TECHNICAL GUIDANCE FOR PHYSICAL MONITORING AT OCEAN DISPOSAL SITES

Environment Canada
Disposal at Sea Program

November 1998

FORWARD AND ACKNOWLEDGMENTS

Canada is a maritime nation. It possesses the longest coastline of any nation in the world and has a vital interest in preserving a healthy marine environment. Though by world standards the Canadian maritime environment is relatively uncontaminated, Canada's territorial waters do have some problems, especially in harbours, estuaries and near shore areas. The permit assessment and ocean disposal site monitoring activities undertaken by Environment Canada represent some of the measures in place in Canada to prevent marine pollution by the disposal of wastes at sea. These activities also provide users with assurances that the environmentally preferable and practical disposal alternatives are being used and that suitable disposal sites continue to be available.

The Disposal at Sea Program, and its regulatory controls, have been in place since 1975. Between 1975 and 1990, disposal site monitoring was done on a research basis. In 1991, work and consultation began on the development of a systematic national program to monitor disposal sites, based on a need for long term assessment of compliance and effect, which was identified at both the national and international levels. This document is the result of that development effort.

This document, *Technical Guidance for Physical Monitoring at Ocean Disposal Sites*, provides advice to managers and professionals on developing and implementing monitoring projects at ocean disposal sites that receive dredged and excavated material. Technical guidance is provided on the use of various physical assessment tools and on the available techniques including

- positioning equipment
- sampling equipment
- techniques for direct observation of ocean disposal sites and to define their boundaries
- sediment transport models to predict short-term and long-term effects.

This national Technical Guidance was prepared through an extensive review and consultation process with scientists and experts across Canada and from around the world. The authors are especially grateful to Jim Osborne, Linda Porebski, and John Karau for their guidance and support. Enquiries should be directed to:

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This document should be cited as follows:

Technical Guidance for Physical Monitoring at Ocean Disposal Sites. (1998) Environment Canada, Marine Environment Division. 49 pp.

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INTRODUCTION

Disposal site monitoring forms one element of ocean waste disposal management. Monitoring information is used to assess permit decisions, review the adequacy of controls and identify needs for remedial actions, or further study and research. Guidelines covering site monitoring have been published by Environment Canada (1998). These guidelines outline the triggers to disposal site monitoring, discuss developing monitoring plans to test impact hypotheses, and provide guidance on core monitoring programs and tiered monitoring requirements.

The triggers to site monitoring are related mainly to disposal of dredged material containing contaminants above trace levels, or to the potential for impacts to sensitive areas (biological resources), habitat loss or conflict with other uses of the sea. Core monitoring parameters include basic physical and sedimentary information about the site and the material to be dumped, in addition to data on chemicals contained in the sediments. Tiered monitoring requires, as a minimum, predictions of the depositional area initially covered by the dumped material, and if there is a potential for resuspension and transport, where the material will finally come to rest (to within detectable limits). This information constitutes a definition of the disposal site boundaries. Site monitoring is used to check the predictions of the disposal site limits. Depending on the nature of the site, and the monitoring objectives, surveys make take place once, or be repeated periodically. Physical disruption of habitat will result from most dumping activities; the degree of disruption is indexed by changes in sediment character such as thickness of the spoil deposit, difference in sediment texture of the deposit and the spatial extent of the spoil deposit.

Planning monitoring programs to meet the guidelines requires knowledge of both geological surveying and sampling methods, and of models for predicting the initial depositional characteristics and sediment transport. This guidance document provides information on surveying methods and numerical computer modelling techniques appropriate for disposal site analysis and monitoring.

Scope

Two general reviews are presented, the first dealing with geological surveying and sediment sampling methods, and the second outlining short-term fate disposal models and sediment transport models applicable after material has settled to the seabed. In both reviews the information is presented so that the reader can evolve strategies for measurement and modelling appropriate to a site under consideration. The methods and equipment discussed under these two topics are confined to generally accepted and accessible technologies. It is recognized that geophysical surveying techniques, and the use of specialized in situ sensors or submersible-deployed sensors, are rapidly evolving areas but often such equipment is not generally available and it is expensive to use.

Similarly, the field of sediment transport modelling is constantly advancing and new calculation methods are being proposed all the time. Often, however, these new methods have limited support with data and are not tractable to non-specialists because computer program support is too limited, or the data required from the field is too difficult to obtain. In order to provide practical guidance, models discussed in this review are confined to programs that are generally available or are accessible with technical support, and that have a good basis in calibration with data.

A Note on Terminology: References to sediment texture follow the terminology of Percival and Lindsay (1997). The term "shallow-water" was used for water depths of less than 100 m and generally greater than 30 m and the term "deepwater" for water depths greater than 100 m and generally greater than 200 m. Other geological terminology are summarized in the Glossary.

Sediment Size Nomenclature (Percival and Lindsay, 1997)

Grain Size (mm)	Phi-scale ø	Sieve Size	Wentworth Size Class	
4096	-12			
1024	-10	Use	boulder	
256	-8	wire		
64	-6	squares	cobble	
16	-4			**GRAVEL**
4	-2	5	pebble	
3.36	-1.75	6		
2.83	-1.5	7	granule	
2.38	-1.25	8		
2.00	-1.0	10		
1.68	-0.75	12		
1.41	-0.5	14	very coarse sand	
1.19	-0.25	16		
1.00	0.0	18		
0.84	0.25	20		
0.71	0.5	25	coarse sand	
0.59	0.75	30		
0.50	1.0	35		
0.42	1.25	40		
0.35	1.5	45	medium sand	
0.30	1.75	50		
0.25	2.0	60		**SAND**
0.210	2.25	70		
0.177	2.5	80	fine sand	
0.149	2.75	100		
0.125	3.0	120		
0.105	3.25	140		
0.088	3.5	170	very fine sand	
0.074	3.75	200		
0.0625	4.0	230		
0.0530	4.25	270		
0.0440	4.5	325	coarse silt	
0.0370	4.75			
0.0310	5.0			
0.0156	6.0	400	medium silt	
0.0078	7.0		fine silt	**MUD**
0.0039	8.0		very fine silt	
0.00098	9.0	>400		
0.00049	11.0			
0.00024	12.0		clay	
0.00012	13.0			
0.00006	14			

GEO-PHYSICAL TECHNIQUES

1. GEOLOGICAL SURVEY STRATEGIES AND POSITIONING

This part provides a review of geological survey techniques that may be used in ocean dumpsite monitoring. It gives a brief overview of (a) survey techniques and (b) strategies for application of the techniques to different types of sites and differing survey objectives. This is not intended as a "how to" manual on application of the techniques nor is it intended as a detailed specification manual; salient references are provided for this type of information.

Cost estimates have been included to provide an order of magnitude comparison. Costs are based on "typical" 1993/1994 rates that are charged by commercial, marine survey firms. Costs are likely to vary greatly depending on the survey objectives and can only be accurately estimated once these objectives have been defined for a specific site.

1.1. Decision-Making Framework: Defining the Survey Objectives

Table 1 provides a four-level approach for defining the survey objectives with the different levels reflecting increasing degrees of detail. The Baseline category is the basic level of information on a site and may be developed from existing data or a site-specific survey conducted in support of the permit application. This information is used in initial modeling to evaluate impact hypotheses.

Level I surveys are designed to document the initial extent of disposed material on the seabed. A combination of acoustical surveys and sampling may be required for this level of survey. If a repetitive monitoring program is anticipated, then a Level II survey is recommended; survey standards and methods may differ from a Level I survey to reflect the need to collect data that will be comparable between surveys. Level III surveys reflect the need to make quantitative comparisons between data of repetitive surveys; to establish sediment or contaminant budgets that can be compared with statistical confidence.

Table 1. Categories of Survey Objectives

Category	Survey Objectives
Baseline	define natural seabed conditions
Level I	delineate the area of initial disposed materials on the seabed
Level II	conduct repetitive surveys to qualitatively delineate changes in the spatial extent of disposed material
Level III	conduct repetitive surveys to quantitatively estimate dispersal rates

1.2 Site Characterization

There is a wide range of survey techniques that can be applied to disposal site monitoring (Table 2). However, characteristics associated with each site will dictate the unique suite of techniques that are appropriate for monitoring at a specific site; that is, it is not practical to specify a set of survey techniques for disposal site monitoring unless the site characteristics are known. Site categorization at the initial Baseline Level is important in the proper formulation of the impact hypotheses and in the selection of appropriate survey techniques. General site categories include:

dispersive or non-dispersive sites—dispersive sites are those where it is anticipated that disposed material will be transported from the initial area of deposition; non-dispersive sites are those sites where most of the deposited material is expected to remain in place (Fredette, *et al.*, 1990b). Often bedforms and seabed texture will indicate whether a site is dispersive. Fine muddy sediments with a smooth texture usually indicate a depositional regime and a non-dispersive site. In contrast, coarser sediments, exhibiting flow-transverse or along-flow bedforms infer sediment motion and a dispersive site. Amos and King (1984) give a good guide to bedform interpretation.

contrasting or non-contrasting sediments—contrasting sediment sites are those sites where there is a significant difference in sediment characteristics between the disposed material and the natural seabed sediment (*e.g.*, sand and gravel disposed onto a silt and clay seabed). Non-contrasting sediment sites are those sites where disposal site sediments and natural seabed sediments are likely to have similar sediment character (*e.g.*, muddy sands disposed on top of sandy muds.) Sites with contrasting sediments are more likely to be detectable by acoustical survey methods than are non-contrasting sediment sites.

thick or thin disposal site sediments—the relative thickness of the disposed materials will affect monitoring strategies. The terms thick and thin cannot be defined absolutely and vary depending on sediment contrast, water depth and other factors. The terms thick or thin relate to the detectability by acoustical survey techniques; very thin materials (*e.g.*, less than 30 cm) will be difficult to detect by acoustical means whereas thick materials (*e.g.*, greater than 1 m) will usually be detectable. Sites with "thin" mantles of sediment may be better monitored with a coring program.

Table 2. Geological Surveying Techniques

Geophysical	**Visual**
depth sounding	bottom photography
sweep mapping[1]	video imaging
sub-bottom profiling	diver observation
side-scan sonar imaging	sediment-profiling
swath mapping[2]	photography
Sampling	**Advanced Methods**
grab sampling	magnetometer surveys
coring	resistivity surveys
diver sampling	tracer studies
	in situ methods

1. *A three-dimensional bathymetric map produced from an array of multiple, boom-mounted transducers (Figure 2)*
2. *Three-dimensional bathymetric and side-scan maps (or swaths) produced from a single, multi-beam transducer*

Table 3 provides some examples of different combinations of site characteristics, probable primary survey techniques and associated rationale for use of techniques. The table provides an indication of the complexity of choosing appropriate instrumentation for a site survey. The final selection will depend on (a) the survey objectives (i.e., Level I, II or III), (b) the site characteristics and (c) the anticipated frequency of site re-surveys.

1.3 Positioning

The function of navigation or positioning technology in a marine geological survey is to assist with or control the location of survey line patterns and seabed sample sites. There is a variety of navigation and position-fixing systems available, and these can be stand alone or electronically integrated with echo sounder and other data acquisition equipment.

The criteria for selecting a positioning system depends primarily upon the purpose and objectives of the study, the physical conditions, seabed topography and size of the study area, equipment availability, the minimum distance between sampling stations, site accessibility, station reoccupation, the desired degree of precision and accuracy, and financial constraints (USEPA, 1987). For example, monitoring or reconnaissance surveys over large study areas do not normally require as highly accurate or precise positioning as that needed for small site-specific surveys where the same stations need to be monitored or sampled repeatedly.

Table 3. Selected Survey Strategies Based on General Site Characteristics

Dispersive Nature (initial estimate of transport potential)	**Sediment Contrast** (difference between disposed material and natural	**Thickness** (relative thickness in terms of acoustic detectability)	**Possible Primary Survey Strategy/ Techniques**	**Rationale**
Dispersive	High Contrast	Thick	• high resolution bathymetry • side-scan sonar • sub-bottom profiling	since disposed materials are thick and transport potential high, chance for detectability with repetitive high resolution bathymetric surveys is good; sub-bottom profiling may be useful if overlying material is finer; side scan sonar should provide a good spatial image of dispersion
		Thin	• side-scan sonar • coring • grab sampling	side-scan sonar should provide a good spatial image of dispersal; coring will provide a high resolution of the thickness but many cores may be required if side-scan shows patchy distribution; grab sampling may be useful if materials widely dispersed
	Low Contrast	Thick	• high resolution bathymetry • coring • grab sampling	since disposed materials are thick and transport potential high, chance for detectability with repetitive high resolution bathymetric surveys is good; coring or grab sampling may be useful in areas away from the main deposit; low contrast limits use of acoustics
		Thin	• coring • grab sampling	since acoustics are unlikely to detect materials, coring with post-survey analyses may be the only feasible means of monitoring dispersal; alternatively one could consider sediment tracer surveying methods
Non-dispersive	High Contrast	Thick	• high resolution bathymetry • side-scan sonar • sub-bottom profiling	same as dispersive sediment category but a lesser frequency of repetitive survey might be required
		Thin	• side-scan sonar • coring	side-scan sonar may be adequate for initial detection but disposed material may be masked by natural sedimentation over time; a high density coring program may be appropriate
	Low Contrast	Thick	• high resolution bathymetry	repetitive high resolution bathymetry surveys may be useful; minimal detectable volumes of such surveys should be calculated in advance; other acoustical survey techniques unlikely to detect change
		Thin	• coring	coring with careful handling and processing of sediments may be the only means of detecting transport from the disposal site onto the natural seabed

1.3.1 Surface Vessel Positioning

A review of positioning systems is provided in the *Guidance document on the Collection and Preparation of Sediments for Physicochemical Characterization and Biological Testing* (Environment Canada, 1994d, Table 2); the document lists systems, distance ranges of the systems, accuracy, advantages and disadvantages. The information applies only to surface vessel navigation, however, and does not address problems in positioning the sampler, or in the case of sonar surveys, the position or attitude of the towfish.

Each of the available types of positioning methods (optical or line of sight, short and long range electronic, and satellites) has advantages and disadvantages as well as manufactured specified accuracies and range characteristics. However, the "operational accuracy" under normal field conditions often falls short of the manufacturers stated accuracies (see Section 1.3.3).

Figure 1 illustrates some possible positioning errors. These include: (a) the assumed position of the sampler relative to the vessel position (vessel position is determined by the position of the ship's antenna, in this case) and (b) the actual position of the sampler, which may not be directly below the "assumed sampler position" due to currents or to residual "way" of the vessel. Where currents are strong or water depths are large, the later error may be significant. The actual position of the sampler can be accurately determined using either an underwater acoustical ranging system that determines the relative position of the sampler from the vessel position or using a seabed navigation system that determines position of the sampler relative to an acoustic navigation network.

Special Note on GPS Navigation. GPS (Global Positioning System) potentially offers the possibility of sub-metre positional accuracy on a global basis (Frodge, *et al.*, 1994; Hurn, 1993; Lapucha and Barker, 1994; Wells, *et al.*, 1992). However, this level of accuracy is not normally achievable, especially when attempting to relocate previously sampled or survey positions (Hurn, 1989; Lieck, 1990).

Uncorrected GPS navigation typically has a ±100 m accuracy due to intentional degrading of the satellite signals. Given this, such positional data require correction. By carefully recording GPS positions at a fixed shore station at the same time positions are being collected aboard the survey vessel, the vessel fixes can be corrected to sub-metre accuracy *after* the survey; this is known as Post-Processing, Differential GPS. The important point is that the vessel position *during* the survey is only known to ±100 m.

By transmitting positional information from a fixed shore station to the survey vessel, the GPS position on the vessel can be corrected to sub-metre accuracy during the survey. (kinematic or real-time Differential GPS or DGPS). The Canadian Coast Guard (CCG) currently broadcasts a Differential GPS correction and off-the-shelf DGPS systems are commercially available. Thus DGPS offers the potential of real-time survey accuracies in the sub-metre range where CCG broadcast corrections are available. As well, dedicated differential transmitting units may be leased from survey companies for establishing line-of-sight, kinematic DGPS where no CCG broadcasts are available.

1.3.2 Subsurface Positioning

Table 4 summarizes the primary techniques that can be used to position samplers or survey instruments relative to the seabed. Subsurface positioning becomes critical when seabed conditions are highly variable (*e.g.*, patchy) and when repetitive surveys are required. Besides accurately positioning samplers, accurate location of the towfish or submersible/remotely operated vehicle (ROV) is critical if seabed targets or stations are likely to be resurveyed.

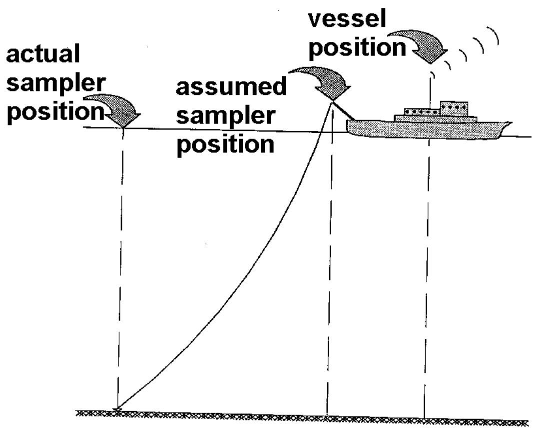


Figure 1. Common positioning errors between sample and vessel locations

Table 4. Underwater Positioning Systems

Category	Accuracy	Range	Advantages	Disadvantages
Layback (towfish) and wire angle technique (samplers)	varies; generally =±10 m for towfish; ±5 m for samplers	n/a	simple, mechanical method of estimating towfish (i.e., amount of cable & depth of fish used to correct) or ampler (i.e., wire angle + wire length used to correct)	towfish may not track directly behind vessel, thereby introducing error; wire angle may be very difficult to estimate from rolling vessel
Seabed targets or drag marks	generally ±5 m	depends on side-scan range	targets are placed on seabed to show up on side-scan image; drag marks may be made for repetitive surveys	targets may be difficult to resolve from background clutter; targets require deployment and recovery; drag marks may infill
Seabed transponder target	generally +5 m	depends on side-scan range	transponders of proper frequency show up as targets on side-scan sonar image	requires annual replacement or deployment/recovery for each survey; target must be within side-scan range
Seabed beacon (pingers)	variable	< 1 km	simple method of relocating a position by diver, ROV or submersible (vehicle “homes” in using directional receiver)	requires subsurface platform to relocate beacon
Ship-based Range/bearing systems	±2 m	500 m	give a position relative to the ship using range and bearings; simple installation aboard the ship with acoustical transponder on sampler, ROV or towfish	requires real-time micro-processing to interface with surface navigation; may be sensitive to ship’s noise; expensive and personnel intensive
Seabed navigation network	±2 m	~5 km	planimetric image of survey area displayed on screen showing transponders and targets; relative positioning within transponder network highly accurate; primarily used for submersible and ROV surveys as part of engineering surveys	involves installation of three or more acoustic transponders on the seabed; subsurface transponders must be deployed and recovered; absolute position only as good as surface vessel position

Subsurface positioning adds a significant level of complexity to a survey in the form of additional equipment both on the ship and on the "over-the-side" instruments, additional on-board processing of data and additional expertise to operate the equipment. Subsurface positioning systems are not routinely used in seabed surveys (usually used in engineering surveys) although systems are available for commercial lease in Canada. Costs of the systems vary significantly with an acoustic bearing-range system leasing for approximately $5,000 per day including costs of operators.

1.3.3 Operational Limitations

Given the inherent error associated with both surface and subsurface positioning systems, where a combination of these systems is used, these inherent errors will be additive. As well, there are operational limitations on positioning accuracy that fall short of the manufacturers' stated accuracies.

For example, when using range-range electronic positioning systems, position accuracy is dependent on the "angle of cut" which often differs from the optimal right angle. Poor operational conditions (strong winds, waves and currents) also reduce the ability of survey vessels to follow position system controlled steering commands. It is also very difficult for a vessel to remain at a station or return to the same station in rough sea conditions. Therefore, despite having a positioning system with ±3 m accuracy, operational constraints may result in accuracies of only ±20 m.

New multibeam swath or sweep surveys usually provide high density depth information that is roll- and pitch-corrected. These systems are less sensitive to the operational limitations discussed above as bathymetric data are likely to overlap pervious surveys despite deviations from the intended survey lines.

Some examples of different positioning systems, anticipated accuracies, operational accuracies and approximate costs are provided below. Please note the cost guidelines are appropriate for accessible, southern marine waters in Canada. For Arctic operations, one must add transportation and extended mobilization costs.

Example 1. Positioning for a Shallow-Water Surficial Sediment Survey

Background: water depth 20-30 m; non-dispersive site (anticipated) of mine tailings; natural seabed sediments of silt; tailings to fine sand; box core samples to be collected to document dispersal of tailings and concentration levels of tailings; initial sampling grid of 5x5 (25 samples) with 100 m grid spacing anticipated; multiple repetitive surveys anticipated.

Positioning System: DGPS (real-time) to be utilized so anticipate ±2 m accuracy of vessel antenna.

Operational Constraints to Positioning: correction to be applied to difference between positions of the antenna and sampler (4 m difference but correction will vary depending on ship's heading when sampler hits the bottom); tidal currents are minimal so difference between assumed position of sampler and actual position of sampler assumed to be within ±2 m (i.e., close to directly below the vessel); overall operational accuracy of ±4 m with respect to sample grid; if sample grid is reoccupied at a later time, the best vessel position will likely be no better than ±5 m to the original sample location because of difficulties in positioning the vessel and dropping the corer; the absolute position of the second sample will be known to ±4 m but it is unlikely to be "at" the same position as the first sample.

Costs: the anticipated field program is one day; anticipated mobilization and demobilization of a leased DGPS would bring the total lease period to 3 days. Three options are available:

1) where CCG broadcasts corrections, lease of a survey-grade system for 3-4 days would cost about $600;
2) where no CCG broadcast is available, post-survey processing could be done; leasing a survey grade GPS would cost $450 and commercially purchasing DGPS data is about $200; however, the actual position in the field will only be to about ± 100 m.

3) where no CCG broadcast is available, a dedicated real time DGPS can be setup specifically for the survey—this would involve the installation a shore station/transmitter and an onboard processing system on the survey vessel; commercial costs would be in the range of $3,000-$4,000. This would provide real-time DGPS positioning.

Example 2. Positioning for a Deepwater Side-Scan Sonar Survey

Background: water depth 300 m; non-dispersive (assumed), multiple-use site; material disposed of is an excavated till; natural seabed sediments of silt; side-scan sonar survey to be conducted to ascertain actual location of material disposed of relative to target; 500 kHz side-scan to be used with slant range and speed correction; image width 200 m. Initial survey to be conducted prior to disposal and second survey to be conducted afterwards.

Positioning System: DGPS (real-time) to be utilized so anticipate about a 2 m accuracy of vessel antenna and seabed transponder targets.

Operational Constraints to Positioning: area of relatively strong tidal currents will complicate knowledge of towfish position; towfish to be positioned using ship's position, heading information of vessel and layback estimated from knowledge of depth of fish and amount of wire from vessel to towfish; because of the amount of wire out, and the presence of strong tidal currents, estimated position of the towfish is probably about ±30 m. Since there is previously disposed material on the seabed, a more detailed sonar image positioning is required. The operator chooses to deploy four subsurface transponder targets on the seabed; the position of these targets (target includes a large mooring block, a pinger and a 300 m long surface mooring line) is located within ±5 m using surface navigation. These targets provide absolute reference points on the "before" and "after" sonar images. However, it is probable that transponders would have to be recovered prior to the spoil placement to avoid burial, and then redeployed following placement. A small sonar mosaic is compiled for the proposed target area.

Costs: the anticipated field program is one day; anticipated mobilization (2 days including transponder deployment) and demobilization (2 days including transponder recovery) of a leased DGPS and subsurface transponders would bring the total lease period to 1 week. Assuming that DGPS using CCG broadcast corrections is available at the site the positioning approach would be: lease of a survey-grade system for 3-4 days which would cost about $600; a one-week lease of the seabed transponder targets would require an additional lease of $200/week/target (x4) bringing the total navigation system costs to $1400.

2. SURVEY TECHNIQUES

A variety of techniques are available for monitoring material disposed at sea. These techniques are broadly classified into four categories:

> *Geophysical Techniques*—may be capable of resolving the disposal site deposit using acoustical reflectance off the seabed or subsurface layering and include: depth-sounding, sweep mapping, sub-bottom profiling, side-scan sonar imaging and swath mapping.
>
> *Sampling Techniques*—result in collection of a sediment sample that is subjected to detailed analysis for mineralogical composition or textural character (grain size) and include: grab sampling, coring, sampling by diver, or sampling by ROV or submersible.
>
> *Visual Techniques*—provide photographic or video images of the seabed and include: still photographs from cameras, video imagery from ROVs or towed sleds, images from sediment-profiling cameras or direct observations by submersibles.
>
> *Advanced Techniques*—are not commonly used in seabed monitoring studies but may be useful in certain cases, such as research and development studies, and include: seabed magnetometer surveys, electromagnetic resistivity surveys, tracer studies and *in situ* instrumentation.

These techniques are discussed with respect to applicability in ocean disposal site monitoring, particularly concerning spatial mapping of the disposed sediment (horizontal extent and thickness) and ability to use data for estimating volume and budgets of contaminants. For additional information on field tools, Hands (1993) provides a similar review.

2.1 Depth Sounding

Depth sounding surveys are conducted using a depth sounder that produces a line trace of the seabed position relative to the water surface. The seabed profile is of the surface only. By running a series of profiles on a grid, bottom bathymetry can be contoured to produce a bathymetric map. Accuracy of the bathymetry will be a function of (a) the instrumentation (high frequency transducers with narrow cone widths produce the most accurate data), (b) the seabed slopes, (c) sea-state conditions during the survey, (d) the water depth and (e) navigation precision (Milne, 1980). As a general rule-of-thumb, accuracies of 1% of the water depth can be achieved under optimal conditions.

Depth Sounding

Advantages

- simple instrumentation; no over-the-side instruments are required
- can be interfaced with navigation for recording & digitally processed
- can provide an indication of seabed character (soft vs. hard) and may be of use in discriminating disposed sediment from natural seabed sediments
- real-time electronic processing systems can classify seabed sediments

Disadvantages

- provides limited spatial picture; many survey lines are required to produce a map
- repetitive surveys highly dependent on navigation accuracy
- depth sounding alone not capable of detecting limits of disposed material as the material is likely to be very thin at edges.

Sounding traces also provide an indication of seabed character in that strong reflections indicate "hard" bottoms and weak reflections indicate "soft" bottoms. Systems have been developed to classify bottom materials by processing the electronic return signals from the seabed (Kavli, *et al.*, 1994). Instrumentation has been developed that is capable of classifying sediments into broad categories such as rock, gravel, sand and mud. In some systems, multi-frequency transducers are used to classify the seabed; in other systems, a single-frequency return wave-form signal is recorded and processed to classify sediments (Prager, *et al.*, 1993).

Repetitive surveys of the seabed can be conducted to monitor seabed change; for example, a series of surveys over a 5-year period tracked the gradual evolution of dredged material mounds migrating toward the coast in the Gulf of Mexico (Hands, 1994). However, errors associated with the various accuracy limitations identified above will generally preclude detection of seabed changes of less 0.3 m in shallow environments (less than 30 m) and changes of less 1 m in deepwater environments (greater than 100 m). Where slopes are relatively steep or seabed conditions are rough, the detection limit will increase.

Where the disposed sediment exceeds 1 m in thickness above the seabed and the surrounding seabed is relatively flat, the disposed material can probably be detected by gridded depth-sounding surveys although the edges of the disposed sediment would not be accurately defined unless the disposed sediment has markedly different reflectance characteristics. Any repetitive survey will require highly accurate navigation system such as a range-range system or DGPS (see Section 1.3).

Survey costs for bathymetry surveys can vary greatly. For simple reconnaissance surveys, where radar or LORAN-C positioning is used, leasing costs for a survey-grade sounder are about $100 to $200 per day. Depending on the degree of digital logging, trained operators may be required for more sophisticated logging systems ($500-$700/day per operators). Typical disposal-site type area maps may require 3-5 days of post-survey processing to produce large-format bathymetry maps.

2.2 Sweep-Mapping Systems

Sweep mapping systems are commonly used in shallow-water bathymetric surveys to produce high-resolution bathymetry maps. A survey vessel is equipped with booms and a series of transducers (Figure. 2) such that a wide swath or "sweep" of synchronous bathymetry is collected; the system is essentially a series of echo soundings but is normally processed on board to produce a swath bathymetry map.

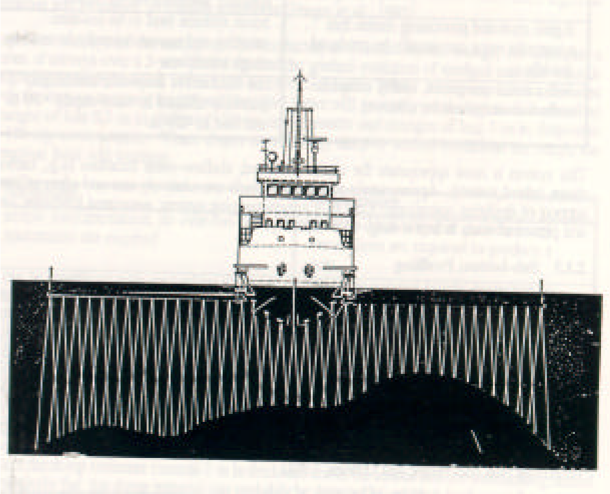


Figure 2. Sweep mapping system with booms and 16 transducers. (from NAVITRONICS)

Sweep-Mapping Systems

Advantages

- high resolution bathymetric map is produced
- digital on-board processing means that composite maps can usually be produced quickly
- with careful navigation, nearly complete seabed coverage can be achieved

Disadvantages

- sweep systems are equipment and personnel intensive; usually requires a specially designed survey vessel
- boom systems tend to be sea-state sensitive and cannot normally be used in rough conditions
- not suitable for deepwater conditions; generally utilized in water depths less than 30 m and best in less than 20 m.

As these types of survey vessels are sensitive to sea-state conditions, this system is most appropriate for use in protected, shallow-water locations (e.g., harbours, rivers, inland waters). Appropriately configured vessels are relatively rare and often utilized in support of dredging operations. The costs of a sweep-mapping system, associated hardware, vessel and personnel are about $4,800 per day.

2.3 Sub-bottom Profiling

Sub-bottom profiling uses the same principals as a depth sounder: transmitting a sound pulse from a transducer, reflecting the pulse off sea floor and recording of the reflected sound pulse. Sub-bottom profiling, however, uses more power and lower sound frequencies, permitting the sound pulse to penetrate into the sediments. The trade-off for using lower frequencies is reduced precision in measurements such that layering immediately adjacent to the seabed (within 0.25 m of the bottom) is commonly "masked" by the acoustic signature of the bottom signature. The minimum detection thickness of a surface layer of sediment is generally in the range of 0.25 m for shallow-water conditions, although Simpkin and Davis (1993) indicate targets of 0.15 m can be resolved, and in the range of 1-2 m for deep-water conditions (see also Parent and O'Brien, 1993).

Sub-Bottom Profiling

Advantages

- instruments are relatively simple; usually run as a towed fish, but can be deployed over-the-side
- can be interfaced with navigation for recording
- provides an indication of the immediate subsurface layering; may be capable of discriminating disposed material thickness if greater than 1 m (depends on survey conditions and sediment contrast)
- may be able to estimate thickness of disposed material and develop an isopack map of it

Disadvantages

- provides limited spatial picture; many survey lines are required to produce a map
- repetitive surveys highly dependent on navigation accuracy
- not capable of detecting thin, near surface layering; may not detect disposed material if there is not sufficient contrast between disposed sediment and natural seabed sediment

Resolution constraints make sub-bottom profiling unsuitable for most thin dredge material deposits but potentially suitable for some "thick" disposal site monitoring projects; accurate navigation would be required if sediment thickness contouring is an anticipated product.

Since sub-bottom profiling is normally conducted in conjunction with echo-sounding surveys, only the costs of hardware and associated personnel are provided here. Day rates for graphic-type systems (e.g., paper recording output) range from $200-$300 for simple systems to $600 per day for a digital recording system. Specialized technical and professional personnel are required on board ($1,200-$1,500/day) and post-survey processing might range from $5,000 to $20,000.

A specialized technique of sub-bottom profiling is "acoustical coring" where return signals are subjected to real-time processing for specific points to enhance resolution and allow a correlation between acoustical impedance of the sediment and grain size. (Caulfield and Yim, 1982; Caulfield, *et al.*, 1983; Tarbottom and Murphy, 1987; McGee, *et al.*, 1994) While this technique has not been widely used, it has been adopted by the US Army

Corps of Engineers for specific projects. (Tarbottom, 1994, pers. comm.)

2.4 Side-Scan Sonar Imaging

Side-scan sonar produces a planimetric or "map-like" image of the seabed; the images are analogous to aerial photographs over land. Acoustic impulses are transmitted laterally from a towed fish, reflect off "bottom roughness" and the reflected return signals are recorded at the towfish. The strength of reflected signals are very dependent on bottom surface roughness so if there is a strong contrast between the surface roughness of the disposal deposit and the seabed deposit, then the spatial extent can be mapped. For example, if the disposal deposit is mud and the natural seabed is gravel, the extent of the mud can probably be mapped with a high degree of accuracy, providing that the mud is thick enough (probably greater than 10-20 cm) to mask the gravel surface.
Side-scan imagery has proven useful in identifying offsite disposal (Hart, 1992; Jubinski, 1994, pers. comm.).

The resolution of side-scan sonar surveys is dependent on (a) the instrumentation, where higher frequency instruments usually have higher resolution, (b) the towfish stability and orientation, (c) navigation accuracy, (d) instrument tuning and adjustment during the survey and (e) interpretative experience of the operators. Typical swath widths of a high resolution side-scan survey are in the order of 100 m per channel (200 m total) so that numerous survey lines may be required to delineate the extent of the disposal deposit and surrounding seabed; with scale rectification of the imagery (analogous to photogrametric rectification of satellite imagery or air photos) and georeferencing of survey lines, a side-scan mosaic may be constructed. Mosaics are commonly developed as part of engineering assessments of the seabed (Figure 3).

Side-scan mosaics are essential if repetitive surveys are anticipated because they represent the only means of georeferencing the survey data and producing overlays of the imagery. The accuracy of the overlays will be highly dependent on navigational accuracy. Because of limitations of navigational accuracy, knowledge of the towfish position during both surveys and slant range corrections of the acoustical signals, there will be a minimal positional uncertainty of about ±20 m associated with a particular seabed feature during a single seabed survey unless some type of seabed targets or transponders are used to control the imagery (see Section 1.3.). An additional complication in interpretation would be the "feathering" of the disposed material as it is dispersed over the natural seabed sediment, making the contrast between the natural and disposed sediments indistinct.

Side-scan sonar surveys are one of the most useful tools for disposal site monitoring but have limitations. The ability of the technique to provide a real-time planimetric image is extremely valuable in optimizing the sampling program. Post-survey processing and construction of mosaics offers the potential to construct overlays of repetitive surveys, although positional uncertainties of individual features may limit interpretation to "patterns of change" rather than quantitative displacement estimates.

The technique is most useful where (a) high contrasts exist between disposed sediments and natural seabed sediments (e.g., mud placed over gravel or gravel placed over mud), (b) currents are relatively weak so contrast remains high and disposed sediment

Side-Scan Sonar Imaging

Advantages

- provides a map or planimetric image of the seabed; produces a map image of seabed roughness, which may be indirectly related to the disposed sediments
- can be interfaced with navigation for recording and development of geo-referenced mosaics
- in-field interpretation allows modification of the survey plan to optimize associated sampling strategies
- repetitive survey imagery may be used to produce overlays and estimate material displacements

Disadvantages

- instrumentation is relatively complex, requires experienced technicians to operate and may require considerable post-survey processing and interpretation
- repetitive surveys highly dependent on navigation accuracy

is not "feathered" onto the natural seabed and (c) sedimentation rates are low so disposed sediments do not become covered or acoustically "masked".

One procedure for improving navigational reproducibility of repetitive side-scan surveys is to utilize acoustic transponders as targets on the seabed or to construct a "seabed grid" by creating scour or drag marks on the seabed. These drag marks provide an absolute reference framework that is highly visible on the side-scan imagery. Trawl marks produced by fishing vessels are frequently used to map bottom features on the Grand Banks (Woodworth-Lynas, *et al.*, 1991; Messieh, *et al.*, 1991).

Although useful, the technique is complex, requiring towed instrumentation, trained technicians, experienced scientists and often considerable post-survey processing. Costs for instrumentation, technicians and scientists for a reconnaissance-type survey with minimal post-survey processing would be about $1,500-$2,000/day. Costs for a "mosaic-grade" survey would be in the range of $2,000-$2,500/day; additional post-survey processing might range from $5,000 to $10,000 depending on the degree of processing and interpretation required.

2.5 Swath Mapping

Recent advances in micro-computers, ship-board processing and seabed acoustics have resulted in the development of multibeam, single transducer swath mapping systems (Alleman, *et al.*, 1993; Blackinton, *et al.*, 1991; Rogeau, 1992). The multibeam, single transducer may be fixed to the vessel or mounted in a towfish. Signals are transmitted perpendicularly to the ship's track to produce a line or swath of reflection data. The data are processed to produce a swath map of bathymetry (see, e.g., Alleman, *et al.*, 1993) or a combined swath map of bathymetry and side-scan imagery (see Fig. 2.3; Blackinton, *et al.*, 1991). Operationally, the equipment is similar to side-scan sonar but data processing is significantly more complex and greater expertise is required.

Swath Mapping

Advantages

- same advantages as side-scan sonar with additional advantage of a co-registered bathymetry map
- in-field interpretation allows modification of the survey plan to optimize associated sampling strategies

Disadvantages

- same disadvantages as side-scan; processing system is more complex and therefore expensive
- repetitive surveys highly dependent on navigation accuracy

It is not known if swath mapping systems have been used in any disposal site monitoring; however, disposal deposits were detected in the Strait of Georgia during a high resolution cable survey across the strait (Figure 3; P. Jalinsky, 1994, pers. comm.). These systems have been primarily used for deepwater, reconnaissance level surveys although high-frequency systems have been used operationally in shallow-water (Alleman, *et al.*, 1993).

Costs for swath mapping can be very high. Day rates for the system that was used in the Strait of Georgia survey (Figure 3) were about $20,000 per day for the swath mapping system, integrated navigation, deck winches, data display and logging and personnel. Post-processing involves some set-up costs ($4,000/survey) but charts (Figure 3) can be produced relatively inexpensively, $400-$600/chart. Shallow-water surveys such as those described in Alleman, *et al.* (1993) are substantially less expensive due to simpler logistics.

2.6 Sampling Surveys

Sampling surveys provide sediment samples that can be (a) visually examined or (b) analytically tested in a laboratory. Environment Canada (1994d) provides a summary of possible analytical testing procedures, which include textural or grain-size analyses, mineralogical analyses or trace metal or organics testing. At a very general level, seabed sediment texture provides an index of current energy where the presence of coarser material indicates high current regimes and the presence of fine material indicates low current regimes. Patterns of sediment texture often provide an index of sediment transport patterns or of sediment sources and sinks. The textural data may be used in support of "trend analysis" to monitor sediment dispersal patterns (Hands, 1991 and 1992; McLaren and Bowles, 1985; McLaren and Thomas, 1988).

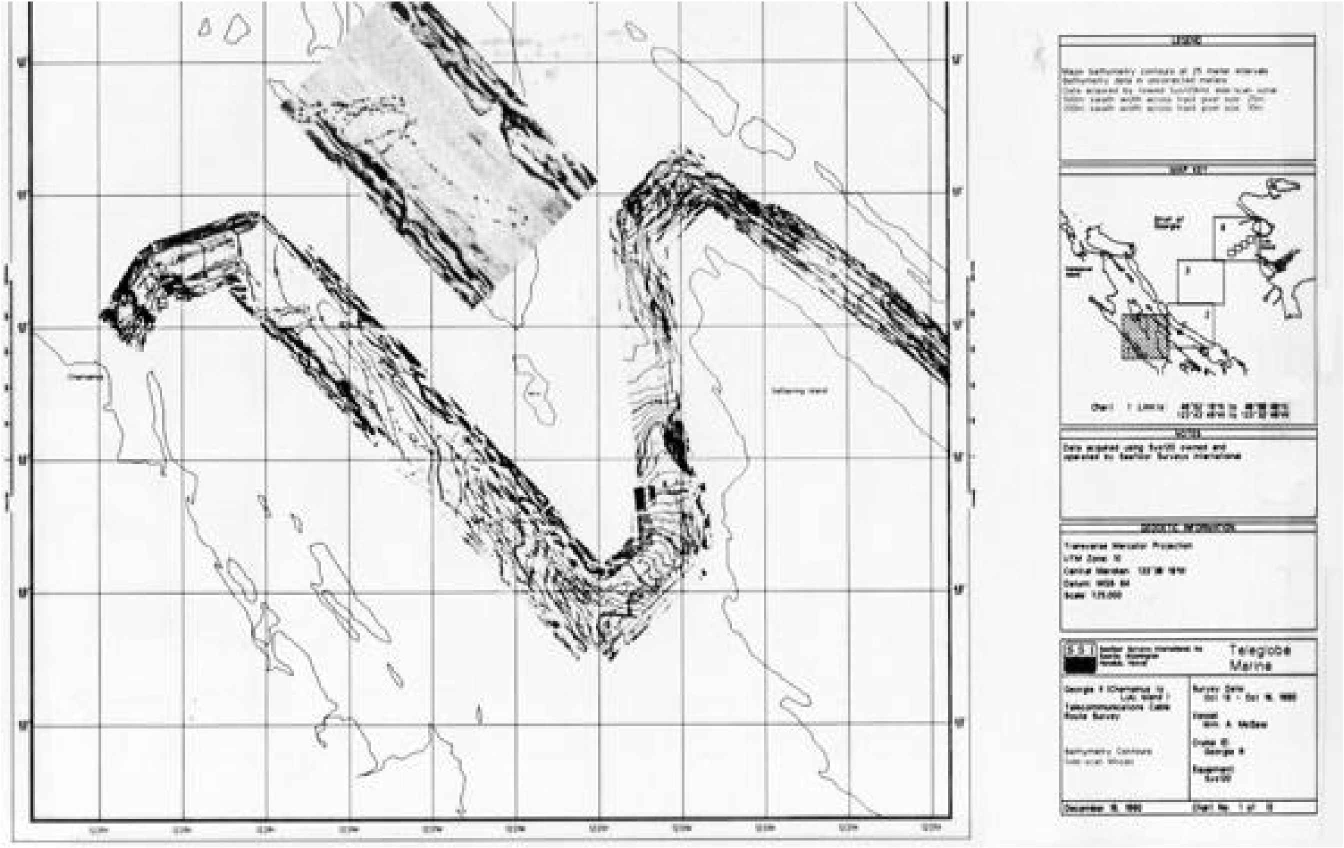


Figure 3. Swath-mapping mosaic with co-registered bathymetry and side-scan imagery from the Gulf Islands area of British Columbia. Black dots on imagery (inset) are interpreted as spoil piles scraped from a barge (provided by Seafloor Surveys International Inc.)

Sampling surveys are usually used in conjunction with some type of geophysical survey to verify the interpretation of spatial "acoustic units" in the case of a side-scan survey or of "acoustic layers" in the case of a sub-bottom profiling survey. The combined use of geophysical and sampling data allows the interpretation of acoustic units to be used as a statistical stratification framework such that samples provide the means to characterize the acoustic units (McGee, *et al.*, 1994). Sampling can either be collected on a systematic grid or random basis within each unit.

Sly (1969) provides an excellent summary of sampling devices; although the review is old, many of the sampling devices that were evaluated (Figure 4) are still in routine use in seabed monitoring studies. Samplers are also discussed and illustrated in Fredette, *et al.* (1990a).

2.6.1 Grab Sampling

Grab samples are collected at a point while the ship is stationary with an over-the-side sampling device. The sampling device is usually triggered in some way so that it closes when the device touches the seabed. Typical grab sampling devices include: Ponar, Smith-McIntyre, VanVeen and Shipek samplers (Figure 4). The devices usually collect from an area of the seabed in the order 100 to 1,000 cm^2 and usually from a depth of less than 10 cm into the seabed.

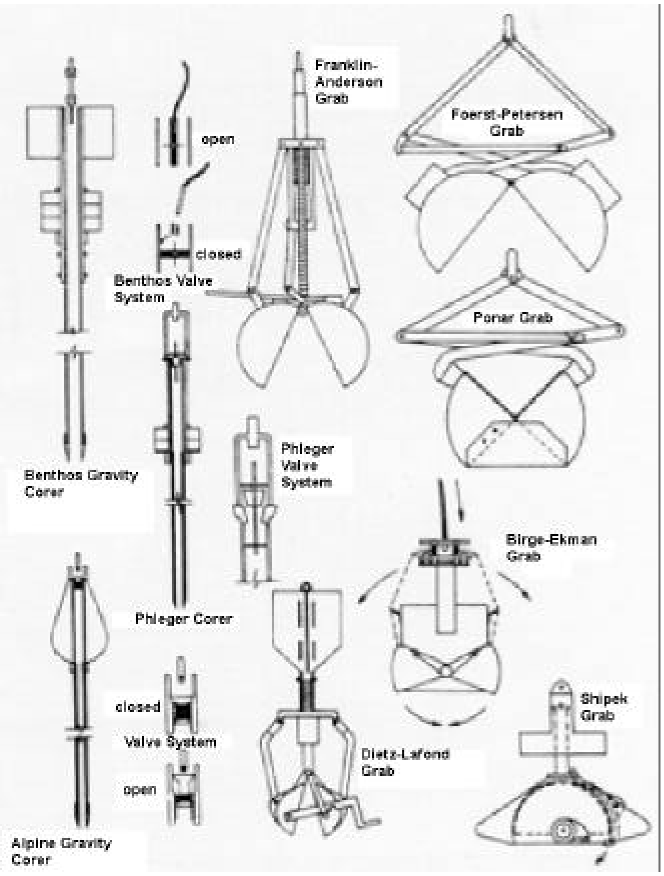


Figure 4. Examples of grab samplers and corers (from Sly,1969).

Grab Sampling

Advantages

- generally very simple devices to operate; large volume samples are collected (minimum size is usually about 1 kg)
- collects a sample that is usually representative of the surficial seabed material; grab samplers may disturb or mix sediment, but with careful handling an undisturbed sample of the top surface layer may be obtained
- visual description as per Folk (1968) can provide a first-cut classification of samples and allow field plotting and confirmation of side-scan interpretations
- a wide variety of analyses can be performed on the same sample allowing differing trends to be monitored (e.g., trace metals, grain size, etc.)
- simplicity of technique is conducive to sample replication

Disadvantages

- a large number of samples may be required if the distribution of bottom sediments is patchy; interpretation will be difficult
- collects a "disturbed" sample and may mix thin sedimentary units representing different environments, complicating interpretation
- sample collection at same point between repetitive surveys sensitive to navigation (±10 m); can be a problem with patchy bottom sediments
- generally requires post-survey processing of samples; results may take weeks to months to plot

One of the greatest misinterpretations of grab sampling data comes from the violation of the assumption that the collected sample is representative of the seabed sediment. The following conditions may create problems in sample representation: (a) the distribution of surficial materials is patchy, (b) the sampler has penetrated through a thin surface layer (generally of less than 10 cm in thickness) and mixed surface and subsurface sedimentary units that may have been deposited under different hydrodynamic conditions, (c) the sampler may be not be large enough to sample large clasts (boulder, cobble or pebble) or (d) the sample is "washed" during retrieval resulting in loss of fine sediments. Careful use of complementary techniques can be used to minimize these effects. For example, the use of a few cores in conjunction with grab sampling will help identify any thin surface layers or the use of video imagery during sample collection will help identify uniformity of surficial sediments.

Costs associated with sediment grab sampling are low in comparison with other techniques. Samplers can generally be leased for a few tens of dollars per day and in the simplest form, can be "hand-hauled" using a davit on a small vessel. Heavier samplers may require a winch system, particularly in deep water where the weight of the cable is significant. A 10x10 sampling grid over a one kilometre survey area can generally be completed in one day (probably two days if previously defined points are to be re-sampled). Visual classification of the samples during the collection process is essential for optimizing the survey program. Analysis of the samples can range from tens of dollars per sample for granulometric analyses to thousands of dollars per sample for specialized contaminant testing (e.g., dioxin analyses).

2.6.2 Coring

With coring, a column of sediment is collected in a tube or box. Bouma (1969) provides a general description of coring systems. The column or sediment core provides an indication of near subsurface layering. When the core penetrates through the sediments, there may be some disturbance of the sediments (e.g., de-watering) but the basic layering is usually preserved and can be sampled. Typical sampling devices include: gravity corers, (Figure 4), vibra-corers or box corers (Figure 5). See also Section 2.7.2 for description of the Sediment Profiling Camera, which provides a "core-like" image of the near surface sediment.

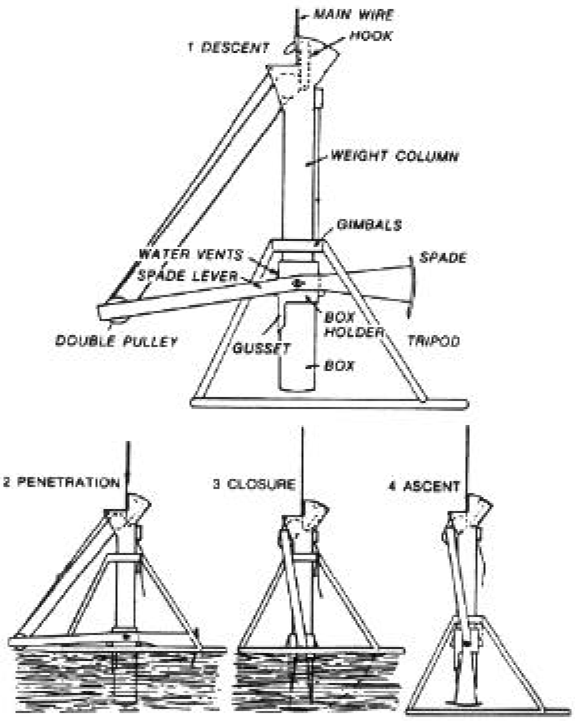


Figure 5. Features and operation of a box corer (from Lee and Clauser, 1979).

Coring

Advantages

- generally very simple devices to operate
- provides a clear picture of near shallow subsurface conditions; useful in confirming sub-bottom profile interpretation
- box corers may be used to collect relatively undisturbed samples

Disadvantages

- gear is heavier than grab samplers and usually requires larger cranes and vessels for recovery; on board core extraction , handling and storage must be carefully planned
- sample size may be small (a few 10s of grams) and preclude multiple analysis; top surface layer (1-3 cm) may be lost with conventional piston and gravity corers and compression of the core profile may occur
- penetration depth often limited in sandy nearshore and shelf areas; vibra-coring (with significantly more complicated vessel support) may be required for deeper penetration

Coring introduces an additional level of operational complexity in comparison to grab sampling because normally significantly heavier lifting gear is required; this usually means larger vessels, larger cranes or A-frames and heavier winches. Some box corers may be used in shallow-water from small survey vessels and offer the potential for relatively undisturbed bottom samples. Vibracoring, which is often required for coring coarse nearshore systems, requires lifting for a frame that will sit on the seabed, large compressors and multiple point anchoring capability (Fuller and Meisburger, 1982).

As such, it is important to use geophysical survey information to optimize the core sampling strategy. Lease rates of coring systems are in the order of tens to hundreds of dollars per day, depending on the complexity of the system. Although small corers may be deployed from small vessels, larger vessels with substantial davits or A-frames may be required, depending on the corer. Sample collection rates may range from a few cores per day (e.g., many vibra-corers) to a hundred per day for short "dart" corers on a soft seabed. Core data can be interpreted to provide insight to both the present and past sedimentation events and, as such, provide critical information for assessment of the dispersive nature of the disposal site. It may be possible to date horizons within the core to estimate sedimentation rates at the site.

2.6.3 Diver Sampling

In shallow-water sites (less than 30 m) of limited extent, the use of divers to collect samples may provide a cost effective means of collecting samples. The diver can determine if the sample site is representative of surrounding bottom conditions or subsurface bottom sediments. The sedimentary environment that is being sampled is known precisely. The diver may collect either grab samples or shallow core samples.

Where visibilities are greater than 10 m and water depths shallow (less than 20 m), large areas of the seabed may be surveyed by diver using a towed sled behind the survey vessel.

Diver collected samples are expensive in comparison to routine grab sampling. However, the quality of the sampling is substantially improved as the diver can assess the "representivity" of each sample before collection, can provide visual descriptions of the seabed and can selectively sample. Personnel charge-out rates of $500-600 per day are common for qualified, scientific divers and a minimum of two are required. The number of samples that can be collected will vary significantly due to depth, visibility, sea state conditions and the sampling grid.

Diver Sampling

Advantages

- provides for high degree of confidence in assessing sample representation of seabed conditions
- very precise sampling possible; relocation of sampling points using seabed stakes is possible
- may be combined with towed diver "sled" to increase aerial coverage

Disadvantages

- useful for only small survey sites as diver underwater time generally limited to 1-2 h/d or 3 dives per day.
- limited to shallow water due to diving limitation
- greater safety risks than other types of surveys

2.7 Visual Survey Techniques

Visual information about the seabed provides a means of (a) verifying geophysical interpretations about "acoustic units" and (b) verifying sample representation of surrounding seabed conditions. Still camera photography can be used in as stand-alone-tool or in conjunction with grab samplers or corers. Recent advances in underwater video cameras make this one of the most useful visual observation tools. Many video systems are used in shallow water projects (<100 m) and specialized systems have been used in up to 4,000 m (Ballard, 1988).

2.7.1 Still Bottom Photography

Still camera photography of the seabed is one means of providing the geologist with an image of the seabed and improving confidence levels about sample representation. Still camera systems are self-contained units lowered to the seabed on a cable. As the camera system nears the seabed, a bottom trip triggers the flash and shutter producing an image of the seabed from 1 to 2 m above the bottom. Modified photography systems have been deployed on deepwater tow systems to produce mosaics (e.g., see Ballard, 1988).

Still Bottom Photography

Advantages

- relatively simple operation but camera systems may be expensive
- imagery easily cataloged for comparison with repetitive surveys
- provides a high resolution image of the seabed
- improves confidence in sample representation

Disadvantages

- limited area of the seabed imaged; usually 1-2 m^2
- real-time processing usually not possible; post cruise processing requires days to weeks

Simple, shallow-water, bottom-triggered systems lease for a few tens of dollars per day and require no specialized handling. (standard wire winch). Systems deployed on sleds may require specialized winches and operators and are likely to lease for thousands of dollars per day.

2.7.2 Sediment-Profiling Camera

The sediment profiling camera has been widely used in ocean disposal projects in the US to provide a high resolution image of the near-surface seabed sediments (Fredette, *et al.*, 1990a). The camera system is lowered to the seabed on a frame (Figure 6) and a viewing prism penetrates the upper layer of sediment and an image is recorded on film; the prism can penetrate the sediments to 18 cm. Interpretation of the imagery can provide information on grain size, redox area, sediment surface micro-relief, epifauna, infauna, and apparent species richness (Germano, 1983; Rhoads and Germano, 1982). Lease rates of the sediment profiling camera are in the range of $1,000 per day and approximately 150 images can be collected in a day (Fredette, *et al.*, 1990a). Analysis of the images costs $40-60 per image.

2.7.3 Video Camera Systems

Video camera systems provide real-time imagery of the seabed during the survey providing immediate information on the seabed conditions and sample representation of those conditions. Camera systems usually include a light source and are tethered with an umbilical cable to the support vessel. A variety of support platforms are possible including diver-held systems, remotely-operated vehicle systems (ROVs), towed systems or submersibles. Simple video camera systems can be fixed to either grab samplers or corers to provide information about the surficial seabed character.

The Canadian-made ROPOS system (Remotely Operated Platform for Ocean Science) has operated to 2,500 m depths and includes: a black

Video Camera Systems

Advantages

- provides a real-time image of the seabed allowing immediate assessment of sample representation and interpretation of acoustic units
- recording can include a narration that is synchronous with the imagery
- possible to mount camera systems on samplers or corers to provide direct, real-time observation of sample location

Disadvantages

- usually limited to shallow water depths (<100 m) due to problems with handling the umbilical; operation at depths >30 m usually require special handling capabilities
- precision relocation of points may be difficult without sophisticated underwater positioning systems
- imagery may be difficult to catalog and access; relocation of targets from repetitive surveys is difficult

and white video camera, a colour video camera, a manipulator arm and sector-scanning sonar; this system has been used to survey the Pt. Grey Ocean Disposal site (Shepard, 1994, pers. comm.).

The primary advantage of the video imagery is to provide the scientist with a real-time view of the seabed during the survey. This allows for an immediate, high confidence interpretation of acoustic units identified on the side-scan sonar surveys and allows for the sampling program to be optimized to provide the best representation of the geological units (e.g., disposed sediment vs. natural seabed sediment).

Small, shallow-water ROV systems typically lease for hundreds of dollars per day and depending on the supplier may require use of a trained technician. Fixed, black and white camera systems can probably be obtained for tens of dollars per day. Deep-water ROVs such as ROPOS require large support vessels, a team of operators/technicians, integrated navigation systems and lease for more than $20,000 per day (B. Lea, pers. comm., 1994).

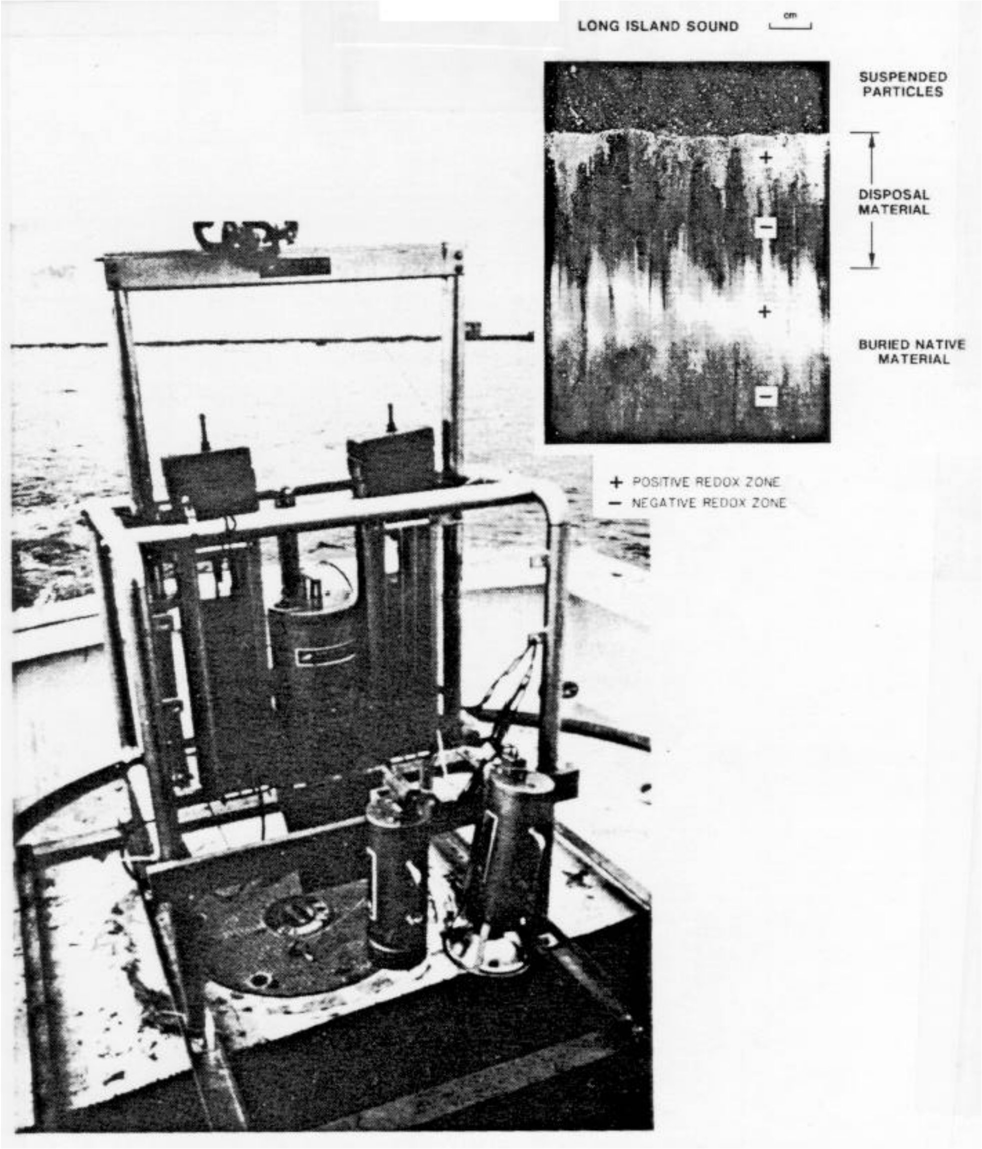


Figure 6. Frame for the sediment profiling camera and image (inset) showing typical detail from an image (from Fredette, et al, 1990a)

2.7.4 Diver Observations

For shallow-water sites of limited extent diver observations may be a cost-effective means of (a) interpreting geophysical data, (b) interpolating between sampling points and (c) assuring representation of the seabed samples or cores. Spot or bounce dives can be used to examine the seabed at points or along lines; use of a towed sled for the diver may be useful in increasing observational coverage.

The section on diver-collected samples (Section 2.6.3) provides cost information on diver rates.

Diver Observations

Advantages

- provides for high degree of confidence in assessing sample representation of seabed conditions
- real-time survey data that allows optimization of the sampling and survey programs
- may be combined with towed diver "sled" to increase spatial coverage

Disadvantages

- useful for only small survey sites as diver underwater time generally limited to 1-2 h/d or 3 dives per day.
- limited to shallow water due to diving limitations
- greater safety risks than other types of surveys

2.8 Advanced Techniques

The following techniques are consider "advanced" because they are not routinely used in ocean disposal site monitoring. They are included because they are (a) occasionally used or (b) offer potential for certain site conditions. For example, a seabed magnetometer survey might be useful for monitoring mine tailings dispersal of ore rich in ferrous minerals.

2.8.1 Magnetometer Surveys

Proton magnetometers are routinely used in offshore hydrocarbon exploration and for location of ferrous objects in the offshore (e.g., shipwrecks, pipelines). Magnetometers measure magnetic fields and ferrous objects create field anomalies. It is not certain (at this writing) if magnetometer surveys have been used in the support of ocean disposal site monitoring. However, the potential exists for materials that may produce anomalies in the natural magnetic fields of the seabed (e.g., mine tailings discharge).

Magnetometer Surveys

Advantages

- offers potential for direct measurement of a contaminant
- instrumentation is relatively simple and could be dragged along the seabed
- when used with other survey data, it may be possible to correlate signal strength to thickness of the deposit

Disadvantages

- does not appear to be a well tested technique

2.8.2 Resistivity Surveys

Recent work in British Columbia has shown the promise of resistivity surveys for measuring shallow subsurface sediment properties (Cheesman, *et al.*, 1993). Measurements of electrical conductivity are made using a sensor towed over the seabed and these continuously recorded measurements are used to estimate "apparent porosity", which provides an indirect indication of subsurface density; the system, as presently configured, is capable of measuring density in three subsurface layers.

Resistivity Surveys

Advantages	Disadvantages
• provides relatively simple means of measuring an important surficial sediment property—porosity	• technique is very new and relatively untested although it has been tested over two mine tailings deposits
• instrumentation is relatively simple and can be dragged along the seabed	• presently measures only a single sediment property
• technique is capable of resolving the interface between coarse sediments over fine sediments; this interface is often not resolvable on sub-bottom profiles	

The technique has been conducted in two mine tailings areas of British Columbia (Jordan River and Britannia Beach) with positive results (L. Law, pers. comm., 1993). The technique offers the significant advantage of being able to profile through coarse surface sediments (e.g., coarse sands and gravels) and of being able to resolve layers of coarse sediments over fine sediments; this layering system is often difficult to resolve with seismic profiling and is difficult to core.

Because of the newness of this technique, costs have not been commercially established but are likely to be in the range of tens of thousands of dollar per survey not including vessel costs.

2.8.3 Tracer Studies

Tracers allow "tagging" of sediment particles to provide an indication of sediment movements. Both fluorescent compounds and radioactive isotopes have been used to monitor sediment transport; while fluorescent tagging provides a qualitative indication of sediment transport, radioactive tagging provides a quantitative information on the movement of the sediment.

Radiometric tracer studies have been conducted in Canada to monitor sediment transport in continental shelf environments (Hodgins, *et al.*, 1986a). The technique involves the introduction of a radio-isotope tracer into seabed sediments with subsequent surveys using a seabed scintillometer to measure emitted radiation. The surveys on the Scotian Shelf used an irradiated glass, crushed to sand-size consistency (Hodgins, *et al.*, 1986b). Surveys were carried out over one winter at intervals of 1, 2.5, and 1 month. These surveys documented centroid displacements of the order of 1-2 m/d for the most active site.

Tracer Studies

Advantages	Disadvantages
• provides a means of directly monitoring sediment dispersal	• handling procedures and permitting requirements are likely to be complex for radiometric tracers
• technique has been used in both nearshore and shelf conditions so limitations are known	• instrumentation is relatively complex and requires specialized operators
• provides near real-time results so field survey can be optimized	• limited to sand-sized sediment materials; amount of material dependent on dynamics at the site
• radiometric studies provide quantitative information	• results from radiometric studies may be difficult to interpret
• fluorescent studies provide qualitative	• qualitative information may provide insight into

information	sediment dynamics but cannot be used for modeling

Although the technique has not been directly used in an ocean disposal site study, it offers the potential to provide an indirect means of monitoring potential sediment dispersal. Fluorescent tracer studies could be conducted as part of a grab sampling/coring program, adding little additional cost; sand dying and deployment may add a few thousand dollars to the program cost. Radiometric sand tracing studies are expensive and are likely to cost about $100,000/survey ($200,000 for one repetitive survey).

2.8.4 *In situ* Monitoring Systems

There are numerous systems that can be used for *in situ* monitoring of currents or sediment movements at the site. These include specialized camera/current meter type packages or specialized research instrumentation. For example, the Bedford Institute of Oceanography has designed an instrument, called the Sea Carousel, for measuring seabed shear stress, an important parameter for use in modeling of sediment transport (Amos, *et al.*, 1992a; 1992b). This instrumentation has been tested at a disposal site in the Bay of Fundy (Amos, *et al.*, 1993).

Inexpensive and expendable transmissometers have been used to document suspended sediment pulses in BC fjord (Prior, *et al.*, 1987). Simple vane-tilt devices are under development to document episodic transport events and can be used to calibrate sediment transport models (Bornhold, pers. comm., 1994).

In situ monitoring systems are generally expensive, give results over a limited time and require specialized interpretation. While this type of instrumentation is an important as a research tool, *in situ* instrumentation is not something likely to be used in routine monitoring programs. For specialized, large scale monitoring programs, they may be appropriate and users should seek specialist advice as to their applicability.

2.9 Canadian Equipment and Expertise

There is considerable expertise in marine seafloor surveys within Canada, both in private industry and government research laboratories. Much of this expertise was developed during offshore oil exploration activities in the 1970s and 1980s and has been exported to other parts of the world.

All the equipment reviewed in this report is available in Canada, and much of the equipment has been used in seabed monitoring studies.

SEDIMENT TRANSPORT MODELS

1. SEDIMENT TRANSPORT MODELING AS A TOOL FOR MONITORING PROGRAM DESIGN

Determining the fate of dredged material forms one of the essential steps in developing a disposal site monitoring program. Initially this involves delineating the disposal site boundaries based on the placement operations. The second step involves examining the susceptibility of the deposited materials to sediment transport by waves and currents. These transport processes will determine the long-term fate of the materials, and hence the area contacted by sediment-borne contaminants.

Numerical computer models can provide estimates of both the initial area of deposition, and the susceptibility of the dredged material to sediment transport. The initial area of deposition, and the thickness of the material covering the seabed are determined using a short-term fate model. The time scales of motion and subsequent movement are of the order of a few minutes to a few hours depending on the material composition.

Time scales for sediments to be transported out of a given site following deposition vary widely depending on the hydrodynamic and sedimentary regimes. These time scales can range from a few hours to many months. Accordingly, the formulation of long-term fate models differs considerably from the models available for initial deposition.

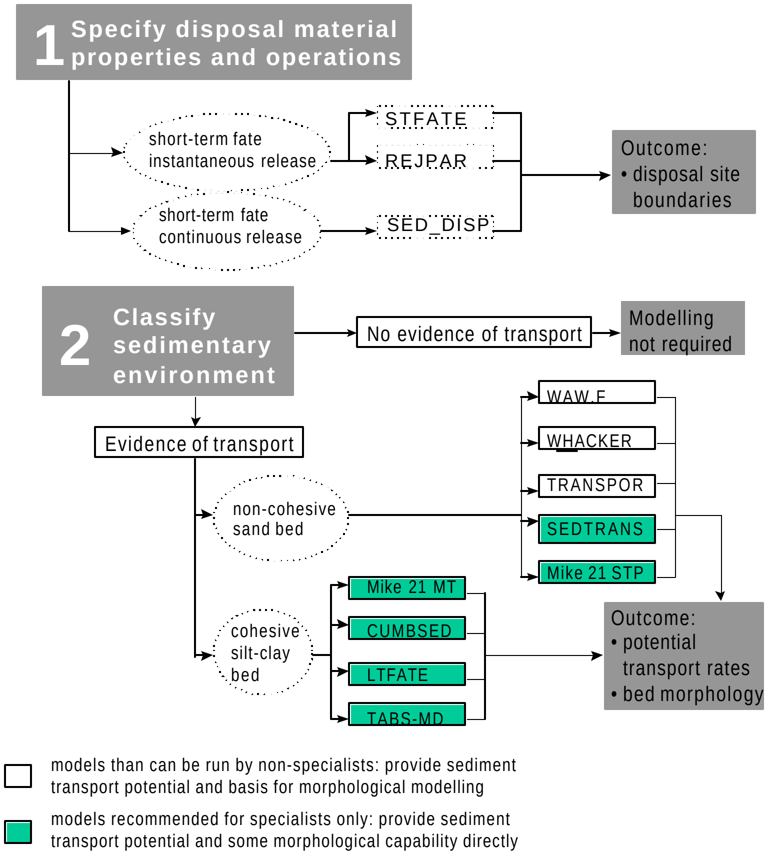


Figure 7. Decision steps in modeling and available models

This guidance provides a brief introduction to computer models in both categories, and summarizes the models that are available in the fall of 1993 for use in Canadian waters.

1.1 Modeling Steps and Decisions

An approach to disposal site modeling is shown in Figure 7. Step 1 involves specifying the material to be disposed—its physical and chemical properties, specific weights and volumes—and the methods of disposal. Generally the disposal method will govern the choice of short-term fate model. An instantaneous release, or a sequence of such releases, can be modeled using STFATE. Continuous releases can be examined with SED_DISP. In either case, the outcome is a mapping of the disposal site boundaries. These models are discussed in greater detail in Section 5.

Step 2 treats the long-term fate of the deposited material. First, the ambient sedimentary environment is classified for its gross features: sand bottom or mud bottom, flat bottom or features providing considerable seabed relief, and whether bedforms are evident or not. Grain size data from grab samples or cores can also be used to infer bed movement, suggesting whether the area is one of net deposition, net erosion or in equilibrium (see Section 6 on sediment trend modeling). The outcome is a first assessment for evidence of sediment transporting processes. If there is no such evidence, then modeling may not be required or application of a simple model may be warranted to confirm the geological interpretation. If there is evidence of transport taking place, then the bed material must be classified for its grain size distribution and cohesiveness.

Where the bed is non-cohesive sands and gravels, then a number of models are available. The first three are the easiest to use, and can be run by non-specialists on personal computers. They provide potential sediment transport rates. The term potential simply means that the depth of bed sediments is assumed to be infinite and, thus, there is no limit to the supply of material. The key to success will lie in determining the hydrodynamic input data and, for some models, the bed roughness characteristics. If sediment transport rates are found to be high, then the dispersion of the deposited material over the region will also be extensive. In this case, morphological modeling—providing predictions of seabed evolution—will be necessary. All the first three models can be cast into morphological models; the final two models in the list already perform bed evolution calculations.

In general, it is a big step from a potential transport model at a point to a full morphological model. This step is not recommended for people who are unfamiliar with numerical modeling and with sediment transport theory.

Where bed sediments are cohesive, particularly those with soft, fluffy bottoms high in organic content, specialized mud transport models are required. Three are accessible (see Figure 7) but all have complex codes designed to be run by specialists in conjunction with extensive field data.

The outcome of the long-term modeling is either: 1) an estimate of the rate of transport of the ambient or the ambient and deposited sediments for a range of current and wave conditions at the site; or 2) a prediction of the zones of erosion and deposition of bed materials over the region surrounding a disposal site. One limitation of all sediment transport models, that predict the potential transport rate at a point, is that one does not get an estimate of how far the material will be dispersed. On the other hand, the amount of material removed from a disposal site can be obtained; then by summing the rates for the current and wave climate over time at the site, an estimate of the time to disperse the total load disposed can be found. The steps of estimating dispersion distance or removal times will require additional programming to run the sediment transport models themselves.

All sediment transport models are highly dependent on the forcing hydrodynamics. Errors of 10% to 20% in current and wave data can be magnified through sediment transport models into very large errors in estimated transport rates (orders of magnitude). Thus, considerable effort must be devoted to input data for waves and currents. Often such data are not available from measurements, and can only be obtained by running specialized numerical models. Where sediment transport is highly dependent on storms—which is often the case in shallow coastal waters—then wave hindcast models may be required, along with current prediction models, to parameterize the input conditions causing sediment resuspension and transport. Similar to the mud transport models described here, these hydrodynamic and wave prediction models require data for boundary conditions, calibration, and verification, and are often best run by experienced specialists in new areas.

The hydrodynamic input data required to run any of the following sediment transport models should be kept in mind as users contemplate applying one or more of these models to a particular site.

It is emphasized that most sediment transport models are highly empirical and lack the necessary physics to be applied to different sites with equal confidence. Results from models should generally be used as indicators of whether one site is depositional or not, and to give rough estimates of the magnitude of sediment transport and the wave-current conditions under which it will occur. As requirements for accuracy increase, so too will the need for field data for calibration and verification and the need for specialist interpretation.

2. INITIAL DEPOSITION MODELING

Numerical models in this class are used to calculate the area of seabed covered by the deposited material, the thickness of the layer, and the spatial distribution of the dredged material. The site boundaries are then mapped using these output data. There are two types of models distinguished by the release history:

1) short-term fate models for an instantaneous release, usually of dredged material from barges and hoppers; and
2) short-term fate models for continuous releases, usually associated with continuous dredging activity or offshore hydrocarbon drilling and production facilities.

Instantaneous releases from hoppers and barges are usually associated with either mechanical or hydraulic dredging operations. The water content of the material to be deposited may thus vary over a wide range (15% to 95%). Continuous releases of sediment particles generally have a high water content, with values depending on the nature of the dredging technique or on the mud recovery and cuttings washing systems used in the petroleum industry.

2.1 Short-term fate model STFATE: Instantaneous Release

The STFATE model is one module of the Automated Dredging and Disposal Alternatives Management System (ADDAMS) developed by the US Army Corps of Engineers Waterways Experiment Station in Vicksburg, Mississippi, and deals specifically with instantaneous releases of dredged spoils.

Theoretical Basis

The material behaviour, shown schematically in Figure 8, is described in three phases:

1) *convective descent* - where the cloud motion is dominated by gravity and its initial momentum,

2) *dynamic collapse* - occurring when the cloud impacts the seabed or achieves neutral density such that the vertical motion is retarded and horizontal spreading dominates, and

3) *passive transport-diffusion* - commencing when the material is transport by ambient currents and background turbulence.

The total load to be discharged from the barge or hopper is divided into multiple clouds with an assumed hemispherical shape. Disposal is represented by a sequence of such clouds. Since the solids concentration of the discharged material is assumed to be low, each cloud behaves as a dense liquid during convective descent and the model is based on a buoyant thermal plume analysis. The governing equations express conservation of mass, momentum, buoyancy, particles and vorticity.

During the descent phase, fine particles and dissolved contaminants are stripped from the clouds and introduced into the water column. The stripping process is based on observations that roughly 5% of material is lost from the convecting cloud in 100 feet of water.

During dynamic collapse, the model is based on the same conservation equations as in the convective phase, with a shape function that depends on whether the cloud stalls in the water column or hits bottom. In the former case, an oblate spheroid shape is prescribed. In the latter, an ellipsoid is assumed.

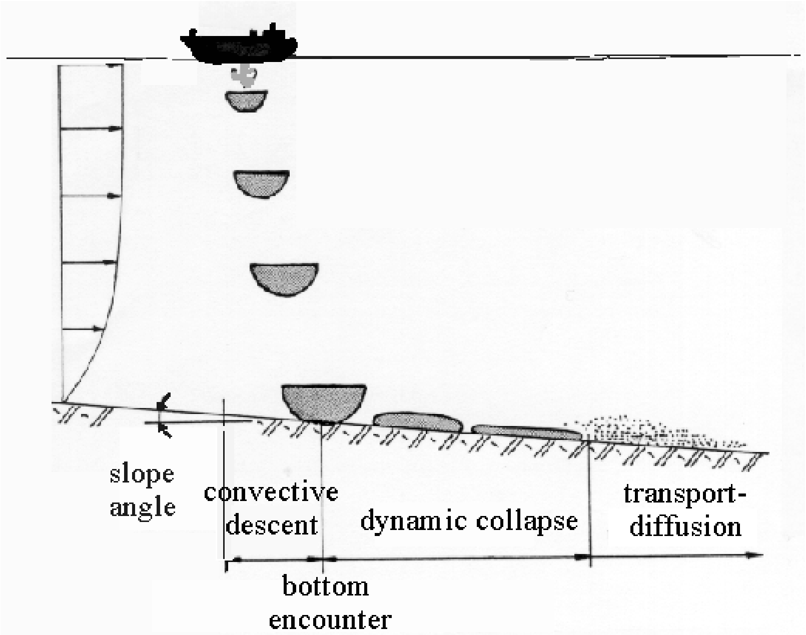


Figure 8. Schematic illustration of dredged spoil disposal showing the three phases of settling to the seabed.

The collapse phase is terminated when the rate of spreading from turbulent diffusion exceeds that from the collapsing cloud. Laboratory experiments and field data indicate that fine material is lost to the water column at the top of the collapsing cloud. This material and the stripped material is then subject to transport by ambient currents and diffusion from turbulence, as well as particle settling. In this manner, fine sediment fractions settle out after the coarser fractions have been deposited and cover a larger area.

The model is solved on a Cartesian grid with uniform spacing in each direction; this grid provides the spatial resolution of the area of interest. It is restricted to open water without shoreline boundaries.

STFATE does not provide for re-suspension of deposited material once it has reached the seabed. However, a critical shear stress criterion is used to control the original deposition process. When the bed stress from ambient currents exceeds the critical value for the grain size of the solid fraction in suspension no deposition takes place. Thus, the model can be applied at dispersive sites.

STFATE also has provision for calculating contaminant and suspended sediment concentrations in the water column. Thus, one can gain an idea of the physical and chemical impacts of the disposal operation on the water column.

Input Data

Input data are specified in six categories:

1) *site description* - grid specifications, bottom slope and ambient water density;
2) *oceanography* - ambient current profiles (2-point);
3) *I/O and Execution* - choice of simulation, run duration, and control of output options;
4) *material description* - solid fractions, fall velocities, water contents, layers in disposal vessel, and stripping characteristics;

5) *disposal operations* - location, speed, duration, vessel properties;
6) *empirical coefficients* - various empirical coefficients governing friction, entrainment, stripping, collapse, apparent mass and diffusion coefficients (default values are given for all coefficients).

Input to the model is controlled by a menu-driven user interface, and is relatively easy to use once the modeller becomes familiar with the overall program structure. Results are most sensitive to the material description and disposal operations; careful thought should be given to these input data.

Output Data

Model output data are quite comprehensive and include:

1) an echo print of all input data;
2) snapshots at discrete time intervals of the cloud parameters (position, velocity, size, density contrast, concentrations) during the convective descent and collapse phases, and at the end of the collapse phase;
3) at various times, snapshots of suspended sediment concentration;
4) at various depths, maximum tracer/contaminant concentrations within the grid and on the grid boundaries.

The basic output is stored in a disk file. Printing and plotting options are provided in the software package. An example of the graphical output, giving deposited thickness in feet, is shown in Figure 9, corresponding to a 3,000 m^3 split-hull barge emptying in 30 s into a water depth of 80 m with an ambient current of 0.18 cm/s. Tabular output, giving the total deposition thickness, is shown in Figure 10 together with the definition of the disposal site boundaries.

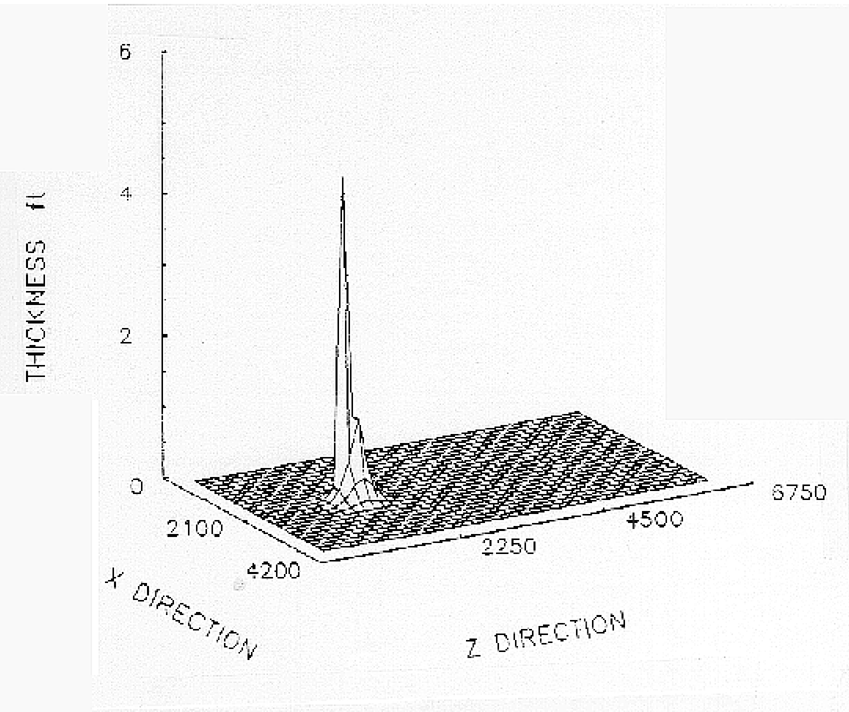
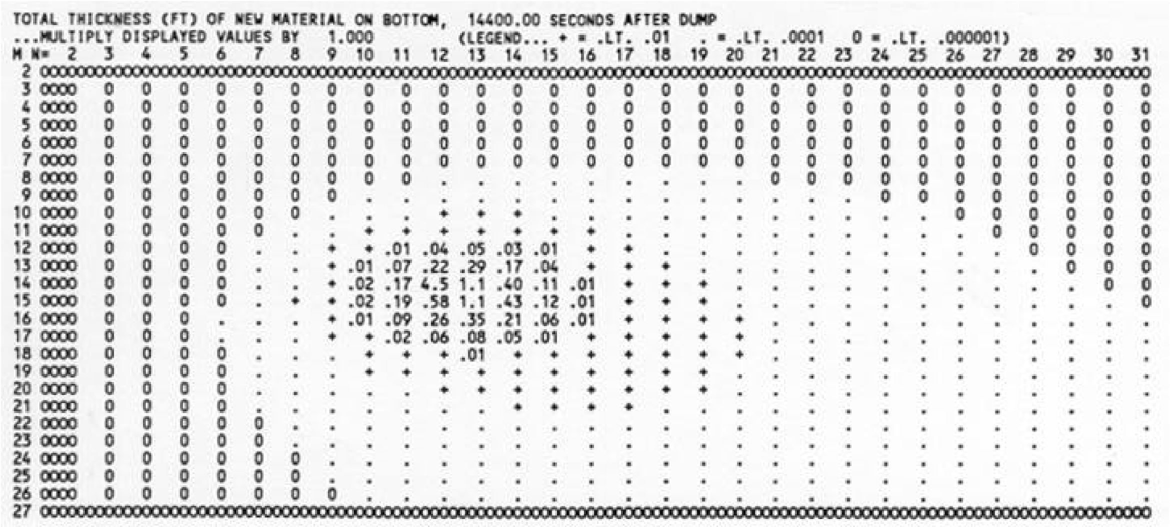


Figure 9. Example of a three dimensional plot of total deposition thickness from STFATE.



```
TOTAL THICKNESS (FT) OF NEW MATERIAL ON BOTTOM,  14400.00 SECONDS AFTER DUMP
...MULTIPLY DISPLAYED VALUES BY    1.000        (LEGEND... + = .LT. .01    . = .LT. .0001   0 = .LT. .000001)
M N=  2     3    4    5    6    7    8    9   10   11   12   13   14   15   16   17   18   19   20   21   22   23   24   25   26   27   28   29   30   31
 2 0000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
 3 0000     0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
 4 0000     0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
 5 0000     0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
 6 0000     0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
 7 0000     0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
 8 0000     0    0    0    0    0    0    0    0    0    .    .    .    .    .    .    .    .    .    0    0    0    0    0    0    0    0    0    0    0
 9 0000     0    0    0    0    0    0    0    .    .    .    .    .    .    .    .    .    .    .    .    .    .    0    0    0    0    0    0    0    0
10 0000     0    0    0    0    0    0    .    .    .    +    +    +    .    .    .    .    .    .    .    .    .    .    .    0    0    0    0    0    0
11 0000     0    0    0    0    0    .    .    +    +    +    +    +    +    +    .    .    .    .    .    .    .    .    .    .    0    0    0    0    0
12 0000     0    0    0    0    .    .    +    +  .01  .04  .05  .03  .01    +    +    .    .    .    .    .    .    .    .    .    .    0    0    0    0
13 0000     0    0    0    0    .    .    +  .01  .07  .22  .29  .17  .04    +    +    +    .    .    .    .    .    .    .    .    .    .    0    0    0
14 0000     0    0    0    0    .    .    +  .02  .17  4.5  1.1  .40  .11  .01    +    +    +    .    .    .    .    .    .    .    .    .    .    0    0
15 0000     0    0    0    0    .    +    +  .02  .19  .58  1.1  .43  .12  .01    +    +    +    .    .    .    .    .    .    .    .    .    .    .    0
16 0000     0    0    0    .    .    .    +  .01  .09  .26  .35  .21  .06  .01    +    +    +    +    .    .    .    .    .    .    .    .    .    .    .
17 0000     0    0    0    .    .    .    +    +  .02  .06  .08  .05  .01    +    +    +    +    +    .    .    .    .    .    .    .    .    .    .    .
18 0000     0    0    0    0    .    .    .    +    +    +  .01    +    +    +    +    +    +    +    .    .    .    .    .    .    .    .    .    .    .
19 0000     0    0    0    0    .    .    .    +    +    +    +    +    +    +    +    +    +    .    .    .    .    .    .    .    .    .    .    .    .
20 0000     0    0    0    0    .    .    .    .    .    +    +    +    +    +    +    +    +    .    .    .    .    .    .    .    .    .    .    .    .
21 0000     0    0    0    0    .    .    .    .    .    .    .    +    +    +    +    .    .    .    .    .    .    .    .    .    .    .    .    .    .
22 0000     0    0    0    0    0    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .
23 0000     0    0    0    0    0    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .
24 0000     0    0    0    0    0    0    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .
25 0000     0    0    0    0    0    0    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .
26 0000     0    0    0    0    0    0    0    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .
27 0000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
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Figure 10. Example of the tabular output showing total deposition thickness from STFATE.

2.2 Short-term fate model REJPAR: Instantaneous Release

REJPAR is a simple PC-based model that describes the initial descent and spreading phases of a sediment load released instantaneously from a barge or scow. It was designed and programmed for application in estuaries characterized by strong tidal currents, and requiring the minimum of input data to give reasonable predictions. The model is described by Drapeau, *et al.* (1992).

Theoretical Basis

This model is similar to STFATE in that it described the material behaviour in two distinct phases:

1) *convective descent* - where the sediment motion is dominated by vertical momentum and entrainment during its descent from the scow to the point of initial contact with the seabed; and
2) *density current spreading* - commencing when the cloud reaches the seabed and spreads laterally as a density current along the bottom.

Drapeau considers only two variables for the convective descent phase: the cloud radius and the bulk vertical velocity. The entire sediment load is treated as a single cloud. These two parameters are found from empirical relations derived earlier by Krishnappan (1975) from a series of flume experiments. The radius and velocity are then combined to define the bulk flux of sediment into the density current.

Only a fraction of the disposed sediment will contribute to the formation of a density current. Drapeau, *et al*, define this fraction by comparing the bulk descent velocity to the natural settling velocity of the sediment grains. If the two are equal, then no sediment is available to form the density current and all material settles to the bottom within the final descent radius. If the bulk descent velocity exceeds the natural settling velocity, however, then there is excess energy available to generate the density current flow. The amount of sediment contributing to the density current is expressed as a empirical constant multiplied by the non-dimensional excess velocity (bulk descent velocity minus the settling velocity normalized by the descent velocity). The empirical constant is given as 0.5.

The density current is assumed to spread radially outward from the initial radius defined at the point of bottom contact. The density current dynamics are assumed to follow the work of Middleton (1966a,b) in which the outward radial velocity and the initial density current layer thickness are related through the density difference (in this case between the sediment laden flow and sea water). It is further assumed that as the density current spreads outward, its volume remains constant; by geometry this assumption requires that the layer thickness diminish with time and distance out from the point of impact. The model also accounts for loss of sediment by settling from the density current. This loss works to decrease the layer thickness and is accounted for in the solution algorithm.

Advection by tidal current is modelled only in the second, density-current phase.

Unlike STFATE, REJPAR does not contain any stripping mechanics and hence there is no prediction of suspended sediment concentration above that produced within the density current.

Input Data

The following input data are used in REJPAR:

1) *site data* - water depth (uniform depth assumed);
2) *oceanography* - current time-series or tidal ellipse (assumes currents are uniform over depth);
3) *material description* - sediment volume per disposal load, number of loads, and per cent by weight of sediments in each of 3 grain size classes;
4) *disposal operation data* - radius of navigation error (random selection of actual disposal location within a positioning error specified by the user).

Output Data

The model is intended to calculate the total accumulation of sediment on the sea bottom from many disposal operations in a particular area, expressed in centimetres. It is assumed that the disposal operations occur within the navigational error of the centre of a 10 m mesh covering a 2 km by 2 km area. This mesh is not user defined, but rather defaults to these values; it is used only to accumulate the deposited sediment.

The output consists of three data files: 1) the sedimentation matrix file giving the thickness over the mesh, 2) a North-South cross-section, and 3) an East-West cross-section. These data files can be plotted and contoured, and shown as a three-dimensional wire-mesh plot (Figure 11).

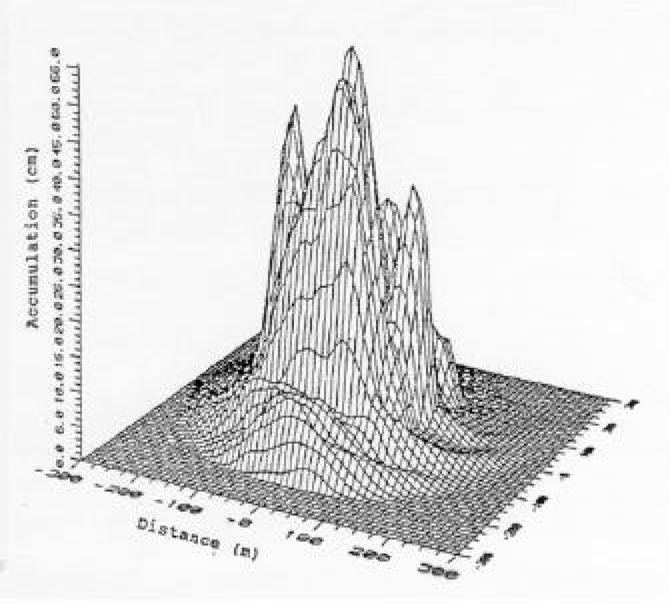


Figure 11. Example of the three dimensional plot of spoil thickness from REJPAR (from Drapeau, et al, *1992)*

According to Drapeau, *et al*, the graphics are generated using the Surfer software package from Golden Software, Boulder, Colorado.

2.3 Short-term fate model SED_DISP: Continuous Release

Depositional patterns for continuous releases of particulate material lasting many months to years can be estimated using the model SED_DISP. It was developed in 1992 for the treatment of offshore well drilling mud and cuttings, but applies equally well to any other long-term release of particulates described by a set of grain size classes.

Theoretical Basis

Two fundamental assumptions are made in SED_DISP: 1) that the fall velocity and transport of individual particles is independent and 2) that the ambient currents can be treated as time-steady flows. The first assumption means that the behaviour of the sediment particles does not depend upon the physical properties of the solid-liquid slurry, including its inertia and buoyancy, at the discharge point. In some circumstances, this assumption is too restrictive close to the release point. In these cases, a buoyant plume model is applied to predict the location where the plume reaches neutral density and stalls. At that point, the liquid phase is in equilibrium with the ambient water, there is no residual inertia, and the material can settle out according to particle dynamics. Buoyant plume models are available from the U.S. Environmental Protection Agency (see Baumgartner, *et al.*, 1993, for details).

The second assumption is made for the treatment of the input current data. Currents are clearly the dominant factor governing the short-term fate of the discharged material. When the discharge occurs over a long period of time, the final deposition patterns will reflect the sum of all current speeds and directions that are found at the site. Thus, it is important to calculate deposition for all flow conditions. SED_DISP is specifically formulated to utilize a bivariate speed-direction histogram for current input; this histogram gives the frequency of occurrence of each flow condition and is routinely calculated from current meter data.

Each flow condition, given by one speed and one direction from the histogram, is assumed not to vary with time over the settling duration. By nature, tidal ocean currents tend to rotate through 360° every 12 to 24 hours; thus, the steady-flow assumption appears restrictive. The settling time for mud and clay fractions, however, often exceeds many days for water depths of a few tens of metres or more. In view of this settling duration, the steady-flow assumption, which averages out the rotary tidal influence to give a net flow, is reasonable and the model is applicable to a wide range of locations. For coarser sand and gravel fractions, the settling time is only a few minutes and the assumption is valid without qualification.

Current input can be spatially varying for each flow condition. This is an important feature if the structure at the discharge point modifies the flow field; in such a case, both the mean flow and the rate of turbulent diffusion vary in the boundary layer around the structure and in the wake. Current velocity components and values of the diffusion coefficient are input to the model on a regular Cartesian grid. These data are usually derived with a hydrodynamic model.

SED_DISP is comprised of two modules: a sedimentation calculation and the deposition calculation. Each grain size fraction is defined by a number of particles, typically several thousand. The position of each particle is given in three-dimensional space by its x,y,z coordinates. These positions change as the particles are transported by the mean current, as they settle at a prescribed fall velocity, and as they are diffused by turbulence. The calculation proceeds until all particles reach the seabed or are carried outside the model boundaries. Diffusion is modelled as a random walk process, scaled by the eddy diffusion coefficient. The outcome of the sedimentation module is the rate of accumulation in $kg/m^2/h$ in each model grid cell for each grain size fraction, for each current input condition.

The deposition module sums these sedimentation rates multiplied by the frequency of occurrence for the current condition over the discharge period. The result is the total weight of deposited sediment in kilograms in each grid cell. Deposition thicknesses are calculated by dividing by the submerged specific weight in kg/m^3.

Input Data

The following input data, stored in files, are required:

1) *run parameters* - number of effluent types, sediment property data for each effluent, number and location(s) of discharge points (more than one allowed), grid dimensions and spacing, discharge durations, and various control parameters;
2) *current data* - bivariate histogram of speed versus direction (16 directions are recommended), velocity component and eddy viscosity data distributed on the grid;
3) *grid mask* - integer array defining each grid cell as a water or land/platform point for control of the calculations.

SED_DISP provides the capability of treating more than one effluent type—this is a valuable feature when operations change the grain size distribution of the discharged material with time. Each effluent type is specified using a spreadsheet program containing the information shown in Table 5. The data consist of the component designation, its grain size, fall velocity, deposited specific weight (density), and per cent composition by weight, as well as the discharge rate. The number of particles for each size class is also given in the table. The accuracy of the solution depends on having a sufficient number of particles in each size class; usually 2,000 or more per class is ample.

Table 5. Sample Input File for SED_DISP Discharge Rate = 200 kg/h

#	Component	D (mm)	w (m/s)	Density (kg/m^3)	Composition (% wt)	Rate Discharged (kg/h)	No. of Particles
1	granular	5	0.297	1835	16.0%	32.00	4,000
2	co. sand	1.25	0.148	1962	9.0%	18.00	4,000
3	med. sand	0.25	0.066	1996	4.0%	8.00	4,000
4	agglomerated	0.15	0.051	1999	15.0%	30.00	4,000
5	silt/mud	0.06	0.00331	2002	56.0%	112.00	4,000
					100.00%	200.00	

As shown in Table 5, agglomeration of fine particles can be accommodated by adding an appropriate class, and specifying an effective fall velocity for the flocculated particles

Output

Output data from SED_DISP consists of files echoing the input data, and files giving the total deposition (kg/m^2) and the corresponding thickness (cm) after the specified release period. If more than one effluent type is used, these results are also given for each type. These data are stored in arrays corresponding to the grid.
Plotting software is available for contouring output or displaying the data in cell-matrix format on a post-script printer. Examples are shown in Figures 5 and 6 for an offshore drilling program featuring two discharge chutes, symmetrically placed on either side of one platform axis. This information can then be used to define the initial deposition area boundaries.

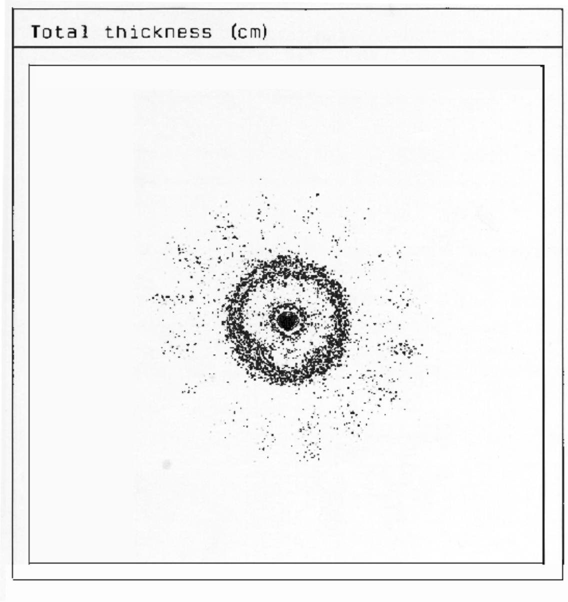


Figure 12. *Example of a SED_DISP contour plot of deposition thickness.*

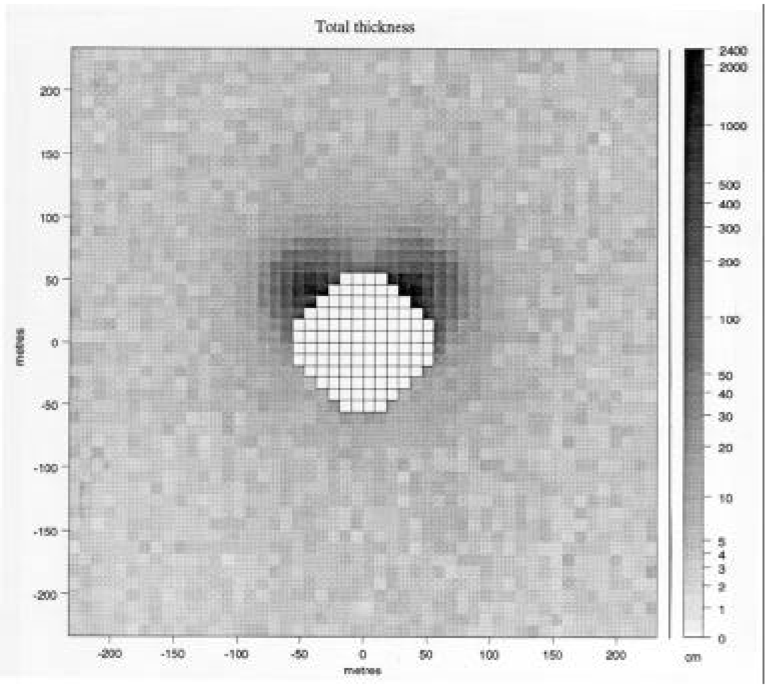


Figure 13. *Example of a post-script printer plot of deposition thickness from SED_DISP*

3. POST-DISPOSAL SEDIMENT TRANSPORT MODELS

3.1 SEDTRANS (Non-cohesive Sediments)

SEDTRANS is a total load model for non-cohesive sediments under the action of currents or waves and currents. It has been developed over the past 15 years by the Geological Survey of Canada, and the model has evolved as a better understanding of continental shelf transport processes has been gained from field observations. The model has been described in several publications, the most recent of which are Amos (1988), and Martec (1989). It has been applied in one-dimensional form (transport at a point) (Davidson, 1984), and in two-dimensional form over a grid of points covering a large area (Amos and Judge, 1991).

Basic Formulation

Bottom stresses for steady currents are determined using a reference velocity 1 m above the seabed and a published constant drag coefficient. Stresses under waves alone are calculated using the maximum wave-induced particle displacement found from linear wave theory, modified Jonsson (1966) friction factors, and a bottom roughness height scaled by the grain size (D or D_{50}). Bed stresses under combined wave and current conditions are based on Grant and Madsen's (1979) theory.

Thresholds for initial motion are applied to bedload transport (from Miller, *et al.*, 1977) and to suspended load transport using Bagnold's (1966) fall velocity relationship. One of the most important aspects of SEDTRANS is that the portion of each wave period during which currents exceed the threshold values is computed. This calculation yields the instantaneous bed stresses which are integrated to give a wave-averaged transporting stress. This averaged stress is substituted into one of four user-selected transport formulas (E-H, Einstein-Brown, Yalin (1963) and Bagnold). Sediment transport directions are assumed to be in the direction of the mean bed stress which is colinear with the current for currents alone, or as determined from Grant and Madsen (1979) for combined wave and current conditions.

The model can be used to simulate a grain-size distribution characterized by D_{50}, or applied sequentially to a number of grain sizes representing a given distribution. In the latter case the transport is found by summing over all grain sizes.

Input Data

Input data consist of:

1) *sedimentary data* - grain size D_{50}, mineral specific weight or a set of grain sizes and corresponding specific weights, bottom roughness height;
2) *hydrodynamic data* - slowly-varying current at a reference elevation of 1 m above the seabed, wave height, wave period and wave propagation direction (significant wave height has been used in examples);
3) *site data* - water depth, specific weight of water;
4) *run control data* - grid information, sediment transport formula, output options.

The model is set up to run time-series of current and wave conditions over a grid where these data have been generated from hindcast models.

Output

SEDTRANS provides estimates of the sediment transport rate in kg/m/s and corresponding direction at each grid point for each input current/wave condition. Some plotting routines are available for mapping the transport rates.

3.2 WAW.F (Non-cohesive Sediments)

The WAW.F model is based on the Willis (1979) modification of the Ackers and White model. The modification accounts for the influence of waves on sediment transport. Like the original AW model, this is a total load calculation. The model was developed by Seaconsult Marine Research Ltd. and is described in Hodgins and Sayao (1986), and Sayao, *et al.* (1987).

Basic Formulation

For application in combined wave current conditions, the AW formula was extended as follows:

$$Q_s = \rho_s U D_{35}\{P_{fg}/(<u_*>\tau_{fg})\}^n \{P_{cg}/(\tau_{cg}U)\}^{1-n} C_1\{F/A-1\}^m \qquad (1)$$

where P = stream power, and
fg,cg = subscripts for fine-grain and coarse-grain.

Under steady unidirectional flows, equation (1) reduces to

$$Q_s = U D_{35}\{U/<u_*>\}^n C_1\{F/A-1\}^m \qquad (2).$$

In WAW.F the parameters $<u_*>$, τ and P are all calculated for both the fine grain and coarse grain fractions.

The combined wave-current friction factor (f_{cw}) is evaluated using Tanaka and Shuto's (1984) method and it is assumed that this friction factor can be applied to the oscillatory term only. It is further assumed that the dimensionless Chezy coefficient, c, can be applied to the mean current term. The effective roughness applied to the Chezy coefficient for fine grains includes a factor for bedforms. Bedform geometry is predicted using design curves from Mogridge (1973) and the effective roughness is calculated after van Rijn (1982). In this way the influence of bedform roughness is taken into account.

The combined wave-current bottom stress is then defined by

$$\tau = \rho\{U^2/c^2 + W^2 f_{cw} u_o^2/4\} \qquad (3)$$

where u_o= amplitude of the horizontal oscillatory motion, including the effect of current, calculated from linear wave theory, and

W= Willis' (1979) empirical wave shear coefficient.

The factors c and f_{cw} incorporate the effective bed roughness into the calculation; the user does not have to specify their values, rather they are calculated internally. The W-factor is introduced to modify the shear stress term under waves to compensate for the different thresholds for initial motion under waves and under currents.

The direction of sediment transport is taken in the direction of the mean current U at each time step. The model is applied at one location for an input time-series of hourly current and wave conditions. The model could easily be cast as a subroutine and embedded in a grid-point model for morphological calculations, but this has not been done to date.

Input Data

Input data consist of:

1) *sedimentary data* - grain sizes D_{35} and D_{90}, and mineral specific weights,
2) *hydrodynamic data* - slowly-varying current at a reference elevation of 0.5 m above the seabed (assumed to be representative of the depth-averaged velocity used by AW, root-mean-square wave height, wave period and wave propagation direction),
3) *site data* - water depth, specific weight of water,
4) *run parameters* - output options, inclusion/omission of Willis' shear factor.

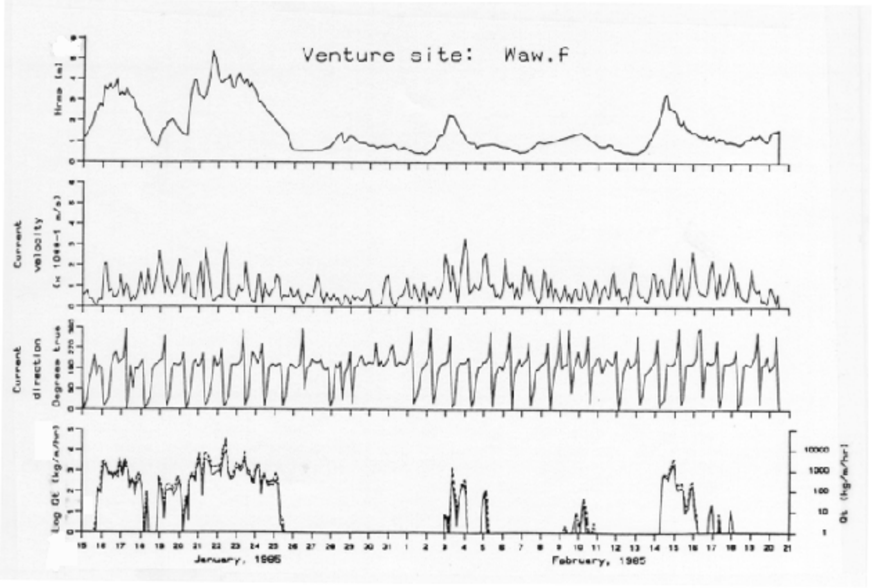


Figure 14. Example of time-series wave and current input data and time series sediment transport Q_t from WAW.F (from Hodgins and Sayao, 1986).

Output

WAW.F provides estimates of the sediment transport rate in kg/m/h and corresponding direction at each grid point for each input current/wave condition. An example of the model output is shown in Figure 14; these results are from the Scotian Shelf in 30 m of water for a well sorted sand environment. Wave and current data were measured in this analysis (see Hodgins and Sayao, 1986).

3.3 WHACKER (Non-cohesive Sediments)

The WHACKER model was developed by D. Willis in 1979 at the National Research Council and published in Willis (1979). It is a modification of the Ackers and White total load model, extending the formulation for combined wave/current conditions. WHACKER served as the basis for the WAW.F model described previously, and in most respects the two codes are similar.

Basic Formulation

For application in combined wave current conditions, the AW formula in WHACKER is given by (1), and the method of evaluating the terms is very similar. One difference in formulation is that WHACKER uses Jonsson's (1966) approach computing the bed stress due to waves, as opposed to Tanaka and Shuto's (1984) more recent formulation for the combined wave/current bed stress used in WAW.F. The bed roughness is specified as direct input to WHACKER.

The model is applied at one location for an input time-series of current and wave conditions. The model has been recast as a subroutine and embedded in a grid-point model for sediment transport (Willis, 1991).

Input Data

Input data consist of:

1) *sedimentary data* - grain size D_{35} and mineral specific weight, bed roughness height,
2) *hydrodynamic data* - current speed at some reference elevation above the seabed, wave height, and wave period, and
3) *site data* - water depth, specific weight of water,

Output

WHACKER provides estimates of the sediment transport rate in kg/m/s at each location for each input current/wave condition.

3.4 TRANSPOR (Non-cohesive Sediments)

The Delft Hydraulics Laboratory in the Netherlands has been involved in development of sediment transport models for many years. Leo van Rijn (1989) summarized much of their work, and published a detailed predictor model TRANSPOR, in the *Handbook, Sediment Transport by Currents and Waves*.

Basic Formulation

The bedload using van Rijn's method is given by:

$$Q_{sb} = \langle u_* \rangle D_{50} T^{1.5} / (4 D_{gr}^{0.3}) \qquad (4)$$

where the shear velocity $\langle u_* \rangle$ is calculated from the current speed and the grain roughness. T is a dimensionless stirring parameter proposed by van Rijn, related to the combined wave/current stress and the critical stress.

The suspended load Q_{ss} is evaluated from the integral

$$Q_{ss} = \int_a^d U(z)C(z)\,dz \qquad (5)$$

where
C = time-averaged, depth-dependent concentration,
z = vertical dimension,
U = mean flow, depth dependent velocity (calculated using a theoretical boundary layer law).

The variation C(z) is calculated by numerically integrating

$$dC/dz = -(1-C)^5 C w_s/\_ \qquad (6)$$

in which w_s is the grain fall velocity and _ is the eddy viscosity. The integration requires the concentration at the reference height a, given by

$$C(a) = 0.015 D_{50} T^{1.5}/(a\ D_{gr}^{0.3}) \qquad (8)$$

Finally, $Q_{sb} + Q_{ss}$ is the total transport produced by the current.

An important aspect of van Rijn's method lies in the separate evaluation of bed stresses due to waves, currents and the interaction of waves and current using roughness lengths appropriate for each. The bed stresses are combined to given an effective stress, and the T-parameter which embeds the critical stress. In addition, the treatment of the boundary layer flow, the reference height and the reference concentration all reflect differences in bed roughness from grain sizes and bedforms.

The TRANSPOR model is provided as a FORTRAN source code, which can be run alone, or easily adapted as a subroutine in a main program. The model is applied at one location at a time for which sedimentary and hydrodynamic inputs are known.

Input Data

The input information for TRANSPOR is:

1) *sedimentary data* - grain sizes D_{50} and D_{90}, effective fall velocity w_s (= $0.8D_{50}$), current-related bed roughness, wave-related bed roughness, mineral specific weight, reference height for bed concentration,
2) *hydrodynamic data* - significant wave height and wave spectrum peak period, depth-averaged mean current speed and angle between waves and current, thickness of the near-bed wave-related mixing layer, ratio of sediment to fluid mixing,
3) *site data* - water depth, seawater specific weight,
4) *global constants* - gravitational acceleration, kinematic viscosity coefficient.

Van Rijn's model requires many more direct input parameter values than the total load models described previously. Specifically parameters like the reference height for the bed sediment concentration, the thickness of the near-bed mixing layer and the two roughness length scales, which are difficult for non-specialist users to provide. Van Rijn's documentation, however, gives guidelines on how to select values for these parameters, including equations for roughness related to ripple characteristics. Thus, knowledge of bed conditions is required.

It is also reasonably straightforward to set-up van Rijn's model as a subroutine, and provide the input data through an argument list using data statements and/or formulas in the calling routine.

Output

TRANSPOR provides estimates of the suspended load transport through numerical integration and through an empirical formula, and of the bed load transport through the formula given above, both in units of kg/m/s. The total flux is the sum of the two components.

The sediment transport flux predicted with this model is that produced only by the current, with the influence of the wave field on the current-related transport taken into account. This flux is in the direction of current flow. Any additional flux related solely to the wave field must be added to the outcome of this model; van Rijn provides suggested equations for this component of the transport in the model documentation, but they are not included in TRANSPOR. In general the current-related transport will dominate the prediction unless the near-bed wave orbital velocities become large compared with the current, as in shallow water.

Van Rijn has compared his method with both field (rivers) and laboratory data. Examples for bedload and suspended load are shown in Figure 15.

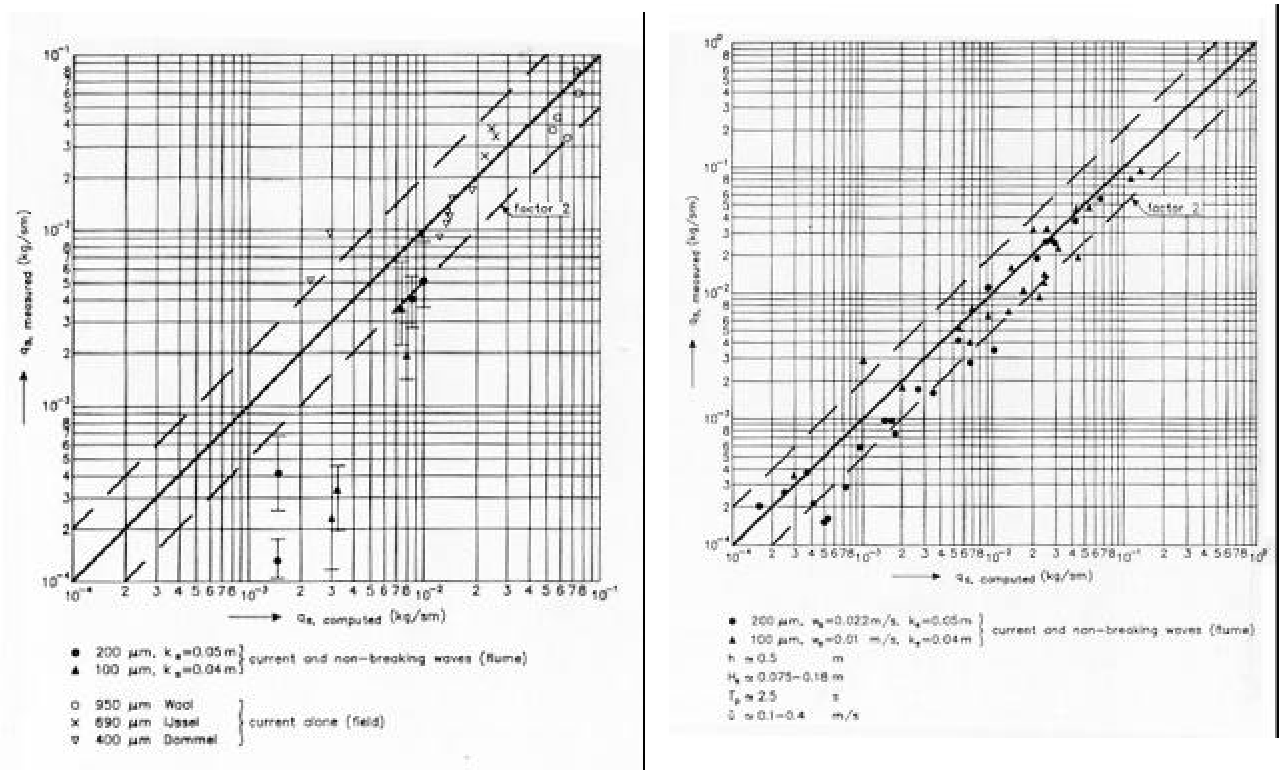


Figure 15. Comparison of van Rijn's detailed predictor model TRANSPOR with measured sediment transport rates for bed load and suspended bed load (from van Tijn, 1989)

3.5 Mike 21 STP (Non-cohesive Sediments)

STP is one module of the Mike 21 suite of programs developed and marketed by the Danish Hydraulic Institute. STP is a detailed predictor intra-wave model that gives estimates of the time-averaged bedload and suspended load transport under wave and current conditions. It includes the effects of wave breaking where these are relevant (shallow water). The STP module is embedded into the Mike 21 system program which provides input hydrodynamic data and a bed evolution calculation using the transport fluxes from STP.

Basic Formulation

The total sediment load is divided into bedload and suspended load components. The bedload is calculated as a function of the bed stress expressed in terms of the shear velocity, i.e.,

$$Q_{sb} = f\,\{<u_*>^2/[(\rho_s - \rho)gD_{50}/\rho]\} = f\,\{\theta\} \qquad (8)$$

The functional form for Q_{ss} is not given in the documentation.

The suspended load transport is calculated by numerically integrating the vertical diffusion equation

$$dC/dt = w_s \partial C/\partial z + \partial/\partial z\,(\in \partial C/\partial z) \qquad (9)$$

where $C(z,t)$ = sediment concentration by volume
t = time
z = vertical dimension, and
$\in$ = vertical eddy diffusion coefficient.

The eddy diffusion coefficient for sediment is assumed to equal the eddy viscosity coefficient in the combined wave-current boundary layer; this latter coefficient is calculated using assumed boundary layer relationships under non-breaking waves. Under breaking waves, a turbulence model by Deigaard et al. (1986) is invoked to give the eddy viscosity. The near-bed boundary condition is taken as the bed concentration at a reference height of $a=2D_{50}$. This approach is analogous to that used by van Rijn and is a standard method to solve the equations.

The STP formulation is based on the published model of Fredsoe, *et al.* (1985), modified to take wave ripples into account. The variation of C(a) is specified as a function of the Shields' parameter θ based on laboratory measurements from Nielsen (1979).

The module is applied to a grid of points using time-series input data for currents and waves.

Input Data

The input data requirements are:

1) *sedimentary data* - grain size D50 and corresponding fall velocity ws over the model grid,
2) *hydrodynamic data* - depth-averaged current speed and direction, significant wave height and spectral peak wave period, and wave direction at the water points of the grid,
3) *site data* - water depth over the grid,
4) *run parameters* - model grid size, spacing and land-water definition, simulation duration and time step, and output options.

When used in conjunction with the Mike 21 ST system for morphological modeling, the STP module is used to produce a catalog of sediment transport rates. The model is applicable for medium to coarse sand environments. In fine sand to silt regimes, it is believed that space and time lags in suspended concentrations might damp transport rates due to the time the model takes to adjust the concentration profile to changing hydrodynamic conditions.

Output Data

The STP module is intended for use within the Mike 21 suite of programs; thus, its output is geared towards providing data suitable for computing seabed changes (morphology) and interacting with the hydrodynamic (wave and current components). The basic output from STP is a total sediment load time-series in $m^3/m/s$ and corresponding direction of movement at each model grid point. Development of the model to 1993 includes partitioning of graded sediments into a set of grain size classes, and treating each size class separately in terms of transport.

3.5 Mike 21 MT Mud Transport Module (Cohesive Sediments)

Like STP, MT is another module of the Mike 21 suite of programs developed and marketed by the Danish Hydraulic Institute. MT is a detailed predictor giving the depth-averaged sediment concentration in the water column under wave and current conditions, as well as changes in bed morphology. The MT module is embedded into the Mike 21 system program which provides input hydrodynamic data and a bed evolution calculation. MT is available in different versions, distinguished by their treatment of the bed layers and sediment grain size classes, ranging from multiple layers as shown in Figure 16 and several grain size classes to simpler single-fraction models with prescribed bed density and shear strength properties (linear with depth).

Basic Formulation

Conceptually the mud transport model solves an equation expressing conservation of sediment particles in the water column governed by advection by currents, turbulent diffusion, and supply/loss processes from the seabed and from rivers. MT uses a depth integrated form of the conservation equation:

$$\partial C/\partial t + U\,\partial C/\partial x + V\,\partial C/\partial y = \partial/h\partial x[hA_x\,\partial C/\partial x] + \partial/h\partial y[hA_y\,\partial C/\partial y] + Q_LC_L/h - S \qquad (10)$$

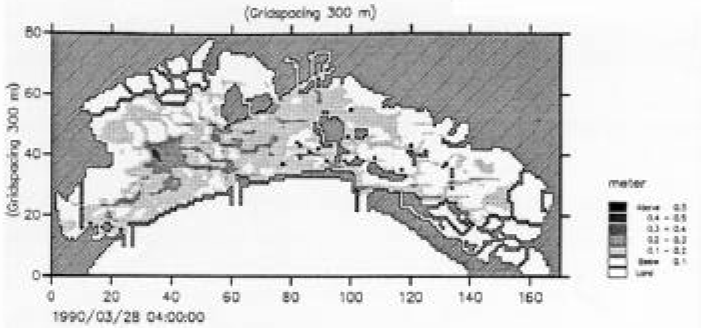
where C = depth-averaged concentration,
A_x,A_y = diffusion coefficients,
U,V = depth-averaged velocities,
h = water depth,
Q_L = source discharge per unit area,
C_L = source sediment concentration, and
S = erosion/deposition source term.

Much of the effort in solving equation (10) is directed at specifying the term S, making use of different critical stresses for erosion of the bed and deposition. Application of the model is critically dependent on site-specific data on time-varying sediment concentrations for calibration of these threshold stress conditions.

Input Data

The MT module is intended to run within the Mike 21 system model which includes the hydrodynamic modules for currents and waves running on the same grid, as well as the interfacing software and graphical output routines. In addition to the current and wave data, the model requires sedimentary data for each mud layer at each grid point which include parameters for bottom roughness at the sea bed, and parameters controlling critical stresses, consolidation, flocculation and settling velocity.

Wind-waves



Suspended sediment concentrations

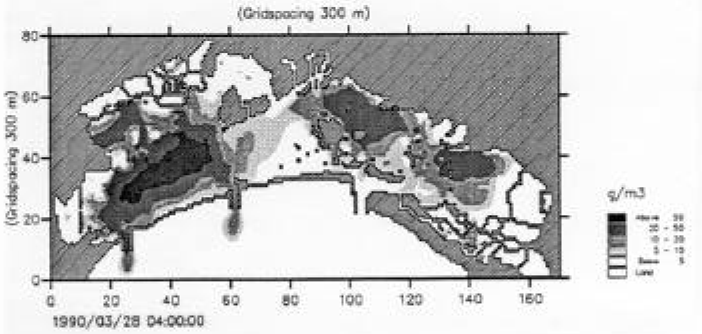


Figure 16. Example of output from the Mike 21 MT model showing storm wave conditions (upper panel) and depth averaged sediment concentration (lower panel) at one time of the simulation for the Venice Lagoon system.

Many of these parameters will require calibration using site specific data. Thus applications of mud transport models are heavily data dependent, and usually iterative as the individual modules are calibrated and verified (including the current and wave modules) against field information. Once the system model performance has been established, then it can be run in a production mode to evaluate natural conditions, or changes associated with dredging and spoil disposal.

Output Data

Output from MT consists of the depth-averaged sediment concentration at each water grid point for each time step specified by the user. The model is run with time-series wave and current input, and produces a corresponding time-series of concentrations. When run within the full Mike 21 suite, output on changes in seabed elevation are also predicted.

An example of output from MT applied to the lagoon system surrounding Venice, Italy, is shown in Figure 16. The upper panel illustrates the significant wave height field under strong wind conditions, while the lower panel illustrates the corresponding sediment concentration field.

3.7 CUMBSED (Combined Cohesive and Non-cohesive Sediments)

CUMBSED is a mud transport model developed by D. Willis at the National Research Council of Canada. It was developed and applied to a study of Cumberland Basin in the Bay of Fundy to characterize the bed erosion and deposition characteristics, and changes in sediment transport. The sediment regime can be comprised of cohesive muds, non-cohesive sand, or a mixture of both. The model includes consolidation with time of the deposited muds.

Basic Formulation

Much of the basic physics in CUMBSED parallels that in the Mike 21 MT module discussed previously, in terms of critical stresses for erosion and deposition, consolidation, and the assumption that the suspended concentrations are uniformly distributed in the water column and can be accounted for through the solution of equation (10). Willis has partitioned the suspended transport into mud and sand fractions. Mud is eroded, transported and deposited in a manner similar to the MT model; however, the sand fraction in motion is calculated using routines adopted from WHACKER—that is using the AW total load formula as extended by Willis to account for waves.

The seabed in CUMBSED is schematized into 5 layers superimposed on a fully consolidated but erodable sub-bed (Figure 17). The mud layers (which may each contain a fraction of sand) are defined by a fixed lower elevation relative to a datum, and a depth of zero concentration corresponding to all material in suspension. The depth of the water column changes as layers are eroded and redeposited during the tidal cycle.

CUMBSED is written as a set of subroutines designed to be interfaced with a hydrodynamic model. Both hydrodynamic and mud transport models are run on a grid applied to the region of interest, and exchange data at a user-defined time step.

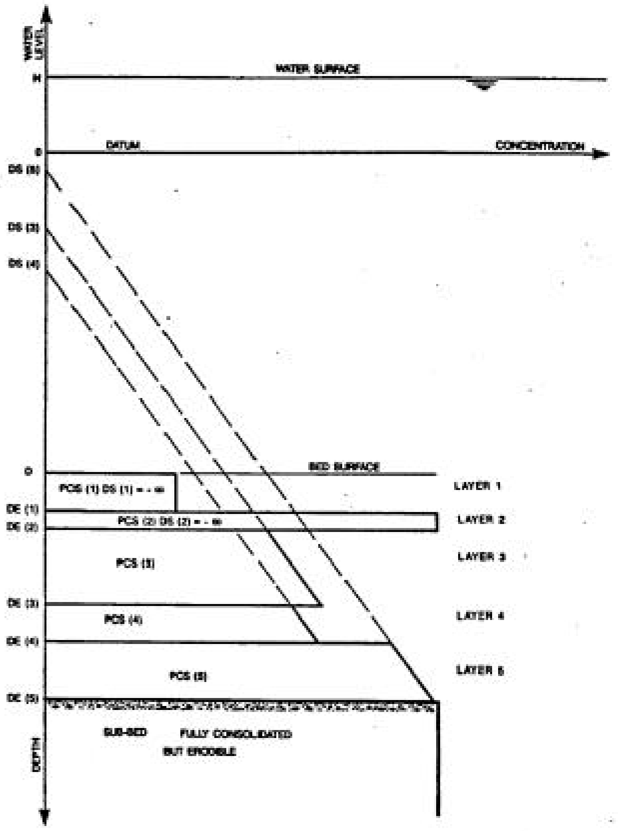


Figure 17. Willis' mud seabed schematization used in CUMSED.

Input Data

Like the Mike 21 MT model, CUMBSED depends heavily on site specific data for definition of the sedimentary and geotechnical properties of the layers, and data for calibrating critical stresses for erosion and deposition, and settling velocities for mud flocs. It also requires a verified hydrodynamic model for current prediction, and where appropriate a wave prediction model.

Output Data

The output from CUMBSED consists of time-series of depth-averaged sediment concentrations (mud and sand fractions), and bed elevation with respect to the model datum.

3.8 TABS-MD (Combined Cohesive and Non-cohesive Sediments)

TABS-MD is a two-dimensional modeling system comprising modules for hydrodynamics, sediment transport and water quality. It was developed originally by the U.S. Army Engineer Waterways Experiment Station for specialized modellers (Thomas and McAnally, 1985). Subsequently, the model has been extended through work at Resource Management Associates in Lafayette, CA (commercial vendor) and at Brigham Young University in Salt Lake City, Utah (licenser of FastTABS).

Basic Formulation

The complete modeling system is comprised of modules, each coded in FORTRAN 77, that are linked together to give the desired solution. Although three-dimensional modeling is considered possible, the system is developed and reliable in two spatial dimensions at this time. It is considered applicable to environmental problems in coastal seas, estuaries and rivers. It is not intended for the study of fluid-structure interactions where small-scale vortices or eddy shedding phenomena are present.

The hydrodynamics considered are slowly-varying flows produced by tides, runoff and storm surges. They are computed from the conventional shallow-water wave equations (Dronkers, 1964). These equations are solved on an irregular triangular or quadrilateral mesh using finite element methods. The finite element solution uses Galerkin weighted residuals. Flooding and drying cells are permitted, as well as specification of horizontal turbulent coefficients, and the introduction of hydraulic control structures.

Sediment transport is computed using an formula similar to equation (10). As is the case with the previous two models, considerable effort is directed at specifying the sea bed interaction terms. Where the sea bed is comprised of non-cohesive sands, TABS uses the AW formula to estimate the total load flux. This flux is converted to concentration for use in the conservation of sediment mass equation (10). For cohesive sediments (clays and silts) the sea bed source term is specified in terms of Krone’s (1962) relations for the critical stress of deposition. When the bed stress exceeds Krone’s criteria, the method developed by Ariathurai, *et al.* (1977), based on Partheniades’ (1962) findings, is used to compute the material removed from the bed. The outcome of these sediment calculations is a prediction of the change of the sea bed elevation—thus, one obtains estimates of evolving bed morphology. Where the supply of sediments is depth-limited, erosion is controlled by the available supply of material.

User Considerations

TABS-MD is a complicated software package which shares many of the same data requirements as Mike 21-MT and CUMBSED. One of the major differences with TABS, however, is the requirement to generate a finite element mesh and supply the bathymetric and sediment facies data over the variable grid. Even with mesh generating software (available with FastTABS) this process is complicated and requires a great deal of data. The benefit of the finite element mesh lies in its variable spacing giving high resolution where it is needed; thus, the choice of TABS is governed to some extent by the need for such resolution, traded off against the time to set-up the model and the computer resources needed to give solutions for the mesh.

Documentation for the older versions of TABS is available from the U.S. Army Engineer Waterways Experiment Station (Thomas and McAnally, 1985). Documentation for FastTABS is available from Brigham Young University, and supporting services (training, consulting) are available from Resource Management Associates for TABS-MD.

Case studies using TABS were not available to this review and typical accuracies cannot be quoted. Users considering this system should carefully study the limitations described in the documentation to be sure the algorithms apply to their situation, and to ensure that the required input data are available. They should also examine previous applications and talk to those modellers to ensure that the mesh sizes and overall mesh dimensions will provide necessary resolution and will actually compute in reasonable times on the selected computer hardware. Potential users must also satisfy themselves that sufficient data exist to calibrate the model, most especially for applications to cohesive sediments. Finally, users who anticipate transferring the modeling software to their own computers should consider the graphics for displaying input and output data. Existing versions of TABS utilize DISSPLA Version 11.0, available from Computer Associates. Conversion to other software may require considerable programming effort.

3.9 LTFATE (Combined Cohesive and Non-cohesive Sediments)

LTFATE is a site analysis program providing coupled hydrodynamic, sediment transport, and bed morphology calculations over time as a function of local waves, currents, bathymetry and sediment size. It is intended to evaluate the dispersive characteristics of a potential disposal site, and is applicable in reservoirs, rivers and estuaries, and coastal seas. This model uses depth-averaged hydrodynamic input and may be applicable to many sites in Canadian waters. LTFATE was developed by the U.S. Army Engineer Waterways Experiment Station, and is described in detail in Thevenot, *et al.* (1993).

Basic Formulation

The objective of LTFATE is to predict the long-term evolution of a dredge spoil mound under the action of tidal currents and normal wave climate, or under the action of tidal currents and storm-generated waves. The input data on currents and waves are organized in a suitable fashion for this purpose. The mound evolution is calculated using sediment transport models.

If the spoil material is non-cohesive, the AW model is used with Swart’s (1976) modification to account for wave-induced transport. The bed evolution calculation also accounts for slope failure when the mound slope exceeds the angle of repose for the sediments.

Cohesive sediments are treated using an algorithm developed by Teeter and Pankow (Thevenot, *et al.*, 1993). Sediment settling is calculated according to Ariathurai, *et al.* (1977) and the depositional flux of sediments to the sea bed follows the work of Mehta from the University of Florida. Resuspension is based on the findings of Ariathurai, *et al.* (1977). This model shares many common elements with TABS for cohesive transport.

Consolidation of fine sediments following deposition is also considered.

Treatment of Environmental Data

LTFATE contains wave and tidal simulation packages specific to certain types of data. In particular wave data are specified as normal climate statistics in terms of frequency of occurrence of significant wave height, peak spectral period and dominant wave direction. An algorithm developed by Leon Borgman is then used to convert the frequency data into time-series containing the correct autocorrelation properties for the site of interest (Borgman and Scheffner, 1991). Shallow water effects are taken into account. The U.S. Army Engineer Waterways Experiment Station use the wave statistics hindcast in the Wave Information Study (WIS) for U.S. coastal waters.

Tidal data giving water levels and currents at known depths are reconstituted from the astronomical harmonic constants applicable to the site. Usually these data must be measured or calculated using a tidal model (Westerink, *et al.*, 1993); they are not generally known through coastal waters. Users of LTFATE in Canada must ensure that harmonic constants obtained from Canadian sources are equivalent to those calculated in the U.S. for which LTFATE is programmed.

4. FINAL NOTES ON USING MODELS

Sediment transport models described in this summary fall into two categories:

1) those that are relatively simple and could be used by organizations planning marine disposal activities who are not sediment transport specialists, and
2) models which are sufficiently complex in formulation and input data requirements that they must be applied by their developers or specialist consultants.

Morphological models and mud transport models fall into the second category.

For some potential disposal sites in Canadian marine waters, the simple models (WHACKER, WAW.F and TRANSPOR) will give a reasonable indication of potential transport rates and which hydrodynamic conditions produce sediment movement. These simple models are also a valuable complement to geological surveying, helping to confirm interpretation of observed bedform features. While relatively straightforward in terms of data input, formulation, and understanding of the output, these models are not particularly accessible by non-specialist users. This is true for several reasons but mainly because the available software has uneven documentation, poor or no user interfaces, and output in forms not specifically directed at marine disposal problems.

Many potential disposal site areas and often the material to be dumped, however, consist of fine-grained, slightly cohesive sediments. In these cases the simpler models do not apply and modeling, if it is to be used, must use formulations appropriate to the sedimentary regime. In these cases the modeling will likely be undertaken by specialists, familiar both with the modeling theory, and the data needs for calibration and verification and for placing confidence limits on the predicted transport rates and sea bed changes.

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