TECHNICAL COMMUNICATION

Dredged Material Behavior During Open-Water Disposal

Clifford L. Truitt

Coastal Engineering Research Center
US Army Engineer Waterways Experiment Station
Vicksburg, MS 39180-0631

ABSTRACT

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This paper summarizes information on sediment transport as suspended solids into the water column during dredged material disposal by barge and hopper at open-water sites. The review provides an overview of field data referenced in the more widely quoted studies on open-water disposal and compares collection methods and results. The data confirm the behavior model of a near-bottom radial surge with high solids concentration and little dispersion in the upper water column. The importance of using mass units of measurement rather than only volumetric units in accounting for the fate of dredged material is also discussed.

ADDITIONAL INDEX WORDS: *Dredging (disposal), dredged material disposal, ocean waste disposal, disposal site monitoring.*

INTRODUCTION

The many unknowns associated with the processes and impacts of open-water disposal of dredged material and the resulting environmental concern led to restrictions on the use of aquatic disposal sites in the late 1960s and early 1970s. This concern, however, fostered an expanded interest in research on the subjects, including a number of interrelated work units under the US Army Corps of Engineers' Dredged Material Research Program (DMRP). One of the principal focuses of the DMRP and later studies was the nature and effects of suspended solids (usually as turbidity) associated with dredging and disposal operations. Certainly no aspect of the subject was resolved completely, but considerable progress was made in the 1970s in describing, quantifying, and modeling the dredged material behavior at disposal sites.

The use of open-water disposal sites subsequently increased, and turbidity has been less frequently cited as a concern in planning conventional projects. However, with the passage of the Water Resources Development Act of 1986 dredging will begin in areas that have not recently been maintained and in which the potential exists for encountering contaminated sediments. Questions are now appearing concerning the movement of such contaminated dredged material during disposal by surface release from barges and hoppers. Since contaminants are typically bound to the solid phase of sediment (particularly the fine-grained fractions), an understanding and predictive capability of the movement of this sediment as suspended solids can lead to insight into the fate of the contaminants.

This paper is intended to help guide the direction of present and future investigations into disposed sediment fate by providing a state-of-the-science review of the published studies to date. Efforts were made to be thorough in the listing of studies and to use original references as sources. However, if there have been any omissions, the author would welcome additional references.

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OVERVIEW OF THE DISPOSAL PROCESS AND THE NATURE OF SUSPENDED SOLIDS

The Disposal Process

The mechanics of the behavior of dredged material placed at an open-water site by instantaneous discharge from a barge or hopper have been described and/or modeled by a number of investigators (CLARK *et al.*, 1971; KOH and CHANG, 1973; GORDON, 1974; BRANDSMA and DIVOKY, 1976; JOHNSON and HOLLIDAY, 1978; BOKUNIEWICZ *et al.*, 1978; TRAWLE and JOHNSON, 1986; and others). These descriptions typically divide the behavior of the material into three distinct transport phases or stages generally according to the physical forces or processes that dominate during each period. The most common terminology in use today for these stages is convective descent, dynamic collapse, and long-term or passive diffusion. Figure 1 is a schematic representation of these stages.

Where dredged material is released from a barge, it descends through the water column as a dense fluidlike jet. Within this well-defined jet, there may be solid blocks or clods of very dense cohesive material. SUSTAR and WAKEMAN (1977) and BOKUNIEWICZ and GORDON (1980) described the factors affecting this descent. Both concluded that the proportion of material that forms into clods in the discharge depends primarily on the mechanical properties of the sediment (especially moisture content and plasticity) and how those properties have been affected during the dredging operation. During the descent, large volumes of site water are entrained in the jet; as a result of several factors, including turbulent shear, some material is separated from the jet and remains in the upper portion of the water column. This so-called "lost" material (*i.e.*, unaccounted for in a mass balance) is transported out of the immediate site and is frequently viewed with concern when dealing with contaminated sediments.

To complete the stages of the disposal process, the descending jet and its core of cohesive

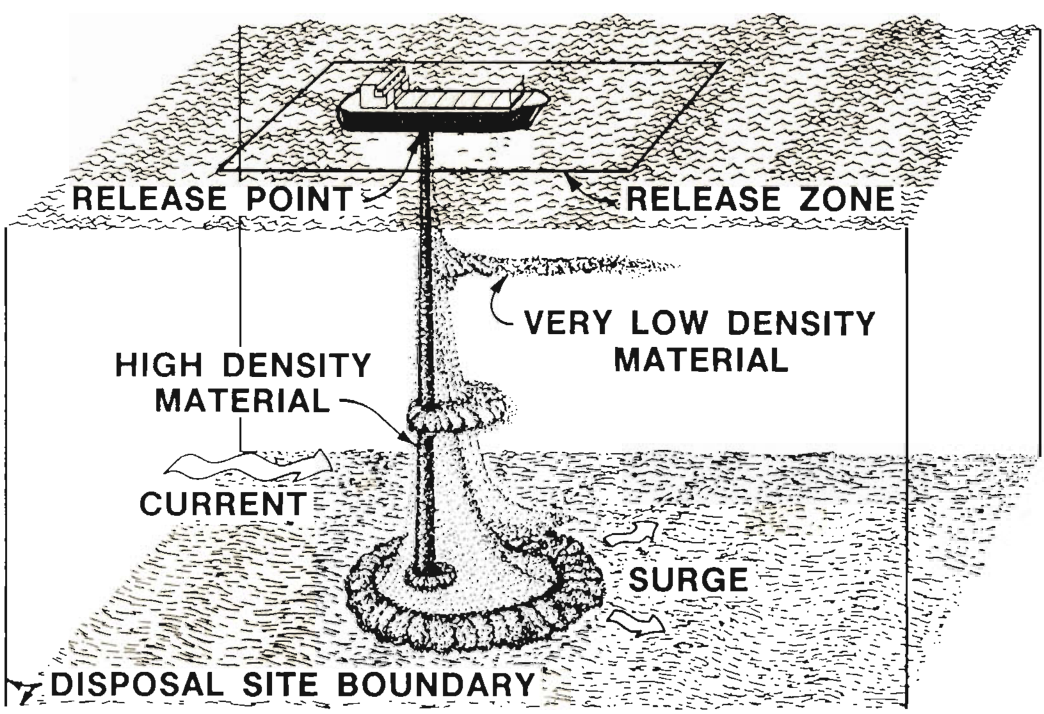

Figure 1. Transport processes during open-water disposal. (adapted from PEQUEGNAT *et al.*, 1981).

material then collapse, usually as a result of impact on the bottom or, more rarely and at deeper sites, when it encounters a layer in the water column with ambient density equal to or greater than the jet. In the latter period of the collapse, that portion of the discharge that is not deposited when it impacts initially will move radially outward as a density/momentum-driven surge until sufficient energy is dissipated and the material begins to rapidly settle on the bottom. At this time diffusive processes dominate and any material remaining from the surge will be mixed with the lower water column and diluted and will continue to settle, although more slowly.

Suspended Solids versus Turbidity

The suspended solids concentrations in the water column and even those that comprise the surge are frequently reported as turbidity or a turbidity plume. As summarized by STERN and STICKLE (1978), the term turbidity represents a complex composite of several variables that collectively influence the optical properties of water, and attempts to correlate turbidity with the weight concentration of suspended matter (suspended solids) are often impractical. Nevertheless, because of the time during which a disposal operation occurs (seconds to tens of minutes), considerable resources are needed to collect continuous water samples for gravimetric analysis. A majority of the data collected to date relies on some type of turbidiy measuring device such as a transmissometer or other optical instrument. The approach most often used is to collect as many samples as possible for gravimetric analysis and to use those results to provide a local calibration for the turbidity values measured before and during the operation.

FIELD INVESTIGATIONS OF LOSSES DURING DISPOSAL

Long Island Sound

An early comprehensive field study of open-water disposal was reported by GORDON (1974). The results were based on observations of seven individual dumping operations at the New Haven site in Long Island Sound. The operations used clamshell equipment and bottom-dumping scows held stationary during discharge of the dredged material. Volumes of individual dumps ranged from approximately 900 to 2300 cu m. The project involved predominately maintenance dredging, and the dredged material was 60 to 90 percent in the silt to clay-size range. Water depths at the disposal site were 18 to 20 m, and measured bottom currents had maximum velocities of 16 to 30 cm/sec and minimums of 6 cm/sec.

A transmissometer calibrated with sediment from the study was used to observe the solids plumes. A number of techniques including profiles with depth at fixed stations and tracking of the disposal plume were used, and the results were composited for analysis.

GORDON calculated that approximately 1 percent of the total material exiting the barges remained suspended in the upper water column and was dispersed over a significant distance. The remaining material moved along the bottom in a very well-defined surge. He provided additional calculations of the flux of material in this bottom surge at various distances from the impact point and concluded that 80 percent of the original volume of material was deposited on the bottom within a radius of 30 m and 90 percent within 120 m. The surge was confined to the bottom in a layer 4 to 5 m thick (a thickness equal to roughly 20 percent of the total water depth at the site).

San Francisco Bay Studies

A second major source of information on open-water disposal is found in the reports of a comprehensive investigation, "Dredge Disposal Study: San Francisco Bay and Estuary," undertaken by the U.S. Army Engineer District, San Francisco. In the main report, SUSTAR and WAKEMAN (1977) summarized and interpreted the results of several related investigations.

Releases were monitored in 1974 at three principal sites: barge operations at the Alcatraz site and at site LA-5 south of the Farallon Islands (the "100-fathom site") and hopper-dredge operations at the Carquinez site. The deepwater Farallon site yielded to no quantifiable data on losses in the water column, but surveys and underwater photographic coverage confirmed that, even in depths of 180 m, most of the material released could be subsequently identified on the bottom and that the spread was limited to an area approximately 150 by 300 m. Preliminary measurements using a transmissometer were made at the Alcatraz and Carquinez sites to define plume behavior and refine the monitoring techniques.

The following year, an intensive monitoring program was conducted on hopper-dredge disposal operations at Carquinez. The dredged material was classified as silty clay to clayey silt and was discharged through twin 1000-cu-m hoppers. Water depth during disposal was typically 14 m and currents ranged from 9 to 25 cm/sec. Both transmissometers and gravimetric analysis were used to measure the suspended solids at the site.

The data from Carquinez, supported by observations and measurements at the other sites, indicated that concentrations in the range of grams per liter were recorded in a well-defined layer within 1.8 to 2 m of the bottom (15 percent of the water depth). Only twice during the study period, another instrument that was placed approximately 3 m off the bottom registered concentrations higher than 300 mg/L. Total unaccounted suspended solids in the upper portion of the water column above the surge were calculated to be 1 to 5 percent of the material released. Further, the report suggested that the source of much of the surface plume was spillage/overflow from the hoppers as the vessel turned on its disposal runs and from vessel disturbance of the released jet.

Dredged Material Research Program Sites

BOKUNIEWICZ *et al.* (1978) summarized several field studies of the mechanics of placing dredged material at various open-water sites. Results were reported for both hopper dredge and barge/scow disposal operations under a variety of site conditions. A total of six sites were studied, including the previous New Haven study by GORDON (1974) and another site in the Long Island Sound area. A number of parameters were monitored in each study and considerable data on insertion, descent, and surge velocities were reported. A specially designed transmissometer was used to measure solids concentrations and was supplemented by water samples for gravimetric analysis. The work done during the study at a site off Seattle, WA is especially notable because the water depths of over 60 m were deeper than any other site studied in detail.

Throughout a wide range of sediments, equipment types, and site conditions, the same basic description of the transport processes was found to be valid. Significant concentrations of solids were found only in a well-defined bottom layer, and impacts in the upper water column were minimal. The authors concluded that the amount of material in suspension that was transported through the upper water column during the placement process was very small (less than 1 percent in most cases). The thickness of the surge layer was confirmed to depend on total water depth at the site. A further conclusion was presented on the effects of currents at the disposal site: because of the large volume of water entrained by the descending jet, it will acquire the lateral speed of the (currents in the) receiving water. However, this was observed to result only in displacing the point of impact by a predictable distance, and no greater dispersion, disruption of the jet, or additional loss of material was noted.

New York Bight

In evaluating the losses associated with dredging, transporting, and disposing of material from New York Harbor, TAVOLARO (1982, 1984) used a mass-balance approach rather than water-column sampling at the disposal site. The project involved both maintenance and new work, but both were dredged by clamshell equipment. Disposal took place at the Mud Dump site in New York Bight in 15 to 25 m of water. In addition to the innovative mass-balance approach, TAVOLARO'S monitoring work was exceptional in that he collected data from 229 barge loads representing over 600,000 cu m of dredged material. Generally the procedure consisted of securing sufficient geotechnical information so that volumetric measurement could be converted to units of dry mass for the in situ barge, and postdisposal conditions. The volume at the site following disposal was calculated by comparing predisposal and postdisposal bathymetry. After converting to mass units the losses during disposal were then inferred by subtracting the mass measured at the site from the mass in the barges. He concluded that 3.7 percent of the material mass was unaccounted for during the disposal operations.

Duwamish Waterway

The latest field study available on an open-water disposal operation was summarized by TRUITT (1986). The results were part of a broader monitoring program conducted during a disposal demonstration project by the U.S. Army Engineer District, Seattle. In summary, a single barge load of approximately 840 cu m of silty shoal material was discharged into a previously defined depression at the bottom of the Duwamish navigation waterway. Water depth ranged from 20 to 21 m, and the bottom of the depression was about 2 m below the surrounding bottom. Maxmium sustained bottom currents were 6 cm/sec with occasional readings in the upper water column approaching 30 cm/sec. Stations were established along radials from the release point, and water samples were collected essentially continuously for subsequent gravimetric analysis to determine the concentrations of suspended solids. In order to provide a check of the results, a mass balance similar to that undertaken by TAVOLARO was performed using replicate bathymetry and geotechnical data.

The results of the mass-balance calculation were presented within ranges representing estimates of the error associated with the bathymetry. These ranges overlapped, increasing confidence in the independent calculations. Between 7 and 14 percent of the material (as measured in the barge) was either transported out of the immediate vicinity or could not be accounted for in the mound. However, this amount (7 to 14 percent) represents the total flux of solids through the entire water column at a radius of approximately 30 m from the disposal depression. It is therefore analogous to the sum of the material in the bottom surge layer *and* in the upper water column as reported by earlier investigators.

Figure 2 is an example of a profile of solids concentration with depth at one station. Notice that the maximum concentrations (700 mg/L) in the near-bottom layer are lower than the values measured by GORDON (1974) and others. This is due to the confining effects of the depression. Little impact can be seen in the upper portions of the water column. Adjusting the loss calculations to reflect only the suspended solids passing through the water column above the bottom layer yields a value of 2 to 4 percent of the original mass that is likely to be dispersed over significant distances. The remaining material formed a surge layer in spite of the depression, but the concentrations in this layer are low. At 30 m, they represent approximately 5 to 11 percent of the original material compared to 18 percent typically measured by GORDON (1974) at a site with a level bottom.

The study confirmed that only a small amount of suspended sediment is typically transported away from the jet through the upper water column during disposal. The principal transport mechanism at the disposal site was the bottom surge or density flow, and control measures such as disposal into a depression can be effective in arresting that transport.

Conclusions from Field Studies

The five studies discussed above appear to be the only reports of actual field measurements of short-term dispersion or loss of material resulting from open-water disposal of dredged material by barge or hopper operations. The data are summarized in Table 1. Each investigation confirmed the validity of the description of the transport processes suggested by CLARK *et al.* (1971). Over a wide range of site conditions, materials, and operational and/or measurement techniques, the results shown in Table 1 are remarkably consistent.

ADDITIONAL REFERENCES

A number of other authors have quoted values for losses of dredged material during open-water disposal or have made conclusions without citing specific details or sources of information. The following authors, given with their sources, are perhaps the most frequently cited.

BOKUNIEWICZ and GORDON (1980) stated that the amount of dredged material lost to the surrounding water during the placement process will be small, generally 1 to 5 percent of the amount released, regardless of the proportion of the material that forms into clods. Their con-

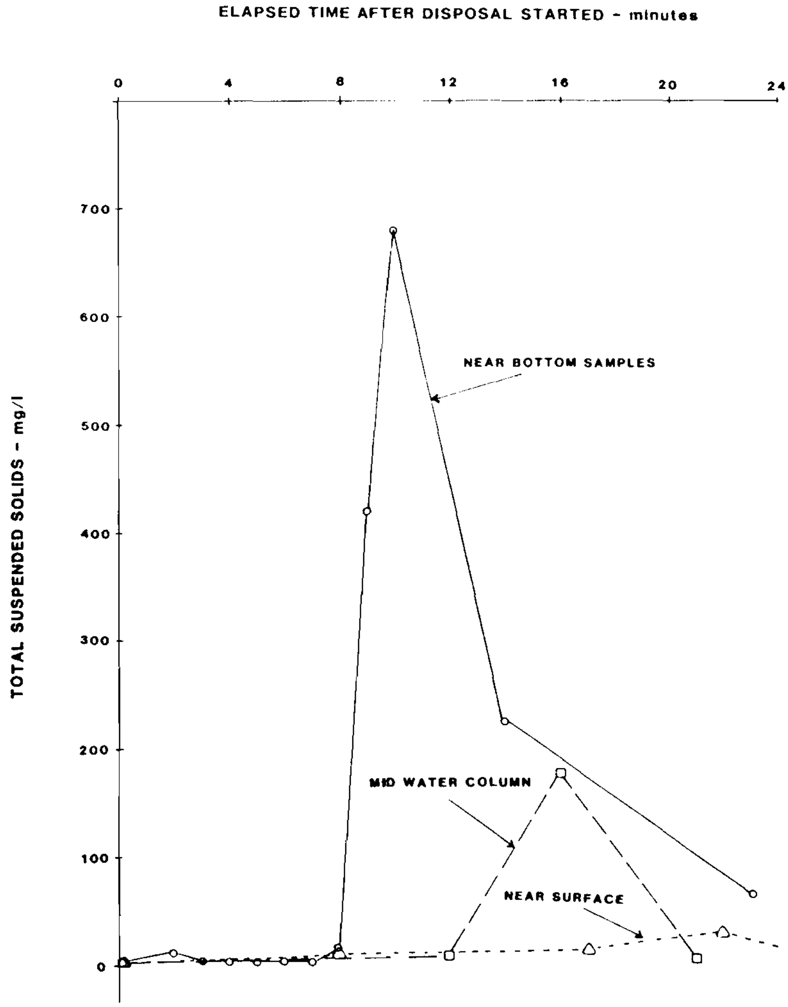

Figure 2. Time-series of total suspended solids at three depths showing well-defined bottom layer and minimal effects in upper water column (TRUITT, 1986).

clusions were based on the work of GORDON (1974) and SUSTAR and WAKEMAN (1977). BOKUNIEWICZ (1985), writing a chapter in the series, *Wastes in the Ocean*, again quoted the values of 1 to 5 percent of the released material remaining in suspension. JOHANSON, BOWEN, and HENRY (1976) also relied on the study by GORDON (1974) to conclude that the turbidity cloud contains less than 1 percent of the dumped material. ALDEN, DAUER, and RULE (1982) mentioned monitoring three test dumps as part of an investigation of the Norfolk, VA open-water disposal site. Although no specific details or sources were given, they concluded that the disposal resulted in little change in the physical condition of the water column.

MASS AND VOLUMETRIC BALANCES

In any discussion of losses during dredged material disposal, some consideration must be given to the manner, volumetric or mass, in which quantities are measured and compared. This is especially important when the data col-

TABLE 1. *Summary of Field Studies of Dredged Material Behavior During Open-Water Disposal*

		Site Characteristics		Dredging/Disposal Characteristics					Sediment in Upper Water Column
Data Source	Site	Water Depth (m)	Bottom Currents (cm/sec)	Dredged Sediment	Dredge Type	Disposal Type	Typical Volume (cu m)	Monitoring Technique/ Device	(Percent of Original)
GORDON (1974)	Long Island Sound	18–20	6–30	Silt-Clay	Clamshell	Scow	900–2300	Transmissometer	1
SUSTAR and WAKEMAN (1977)	Carquinez*	14	9–24	Silt–Clay	Trailing Suction Hopper	Hopper	1000	Transmissometer and Gravimetric	1–5
BOKUNIEWICZ et al. (1978)	Ashtabula (Lake Erie)	15–18	0–21	Sandy silt	Trailing Suction Hopper	Hopper	690	Transmissometer and Gravimetric	1**
	New York Bight	26	6–24	Marine silt	Trailing Suction Hopper	Hopper	6000	Transmissometer and Gravimetric	1**
	Saybrook (Long Island Sound)	52	21–70	Marine silt	Clamshell	Scow	1100	Transmissometer and Gravimetric	1**
	Elliott Bay	67	0–21	Sandy silt	Clamshell	Scow	380–535	Transmissometer and Gravimetric	1**
	Rochester (Lake Ontario)	17–45	0–21	Riverine silt	Trailing Suction Hopper	Hopper	690	Transmissometer and Gravimetric	1**
TAVOLARO (1982)	New York Bight	15–25	N/R	Silt-Clay	Clamshell	Scow	1375–3000	Mass Balance	3.7
TRUITT (1986)	Duwamish Waterway	20–21	6	Silt-Clay	Clamshell	Scow	840	Gravimetric and Mass Balance	2–4

*Limited data at two additional sites included.
**Synthesis of all sites reported.

lection and analysis involved direct before-and-after comparisons. TAVOLARO (1982, 1984) clearly established that apparent volumetric changes may not be true losses when evaluated solely on a mass basis. A known initial volume in a barge, say 1000 cu m, and 900 cu m identified in-place at the site following disposal does not imply that 10 percent of the original material was lost during placement. It is easy to see the problem with this approach, even during a short-term time frame, given the calculation by BOKUNIEWICZ *et al.* (1978) that a descending jet may entrain a volume of site water equal to 70 times its original volume! After undergoing such a tremendous (and rapid) bulk change, the *volume* in place may have only a limited relationship to the original volume. Over longer periods of time, volatilization and consolidation further obscure the usefulness of considering only volumetric data for accounting for the fate of the material. Finally, the measuring capability of routine monitoring equipment and techniques is such that differences in the range of 1 to 5 percent may be generally undetectable.

CONCLUSIONS

The published field data support the theoretical description of the transport phases in typical open-water disposal operations. The short-term impacts resulting from suspended sediment are confined to a well-defined layer near the bottom. The initial thickness of this layer before spread and diffusion is related primarily to the depth of water at the site. A thickness above the bottom equal to 15 to 20 percent of the total water depth was observed in the majority of the studies (although this figure has not been confirmed at sites over 60 to 70 m in depth). Above this bottom layer, suspended sediment concentrations are one to two orders of magnitude less and the total amount of solids dispersed over longer distances is 1 to 5 percent of the original material. Any monitoring program designed to account for dredged material fate during disposal should include measurements of mass and not rely solely on volumetric balances.

ACKNOWLEDGEMENTS

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□ RESUMEN □

Este articulo resume la información sobre transporte de sedimentos como sólidos en suspensión en una columna de aqua durante del vertido por gabarra de material de dragado en mar abierto. Asimismo, se da una colección de datos de campo, estudios sobre vertidos en mar abierto y se comparan métodos y resultados. Se discute, además, la importancia de utilizar unidades de masa en las medidas, en lugar de volumétricas, a la hora de averiguar el destino del material de dragado.—*Department of Water Sciences, University of Santander, Santander, Spain.*

□ RÉSUMÉ □

Résume l'information sur le transport solide en suspension dans une colonne d'eau pendant la décharge du matériel dragué par des barges et des maries salopes en mer ouvertes. Fournit un aperçu des références sur les données de terrain dans les études les plus citées sur la décharge en mer ouverte; compare les méthodes de collecte et les résultats. Les données confirment le modèle de comportement de l'onde radiale près du fond, où les concentrations en matières solides est forte, alors que la dispersion est faible dans la partie supérieure de la tranche d'eau. L'importance de l'usage d'unités de masse plutôt que d'unités volumétriques pour le devenir du matériau de dragage est aussi discuté.—*Catherine Bressolier, Labo. de Géomorphologie, UA 910, Montrouge, France.*

□ ZUSAMMENFASSUNG □

Dieser Artickel faßt Informationen über den Eintrag von Schwebstoffen in die Wassersäule zusammen, die während des Absetzens von Baggergut durch Lastkahn und Baggerprahm im offenen Meer anfallen. Der Überblick stellt die in der breit gestreuten Literatur über Abfallbeseitigung im offenen Meer veröffentlichten Daten zusammen und vergleicht die Methoden und Ergebnisse. Dabei bestätigt sich das Modell für radiale Brandung in Bodennähe mit hoher Konzentration von Feststoffen und wenig Dispersion in der oberen Wassersäule. Schließlich wird die Bedeutung von Massen- gegenüber nur Volumeneinheiten als Maß zur Berechnung des Entwicklungsganges des abgesetzten Materials diskutiert.—*Helmut Brückner, Geographisches Institut, Universität Düsseldorf, F.R.G.*