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Monitoring the Temporal Dispersion of a Sewage Sludge Plume*

Remotely sensed monitoring and data analysis techniques may be used to study temporal dispersion characteristics of plumes resulting from dumping of sewage sludge.

(Abstract appears on following page)

INTRODUCTION

LARGE QUANTITIES of sewage sludge, dredge spoils, industrial waste, and cellar dirt are dumped (Pararas-Carayannis, 1973; Muller *et al.*, 1976) in the apex of the New York Bight (Figure 1). Little is known about the local dispersion of these wastes in coastal waters. Previous investigations of the dispersion of sewage sludge plumes include studies on the fate of sludge-derived ammonium in the water column (Duedall *et al.*, 1975), short term water column disturbances (Duedall *et al.*, 1977), surface distributions of suspended solids (Johnson *et al.*, 1977), and the distribution of suspended material in the water column as measured by an acoustical system (Proni *et al.*, 1976). The experiment described by Johnson *et al.* (1977), designated as STAX I (Sludge Tracking Acoustics Experiment), demonstrated the applicability of remote sensing techniques for identifying and synoptically mapping surface water distributions of suspended solids in plumes resulting from sewage sludge dumps.

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It is the purpose of this investigation as part of the STAX II experiment, conducted on July 15, 1976, to apply the previously reported methodology (Johnson *et al.*, 1977) to study the temporal dispersion of a sewage sludge plume in the New York Bight apex. The work described here was conducted jointly by NASA, NOAA, and SUNY.

TEST SITE

The area selected by NOAA for this experiment was in the apex of the New York Bight (Figure 1). Within the apex, sewage sludge is dumped on a daily schedule in an Environmental Protection Agency (EPA) designated area about 18 km (9.7 nautical miles) south of Long Island.

EXPERIMENTAL METHOD

A sewage sludge dump and its plume were monitored by aircraft remote sensing and by the surface vessels *Black Coral* (NOAA) and *Onrust* (SUNY). Data from the aircraft platform were collected by a multispectral scanner and two mapping cameras. The sea-truth data were obtained by water sampling and acoustic profiling (from the *Black Coral*

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ABSTRACT: *Sewage sludge from the Metropolitan New York City area is dumped in the apex of the New York Bight. Possible environmental effects due to this dumping are being studied. Results of a joint National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), and State University of New York (SUNY) experiment on July 15, 1976, indicate remotely sensed monitoring and data analysis techniques may be used to study temporal dispersion characteristics of plumes resulting from dumping of sewage sludge. Remotely sensed data were collected by multispectral scanner and photography from a NASA aircraft platform. Multiple flights were made over the plume from a spot dump (rapid discharge from a stationary barge) at about 15 minute intervals for two hours after the dump, which was made at 10 A.M. (local time). Afternoon flights over the dump area indicated that the plume was well dispersed by about five hours after the dump. Concurrent sea-truth measurements were made from NOAA and SUNY ships in and around the dump plume. Concentrations of suspended solids in the plume were correlated with multispectral scanner radiance data to obtain a regression equation which was then used to map quantitative distributions of suspended solids in the plume. For the spot dump monitored, reflected radiances from the surface waters reached peak values about 45 minutes after the dump. After this time, spectral analysis indicated that the calibrated equation could be applied. The plume was dispersed within about five hours. Spectral characteristics of the experiment plume were similar to sewage sludge plumes that have been monitored in other experiments in the Atlantic Coastal Zone. These plumes are readily distinguished from acid wastes that are dumped in the same geographical area.*

only) in and around the sludge plume. In this paper, only the multispectral scanner data are considered, using the mapping camera data for visual location and identification of the surface features. Also, only sea-truth measurements of suspended solids at or near the surface are considered in the analysis. Prior investigations indicated that chlorophyll *a* analyses may produce ambiguous results (Johnson *et al.*, 1977). Results from acoustic investigations are presented in other reports (Proni *et al.*, in press).

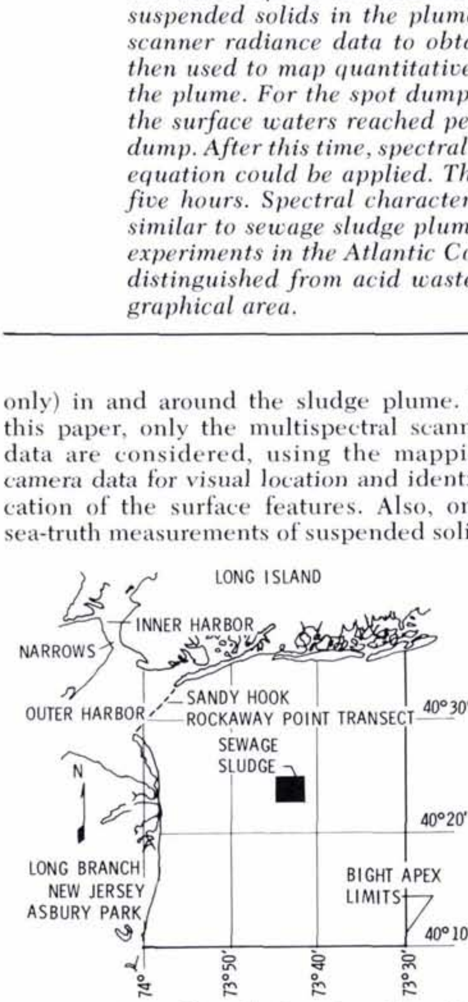

FIG. 1. Sewage sludge dump area in the New York Bight apex.

On July 15, 1976, 2,886 m³ (102,000 ft³) of sewage sludge was dumped from the *M/V North River* in the sewage sludge dump area. The material was dumped from the stationary barge from about 9:58 A.M. to 10:04 A.M. eastern daylight time (EDT). Based on analyses furnished by EPA, Region II, from samples obtained at the plant (Newtown Creek) during loading of the vessel, specific gravity at 20°C was 1.00 and percent solids was 3.54.

SEA-TRUTH MEASUREMENTS

The dumping vessel was identified as it approached the dumping area and observed closely as it performed its normal dump. Immediately after the dump was completed the barge moved out of the area to provide maximum operational flexibility for the scientific monitoring ships. The *Black Coral* made a number of transects in and around the plume to study its dispersion character-

TABLE 1. SEA-TRUTH MEASUREMENTS AND REMOTELY SENSED DATA

Sampling Time EDT	Location*	Suspended Solids mg/l	Remotely Sensed Radiances (mw/cm^2-sr-μm) M2S Band 1	2	3	4	5	6	7	8	9	10
11:05 a.m.	In Plume	4.00	6.280	**	4.475	**	2.281	**	1.578	1.307	0.599	0.205
11:45 a.m.	In Plume	6.93	7.133	5.971	5.501	4.001	2.967	2.541	1.992	1.384	0.789	0.323
1:25 p.m.	Water	1.01	No concurrent remote sensing data collections; in analysis									
1:45 p.m.	Water	1:33	radiance ratio is 1.00 for ocean water.									

* Location procedure descibed in text.

** No usable data in these bands at sea truth location.

istics acoustically and to provide guidance to the *Onrust* for the water sampling. Surface and depth transect measurements were made by the *Onrust;* however, due to the dynamic nature of the plume and movement of the monitoring ships, only four measurements were suitable for the remote sensing data analysis. These measurements and times of the sampling are listed in Table 1 along with the corresponding remotely sensed radiance values, which will be discussed in a later section.

REMOTE SENSING MEASUREMENTS

Remote sensors that measure electromagnetic reflectance in the visible and near infrared (NIR) spectral range were flown over the test site. The NASA Johnson Space Center (JSC) NP-3A aircraft flew at a nominal altitude of 3.0 km (10,000 ft) and at a speed of 444 km/hour (240 knots). Two onboard remote sensor systems collected data for these analyses; an 11-band M2S multispectral scanner, which measured radiances in each of 10 bands in the visible and NIR spectral range and one thermal band; and two mapping cameras, which used aerial color and false color IR film. Spectral and spatial characteristics of the remote sensors are listed in Table 2. Only data in the visible and NIR spectral range are considered in the analysis.

TABLE 2. SPECTRAL AND SPATIAL CHARACTERISTICS OF REMOTE SENSORS (AT 3.0 KM ALTITUDE)

I MODULAR MULTISPECTRAL SCANNER (M2S)

BAND	BANDWIDTH
1	380-440 nm
2	440-490 nm
3	495-535 nm
4	540-580 nm
5	580-620 nm
6	620-660 nm
7	660-700 nm
8	700-740 nm
9	760-860 nm
10	970-1060 nm
THERMAL	8000-13,000 nm
SCAN WIDTH, m	8500
RESOLUTION, m	8

II ZEISS MAPPING CAMERAS

	SPECTRAL RANGE	FILM	RESOLUTION, m	FOOT PRINT, m
NO.1	400-700 nm	COLOR	0.4	4550 x 4550
NO.2	500-900 nm	COLOR IR	0.4	4550 x 4550

Digital data from the M2S scanner were recorded inflight on magnetic tape in a high density format. Inflight calibration was also provided for each line of data. Screening imagery from the scanner in conjunction with the mapping camera products were used to locate areas of interest in the scanner data. Digital data (measured in counts) in these areas were transferred to computer compatible tapes (CCT) with a typical format of 800 bits per inch. Inflight calibration based on a standard lamp provided information to convert instrument count data to average radiances in each band.

Remote sensing data collections were made over the plume and surface ships starting about 15 minutes after the dump, then at 15-minute intervals, for two hours and 15 minutes after the dump. A total of nine data collections were made during the morning period of the experiment. In the afternoon, two data collections were made over the dump area. The monitoring ships were used as targets in the afternoon since the plume was not visible. Times of the remote sensing data collections are listed in Table 3.

Example radiances in each of the M2S bands for the ocean water and in the sewage sludge plume at 10:12 A.M., 10:58 A.M., and 11:43 A.M. EDT (about 15, 60, and 105 minutes after the dump, respectively) are shown on Figures 2 and 3, respectively. Note the general increase in radiances due to higher sun angles as elapsed time after the dump increases.

PREPROCESSING OF REMOTELY SENSED DATA

Data preprocessing included locating the water sampling points in the imagery and

TABLE 3. TIMES OF REMOTE SENSING DATA COLLECTIONS OVER THE SEWAGE SLUDGE DUMP AREA

REMOTE SENSING DATA COLLECTION NUMBER	TIME, E.D.T.
MORNING	
1	1012
2	1028
3	1043
4	1058
5	1113
6	1126
7	1143
8	1158
9	1212
AFTERNOON	
10	1444
11	1542

determining radiance values in the M2S bands to be compared to the sea-truth measurements obtained from the *Onrust*. In the analysis, representative radiance values were determined by taking a 7 by 7 picture element (pixel) field centered at the best estimate of the sea-truth measurement. This pixel field was determined empirically as the minimum size that compensated for uncontrollable spectral and spatial errors. The average count in the 7 by 7 field was multiplied by a radiance conversion value obtained from calibration of the inflight system to known radiance sources. Evaluation of inflight calibration data indicates less than 2 percent, or negligible, instrument drift. Average radiances in individual band ranges have the units mw/cm^2-sr-μm or an average radiance per unit band width.

DATA ANALYSIS, RESULTS, AND DISCUSSION

In this experiment, the primary objective was to evaluate the temporal dispersion of the target sewage sludge plume. However, as the plume dispersed after the dump, sun angle increased from the horizon (with time). This increased sun angle produces

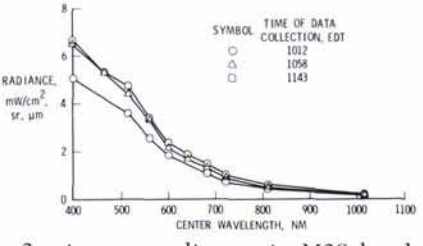

FIG. 2. Average radiances in M2S bands for ocean water, about 15, 60, and 105 minutes after sewage sludge dump.

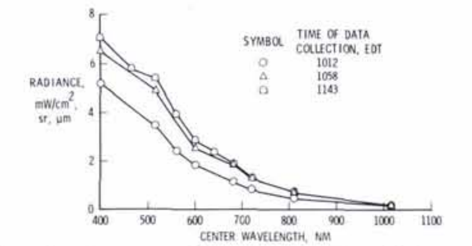

FIG. 3. Average radiances in M2S bands for sewage sludge plume, about 15, 60, and 105 minutes after dump.

higher reflected radiances from the background water as well as from the sewage sludge plume, as shown in Figures 2 and 3. A means of normalizing radiance changes due to sun angle and homogenous atmospheric changes used previously in spectral analyses of this plume and other ocean dumped materials (Johnson, 1977) was to determine ratios of plume radiances to ocean water radiances in each M2S band for each scene. After reviewing the remotely sensed data, it appeared that M2S Band 7 (700-740 nm) ratios are suitable for monitoring plume changes. Changes in the plume as indicated by the M2S Band 7 ratios for one hour and 45 minutes after the dump are shown in Figure 4. (Data for the last two remote sensing data collections were "noisy" and require additional analysis.) Interestingly, the spot dump reaches peak radiance ratio values about 45 minutes after the dump. This may be due to surfacing of floatable materials or organic liquids that are initially entrained with the heavier materials. However, as indicated by Duedall *et al.* (1977), the concentration of suspended solids in a spot dump plume appears to decrease with time after initial high values. Thus, it is suspected that a single radiance-suspended solids relationship is not applicable during the entire dispersion of a spot dump plume. However, it appears

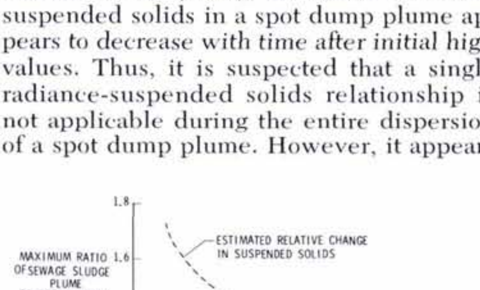

FIG. 4. M2S band 7 radiance ratio values (maximum plume to ocean water) after sewage sludge dump. Also shown is estimated relative change in suspended solids from Duedall *et al.* (1977).

that after about 45 minutes the radiance-ratio change is similar to that observed previously for suspended solids (Figure 4) and may be used to relate remotely sensed data to suspended solids.

Due to the limited number of observations in which sea-truth measurements were made concurrently with remotely sensed data (or sea-truth locations could be located reliably in the remotely sensed data), the regression analysis was limited to M2S Band 7 ratios as the independent variable. The dependent variable was suspended solids. Four observations and the corresponding ratio values were applicable; two of these were in ocean water (Table 1). The two usable suspended solids concentration measurements in the plume were made 65 and 105 minutes after the dump. The best fit linear regression equation was

$$\text{Suspended solids (mg/l)} = -21.05 + 22.22 \text{ RA7}$$

where RA7 is the ratio of plume to ocean water radiances in M2S Band 7, both for the same scene. The correlation coefficient (measure of relative change between variables) is 0.99, and the standard error of estimate (measure of scatter about the fitted regression line) is 0.42 mg/l. Note that total suspended solids concentrations are used and, thus, include ocean water material, as well as the plume. The comparison of remotely sensed data (radiance ratio) and measured suspended solids is shown in Figure 5. A linear equation appears to be adequate. Previous investigations have indicated a linear equation in this range of suspended solids (Johnson *et al.*, 1977).

Quantitative Mapping

Quantitative distributions of suspended solids may be determined and mapped in each of the remotely sensed scenes where the plume is changing in a homogenous manner (e.g., overflights 3-9, from 45 minutes to two hours 15 minutes after the dump). For the water quality parameter, suspended solids concentrations were determined at each pixel by using the calibrated regression equation. This field of data is typically smoothed to remove local spectral and spatial noise features, and a contour map is developed by a computerized plotting routine. The smoothing routine used in this analysis is an averaging on a line-by-line and column-by-column basis in the data field, where the middle value is replaced by the mean of it and the two adjacent values. Edge values remain the same. In this analysis, each pixel in each line of data was used to generate the field of data for mapping. Two smoothing passes were made for the suspended solids concentrations.

Quantitative distributions of suspended solids in the sewage sludge plume for the data collection about 45 minutes after the dump are mapped in Figure 6. As indicated on the figure, both monitoring ships are around the plume. The scattered plume areas above and to the left of the main plume are due to residuals as the dumping barge moved out of the spot dump.

A further application of the computerized quantitative determinations is a histogram of the number of pixels for suspended solids concentration ranges. This information may be useful to measure the spread-concentration of the plume in the surface waters. The histogram for the scene 45 minutes after the dump is shown in Figure 7, where the number of pixels in remotely sensed suspended

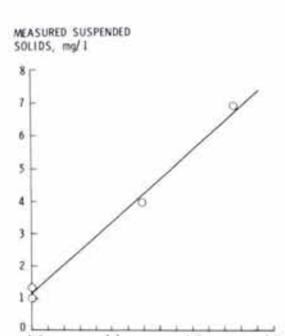

FIG. 5. Comparison of Measured Suspended Solids to Remotely sensed radiance ratios (plume at sea truth location to ocean water in the same scene).

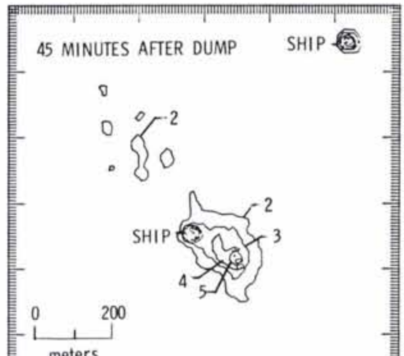

FIG. 6. Quantitative distribution of suspended solids concentrations, mg/l, in a "spot" sewage sludge dump in the New York Bight on July 15, 1976.

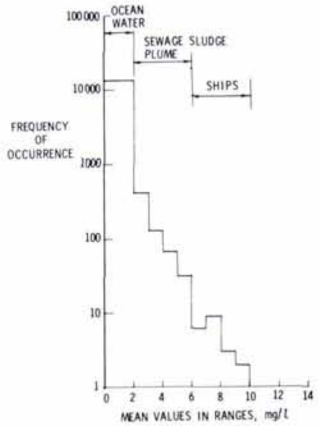

FIG. 7. Histogram of number of pixels in each suspended solids range (see Figure 6).

solids concentration ranges are indicated (the lowest range from 0-1.99 mg/l, mean value 1.0, includes background water). The histogram is based on suspended solids value ranges after the two smoothing operations and, thus, corresponds to the quantitative mapping shown in Figure 6. The total field is 120 by 120 pixels.

Concluding Remarks

Calibrated regression equations that relate remotely sensed data to sea-truth measurements may be used to provide maps of the synoptic distributions of suspended solids in plumes resulting from ocean dumping of sewage sludge. It appears that the spot dump of sewage sludge monitored in this experiment was about 45 minutes old before a uniform pattern of radiance to suspended solids change was established. After applying a normalizing technique to eliminate changing sun angle and homogenous atmospheric effects, a single regression equation was developed to study spatial and temporal dispersion patterns of the plume. It appears that developing the regression equation using ratios (to ocean water) may be an effective means to determine suspended solids distributions in remotely sensed scenes, even though in some cases sea-truth measurements have not been made concurrently with that particular remote sensing data collection. This approach may provide a means for more effective experiment design, data analysis, and interpretation.

Results of this experiment are encouraging for the use of remotely sensed data for studying pollution plumes and their spatial and temporal dispersion characteristics. Additional experiments should be performed in different environments and with different materials to define more accurately the role of remote sensing in monitoring and studying the effects of pollution in the coastal zones.

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