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AN ASSAY OF THE MARINE RESOURCES OF MASSACHUSETTS BAY

by

J. B. Lassiter III

J. E. Soden

R. J. Powers

Massachusetts Institute of Technology

Cambridge, Massachusetts 02139

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Administrative Statement

The authors have developed this background material for those interested in the potential conflicts between offshore aggregate extraction and fisheries management. It is not intended as a definitive study of the issues which surround the debate on offshore mining. Rather, this report develops techniques for estimating marine sand and gravel resources and presents a method for identifying and evaluating usage interactions between mining and fishing in the western portions of Massachusetts Bay.

Funds for this research project and the report came in part from the NOAA Office of Sea Grant, U.S. Department of Commerce, on Grant No. NG-43-72; from the Commonwealth of Massachusetts; from the Henry L. and Grace Doherty Charitable Foundation, Incorporated; and from the Massachusetts Institute of Technology.

Ira Dyer
Director

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PREFACE

This report is in two sections. The first section deals with estimation techniques for and comparisons of sand/gravel resources along the western margin of Massachusetts Bay. This work is described in a reprint of the authors' work presented at the 1974 Offshore Technology Conference (OTC 2055). In accord with Sea Grant policy, this print is being used as a summary of the work in the area. The authors are indebted to a number of people for this section of the report: R. J. Blumberg, Director, Division of Mineral Resources for the Commonwealth of Massachusetts, Drs. J. Schlee and J. Hathaway of the United States Geological Survey, and L. Goodier of Arthur D. Little, Incorporated, to name only the most patient.

The second part of the report offers overlays of aggregate and fisheries resources. This is simply provided for general information. This was made possible by Ned Shenton of The Research Institute of the Gulf of Maine, Incorporated (TRIGOM), Portland, Maine, who provided extensive assistance to the authors. The authors were unable to find any comparable source of useable information.

SECTION I

An Assay of Marine Mineral Resources in Massachusetts Bay

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Dallas, Texas 75206

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An Assay of Marine Mineral Resources in Massachusetts Bay

By

J. B. Lassiter, James E. Soden, and Robert Powers, M.I.T.

Abstract

A probabilistic model for estimating the volume of sand and gravel resources in an offshore area has been developed. This model has been applied to the analysis of core and grab sample data taken along the western margin of Massachusetts Bay. Through the use of Bayesian and classical statistical techniques, expected volumes of sand and gravel have been calculated for specified subdivisions of the western Massachusetts Bay offshore area. These probabilistic estimates are compared with other available estimates for the region. Problems and prospects in applying this type of modeling to offshore mining are discussed.

Introduction

For some years, proponents of operations research have proposed the use of probabilistic modeling in the exploration for and development of mineral resources. These techniques have met with some limited success in both the petroleum and hard rock mining industries. However, the most widely used method for estimating the volume of extractable resource associated with a specific deposit is what we might call the "educated trapezoidal rule". In other words, the geologist and mining engineer gather the available data, delineate the deposit, estimate the spatial distribution in grading, and then calculate the implied volume of extractable resource as a function of market price. The "educated trapezoidal rule" is the implicit application of the subjective judgment of the people involved coupled with the objective information available. In this paper, we will develop a probabilistic model for determining the volume of economically extractable sand and gravel from an offshore region. We will apply this model to a relatively well-known offshore region and compare the model estimates with those from other available sources. In doing this, we will not attempt a complete economic analysis, but rather will restrict ourselves to the first question which the geologist must answer, namely: how much recoverable sand and gravel of a specified grade is located in a specific area?

In the development of the model, the western margin of Massachusetts Bay was chosen as an offshore region which could serve as the baseline

References and illustrations at end of paper

against which model predictions could be measured. A number of individuals such as Emery (1965), Schlee (1968), and Manheim (1972) had pointed out the presence of significant sand and gravel deposits near major northeastern metropolitan areas, among them Boston. Extensive studies by the staffs of the Woods Hole Oceanographic Institution, the U.S. Geological Survey, the U.S. Army Corps of Engineers and the Division of Mineral Resources of the Commonwealth of Massachusetts had resulted in a large amount of physical and subjective data with which to compare our model. In addition, the prospect of a New England Offshore Mining and Environmental Study (NOMES) in the area had incited considerable public debate on the topic of sand and gravel deposits in western Massachusetts Bay. With these factors in mind, we chose this area for our comparative baseline.

Model development and assumptions

Three types of data are typically used in determining the nature and extent of offshore sand and gravel deposits. These are surficial sediment grab samples, shallow core samples and acoustic profiling records. These data may, on occasion, be augmented by photographic evidence, occasional offshore drilling records, and inferential geological interpretations from adjacent regions. Thus, any predictive model must be designed so as to extract desired information from this data base. First we must recognize what each of these types of data offer us. The grab samples provide a two-dimensional survey of the region showing variations in surficial sediment composition. The shallow core samples show vertical variations in sediment composition and, taken in conjunction with grab samples, yield a three-dimensional survey. The acoustic profiles (coupled with considerable judgment) provide a systematic tool for interpreting between the widely dispersed core and grab samples. Seemingly, this is all the information we really need to know. We simply compute the volume integral over the three spatial dimensions subject to economic and dredging constraints. (Typically, these constraints take the form of minimum percentages of sand and gravel in the sediment, minimum veneer thickness which can be dredged, or a maximum limit on fines or cobble contamination.) This is the essence of the "educated trapezoidal rule". The difficulties lie in the practical problems facing the geologist. The grab and core samples are usually widely dispersed and are often sparse in the most interesting areas. The acoustic profiling records are often ambiguous even after detailed interpretation and may not be available for the areas where core samples have been taken. Finally, calculating the volume of extractable sand and gravel as a function of economic and technical constraints can pose prohibitive computational problems. In light of this, we propose the probabilistic model as a supplement to the "educated trapezoidal rule".

Based on the work of Devanney (1971) we offer the sand and gravel probability tree shown in Figure 1. This will be used to calculate expected sand and gravel volumes for comparison with baseline Massachusetts Bay surveys by the Raytheon Company (1972). Data from both Raytheon and the U.S. Geological Survey (Schlee et al., 1971, and Hathaway, 1971) has been used in our analysis. For the purposes of the model, we will simplify the number of geological occurrences to include four predominant types: bedrock outcroppings; glacial till; sand and gravel deposits; and silt and clay deposits. In other words, any grab sample will see one of the four occurrences listed above. These occurrences are purely definitional, particularly in the cases of sand/gravel and silt/clay deposits. Node A of Figure 1 accounts for the occurrence of both bedrock outcroppings and glacial till. These are considered to be unmineable. Node B in Figure 1 notes the occurrence of either sand/gravel or silt/clay in remaining surficial grab samples. Original inspiration for this simple subdivision came from an examination of Raytheon core analyses which indicated that high surficial silt/clay sample contents often implied high silt/clay contents at depth. On the basis of this observation, we assume a binomial model for the occurrence of sand/gravel or silt/clay. (In other words, either you have sand/gravel or you don't.) The coupling of the surficial sediment is accomplished beginning with nodes C-1 and C-2 of Figure 1. Here we postulate another binomial model where, given certain surficial sediments, there is a finite probability that there are no underlying sediments.

Nodes D-1 and D-2 extend this argument further. Assuming that sand and gravel deposits are present beneath the surficial sediment, there is a finite probability that the deposit is so contaminated with fines (silt/clay) as to render it economically useless. Estimates of fines cut-offs range from 5% to 20% by weight.

Assuming that sand and gravel are present, one asks how much is likely to be available for extraction. This is accomplished by determining from the core data and the acoustic profiles a mean core depth for all of those samples which have not been previously weeded out by the probability tree. By combining these mean core depths with surficial area and by folding the probability tree back to node A, expected volumes of economically extractable sand and gravel may be obtained for each area under study.

The task remaining for the closure of the model is to determine the probabilities associated with the nodes of Figure 1. We will use the core and grab samples coupled with subjective judgment in order to make the determination. This combination of experimental observations (samples) and subjective judgment (expert opinion) is the heart of Bayesian analysis. To a user of Bayesian analysis, anything about which he is uncertain is treated as a random variable, which may be represented by a probability distribution over the range of possible values that it can assume. In this case, we are uncertain of the probabilities that a particular core sample will indicate a given depth of economically extractable sand and gravel. It follows then that we may treat these probabilities as random variables capable of assuming any value between 0.0 and 1.0 and perform a Bayesian analysis to obtain the probability distributions on the unknowns--sediment type and sediment depth.

The binomial nodes of Figure 1 (A, B, C-1, C-2, D-1 and D-2) under the assumptions of our model may be represented as a binomial probability density function with a beta probability density function on the unknown parameter of the distribution--the probability that the sediment is of a certain type. Translated into slightly less forbidding terminology, the probability at node A denotes the presence of bedrock/till through a coin-flip-type distribution. Here we have stipulated that the material on the sea floor is either bedrock/till or it is not, no in-betweens being allowed. The binomial distribution (the coin-flip distribution) gives the probability of exactly x occurrences of bedrock in n separate grab samples covering the offshore region given that the probability of obtaining a particular sediment type on one sample is known. This is the same question as how many heads will appear in a given number of coin tosses. In the case of a coin, we can say that the probability of obtaining a head on a single flip is 0.50. Unfortunately, in the case of grab samples, we cannot so easily establish the probability that any given grab sample will indicate bedrock/till. Thus, we will treat this probability as a random variable capable of assuming any value between 0.0 and 1.0. The beta probability density function is convenient for representing such a random variable, and the mathematics for dealing with the beta distribution are well established (Devanney, 1971). Using the Bayes theorem, we can couple the binomial distribution with the beta distribution and obtain a reasonably simple formula for determining the probability that bedrock/till is present. This new composite probability function is extremely useful in that it allows us to incorporate prior opinion with experimental results. This is possible because the new distribution is a function not only of our present sample, but also of all previous samples. This process of observing and then combining is known as updating a Bayes prior. For example, our a priori or expert opinion might say that the probability of bedrock/till is highly peaked about some specific value, say 0.60. After observing 30 bedrock/till grab samples in 30 tries, the updated prior would be strongly influenced by the experimental results and might approach a value near 1.0. On the other hand, if our experimental results indicated that there were 18 bedrock/till indications in 30 tries, the updated prior would be essentially unchanged and would remain near 0.60. If we had no prior opinions as to the probability of bedrock/till indications on a given sample, the updated prior would be solely due to the experimental results. Thus, our final results for the binomial nodes of Figure 1 are a function

of both expert opinion and actual sample results.

Having established the procedure for handling the binomial nodes, the technique used in modeling sediment depth remains to be discussed. Sediment depth may vary from 0.0 ft to, in theory, infinity. Under the assumptions of our model, this may be represented by a gamma probability density function with a beta probability function on the unknown parameter of the distribution--the probability that a given depth occurs. Again, translating, the sediment thickness or depth may vary from 0.0 to some upper bound, say 10 ft. Unfortunately, the mathematics for dealing with the upper bound have not been developed, so we will have to approximate this by assuming that the sediment may be infinitely thick. The gamma probability density function is convenient for dealing with this problem and has been combined with a beta probability density function on the unknown parameter--the probability that a given core will indicate a given depth (Devanney and Stewart, 1973). By assigning a prior highly skewed towards depths less than 10 ft, we will assign very low probabilities to "infinitely deep core samples", which tends to obviate our current mathematical problem of not being able to handle a bounded distribution. With this theory behind us, the model is complete. For a more complete discussion, the reader is referred to Soden (1973).

Obviously, the model proposed contains a number of explicit and implicit assumptions. The more noticeable explicit assumptions deal with the use of the binomial and gamma probability functions to describe rather complex geological occurrences. While the use of the distributions appears well-grounded, their adoption must be treated as pure hypothesis subject to test by comparison with other data. During the development of the model, it became apparent that there were two implicit assumptions which required further study. These were the absence of a spatial relationship between core samples and the presence of a definite relationship between surficial samples and samples at depth. In Figure 2, we show the autocorrelations between one-mile groupings of core samples. This figure indicates that samples separated by more than one mile may be considered to be independent of one another. This is a necessary condition for the use of the techniques outlined in this paper. In Figure 3, we show the results of a test of the hypothesis that two populations of core samples, one with less than 60% silt/clay in the surficial portion and the other with more than 60%, have more than 50 in of sand and gravel beneath them in the first 10 ft. As can be seen, the test fails when all samples are considered. We have used this as an indication that it is extremely unlikely that areas whose surficial sediment contains in excess of 60% silt/clay will yield appreciable sand/gravel content at depth. Unfortunately, we were unable to say anything quantitative for areas whose surficial silt/clay content was less than 60%. For western Massachusetts Bay, we obtained 121 grab samples together with 45 core samples for an area of some 250 sq mi. With this limited number of core samples and the inability to directly couple surficial sediment concentrations with concentrations at depth, we were forced to give up a large degree of model resolution. Again, the degree to which this is limiting must be judged from comparison with other published estimates. While we did not attempt to make extensive use of acoustic profiling records, it would be possible to do so and to avoid at least part of this problem.

Model testing for Massachusetts Bay

In comparing the predictions of the probabilistic model with estimates from other available sources, it is necessary to establish the sensitivity of the model to three major types of variation:

1. The choice of areal subdivisions
2. The inclusion of a priori expert opinion
3. The choice of economic cutoffs due to deposit thickness and deposit fines content.

Figures 4, 5, 6, and 7 show the areal subdivisions investigated. Subdivisions were chosen based loosely on geological interpretations which indicated different geological regimes in Massachusetts Bay. All of these are subdivisions of the same area as covered by the Raytheon survey of Massachusetts Bay performed under contract with the Commonwealth of Massachusetts Division of Mineral Resources. The first three subdivisions are essentially arbitrarily

equal area blocks. The fourth subdivision groups the different geological regimes which could be identified from a survey of the Massachusetts Bay literature. We felt that this would provide a more realistic division representing the inclusion of expert opinion on our work. While the choice of finer and finer subdivisions is attractive from the point of view of including priors on the beta probability density functions, one pays the penalty of constantly diminishing samples per areal subdivision. Table 1 shows the comparison of the probabilistic model estimates with the Raytheon data. A survey of Table 1 shows several things. First, the variation in total volume is only weakly influenced by the choice of priors. This simply points out that on an aggregate scale the Bayes updating makes very good use of the available experimental results. Only in areas where samples are relatively limited in number will the choice of prior have any significant effect. (BYNTH1 is an example of such an area.) Other local discrepancies are due to the difficulty in accounting for minimum dredgeable depths. Investigation of the data has revealed that these discrepancies can be accounted for by placing minima as well as maxima on dredgeable depths. This has been confirmed in conversations with D. Sensibar of the Construction Aggregates Corporation. Some areas have the opposite problem in that the model predicts no sand and gravel while the Raytheon study has identified the presence of available deposits. (BYNTH2 is such an area.) This appears to be due to subjective interpretations of acoustic profiling and associated cores available to Raytheon. (Being Bayesians, the term subjective is never a slight.) Area BYCEN2, however, gives an indication of model results in a location where significant core sampling and grab sampling has taken place. We, given our data, simply cannot account for deposits which have not been cored or grabbed. Rather than assign a prior which would rectify this problem, we have chosen to present the untampered results. Variations in allowable fines content from 5% to 20% essentially double the estimates shown.

Conclusions

Tests of the predictive model have been carried out against baseline estimates accomplished by more conventional means. General agreement of results has been demonstrated, and the value of this modelling approach to determinations of offshore sand and gravel resources has been demonstrated by example. The authors do not believe that this type of an approach is a panacea for evaluating exploratory sampling programs. Rather, they see it as an alternative tool helpful in some cases where pre-existing data is available. The body of available operations research techniques has certainly not been fully applied in the extractive industries. It is our opinion that these techniques have been both oversold and poorly applied in many cases.

By way of a technical note, much of this type of modelling could be improved if a beta probability density function with a beta density prior in the unknown parameter--probability of occurrence of a given depth of deposit--could be developed. This would allow the calculation of an optimal sample size for a given area. (Optimal sample size may be here defined as that point at which obtaining a sample exceeds the benefits of the additional information gained.) The mathematical problems in both a numerical and theoretical sense are not trivial. However, it is our opinion that the work would be worthwhile.

Acknowledgements

The authors wish to acknowledge the support which they received through the MIT Sea Grant Program in the funding of this research as part of the Marine Resources Assay of Massachusetts Bay. In addition, Mr. R. C. Blumberg, Director of the Division of Mineral Resources of the Commonwealth of Massachusetts, Drs. J. Schlee and J. Hathaway of the U.S. Geological Survey, Mr. J. L. Goodier of Arthur D. Little, Dr. D. Duane of the U.S. Army Corps of Engineers, and Mr. C. F. Willet of the Raytheon Company were particularly helpful in providing access to and interpretation of data used in this study, as well as in discussions of offshore mining techniques. Additionally, the authors wish to thank the many others too numerous to mention whose advice and assistance contributed greatly to the success of this project.

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TABLE 1

VOLUME OF MINEABLE DEPOSITS

Total volume by subdivision
(in order of increasing definition of areas)

Area	Model Total (w/Priors) (yd^3)	Model Total (Data Only) (yd^3)	Raytheon Survey (yd^3)
Subdivision 1 (1 area)	2.19×10^8	2.09×10^8	1.96×10^8
Subdivision 2 (3 areas)	2.01×10^8	1.75×10^8	1.96×10^8
Subdivision 3 (10 areas)	1.40×10^8	1.50×10^8	1.96×10^8
Subdivision 4 (10 areas)	1.24×10^8	1.39×10^8	1.96×10^8
Volume of representative subareas			
BYNTH1	2.16×10^7	4.24×10^7	0
BYNTH2	0	0	$.10 \times 10^7$
BYCEN2	4.53×10^7	3.14×10^7	3.50×10^7

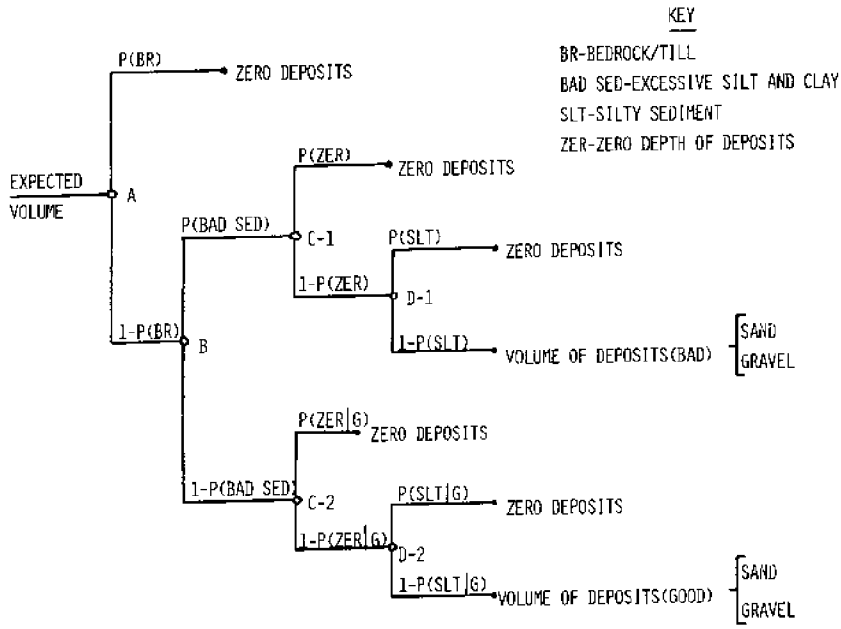

Fig. 1 - Sand and gravel probability tree.

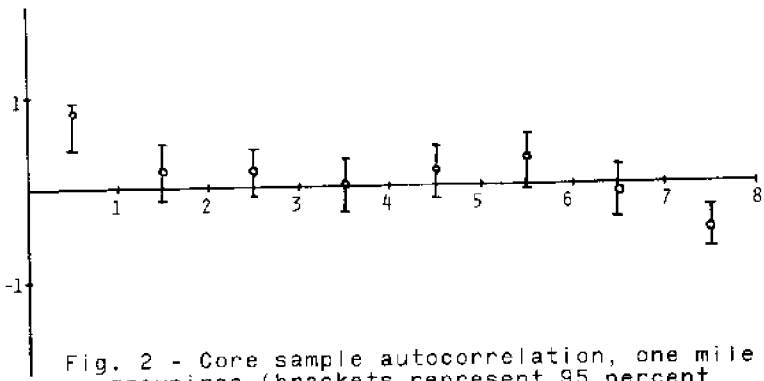

Fig. 2 - Core sample autocorrelation, one mile groupings (brackets represent 95 percent confidence groupings).

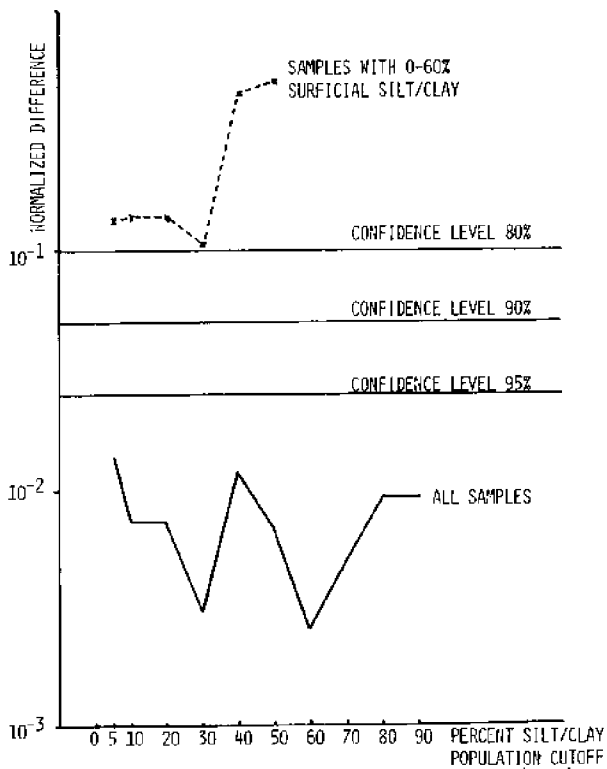

Fig. 3 - Proportion hypotheses test, 50 in. proportion cutoff.

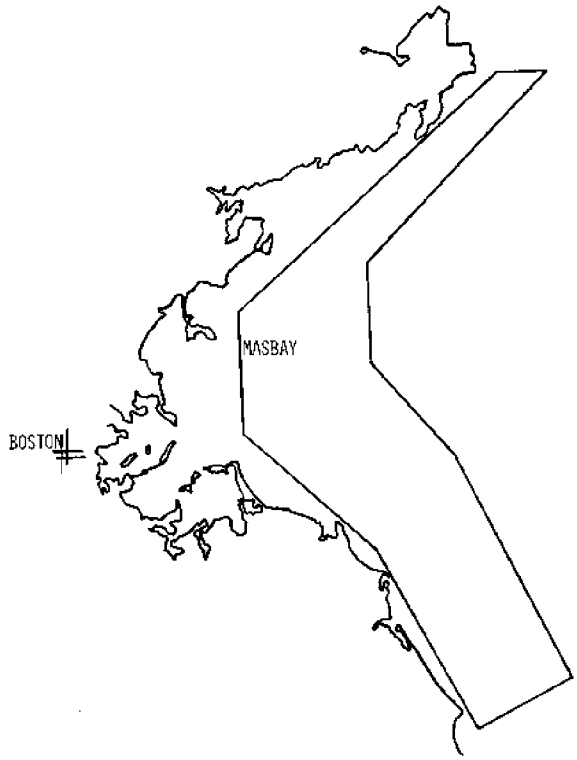

Fig. 4 - Areal subdivision one.

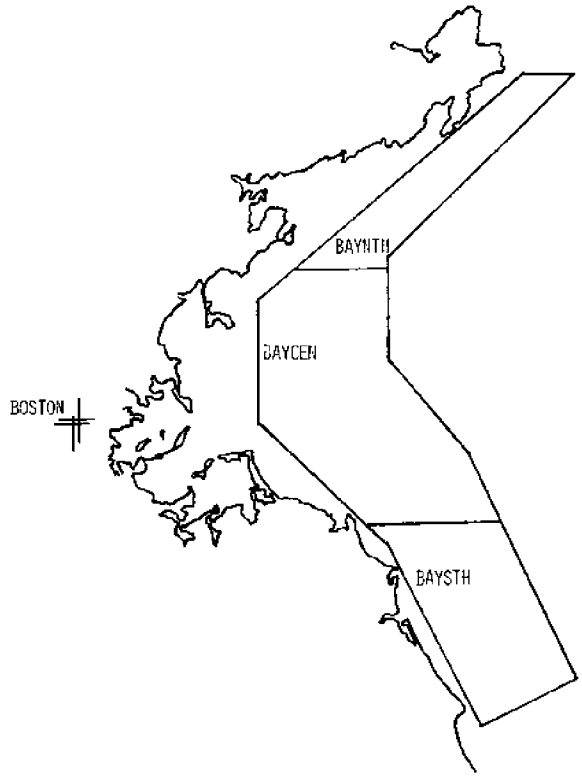

Fig. 5 - Areal subdivision two.

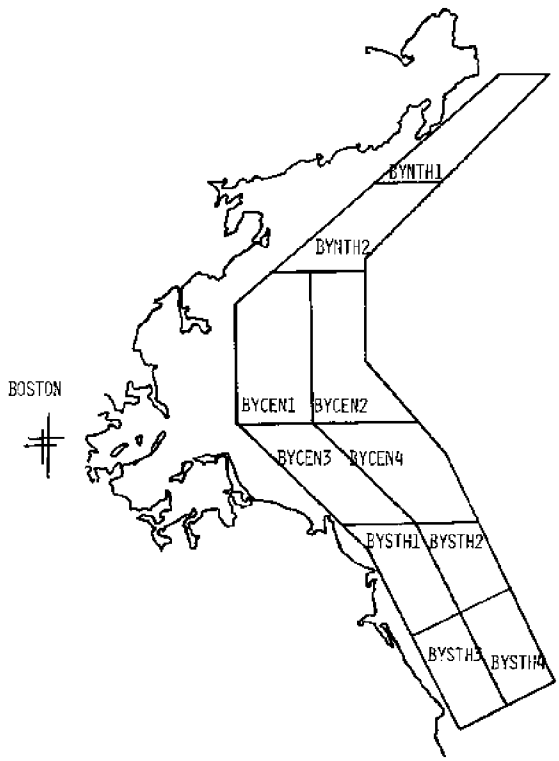

Fig. 6 - Areal subdivision three.

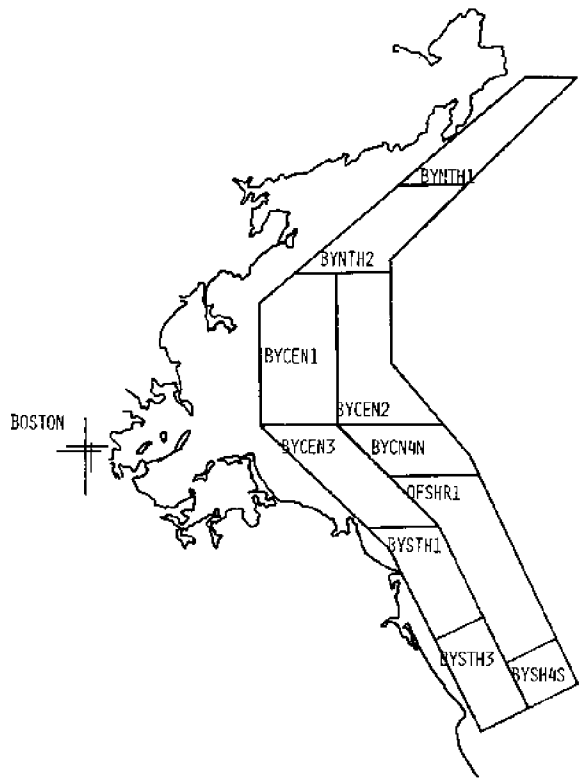

Fig. 7 - Areal subdivision four.

Section II

Aggregate and Fisheries Overlays for Massachusetts Bay

Use of the Offshore Aggregate/Species Overlays

Two basic forms of information are available in this section. The first of these is the volume of mineable aggregate deposits given by areal subdivision in Tables II-1 and II-2. Table II-1 assumes that no mineable deposit exists beneath surficial sediments containing in excess of 60% silt and/or clay and that no deposit having a silt and/or clay content in excess of 5% can be processed economically. Table II-2 follows the same pattern as Table II-1 except that the fines contamination is allowed to rise from 5% to 20%. As can be seen from comparing Tables II-1 and II-2, the sensitivity of mineable deposits to variations in fines contamination depends on the coarseness of areal subdivisions. On a very coarse grid (MASBAY--Areal Subdivision I), the mineable deposits increase by only a factor of two. On a very fine grid (BYSTH1--Areal Subdivision III), the mineable deposits increase by an order of magnitude. The reasons for this are straightforward and are discussed in Section I. Therefore, using Tables II-1 and II-2, the user can obtain several different estimates of the aggregate available for extraction from a specific offshore area.

The second form of information lies in the fisheries distribution, which we have redrawn with the kind permission of Mr. Ned Shenton of The Research Institute of the Gulf of Maine, Incorporated (TRIGOM). These figures show general distribution and average concentrations gathered

from numerous sources such as the National Marine Fisheries Service. Such information is by its very nature difficult to collect and to analyze. TRIGOM is to be contratulated for their efforts in supplying Figures II-1 through II-22. The species shown include cod, mackerel, butterfish, striped bass, tuna, silver hake, white hake, haddock, inshore halibut, redfish, pollack, winter flounder, yellowtail flounder, northern shrimp, surf clam, ocean quahog, sea scallop, alewife, bluefish, American plaice, American eel, smelt, shad, blueback, longhorn sculpin, little skate, and spiny dogfish. "General distribution" means that the species is known to frequent the area. "Catch per tow" may be treated as a measure of species concentration. Quantified catch data is too sparse to consider using at this time.

The volume of mineable deposits tables and the species distribution figures are joined together by using the areal subdivision overlays. For example, using the overlay for Areal Subdivision Three with Figure II-1, Cod Species Distribution, we can see that a major cod spawning area occupies areal subdivisions BYCEN2, BYCEN4, BYSTH2, and BYSTH4. We can also see that the adult species are well seaward of the potential mining areas. Referring then to the volumes of mineable deposit, Table II-1, we can see that at least 50% of the available reserves conflict with the cod spawning area (3.14×10^7 yds + 7.13×10^7 yds + 0 + 0 = 1.03×10^8 yds out of 2.09×10^8 yds total).

Unfortunately, sand/gravel bottoms make good hatcheries. Does this mean that mining should be prohibited? We have no definitive information which proves one way or the other how spawning and mining relate to one another.* We simply point out that someone had better check. A definitive study of the environmental effects of offshore mining is sorely needed. Delays in facing this problem will return to haunt us.

In closing, only after a careful analysis of the environmental effects of ocean mining has been performed, will we be able to address the basic issue--what are the costs (market and non-market) of offshore mining. This brief report is offered simply as a guide to those of us who don't have the resources to find the answers--but have the opportunity to raise the questions. We can expect these issues to continue to reappear. What are the costs? What are the alternatives?

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*It is possible that a mining operation far from the spawning area may still have incremental effects on a species. We just do not know.

Table II-1

Volume of Mineable Deposits as Determined by the Model

(60% Surficial Silt/Clay Break-off)
(5% By Volume Silt/Clay Break-off)

Area	Total (w/Priors)*	Total (No Priors)*	Raytheon Survey (yd^3)
MASBAY	2.19×10^8	2.09×10^8	1.96×10^8
BAYNTH	2.39×10^7	1.95×10^7	$.10 \times 10^7$
BAYCEN	1.65×10^8	1.47×10^8	1.51×10^8
BAYSTH	1.47×10^7	9.17×10^6	4.47×10^7
BYNTH1	2.16×10^7	4.24×10^7	0
BYNTH2	0	0	$.10 \times 10^7$
BYCEN1	0	0	6.93×10^7
BYCEN2	4.53×10^7	3.14×10^7	3.50×10^7
BYCEN3	0	0	1.16×10^7
BYCEN4	6.66×10^7	7.13×10^7	3.48×10^7
BYSTH1	6.47×10^6	5.03×10^6	0
BYSTH2	0	0	$.89 \times 10^7$
BYSTH3	0	0	$.47 \times 10^7$
BYSTH4	0	0	3.11×10^7
BYCN4N	5.09×10^7	5.99×10^7	2.06×10^7
OFSHR1	0	0	1.94×10^7
BYSH4S	0	0	3.48×10^7

Table II-1

(Continued)

Volume By Subdivision

(In Order of Increasing Definition of Areas)

Area	Total (w/Priors)	Total (No Priors)	Raytheon Survey (yd^3)
Subdivision 1 (1 area)	2.19×10^8	2.09×10^8	1.96×10^8
Subdivision 2 (3 areas)	2.01×10^8	1.75×10^8	1.96×10^8
Subdivision 3 (10 areas)	1.40×10^8	1.50×10^8	1.96×10^8
Subdivision 4 (10 areas)	1.24×10^8	1.39×10^8	1.96×10^8

*Priors are the quantitative assessment of the subjective judgment of an expert. A prior is expressed as a probability in Bayesian probability theory.

Table II-2

Volume of Mineable Deposits as Determined by the Model

(60% Surficial Silt/Clay Break-off)
(20% By Volume Silt/Clay Break-off)

Area	Total (w/Priors)*	Total (No Priors)*	Raytheon Survey (yd^3)
MASBAY	4.14×10^8	4.06×10^8	1.96×10^8
BAYNTH	2.39×10^7	1.95×10^7	$.10 \times 10^7$
BAYCEN	2.52×10^8	2.47×10^8	1.51×10^8
BAYSTH	9.23×10^7	8.66×10^7	4.47×10^7
BYNTH1	2.16×10^7	4.24×10^7	0
BYNTH2	0	0	$.10 \times 10^7$
BYCEN1	5.75×10^7	4.13×10^7	6.93×10^7
BYCEN2	8.34×10^7	8.67×10^7	3.50×10^7
BYCEN3	0	0	1.16×10^7
BYCEN4	6.66×10^7	7.13×10^7	3.48×10^7
BYSTH1	2.37×10^7	2.46×10^7	0
BYSTH2	0	0	$.89 \times 10^7$
BYSTH3	3.64×10^7	3.23×10^7	$.47 \times 10^7$
BYSTH4	0	0	3.11×10^7
BYCN4N	5.09×10^7	5.99×10^7	2.06×10^7
OFSHR1	0	0	1.94×10^7
BYSH4S	0	0	3.48×10^7

Table II-2

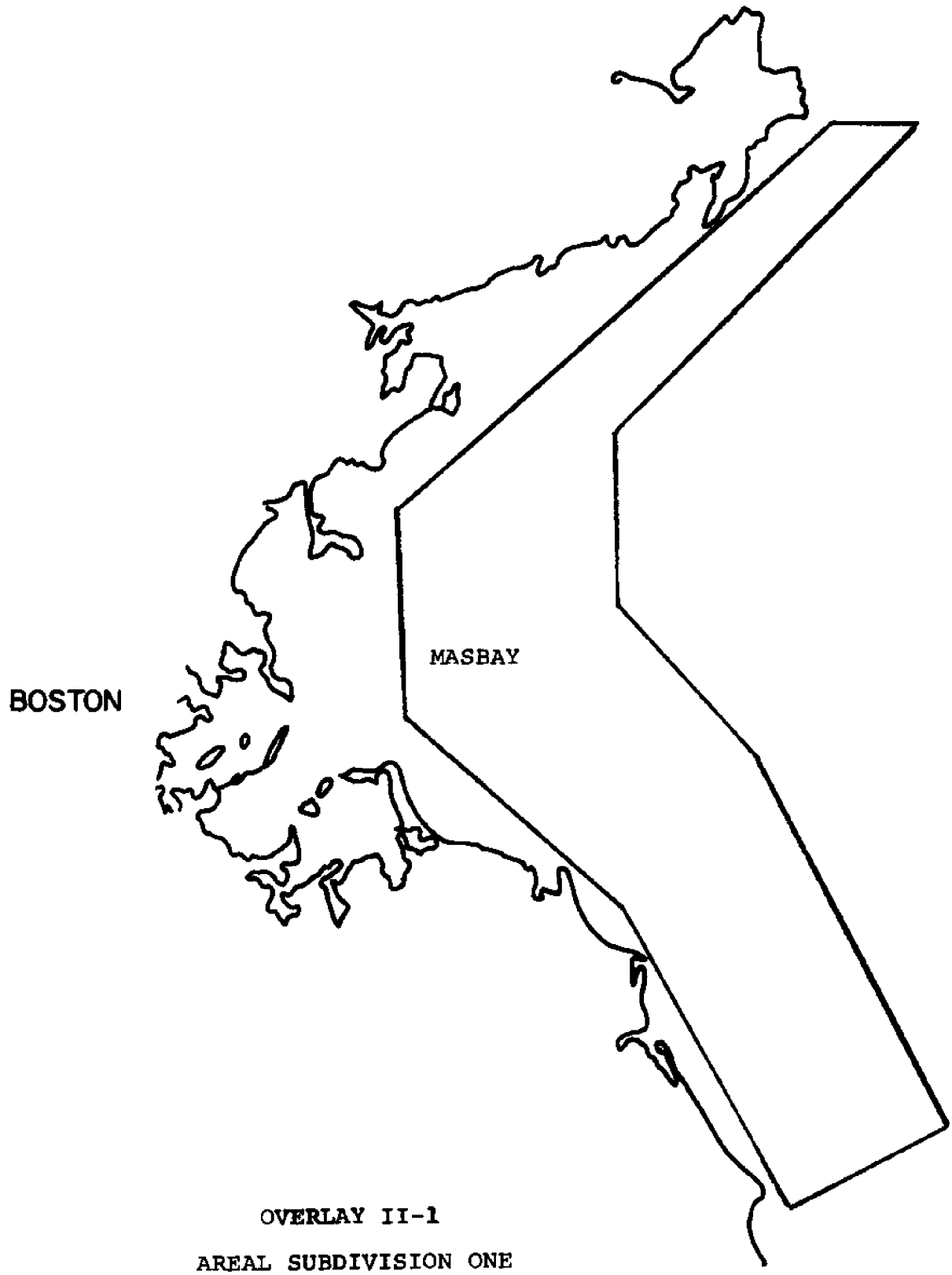
(Continued)

Volume By Subdivision

(In Order of Increasing Definition of Areas)

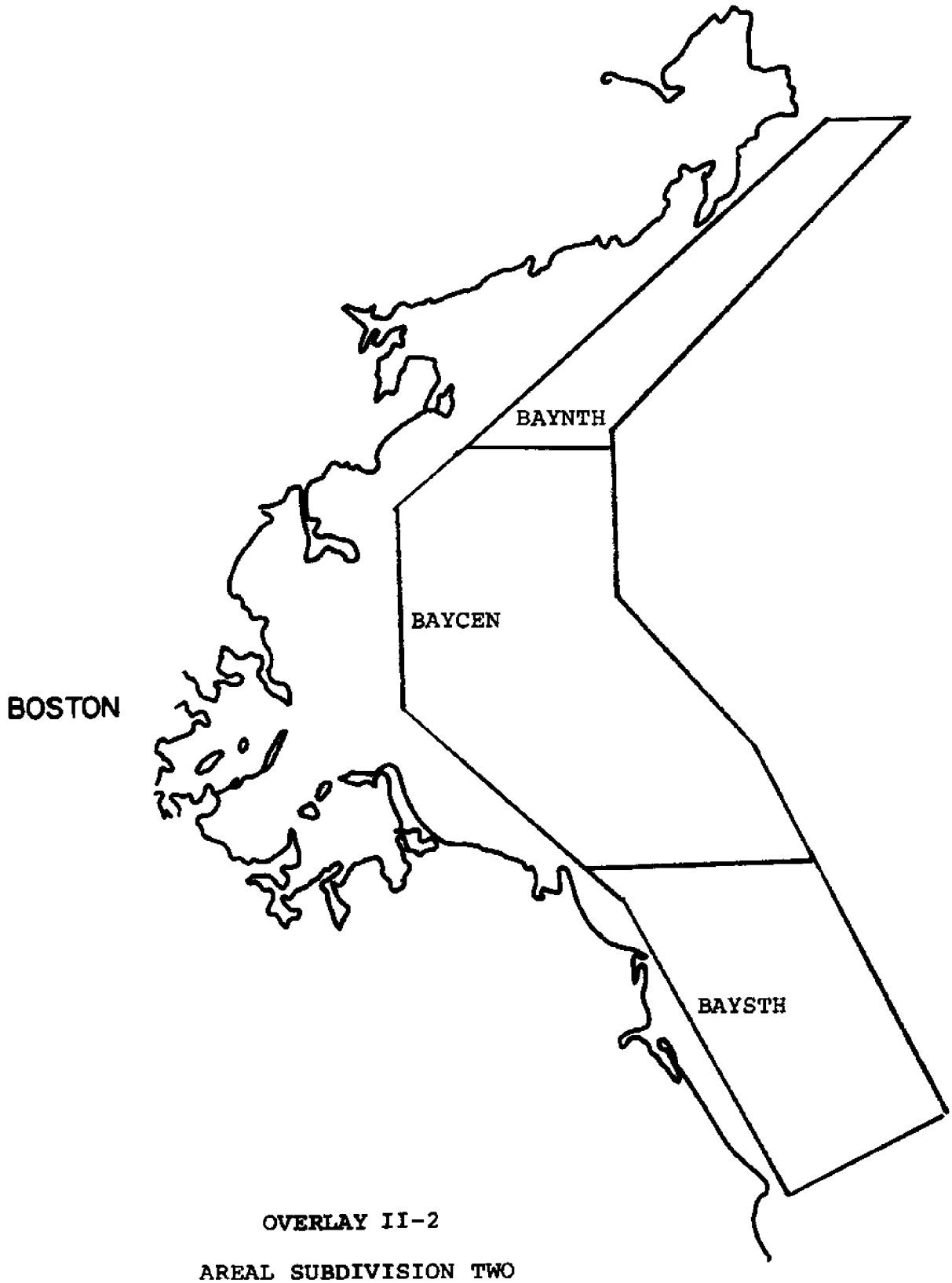
Area	Total (w/Priors)	Total (No Priors)	Raytheon Survey (yd^3)
Subdivision 1 (1 area)	4.14×10^8	4.06×10^8	1.96×10^8
Subdivision 2 (3 areas)	3.68×10^8	3.53×10^8	1.96×10^8
Subdivision 3 (10 areas)	2.89×10^8	2.99×10^8	1.96×10^8
Subdivision 4 (10 areas)	2.73×10^8	2.87×10^8	1.96×10^8

*Priors are the quantitative assessment of the subjective judgment of an expert. A prior is expressed as a probability in Bayesian probability theory.



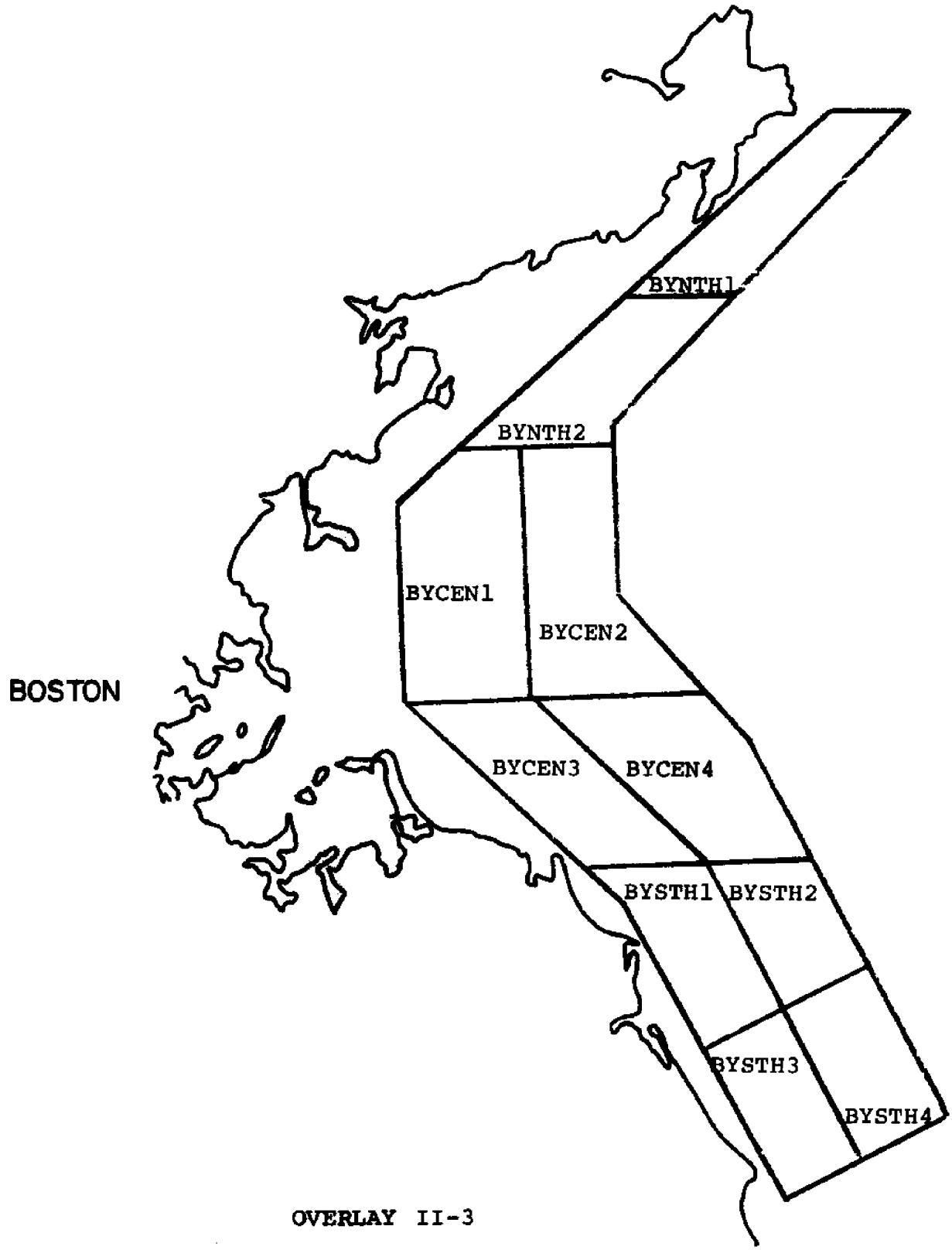
OVERLAY II-1

AREAL SUBDIVISION ONE



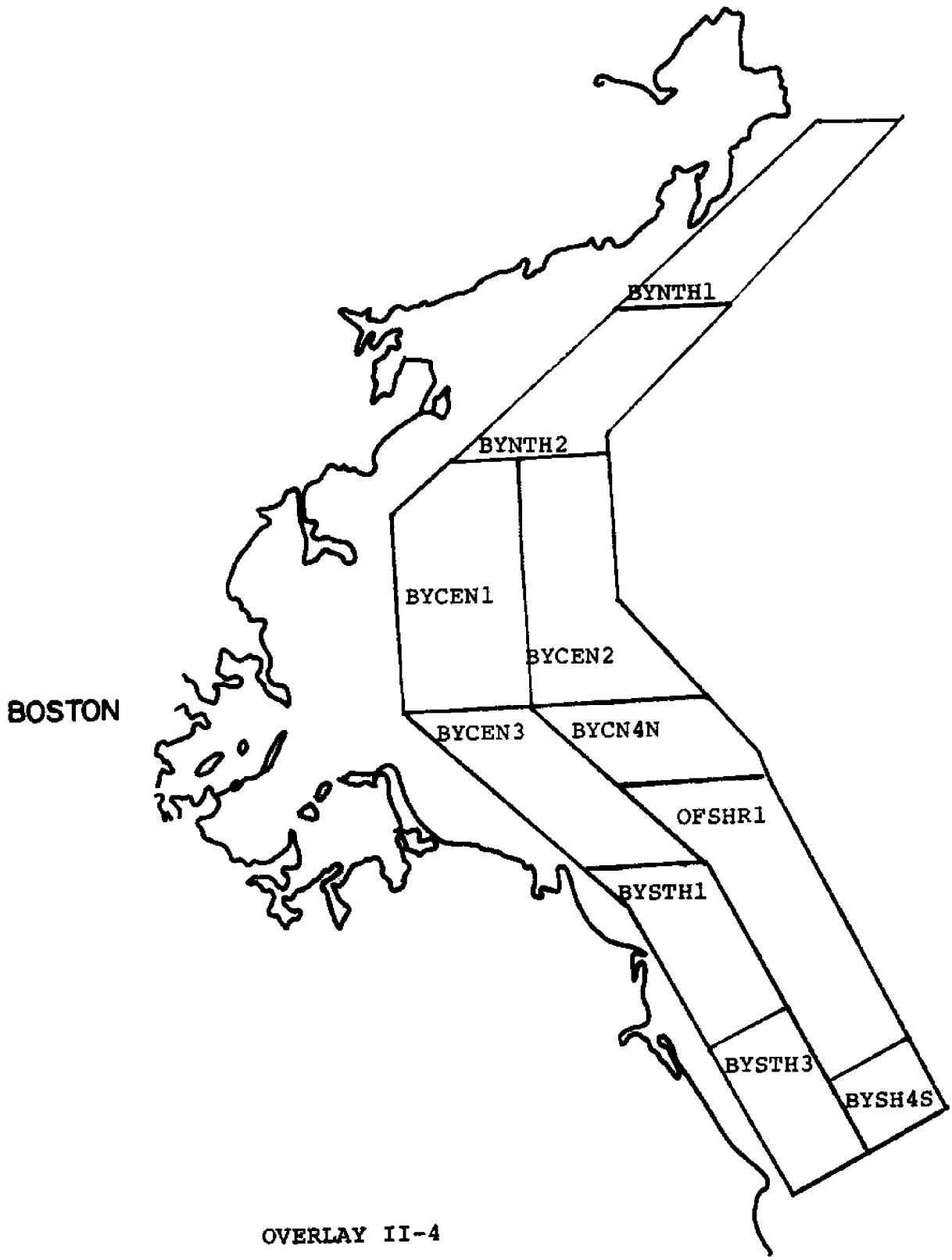
OVERLAY II-2

AREAL SUBDIVISION TWO



OVERLAY II-3

AREAL SUBDIVISION THREE



OVERLAY II-4

AREAL SUBDIVISION FOUR

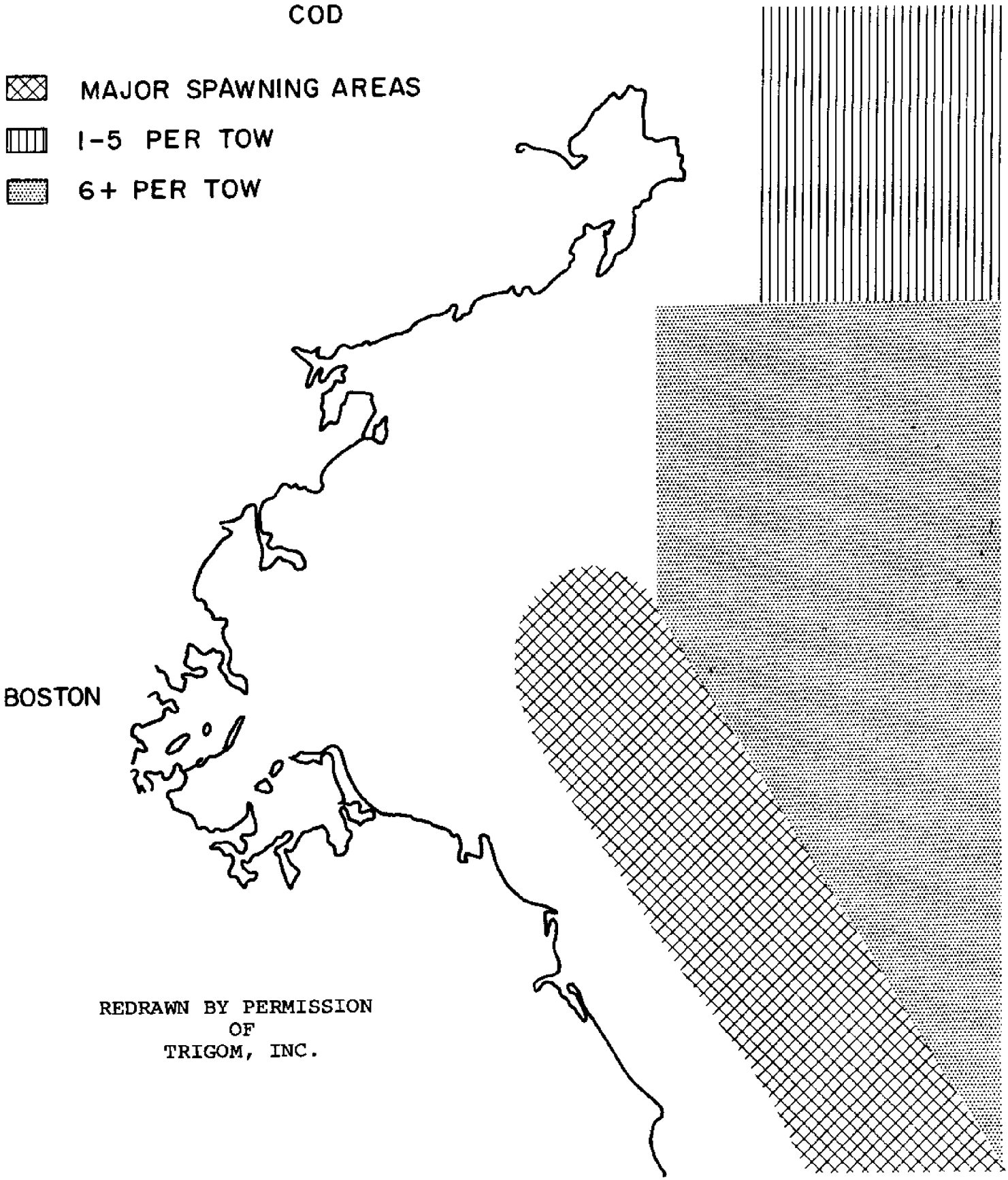
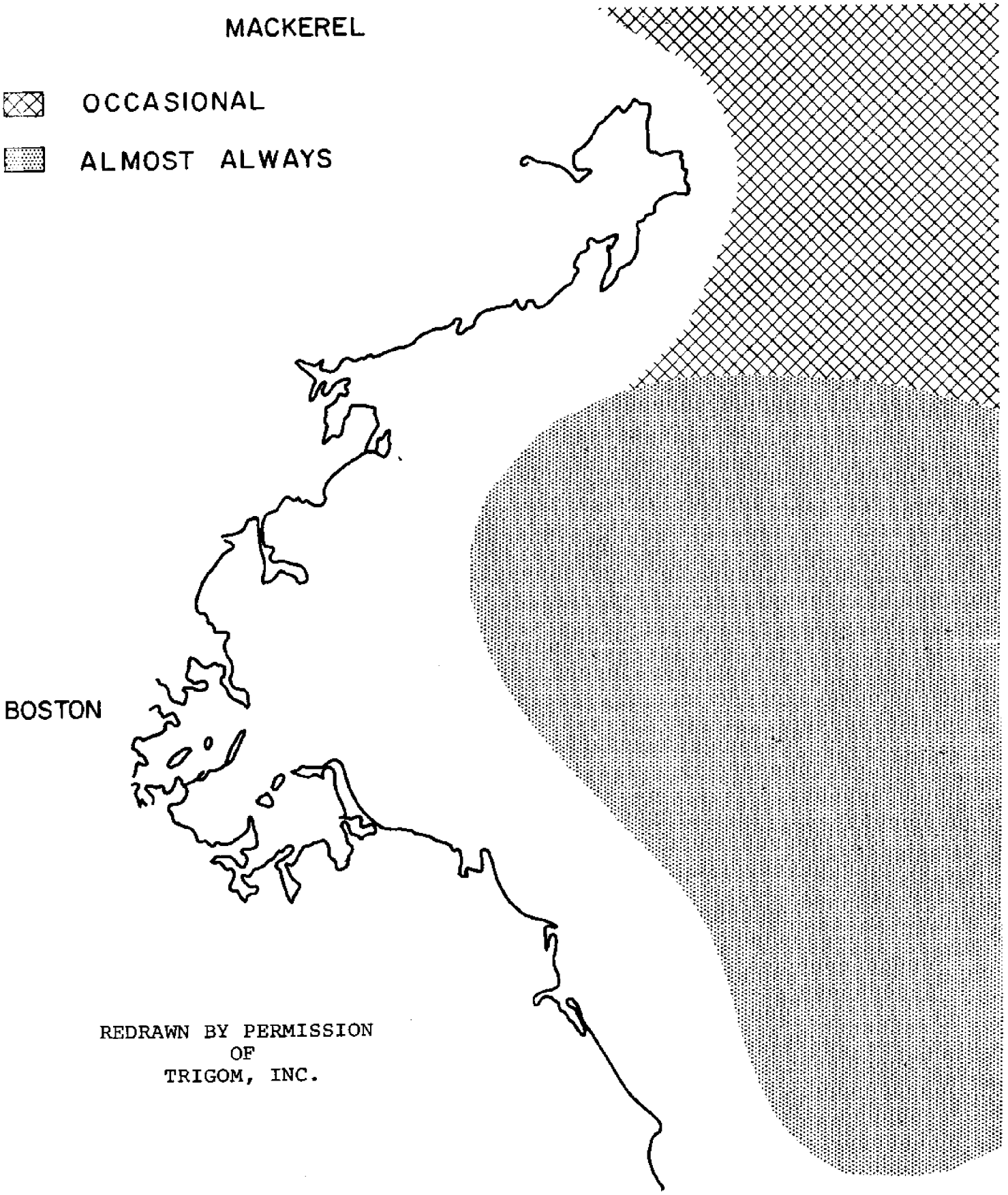
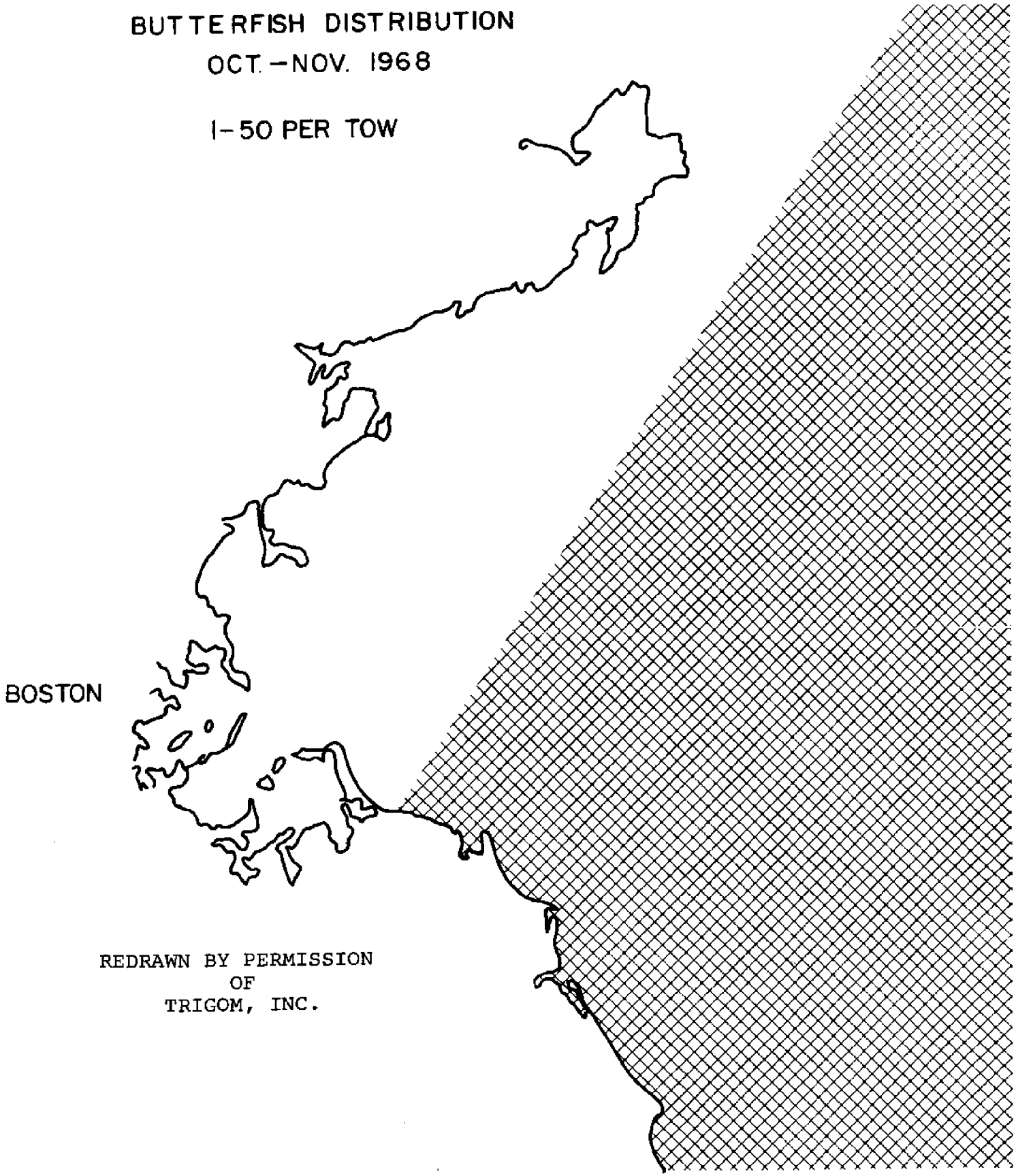

COD
MAJOR SPAWNING AREAS
1-5 PER TOW
6+ PER TOW
BOSTON
REDRAWN BY PERMISSION
OF
TRIGOM, INC.

FIGURE II-1



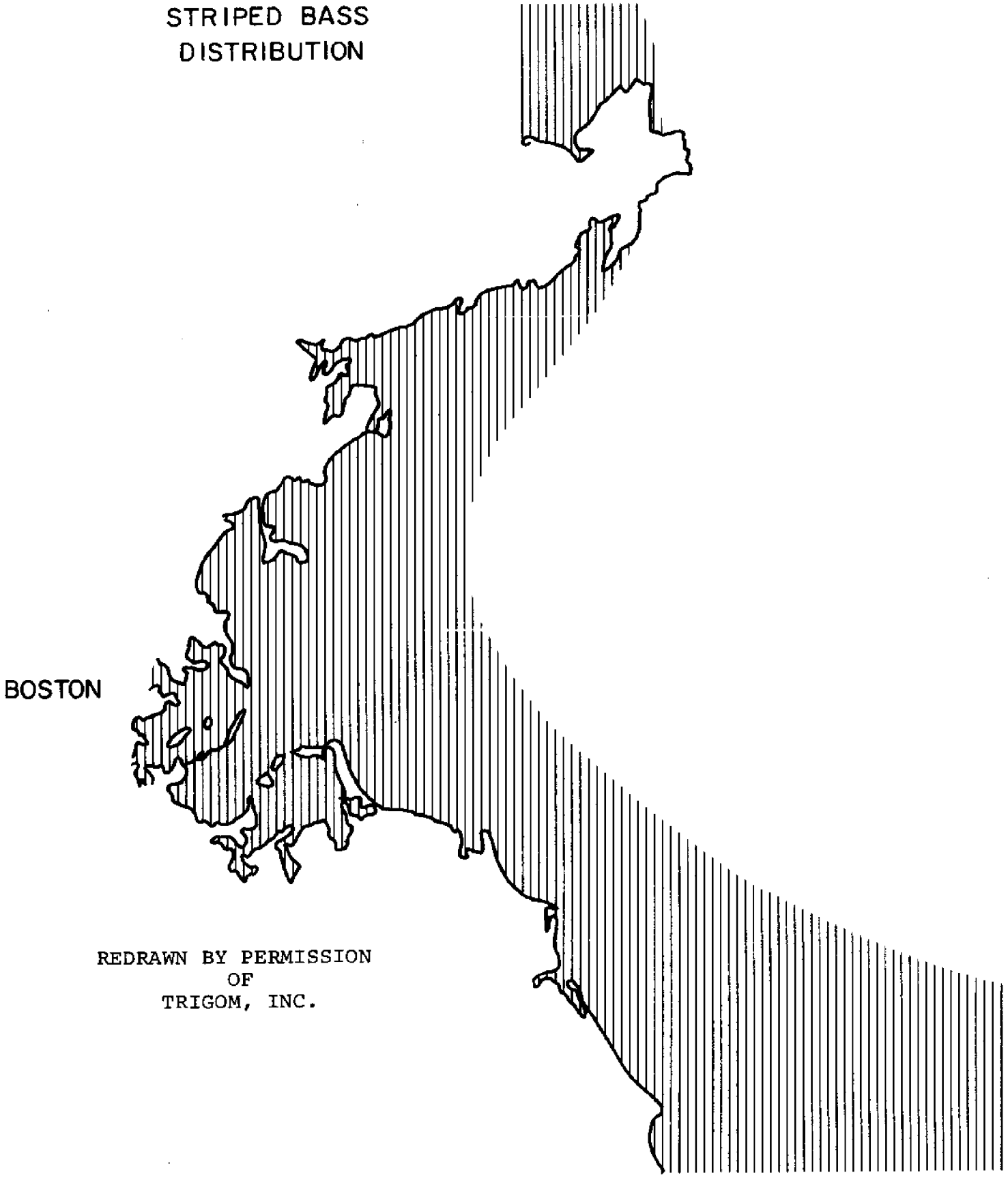
REDRAWN BY PERMISSION
OF
TRIGOM, INC.

FIGURE II-2



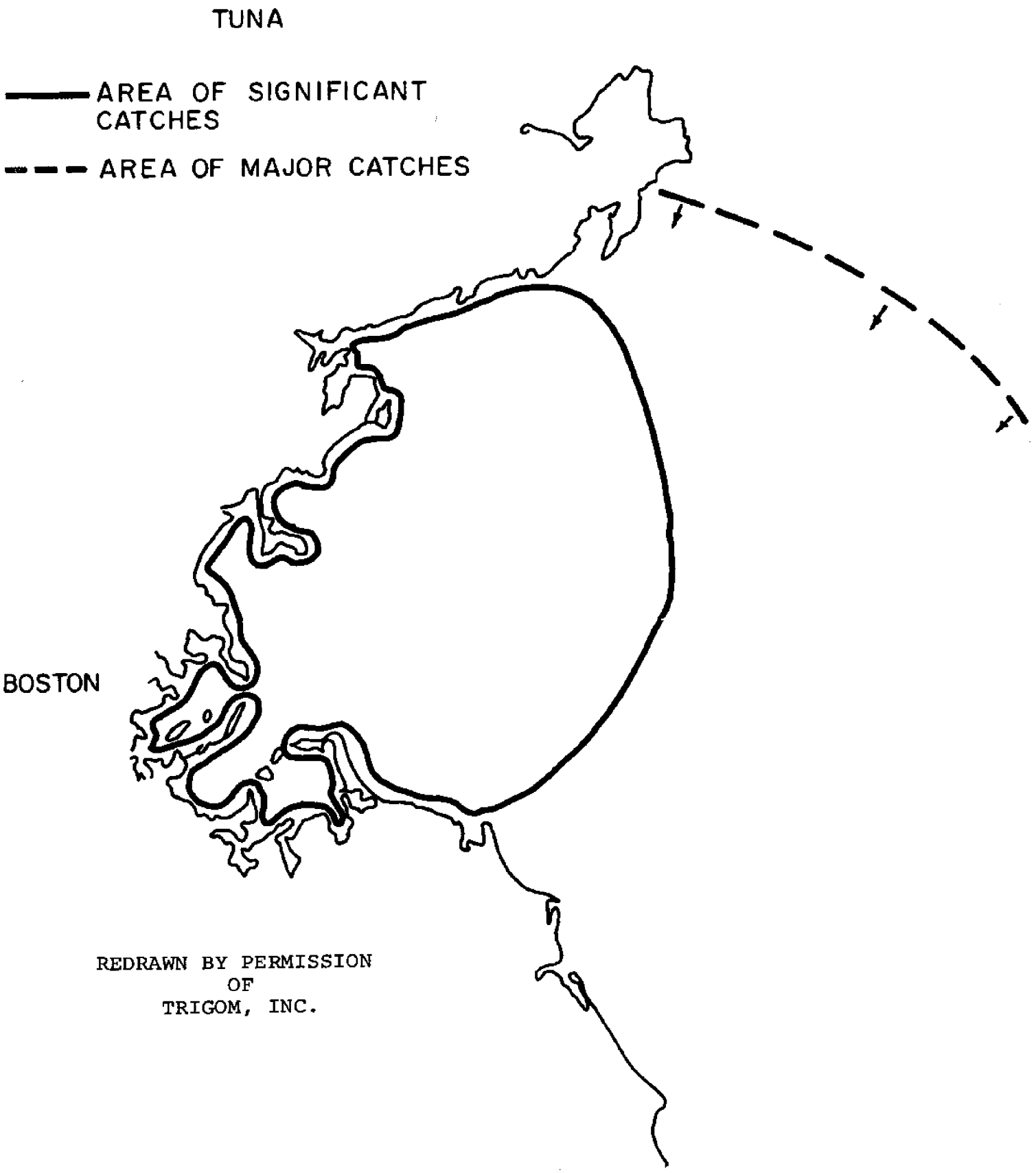
REDRAWN BY PERMISSION
OF
TRIGOM, INC.

FIGURE II-3



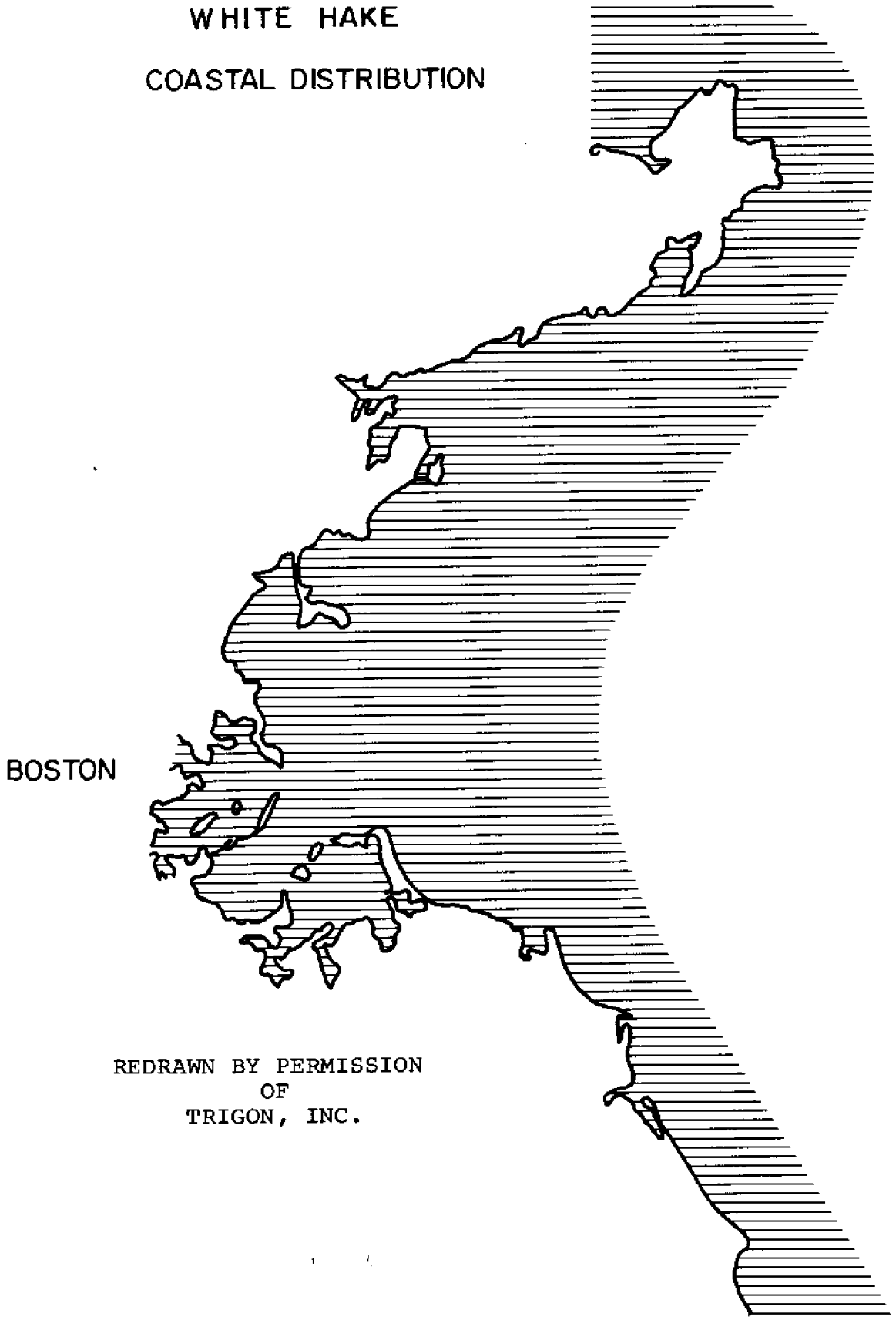
REDRAWN BY PERMISSION
OF
TRIGOM, INC.

FIGURE II-4



REDRAWN BY PERMISSION
OF
TRIGOM, INC.

FIGURE II-5



REDRAWN BY PERMISSION
OF
TRIGON, INC.

FIGURE II-6

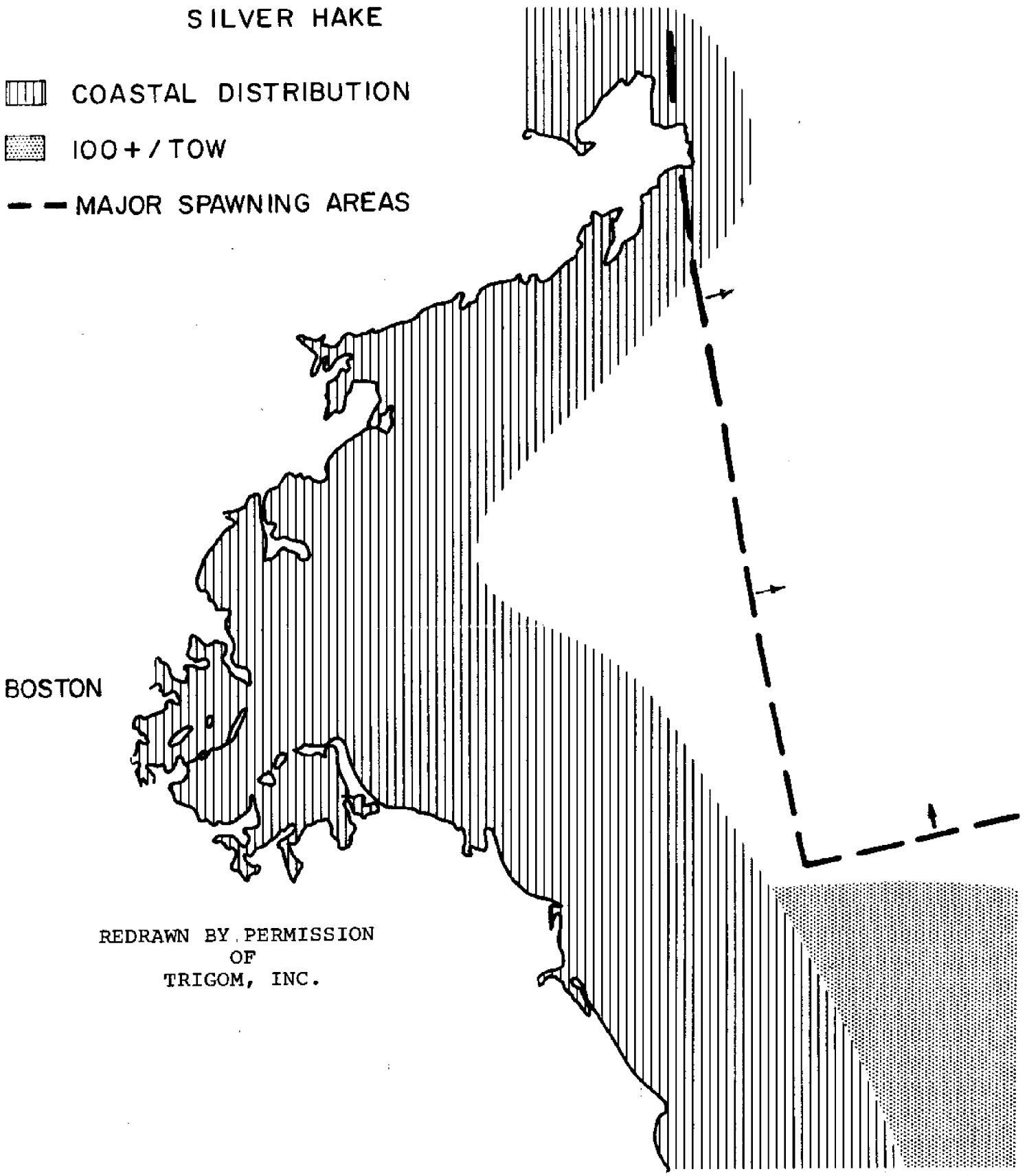

SILVER HAKE
COASTAL DISTRIBUTION
100+/TOW
MAJOR SPAWNING AREAS
BOSTON
REDRAWN BY PERMISSION
OF
TRIGOM, INC.

FIGURE II-7

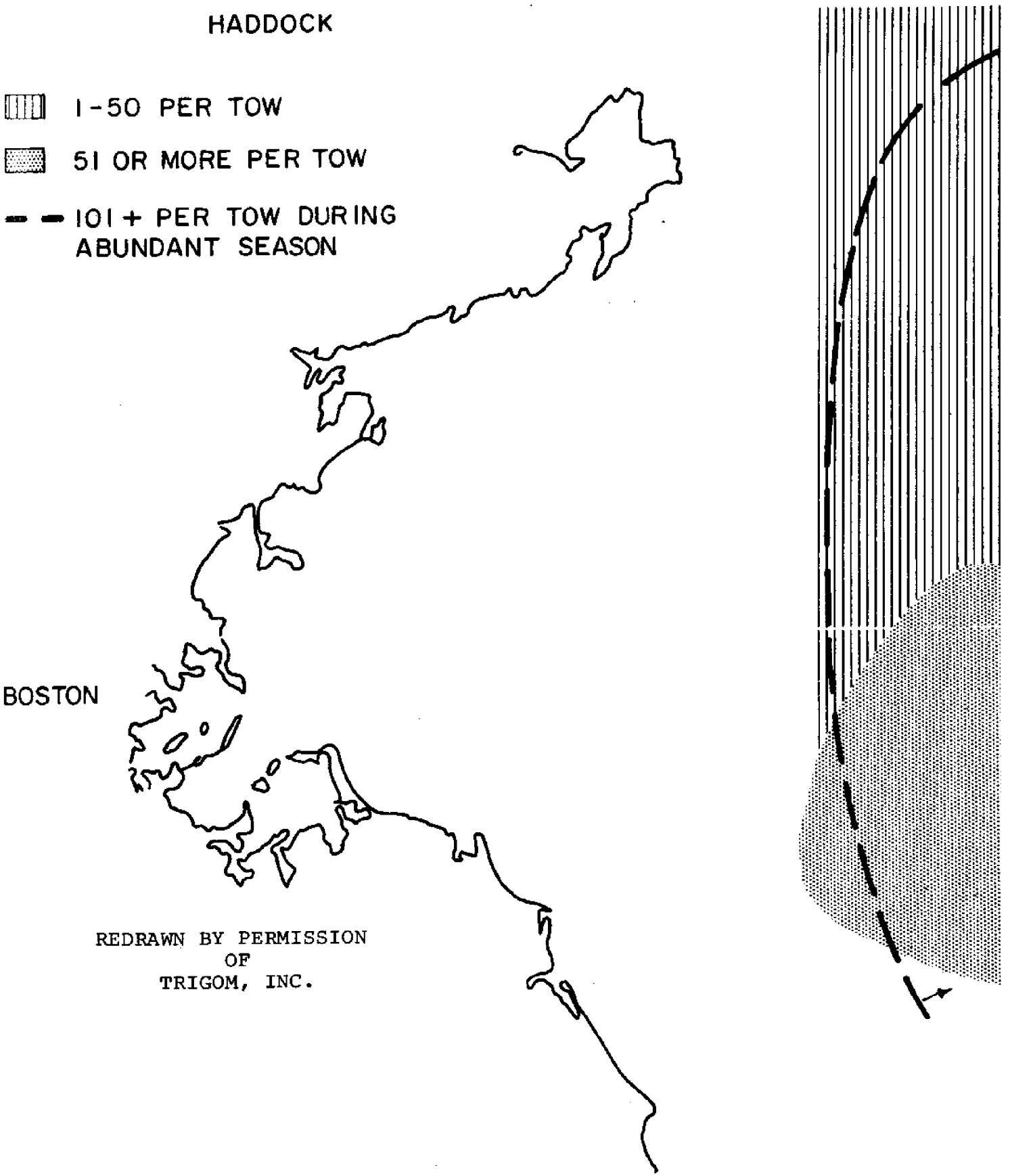

HADDOCK
1-50 PER TOW
51 OR MORE PER TOW
101+ PER TOW DURING ABUNDANT SEASON
BOSTON
REDRAWN BY PERMISSION OF TRIGOM, INC.

FIGURE II-8

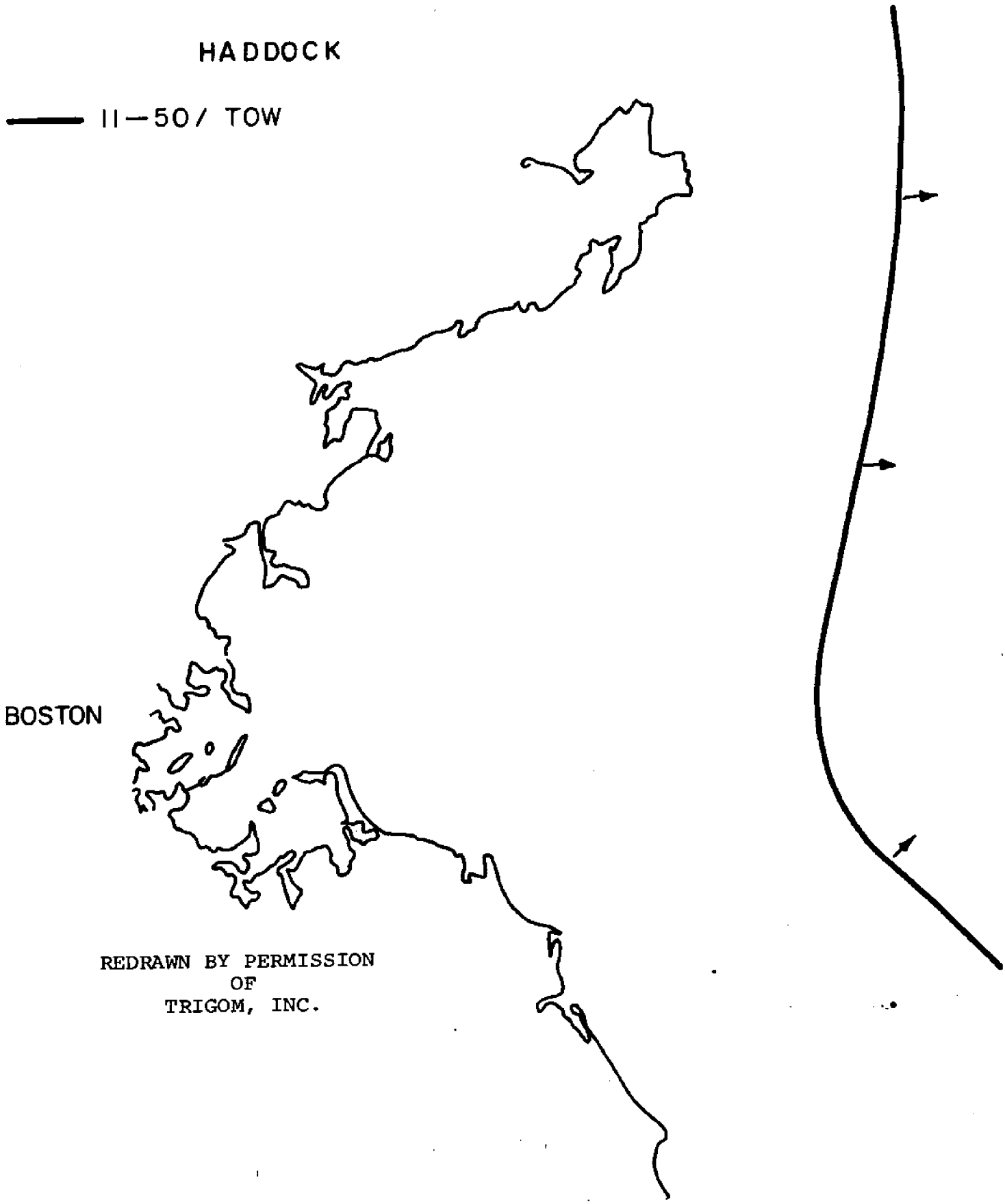
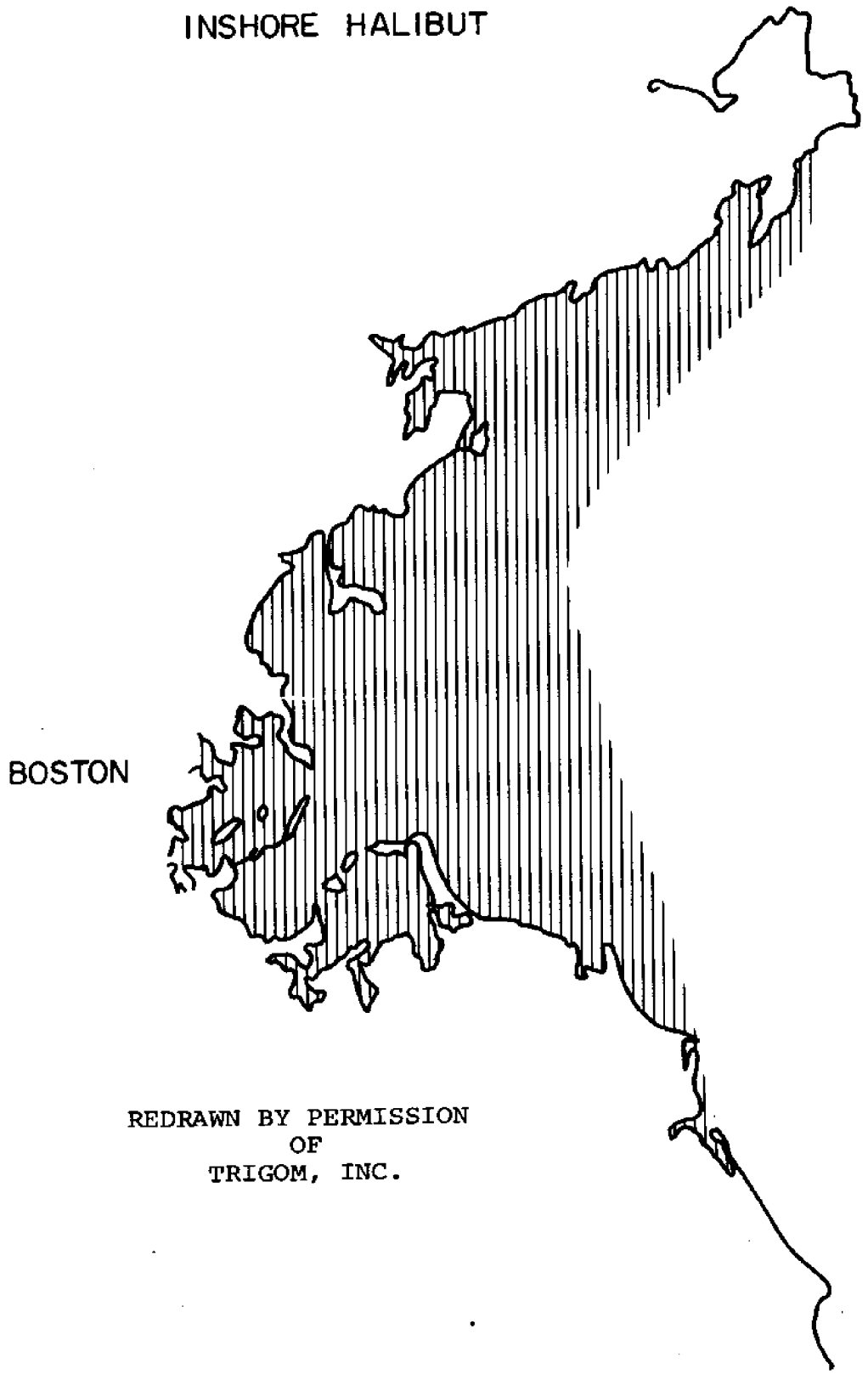

HADDOCK
11—50/ TOW
BOSTON
REDRAWN BY PERMISSION
OF
TRIGOM, INC.

FIGURE II-9



REDRAWN BY PERMISSION
OF
TRIGOM, INC.

FIGURE II-10

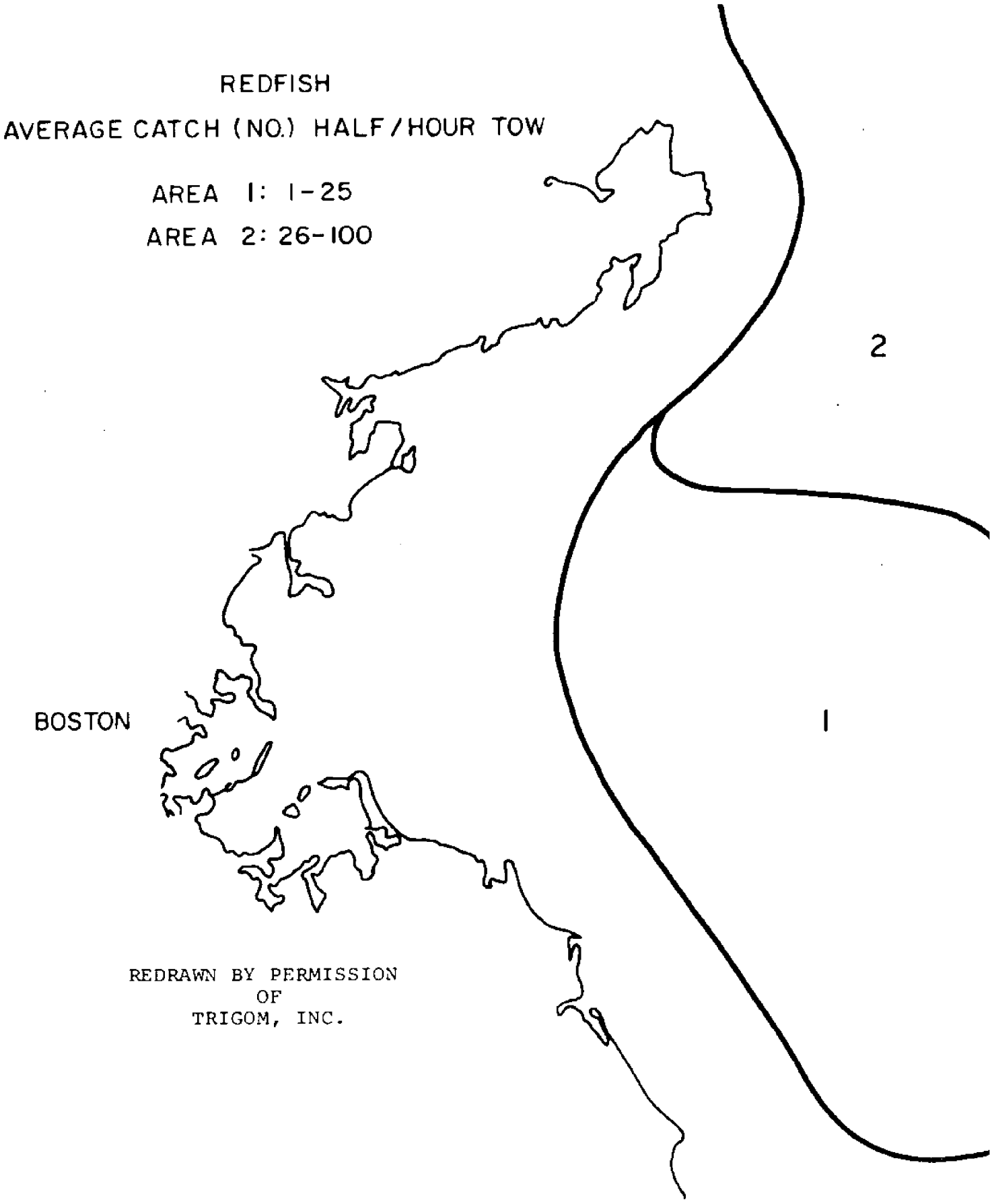
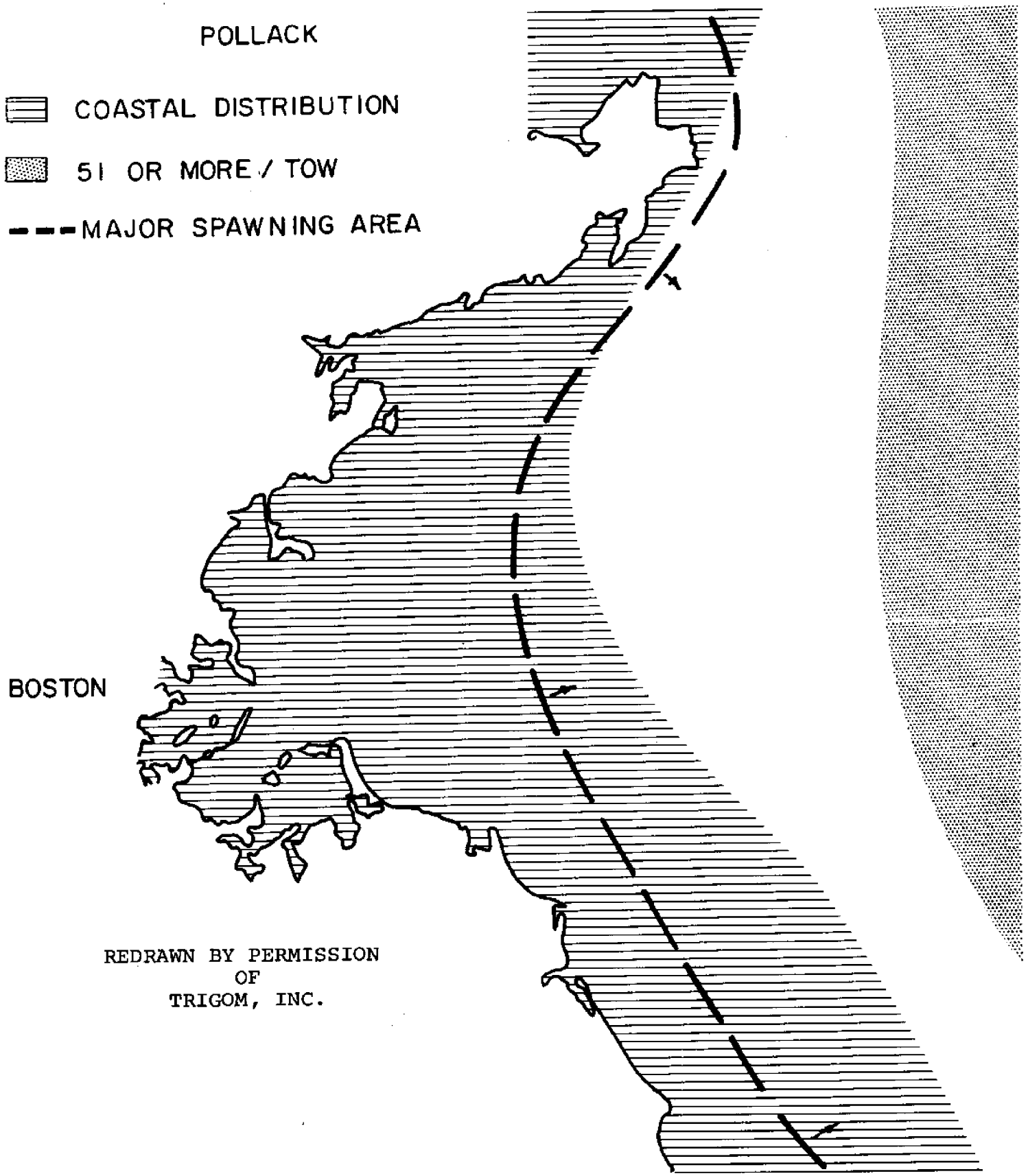
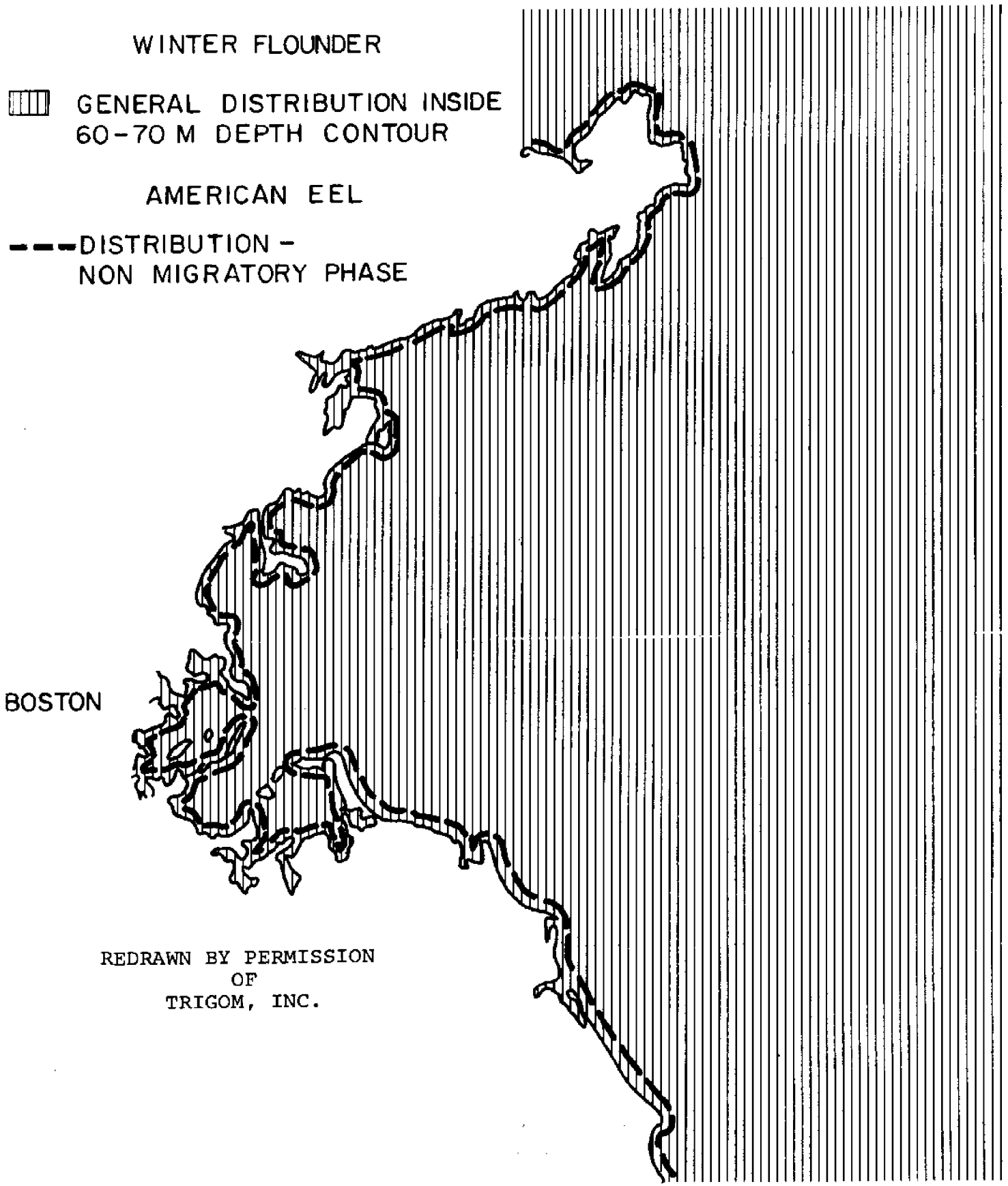

REDFISH
AVERAGE CATCH (NO.) HALF/HOUR TOW
AREA 1: 1-25
AREA 2: 26-100
2
BOSTON
1
REDRAWN BY PERMISSION
OF
TRIGOM, INC.

FIGURE II-11



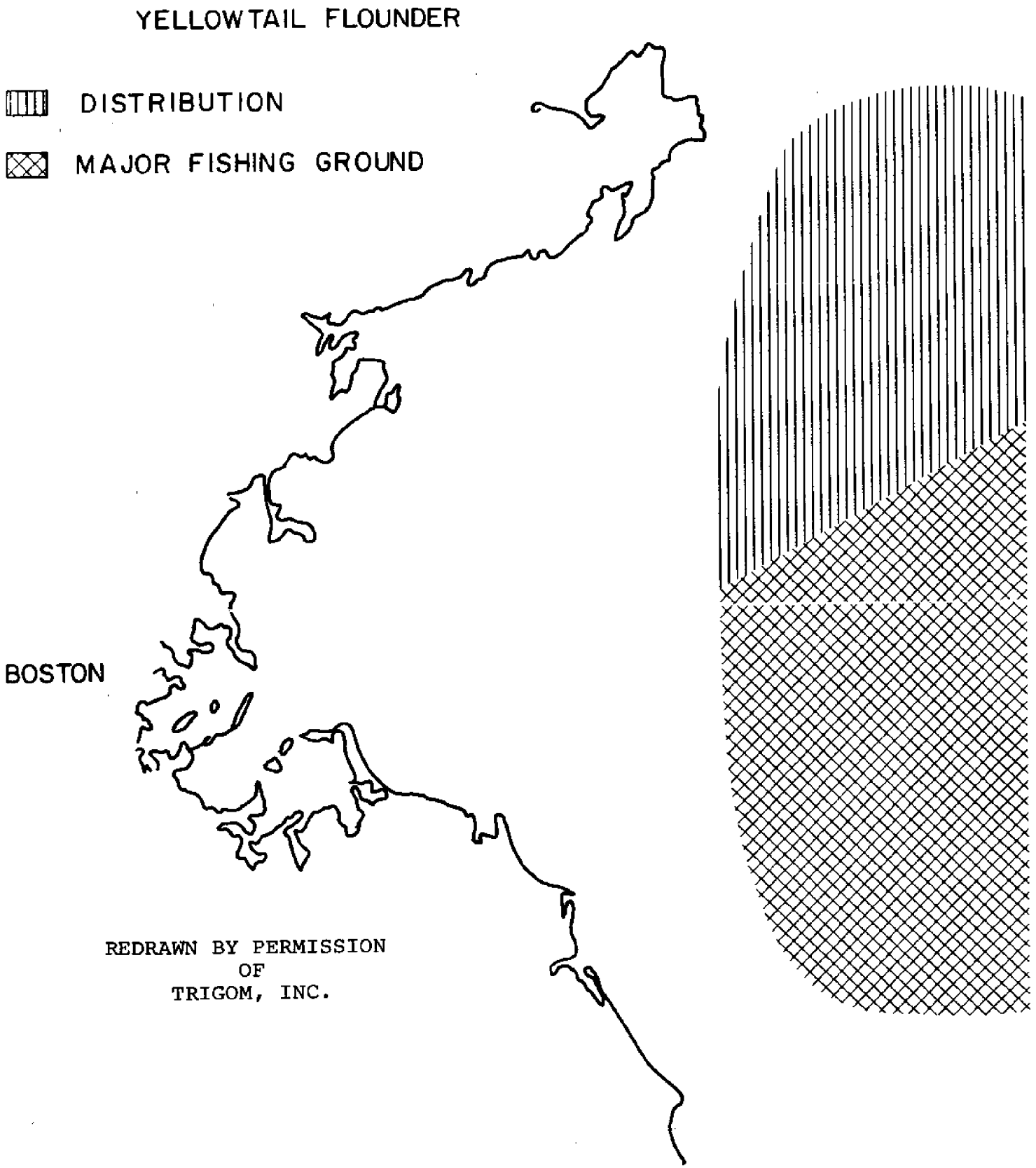
REDRAWN BY PERMISSION
OF
TRIGOM, INC.

FIGURE II-12



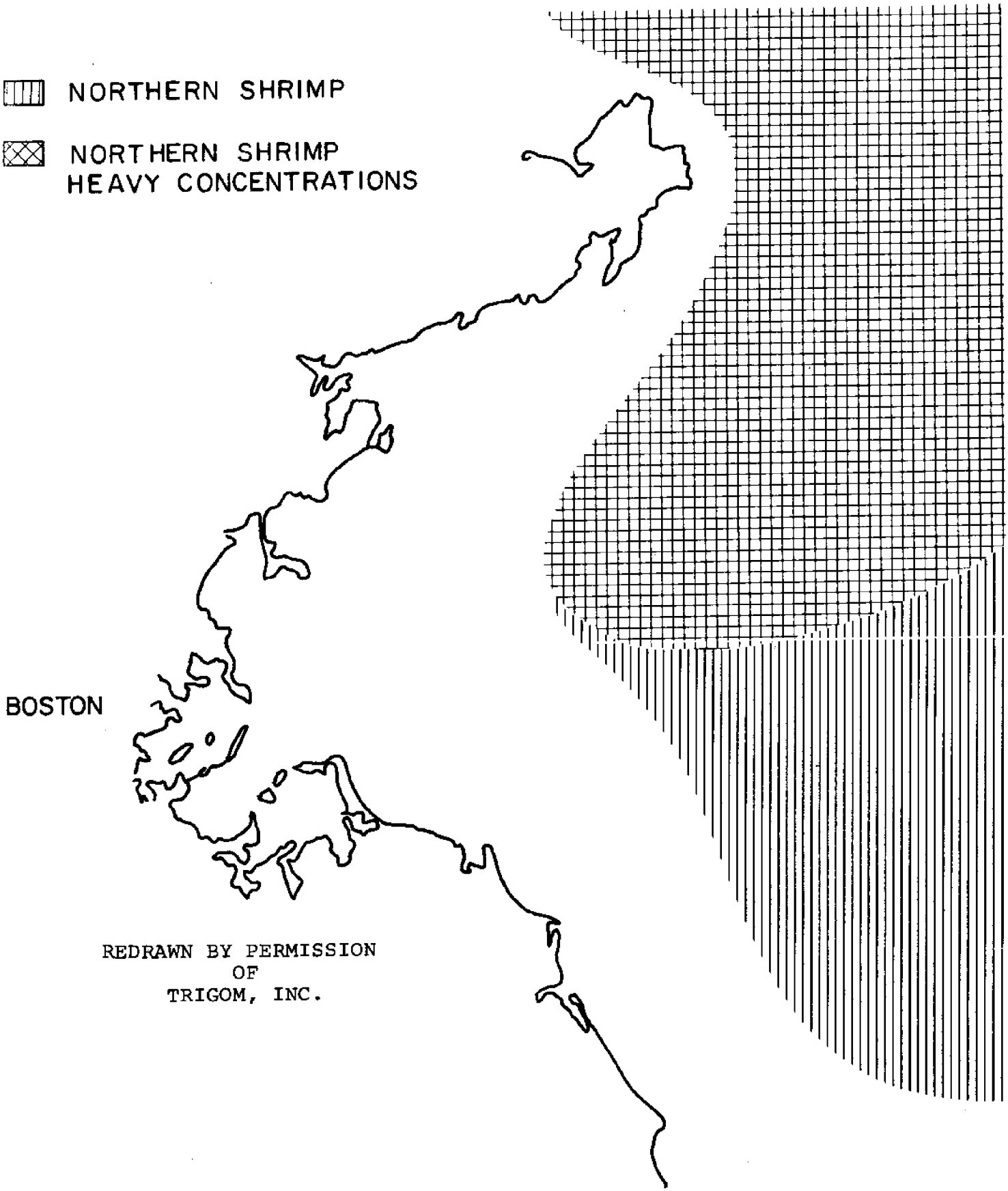
REDRAWN BY PERMISSION
OF
TRIGOM, INC.

FIGURE II-13



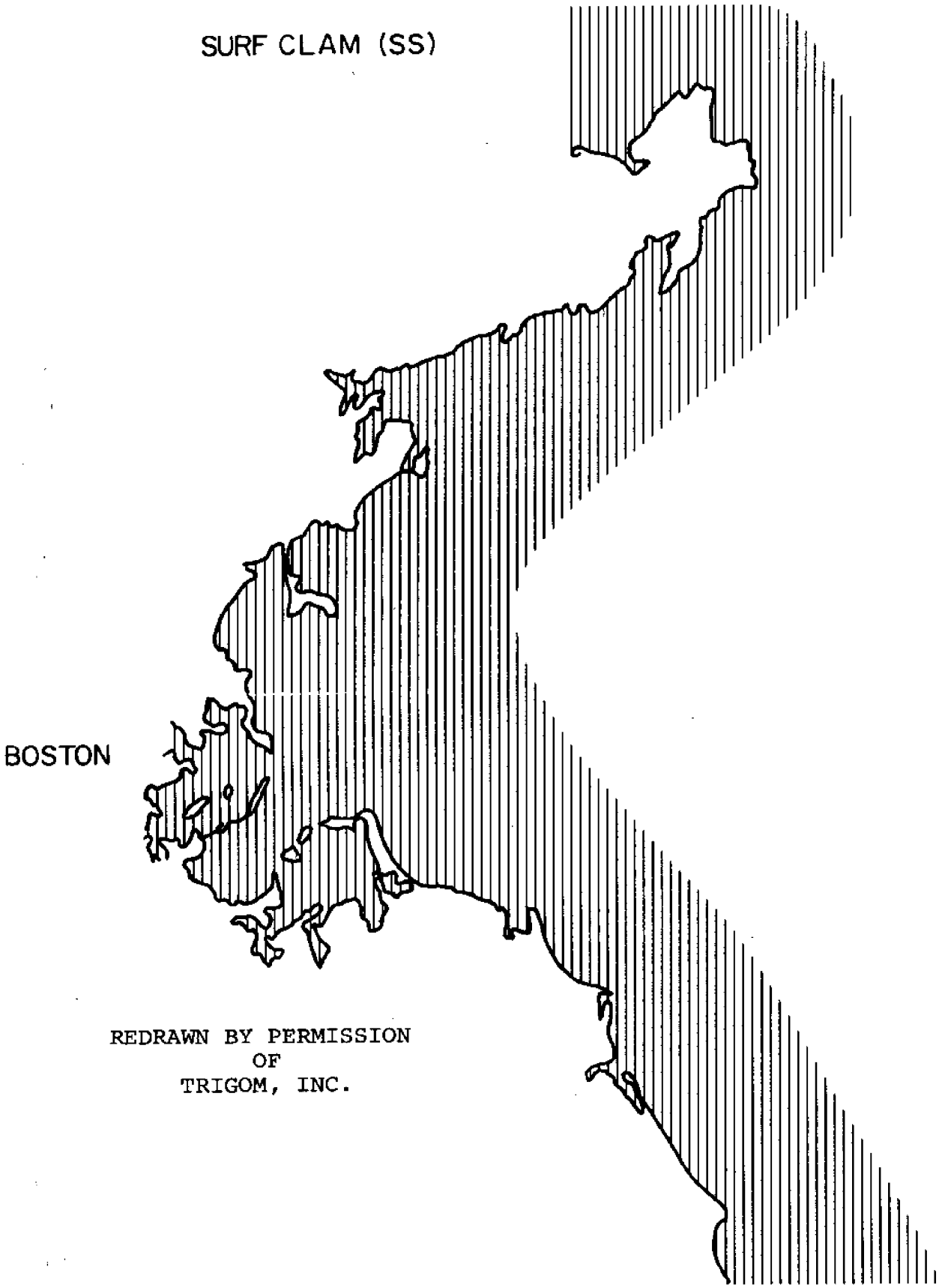
REDRAWN BY PERMISSION
OF
TRIGOM, INC.

FIGURE II-14



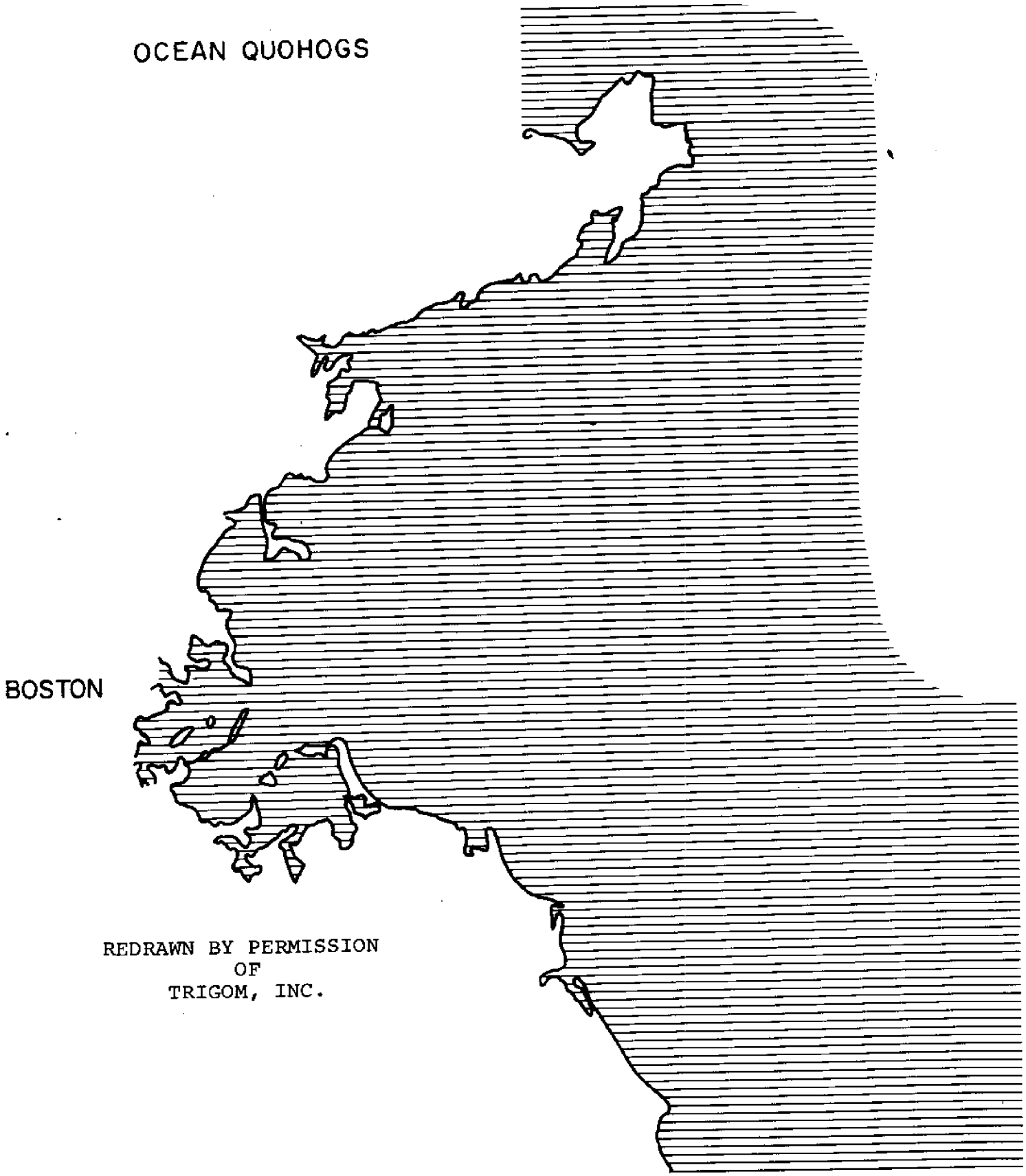
REDRAWN BY PERMISSION
OF
TRIGOM, INC.

FIGURE II-15



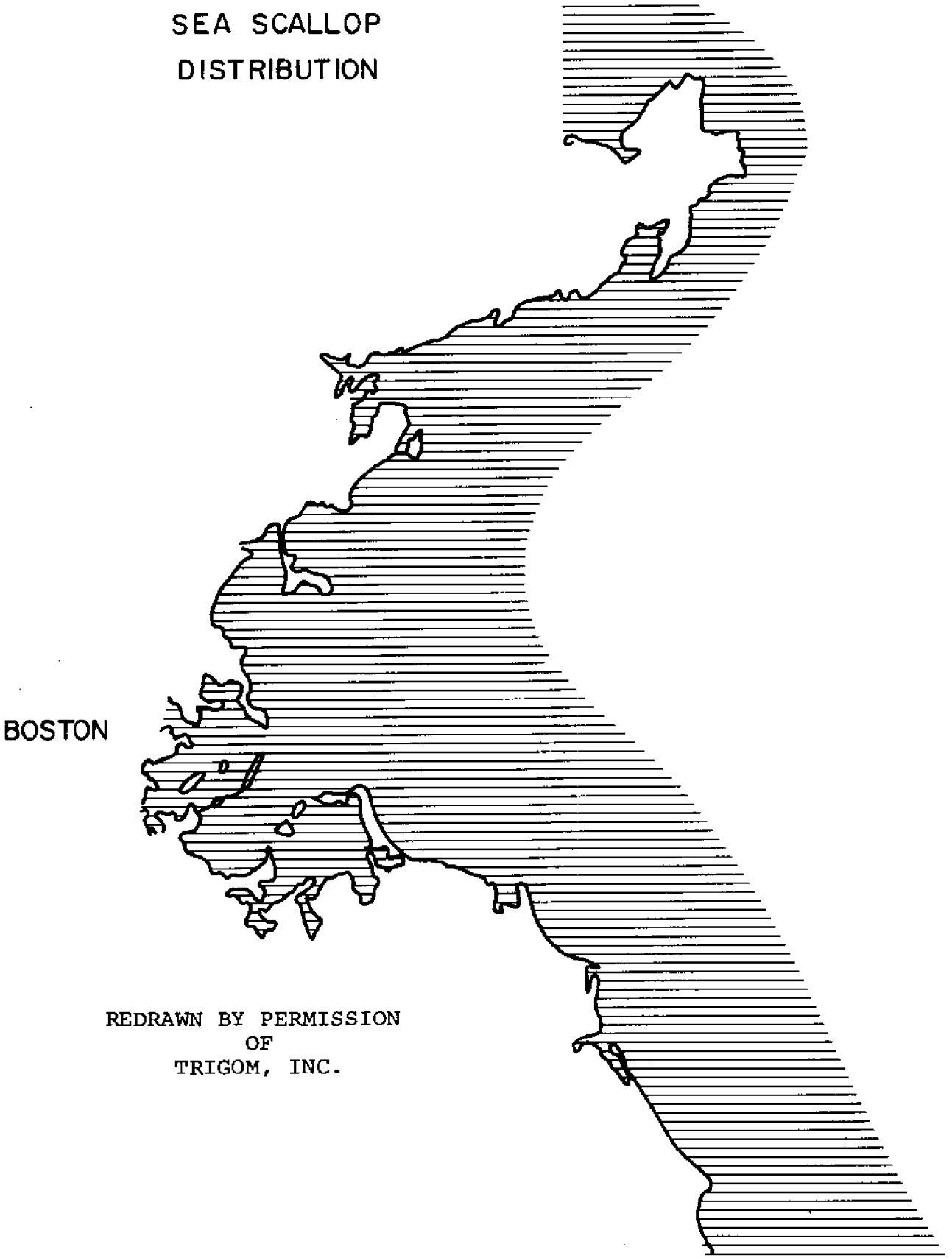
REDRAWN BY PERMISSION
OF
TRIGOM, INC.

FIGURE II-16



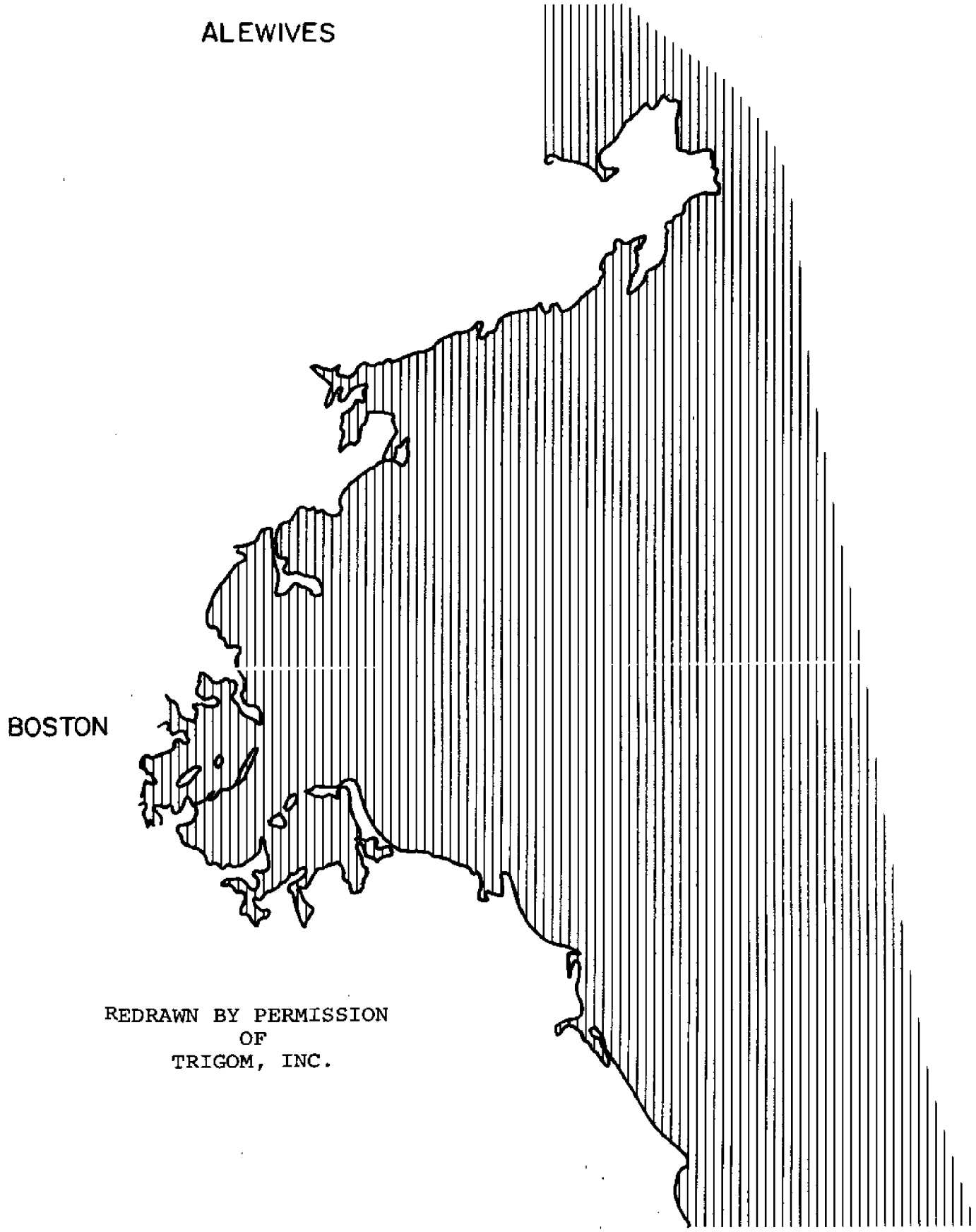
REDRAWN BY PERMISSION
OF
TRIGOM, INC.

FIGURE II-17



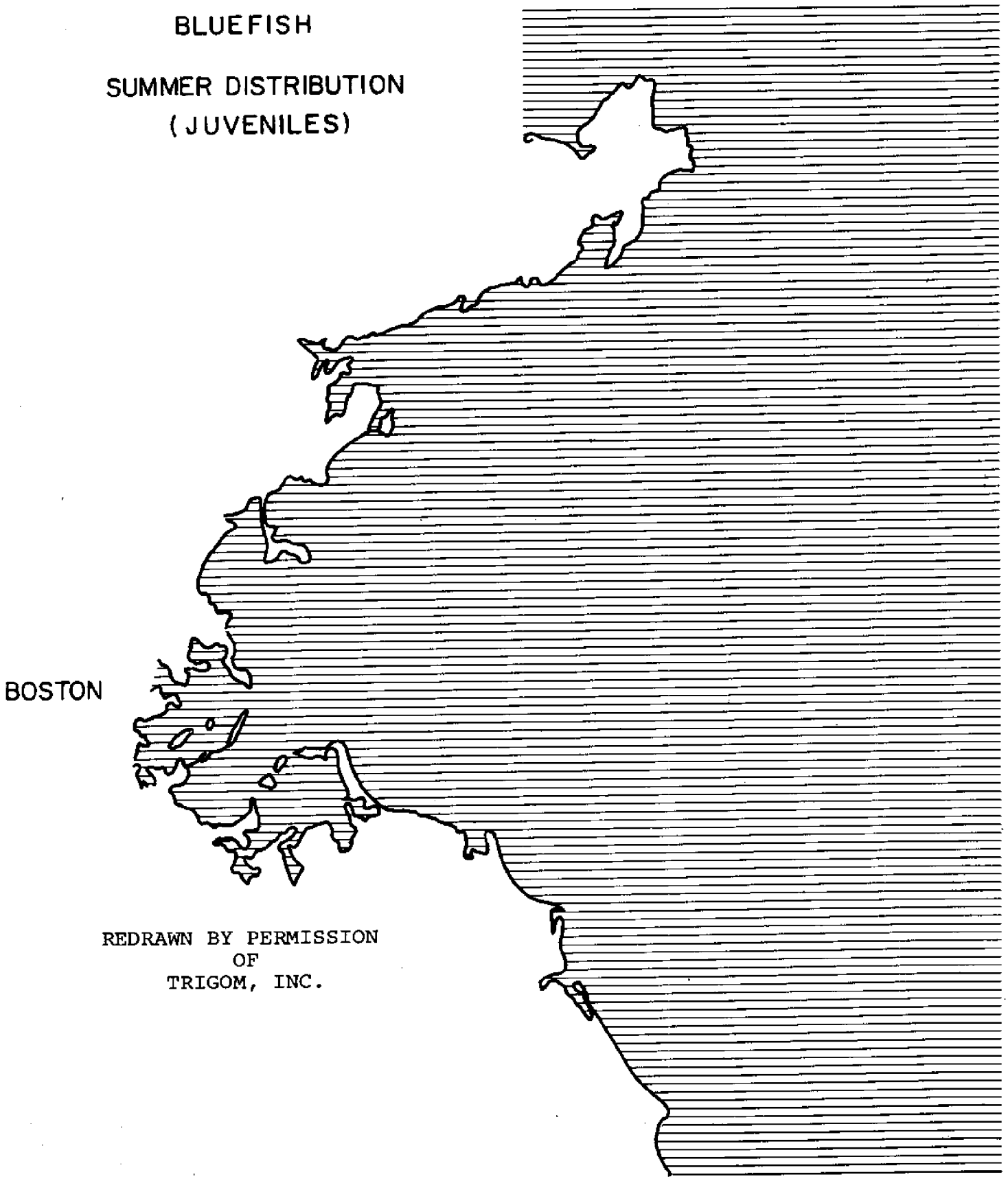
REDRAWN BY PERMISSION
OF
TRIGOM, INC.

FIGURE II-18



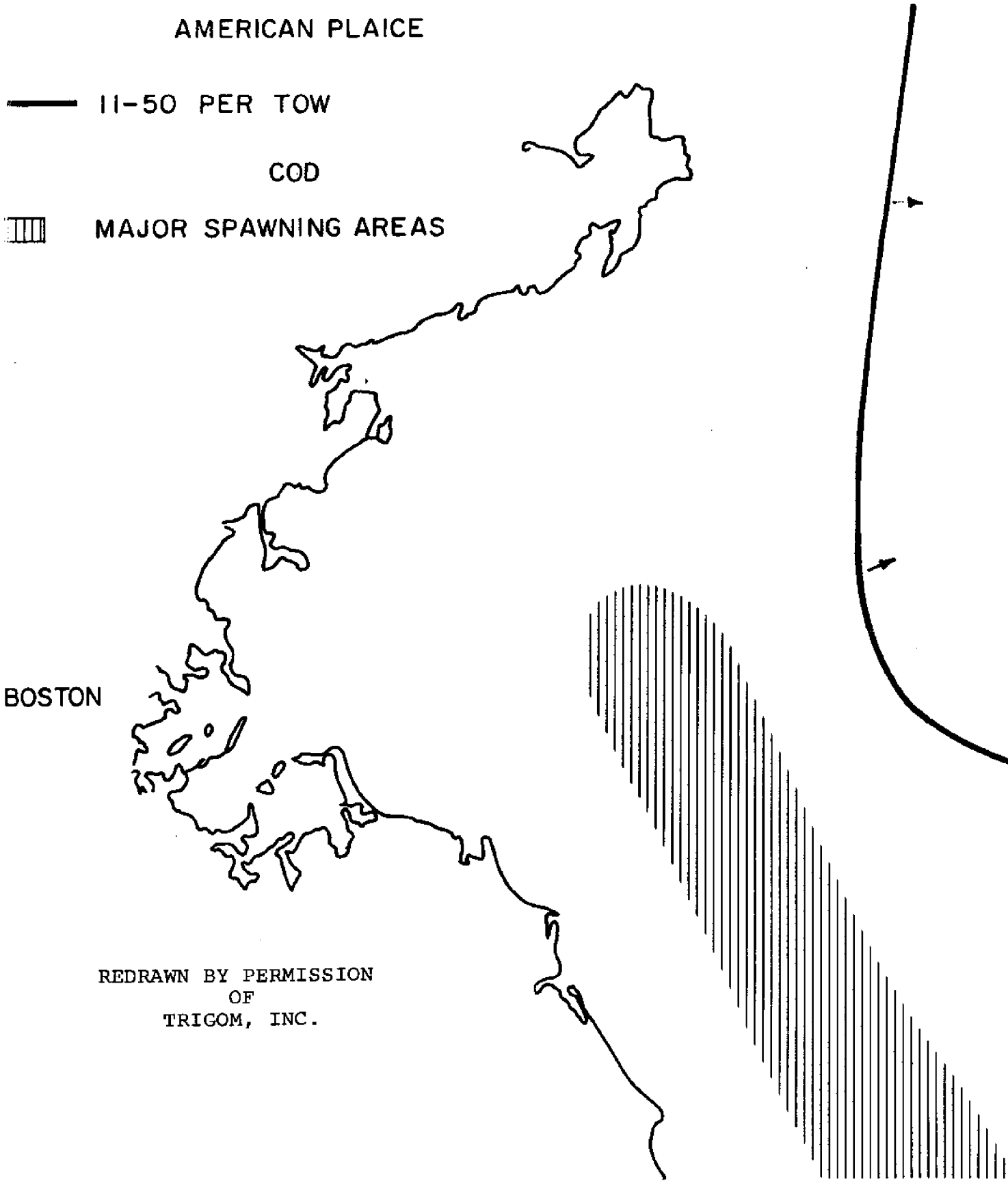
REDRAWN BY PERMISSION
OF
TRIGOM, INC.

FIGURE II-19



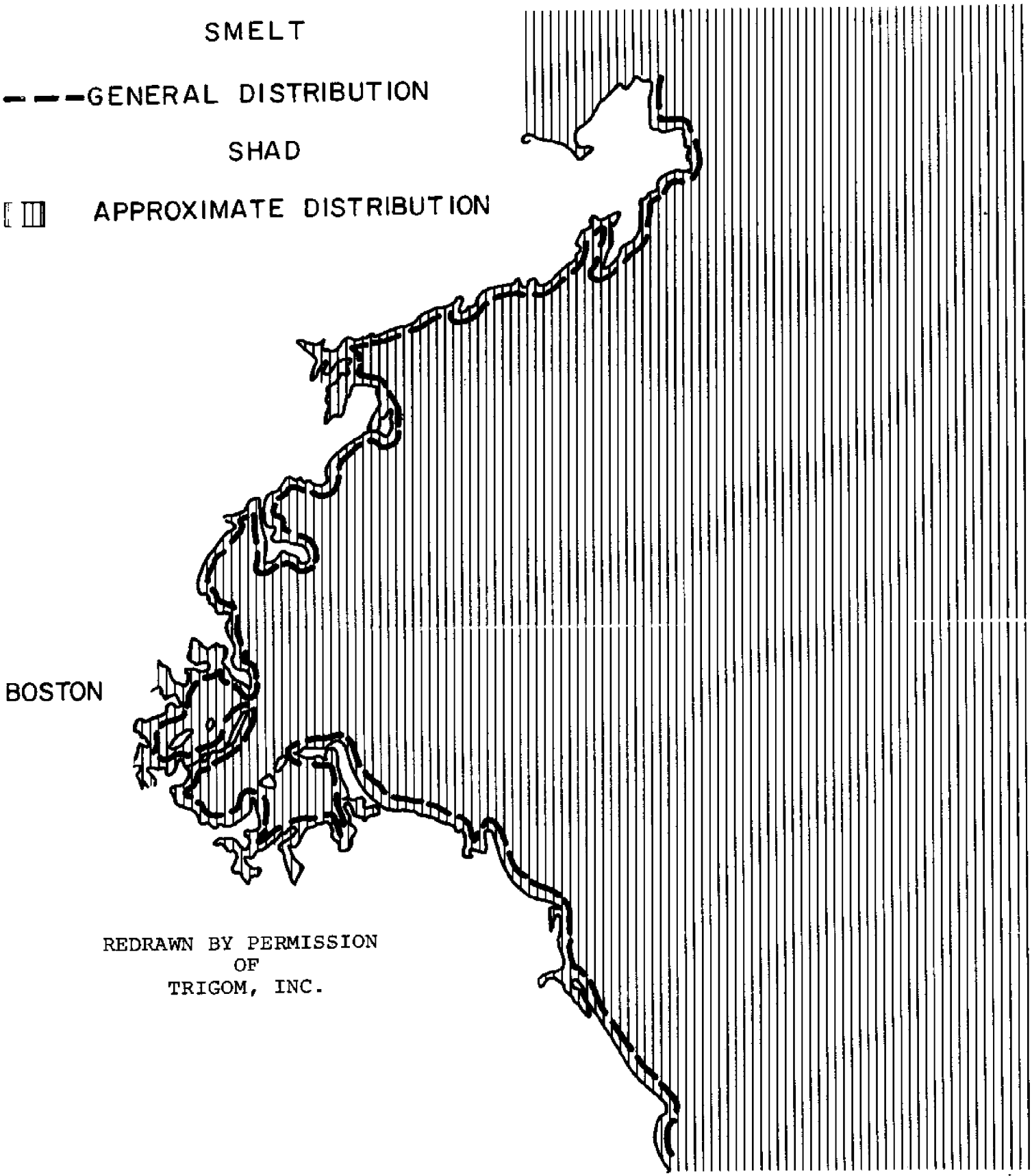
REDRAWN BY PERMISSION
OF
TRIGOM, INC.

FIGURE II-20



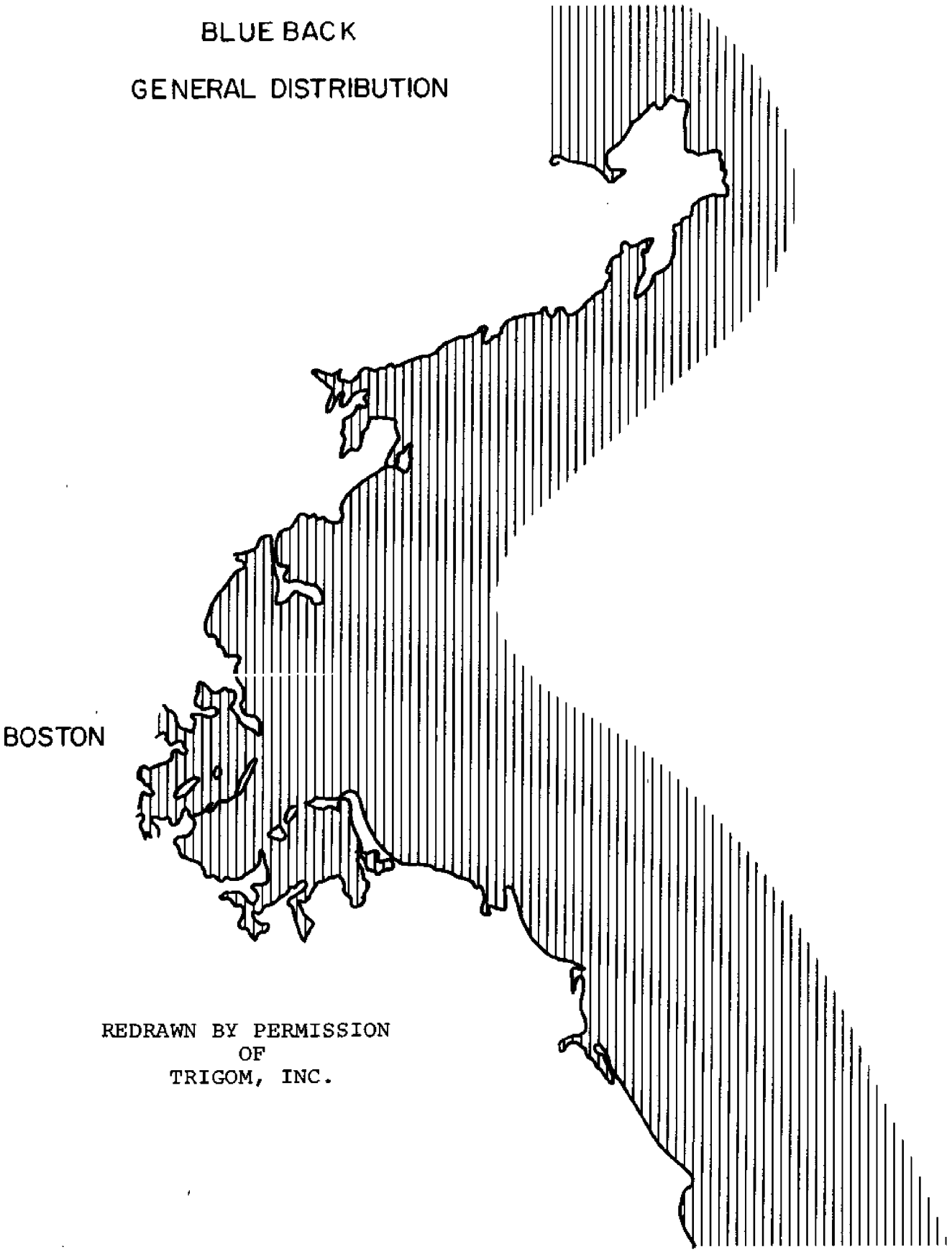
REDRAWN BY PERMISSION
OF
TRIGOM, INC.

FIGURE II-21



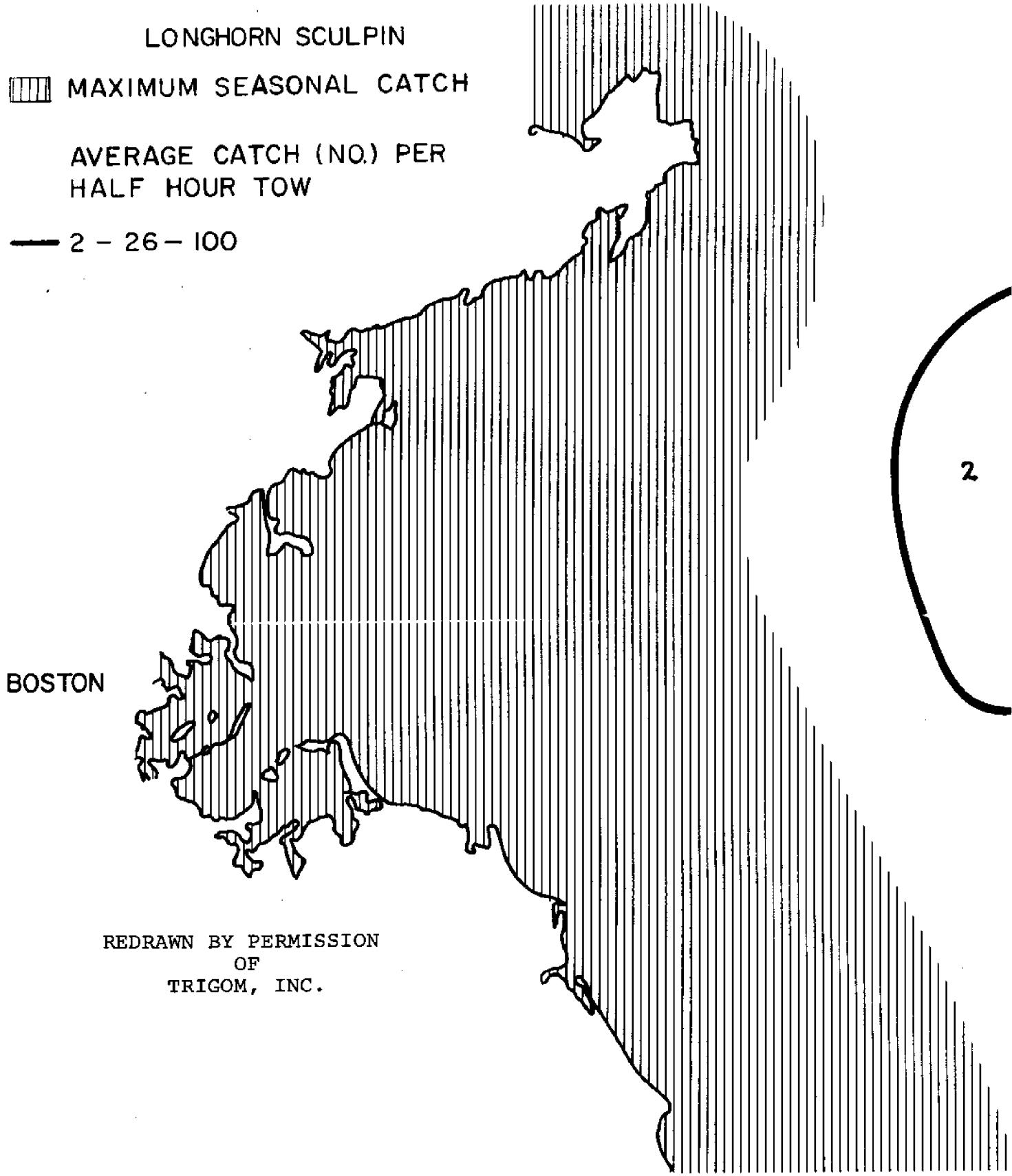
REDRAWN BY PERMISSION
OF
TRIGOM, INC.

FIGURE II-22



REDRAWN BY PERMISSION
OF
TRIGOM, INC.

FIGURE II-23



REDRAWN BY PERMISSION
OF
TRIGOM, INC.

FIGURE II-24

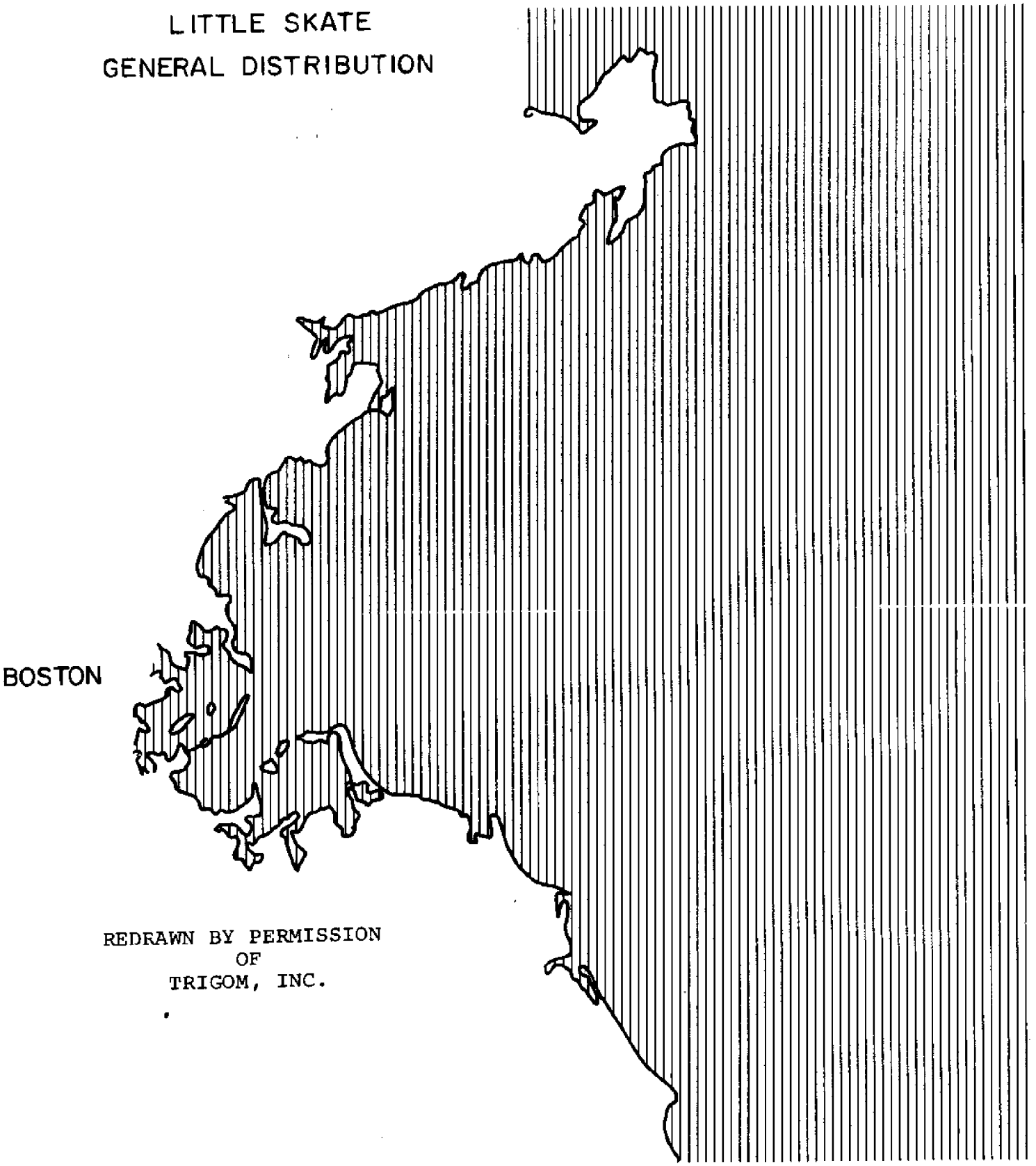
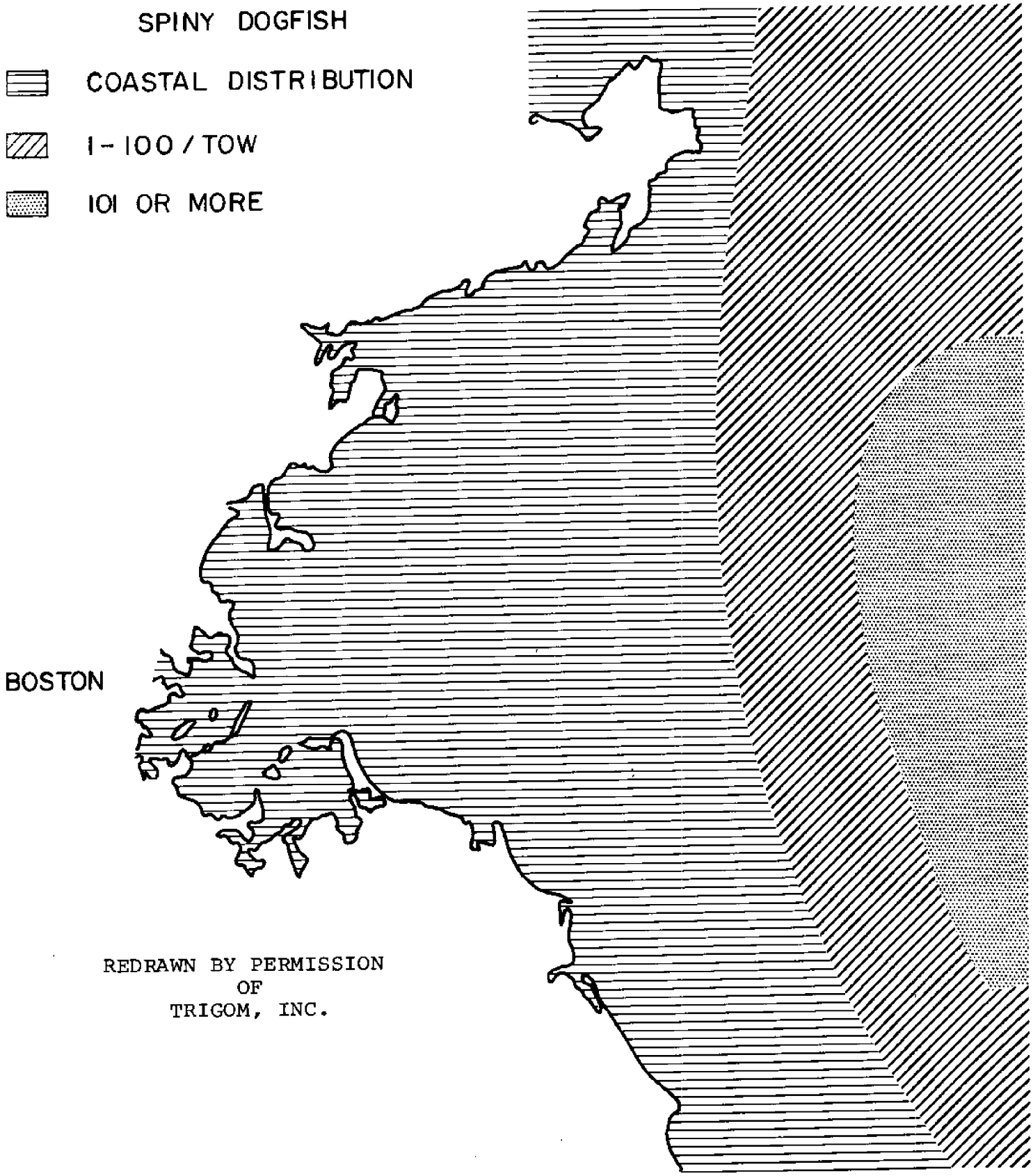

LITTLE SKATE
GENERAL DISTRIBUTION
BOSTON
REDRAWN BY PERMISSION
OF
TRIGOM, INC.

FIGURE II-25



REDRAWN BY PERMISSION
OF
TRIGOM, INC.

FIGURE II-26

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BIBLIOGRAPHY

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