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Trend-Surface Analysis of Chemical and Physical Variables from a Pilot Survey of Morecambe Bay

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1. Introduction

This paper presents the results of a trend-surface analysis of data on the chemical and physical properties of sand and mud samples taken during the pilot survey of Morecambe Bay. The data were not originally collected with this analysis in mind, but it was felt that the methods of trend-surface analysis were particularly appropriate to the objectives of the survey and the method of investigation. Trend-surface analysis has been described in detail by Merriam and Harbaugh, 1968, but has not been applied extensively to surveys of chemical, physical, or biological variables in ecological studies. The application described in this paper, therefore, represents a trial of the technique under practical conditions in Britain. The paper nevertheless concentrates on results rather than techniques, and more detailed descriptions of the application of trend-surface plotting to ecological surveys will appear in other papers.

The data for the pilot sample of Morecambe Bay were derived from forty-four sampling points within the Bay, from which samples of the sand and mud were taken. The physical and chemical properties of these samples were determined by the Chemical Service of the Merlewood Research Station for two depth zones, namely 0-5cms. and 0-10cms. Because of the preliminary nature of the investigation, many of the chemical and physical variables selected for analysis were strongly intercorrelated, and it is clear that not all of them are necessary to describe the variability of the physical and chemical changes occurring over the extent of the Bay. The nature of the primary dimensions of the variability measured by the variables is investigated in another paper, and will not be further discussed here, except to the extent that some variables show similar trends when plotted.

2. Variables included in the Analysis

The variables determined on the samples of sand and mud taken from two vertical cores at the forty-four sampling points, and including the 0-5cms. zone, are listed in Table 1.

Similarly, the variables determined on the samples taken from the 0-10cms. zone at forty-one of the sampling points are listed in Table 2. Some of the determinations on the samples from all forty-four sampling points gave obviously false results in the analysis, and, in order to simplify the subsequent handling of the data, the whole of the data for three points have been discarded at this zone.

3. Brief Description of the Method of Analysis

The regression of each of the variables of the two sets listed in Tables 1 and 2 were calculated on the linear, quadratic, and cubic terms of the grid co-ordinates of the sampling positions within Morecambe Bay. Three separate regressions were computed for each variable, namely:-

$$Z = a + bX + cY$$

$$Z = a + bX + cY + dX^2 + eY^2 + fXY$$

$$Z = a + bX + cY + dX^2 + eY^2 + fXY + gX^3 + hY^3 + iX^2Y + jXY^2$$

where X and Y are the grid co-ordinates, Z is the dependent variable, and a, b, c, d, e, f, g, h, i, j are fitted constants.

Table 1 List of Variables determined on Cores from 0-5cms.

Variable Number	Description
1	H_2O per cent
2	Loss on ignition, per cent dry
3	Density
4	Na (ppm) in intersticial water
5	P (ppm) in intersticial water
6	NO_3+NO_2+N (ppm) in intersticial water
7	NH_4 - N (ppm) in intersticial water
8	Na (mg/1) in wet sand
9	P (mg/1) in wet sand
10	NO_3+NO_2+N (mg/1) in wet sand
11	NH_4 - N (mg/1) in wet sand
12	Na per cent in dry sand
13	P per cent in dry sand
14	NO_3+NO_2+N per cent in dry sand
15	NH_4 - N per cent in dry sand
16	K per cent total
17	Ca per cent total
18	P per cent total
19	N per cent total

Table 2 List of Variables determined on Cores from 0-10cms.

Variable Number	Description
1	H_2O per cent
2	Loss on ignition, per cent
3	Density
4	Na (ppm) in intersticial water
5	P (ppm) in intersticial water
6	NH_4 - N (ppm) in intersticial water
7	Na (mg/1) in wet sand
8	P (mg/1) in wet sand
9	NH_4 - N (mg/1) in wet sand
10	Na per cent in dry sand
11	P per cent in dry sand
12	NH_4 - N per cent in dry sand
13	K per cent total
14	Ca per cent total
15	P per cent total
16	N per cent total
17	Coarse sand per cent
18	Fine sand per cent
19	Silt per cent
20	Clay per cent

The fitted regressions represent the linear, quadratic, and cubic trends of the dependent variables over the space sampled by the sampling points, and, by applying the normal methods of multiple regression analysis, it is possible to determine if any significant proportion of the variability of the dependent variable is accounted for by the linear trend, and whether any significant improvement in the fit can be obtained by adding the quadratic and cubic terms. In this way, it is possible to describe the general trends of the variation over the sampled area, and to separate random variation from variation indicating general trends. It is, of course, possible that the variation over the area is following trends that are too complex to be expressed by the form of the regressions chosen in this application. Preliminary examination of the data, and consideration of the pattern of distribution of the sampling points, however, suggests that little would be gained by the use of more complex trend equations for the Morecambe Bay data.

The regression equations which accounted for significant proportions of the variability of the dependent variables were used to predict the values of the variables over the whole range of the sampled area. These predicted values were then plotted automatically by computer as contour maps showing the general trends of the variability.

4. Results: Cores from 0-5cms.

The proportions of the variability accounted for by the linear, quadratic, and cubic terms of the regressions of the dependent variables of Table 1 on the grid co-ordinates are given in Table 3.

For six of the variables measured on cores from 0-5cms. (i.e. for moisture content; sodium content of intersticial water, dry sand, and wet sand; and for NO_3+NO_2-N in wet sand and dry sand) only the linear terms of the regressions on grid co-ordinates were statistically significant. For moisture content, and for NO_3+NO_2-N in wet and dry sand, the regression equations accounted for about one quarter of the total variability, but for the sodium contents, the regressions accounted for 29 to 49 per cent of the total variability, the 49 per cent being obtained in the variation of the sodium content in the intersticial water.

The trend surfaces for these variables are plotted in Figures 1-6. In these, and all subsequent trend surface plots, the dotted areas represent land surrounding the sampled area of Morecambe Bay. The figures giving the contours of the trends are proportional to the predicted values of the variables, so that 0 represents a very low value and 9 represents a very high value. The interval between the contours is shown beneath each figure, and provides a reference scale to the extent of the variation.

It is clear that, for the six variables showing only linear trends, the variation is mainly in the NE-SW axis. For the moisture content and NO_3+NO_2-N, the quantities decreased as the sampling points moved to the SW, i.e. towards the mouth of the Bay. For the sodium content, the quantities increased as the sampling points moved towards the mouth of the Bay. The coefficients defining the predictive equations used in plotting these trend surfaces are given in Table 4.

Table 3 Proportions of Variability accounted for by the Linear, Quadratic, and Cubic Terms of the Regressions on Grid Co-ordinates: 0-5cms.

Variable	Proportion of Variability			Cumulative proportions	
	Linear	Quadratic	Cubic	Quadratic	Cubic
1	0.2391**	0.1223	-	0.3614	-
2	0.0859	0.0290	0.1705	0.1149	0.2854
3	0.1207	0.1134	0.1226	0.2341	0.3567
4	0.4901***	0.0338	-	0.5239	-
5	0.0664	0.0285	0.0989	0.0949	0.1938
6	0.2242**	0.0238	0.1656*	0.2840	0.4136
7	0.1065	0.0291	0.0645	0.1356	0.2001
8	0.3806***	0.0206	0.0115	0.4012	0.4127
9	0.1123	0.0052	0.0741	0.1175	0.1916
10	0.2565**	0.0197	0.1408	0.2762	0.4170
11	0.1156	0.0432	0.0635	0.1588	0.2223
12	0.2926***	0.0195	0.1308	0.3121	0.4429
13	0.1208	0.0025	0.0682	0.1233	0.1915
14	0.2676**	0.0197	0.1220	0.2873	0.4093
15	0.1145	0.0546	0.0580	0.1691	0.2271
16	0.1202	0.2530**	0.0325	0.3732	0.4057
17	0.0268	0.2698**	0.1292	0.2966	0.4258
18	0.2478*	0.1861**	0.0551	0.4339	0.4890
19	0.0146	0.2250**	0.0553	0.2396	0.2949

Table 4 — Coefficients defining Predictive Equations

Variable	Constant	X	Y
1	10.805037	1.234637	0.849749
4	25888.758	-1707.914	-1727.019
8	8418.4520	-473.3568	-562.4992
10	-1.437259	0.059472	0.212563
12	534.1207	-27.526261	-32.88919
14	-0.110950	0.004728	0.016197

Table 5 — Coefficients defining Quadratic Predictive Equations

Variable	Constant	X	Y	X^2	Y^2	XY
16	2.174973	[illegible].629653	-0.908752	0.046121	0.101193	-0.134343
17	53.83254	-6.132583	-11.50361	0.782382	0.609587	0.041382
18	0.102451	0.048568	-0.046276	0.006018	0.006340	-0.012570
19	0.465642	0.008939	-0.137763	0.010967	0.013105	-0.012498

For four of the variables measured on cores from 0-5cms. - the percentages of potassium, calcium, phosphorus, and nitrogen of the total sample - the quadratic terms of the regressions of the variables on the grid co-ordinates were significant in addition to those of the linear terms. The percentages of the total variability accounted for by the quadratic trend surfaces were 37, 30, 43, and 24 per cent respectively.

The trend surfaces for these variables are plotted in Figures 7-10. For calcium and nitrogen, the surfaces are fairly similar, the lowest concentrations of the elements being found in the centre of the Bay, with a slight increase towards the shore and a greater increase towards the mouth of the Bay. Potassium shows highest values close to the shores, with a long trough in the centre of the Bay extending out towards its mouth. Phosphorus shows a rather similar, but shallower, trough. The coefficients defining the predictive equations used in plotting these surfaces are given in Table 5.

It is perhaps worth noting here that, because of the very high degrees of intercorrelation between the regressor variables, there is no point in attempting any interpretation of the coefficients in Table 5, or in Table 6 which follows. Only for NO_3+NO_2-N in interstitial water were the cubic terms of the regression on the grid co-ordinates significant, the full cubic regression accounting for 41 per cent of the total variability. The trend surface for this variable is plotted in figure 11, and represents a rather complex surface with the lowest values close to the Morecambe and Aldingham coasts, with a slight rise towards the Kent and Leven estuaries, and a more rapid increase towards the mouth of the Bay. The coefficients for the trend surface of this variable are given in Table 6.

Table 6 Coefficients defining Cubic Predictive Equation

Regressor Variable	NO_3+NO_2-N in interstitial water
Constant	239.82984
X	-94.606070
Y	-49.645710
X^2	5.912160
Y^2	1.784825
XY	19.443900
X^3	2.341357
Y^3	-0.275767
X^2Y	-4.574609
XY^2	1.107741

Table 7. Proportions of Variability accounted for by the Linear, Quadratic and Cubic Terms of the Regressions on Grid Co-ordinates: 0-10 cms.

Variable	Proportion of Variability			Cumulative Proportions	
	Linear	Quadratic	Cubic	Quadratic	Cubic
1	0.2385**	0.2092**	-	0.4477	-
2	0.0385	0.1428	0.0137	0.1813	0.1950
3	0.1528*	0.1728*	0.0445	0.3256	0.3701
4	0.4222***	0.2227***	-	0.6449	-
5	0.2555**	0.0657	0.0340	0.3212	0.3552
6	0.0622	0.0093	0.1692	0.0715	0.2407
7	0.3340***	0.2330**	-	0.5670	-
8	0.2263**	0.0962	0.0301	0.3225	0.3526
9	0.0871	0.0171	0.1279	0.1042	0.2321
10	0.3257***	0.2587***	0.0099	0.5844	0.5943
11	0.2298**	0.1013	-	0.3311	-
12	0.0937	0.0198	0.2250*	0.1135	0.3685
13	0.1845*	0.1988*	0.0216	0.3833	0.4049
14	0.0747	0.2189*	-	0.2936	-
15	0.3183***	0.1771*	0.0200	0.4954	0.5154
16	0.0055	0.1552	0.0728	0.1607	0.2335
17	0.1312	0.1964*	0.0308	0.3276	0.3584
18	0.1390	0.2019*	0.0131	0.3409	0.3540
19	0.1671*	0.2164*	-	0.3835	-
20	0.0298	0.1164	0.0929	0.1462	0.2391

Table 8. Coefficients Defining Linear Predictive Equations

Variable	Constant	X	Y
5	-0.208553	-0.264477	0.226245
8	-0.184808	-0.089267	0.095143
11	-0.017017	-0.006209	0.007277

The regressions for the percentages of potassium, calcium, and phosphorus accounted for 38, 29 and 49 per cent respectively of the total variability of the variables, and the corresponding trend surfaces are plotted in figures 20, 21, and 22. The three surfaces are very different in form. That for potassium suggests a shallow trough rather similar to the trends for moisture content, and with relatively high values in the two estuaries and along the coasts. The surface for calcium is a bowl-shape, with the lowest values of calcium in the centre of the Bay. The surface of the percentage of phosphorus shows relatively high values along the SE shores of the Bay, with low values at the mouth of the Bay, and only moderate values to the N.

The quadratic regressions for the percentages of coarse sand, fine sand, and silt on the grid co-ordinates accounted for between 33 and 38 per cent of the total variability, and the corresponding surfaces are plotted in figures 23, 24, and 25. The percentage of coarse sand is at its lowest in the northern part of the Bay, but increases fairly rapidly towards the mouth of the Bay. In contrast, the percentage of fine sand is highest in the northern part of the Bay but decreases rapidly towards the mouth of the Bay. The percentage of silt shows its lowest values in the mouth of the Leven estuary and round Humphrey Head, but again increases fairly rapidly towards the mouth of the Bay.

The coefficients defining the predictive equations used in plotting the quadratic trend surfaces are given in Table 9.

<u>Table 9.</u> <u>Coefficients Defining Quadratic Trend Surfaces</u>

Variable	Constant	X	Y	X^2	Y^2	XY
1	-88.8408	16.7678	20.2613	1.48068	-0.31863	-3.80310
3	3.67132	0.37824	-0.70724	-0.01726	0.05818	-0.03830
4	-121434.	8139.87	34893.5	-2982.94	-2952.23	1608.20
7	-57191.7	6777.33	14156.6	-976.822	-993.153	-61.3520
10	-4596.46	507.361	1137.43	-72.1035	-79.0441	-5.32430
13	-1.95020	0.45402	0.34417	0.04784	0.00656	-0.11018
14	19.6112	-2.04418	-4.09845	0.46608	0.34915	-0.17731
15	0.01668	0.06090	-0.02815	0.00148	0.00435	-0.00965
17	859.585	-36.5127	-215.795	-4.49771	12.1970	9.72777
18	-872.557	51.2647	239.101	0.92230	-14.3253	-8.05598
19	117.354	-13.3852	-25.1964	0.94864	1.50062	0.86325

For only one variable, i.e. NH_4-N in dry sand, were the cubic terms of the regression of the variable on the grid co-ordinates significant, the full cubic regression accounting for about 37 per cent of the total variability. The trend surface for this variable is plotted in figure 26, and represents a rather complex ridge running from Morecambe to Humphrey Head, with low values at the mouth of the Bay. The coefficients defining this surface are given in Table 10.

There were no significant regressions of the other variables - loss on ignition, density; phosphorus in intersticial water, dry sand, or wet sand; NH_4-N in intersticial water, dry sand or wet sand - measured in cores from 0-5cms. on the grid co-ordinates, and no significant trends across the sampled area can, therefore, be ascribed to these variables. The observed variation can either be attributed to random fluctuations or to isolated groups of high values.

The analysis of the results from these samples suggests, therefore, that at least some of the observed variation in most of the variables can be attributed to general trends across the sampled area. These trends follow three broad patterns. For moisture content, sodium content, and NO_3+NO_2-N in wet and dry sand, the general trend is linear, with the main axis of variation running NE-SW. Moisture content and NO_3+NO_2-N decrease in value towards the mouth of the Bay, while the sodium content increases. For the total percentages of potassium, calcium, phosphorus, and nitrogen, the general trends are more complex, with low values in the centre of the Bay, rising to higher values near the shores. The most complex surface is given by NO_3+NO_2-N in the intersticial water, where there are low values close to the Morecambe and Aldingham coasts, a slight rise towards the Kent and Leven estuaries, and a more rapid rise towards the mouth of the Bay. The variables of loss on ignition; density; phosphorus in intersticial water, dry and wet sand; and NH_4-N, showed no significant trends in their variability.

5. Results: Cores from 0-10cms.

The proportions of the variability accounted for by the linear, quadratic, and cubic terms of the regression of the dependent variables of Table 2 on the grid co-ordinates are given in Table 7.

For four of the variables measured on cores from 0-10cms. (i.e. for moisture content, and for phosphorus in intersticial water, wet sand, and dry sand) only the linear terms of the regressions on the grid co-ordinates were statistically significant, the proportion of the variability accounted for being approximately one quarter in all four variables. The trend surfaces of these variables are plotted in figures 12-14, and show the level of phosphate tending to decrease along the NW-SE axis. The coefficients defining the predictive equations used in plotting these surfaces are given in Table 8.

For eleven of the variables measured on cores from 0-10cms. - the moisture content, density, sodium in intersticial water, wet sand, and dry sand, percentage potassium, percentage calcium, percentage phosphorus, and the percentages of coarse sand, fine sand, and silt - the quadratic terms of the regressions of the variables on the grid co-ordinates were significant.

For moisture content and density, the quadratic regressions accounted for 45 and 33 per cent respectively of the total variability. The trend surfaces for these variables are plotted in figures 15 and 16. The trends for moisture content suggests a shallow trough with its highest values close to the shores of the Kent and Leven estuaries. The surface for density shows relatively low values in the Kent estuary and along the Arnside coast.

The quadratic regressions for sodium in intersticial water, wet sand, and dry sand accounted for from 57 to 64 per cent of the total variability, and the trend surfaces for these variables are plotted in figures 17, 18 and 19. All three surfaces suggest a dome-shaped structure with the highest values south of the Leven estuary, the highest values in intersticial water being slightly further south than in wet sand or dry sand.

Table 10. Coefficients Defining Cubic Predictive Equation

Regressor Variable	NH_4-N in dry sand
Constant	-9.412024
X	0.418250
Y	3.363721
X^2	0.785683
Y^2	-0.218914
XY	-0.848899
X^3	-0.073422
Y^3	-0.000337
X^2Y	0.000914
XY^2	0.055680

There were no significant variables of the other variables measured on the 0-10cms. cores - loss on ignition, NH_4-N in intersticial water and wet sand, percentage nitrogen, and clay percent - on the grid co-ordinates.

The analysis of these variables again suggests that a considerable proportion of the variability of most of the variables assessed can be attributed to broad trends across the sampled area of the Bay. Again, the trends follow a relatively small number of basic patterns, and only one of the variables shows a complex pattern of variability not apparently related to those of the other variables.

6. Discussion

The method of trend surface analysis used in this investigation has shown itself capable of revealing broad trends in the patterns of variation of individual variables across the Bay. Some of these patterns are immediately acceptable, others are surprising and suggest the need for verification of interpretation. There are some obvious objections to the analysis, notably in the extrapolation of the trends at the seaward end of the Bay, and the absence of any indications of the main channels within the Bay, but the main purpose of the exercise has been to reveal the underlying trends upon which other variations may be superimposed. Perhaps the most difficult barrier to overcome is the very natural tendency for the biologist to want to associate particular spots on the map with actual values, rather than to visualise the broad trend of variability across the whole Bay, and, in fact, to read more into the trend surfaces than is justified by the nature of the technique.

Nevertheless, the investigation has shown that reasonably convincing trends can be revealed and plotted from limited amounts of survey material, and the wider use of the technique could reduce the numbers of samples that are customarily taken by ecologists in surveys of this kind. The method of analysis requires very little additional work, beyond access to a suitably programmed computer, and all the maps and equations are produced automatically by the computer.

It is of some interest that the two sets of data, from cores at 0-5cms. and at 0-10cms., produced broadly similar results, but that there were obvious differences between the patterns at the two levels of sampling. This was certainly to be expected, and the greater number of significant trends for the variables measured on the 0-10cms. cores suggests that sampling at this depth gives a more consistent picture of the environmental factors of the Bay. The similarity between the basic patterns for many of the variables again suggests that these variables are intercorrelated, so that further economy of effort could be obtained by reducing the number of variables assessed to a smaller number of basic dimensions. A method of making this choice is discussed in another paper.

7. Reference

Harbaugh, J.W. and Merriam, D.F. 1968. Computer applications in stratigraphic analysis. John Wiley & Sons, Inc., London and New York.

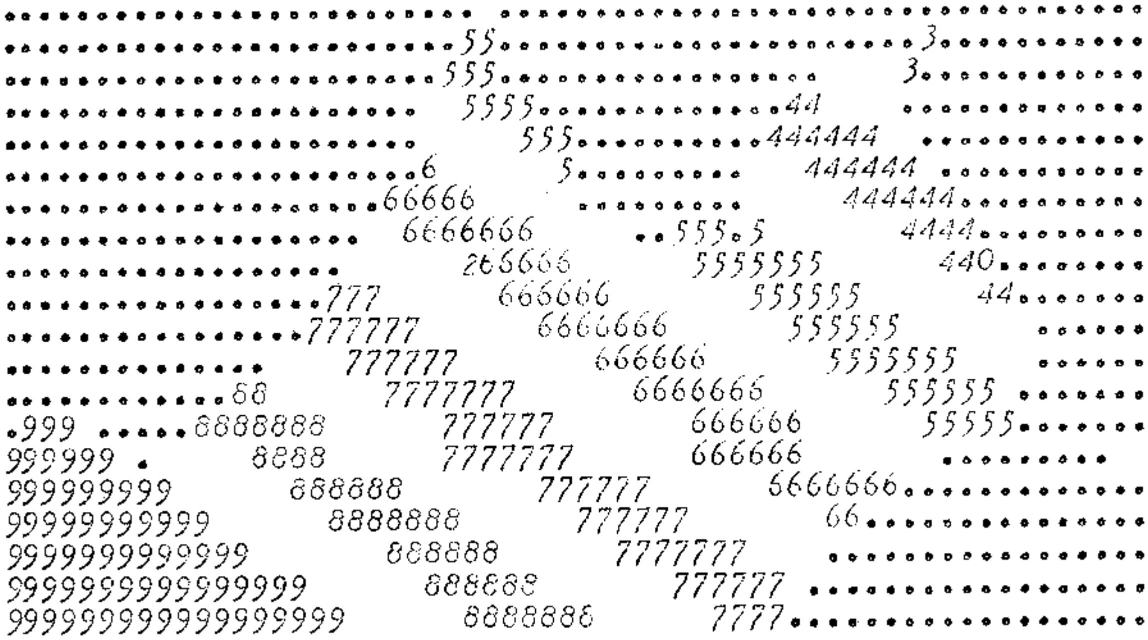
h2o percent figure 1

contour step = 0.5

na (ppm) in intersticial water figure 2

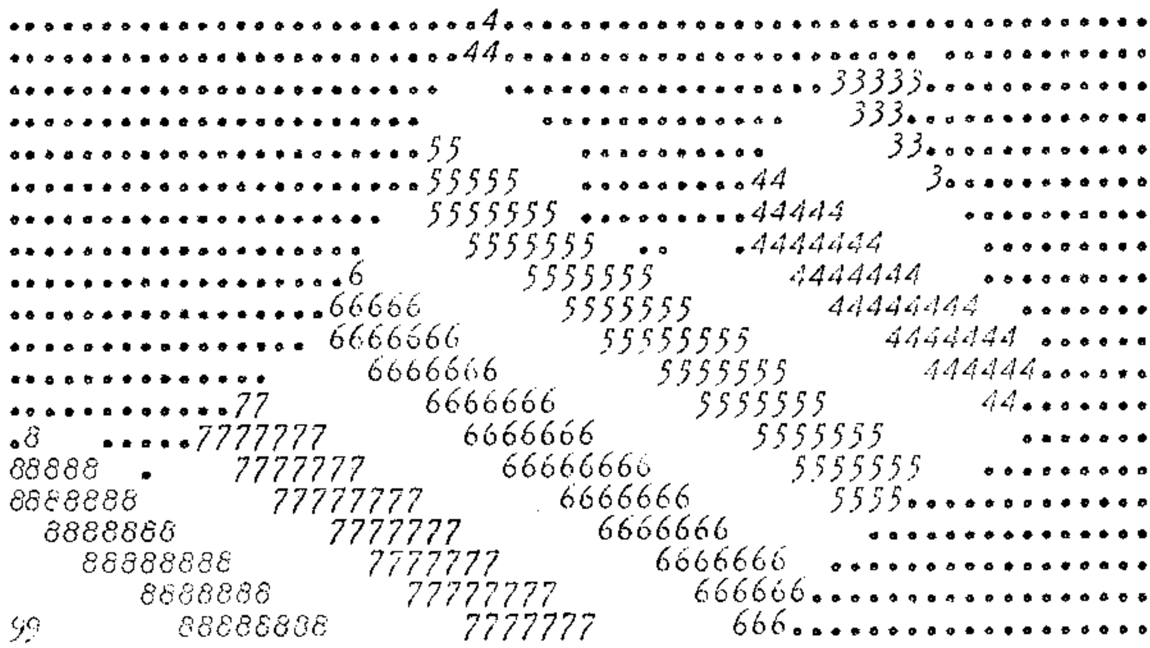
contour step = 500

ra (mg/l) in wet sand figure 3



contour step = 150

ra percent in dry sand figure 4

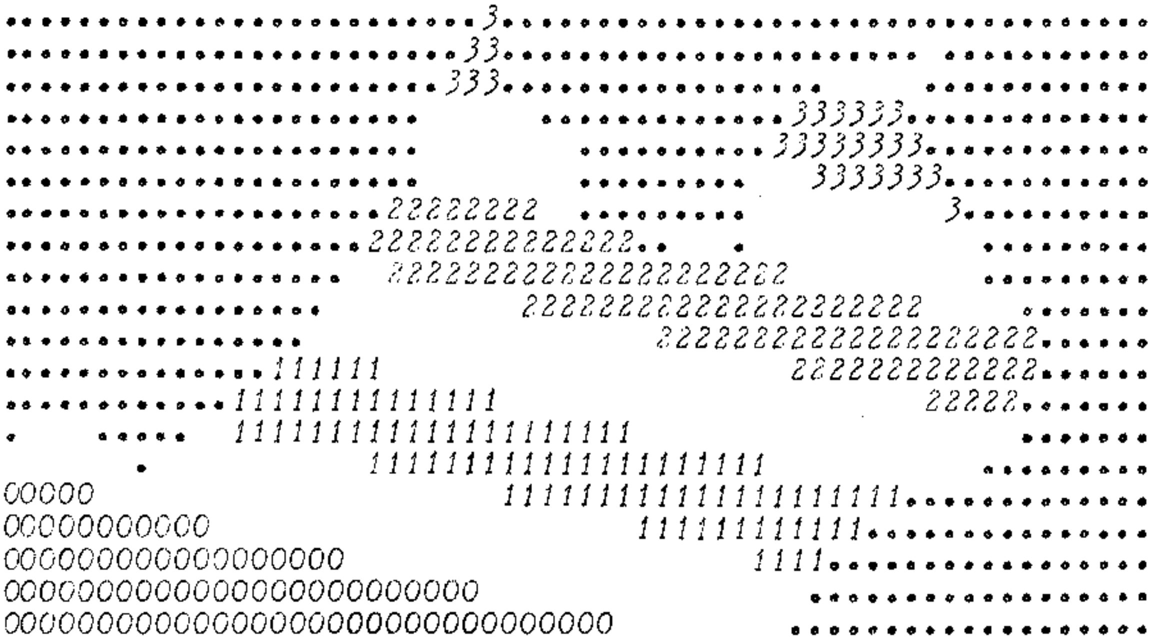


contour step = 10

no3+no2-n wet sand figure 5

contour step = 0.005

no3+no2-n dry sand figure 6



contour step = 0.005

k percent total

figure 7

contour step = 0.015

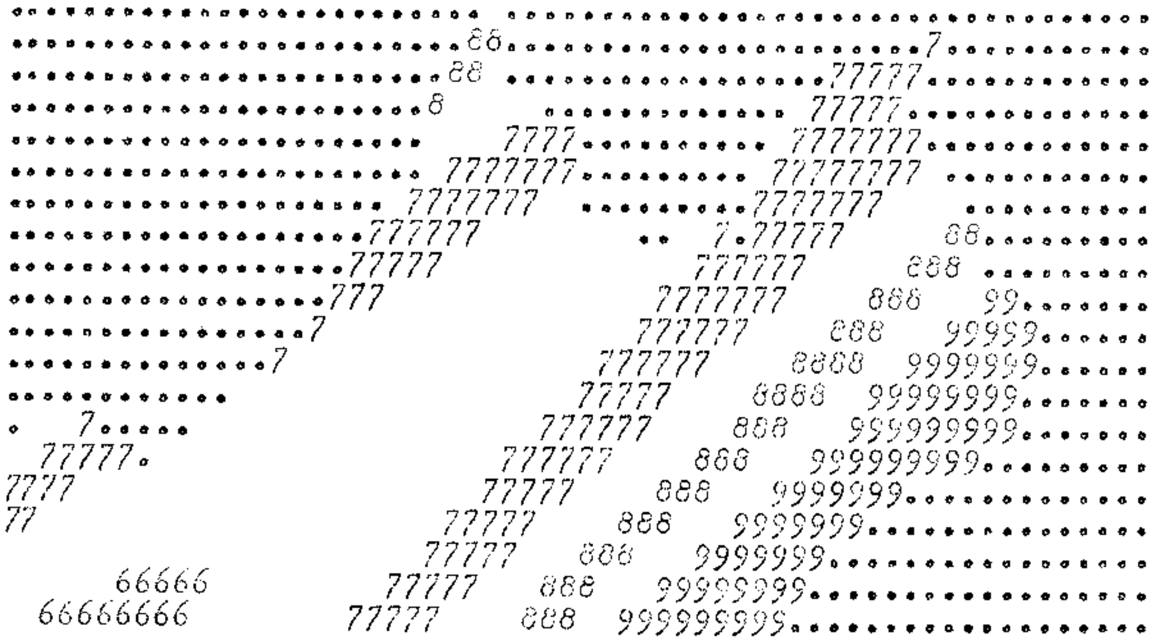
ca percent total

figure 8

contour step = 0.5

p percent total

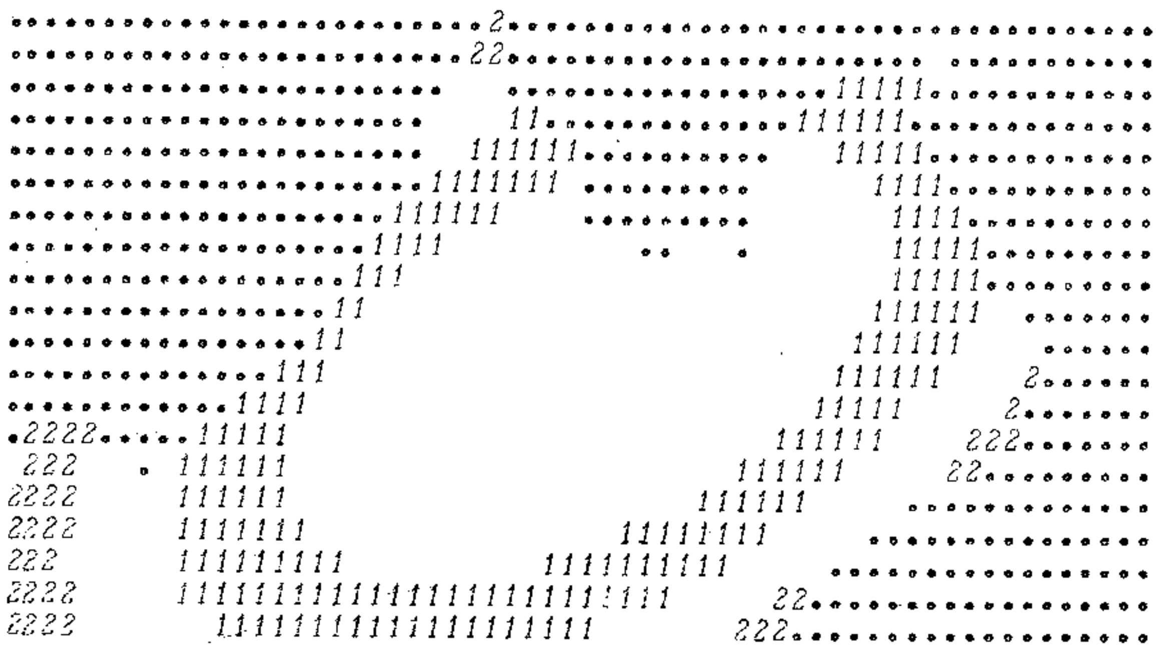
figure 9



contour step = 0.002

n percent total

figure 10



contour step = 0.005

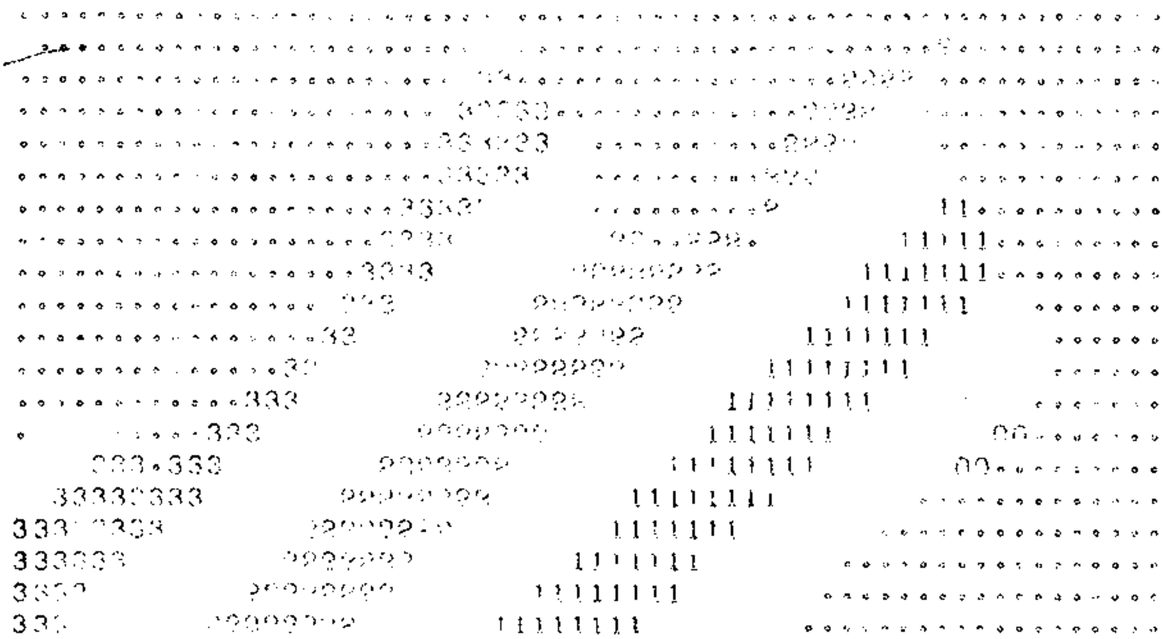
no3+no2-n (ppm) in intersticial water

figure 11

contour step = 0.2

P-[illegible] INTERSTICIAL WATER

[illegible] 12



CONTOUR STEP = 0.10

P WET SAND

FIGURE 13

CONTOUR STEP = 0.05

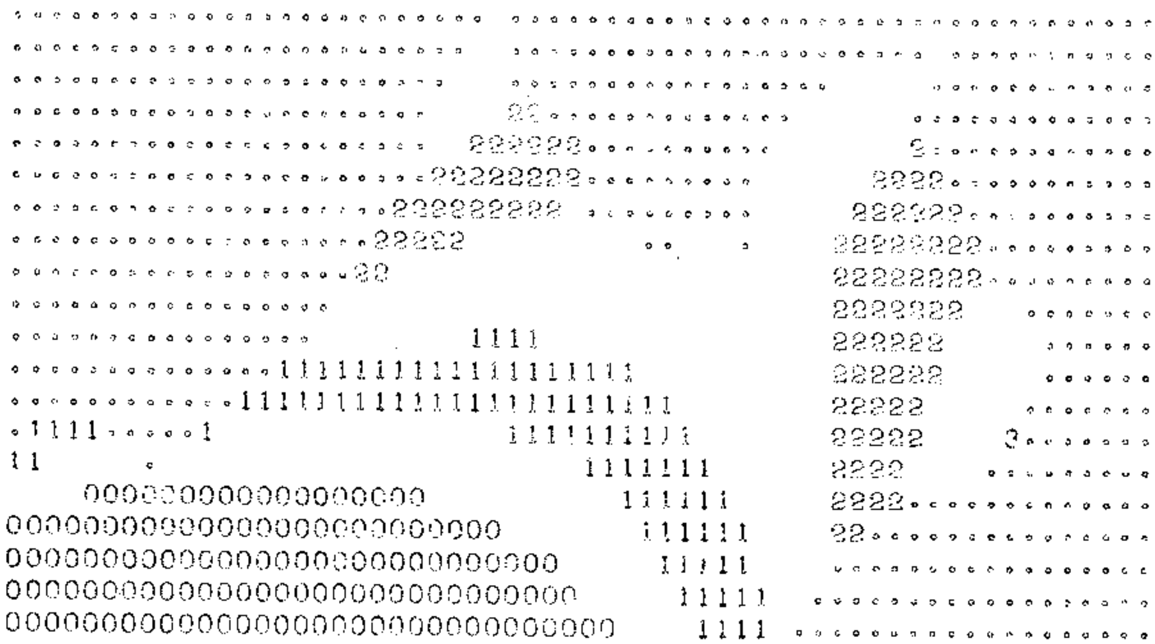
P DRY SAND

FIGURE 14

CONTOUR STEP = 0.0025

MOISTURE CONTENT

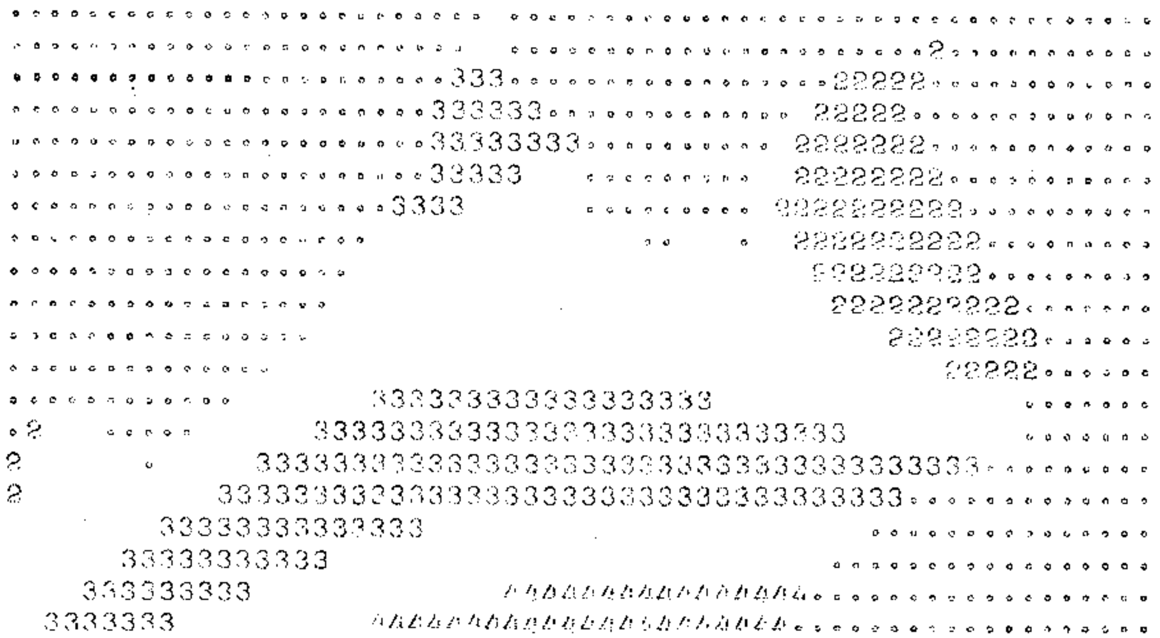
FIGURE 15



CONTOUR STEP = 1.0

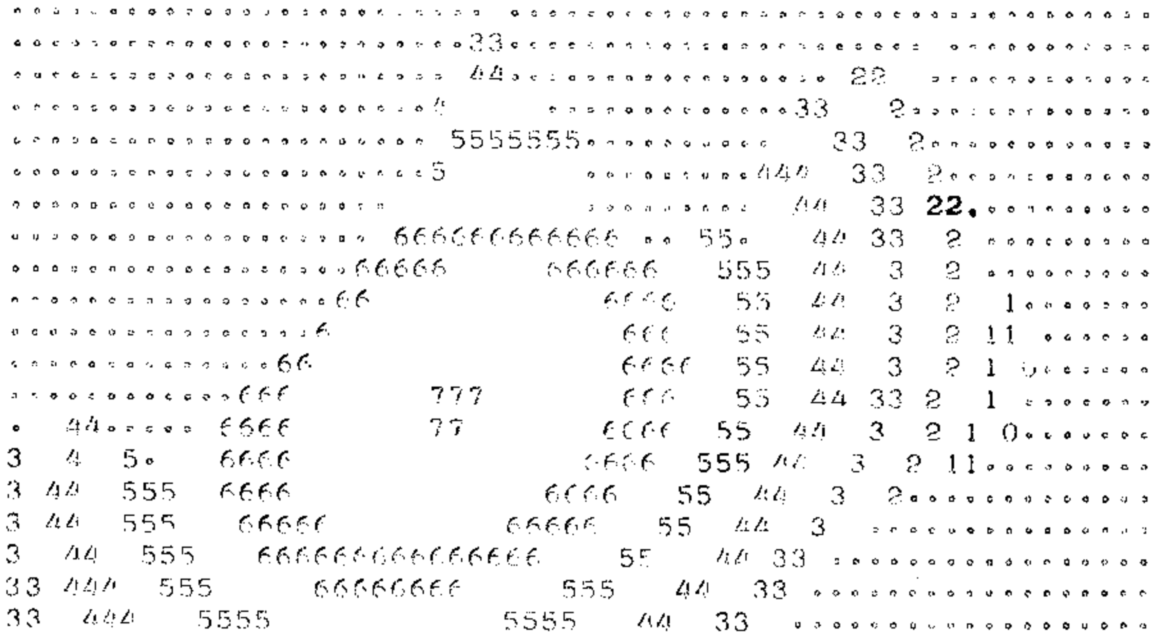
DENSITY

FIGURE 16



CONTOUR STEP = 0.025

NA INTERSTICIAL WATER FIGURE 17



CONTOUR STEP = 500

NA WET SAND FIGURE 18

CONTOUR STEP = 250

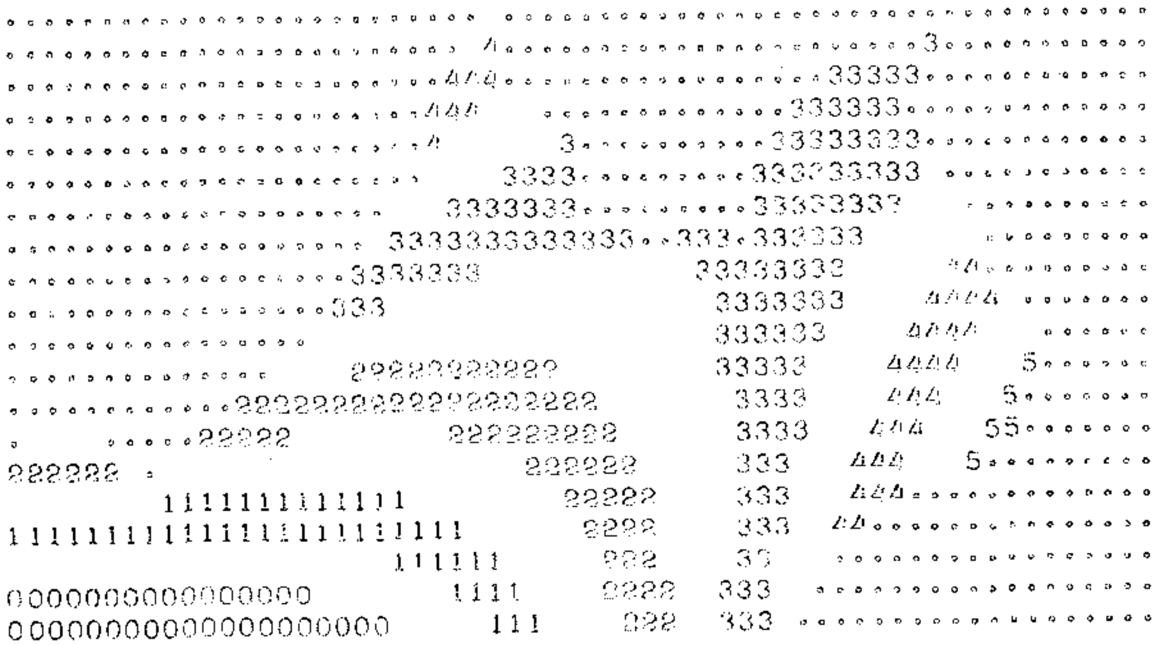
MA DRY SAND

FIGURE 19

CONTOUR STEP = 20

K PERCENT

FIGURE 20



CONTOUR STEP = 0.020

CA PERCENT **FIGURE 21**

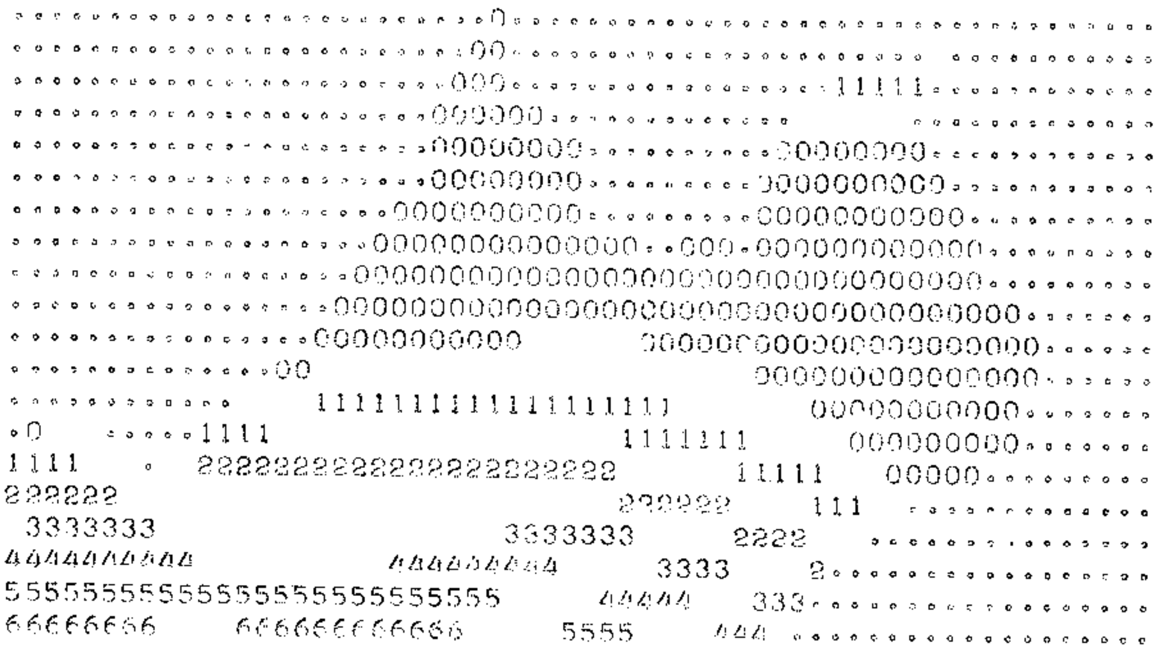
CONTOUR STEP = 0.10

P PERCENT FIGURE 22

CONTOUR STEP = 0.002

COARSE SAND PERCENT

FIGURE 23



CONTOUR STEP = 2.0

FINE SAND PERCENT

FIGURE 24

CONTOUR STEP = 5.0

SILT PERCENT FIGURE 25

CONTOUR STEP = 0.5

MB DRY SAND FIGURE 26

CONTOUR STEP = 0.01