CHAPTER 121

Factors Governing The Distribution of Dredge - Resuspended Sediments

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ABSTRACT

Field observations are analyzed to determine the primary factors governing the distribution of sediments suspended by clam-shell bucket dredge operations. These data show the plumes produced under typical estuarine conditions to be relatively small scale features having maximum longstream dimensions of approximately 700 m. Plumes can be considered to consist of three contiguous zones: an initial mixing zone, a secondary zone and a final mixing zone. The initial mixing zone immediately adjacent to the dredge has dimensions governed by bucket induced mixing and suspended material concentrations determined by dredge efficiency. Observations indicate that dimensions can be reasonably estimated using wake theory and that efficiencies result in the introduction of 2-4% of the sediment mass contained in each bucket load. Resultant concentrations range between 200 and 400 mg/ℓ. Progressing downstream into the secondary mixing zone concentrations decay rapidly due primarily to gravitational settling. The observed decay rates indicate an average settling velocity of 4.7cm/sec well in excess of values based on the grain size characteristics of the dredged sediment. The behavior suggests significant particle agglomeration within this area. At the downstream limit of this zone distributions become essentially exponential in character and remain so through the final mixing zone. In this area concentrations progressively approach the upstream background levels and variations are governed primarily by diffusion. In each of these zones the observed distributions appear amenable to relatively straightforward modeling.

Introduction

In many coastal areas of the United States routine channel dredging represents the most common marine engineering operation. Much of the sediment removed during these projects is contaminated by a variety of organic and inorganic compounds, and as a result dredge-induced suspensions have the potential to perturb water quality and impact local biota. During the past few years a variety of investigations have been conducted to assess both the short and long term character of these impacts (see the review by Morton, 1976). In addition some investigations have examined dredge efficiency (Yagi, et. al., 1977) and developed schemes intended to reduce and/or predict project related turbidity (Huston and Huston, 1976; Barnard, 1978). The majority of these studies however, provided little quantitative information concerning the distribution and dispersion of materials suspended by the dredge. This paucity of data has tended to limit the development of predictive schemes applicable within coastal and estuarine waters.

During the summer and early fall of 1977 several detailed surveys of dredge-induced suspended material plumes were conducted within the lower Thames River estuary near New London, Connecticut (Bohlen, et. al., 1978). Suspended material distributions were sampled and both concentration levels and composition were analyzed. These data provide a reasonably comprehensive view of the longstream character of the dredge-induced plume and permit evaluations of both dredge efficiency and some of the primary factors governing the distribution and dispersion of the suspended sediments. This paper presents the results of these evaluations.

Study Area and Project Characteristics

Long Island Sound (Fig. 1) represents one of the major embayments along the eastern coast of the United States. Extending a distance of approximately 120 Km to the east of New York City, the Sound has a varied coastline providing several major port areas and numerous smaller, recreational anchorages. Regional hydrography dominated by the interactions between freshwaters supplied by three river systems entering along the northern margin and the local tidal currents favors nearshore deposition of fine grained sediments and requires regular dredging to maintain port and harbor viability. These dredging operations typically employ one of three methods; hydraulic, dragline or clamshell bucket. Hydraulic and dragline techniques have typically been restricted to relatively small volume projects. Major projects involving the removal of more than 100,000 m^3 of material generally have employed clamshell buckets and hopper barges to transport spoils for disposal at selected offshore sites.

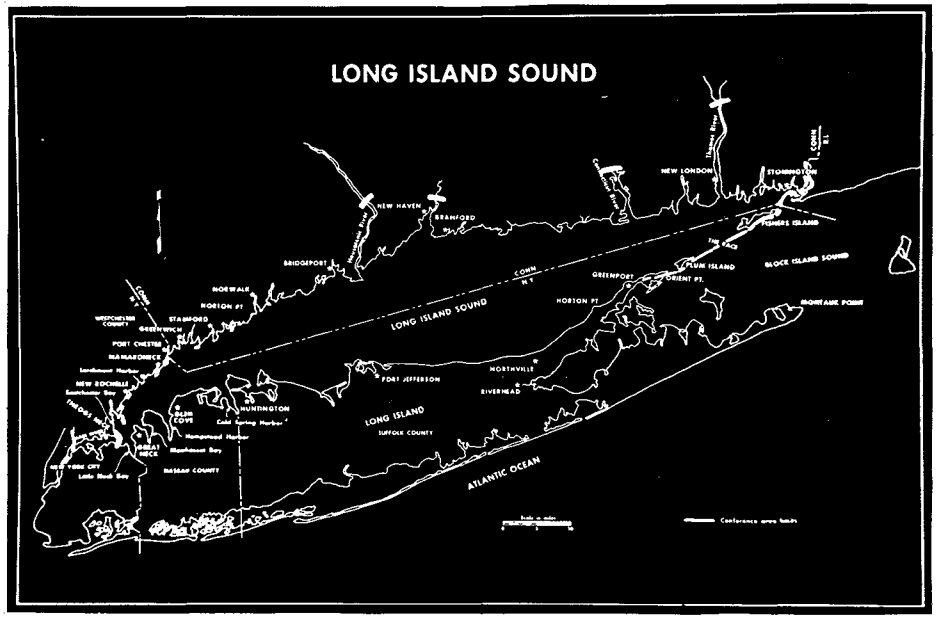


Fig. 1. Long Island Sound. Note the location of the Thames River entering near the eastern limit in the vicinity of New London, Connecticut.

Since 1974 the lower Thames River (Fig. 2) has been the site of a major dredging project intended to increase the depth of the main navigational channel to approximately 10 - 12 m. This stream is a typical small estuary having an annual average streamflow of approximately 75 m^3/sec and tidal range of 0.78 m at New London. The combination produces a density field displaying persistent vertical stratification and an evident seasonal variability. Wind stress effects are generally negligible.

In July of 1977 dredging of the northern reach of the project area (outlined in Fig. 2) was initiated. Local sediments consisting primarily of fine-grained sands and silts (Fig. 3a) were removed using a floating barge-mounted crane equipped with a 10 m^3 open clamshell bucket (Fig 3b). Spoils were placed in a 1500 m^3 hopper barge typically moored alongside the operating dredge. This operation served to introduce sediments into the water column due primarily to bottom impact and washover from the open bucket during the subsequent ascent phase (Fig. 4a). The volumes of material supplied by overflow from the barge were negligible.

Survey Methods and Procedures.

In August and September, 1977 the suspended material plume extending downstream of the operating dredge was surveyed in detail (see Fig 2 for dredge locations). Hydrographic conditions during both survey periods were essentially identical although a slight increase in streamflow in September caused a decrease in near surface salinity and increased the degree of vertical stratification characteristic of the local density field (Fig. 4b).

The field methods and analytical procedures used in these surveys have been described in detail in an earlier paper (Bohlen, et. al., 1978). Very briefly, optical techniques were used to define the limits of the plume and to establish a network of stations along the defined centerline. At each station the suspended material field was sampled directly using 5ℓ van Dorn bottles. These samples were returned to the laboratory and vacuum filtered using dried and pre-weighed Nuclepore filters (0.40μ pore-size-57mm dia.). After careful washing, the filters were dried and re-weighed to determine the by-weight concentration of total suspended solids. Both surveys were conducted during the ebb tidal cycle.

Results and Conclusions.

The suspended material distributions along the centerline of the plume downstream of the operating dredge for each survey period are

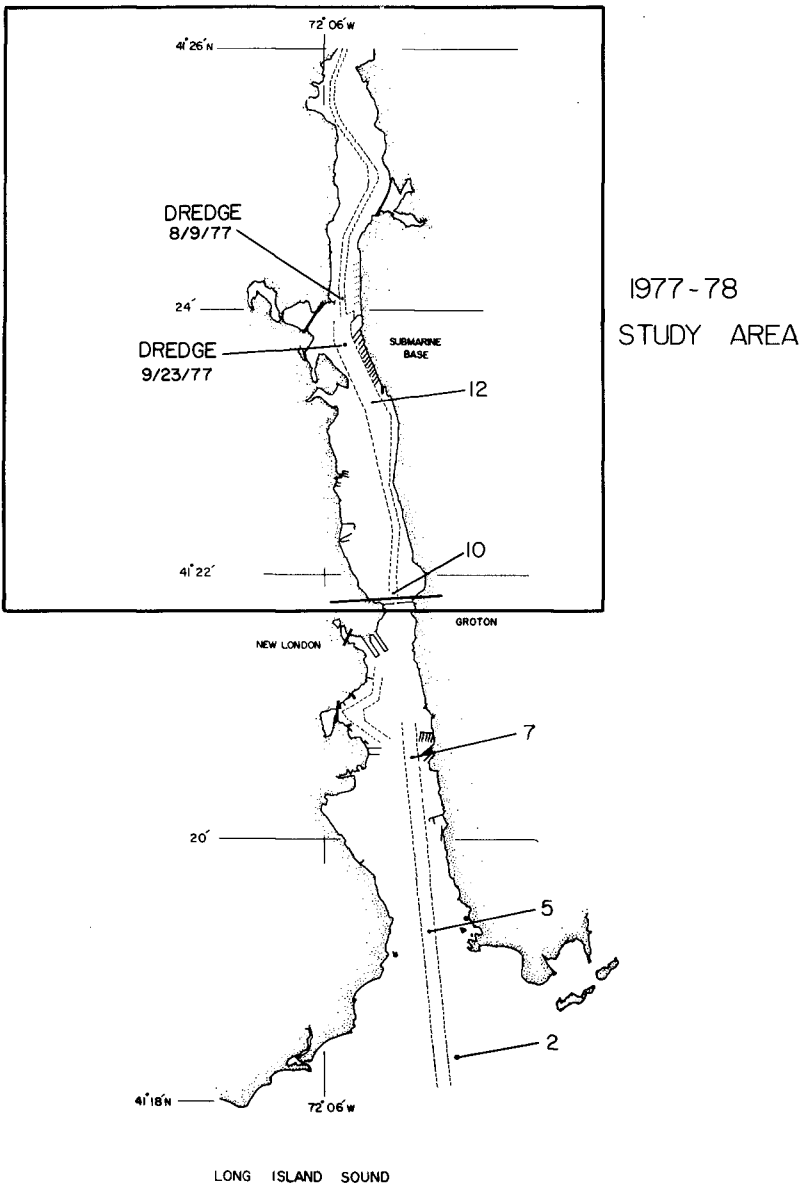
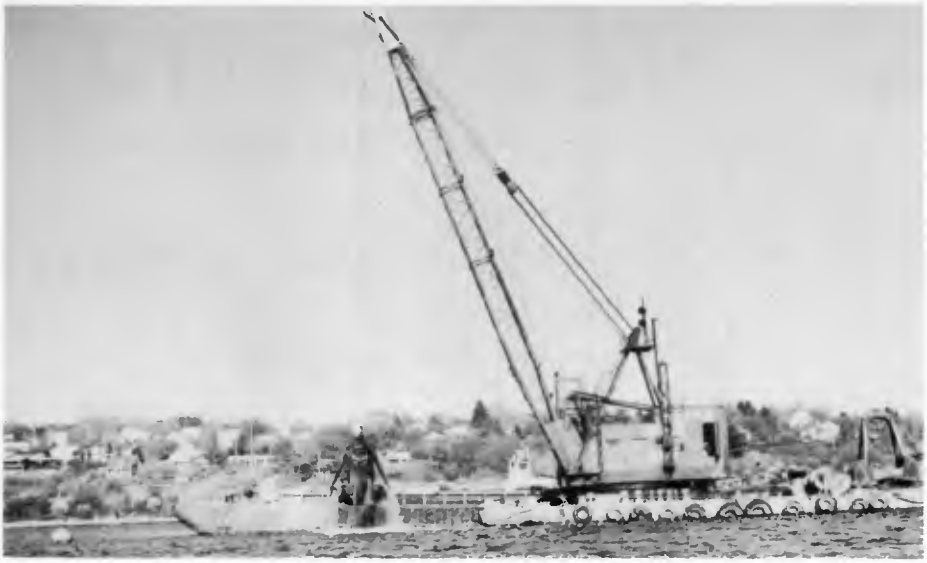


Fig. 2. Lower Thames River Estuary showing dredge locations during August and September, 1977 surveys. From (Bohlen et. al., 1978).



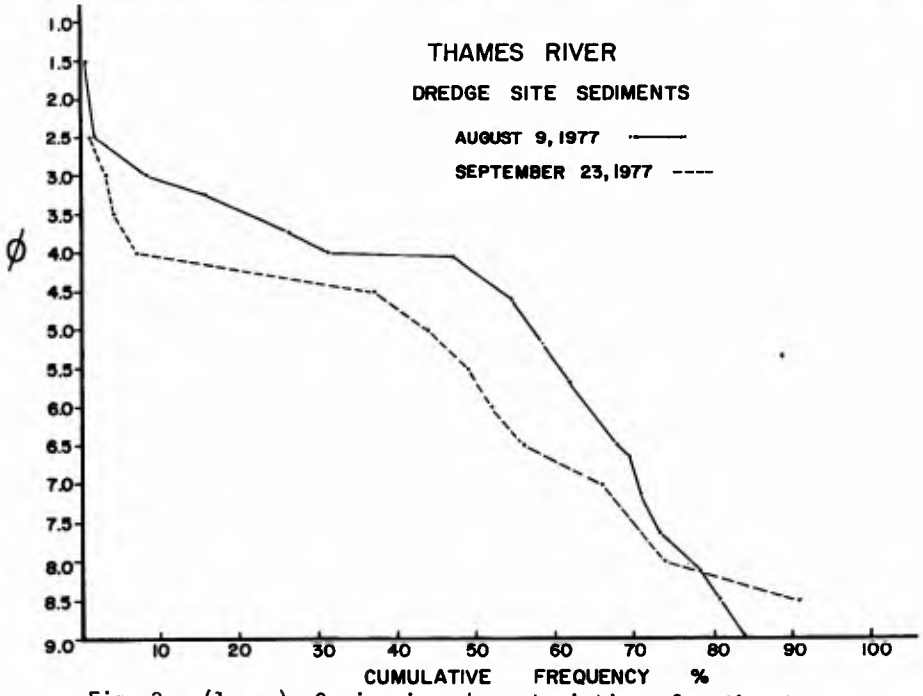


Fig. 3a (lower) Grain size characteristics of sediments being dredged in Thames River.

Fig. 3b (upper) Operating dredge and barge.

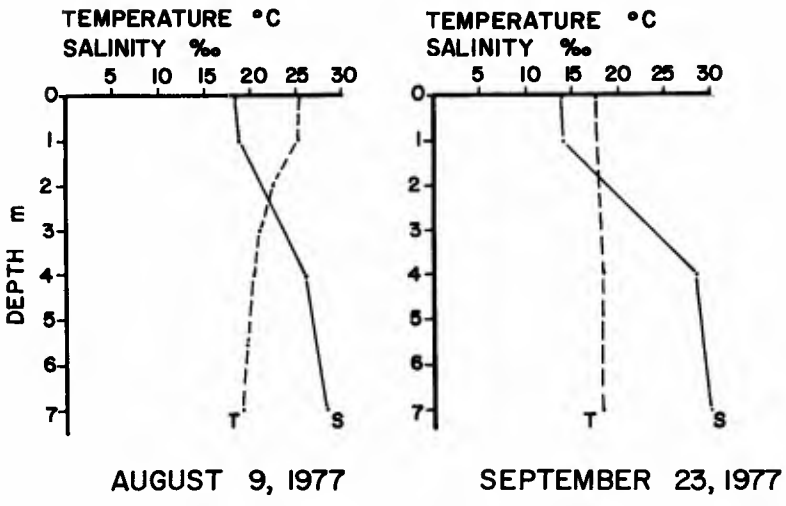


Fig. 4a (upper) Sediment washover from ascending bucket

Fig. 4b (lower) Reference temperature and salinity distributions during August & September surveys.

shown in Figs. 5 and 6. Qualitatively, these distributions are quite similar. As expected maxima occur in the area adjacent to the dredge with concentrations averaging between 200 and 400 mg/l. These values exceed the ambient or background levels measured at an upstream station clear of dredge influence by factors ranging from 4 to 10. Proceeding downstream concentrations decay rapidly and in both cases return to background within approximately 700 m.

The observed suspended material distributions are similar in character to those displayed by a variety of dispersing materials and/or particles (see Sayre and Chang, 1968 e.g.). As such they can reasonably be considered to consist of three principal areas or zones.

a. An initial mixing zone - immediately adjacent to the dredge where bucket induced suspensions and mixing combine to produce the initial suspended material concentrations.

b. A secondary zone - analogous to the convection dominated region in classical dispersion theory (Fischer, 1967). Material concentrations in this area are expected to vary primarily in response to advection and gravitational settling. And,

c. A final zone - extending downstream from the limit of the secondary zone to the point where material concentrations again approach background levels. The field observations provide some useful insights into the factors governing the suspended material distributions in each of these zones.

1. The initial mixing zone. - This area is clearly bucket dominated. During each dredging sequence, bottom impact and washover serve to introduce sediments which are subsequently mixed through the water column by the mechanical agitation produced by the vertical ascent and descent of the bucket. The resultant vertical column of materials, representing the initial source or concentration immediately proceeds to move downstream at a rate governed by the local mean velocity. Following approximately 1 min. another column of materials is introduced by the next pass of the bucket. This delay results in an intermittent source favoring a high degree of spatial variability in the vicinity of the dredge (see Fig. 7). The displacement in peak concentrations observed during the September, 1977 survey (Fig. 6) is evidence of this spatial inhomogeneity.

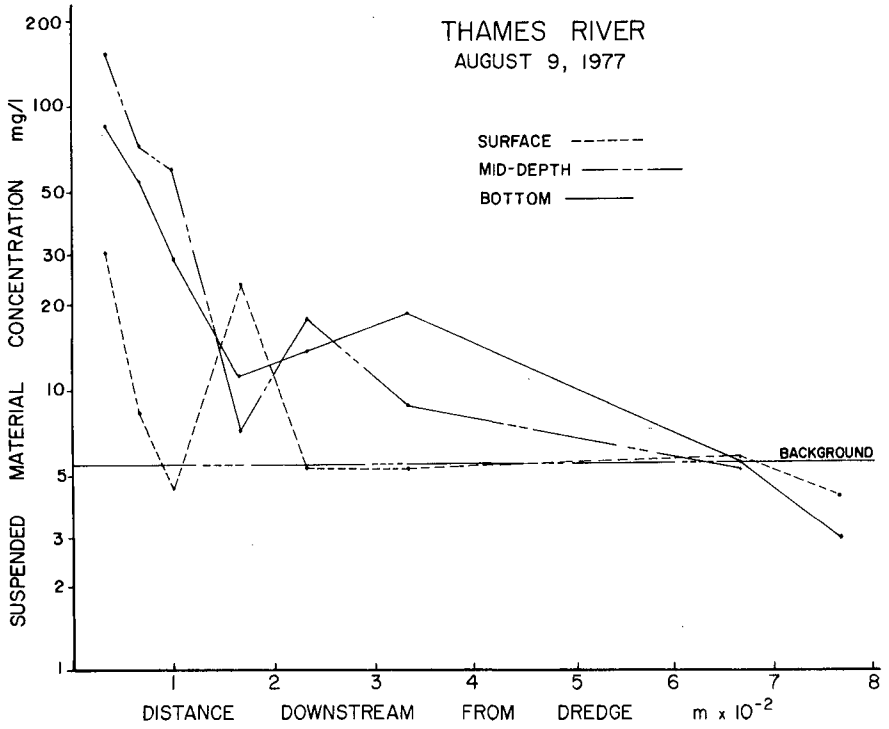


Fig. 5. Suspended material concentrations along the centerline of the plume downstream of the operating dredge. August 9, 1977. (from Bohlen, et. al., 1978).

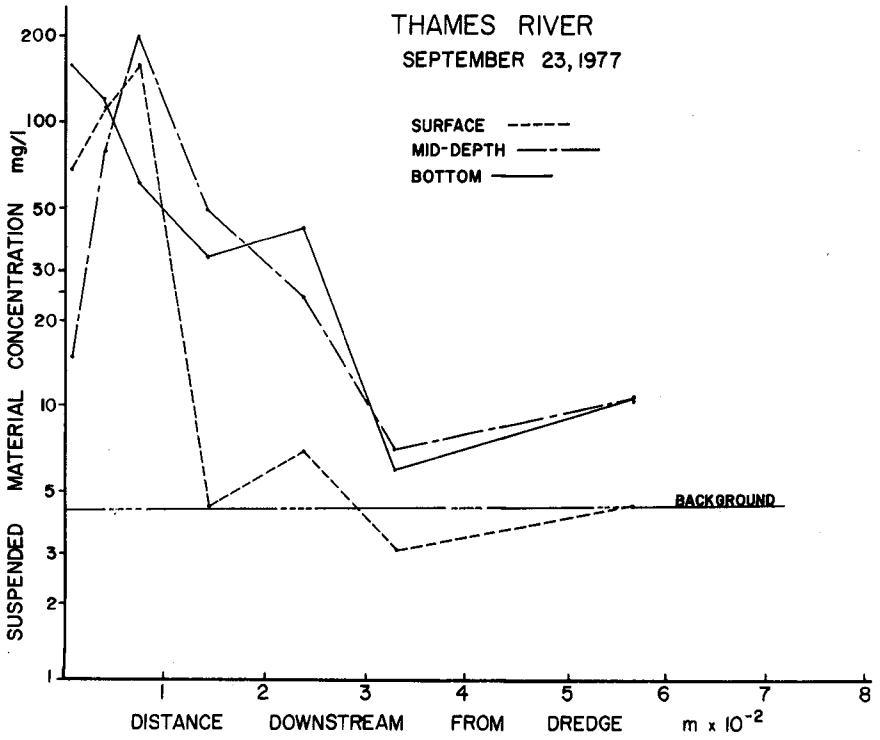


Fig. 6. Suspended material concentrations along the centerline of the plume downstream of the operating dredge, September 23, 1977. (from Bohlen et. al., 1978).

The initial dimensions of the vertical source columns are a function of the water depth and the horizontal area influenced by bucket induced mixing. The observations indicate that this latter area is several times larger than the cross-section of the bucket and has dimensions that appear to be simply proportional to the wake of the closed bucket. Examination of a typical dredging sequence (Fig. 7) shows the ascending bucket producing a very nearly circular wake having a diameter of approximately 16 m. The resultant mixing area of 201 m^2 is substantially larger than the 12 m^2 cross-section of the bucket.

Given the above characteristics it appears possible to develop reasonable estimates of the horizontal mixing area using classical wake theory (Schlichting, 1968). If a simple equivalence is assumed between drag on the bucket and fluid momentum it can be shown that,

$$b \sim (\beta\, C_D\, A_f\, d)^{1/3} \qquad (1)$$

where

b = half width of the wake

$\beta = \ell/_b$ = Const with ℓ defined as the characteristic mixing length within the wake

C_D = drag coefficient of the bucket

A_f = frontal area of the bucket

d = water depth

Observations of the residual wake (Fig.7) indicate characteristic eddy scales or mixing lengths within the wake of approximately 1 m yielding β values between 0.1 and 0.2. These values in combination with the observed wake dimensions, a bucket frontal area of 12 m^2, and water depths averaging 10 m suggest drag coefficients ranging between 20 and 40. At present the accuracy and general applicability of these numbers cannot be specified because of generally insufficient data. As a result, although the wake method appears internally consistent in terms of the limited observations provided in this study, its utility as a general means to predict the horizontal area of bucket induced mixing must remain speculative.

The mass of sediment suspended within the initial mixing zone is a function of the efficiency of the dredging process. Given the observed dimensions and suspended material concentrations ranging between 200 and 400 mg/ℓ, an assumed specific gravity of 1.5 and negligible porosity indicates that approximately 2 to 4% of the mass of each bucket load is introduced into the water column. These numbers are similar to those observed in previous studies (Bohlen and Tramontano, 1977; Gordon, 1973) and appear to be representative of the general class of

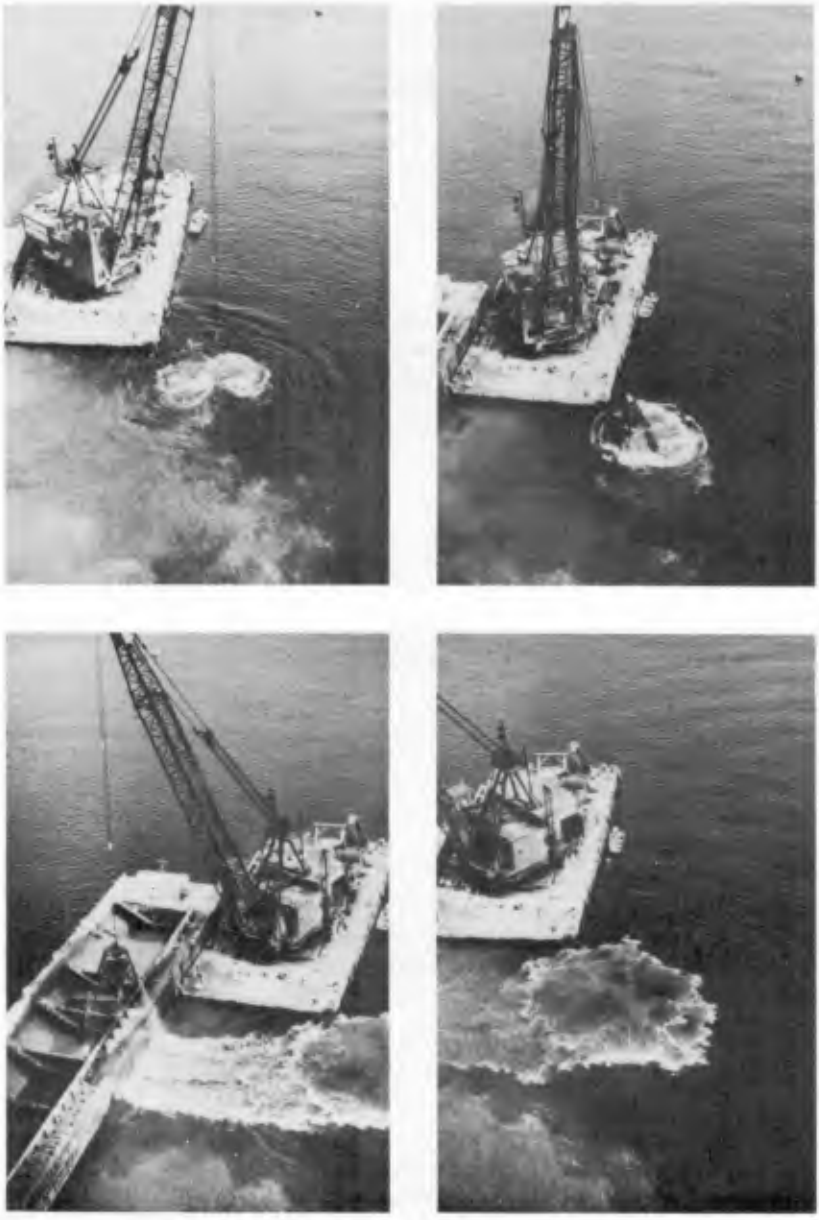


Fig. 7. A typical dredging sequence - beginning ascent upper left - residual wake - lower right. Thames River 1977 - 1978.

clam-shell bucket operations conducted in relatively cohesive, fine-grained sediments. If future work proves the value of the above wake method as a means of predicting mixing volumes, these values should permit reasonable estimates of the initial concentration levels adjacent to the dredge.

2. The Secondary Zone - Proceeding downstream from the initial mixing zone the cloud of suspended materials begins to disperse due to the combined effects of advection, turbulent diffusion, and gravitational settling. Concentrations decrease rapidly with values during the August survey falling by more than a factor of 10 within the first 100 m (Fig. 5). Such rapid rates of decay suggest that gravitational settling dominates the concentration variations in this area since the observed width of the plume is insufficient to provide the required dilutions. An estimate of the settling velocities required to affect the observed reductions can be developed using the methods described by Sumer (1977). He showed that the settling length L required to produce a given percent removal of materials suspended in typical channel flows could be evaluated using

$$L = \frac{-6 \left(\frac{\overline{U}}{u_*} \right) d}{k\lambda} \ln (1-r) \qquad (2)$$

where $\overline{U}$ = the average cross-sectional velocity

u_* = the shear velocity = $\overline{U}\sqrt{f/8}$

f = Darcy - Weisbach friction factor, assumed = 0.02

d = water depth

k = von Karman's constant = 0.42

λ = mean rate at which particles settle out of suspension

r = percentage of sediments removed

Solving for the case of the August survey where $\overline{U}$ = 30cm/sec and r = 0.9 at L = 100 m yields a λ = 40 corresponding to an average assemblage settling velocity of 4.78cm/sec. This value is equivalent to the settling velocity of an individual quartz sphere having a mean diameter of 0.35 mm and is substantially higher than values computed using the average grain size characteristics of the dredged materials (Fig. 3a) in combination with standard graphical techniques (Vanoni, 1975). The cause of these differences is not immediately apparent. Some bias is undoubtedly introduced due to the neglect of diffusion. Given the spatial scales however, the magnitude of this error should be small. More likely, the differences result from the character of the settling process in this area. Within these high concentration zones particle-by-particle settling can be limited by processes tending to favor agglomeration of particles and the formation

of particle assemblages having settling velocities substantially higher than the individual member particles. Additional work remains before the details of these processes can be quantitatively specified. For the moment the field data are best taken as an indication of the effectiveness of these processes and the possible hazards inherent in the application of single particle settling velocities within models of suspended material plumes.

As rapid gravitational settling acts to remove the coarser grained materials from the water column, the initial distribution of suspended sediment concurrently spreads laterally under the effects of local turbulent mixing. The former process tends to reduce the average grain size of the materials in suspension while the latter reduces the influence of convective processes as the spatial scales of the plume approach those characterizing the local turbulence field. In time this combination produces conditions in which the distribution of suspended material behaves in a manner similar to that displayed by a neutrally buoyant dispersant. By definition, this occurs at the downstream limit of the secondary mixing zone. An estimate of the distance required for this transition to occur can be developed if the assumption is made that subsequent downstream distributions will be diffusion dominated. Applying a simple Fickian construct, the resultant distributions will have centerline concentrations varying exponentially with a form:

$$C(x) \cong C_o \, e^{\frac{\bar{U}x}{2\kappa}} \qquad (3)$$

where x = longstream dimension

C_o = an initial suspended material concentration

k = a dispersion coefficient $\sim u_* d$

Using the August survey data to test the "goodness of fit" of this expression (Fig. 8) indicates that slightly more than 100 m is required before the exponential reasonably conforms to the observed distribution. This is one indication of the downstream extent of the secondary mixing zone.

Another measure of the extent of the secondary mixing zone can be developed by considering the lateral spreading characteristics of the plume as it progresses downstream. The typical time t required for this cross-sectional mixing can be extimated using:

$$t = \frac{\ell^2}{K_z} \qquad (4)$$

where ℓ = characteristic cross=stream length scale

K_z = lateral diffusion coefficient = $0.2\, d u_*$

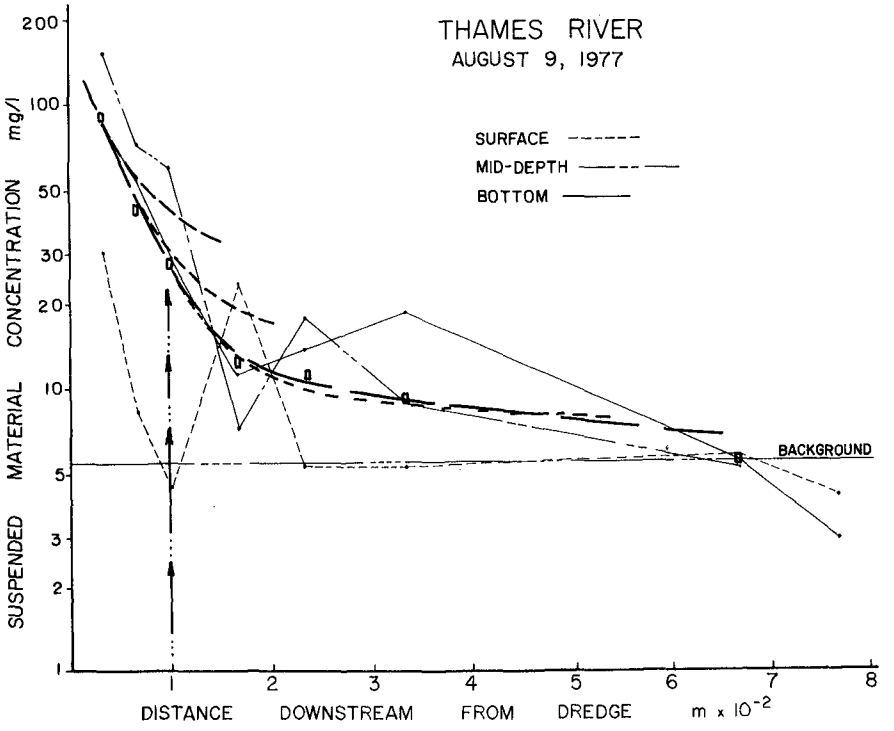


Fig. 8. Tests of the suitability of an exponential distribution function

Vertical average suspended material concentration

Exponentials beginning at various longstream locations

Inferred downstream limit of secondary mixing zone.

Fischer (1973) showed that this expression provides a useful means for evaluating the extent of the convection dominated zone. Since downstream of this zone the distributions of a neutrally buoyant dispersant can be predicted using one dimensional diffusion equations with solutions similar in form to (3), use of (4) should provide estimates similar to those given by the above curve fitting routine with the added advantage that these predictions require a minimum of data.

Evaluation of (4) for the Thames River study area using the August survey data indicates that

$$t \cong 300 \text{ sec}$$

Applying Fischer's (1973) criteria the concurrent convective time scales can be expected to range between 150 and 300 sec. At the observed average velocities these convective times imply that materials suspended by the dredge will have moved downstream distances of 50 to 100 m before the distributions become primarily diffusion dominated. The similarity between these values and those provided by the above curve fitting suggests that this method may provide the best means of predicting the longstream extent of the secondary mixing zone and encourages further investigation.

3, The final Mixing Zone - Downstream of the secondary zone, concentrations continue to progressively decay but at rates significantly lower than those observed nearer the dredge. The distributions in this, the final mixing zone are diffusion dominated although gravitational settling continues to act. The vertical average suspended material concentrations are essentially exponential in character (Fig. 8). Dispersion coefficients for this area were estimated using the guidelines provided by Fischer (1973). Constants of proportionality of 5-25 for the longitudinal coefficient and 0.15 to 0.25 for the lateral coefficient provided reasonable agreement with the field data. Despite this agreement however, additional work is required in this area with particular emphasis on the character and magnitude of dispersion and time and space varient interactions produced due to gravitational settling.

Summary

The field observations show that the suspended material plume induced by an operating, clam-shell bucket dredge is essentially a small scale feature. Under typical estuarine conditions the observed plumes had average longstream dimensions of approximately 700 m. The resultant distributions can be divided into three primary zones:

- An initial mixing zone - immediately adjacent to the dredge, where bucket operations tend to suspend and mix materials over a well defined vertical column.

- A secondary zone - extending downstream a distance of approximately 100 m in which material distributions vary primarily in response to gravitational settling.

-final mixing zone - where concentrations continue to decrease progressively approaching pre-project or background levels with variations governed primarily by turbulent diffusion.

Each of these areas appears amenable to reasonably straightforward modeling schemes sufficient to permit quantitative prediction of the suspended material distributions.

A variety of work however, remains to be done. In particular additional information on the adequacy of the wake method as a means of estimating mixing area is required. In addition more detailed observations of dredge efficiency should be obtained so that the functional relationships between sediment type, bucket size, character and operational techniques and the mass of sediment introduced into the water column can be established. Finally a comprehensive in situ investigation of sediment settling velocities is required. Each of the above studies would provide information essential within future efforts to quantify suspended sediment dispersion in the vicinity of coastal dredging operations.

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References

Barnard, William D., 1978. Prediction and control of dredged material dispersion around dredging and open water pipeline disposal operations. U.S. Army Corps of Engineers, Waterways Experiment Station. Synthesis Report No. D 78, Vicksburg, Miss. 122 pps + App.

Bohlen, W.F., Cundy, D.F., and J.M. Tramontano, 1978. Suspended material distributions in the wake of estuarine channel dredging operations. Estuarine and Coastal Marine Science (in press).

Bohlen, W.F., and Tramontano, 1977. An investigation of the impact of dredging operations on suspended material transport in the lower Thames River estuary. Prepared for National Oceanic and Atmospheric Admin., Middle Atlantic Coastal Fisheries Center, Highlands, New Jersey. 54 pps + Apps.

Fischer, H.B., 1973. Longitudinal dispersion and turbulent mixing in open channel flow. Ann. Rev. of Fluid Mechanics, Vol. 5; 59-78.

Fischer, H.B., 1967. The mechanics of dispersion in natural streams. Proc. Amer. Soc. Civ. Eng.. J of Hyd. Div. Vol 93, Hy 6: 187-216.

Gordon, R.B., 1973. Turbidity and siltation caused by dredging in coastal waters. (Unpublished manuscript). Prepared for United Illuminating Co. by Yale Univ., Dept. of Geology and Geophys., New Haven, Conn. 8pps + Figs.

Huston, J. and Huston, W., 1976. Techniques for reducing turbidity with present dredging procedures and operation. Contract No. DACW 39-75-C-0073. U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Miss.

Morton, J.W., 1976. Ecological impacts of dredging and dredge spoils disposal: A literature review. Unpubl. MS. Thesis, Graduate School, Cornell Univ., 112 pps.

Sayre, W.W. and F.M. Chang, 1968. A laboratory investigation of open channel dispersion processes for dissolved, suspended, and floating dispersants. U.S. Geological Survey Professional Pap. 433-E; 71 pps.

Schlichting, H., 1968. Boundary Layer Theory. McGraw-Hill, New York, N.Y. 747 pps.

Sumer, B.M., 1977. Settlement of solid particles in open-channel flow. Proc. Amer. Soc. Civ. Eng.. J. of Hyd. Div., Vol. 103, No. Hy 11: 1323-1337.

Vanoni, V.A., 1975. Sedimentation engineering. Amer. Soc. of Civ. Eng. Manuals and Reports of Engineering Practice, No. 54, ASCE, New York, N.Y., 745 pps.

Yagi, T., Koiwa, T., and Miyazami, S., 1977. Turbidity caused by dredging. Proc. of WODCON VII: Dredging. Environmental Effects and Technology: 1079-1109.