1965

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W. Harrison
Virginia Institute of Marine Science

Marvin L. Wass
Virginia Institute of Marine Science

FREQUENCIES OF INFAUNAL INVERTEBRATES RELATED TO WATER CONTENT OF CHESAPEAKE BAY SEDIMENTS

by
W. Harrison
Environmental Science Services Administration
U. S. Coast and Geodetic Survey[1] and
Virginia Institute of Marine Science[2]

and

Marvin L. Wass
Virginia Institute of Marine Science

ABSTRACT

The following relationship was investigated for a total of 44 stations, using sequential (linear) multiregression analysis:

$$A = f(D, S_a, S_i, C, M_z, S_o, W)$$

where A = the frequency of an infaunal invertebrate species, D = water depth at the station, S_a = per cent sand, S_i = per cent silt, C = per cent clay, M_z = mean grain size, S_o = sediment Sorting Coefficient, and W = water content. Three animals were chosen for the dependent variable: Ensis directus, Nephtys incisa, and Retusa canaliculata.

Results of the least-squares search procedure indicate that if the water content is carefully determined this variable always appears as one of the most important, when the independent variables are considered in combinations of two or three at a time. The implication is that water content, a mass property of the sediment that reflects the interrelationships of mean grain size, sorting, grain packing, and mineralogy, is a highly useful environmental variable that should be measured in studies that attempt to establish animal-sediment relationships.

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1. Contribution No. 2, Land And Sea Interaction Laboratory, 439 York Street, Norfolk, Virginia 23510.

2. Contribution No. 186, Virginia Institute of Marine Science, Gloucester Point, Virginia 23062. This investigation was supported in part by U. S. Army Corps of Engineers Contract No. DA-44-110-CIVENG-61-181.

INTRODUCTION

During the period June 7-10, 1962, open-barrel cores were taken with a 57-kg gravity corer at 44 stations in lower Chesapeake Bay (Fig. 1). Samples of benthic fauna were also taken, by using a $1/15\ m^2$ Petersen dredge, followed by screening through a 1-mm sieve. The following seven environmental variables were estimated according to procedures outlined elsewhere (Harrison, Lynch, and Altschaeffl, 1964): water depth, per cent sand, per cent silt, per cent clay, mean grain size, sediment sorting, and gross water content. The descriptive properties of the sediments were determined from subsamples of the top 0.2 m of each core, while water-content was determined on the whole core. The average core length was 0.43 m, while the longest core had a (corrected) length of 0.9 m. Water-content values of 16 of the 44 cores taken were corrected for core shortening. (Grease smeared on the outside of the corer permitted an estimate of the true depth of penetration and the determination of true core length prior to shortening). Although it would have been best if the water-content were measured in the uppermost few centimeters, in practice it is very difficult to obtain precise values in this zone. It was felt, moreover, that a reasonable approximation of near-surface water-content could be obtained from measurements on the whole cores.

Mean grain size was determined as

$$M_z = \frac{\phi 5 + \phi 16 + 4\,\phi 50 + 2\,\phi 84 + \phi 95}{10}$$

and the Sorting Coefficient as

$$S_o = \frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6}$$

where phi (ϕ) is the $\log_2$ transformation from millimeters (arithmetic interval) to phi units (geometric interval). Data for the 44 stations are given in Table 1.

Acknowledgments

The authors are indebted to Dr. William J. Clench, of the Museum of Comparative Zoology, Harvard University, for the identification of representative specimens of *Ensis*.

DATA ANALYSIS

Several methods are available for analyzing observational data that involve interrelationships among independent variables. The method chosen was that of sequential multiregression analysis, and a complete explanation of the technique with several worked examples is given by Harrison and Krumbein (1964), and Krumbein, Benson, and

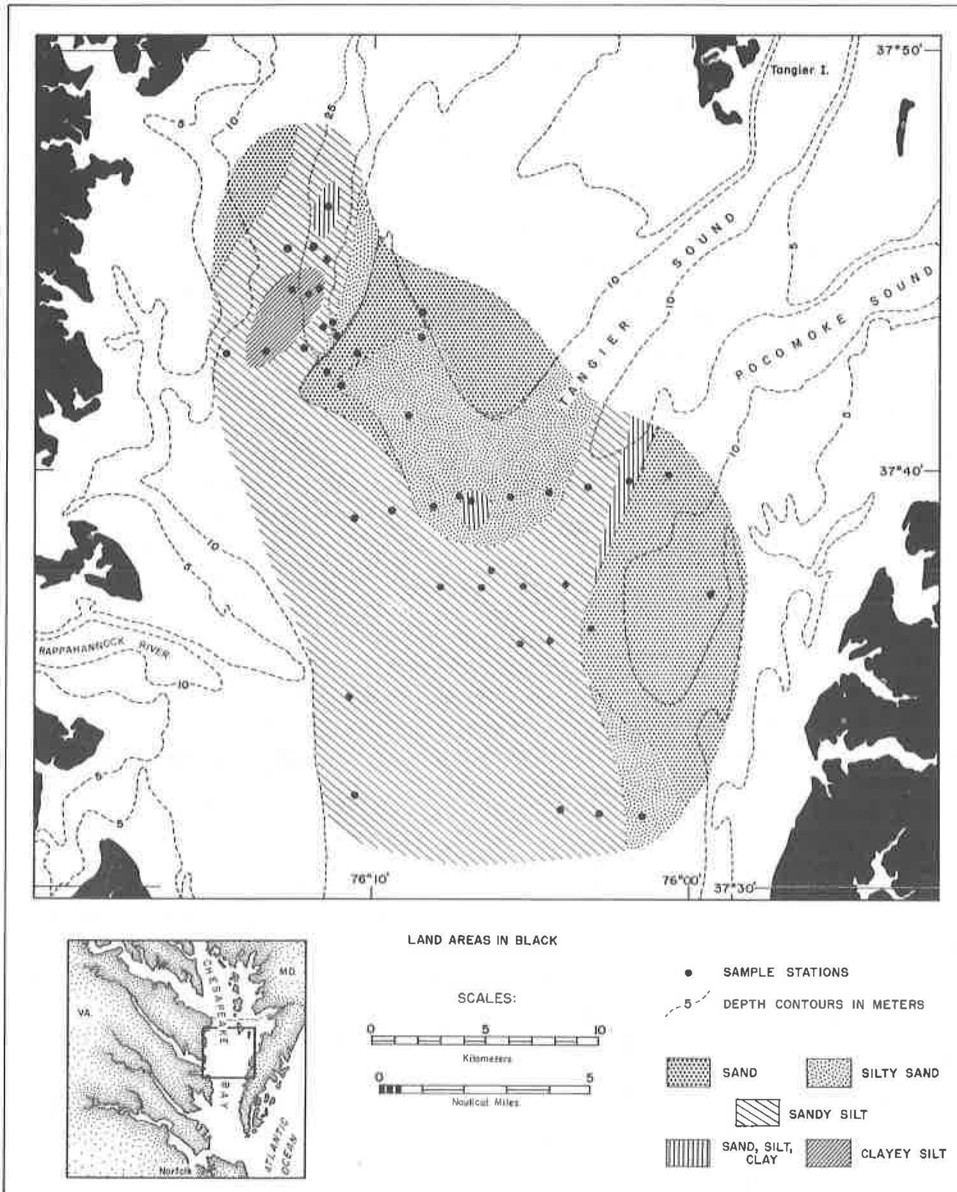

Figure 1. Map of area of investigation, showing sample stations, general bathymetry, and distribution of bottom sediments. Sediment-type designations after Shepard (1954, p. 157).

Hempkins (1964). The technique involves the measure of the relationship of a given dependent variable in terms of several controlling environmental elements (or "independent" variables), by taking the latter one at a time, two at a time, and so on, until all of the environmental elements are included simultaneously.

Thus, in the first analysis, the frequency of Ensis directus at the 16 stations where corrected water-content values were obtained is examined as a function of water depth, per cent sand, per cent silt, per cent clay, mean particle size, Sorting Coefficient, and water-content:

$$E = f(D, S_a, S_i, C, M_z, S_o, W).$$

In sequential multiregression the (linear) relations between the dependent and independent variables are first examined for each independent variable separately. This is accomplished by fitting a least-squares straight line to a scatter diagram of animal frequency against each environmental variable in turn. The straight line has the general form

$$\hat{Y} = a + bX$$

where $\hat{Y}$ is the computed value of the straight line at each point of observation of Y; X is the independent variable; a is the intercept of the line on the Y-axis; and b is the regression coefficient of the straight line. Thus, the linear regression of the frequency of Ensis on water depth would have the form $\hat{s} = a + bD$, where $\hat{s}$ equals the computed value corresponding to any value for D.

The degree of relationship between two variables can be evaluated by examining the reduction in the sum of squares of the dependent variable produced by the regression function. The total sum of squares for any variable is defined as the sum of the squares of the difference between individual measurements and the mean of all measurements:

$$SS_Y = \Sigma (Y - \overline{Y})^2$$

where Y is a single observation and $\overline{Y}$ is the arithmetic mean of the observations. The sum of squares of a dependent variable is a measure of its total variability. This sum of squares can be partitioned into two components, one associated with linear regression and the other with deviations of the data from the straight line. Thus, the total sum of squares can be expressed as the sum $SS_Y = SS_L + SS_D$, where SS_L represents that portion of the total variability "accounted for" by the linear relation, and SS_D represents the remaining variability after the linear relation is removed. The percentage reduction in the total sum of squares due to linear regression is then computed from the relation

$$\text{Per cent reduction in } SS_X = (100)\, SS_L \;/\; SS_Y$$

The IBM 1620 program used in this study computes the linear coefficients and the sums of squares reduction for all combinations of Xs, as stated, and the output lists the Xs involved and the corresponding per cent SS reductions.

Because of limitations on regression analysis with one independent variable at a time, sequential multiregression is used to estimate the simultaneous influence of two or more independent variables on the animal frequency. Sequential multiregression treats the independent variables one at a time, two at a time, and so on for all possible pairs, triplets, etc., of independent variables measured. Thus, the linear relation between frequency of Ensis and water depth and per cent sand simultaneously is:

$$\hat{s} = a + bD + cS_a$$

where b and c are the linear coefficients. Because the individual values of a, b, and c change as different variables are introduced, the percentage reduction in the sum of squares (Table 2) associated with each pair indicates how strongly the pair affects animal frequency simultaneously. And it is a combination of factors in the environment that affects the distribution of species.

The three animal species chosen for analysis were Ensis directus, a razor clam, Nephtys incisa, an errant polychaete, and Retusa canaliculata, a minute gastropod. These three were chosen for two reasons: 1) Ensis was the most abundant organism, comprising 79% of the individuals taken on the cruise, and Nephtys and Retusa, while ranking (in order) only fifth and eighth in abundance and sixth and fifth in frequency, were first and second in frequency of occurrence for several cruises covering a period of 2 1/2 years, and 2) Ensis was represented only as juveniles up to about 2 cm long, while Nephtys and Retusa consisted mainly of adults. Values used for the dependent and independent variables of this study are presented in Table 1.

RESULTS

Results of the least-squares analyses are presented in Table 2, where it is seen that the greatest per cent SS reductions for all seven independent variables amount to 34.13, 48.57, and 54.29 for Ensis, Nephtys, and Retusa, respectively. Variable X2, per cent sand, is the dominant environmental variable in terms of its frequency of occurrence in combinations of two and three Xs at a time. Per cent sand is followed closely in frequency by water-content (X7) and water depth (X1) in the strongest combinations. Water-content, however, is always present in the strongest combinations where Nephtys and Retusa are the dependent variables.

DISCUSSION

The relatively low magnitudes of the per cent SS reductions indicate any or all of the following: 1) the variability of the data is rather large, owing to experimental, procedural (sampling errors), or natural factors; 2) additional important variables need to be included in the analysis; and 3) there is little true relationship between a dependent variable and one or more of the independent variables.

With regard to point 1, the so-called "noise content" of the data, it is seen that a clear difference exists between the total per cent SS reductions for N = 16 and N = 44, for both Nephtys and Retusa.

Table 2

The two strongest per cent reductions in animal-type sum of squares attributable to each of several combinations of seven environmental elements.

Animal	Environmental-element number combinations (X)[1]							Per cent reduction in SS	
Ensis directus (N=16)	1	2	3	4	5	6	7	33.75	All Xs
	1	2						32.42	Two Xs at
		2					7	31.82	a time
	1	2				6		33.42	Three Xs at
		2				6	7	33.22	a time
Ensis directus (N=44)	1	2	3	4	5	6	7a	34.13	All Xs
		2					7a	32.05	Two Xs at
	1	2						30.82	a time
		2				6	7a	33.44	Three Xs
	1	2				6		32.64	at a time
Nephtys incisa (N=16)	1	2	3	4	5	6	7a	48.57	All Xs
				4			7	35.60	Two Xs at
	1			4				33.94	a time
		2		4			7	38.29	Three Xs
			3	4			7	37.98	at a time
Nephtys incisa (N=44)	1	2	3	4	5	6	7a	14.73	All Xs
Retusa canaliculata (N=16)	1	2	3	4	5	6	7	54.29	All Xs
	1						7	39.38	Two Xs at
		2			5			36.02	a time
	1				5		7	51.47	Three Xs
	1	2			5			43.16	at a time
Retusa canaliculata (N=44)	1	2	3	4	5	6	7a	5.10	All Xs

[1] X1 = water depth, X2 = % sand, X3 = % silt, X4 = % clay, X5 = mean size, X6 = Sorting Coefficient, X7 = water content (corrected for core length), X7a = water content (mixed values, corrected and uncorrected for core length).

It will be recalled that the water-content data, where N = 16, are relatively noise free as far as analytical procedures are concerned. (This fact points up the need for using water-content values from open-barrel cores whose lengths have been corrected.) Sampling procedures may have introduced some noise, however, because at the 16 stations where water-content was carefully determined, cores[3] of various lengths were employed. It is quite likely that the noise content of the water-content variable would have been further reduced, had equal-length core samples been used, owing to the known relationship between water-content and depth in the sediment. (Calculations based on precision water-content determinations Harrison, Lynch, and Altschaeffl, 1964, Table 3 , on samples from piston cores taken in the area, show that the discrepancy between estimated and true water-content values for the surficial 5 cm of sediment is many times greater for calculations affected by the core-shortening process than for calculations obtained by assuming that the average water-content value for the whole core, whose length has been corrected, holds also in the 5 cm surface layer.)

The variability about the population mean of animal frequency, the dependent variable, would certainly have been reduced if replicate faunal samplings had been made and mean values used for the animal frequencies. Also to be considered in data reliability, where animals are involved, is the degree of maturity of the animals studied. This is illustrated by Ensis directus which occurs as adults in sandy areas of the lower Chesapeake. The number of eggs produced by an individual is probably quite large. Only one adult razor clam was taken in the area during the entire survey but more would surely have been collected by a sampling device penetrating to greater depths. The area sampled, however, is predominantly clayey and sandy silt with sand in the shoaler parts. The generally adverse nature of the bottom for this animal and the large numbers of juvenile Ensis, up to 39, 450/m^2 indicate a lack of ability to discriminate between substrates by larvae of this species. The results of the least-squares analysis support this assumption because there was so little difference in per cent-SS-reduction by all Xs (Table 2) between the samples run by differing methods of water-content analysis.

Point 2 above, the possibility that additional important variables need to be included in the analysis, will not be treated here, but it is believed that a more comprehensive study of this type should include measurement of such variables as salinity, pH, dissolved oxygen, and turbidity. Biological variables, such as the number of larvae passing a given station in one season or the frequencies of other

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[3]See Harrison, Lynch, and Altschaeffl (1964, Table 2), cores 6, 7, 9, 10, 11, 12, 16, 19, 20, 21, 29, 31, 32, 34, 35, and 36.

Table 1

Values used for the dependent and independent variables in the least-squares analyses.

Station no.	Animal frequency (Ensis)	(Nephtys)	(Retusa)	Water Depth	% Sand	% Silt	% Clay	Phi mean size	Sorting Coeff.	Water cont. (%)
1	4	14	5	32	22	57	21	5.8	1.4	167
2	2	6	1	32	30	60	10	5.2	1.8	145
3	14	16	3	16	22	60	18	5.5	1.0	173*
4	12	16	5	28	27	56	17	5.9	2.1	296*
5	19	16	4	33	29	63	8	5.2	1.6	335*
6	14	13	5	14	19	49	33	6.0	2.3	255*
7	24	8	1	29	16	61	24	5.9	2.1	279*
8	115	19	3	30	19	60	21	5.8	2.2	263*
9	11	12	3	30	30	70	0	4.6	1.0	183
10	25	14	3	29	38	63	0	4.3	0.8	240*
11	670	31	9	31	62	28	10	3.9	2.1	50
12	582	0	6	9	100	0	0	2.5	0.5	62
13	0	11	13	5	21	65	14	5.6	1.9	181*
14	2	14	19	15	17	57	26	0.6	2.2	204*
15	41	17	11	18	19	71	11	5.5	1.7	216*
16	2630	2	10	18	82	12	7	2.9	1.9	34
17	121	26	23	14	46	47	7	4.3	1.8	109
18	100	12	5	27	80	14	6	3.1	1.9	40
19	76	14	0	19	68	22	10	3.7	2.0	73*
20	560	19	2	20	70	22	8	3.7	2.0	82*
21	217	21	2	14	29	64	7	0.5	1.6	145*
22	814	22	4	15	26	61	13	5.1	1.8	145*
23	2264	22	2	15	64	27	9	3.3	1.9	95*
24	192	29	0	13	40	59	1	4.6	1.4	130*
25	48	16	8	14	46	34	20	5.3	2.4	111
26	26	26	0	14	24	61	15	5.4	2.0	94
27	367	21	6	23	40	41	12	4.5	2.0	71
28	233	22	0	13	32	56	13	5.1	1.9	96
29	64	23	0	13	32	39	30	5.5	2.8	117
30	54	22	9	13	90	10	0	2.3	1.1	38
31	282	19	8	15	23	58	19	5.9	2.2	135
32	44	12	6	15	28	60	12	5.2	1.8	80
33	549	9	4	16	24	58	18	5.6	2.1	72
34	242	24	4	16	25	65	10	0.5	1.4	89
35	173	21	4	14	32	54	15	5.2	1.9	99
36	102	10	13	13	21	63	16	5.6	2.0	135
37	111	24	8	15	35	54	11	4.9	1.7	104
38	159	15	3	13	35	65	1	4.3	0.9	109
39	1861	11	0	16	85	11	4	2.6	1.5	44
40	1239	0	4	12	90	10	0	2.4	1.1	47
41	117	18	8	11	29	64	8	5.0	0.7	140
42	920	90	7	13	45	53	2	5.5	1.0	65
43	275	18	1	14	48	52	0	4.1	0.8	74
44	176	18	1	18	69	31	0	3.2	1.2	169

* As determined for corrected core length.

species in the sample, would be important additional independent variables for such an analysis.

Finally, with regard to point 3, the validity of the relationships noted between the animals and the environmental variables, the following can be noted. The reduction of the sum of squares is a measure of the mathematical association between variables, and is not necessarily the measure of a physical relationship. Where the independent variable has physical meaningfulness in the problem, however, it is not extreme to infer that the strength of the mathematical relation is also a measure of the strength of the physical relation. When the independent variables are taken several at a time, however, interrelations among the independent variables themselves may complicate interpretation of the sum of squares reduction. If a particular independent variable is itself dependent on some other variable, the apparent sum of squares reduction may in large part be influenced by such "hidden" relationships. That is to say, the particular independent variable in part repeats information associated with a more meaningful variable, and to that extent it is "redundant".

Redundant variables, that is, variables that in large part restate what some other variable has already measured, are common in early stages of quantification in the observational sciences, especially when physical models are not clearly discernible in the complex of observations. In these cases a method for "sorting out" a set of independent variables in terms of their importance or meaningfulness in controlling the response of some dependent variable, Y, helps to reduce the number of variables in the set to more manageable proportions. This process was conveniently accomplished in this study by the step-wise regression method.

Of the three variables (water depth, X1; per cent sand, X2; water-content, X3) that occur most frequently in the strongest combinations of Table 2, both per cent sand and water-content are redundant with water depth. As water depth increases the per cent sand decreases and sediment water-content increases. (Thus, water-content varies inversely with per cent sand.) Because of these redundant relationships, we may arbitrarily discard water depth and per cent sand in the final evaluation of the single most-significant environmental variable that occurs in combination with the others. It is perhaps not surprising that water-content, a "mass" property of the environment, is in fact (Table 2) the most significant of the environmental variables, when in combination. As a mass property it reflects the interrelationships of mean grain size, sorting, grain packing, grain mineralogy, and other factors.

Of the seven environmental variables considered, Sorting Coefficient was significant only in the three-variable analysis for Ensis. (Water-content and one of the sediment types were highest in per cent SS reduction.) Sediment type has often been shown to be of importance in distribution of infauna (Sanders 1958, 1960), but water-content apparently has not previously been considered in a subtidal area. However, Gee (1961) found a species of amphipod, Corophium arenarium, "more closely defined by water-content than by substratum composition" in an intertidal area. He further concluded that, "Where an area is fairly homogeneous with regard to substrate composition water-content becomes an important factor limiting distribution." The results of this study tend to bear out Gee's conclusion.

CONCLUSIONS

Limitations have been mentioned for the linear model used here in a least-squares search for significant combinations of independent variables found in a set of noisy and redundant data.

It seems clear, however, that while the investigator can make subjective judgments as to the environments preferred by organisms, careful determinations of the environmental variables, coupled with analytical techniques like the least-squares search procedure used here can more accurately suggest or delineate species requirements. The importance of water-content as a determinative environmental variable is suggested in this study by its repeated appearance (Table 2) as an influential independent variable when in combination with one or two of the other independent variables. It would seem wise to provide for careful measurement of this variable in future studies of animal-sediment relationships.

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