and supratidal injury assessments.

Acknowledgments

The authors acknowledge the following organizations and individuals who contributed to this study: Earl Becker, Susan Beyersdorfer, Jeff Bromaghin, Lana Shea, Lance Trasky, and Frances Inoue of the Alaska Department of Fish and Game; Richard McMahon, Dorothy Mortenson, and Jean Tamm of the Alaska Department of Natural Resources; Jim Gibeaut, Eric Gundlach, and Jerry Sexton of E-Tech Inc.; Malin Babcock of the National Marine Fisheries Service; Ray Highsmith, Peter Ribbons, Josh Schimel, and Mike Stekoll of the University of Alaska; Emily Binnian and Stan Moll of the U.S. Geological Survey Earth Resources Observation System Field Office; Bill Edwards and Dave Gibbons of the U.S. Department of Agriculture Forest Service; and Wally Erickson and Dale Strickland of WEST Inc.

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