The Oilspill Risk Analysis Model of the U.S. Geological Survey

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CONTENTS

ILLUSTRATIONS

TABLES

METRIC CONVERSION FACTORS

SI (International System of Units) is a modernized metric system of measurement. An asterisk after the last digit of the factor indicates that the conversion factor is exact and that all subsequent digits are zero, all other conversion factors have been rounded to four significant digits.

To convert from	To	Multiply by
inch (in)	millimeter (mm)	25.4*
foot (ft)	meter (m)	0.3048
mile (mi)	kilometer (km)	1.609
nautical mile	kilometer (km)	1.852*
acre	meter² (m²)	4,047
mile² (m²)	kilometer² (km²)	2.590
gallon (gal)	meter³ (m³)	0.003785
barrel (bbl) (petroleum, 1 bbl = 42 gal)	meter³ (m³)	0.1590
million gallons per day (Mgal/d)	meter³ per second (m³/s)	0.04381

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ABSTRACT

The U.S. Geological Survey has developed an oilspill risk analysis model to aid in estimating the environmental hazards of developing oil resources in Outer Continental Shelf (OCS) lease areas. The large, computerized model analyzes the probability of spill occurrence, as well as the likely paths or trajectories of spills in relation to the locations of recreational and biological resources which may be vulnerable. The analytical methodology can easily incorporate estimates of weathering rates, slick dispersion, and possible mitigating effects of cleanup.

The probability of spill occurrence is estimated from information on the anticipated level of oil production and method and route of transport. Spill movement is modeled in Monte Carlo fashion with a sample of 500 spills per season, each transported by monthly surface-current vectors and wind velocities sampled from 3-hour wind-transition matrices. Transition matrices are based on historic wind records grouped in 41 wind velocity classes, and are constructed seasonally for up to six wind stations. Locations and monthly vulnerabilities of up to 31 categories of environmental resources are digitized within an 800,000 km^2 study area. Model output includes tables of conditional impact probabilities (that is, the probability of hitting a resource, given that a spill has occurred), as well as probability distributions for oilspills occurring and contacting environmental resources within preselected vulnerability time horizons.

The model provides the U.S. Department of the Interior with a method for realistically assessing oilspill risks associated with OCS development. To date, it has been used in oilspill risk assessments for eight OCS lease sales with the results reported in Federal environmental impact statements. A summary of results is presented herein. A "real time" version was also used to forecast the movement of oil from the 1976-77 Argo Merchant oilspill. Additional model runs are planned for future OCS lease sales in frontier areas. Other possible applications include analysis of OCS development alternatives and site selection for oilspill cleanup equipment.

INTRODUCTION

The past decade has been a period of rapid growth in the offshore petroleum industry. The Department of the Interior currently conducts sales of mineral leases for specific areas of the Outer Continental Shelf at the rate of more than two per year, and it is anticipated that lease sales will continue, perhaps even at an increased rate, well into the 1980's.

Oilspills are one of the major concerns associated with offshore oil development in all OCS lease sale areas. Concern is clearly strongest among those who live in coastal areas and who depend, directly or indirectly, on coastal zone resources other than oil for a livelihood. Controversy over the risks and benefits of off-shore oil development inevitably gives rise to a need for quantitative estimates of the oilspill risk involved in a particular development proposal. Within the Federal Government, oilspill risk estimates are required prior to holding an OCS lease sale, at the time the Secretary of the Interior makes decisions on tracts to be withheld from leasing because of unacceptable oilspill risk to specific environmental resources in the proposed sale area. At issue in the decisionmaking for a typical OCS lease sale are anywhere from 100 to 500 nine-square-mile tracts which have been identified as possible production areas by interested oil companies. Also at issue are as many as 20 or 30 specific resources which have been identified by the Bureau of Land Management or the U.S. Geological Survey as vulnerable to oilspills on the basis of research and communication with local authorities.

An important fact that stands out when one attempts to predict oilspill damages for a proposed OCS lease area is that the problem is fundamentally probabilistic. A great deal of uncertainty exists not only with regard to the location, number, and size of spills that will occur during the course of development, but also with regard to the wind and current conditions that will exist and give direction to the oil at the particular times spills occur. While some of the uncertainty reflects incomplete or imperfect data, considerable uncertainty is simply inherent in the problem.

The Geological Survey has developed a model for assessing the oilspill risks associated with petroleum development in Federal OCS lease areas. The model is constructed to deal with three fundamental and essentially independent factors which comprise the total oilspill risk to coastal zone resources: (1) the probability of spill occurrence as a function of the quantity of oil which is to be produced and handled at individual production sites, pipelines, and tanker routes; (2) the probabilities of occurrence of various spill trajectories from production sites and transportation routes as a function of historical wind and current patterns for the area; and (3) the location in space and time of vulnerable resources defined according to the same coordinate system used in spill trajectory simulation. Results of the individual parts of the analysis are combined to estimate the total oilspill risk associated with production and transportation at locations within a proposed lease area. This information is then used in making final tract selections prior to leasing. To date, risk analyses have been conducted for seven Federal lease areas, including sites offshore the North-, Mid-, and South-Atlantic Coasts, the Eastern Gulf of Mexico, Southern California, and the Western and Northern Gulf of Alaska.

The purpose of this report is to describe how the Oilspill Risk Analysis Model of the U.S. Geological Survey works, both in theory and in actual operation. It discusses the assumptions used in developing the model and defines the role of each computer program. While not a detailed operating instruction manual, it provides the broad understanding of the model which is necessary for operating the model and properly interpreting the results.

The report begins with a discussion of how the data base is developed, proceeds to describe how oilspills are simulated, and then reviews the results to date. The section, "Representations of Physical Data," describes how winds, currents, and the locations of environmental resources, or targets, are represented as data and put in the proper form for analysis. Simulation of oilspill movement is the topic of the section, "Oilspill Trajectory Simulation," and the probabilistic calculations of oilspill risk is covered in "Risk Calculation." The section, "Model Verification and Limitations," places the accuracy of risk calculations in perspective with discussions of sensitivity and verification studies. A summary of past results and ideas for future uses of the model are presented in the section, "Model Output and Case Examples." Discussion of "Practical Aspects of Operating and Managing the Model" concludes the paper.

REPRESENTATIONS OF PHYSICAL DATA

The model of the U.S. Geological Survey is designed to use a large amount of information about the physical environment, including sizable files of wind and current data and the locations of numerous environmental resources which may be adversely affected by oilspills. Model programs process all of this data and store it in computer files before any trajectories are computed. All of the files are designed to allow rapid access to the data by subsequent computer programs. An extensive system of internal checks, along with graphic displays and printouts, help ensure that physical data are represented correctly. The following section describes how physical data are collected, processed, checked, and stored.

BASE MAP

A system for representing spatial locations is the foundation of the trajectory simulation model. The model employs a Cartesian coordinate system superimposed over a base map of the study area. All stored data are referenced to this system, and it is used for all internal calculations.

The initial step in establishing a coordinate system is the delineation of the area to be modeled. This area must be large enough so that all oilspill targets likely to be affected, such as land or biological resources, are included; at the same time, the map scale must not be so large that essential details are obscured. Previous OCS lease sale analyses have typically examined areas of about 800 km by 800 km, and included 1,000 km of coastline. The base map boundaries are usually chosen so that the major origins of potential spills, such as the lease area and transportation routes, are centered; if winds or currents are expected to drive spills predominantly in a certain direction, the map is shifted accordingly. Land need only be included to the extent necessary to define the shoreline, and to aid in visual recognition of the map.

Choice of a projection for the base map is particularly important, since representing the surface of the earth by a planar surface necessarily introduces some distortion in scale, or direction, or both. The Universal Transverse Mercator (UTM) projection system has relatively little scale distortion but has a directional distortion of about 10 degrees. Because the equations for correcting this distortion are lengthy and too expensive to perform for each trajectory movement, earlier OCS lease sale analyses used UTM or Lambert projections and neglected distortion. However, neglecting distortion caused serious difficulties in combining data obtained from different maps, and necessitated use of a more general mapping system.

A useful property of the Mercator projection is that there is no distortion in direction; that is, a constant compass direction is a straight line. This makes it extremely easy to align a Mercator projection with a Cartesian coordinate system. The penalty for this, however, is extreme distortion in scale, particularly at high latitudes. Fortunately, the correction factor is a relatively simple function of latitude, which the computer can calculate quickly and easily. Because of these properties, the Mercator projection is ideal for oilspill modeling purposes, and is now used by the model whenever possible.

Once the base map has been selected, a Cartesian coordinate system is superimposed with its origin at the lower left-hand (southwest) corner of the map. The longest side of the map is usually assigned a length of 480 units. The whole study area is then divided into a matrix of square cells of one unit each; the maximum size of this matrix is 480×480 cells. For a typical analysis, each cell represents an area of approximately 2 to 4 km^2, which is thus the basic unit of resolution for spatial data.

Spatial data is stored in a set of 480×480 matrices. Elements of the matrices define, for every cell:

- Presence or absence of land, and land segments.
- Presence or absence of up to 31 targets.
- Identification of a wind station, for determining the appropriate wind vector for oilspill movement (see subsection—Wind Data).
- Identification of a current polygon, for determining the appropriate current vector for oilspill movement (see subsection—Current Data Checking).

Processing data to construct large arrays is a complicated task requiring a great deal of automation. Likewise, the practical limitations of computers require an efficient, though sometimes complex, storage and paging scheme for handling these matrices. Other sections describe the matrices in more detail.

LAND AND TARGETS

One primary function of the model is to relate oilspill trajectory movements to the locations of wildlife populations, fishing areas, and other potential "targets" in coastal and continental shelf areas. Environmental impact statements for Federal OCS leasing require collecting an enormous quantity of data about these resources, and a substantial part of this data base becomes input for the model.

STORAGE OF TARGETS

The model stores indicators of the presence or absence of land and up to 31 other targets in each of a quarter million grid cells. This is done in such a way that each of perhaps 150,000 simulated spills are quickly checked at each step in the trajectory for possible impact on each target.

Two features of the model allow a high level of performance in checking cells. When trajectories are being simulated by program SPILL (see section on "Oilspill Movement,") a paging system burdens computer memory with only a small, easily accessible fraction of the total grid at any time. Additionally, an effective exploitation of IBM storage attributes provides a compact and efficient mechanism for handling data which resides either in main memory or on permanent storage devices.

More technically, each grid cell is assigned one 4-byte integer to indicate the presence of up to 31 categories of targets, and land. Each of the 32 bits (numbered 0-31) corresponds to a different target, or land. Bit 0, the sign bit, corresponds to land, and is "on" when land is present in the cell. Bit i represents the target number i and the interger value 2**(31-i); "on" signals that the target is present in the cell. Thus an integer value of, say, 9 (binary 00000000 00000000 00000000 00001001) would indicate that targets 28 and 31 are present. Simple subroutines can decode these integers to suit various purposes.

TYPES OF TARGETS

Examples of spill-vulnerable targets which have been included in past analyses appear in tables 1 and 2. Sample targets are shown in figures 1 and 2. A simulated spill registers either "hit" or "no hit" on a target. A hit is scored as soon as the simulated spill crosses a cell occupied by the target. Multiple crossings by the same spill count as a single hit.

The selection of targets is clearly of critical importance if the model is to produce useful results. The section, "Model Output and Case Examples" further discusses the targets considered in past risk analyses.

FURTHER REFINEMENTS OF TARGETS—SEASONAL VULNERABILITY

Passage of spilled oil through a target location does not necessarily imply an adverse impact on the target, since vulnerability of a single target may vary according to time of year. Many wildlife populations undergo migrations during the year, and seasonal reproductive activities are often more susceptible to damage from spilled oil than other parts of the life cycle. The economic impact of spilled oil on such targets as beaches may also differ seasonally.

TABLE 1.—*Targets for a risk analysis in the Western Gulf of Alaska (from Slack, Smith, and Wyant, 1977)*

Salmon purse seining and set net areas
Pink and chum salmon intertidal spawning areas
Dungeness crab spawning, rearing, and catch areas
Tanner crab fishing areas
Tanner crab mating and hatching areas
Tanner crab vital rearing areas
Tanner crab important rearing areas
King crab mating and hatching areas
King crab vital rearing areas
King crab important rearing areas
Shrimp fishing areas
Shrimp production rearing areas
Seabird colonies
Summer bird distribution (June, July, August)
Fall bird distribution (September, October, November)
Winter bird distribution (December, January, February)
Spring bird distribution (March, April, May)
Marine mammal foraging areas
Sea lion rookeries and hauling grounds
Harbor seal rookeries and hauling grounds
Sea otter concentration areas
Kelp beds
Foreign fishing areas
Archeological sites

The model accounts for seasonal vulnerability by associating with each target a vector specifying "home" or "away" for each month. When a simulated trajectory crosses a cell which the target matrix indicates may be occupied by a target, program SPILL checks to see if the target is home before registering a hit. Figure 2 shows a blue crab migration route in the Gulf of Mexico. A spill crossing this path might be assumed to not affect the crabs at times other than the migratory period. In assessing risk to migrating blue crabs from proposed offshore oil production in this area, hits on migrating crabs were recorded only when simulated spills contacted this path from September through February.

Modeling seasonal vulnerability inevitably requires some degree of professional judgment since assumptions must be made about the longevity of oilspill impacts. For example, an oilspill hitting a beach in May could still affect recreation in June.

LAND SEGMENTS

The model uses a special accounting system for simulated spills which hit land. The land areas near proposed oil production sites can be arbitrarily divided into two independent sets of land segments, with each set containing up to 99 segments. When a simulated oilspill hits a cell containing land, program SPILL checks to see which land segment contains this cell. The number of simulated spills hitting the shore (broken down into time-to-shore categories) are counted and stored by land segment.

TABLE 2.—*Targets for a risk analysis in the Eastern Gulf of Mexico (from Wyant and Slack, 1978)*

Coral areas
Manatee concentrations
Brown pelican rookeries
Wading or pelagic bird rookeries
Dusky seaside sparrow habitat
Marine turtle nesting areas
American alligator habitat
Mangroves or tidal marsh
Estuarine nursery areas
West Florida adult female blue crab migration route
West Florida blue crab larval transport route
Tortugas pink shrimp nursery grounds
Calico scallops
Oysters and bay scallops
Seagrass beds
Spiny lobster
Sandy beaches
Florida Straits
High density use shoreline
National register sites
Designated wildlife, natural, and conservation areas
Designated national wildlife areas
National marine and estuarine sanctuaries
Florida aquatic preserves
Designated shoreline, national, and State parks
Ports
Foreign islands

Figure 3 shows a typical division of the shoreline of an analysis area into 52 land segments. The example comes from a risk analysis for a proposed Eastern Gulf of Mexico offshore oil production area (Wyant and Slack, 1978).

Compact storage of land segment numbers corresponding to each grid cell is achieved by breaking down IBM computer words in the 480×480 array. The word-breakdown method for overall targets was described earlier; the method for land segments differs, but is similar in principle. The computer time required to access land segment information during a trajectory run is much less than that required for targets, as the land segment array need be consulted only when land is hit. Program SEGMATRX inserts the land segment information into the model in the appropriate format.

A few examples will clarify how an analyst might use the land segment feature of the model. If the estimated overall spatial distribution of spills hitting shore is desired, one set of land segments can simply divide the shore into equal-length units; counts of simulated spills hitting each equal-length segment provide the necessary information. If risk analyses are needed for each individual political jurisdiction in the overall analysis area, the second set of land segments could divide the shore into counties or other political units.

A further advantage of land segments is that they allow consideration of risks to targets which may not have been included in the model runs. For example,

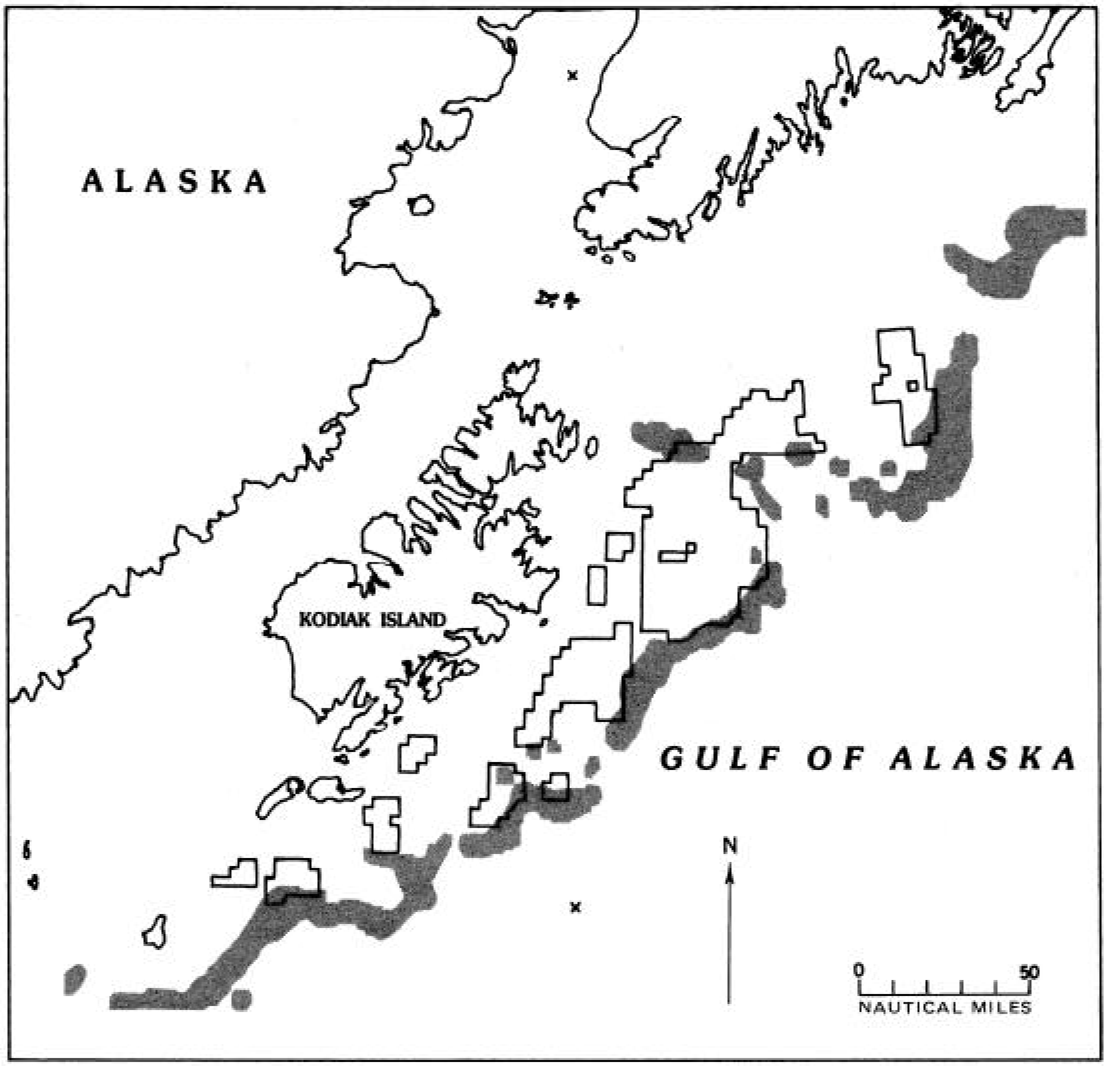

FIGURE 1.—Map showing a sample target in the Western Gulf of Alaska. Hatched areas indicate foreign fishing areas. Rectangles are proposed lease tracts (Slack, et al, 1977).

suppose that after the model has been run, a shoreline species is added to endangered species lists. Risk to the species can be estimated by examining the land segments in which the species resides.

Finally, the model is not applicable in many bays and estuaries. In a risk analysis for the Mid-Atlantic coast (Slack and Wyant, 1978), simulated spills were not permitted to enter the Chesapeake or Delaware estuaries where the trajectory assumptions of the mdoel are not applicable. To count simulated spills which would have entered the bays, the bay entrances were treated as parts of the shoreline, and a land segment was associated with each bay entrance. Counts of simulated spills hitting these land segments allowed analysis of risk to the bays as a whole without addressing the further problems of spill movements within the bays.

CHECKING TARGETS AND LAND SEGMENT DATA

The model is designed to allow treatment of extensive and intricate spatial information. In addition to creating computer storage and run-time problems, the size and complexity of the model's basic data structure creates validation problems. Inattention to errors in data input can often lead to disastrously misleading output. Given the time and tedium required for data

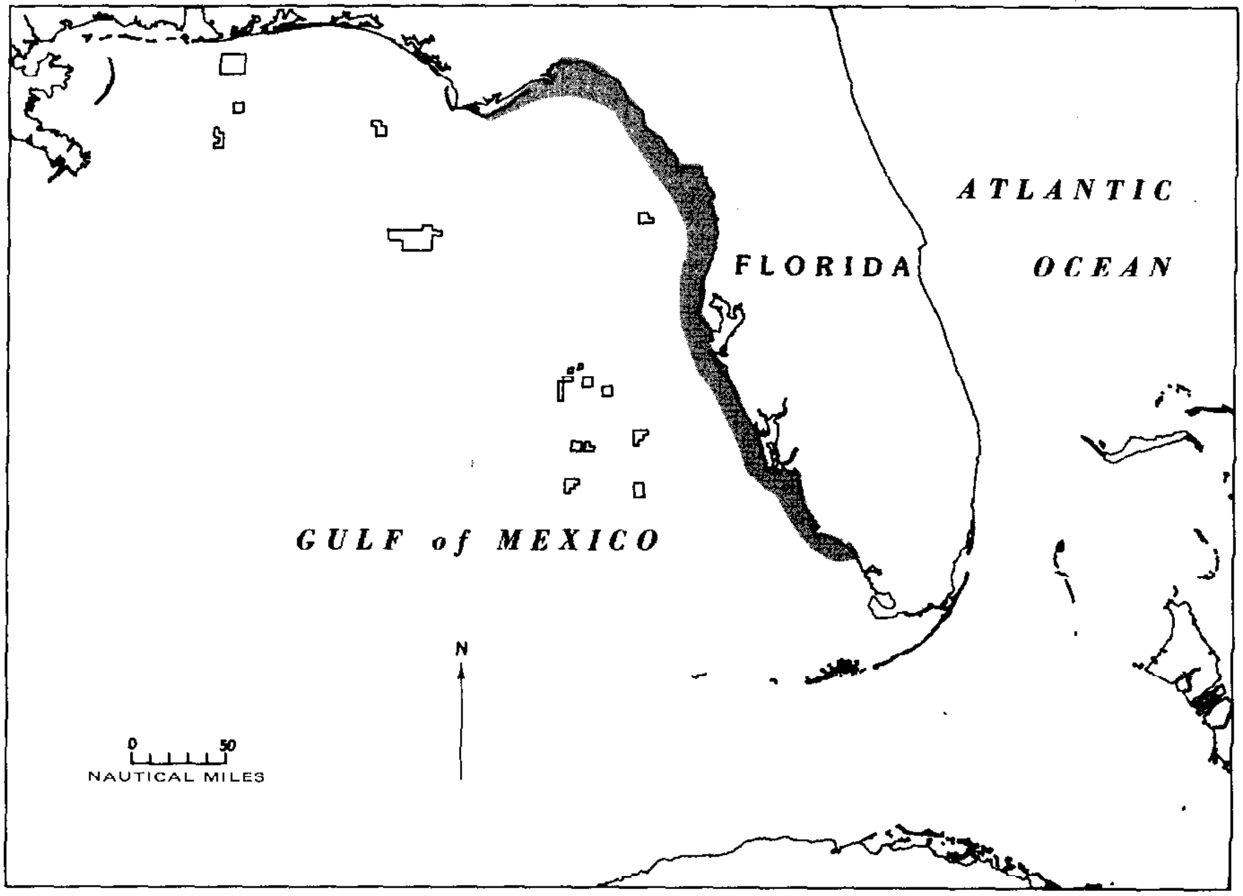

Figure 2.—Map showing a sample target in the Eastern Gulf of Mexico. Hatched area indicates blue crab migration route. Rectangles are proposed lease tracts (Wyant and Slack, 1978).

checking and the greater intellectual satisfaction of tinkering with the analytical specifications of the model, it is always tempting to pay too little attention to this possibility. The computer programs have been designed to make data checking as complete and convenient as possible, and to prompt modelers to thoroughly carry out this phase of an analysis. OBJECTS and other spatial data entry programs routinely provide diagnostic information such as the number of points in the overall grid system used to represent each target. A coded version of the array used to store the target locations is routinely printed in each run of OBJECTS. The most important checking routines, however, are graphical.

Computer graphics provide a powerful tool for quickly and fully examining complex spatial data. This tool is exploited throughout the data entry phases of a model run. Program DIGIPLOT plots each target as it resides on computer tape immediately after entry from a digitizer. (The target's location at this stage is stored as a string of x-y coordinates representing locations along the boundary of the target area on a map laid on the plane of the digitizer table. See the next subsection, "Insertion of Spatial Data into the Model," for more detail.) Timely examination of freshly entered spatial data using DIGIPLOT speeds the data entry phase of a model run and prevents costly cascading of errors through subsequent programs.

When program OBJECTS has inserted target locations into the final grid system, program OBJPLOT produces plots such as figures 1 and 2. These plots allow quick appraisal of how faithfully and completely target location in the final coordinate system agrees with the target location on the original map. These plots also provide an immediate check on the correctness of the various map scalings, rotations, and projections required to combine spatial information from different maps and different sessions on the digitizer.

In addition to providing the key to thorough and economical data checking, these computer-graphics programs are an invaluable tool for communicating the content and output of the Survey model. Model results

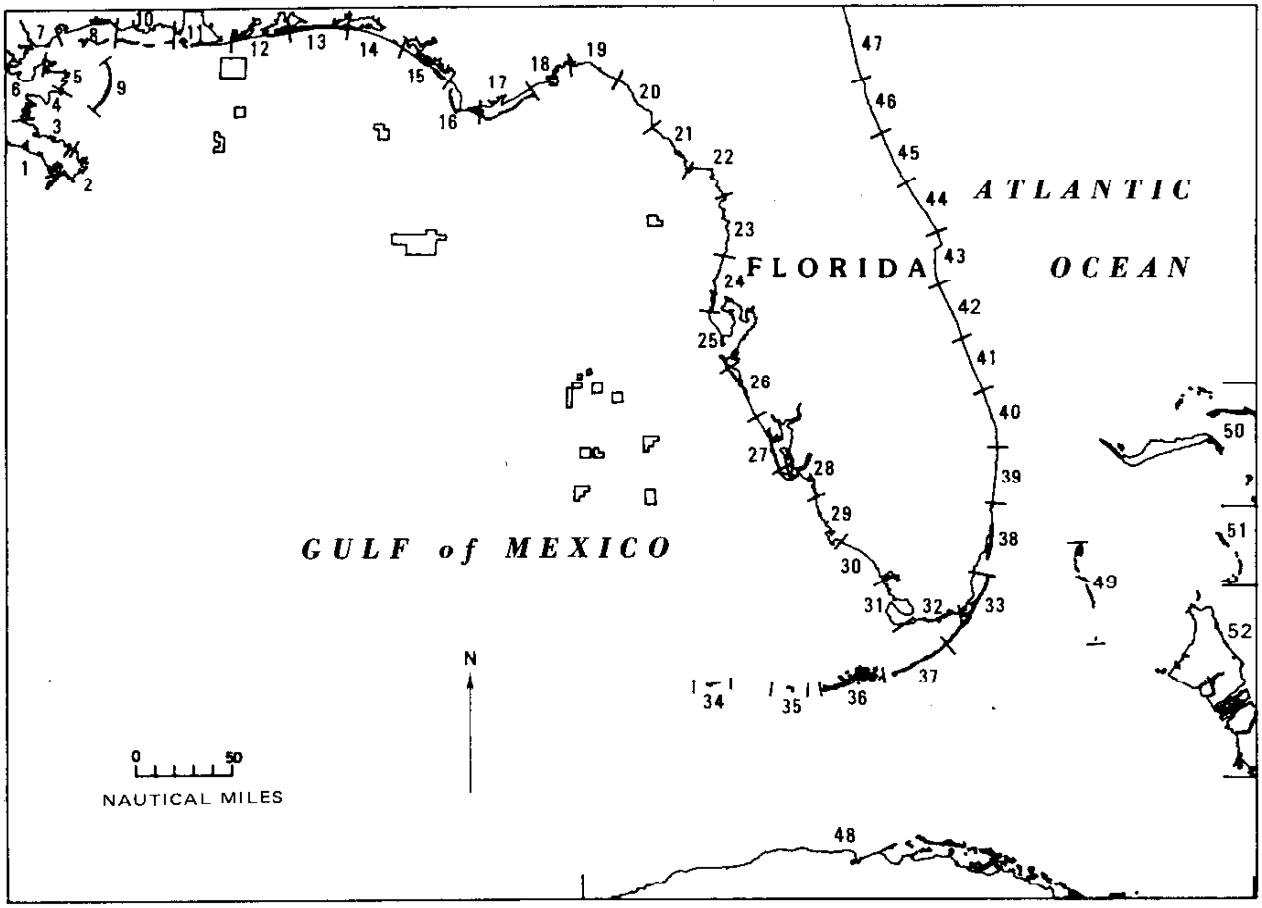

FIGURE 3.—Map showing a typical division of the shoreline into land segments (Wyant and Slack, 1978).

must often be presented to users from a variety of technical backgrounds. Pictures such as figures 1 and 2 are easily understood.

INSERTION OF SPATIAL DATA INTO THE MODEL

This subsection describes the mechanical details of inserting spatial data into the model.

Target location is originally provided on a map of part of the overall analysis area. Each map must have a pair of reference points corresponding to a pair of reference points on the overall map of the area.

The map is laid on a digitizer table, and the outline of a target is traced with the digitizer's electrical crosshairs. This converts the image of the outline to a sequence of points expressed in digitizer table coordinates. The digitizer stores this sequence of coordinates on computer tape.

Program DIGIPRE screens the digitized locations of reference points, targets, and shorelines and stores them on a direct access disk pack in a form accessible to program OBJECTS. Program DIGIPLOT creates diagnostic plots of target locations from these disk files to check against the original maps.

Several options are available for entering spatial data. Correct use of the options speeds the entry process and simplifies data organization and storage. Programs DIGIPLOT and OBJECTS automatically check for large gaps in the point sequences representing target outlines. Thus, the outline of a target with many discrete subareas, such as an island chain, can be traced on the digitizer table and the model will automatically recognize the individual islands. Targets representable as polygons can be entered simply by digitizing the polygon vertices; they need not be traced in their entirety. Some targets can also be entered as isolated points, but this presents some theoretical difficulties, since oilspills are also represented as points.

Land segments are entered much the same as polygonal targets. The order in which the polygon vertices are digitized is important—a specific order is needed to