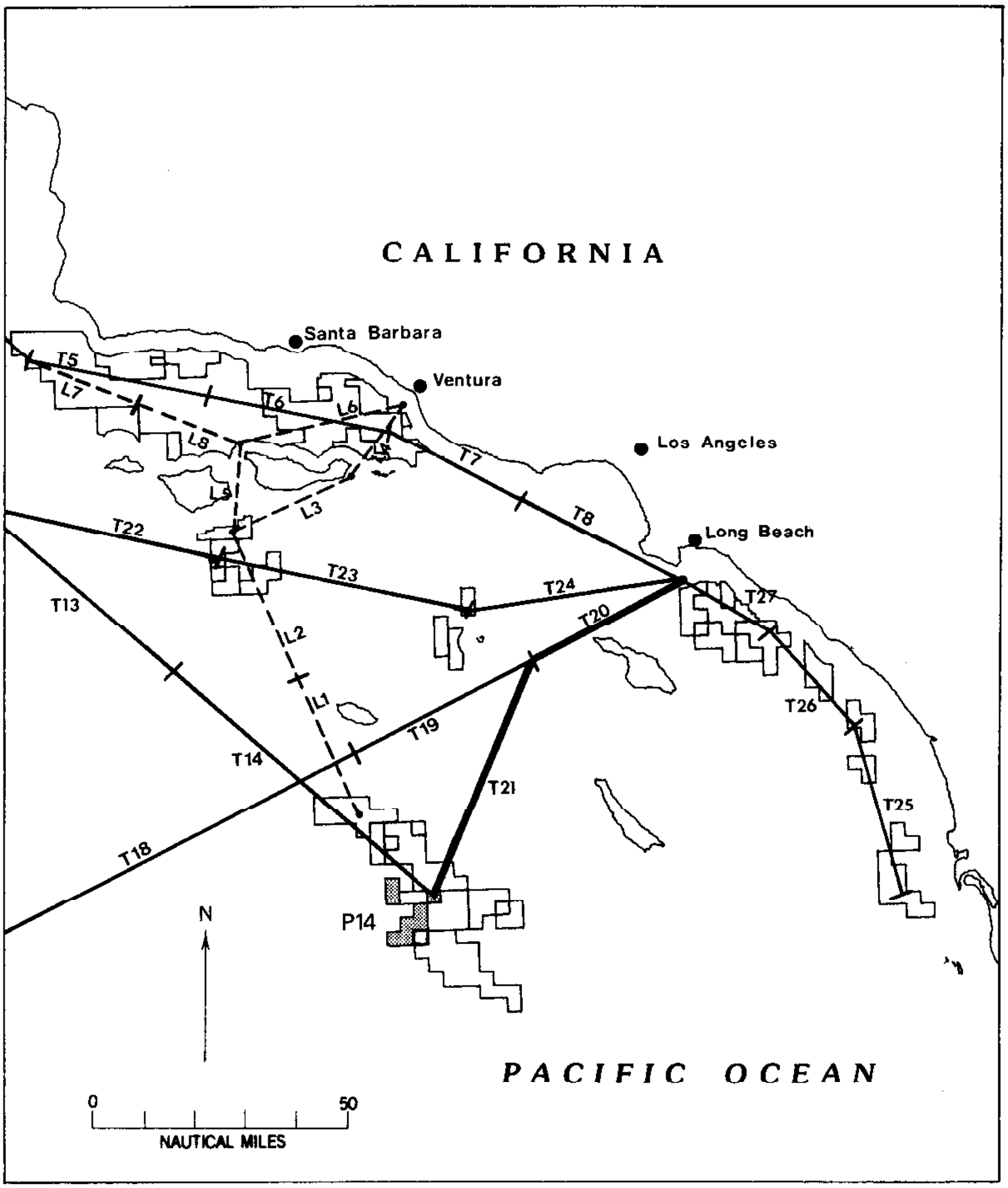

FIGURE 11.—Potential transportation route segments for southern California, showing how oil from tract group P14 would be brought to Long Beach via segments T20 and T 21 (Slack, Wyant, and Lanfear, 1978).

tacting each target or land segment over the production life of a lease area. This final calculation entails three steps which are performed by program NU:

- For each production site or transportation route, the "conditional probability—the probability that a spill, having occurred, will contact the given target or land segment—must be extracted from the output of program HITPROB or program LANDSEG. (The operation of these programs was described in an earlier section.)
- For each production site or transportation route, the conditional probability must be combined with the probability distribution of spill occur-

rence (estimated using the methods described in the section "Spill Occurrence") to yield a single-source probability distribution for the number of hits on the target or land segment. This distribution may be arrived at by one of two methods, according to whether the single source is a "point" source, such as a production platform, or a "distributed" source, such as a tanker route where the oil could be released anywhere along the route.

- All single-source estimated probability distributions in a scenario (see the previous section) must be combined to yield the overall estimated probability distribution for the number of hits on each target and(or) land segment.

The following subsections describe, in more detail, the methods employed.

PROBABILITY OF HITS ON A TARGET FROM A SINGLE SOURCE

Programs HITPROB, LANDSEG, SCENARIO, and NU communicate through files stored on permanently mounted disk packs. After obtaining the conditional probabilities for all targets and land segments for each launch point, program NU begins to process the transportation scenario, segment by segment.

Suppose that for production platforms, the estimated probability distribution of N', the number of spills occurring, is negative binomial. Then, following from the section "Spill Occurrence,"

$$P(N'=n)=\frac{(n+\nu-1)!t^n\tau^\nu}{n!(\nu-1)!(t+\tau)^{n+\nu}} \tag{4}$$

Suppose, further, that the conditional probability (obtained from HITPROB or LANDSEG) that a spill from a point source will hit a given target is p. Then, the estimated probability distribution of N', the number of spills which both occur and hit the target over exposure t, is negative binomial

$$P(N'=n)=\frac{(n+\nu-1)!(pt)^n\tau^\nu}{n!(\nu-1)!(pt+\tau)^{n+\nu}} \tag{8}$$

with mean

$$\lambda=\nu pt/\tau \tag{9}$$

and variance

$$\sigma^2=\frac{\nu pt}{\tau}\left(1+\frac{pt}{\tau}\right). \tag{10}$$

Appendix A contains a rigorous derivation of this result.

For a distributed source defined by several transportation route segments, suppose that the estimated probability distribution of spills is the negative binomial with parameters as before: ν, the number of past observed tanker spills, τ, the amount of past exposure observed, and t, the predicted future exposure. These spills could occur at any point along the route. As the previous sections pointed out, it is often desirable in a risk analysis to be able to weight points along a route in terms of that likelihood of spill occurrence. The constraint on the weights is that the distribution of the total number of spills along the route must be the abovementioned negative binomial distribution, with mean

$$\lambda=\nu t/\tau \tag{11}$$

and variance

$$\sigma^2=\frac{\nu t}{\tau}\left(1+\frac{t}{\tau}\right). \tag{12}$$

This constraint is satisfied by assuming that the distribution of spills at each transportation route segment is negative binomial with parameters ν_i, τ_i, and t_i, where the sum of the ν_i must be ν. Appendix A demonstrates that this structure satisfies the constraint.

To determine the estimated probability distribution for hits on a target from spills along the whole route, the model first constructs the hit distribution for each separate point source along the route (using the previously described methods for single point sources). The model then combines these distributions as described in the next section.

PROBABILITY OF HITS ON A TARGET FROM MULTIPLE SPILL SOURCES

The overall estimated probability distribution for the number of hits on a target is constructed as the convolution of the appropriate single-source distributions derived in previous steps. The meaning of this statement is best conveyed through an example: Let $P_{1,n}$ be the probability of n spills hitting the target from the first source, and $P_{2,n}$ be the probability of n spills hitting the target from a second source,

$$P_{i,n}=\frac{(n+\nu_i-1)!(p_it_i)^n\tau_i^{\nu_i}}{n!(\nu_i-1)!(p_it_i+\tau_i)^{n+\nu_i}} \tag{13}$$

Let P_n represent the probability that n spills hit the target from both sources combined. Then,

$$P_0=P_{1,0}P_{2,0}, \tag{14}$$

$$P_1=P_{1,1}P_{2,0}+P_{1,0}P_{2,1}, \tag{15}$$

$$P_2 = P_{1,2}P_{2,0} + P_{1,1}P_{2,1} + P_{1,0}P_{2,2}, \qquad (16)$$

and,

$$P_n = \sum_{i=1}^{n} P_{1,i}P_{2(n-i)} \cdot \qquad (17)$$

The extension to more than two sources is similar.

Program NU carries out these calculations in the model. Its design is such that the effects on a risk analysis of different assumptions concerning incidence rates, production and transportation scenarios, or resource estimates, can be determined simply and straightforwardly by rerunning the program with different parameter values.

MODEL VERIFICATION AND LIMITATIONS

FORMAL ERROR ANALYSIS

Results of complex systems models are seldom amenable to formal error analysis, that is, to the expression of error in the end result as a function of errors in input quantities. Often, the error as an input quantity will be unobtainable or unquantifiable, or the error's effect on the overall analysis will be too ambiguous. Furthermore, it is especially difficult to attach a single number representing "standard error" to the results of a model run, when the results consist of a set of predicted probability distributions. In fact, the Bayesian methods used in constructing the distributions described here explicitly incorporate some elements of uncertainty (notably those in estimating spill incidence rate) and were developed, in part, for situations where classical error analysis seemed unsatisfactory.

This does not imply that a useful assessment of model reliability cannot be made, or that the results are categorically unreliable. Three modes of testing are available to the model user: (1) an informal assessment of individual model components is often satisfactory; (2) the sensitivity of the model results to particular assumptions can be tested by repeated runs with differing inputs; and (3) parts of the model can be directly tested by comparison with actual spill trajectories. The following sections contain discussions of how these modes of evaluation were applied to the model described here.

INFORMAL ERROR ANALYSIS

Several factors constrain the effective breadth of a model's applicability. The model's structure (how it works, what it includes or excludes), the refinement of the driving data, and the analytical treatment of the component oilspill occurrence and movement processes all play a role. In a general purpose model, these limitations will differ for each application of the model. This requires that the assumptions necessary for specific areas be readily testable; different factors may limit the precision of the results from case to case. As an example, unreliable current data may not seriously affect model output in situations where the movement of oil is largely wind-dominated (as in some proposed North Atlantic oil production areas—see Smith and others, 1976b), but may critically affect model output where currents are the primary mover (as in many proposed Gulf of Mexico oil production areas—see Wyant and Slack, 1978). The computer programs of the model have been built to facilitate case-specific testing. This has been done by modularizing computer programs, by concentrating on simple parameterizations of processes, and by restricting analytical representations of physical processes to those which are relatively simple, general, and widely accepted.

SPATIAL RESOLUTION

The model cannot represent the locations of oilspills or targets with any finer resolution than the cell size (about 1 nautical mile square) of the grid system. This is an artificial restriction, of course, in the sense that the model could be simply modified to diminish the cell size. Increasing the spatial resolution of the model by this means would, however, lead to a spurious and misleading impression of accuracy in the output, given the present accuracy with which the location of many targets and the spreading of large spills can be depicted.

RISK FOR NEAR-SHORE AND CONFINED-AREA SPILL SOURCES

The spill transport equation used in the model has several virtues. It is simple, is widely accepted as a reasonable representation of oilspill movement in open water (Stolzenbach and others, 1977, p. 5-47), and is void of any special assumptions which would disqualify the model for risk forecasting in most proposed offshore production areas. However, due to the fact that the basic oil transport equation is designed to represent the "average" movement of large spills in fairly open waters, the model cannot adequately represent the detailed movement of spills close to shore or in confined estuaries or bays, where tides and highly localized currents may dominate the movement of spilled oil.

SPREADING

The model does not explicitly incorporate spreading. This deficiency is mitigated by several factors. First, because of the large regions over which the model is designed to operate and the resulting scale of model resolution, spreading is less important than overall advection in determining risks. Second, the original digitization of targets and their insertion into the grid system tends to expand the areas occupied by targets (any cell partially occupied is treated as fully occupied), and causes "near misses" of oilspills to be counted as hits. Third, recording the time-of-contact for each hit enables the analyst to estimate spreading effects independently, given information on oil type, sea state, and so on.

DECAY

The modeling of spill decay presents the same difficulties as the modeling of spreading, in that knowledge of factors such as oil type are integral to analytical descriptions of the physical process. As with spreading, the model does not explicitly calculate decay, but is constructed to provide information on spill travel time, thus enabling assessment of the extent to which decay might mitigate predicted impacts. Contacts of spills with targets are compiled in several elapsed-time categories—up to 3 days, 3 to 10 days, 10 to 30 days, and 30 to 60 days—to assist the analyst in this assessment.

SENSITIVITY ANALYSIS

Sensitivity analysis of model assumptions is a useful technique for assessing model strengths and weaknesses. As suggested above, such analyses should be tailored to particular situations; different features of the model are critical in different situations, and the dictates of economy require the appropriate selection from the many possible sensitivity analyses. Design features of the model make such analyses easy to carry out.

Two sensitivity analyses performed during a risk analysis for proposed North Atlantic OCS production areas (Smith and other, 1976b), exemplify the kinds of analyses which can be readily performed. The basic transport equation includes the wind drift angle, which is the number of degrees wind-induced oil movements are deflected from the direction of the wind by Coriolis acceleration. Some controversy surrounds the optimal value of this parameter for spill modeling, but most suggested values fall between 0 and 20 degrees clockwise in the Northern Hemisphere (Stolzenbach and others, 1977, p. 81). For the North Atlantic risk analysis, two separate model runs were made using drift angles of 0 and 20 degrees clockwise. The resulting estimates of probabilities of spills from the proposed oil production areas hitting shore were 21 and 8 percent, respectively.

In another sensitivity analysis for the same area, actual historic wind sequences were substituted for stochastically generated ones (see the section on "Winds"). Table 7 shows the estimated probability of hitting land for spills from one proposed North Atlantic oil production site by the two modes of model operation.

These two studies convey the kinds of evaluations which can be conducted in the course of a risk analysis, and the sensitivity of results to certain key assumptions. Different sensitivities to these particular assumptions can be obtained in different OCS areas.

DIRECT MODEL VERIFICATION

Clearly, predictions of expected numbers or probabilities of spill impacts for a given place and time cannot be "proved" or "disproved" by a single spill. Nonetheless, a limited verification of the trajectory model was achieved for the area covered by the North Atlantic OCS oilspill risk analysis (Smith and others, 1976b). In December 1976 the Argo Merchant spilled 7.7 million gallons of oil and the spill traveled in the direction that the model indicated was most likely (see fig. 12). Extensive overflights and monitoring of this spill provided data for a more thorough evaluation of components of the model. In particular, by comparing actual and simulated spill locations, the validity of current assumptions, transport equations, and wind data source choices could be examined. This work, presented in detail in Grose and Mattson (1977), Pollack and Stolzenbach (1978), and Wyant and Smith (1978), supported the general adequacy of the transport segment of the model.

The spill occurred not as an idealized instantaneous point spill but rather was released over an extended period of time. To facilitate comparisons of simulated trajectories with the actual spill, the spill was modeled as a set of sequentially released points, with each 3-hourly wind applied to the entire, gradually enlarging set. This enabled 2-dimensional construction of spill representations such as that in figure 12. Runs were made using a variety of different parameter values. Graphical output such as that in figure 12 seems to be a particularly appropriate way to communicate the validity of risk forecasts to potential model users in that it quickly and concisely gives a feeling for the model's level of approximation.

TABLE 7.—*Sensitivity of predicted oilspills risks for the North Atlantic study area to the assumption that winds can be modeled as a first-order Markov process.*

Wind sequence	Number of simulated trajectories per season	Percent of simulated trajectories hitting shore				
		Winter	Spring	Summer	Fall	Total
Generated from first order Markov process.	500	1	8	19	3	8
Taken directly from historic record.	300	0	12	8	0	5

TABLE 8.—*Reports prepared for OCS lease sale analyses using the Oilspill Risk Analysis Model of the U.S. Geological Survey*

An Oilspill Risk Analysis for the Southern California (Proposed Sale 48) Outer Continental Shelf Lease Area; James R. Slack, Timothy Wyant, Kennth J. Lanfear; U.S. Geological Survey Water-Resources Investigations 78-80; 1978; 101 p. (Available from NTIS.)

An Oilspill Risk Analysis for the Mid-Atlantic (Proposed Sale 49) Outer Continental Shelf Lease Area; James R. Slack and Timothy Wyant; U.S. Geological Survey Water-Resources Investigation 78-56; 1978; 79 p. (Available from NTIS.)

An Oilspill Risk Analysis for the Eastern Gulf of Mexico (Proposed Sale 65) Outer Continental Shelf Lease Area; Timothy Wyant and James R. Slack, U.S. Geological Survey Open-File Report 78-132; 1978; 72 p.

An Oilspill Risk Analysis for the Western Gulf of Alaska (Kodiak Island) Outer Continental Shelf Lease Area; James R. Slack, Richard A. Smith, and Timothy Wyant; U.S. Geological Survey Open-File Report 77-212; 1977; 57 p.

An Oilspill Risk Analysis for the South Atlantic Outer Continental Shelf Lease Area; James R. Slack and Richard A. Smith; U.S. Geological Survey Open-File Report 76-653; 1976; 54 p.

An Oilspill Risk Analysis for the Mid-Atlantic Outer Continental Shelf Lease Area; Richard A. Smith, James R. Slack, and Robert K. Davis; U.S. Geological Survey Open-File Report 76-451; 1976a; 24 p.

An Oilspill Risk Analysis for the North Atlantic Outer Continental Shelf Lease Area; Richard A. Smith, James R. Slack, and Robert K. Davis; U.S. Geological Survey Open-File Report 76-620; 1976b; 25 p.

MODEL OUTPUT AND CASE EXAMPLES

REPORTS FOR OCS LEASING

For each application of the model to a Federal OCS lease sale, a final report is produced which includes the following items:

- A discussion of the data sources which were used.
- Maps showing the location of the study area and the locations of the targets and land segments.
- Tables of conditional probabilities giving, for each launch point, the probabilities that an oilspill occurring at a given production site will contact targets or land segments within 3, 10, 30, and 60 days.
- Tables and graphs showing the probabilities of oilspills occurring.
- Tables showing the overall probabilities of oilspills occurring and contacting targets or land segments within 3, 10, 30, and 60 days.

A list of reports prepared for seven previous analyses is presented in table 8.

SUMMARY OF RESULTS TO DATE

The model has been used to conduct oilspill risk analyses for eight OCS lease sales in six Federal lease areas, which together represent only a small fraction of the total number of offshore tracts that may be developed eventually. Nevertheless, the six areas studied thus far are distributed among all four of the major OCS regions which will experience oil and gas development (the Atlantic and Pacific coasts, the Gulf of Mexico, and the Alaskan Peninsula) and will serve as focal points for further development in those regions.

The primary objective of oilspill risk analyses conducted by the Geological Survey is to determine the risks of petroleum development for the tracts within a given lease area. Such information is useful to the Federal Government in selecting tracts to offer for sale from a list of tracts proposed for development by the oil industry. It is also of interest, however, to make comparisons in oilspill risk between lease areas, since the sites represent the four major OCS regions and the possibility of large differences in risk exists. An interregional comparison will be the emphasis of the summary presented here. (For more detailed descriptions of studies of individual lease areas, the reader is directed to the bibliography of oilspill risk reports in table 8.)

An important question concerning oilspill risk in Federal areas is whether there are significant geographic differences in spill risk per unit of expected oil production. (Risk per unit production can be measured as expected number of spill impacts on a given resource or shoreline segment per billion barrels pro-

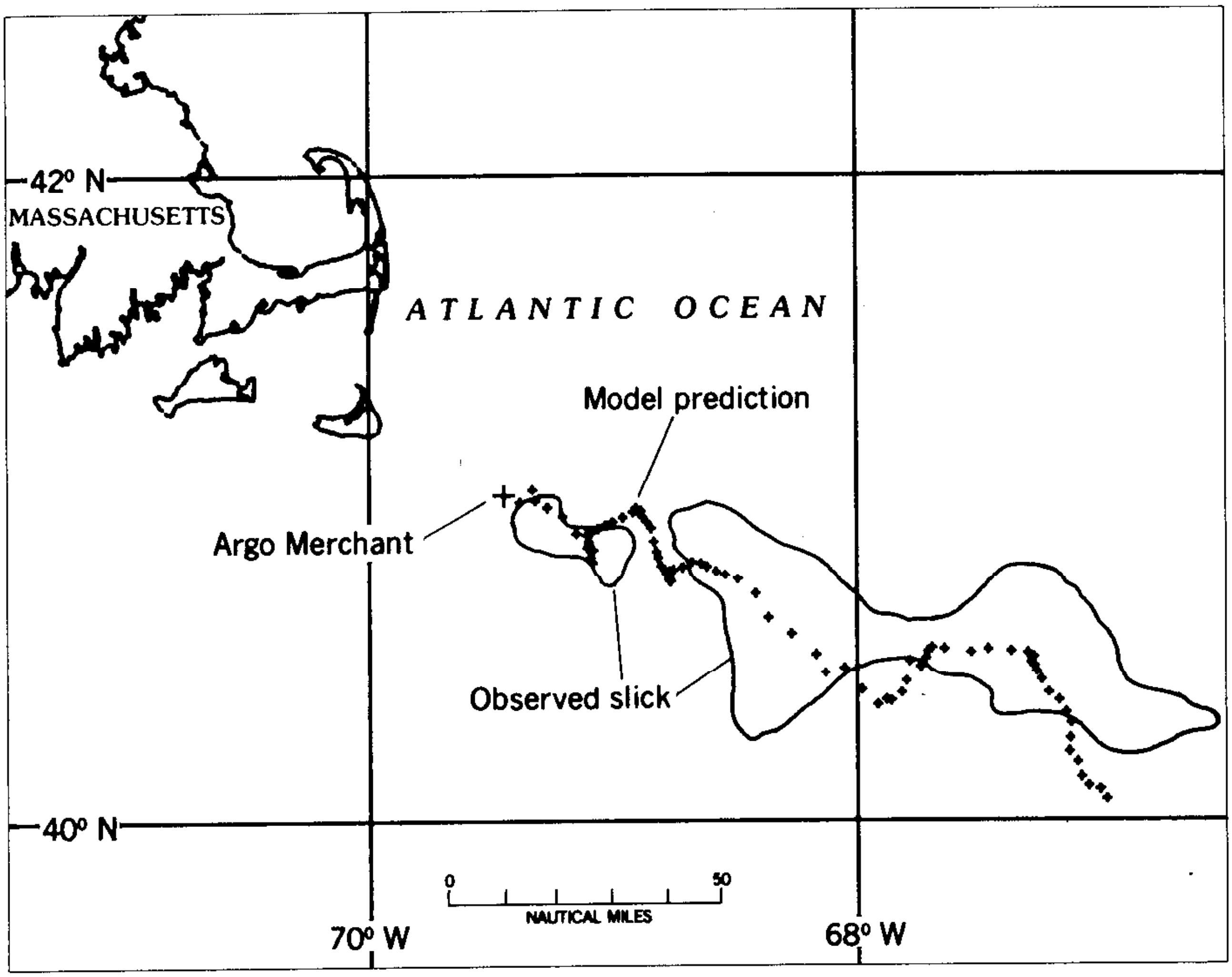

FIGURE 12.—Comparison of the observed slick from the Argo Merchant with a prediction of the Oilspill Risk Analysis Model of the U.S. Geological Survey (Wyant and Smith, 1978).

duced and transported to shore.) Differences in risk per unit production among sites could influence the scheduling of future lease sales. One logical policy, for example, would be to develop the sites bearing the least risk per unit production first, in anticipation of continual improvement in spill prevention and cleanup technology.

Table 9 gives the expected number of oilspills larger than 1,000 barrels occurring and reaching shore during the production life of the six lease areas studied. Where applicable, data for existing and proposed tracts are presented separately. Column 1 summarizes the results of trajectory model runs, and gives the range in conditional probability of spills reaching shore from individual production sites and transportation routes within each lease area, assuming a spill occurs. Column 2 gives the expected number of spill occurrences associated with both production and transportation for the six lease areas. Column 3 gives expected spills reaching shore during the production life of the six lease areas, and represents the sum of the products of conditional probabilities and expected numbers of occurrences of oilspills for individual tract groupings and transportation routes within each lease area. Column 4 gives total estimated oil production for each of the six lease areas. Column 5 gives risk per unit production expressed as expected number of spills reaching shore per billion barrels of oil produced, and is calculated as the quotient of column 3 by column 4.

A value for the average conditional probability of contacting land from spill sites within a given lease area can be obtained by dividing the expected number

TABLE 9.—*Estimated conditional probabilities and expected numbers of spills larger than 1,000 barrels reaching shore as a result of petroleum development in each of the six Federal lease areas*

Lease area	Range of conditional probability of reaching shore from anticipated production areas and transportation routes (percent)	Expected number of spill occurrences	Expected number of spills reaching shore	Estimated oil production (million bbls)	Expected number of spills ashore per billion (bbls. produced)
North Atlantic	2-79	2.4	1.1	500	2.2
Mid-Atlantic					
Existing leases	2-42	3.3	.17	800	0.21
Proposed leases	1-42	0.86	.02	150	0.13
South Atlantic	69-97	3.2	2.5	660	3.8
Eastern Gulf of Mexico					
Existing leases	17-99	7.4	5.1	1800	2.8
Proposed leases	10-94	0.4	.17	70	2.5
Southern California					
Existing leases	1-97	9.3	7.0	1330	5.3
Proposed leases	1-97	5.0	3.8	720	5.3
Gulf of Alaska	28-70	7.5	3.5	1550	2.3

of spills reaching shore (column 3) by the expected number of spills occurring (column 2).[1] In the North Atlantic, for example, the average conditional probability of a spill reaching shore, given that one has occurred on a randomly selected tract, is 46 percent (1.1 ÷ 2.4). It can be seen from table 9, column 1, that even within the same lease area, the probability of oilspills reaching shore from different tracts and transportation routes is quite variable. Ranging from less than 20 percent to nearly 80 percent in a majority of lease areas, the spread in conditional probability reflects variability in wind and current patterns within each area as well as geographic differences, such as the distance of potential spill sites from shore. The variation in risk among different potential drilling sites and transportation routes is, in itself, evidence of the need for an effective methodology for estimating risk prior to tract selection.

More to the point of the present summary, however, are the large differences in oilspill risk between the lease areas, as seen in table 9. By far, the lowest risk of spills reaching shore exists in the Mid-Atlantic area, where the total expected number of spills reaching shore over the production life of both existing and proposed leases is only 0.19. In all other areas, the expectation of spills reaching shore is at least 6 times higher than in the Mid-Atlantic, and for southern California, the expectation is more than 50 times higher. A major reason for low risk values in the Mid-Atlantic area is clear in the results of trajectory model runs for that area (Smith and others, 1976; Slack and Wyant, 1978): the predominance of westerly winds and the great distance of tracts from shore (50 to 100 miles) combine to make the conditional probability of reaching shore comparatively low (1 to 42 percent).

The most significant comparison of oilspill risk among Federal OCS areas is given in the figures for expected contacts with shoreline per unit production (table 9, column 5). It is worth noting that values for expected impacts per unit production are nearly independent of estimated oil production since production estimates appear both in the denominator and numerator of the calculation. Thus any errors in predicting oil production are not carried over into this measure of oilspill risk.

In terms of risk per unit production, the greatest contrast is, again, between the Mid-Atlantic lease area, where the expectation of spills occurring and reaching shore is less than one per billion barrels produced, and the southern California lease area, where the expectation is more than five landings per billion barrels produced. Overall, three lease areas stand out as having comparatively high risks of onshore impacts per unit production. These are the southern California, eastern Gulf of Mexico, and South Atlantic areas—each with risk values greater than 2.5 landings per billion barrels produced. The Gulf of Alaska and the North Atlantic together compose a sort of medium risk category, with landing expectations of 2.3 and 2.2 per billion barrels, respectively.

All of the above statistics refer to the risk of oilspills reaching the shoreline within the boundaries of the digital map used to track spill trajectories. Since so many resources vulnerable to spilled oil are located on or

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[1] It should be pointed out that averages calculated in this way amount to a weighting of the conditional probabilities of landing from each possible spill site by the relative likelihood of spills occurring at that location.

near the shoreline, probability of contacting land is perhaps the best single descriptor of the risk of oilspill damages in OCS lease areas. However, the probability of contacting land is not always an indicator of the probability of impact on all the resources, and it is advisable to avoid condensing the description of oilspill risk into a single number. For this reason oilspill risk analyses have considered risk to an extensive list of specific resources (typically 20-30) for each lease area.

Table 10 compares OCS Lease areas on the basis of oilspill risk to six general categories of coastal and marine resources. The second part shows the expected number of contacts with each resource category per billion barrels produced. For the most part, the oilspill risk values in table 10 follow the same pattern established in table 9; that is, the lowest impact probabilities appear for the Mid-Atlantic lease area, and the highest appear for the southern California lease area. There are three important instances in table 10, however, where oilspill risk is not highest for the southern California area. These are high-density resort and recreation areas (highest for the South Atlantic), critical waterfowl and seabird habitat (highest for the Gulf of Alaska), and marine mammal concentration areas (also highest for the Gulf of Alaska).

OTHER POSSIBLE USES OF THE MODEL

Although the primary purpose of the model is to assess oilspill risks from OCS lease sales, it has several other potential applications. Wyant and Smith (1978) described how the model was used in a "real time" mode to predict movement of oil spilled from the tanker Argo Merchant. A lease sale analysis had only recently been completed that included the area of the grounding, and the necessary data files were already in existence. Because subsequent model runs have expanded the model's data base to include major portions of the U.S. Outer Continental Shelf, operation in the real time mode would be possible in many other situations. Conversion to real time operation is relatively simple: data files must be retrieved from tape archives, and program SPILL must be modified so that each Monte Carlo trajectory run begins with a "present" wind velocity. However, it must be emphasized that such use is an extension beyond the original model design, and may not be as efficient nor as technically sound as using models designed specifically for oilspill cleanup.

The model's risk assessment capabilities are not limited to risks of OCS lease sales; other potential sources of oilspills, such as tanker import routes, can be analyzed as well. Since data files must be established for OCS lease sales in any case, the marginal costs of including other oilspill risks are small.

PRACTICAL ASPECTS OF OPERATING AND MANAGING THE MODEL

The model has been used to analyze oilspill risks in eight OCS lease sales, and its continued use is anticipated for future sales. To give potential users a realistic appraisal of the effort involved in model operation, this section discusses the practical aspects of operating the model. The management system which has evolved over three years of modeling operations is described, and the necessary software and hardware support for the model is identified.

MANAGEMENT SYSTEM

The model is constructed as a network of modules, or tasks. Each module is designed to accomplish a single specific objective using, as input, output produced by earlier modules. The major elements of a complete model run are illustrated in figure 13.

Modular construction is not unusual for large models, as it greatly simplifies the modification process. The internal workings of any module may be freely changed, as long as its input and output remain compatible with associated modules.

The network shown in figure 13 can produce an OCS lease sale analysis—from data input to final report—in four months. Initial priorities are to establish a refined set of input data files for program SPILL, and to identify alternative leasing and transportation scenarios. As program SPILL requires a substantial amount of computer time, every effort is made to find and correct errors in the data submitted to SPILL before the latter is executed. Trajectory test runs help to spot data errors and to identify a satisfactory set of launch points for potential spills. Program SPILL produces nothing more than a disk file containing the outcome of each Monte Carlo trajectory run, which subsequent programs use to generate conditional probabilities. The latter are combined with leasing and transportation scenarios to determine overall probabilities.

The different stages of model development for a typical sale may produce as many as 50 files. All of these are saved on disk, so that the analysis can be restarted at any intermediate point. Printouts associated with creating these files serve a valuable function in quality control, and help to document the progress of a model run.

SOFTWARE

There are 21 computer programs used in the present version of the model, all written in IBM FORTRAN IV, Level H. An extensive library of subroutines and functions (written in either assembly language or FORTRAN), in addition to the system libraries, is also em-

TABLE 10.—*Expected number of oilspill contacts with coastal and marine resources in six Federal lease areas*

[*, less than 0.01; —, not evaluated]

Lease area	High density resort & recreation areas	Commercial fish, shellfish areas	Wildlife refuges, sanctuaries	Critical waterfowl, seabird habitat	Marine mammal concentrating areas	Critical habitat of rare or endangered species.
Contacts during production life						
North Atlantic	1.0	1.38	0.43	0.75	0.1	0.17
Mid-Atlantic						
Existing	.02	.08	.12	.15	.01	.10
Proposed	*	.01	.02	.02	*	.01
South Atlantic	1.4	1.45	.08	.08	.03	.03
Eastern Gulf of Mexico						
Existing	.92	4.75	2.64	.56	*	1.14
Proposed	.06	.24	0.10	.02	*	.08
Southern California						
Existing	1.9	7.0	5.7	3.00	2.66	3.91
Proposed	1.1	3.6	3.0	1.45	1.43	1.97
Gulf of Alaska	—	5.5	0.45	6.62	7.5	—
Contacts per billion barrels of oil produced						
North Atlantic	1.9	2.76	0.86	1.5	0.2	0.35
Mid-Atlantic						
Existing	.03	.10	.15	.19	.06	.13
Proposed	*	.07	.13	.13	*	.07
South Atlantic	2.1	2.18	.12	.12	.05	.05
Eastern Gulf of Mexico						
Existing	.51	2.63	1.46	.31	*	.63
Proposed	.91	3.53	1.47	.29	*	1.23
Southern California						
Existing	1.4	5.3	4.3	2.26	2.01	2.95
Proposed	1.5	5.0	4.2	2.03	2.00	2.75
Gulf of Alaska	—	3.5	.29	4.27	4.8	—

ployed. Proprietary, commercially available subroutine packages are used to control the plotting equipment.

Many of the 21 programs involve relatively straightforward processing of digitized raw data. The output from the present digitizing equipment used by the model requires considerable programmer intervention to correct both human and machine errors. In addition, the raw data do not always arrive in a standard format and often need manipulations such as map projection transformations. Therefore, the "front end" programs of the model are usually recompiled, with the necessary modifications, for each individual run. Complete, formal documentation is obviously difficult to achieve under these circumstances and is not expected to be completed until planned improvements in digitizing equipment are accomplished

The remaining programs of the model, including such major programs as WINDTRAN, SPILL, and NU, are stored on a disk in a partitioned data set. Their operation is controlled by catalogued procedures, and extensive checks and interlocks help to ensure correct usage. Although design improvements still result in program changes, careful documentation is maintained for this group of programs.

HARDWARE

The computer hardware requirements for a model this size are substantial. The model is designed to be run on an IBM System/370, Model 155 computer. (The U.S. Geological Survey National Center in Reston, Virginia, has three such computer systems.) Eight hundred kilobytes (800K) of core storage is required for the largest program, although most of the programs need less than 200 kilobytes. All of the model's files are designed to be stored on a dedicated, on-line 3330 disk-storage unit; about 2,000 tracks are required for each OCS lease sale analysis. Tape drives, a plotter, and a digitizer are also required for full operation of the model. When using the model to its full capability, an analysis for an OCS lease sale can require a total of up to 12 hours of CPU time, although no single program is designed to run for more than 30 minutes of CPU time.

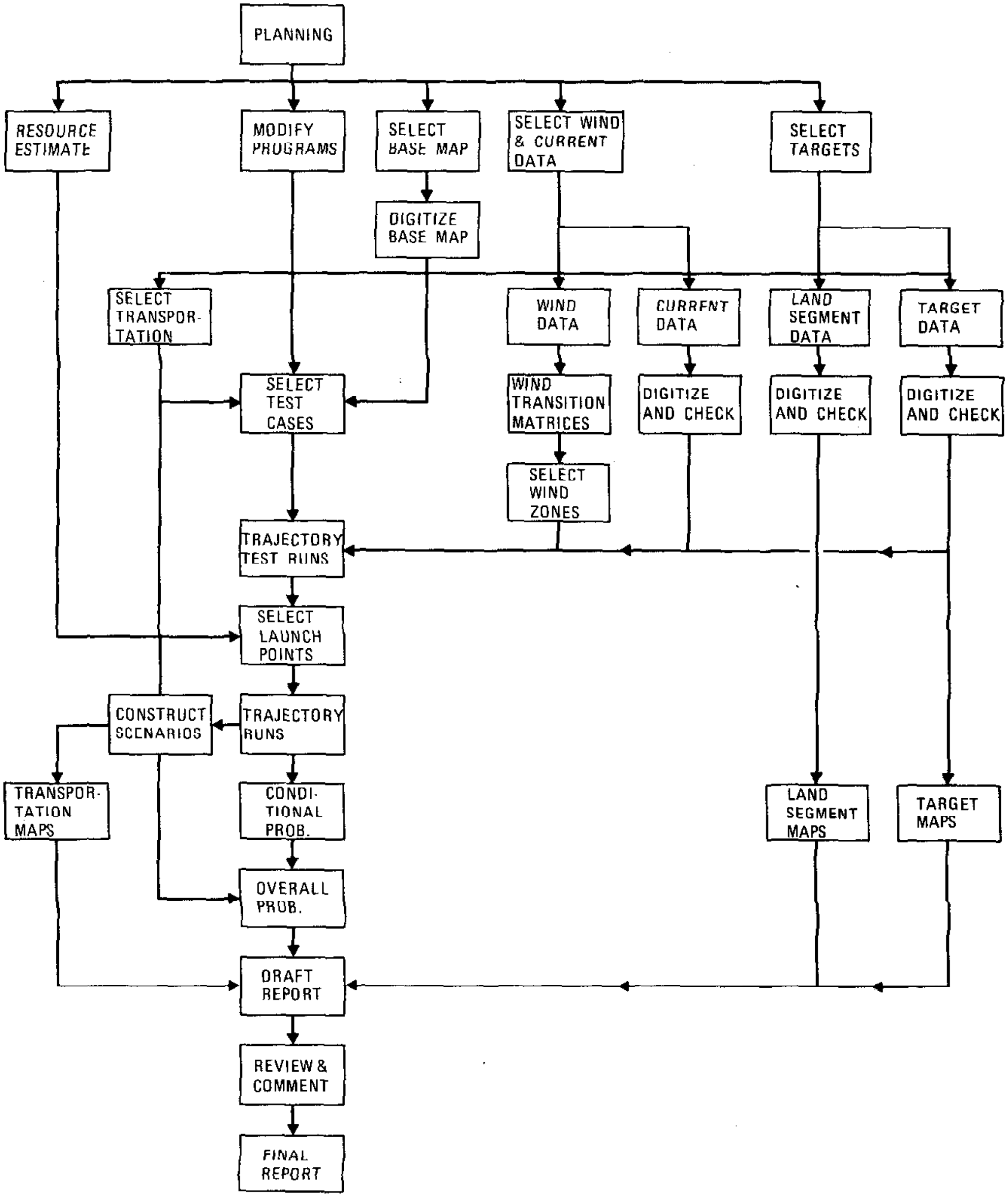

FIGURE 13.—Flow chart illustrating the major elements of a complete model run.

Programs requiring a longer time are broken into several jobs and the output files are concatenated. Some programs, particularly program SPILL, are capable of placing a noticeable strain on computer center operations, and are usually scheduled for execution at off-peak hours.

SELECTED REFERENCES

Allen, J., and Thanarajah, J. C. M., 1977, Laboratory studies of the velocity of wind on the movement of oil slicks: *in* Journal of Hydraulic Research, v. 15, no. 4.

Blummer, M., Sonza, S., and Sass, J., 1970, Hydro- carbon pollution of edible shellfish by an oil spill: Marine Biology International Journal on Life in Oceans and Coastal Waters, v. 5, no. 3, p. 195-202.

Box, G. E. P., and Tiao, G. C., 1973, Bayesian inference in statistical analysis: Reading, Massachusetts, Addison Wesley Publishing Company, 588 p.

Conrad, J. M., 1977, Oil spills: The policy of prevention and the strategy of recovery: Water Resources Research Center, University of Massachusetts, Amherst, Publication No. 93.

Csanady, G. T., 1973, Turbulent diffusion in the environment: Boston, D. Reidel Publishing Co., Geophysics and Astrophysics Monographs, v. 3.

Danenberger, E. P., 1976, Oil spills, 1971-75, Gulf of Mexico Outer Continental Shelf: U.S. Geological Survey Circular 741, 47 p.

Devanney, J. W., III, and Stewart, R. J., 1974, Analysis of oilspill statistics: Report to Council on Environmental Quality, Washington D.C., 126 p.

Draper, N. R., and Smith, H., 1966, Applied regression analysis: New York, John Wiley, 407 p.

Feller, William, 1966, An introduction to probability theory and its applications: New York, John Wiley, 461 p.

Grose, P. L., and Mattson, J. S. eds., 1977, The Argo Merchant Oilspill; A Preliminary Scientific Report: NOAA

Jeffery, P. G., 1973, Large-scale experiment on the spreading of oil at sea and its disappearance by natural forces, *in* Proceedings of Conference on Prevention and Control of Oil Spills (1973): p. 469-474.

Kirwan, A. D., Jr., McNally, G., Pazan, S., and Wert, R., 1979, Analysis of surface current response to wind: *in* Journal of Physical Oceanography, American Meterological Society, v. 9, no. 2.

Murray, S. P., Smith, W. G., and Shaw, C. J., 1970, Oceanographic observations and theoretical analysis of oil slicks during the Chevron spill, March 1970: Coastal Studies Institute, Louisiana State University, Baton Rouge, Louisiana, Technical Report no. 87.

Murty, T. S., and Khandekar, M. L., 1973, Simulation of movement of oil slicks in the Strait of Georgia using simple atmospheric and ocean dynamics: *in* Proceedings of the 1973 Conference on the Prevention and Control of Oil Spills.

Nelson, W. L., 1958, Petroleum refinery engineering, New York, McGraw-Hill.

Offshore Oil Task Group, 1973, The Georges Bank petroleum study, v. II: Massachusetts Institute of Technology Sea Grant Report, 311 p.

Phillips, C. R., and Groseva, V. M., 1977, The spreading of crude oil spills across a lake: *in* Water, Air, and Soil Pollution, v. 8, no. 3, p. 353-360.

Pollack, A. M., and Stolzenbach, K. D., 1978, Crisis science: investigations in response to the Argo Merchant oilspill: Massachusetts Institute of Technology, Cambridge, Massachusetts.

Royer, T. R., 1979, Personal communication to D. Amstutz, U.S. Bureau of Land Management, March 23, 1979.

Slack, J. R., and Smith, R. A., 1976, An oilspill risk analysis for the South Atlantic Outer Continental Shelf lease area: U.S. Geological Survey Open-File Report 76-653, 54 p.

Slack, J. R., Smith, R. A., and Wyant, Timothy, 1977, An oilspill risk analysis for the Western Gulf of Alaska (Kodiak Island) Outer Continental Shelf lease area: U.S. Geological Survey Open-File Report 77-212.

Slack, J. R., and Wyant, Timothy, 1978, An oilspill risk analysis for the Mid-Atlantic (Proposed Sale 49) Outer Continental Shelf lease area: U.S. Geological Survey Open-File Report 78-56.

Slack, J. R. Wyant, Timothy, and Lanfear, K. J., 1978, An oilspill risk analysis for the Southern California (Proposed Sale 48) Outer Continental Shelf lease area: U.S. Geological Survey Open-File Report 78-80.

Smith, J. E., ed., 1968, Torrey Canyon pollution and marine life: Cambridge University Press, Cambridge, United Kingdom.

Smith, R. A., Slack, J. R., and Davis, R. K., 1976a, An oilspill risk analysis for the Mid-Atlantic Outer Continental Shelf lease area: U.S. Geological Survey Open-File Report 76-451, 24 p.

Smith, R. A., Slack, J. R., and Davis, R. K., 1976b, An oilspill risk analysis for the North Atlantic Outer Continental Shelf lease area: U.S. Geological Survey Open-File Report 76-620, 50 p.

Stewart, R. J., 1975, Oil spillage associated with the development of offshore petroleum resources, in Report to Organization for Economic Co-operation and Development, 49 p.

Stewart, R. J., 1976, A survey and critical review of U.S. oil spill data resources with application to the tanker/pipeline controversy: Report to U.S. Department of the Interior, Washington D.C., 69 p.

Stewart, R. J., and Kennedy, M. B., 1978, An analysis of U.S. tanker and offshore petroleum production oil spillage through 1975: Report to Office of Policy Analysis, U.S. Department of the Interior, Contract Number 14-01-0001- 2193.

Stolzenbach, K.D., Madsen, O.S., Adams, E.E., Pollack, A.M., and Cooper, C. K., 1977, A review and evaluation of basic techniques for predicting the behavior of surface oil slicks: Ralph M. Parsons Laboratory, Report no. 222.

U.S. Department of the Interior, Bureau of Land Management, 1977, Proposed 1977 Outer Continental Shelf oil and gas lease sale in the Western Gulf of Alaska: (OCS Draft Environmental Impact Statement), 4 volumes.

Wardley-Smith, J., ed., 1976, The control of oil pollution on the sea and inland waters, Graham and Trotman, Ltd., United Kingdom, 251 p.

Wyant, Timothy, and Slack, J. R., 1978, An oilspill risk analysis for the Eastern Gulf of Mexico (Proposed Sale 65) Outer Continental Shelf lease area: U.S. Geological Survey Open-File Report 78-132.

Wyant, Timothy, and Smith, R. A., 1978, Risk forecasting for the Argo Merchant spill: *in* Proceedings of a Symposium held January 11-13, 1978, at the Center for Ocean Management Studies, University of Rhode Island, p. 28.

Zilitinkevich, S. S., 1978, An evaluation of the oceanic surface drift current speed and direction: *in* Boundary-Layer Methodology, v. 14, no. 1.