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Trend-Surface Analysis of Ocean Outfall Plumes

The analysis indicated a high correlation between digitized photographic image data and measures of dissolved oxygen.

WATER-QUALITY analysis in the vicinity of ocean outfalls is of prime concern to many of our coastal communities. Of special significance is the areal impact of the effluent and the spatial distribution of the discharge-dispersion zone. On the exposed coasts, the spatial distribution of water quality will be dependent on the specific wave and current conditions at the time of pumping and the mixing characteristics of the water column in the vicinity of the outfall.

ABSTRACT: *Measures of water quality associated with ocean outfall effluent plumes are approached through the use of standard photographs which are transformed into numerical data sets and handled by the statistical technique of trend-surface analysis. The solutions for the trend surfaces are presented and the residuals are analyzed to discern their covariation with water-quality variables. A high correlation is indicated for the measures of dissolved oxygen and the values derived from the photographic images.*

Recent contributions to the literature point to the potential for aerial photographic techniques to provide some measure of discrimination of the effluent plume from its general background. Klooster and Sherz[5] depict the capabilities of film-filter combinations to highlight the target effluent plumes whereas Piech and Walker[8] point to the opportunity to use evaluations of photographic images as a means to contrast the target from its background. In a more specific vein, James and Burgess[4] suggest that it may be possible to correlate water-quality data and information derived from aerial photographs. However, Teleki, White and Prins[9] indicate that the future of such correlation lies in the digitization of the photographic images and the application of some method of density slicing to correlate photographs and ground-truth variables.

Following the work of the writers previously cited, this paper hopes to expand on the concept of the application of aerial photographic measurements to water quality study in the following manner:

1. by digitizing the photographic image on a transmission densitometer;
2. by applying trend surface analysis, a least-squares regression technique, to extract the spatial elements of the data matrix; and
3. following transformation of the data matrix, by establishing correlations between the digital values and the water-quality measurements.

This study was conducted during November, 1971, when the northern New Jersey shore communities (Figure 1) were scheduled to pump sewage sludge they had been collecting in storage tanks during that summer. The aerial photographic images were gathered by means of a camera bank consisting of three 35-mm. cameras affixed to a mount and set to fire simultaneously. Each camera had a particular film-filter combination to record a slightly different portion of the reflected light spectrum. One camera

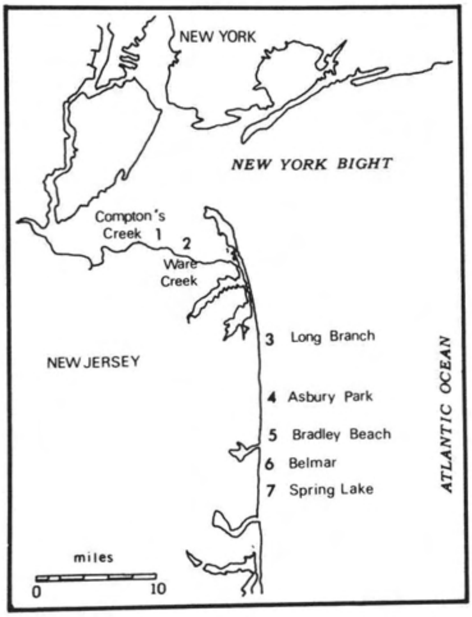

FIG. 1. Location map of sewage outfall areas.

used Ektachrome Aerial Infrared film with a No. 15 filter. Another had Agfachrome with a No. 2A (pale rose) filter and a polarizing filter, and the third had Kodachrome with a polarizing and an ultra-violet filter. The aerial platform was a helicopter which could assume a position directly over the release point and from which all coordination would be accomplished.

At each designated outfall site, seven in total, there was a boat prepared to take water-quality samples in and about the outfall. The boats were directed into position for sampling from the helicopter. On a radio signal, a water sample was collected and a photographic record was made of the sampling site relative to the total plume. If the plume could be identified through its reflected light characteristics, then it could be hypothesized that trends or gradations in plume values may be correlated with water-quality variables describing the effluent.

This association of the film image and water quality could lead to a series of contributions that might be made concerning areas of concentration, dispersion tendencies, the mechanics of mixing, and vectors describing effluent flow. On the other hand, the photographic process collects unwanted and sometimes confusing reflectance data. There may be uneven illumination across the film image. There may be an uneven return in the ambient light values coming back from the water body because of depth differences or other sources of reflected light.

Thus, before the value of the image can be quantitatively assessed as a data source for water quality or the problems of unwanted returns considered, the image must be transformed into a data matrix. This was accomplished by subjecting the image to a densitometer, Macbeth Transmission Model TD 404, for digitization. Measurements were made at 0.1-inch intervals across a 3-inch-by-3-inch area of the photographed plume. The aperture of the densitometer was set at 1 mm. and thus there was no overlap of the data points. The densitometer process produced a 30-by-30 matrix of 900 observations. However, due to a computer program constraint of 500 observations, the matrix was reduced to 20-by-25 which still encompassed the plume but reduced the area of non-plume or "normal" sea water.

The densitometer is measuring the quantity of total light transmission through the transparency. The transparency, in turn, has recorded total reflectivity from the target area. There are several components to the reflectivity recorded at these sites. There is the general reflection from the surface; there is return from the bottom passing through the water column; there is return from the water column; and there is return from the plume, not just the surface reflectivity but return from throughout the column of the plume. Output on the densitometer is directly related to the exposure levels in the three-layer film. High values represent high returns from the target area and specifically serve to identify the return from the plume.

The basic hypothesis to be tested in this project was that the light-reflectivity measurements of the plume, as collected by the photographic system and digitized by the densitometer, can be used as a surrogate value for water-quality variables. This is stating that those measures that describe the plume co-vary with measures that describe the water conditions in the plume. Further, an extension of this hypothesis states that the photographic densitometric method provides data covering an area rather than only points and portrays gradients, concentrations, and diffusion trends that are unavailable or much more difficult to obtain through the conventional point-sampling methods.

The guiding rationale is that there should be a causal relationship between water quality and the light reflectances recorded in the photographic process. The photographic analysis that derives from the hypothesized causality is made complex because there are both target and background reflectivities being recorded on the film and it will be

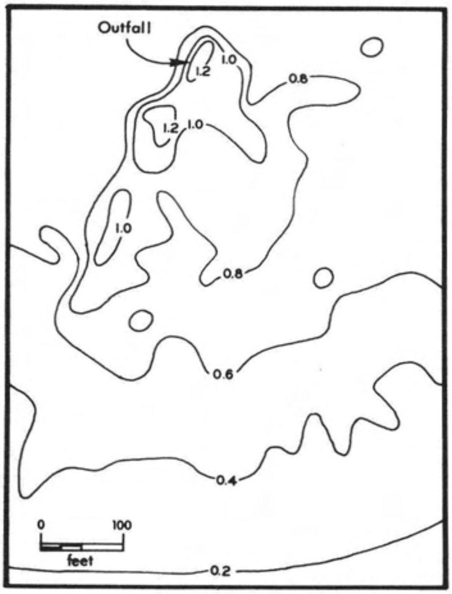

FIG. 2. Contoured densitometric values at Bradley Beach ocean outfall site.

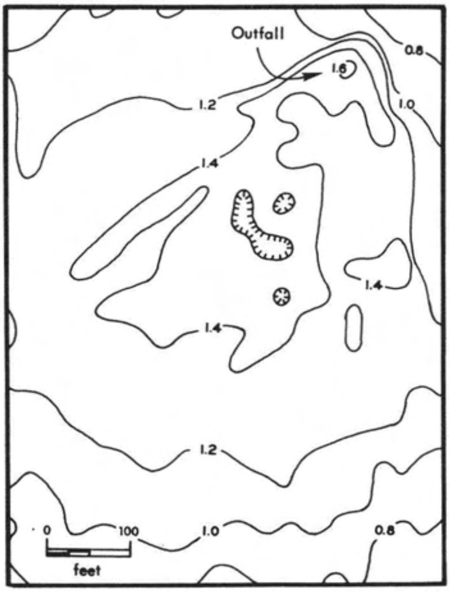

FIG. 3. Contoured densitometric values at Asbury Park ocean outfall site.

necessary to differentiate between the plume and the "normal" conditions beyond the plume. There may also be interference from the littoral environment in the form of waves and currents introducing reflectance variation into the photographic record. In each of these cases, regular or non-random fluctuations in the input may blur the causal inference that the variation in plume strength controls the light reflectance.

Simple isoplethic mapping of the digital measurements is one means of spatially describing the matrix. Figures 2 and 3 are contour maps of the raw densitometric data obtained on the plumes of Bradley Beach and Asbury Park, respectively. The maps do represent the photographic information field (Figures 4 and 5) to some extent but appear to be more complicated and do not clearly show the plume details. In these two cases, the mapping of the transmission values is of little assistance to the photographic interpreter.

In order to separate the target from its background, a least-squares regression model is employed. Because the interest is in the spatial array of the light values (Z) being located in specific positions (X, Y), the data matrix may be efficiently handled by the application of trend-surface analysis. The operations remain the same as in any regression problem even though trend-surface analysis operates in three dimensions instead of the normal two dimensions. The output will pro-

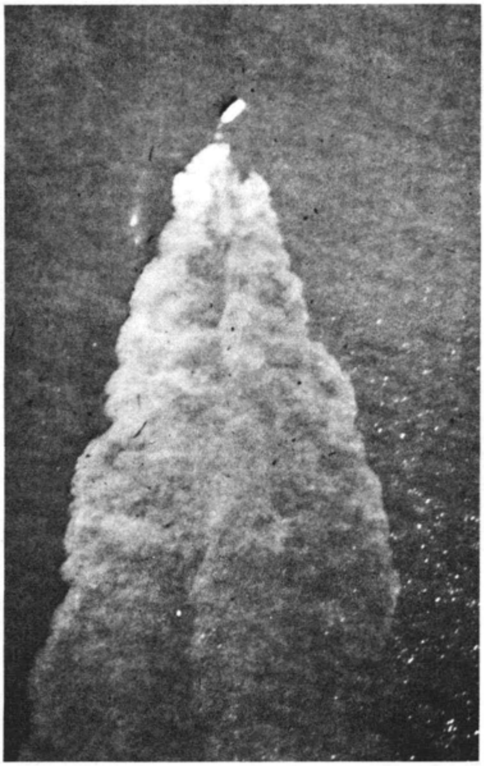

FIG. 4. Vertical photograph of outfall plume at Bradley Beach. The plume is moving from north to south, the shoreline is beyond the left margin of the photograph.

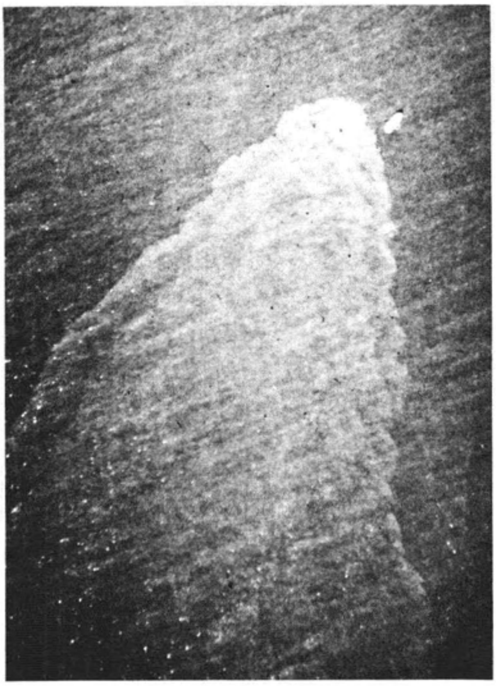

FIG. 5. Vertical photograph of outfall plume at Asbury Park. The plume is moving from north to south, the shoreline is beyond the left margin of the photograph.

vide a structured spatial description and normalized components of a standardized data field. Essentially, the trend-surface model separates a systematic trend (T) from the non-systematic component (e) in the mapped variable (Z). This takes the form of

$$Z\,(x,y) = T\,(x,y) + e\,(x,y). \qquad (1)$$

In its most simple form, a trend surface generates a plane that minimizes the sum of squares of the residual values. This planar model (or linear solution) is analogous to the two dimensional model of linear regression (Figure 6). The second-degree (or quadratic) solution adds one warping to the surface,

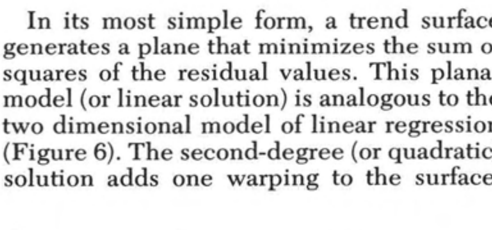

FIG. 6. Schematic diagrams of trend-surface solutions.

thereby providing a curved surface with greater flexibility in order to reduce further the amount of unexplained variation in the data field. Adding another possible warping increases even further the complexity of curvature of the least-squares surface but concomitantally reduces the amount of non-trend variation in this third-degree (or cubic) solution. The process can be continued, adding one possible warping at a time, through the fourth-, fifth-, and sixth-degree solutions. Each higher solution adds more inflexions to the surface and, as the solution becomes more complicated, the surface approaches a better fit to the data field which is reflected in the R^2 statistic.

If the data are available in a regular grid pattern, and if there is no theoretical reason for assuming periodicity (thereby negating the use of a Fourier model) the regular and non-regular components may be separated by the use of orthogonal polynomials[2]. However, this procedure is unduly complicated and the trend may be more easily extracted by a computer-generated least-squares matrix solution. For a non-planar surface this solution will take on the form of a polynomial equation. For example, the third-order (cubic) polynomial is

$$Z = a + bX + cY + dX^2 + eXY + fY^2 + gX^3 + hX^2Y + iXY^2 + jY^3. \qquad (2)$$

The use of trend-surface analysis may encompass two different modes of investigation. The continuous surface depicting the general trend of the data set can be very useful in a simple clarification of the information gathered. Also valuable in the interpretation of the data set is the examination, often through isoplethic mapping, of the residuals from the trend. There is a worthwhile discussion of the uses and limitations of trend-surface analysis in the literature[7]. These residuals constitute a spatially discrete distribution of values that may be used to evaluate the non-systematic components of the data field. As examples, geologists have used the trend-surface mode of study to approximate stratigraphic trends[1] while geographers have made use of the residual maps to separate the unique or local aspects of a distribution from its general or regional trend[3].

Whereas seven ocean outfall sewage plumes were photographed, only two will be presented here; they are the plumes at Bradley Beach and at Asbury Park. The Bradley Beach plume is emitted from an 18-inch pipe with a normal discharge of 1.16 million gallons per day. Wave and current levels were low to moderate at the time of photography and the outfall plumes were quite coherent. Although the plume outline was easily visible from the air, the team members on the vessels indicated that they could discern the boil on the surface over the discharge vent but could not detect the plume or any boundary.

The Bradley Beach outfall is fairly close to the shore (Figure 7) and a series of four water samples was obtained and synchronized with the photography. The specific locations were designated from the helicopter and included one near the outfall and three at increasing distances downcurrent from the boil.

Application of trend-surface analysis to the digitized photographic record produced rather striking results. At the Bradley Beach site, the first-degree surface has an R^2 of 72.8 per cent and describes a linear trend sloping downward to the south-southeast (Figure 8, T1). The major portion of the slope is a function of the outfall head at the top of the matrix and of the consequent diffusion towards the bottom. There is a left-to-right component of the slope as well; this may be the result of deeper water, greater diffusion, or a combination of both. It is the continuous linear-trend surface, then, that generalizes the data matrix as having higher values towards the top and lesser ones to the left. The residual map (Figure 8, R1) describes the more unique aspects

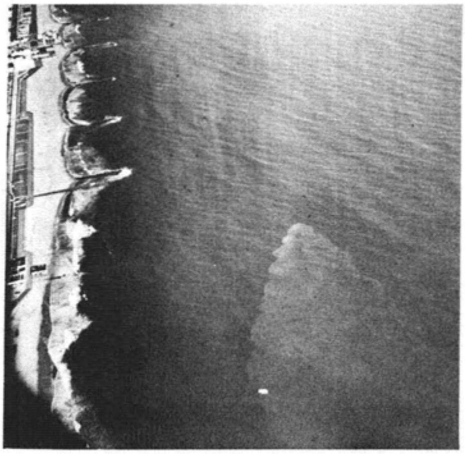

FIG. 7. Location of outfall near Bradley Beach and its relation to the shoreline, looking north.

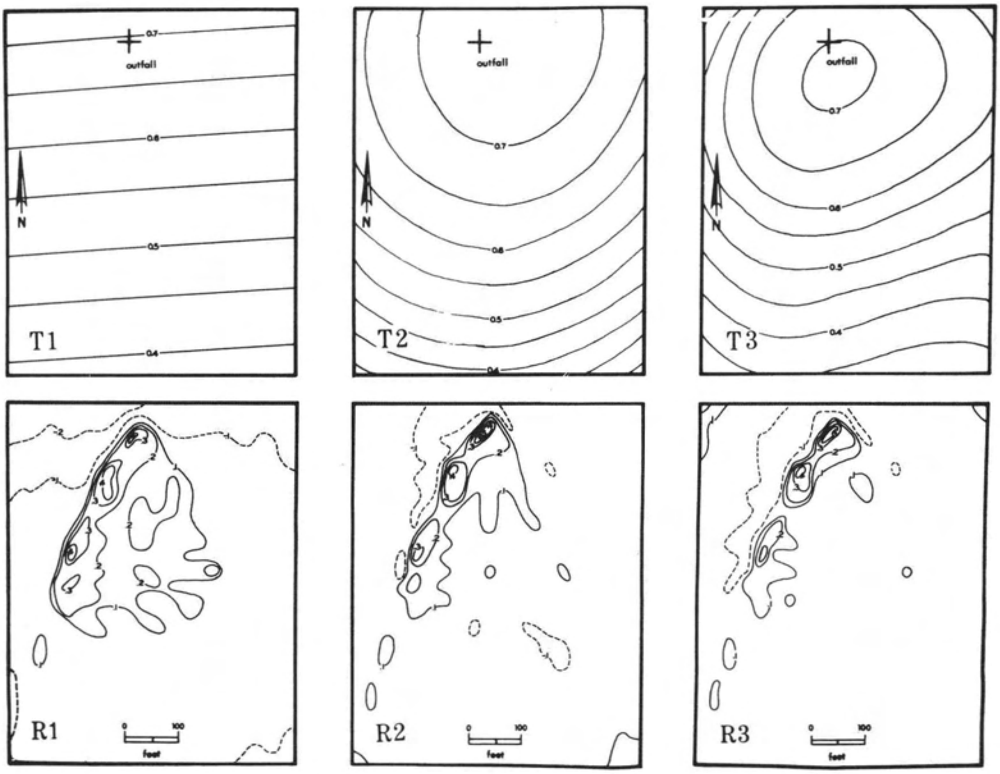

FIG. 8. Trend-surface (T) and residual (R) values for the Bradley Beach site; first-, second-, and third-degree solutions.

of the matrix that are unexplained by the linear surface. The contours show the outline of the plume, the outfall head, and other pockets of extreme reflectance. The negative contours depict the lower values of ambient seawater reflectance.

The second-degree trend (Figure 8, T2) portrays a fan-like feature plunging to the south, or bottom, of the figure; the level of explanation is raised to 85.5 per cent. This surface now incorporates the higher values in the upper middle of the photograph. The residual map (Figure 8, R2) again shows pockets of higher reflectance but the plume shape is reduced more towards a V-like form encompassing the leading edges of the effluent.

The third-degree solution (Figure 8, T3), $R^2 = 88.6$ *per cent,* exhibits a domal feature with the incorporation of the second warping. The dome is nearly centered on the outfall head and there is a radial pattern to the surface showing the decline in reflectance away from the outfall point. Thus the surface now depicts the generalities of the outfall plume in three dimensions. In Figure 8, R3, the residuals from this domal morphology now highlight the sharp landward edge of the plume in shallower water with turbulent diffusion to the south.

The fourth-degree solution, $R^2 = 89.3$ *per cent,* retains the general domal feature but with steeper lateral slopes (Figure 9, T4). Now there does not appear to be a major change in the evolution of the surficial shape but more of a subtle refinement. The residual map (Figure 9, R4) continues to suggest the turbulent diffusion with a concentrated leading edge. Again the negative residuals reflect the inadequacy of the trend component to sufficiently explain the very large difference between the reflectance of normal seawater and the leading edge of the plume.

The slightly more complex fifth-degree surface (Figure 9, T5) adds little further explanation with an R^2 now of 90.7 per cent coming from greater slope increase. Similarly, little change is evident on the corresponding residual map (Figure 9, R5).

Again, the sixth-degree surface (Figure 9, T6) with an $R^2 = 91.1$ *per cent* incorporates slightly more of the complexity with little change in appearance. The leading edge

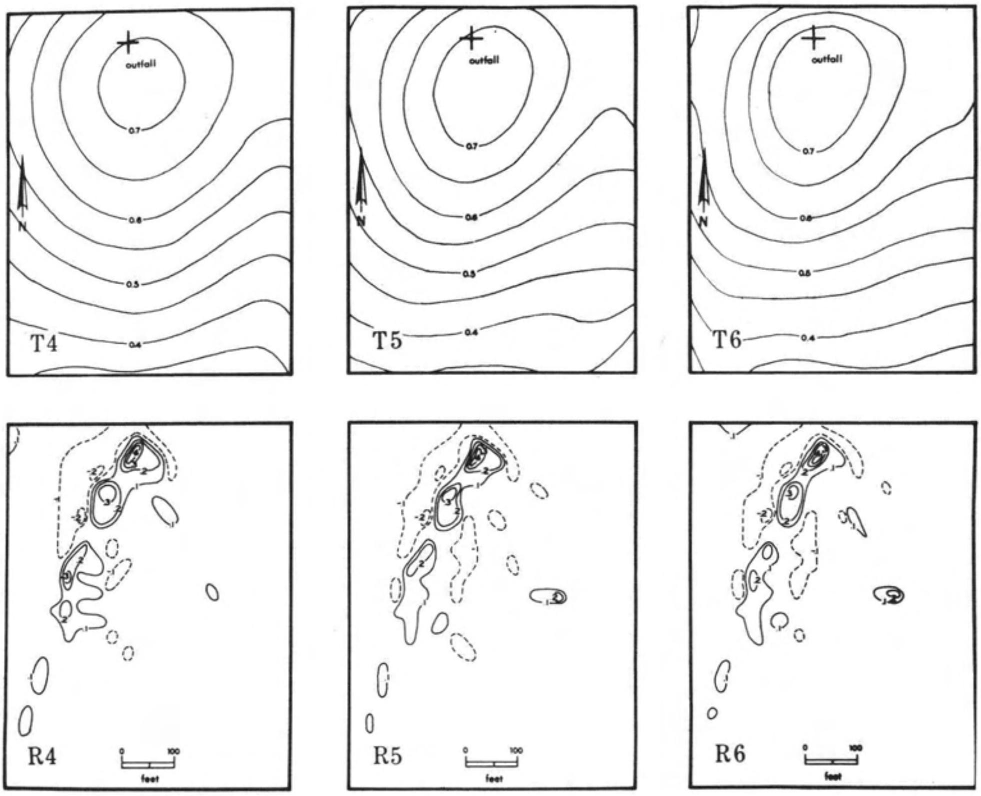

Fig. 9. Trend-surface (T) and residual (R) values for the Bradley Beach site; fourth-, fifth-, and sixth-degree solutions.

concentration and eddy-like diffusion continue to be shown by the residual map of the sixth-degree solution (Figure 9, R6).

The hierarchy of increasing complexity of three-dimensional polynomial solutions yields a closer approximation to the data set by incorporating greater flexibility into the trend surface. As the surface attempts to stretch itself to fit the data, the residuals are continually minimized yet still highlight unexplained variations in the data points.

For this project the third-degree solution was utilized for further study concerning the water quality variables. The mathematical solution for Bradley Beach is

$$A = 0.17230 + 0.01832\ X - 0.01475\ Y + 0.00226\ X^2 + 0.00270\ XY + 0.00309\ Y^2 - 0.00009\ X^3 - 0.00004\ X^2Y - 0.00011\ XY^2 - 0.00013\ Y^3. \quad (3)$$

This surface was chosen because the higher-order solutions do not change the shape of the surfaces greatly and, more importantly, they do not increase the explained variation of 88.6 per cent to any great extent. It might also be mentioned that, when solved to five decimal places, the higher-order solutions contain zero coefficients although this is dependent upon the magnitudes of the X, Y, Z coordinate values. Theoretically, this solution should give the basic structure for a plume in three dimensions. That is, it will allow description of a surface that curves from both top to bottom and left to right.

These surfaces provide a general view of the trends in the data matrix but it is the residuals which identify the sharp edges and separate the unique from the general. The third-degree residual map for Bradley Beach shows very high values for the outfall mouth and the concentrated leading edge on the landward, shallow water, side of the plume. Further, the mechanics of plume dispersion by nearshore currents can be identified in the residuals by pockets of high values within the plume that are indicative of eddy structures associated with turbulent diffusion.

The second site that was submitted to trend-surface analysis was at Asbury Park because it also exhibited a lack of clarity when the raw photographic digital data was contoured (see Figure 3). Similar to Bradley Beach, the Asbury Park outfall was also an 18 inch pipe but it discharged at a rate nearly five times as great, 5.5 million gallons per day. The Asbury Park plume is also near the shore and was very well defined. The sampling procedure was identical to the Bradley Beach sequence and the photographic record depicts the sampling sites as well as the pattern of plume dispersion.

When the Asbury Park plume is subjected to the previously described analysis, the results are similar. The third-degree surface has a comparable R^2 of 82.5 per cent and it describes a dome with a slight offset from the center (Figure 10, T3). The equation describing the solution is

$$Z = 0.86791 + 0.07534\ X + 0.02744\ Y - 0.00371\ X^2 + 0.00025\ XY + 0.00006\ Y^2 + 0.00002\ X^3 - 0.00003\ X^2Y + 0.00002\ XY^2 - 0.00009\ Y^3. \quad (4)$$

There is little to be gained in comparing the equations of the surface maps since the original data of each differs in both the location and magnitude of the mapped observations.

However, the residual maps can and

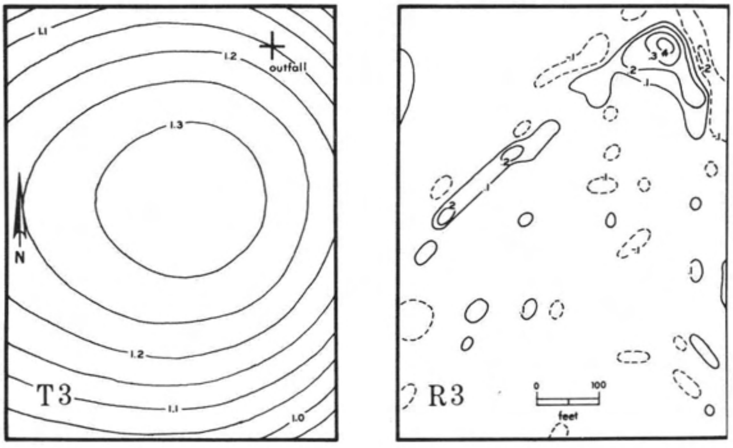

FIG. 10. Trend-surface (T) and residual (R) values for the Asbury Park site; third-degree solutions.

TABLE 1. ANALYSIS OF VARIANCE FOR BRADLEY BEACH

source	sums of squares	R	R^2	d.f.	mean square	F value	confidence level (%)
Due to 1st degree	20.8748	0.853	0.728	2	10.4374	664.803	99.99 +
Deviation from 1st degree	7.7807			497	0.0157		
Due to 2nd degree	4.5006	0.925	0.855	3	1.5002	178.595	99.99 +
Deviation from 2nd degree	4.1437			494	0.0084		
Due to 3rd degree	0.8636	0.941	0.886	4	0.2159	32.224	99.99 +
Deviation from 3rd degree	3.2801			490	0.0067		
Due to 4th degree	0.2138	0.945	0.893	5	0.0428	6.794	99.99 +
Deviation from 4th degree	3.0663			485	0.0063		
Due to 5th degree	0.3952	0.952	0.907	6	0.0659	11.768	99.99 +
Deviation from 5th degree	2.6712			479	0.0056		
Due to 6th degree	0.1293	0.955	0.911	7	0.0185	3.426	99.50 +
Deviation from 6th degree	2.5419			472	0.0054		

should be compared to identify the plume diffusion described earlier. Once again, Asbury Park (Figure 10, R3) indicates the presence of the ocean outfall and the concentrations on the shoreward margin of the plume. Also the turbulent motion is marked in this higher discharge vent by the pronounced pockets of high and low values.

Although the maps support the postulated outfall photograph model, it is statistically appropriate to examine the sum of squares, etc. associated with the trend and its deviations. This is accomplished by Analysis of Variance as discussed by Krumbein[6]. As Tables 1 and 2 show, all six surfaces for each plume add a statistically significant trend component. With 500 data points this is not unreasonable. In spite of this, prior discussion has suggested the third-degree solution as being sufficiently parsimonious in its description. For a general model of outfall plume, the cubic solution is advocated. When a more intensive study of individual plumes may be desired, the higher-degree solutions are easily obtained by the computer.

Spatial applications of the trend surfaces and the residual data are consistent with that of the aerial photograph because both are developed from the total areal information. Depending on the complexity or shape of the target under study, different surfaces may be most efficient in extracting the general trend exhibited by the quantitative description of the structure. Analysis of the trend residuals reveals the unique, or locally extreme fluctuations, in the data. While these residuals are normally distributed, statistical independence, *i.e.*, the absence of autocorrelation, is not assured. This must be considered in the interpretation of the trend and therefore of the residuals as possible implying other information besides that which is inferred.

One of the objectives of this study was to determine whether it was possible to identify spatial co-variation in the residual values describing the photographed plume and any of

TABLE 2. ANALYSIS OF VARIANCE FOR ASBURY PARK

source	sums of squares	R	R^2	d.f.	mean square	F	confidence level (%)
Due to 1st degree	1.3937	0.266	0.071	2	0.6969	18.938	99.99 +
Deviation from 1st degree	18.2833			497	0.0368		
Due to 2nd degree	14.6861	0.904	0.817	3	4.8954	672.445	99.99 +
Deviation from 2nd degree	3.5972			494	0.0073		
Due to 3rd degree	0.1603	0.908	0.825	4	0.0401	5.720	99.99 +
Deviation from 3rd degree	3.4369			490	0.0070		
Due to 4th degree	0.4075	0.920	0.846	5	0.0815	13.048	99.99 +
Deviation from 4th degree	3.0294			485	0.0062		
Due to 5th degree	0.1170	0.923	0.852	6	0.0195	3.207	99.50 +
Deviation from 5th degree	2.9124			479	0.0061		
Due to 6th degree	0.2483	0.930	0.865	7	0.0355	6.289	99.99 +
Deviation from 6th degree	2.6642			472	0.0056		

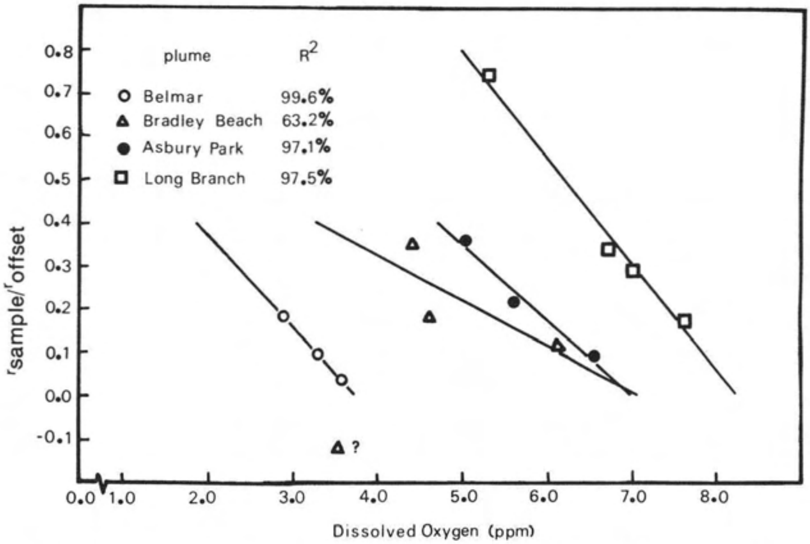

FIG. 11. Comparison of imagery values and a water-quality variable, New Jersey ocean outfall plumes.

the water-quality measures sampled in the discharge. This was accomplished by selecting the residual values from the cubic solution that corresponded with the points at which samples were taken. Then, in an attempt to allow for meaningful comparisons between photos, the residual values were transformed into dimensionless numbers defining the ratio of difference between the filtered target and background. These numbers were derived by dividing the sample location residual by an ambient seawater residual offset by a unit length from the plume margin. The measurement of co-variation is thus between the dimensionless numbers as one variable and, in this case, the amount of dissolved oxygen present in each sample as the other variable.

While the small number of water samples gathered within the plumes restricts the reliability of a simple regression, high (60-99 per cent) coefficients of determination were obtained with positive correlations (Figure 11). Although statistically weak due to the resultant low degrees of freedom, these results do agree with generalized models involving the increase in dissolved-oxygen content values in the direction of effluent dispersion. Carried further, the similarity of slope between the regression lines suggests that the reflectance values correlate well with the measures of dissolved oxygen in the effluent plumes. Except for the one problem reflectance value for Bradley Beach, which was not incorporated into the regression, there also appears to be much more external variation between the plumes rather than within each plume for the dissolved-oxygen measure. This might be restated as even though there are gross differences in pollution levels between plumes, the internal variation within each can be accurately studied by trend-surface analysis of aerial photographs.

The trend-surface analysis does depict the areal pattern and there are several very important insights to be gained in the careful study of this pattern. The two effluent plumes presented in this paper display an unevenness of dispersion characteristics due to the effects of streaming and internal turbulence. More importantly, the statistical analysis highlights the unexpected high values of the landward margin of the plumes. These residuals represent prolonged concentration of the effluent in the shallow waters leading to the beach area, and thus have added to the understanding of effluent behavior in the coastal zone.

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