Data Support for Modelling of Deep-Sea Mining Impacts

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Abstract

The paper critically reviews the presently available experimental data from various tests and experiments connected with the deep-sea mining issue with regard to their feasibility in supporting and validating the developed numerical models. Numerical modelling is applied mainly to predetermining the plume development and seafloor blanketing caused by various sediment discharges. The paper describes processes included in these models and discusses the experimental acquisition of needed model parameters. The existing models and their validation are shortly reviewed and parameters essential to operate and validate them are pointed out. Recommendations for further field studies are given in order to improve the quality of model forecasts.

Keywords

Deep-sea mining, environmental impact assessment, hydrodynamic numerical modelling, data acquisition and assimilation, model verification, validation.

Introduction

Although deep-sea mining does not seem to be profitable at present due to the market situation, the mining technology is being further developed in many countries. Among deep-sea deposits, the manganese nodules are of greatest interest. They form flat fields at the bottom at depths of 4000–6000 m, partially covered by or buried under sediments. As field tests have shown, deep sea mining is technologically feasible (Bischoff and Piper, 1979; Halbach et al., 1988; Padan, 1990). Mining will inevitably be accompanied by serious changes of the seafloor and generate plumes at different depths. The plumes will consist mainly of fine bottom sediments, nodule fines, or fragments, dissolved effluents, and biota debris. Depending on the mining technology, the discharges will take place in different depths and with various intensities. The greatest discharge will appear at the bottom during nodule harvesting, or as a consequence of mining tailings introduction (Thiel, 1991).

Numerical modelling is applied mainly to determine plume developments and seafloor blanketing caused by various sediment discharges in order to predict their environmental impact. However, the reliability of the present numerical models depends on the quality of field data.

At present, we have a stagnation phase in the deep-sea mining issue. This presents a chance for research work on precautionary deep-sea environmental studies, and for consultation in technological methods ensuring the least possible impact before the start of commercial mining. This also implies that the environmental impact assessment has to be formulated without impact examples providing sufficient information, which makes it a difficult task. A characteristic feature of the more recent field experiments is the generation of artificial impacts by different methods. These impacts are small, when compared to the planned recovery on an industrial scale.

Since the field experiments are limited, there exists a need to provide numerical models which allow evaluation and extrapolation to the dimensions to be expected in future commercial mining. The models require data, which are assimilated in different ways, namely as:

1. data to formulate basic assumptions in the models,
2. input data to operate the models,
3. verification data,
4. validation data.

For deep-sea mining impact modelling the specially designed field studies play the most important role among different oceanographic data sources.

Goal of numerical modelling

Modelling concerned with the assessment of the environmental impact of deep-sea mining is mainly applied to forecasting the discharged material plumes, which appear at different depths, and seafloor blanketing caused by settling particles. The impacts to be estimated describe the exposition of marine organisms to large amounts of particles (sediments, ore particles, biota) and other effluents (e.g. dissolved heavy metals) in concentrations exceeding ambient oceanic ones, as well as their settling. Basically, it is necessary to estimate how long the plume will persist before it dilutes and reaches the ambient concentration level or settles at the bottom, and which new sediment coverage will result. The period in which the surface plumes hinder the penetration of the solar radiaton has to be estimated, too.

The probability of occurrence, the recovery rate of organisms, the consequences and overall significance of these influences are the object of present research. Deep-sea ecology, as well as the response of the deep-sea organisms to anthropogenic activities has not yet been understood sufficiently (Thiel et al., 1991). The links between the description of the impact in physicochemical categories and effects on the biota are not clearly known.

There are no well-defined environmental standards defining the limits of excess concentration and its persistence time over a given bottom area, as well as of the resulting deposition thickness.

Required model parameters

The models describing transport of discharged sediment and/or other effluents may differ greatly according to the basic assumptions of the conceptual model. The assumptions mainly depict the scope of the physical phenomena, which are included in the model and their parametrization. For the modelling process, these physical mechanisms and relevant effects of the model environment must be formulated in terms of model variables. Models are reliable, when they are verified, validated and their errors can be quantified.

The data for modelling are input, verification and validation data. The input data describe the initial conditions, configuration or properties of the modelled system (e.g. the geometry, fluid and sediment properties, etc.), as well as parameters needed to run and control the model (e.g. the boundary conditions).

Model verification shows whether the mathematically formulated problem is properly posed and solved. It is done by tests of the model performance and accuracy for well-defined parameter ranges, which together cover the model application domain. For this purpose, we use analytical solutions or data sets for selected physical phenomena included in the model.

The sensitivity analysis is a part of the model calibration, helping to assess the response of the model to parameter variations. It determines the parameters crucial for the accuracy of the model, and help to formulate guidelines for the model application. Parameter studies which compare the results with measurements are also an important step of model calibration. Calibration is usually understood as adjustment of model parameters to a given application in order to obtain improved results.

Validation is based on tests, which are designed to find out, how closely the output of a verified and possibly calibrated model describes the real environment. During validation the model results should be compared to the field data which have not been used in the calibration process.

The main part of all models discussed in this paper is a mathematical description of the sediment transport, based on the transport equation with its appropriate boundary and initial conditions (McLean, 1985). The main physical phenomena controlling plume spreading are: velocity field, processes in the bottom or surface boundary layer, density effects, temperature and salinity profiles, bottom topography, different discharge characteristics, sediment settling velocity, cohesive properties of sediments, scavenging by external particles (e.g. marine snow), sediment erosion and deposition processes.

In the following we attempt to present a list of *input parameters* necessary for a three-dimensional and time-dependent model applied to the deep-sea mining sediment discharges, which includes all relevant physical phenomena.

1. **Current velocity field**. The current measurements are applied to:
    (a) detect the most important hydrodynamic phenomena (tides, inertial waves, eddies, bottom boundary layer) for given transport scales,
    (b) produce typical current scenarios,
    (c) or incorporate them directly into the models.

    Additionally, these measurements are used for formulation of time-dependent boundary conditions. Measurements should be intended on obtaining the velocity field in space and time resolutions appropriate for a given model scale. Special attention must be paid to the characterization of the turbulent bottom or surface boundary layer (bottom roughness, velocity profile, wind influence). Global circulation features enhancing vertical transport, as topographic influences, up- and downwelling, must be also addressed.
2. The **turbulent viscosities and diffusivities** with their spatial and temporal variabilities. They are obtained from the current measurements using statistical methods, or from spreading of easily detectable substances from known sources. Special attention must be paid to the vertical diffusivity, a factor which can balance the settling velocity of the sediment.
3. **Bathymetry** of the area in sufficient resolution for a given model scale is needed in order to take into account topographic influences.
4. **Profiles of salinity, temperature, and turbidity** provide the ambient, normal particle concentrations and density field. They are especially important for modelling the surface discharges, where the thermocline is a boundary between two areas with different hydrodynamical characteristics.
5. **Characteristics of various discharges** (discharge rate and form) must be carefully quantified taking into consideration the mining technology (Ozturgut et al., 1981). Depending on the mining technology, the sediment mass available for discharge at the bottom limits the maximum discharge rates from all possible sources.
6. **Density effects**. The initial concentration and density of the discharge, which deviate from the surrounding waters are important for characterization of density effects. These effects are not only due to suspended sediment, but also due to discharge salinities and temperatures, differing from the surrounding water. Density currents generate near-bottom, flat distribution of the bottom plume in the initial stages after discharge, causing an additional settling effect. The stratification caused by the suspended sediment dampens the vertical mixing (Jankowski et al., 1994).
7. The **sediment settling velocity in situ** is the most complex parameter. The particle size distribution of the sediments from the mining areas shows that most of the

particles have diameters smaller than 60μm, so that the cohesive forces between the particles cannot be neglected (McCave, 1984, Klein, 1993). Settling velocities for the plume particles, interacting with each other, flocculating and breaking up, range from 10^{-3} m/s to 10^{-7} m/s and require special attention. In the models, the settling velocity is treated using the following methods:

(a) to assume the settling velocity to be constant in time and space, and equal to a mean settling velocity of the sediment spectrum (non-cohesive case);

(b) to use a number of sediment classes characterized by settling velocities without interactions between various classes (non-cohesive case);

(c) to use an empirical formula to treat flocculation and break-up, with the settling velocity as a function of concentration and turbulence characteristics (cohesive case);

(d) to use sediment classes and to account for interactions between them (cohesive case).

In order to apply the non-cohesive cases (a) or (b), it is usually assumed that the information provided by the particle diameter and density distributions is satisfactory to obtain the settling velocity. The problems connected with shape, aggregation level and porosity of the particles are dealt with using empirical parameters. The assumption of constant settling velocity implies that the particle diameter distribution remains constant in time. In the case (b), the different sediment classes settle independently and the mean settling velocity diminishes with the age of the plume, as the larger particles settle out.

In order to take into account the cohesive sediment properties influencing the mean sediment settling velocity, the empirical formulations, case (c), are widely used in estuaries and shelf regions. They parametrize the processes of aggregation and break-up of particles using suspended sediment concentration and turbulent shear (McCave, 1984; Dyer, 1989; van Leussen, 1994; Malcherek, 1994). Theoretically considered, the break-up phenomena are insignificant in the low energetic ocean bottom boundary layer. Differential settling dominates other flocculation mechanisms as Brownian motion and turbulent shear. In this case an empirical model is appropriate, in which the settling velocity is a function of the sediment concentration only (Jankowski et al., 1995). The possible flocculation effects may, therefore, accelerate the deposition. Unfortunately, data covering the cohesive properties of the deep-sea sediments in situ are presently too scarce to allow the application of this formulation in a non-speculative way (McCave and Gross, 1991).

Laboratory experiments using sediments from the equatorial Pacific mining areas have shown that flocculation effects are significant in the plumes at concentrations above 100 mg/l (Ozturgut and Lavelle, 1986). These higher concentrations, under which flocculation effects are stronger, are found in the vicinity of the source. Flocculation between plume particles may be insignificant in the diluted plumes far away from the source. Scavenging by rapidly sinking external particles (marine snow) may be more important in this case.

It is difficult, but feasible to describe sediment settling, using a flocculation model based on a spectrum of interacting, i.e. cohesive sediment classes, case (d), (Hill and Nowell, 1995). The most serious problems encountered are uncertainities in interaction rates.

Since it is very difficult to estimate the parameters describing the settling velocity in situ, most estimations are based on laboratory experiments. In situ measurements are still very scarce (McCave and Gross, 1991; Spinrad et al., 1989). There are also difficulties in estimating the role of the organic substances, and interactions between suspended particles and living organisms.

8. The **scavenging rate of the plume particles by external particles** is found by observing the vertical flux of the ambient particles appearing naturally in the ocean, as marine snow. These large, amorphous particles sweep large ranges of the water column, collecting finer particles underway and transporting them downwards. If the mining plume drifts in areas swept by these particles, scavenging may be an effective agent in removal of the diluted plumes consisting of slowly settling fine particles (Lavelle, 1987).
9. **Erosion and deposition** processes can be described without difficulty in the low-energetic boundary layer, typical for the regions of deep-sea mining. The small velocity magnitudes (Bischoff and Piper, 1979; Klein, 1993) allow assumptions that no erosion occurs and that each plume particle, which reaches the bottom, actually deposits. If mining takes place in regions of stronger currents, the formal description of erosion and deposition processes must be introduced. They are parametrized by the bottom shear stress, the critical stress for the erosion, the resuspension rate and the critical stress for deposition. Very little is known about these parameters relevant for the deep-sea sediments (McCave and Gross, 1991).

For model *validation*, data on the model output must be collected in order to compare them with the model results. They are:

1. **Transient, three-dimensional suspended sediment concentration field.** It is usually obtained by nephelometer observations from fixed and variable positions, and water probes sampling.
2. **Current measurements** correlated with the concentration data.
3. **Deposition fluxes**, measured by means of sediment traps and by geochemical methods (bottom sediment sampling).
4. **In-situ particle characteristics** in different plume dispersion stages (plume age) are essential for validation of settling velocity formulations.

Model data acquisition in conducted experiments

From the very beginning of the ocean mining investigations, concern has been expressed about the potential environmental impact due to the exploitation of deep-sea deposits. Tests and experiments related to deep-sea mining started in the early seventies (Thiel et al., 1991). This section concentrates exclusively on the experiments associated with the manganese nodule mining, in which most field work is under way. It does not consider tests with other marine deposits, such as hydrothermal metalliferous sediment deposits in the Red Sea (Amann, 1985; Thiel,

Table 1. Model-relevant deep sea mining tests and experiments.

Name	Date	Organization	Position, Depth	Action
OMI mining test, DOMES, Deep Ocean Mining Environmental Study	March-May 1978	Ocean Management Inc. (OMI), USA, cooper. with National Oceanic and Atmospheric Administration (NOAA)	9°N, 151°W, DOMES Site A, 5100 m	102 h collector work, 900 t nodules recovered
OMA mining test, DOMES	Oct.-Nov. 1978	Ocean Mining Associates (OMA), USA, cooperation NOAA	15°N, 126°W, DOMES Site C, 4300 m	18h collector work, 500 t nodules recovered
DISCOL Disturbance and Recolonization Experiment	1: Feb. 1989 2: Sept. 1989 3: Jan. 1992 4: Feb. 1996	TUSCH research group, Germany, BMBF–sponsored	7°04′S, 88°28′W, Peru Basin, 4150 m	78 plow-harrow tows, 10 km^2 bottom disturbed, recolonization observation
BIE Benthic Impact Experiment	I. 1991/1992 II. July-Sep. 1993	NOAA, USA, cooperation with CGGE (Yuzhmorgeologiya), Russia	12°56′N, 128°36′W, Clarion-Clipperton Fracture Zone, 4800 m	98h benthic disturber action, 1450 t sediment resuspended
JET Japan Deep Sea Impact Experiment	Aug.-Sep. 1994	MMAJ (Metal Mining Agency of Japan), cooper. with CGGE, Russia	9°15′N, 146°15′W, Japanese mining claim, 5300 m	20.5h benthic disturber action, 352 t sediment resuspended
IOM experiment	Summer 1995	InterOceanMetal (IOM) East-European	Clarion-Clipperton Fracture Zone, IOM claim	reports expected

1991). Basic information on the field studies discussed in this section is shown in Table 1.

It is difficult to compare the deep-sea mining field studies, because they were conducted independently and with different methods. The most striking differences are found in the discharge characteristics, including real mining devices in action as well as artificial disturbances. However, there are some common features in the global procedure followed by all these experiments. The main procedure can be divided into the following stages: pre-impact studies, impact monitoring, immediate post-impact survey, and long-term post-impact observations. In this section we describe field studies with an overall aim to find out their strong and weak points.

DOMES project and OMI/OMA tests. In 1975-80 National Oceanic and Atmospheric Administration of USA (NOAA) coordinated the multidisciplinary project DOMES (Deep Ocean Mining Evironmental Study) intended to: (1) establish environmental baselines in three reference areas in the Clarion–Clipperton Fracture Zone (CCFZ), (2) create a database for environmental guidelines, (3) observe actual impacts during mining tests, and (4) develop predictive capabilities for determining the environmental hazards of nodule mining (Bischoff and Piper, 1979). The main result was a classification of the environmental problems according to their importance. Few effects were recognized to be most probable causes for severe negative environmental impacts: (1) the impact on benthic biota due to seafloor destruction by the mining collectors, (2) the impact due to seafloor blanketing at a distance from the mining area, and (3) impact on the upper ocean biota due to the surface discharge plume. Future research needs were pointed out on: (1) the impact of the benthic plume and (2) the trace metal uptake by organisms (Padan, 1990).

During the DOMES project (1978) two successful and so far unique pre-pilot mining tests by Ocean Mining Inc. (OMI) andby Ocean Mining Associates (OMA) were monitored (Ozturgut et al.,1981; Lavelle et al., 1982). The nodule recovery rate was about one order of magnitude lower than during planned commercial production. The observations included monitoring of the benthic and surface plumes.

The parameters describing the OMI test bottom plume were measured in water samples, as well as by nephelometers and current meters moored at fixed different levels above the bottom, providing vertical profiles of velocity and turbidity. The collector system discharge was not exactly known. Only approximations based on optical observations of the deposition at a distance from the collector tracks were available (photograph analyses). As evidence for density currents, the optically detectable deposition, which was found as far as 50 m upstream from the collector tracks was pointed out. Eventually, a computer model was used to obtain the parameters which could not be measured during the test, with special attention to the settling velocity and near-bottom vertical diffusivity (Lavelle et al., 1981). The current varied strongly in the test area. The most striking result was the high mean settling velocity, which was about 10^{-3} m/s, i.e. much higher than expected, with a broad settling velocity spectrum. The large settling velocity caused massive deposition (estimated 90%) in the first 100 m away from the device tracks. The residual plume excess concentrations, measured in the plume 5–8 days of age and transported about 20 km away of the source, were 10 μg/L. The tests showed the inherent problems met when monitoring of the narrow benthic plume by meters in fixed positions. The purely optical analysis of the bottom deposition was a particularly weak point of these observations.

The monitoring of the surface plume was performed during both tests. The modelling made use of the OMI test data only (Ozturgut et al., 1981; Lavelle et al., 1982). The characteristics of the surface discharge were exactly known, in contrast to the benthic ones. Again, the plume measurements using nephelometer transects at 5 m depth (horizontal), water samples (vertical) and particle chemistry (Fe-Mn) indicated that the discharged material settled more rapidly than it had been expected for pelagic clays, i.e. $6 \cdot 10^{-4}$ m/s. Plumes older than 37 h could not be detected any more in the surface mixed layer. It was concluded from these observations and laboratory experiments that flocculation could play a role in settling of the plume. The density effects were excluded, because the discharge came from a moving vessel, and was comparatively small. Density differences were in the range of 1%. During the tests the velocity profiles were not measured, so only pre-impact measurements were available. Some effects, e.g. those due to the significant velocity directional shear, remained unclear, especially with regard to particle settling below the pycnocline.

Both tests were on a smaller scale than the potential commercial mining, and regarded as too limited to allow an extrapolation to the industrial full-scale exploitation (Ozturgut et al., 1981). Monitoring of the plumes concentrated on selected aspects, and complete information was never gathered. Actually, the computer models were applied to obtain the unmeasured parameters. However, observations provided valuable information on the impacts to be caused by deep-sea mining, because mining devices under real conditions were used.

DISCOL. The mining tests in 1978 were the only two mining tests in real conditions ever made, no further tests have been conducted due to the fading interest of the industry. So there was no chance to repeat or improve the measurements in situ with the presence of mining devices in action. The characteristic aim of most of the post-DOMES experiments was to generate an artificial bottom disturbance or resuspension without applying mining technology.

The first group to follow this pattern was the German interdisciplinary TUSCH (German: *Tiefseeumweltschutz*, deep sea environmental protection) research group. They concentrate their experimental activities (Disturbance and Recolonization Experiment (DISCOL)) in the DISCOL Experimental Area (DEA) in the Peru Basin in the Southeast Pacific Ocean, in the vicinity of a potential German mining area (Thiel and Schriever, 1990; Thiel, 1995; Schriever et al., 1996). The main purpose of the study is to evaluate the reaction of organisms to seafloor disturbances. It started in 1989 with baseline pre-impact investigations of the benthic community. In order to obtain an impact similar to mining activities, the bottom was disturbed in a circular area of 3.5 km in diameter using a towed 8 m wide plow-harrow. The area was traversed 78 times, tilling about 20% of the area. All the nodules were buried. The rest of the area was blanketed by resedimentation with varying thickness. This is not exactly the kind of disturbance to be expected by mining, as the nodules were not collected but buried and the bottom was not squeezed by the collector weight. Nevertheless, the disturbance effect was achieved in an area of 10 km^2, as was confirmed by post-impact optical observations. A feature of DISCOL is that no scheduled observations of the plume in suspension and its deposition were made.

Both pre- and post impact observations followed the same pattern: bottom sediment sampling, photographic and video documentation, as well as CTD, hydrographic and sedimentological measurements. These activities were accompanied by long-term current profile measurements for over two years (Klein, 1993). In 1996 they were repeated for a month with higher time and space resolutions.

The modelling in the TUSCH group profits mainly from the basic support data collected during the cruises, i.e. the current measurements, bathymetric surveys, sediment characteristics and geochemical aspects. As mentioned above, no validation data are collected, with the exception of current measurements. The main objectives are collecting input data for modelling and biological evaluation.

It was planned to revisit the DEA every two years and to observe the subsequent recolonization by benthic community, and to continue the baseline studies. The area was actually revisited 6 months after the disturbance, then in 1992, and later in early 1996 (Schriever et al., 1996). The preliminary recolonization experiment results were summarized by Thiel, (1995) and Schriever (1995).

Although a discharge experiment was considered during preparations for the 1996 DISCOL cruise, it was not scheduled. The new experimental idea was to create a small experimental field at the bottom, in a closed chamber, where sedimentological and geochemical experiments could be carried out in situ and under control. Although the experiment failed, this method to circumvent the prohibitive difficulties in monitoring bottom plumes may bring good results in estimating the in situ cohesive sediment properties and geochemical coefficients (Schriever et al., 1996, Koschinsky et al., this issue).

BIE. The next disturbance experiment, Benthic Impact Experiment (BIE), was organized by NOAA in cooperation with Russia's Central Marine Geological and Geophysical Expedition (CGGE). The intention of the experiment was "to simulate the environmental effects of sediment resuspension by deep seabed mining operations and to assess the environmental impact on the deep-sea benthos" (Trueblood, 1993). The main effects to be produced were sediment burial and food resource dilution. After two attempts, the BIE-II experiment was conducted in Summer 1993 in an area in the CCFZ, where background data had been collected previously.

As a characteristic feature of the experiment, the sediment was resuspended by a special device, a *benthic disturber* (Deep Sea Sediment Resuspension System, DSSRS-II) (Brockett and Richards, 1994; Trueblood, 1993). The towed disturber is designed to fluidize, lift and discharge a slurry of bottom sediment and to blanket an area of the sea floor in a manner as can be expected during mining activites. Again, as in DISCOL, no nodules were removed from the bottom. The main impact was due to the deposition and destruction caused by the device sleds. Discharge parameters are given in Table 2. As a result, a deposition with gradual reduction of the thickness at increasing distance from the tracks was achieved in an area of about 2 km^2, ranging from 10 to 1 mm.

For measuring the extent of the deposition 18 sediment traps situated 2 mab (m above bottom) were used. They were placed on both sides of the towing area, accounting for possible current reverse, and in three rows, approximately: 50 m, 150 m and 400 m from the tow zone. Two current meters with nephelometers were deployed 2 mab with sediment traps 5 mab on both sides of the towing zone. During the operation 3 sediment traps and 1 current meter mooring were recovered in order to monitor the progress of the sediment plume dispersion.

The sediment trap contents indicated a rapid deposition north of the tracks. The nephelometers gave distinct signals indicating the passes of the disturber. The photographic data confirmed that the heaviest deposition was within 50 m from the tracks. It was concluded that a portion of the sediment deposited quickly due to the near-bottom sediment-laden density flow. The influence of the changing bottom topography around the tow zone was also made responsible for the quick deposition. Additional CTD casts and radionuclide analyses of sediment cores were used to map the sediment plume and its redeposition pattern. The CTD casts were unsuccessful, due to difficulties to locate the plume properly, but it was hoped that radionuclide measurements could bring more information. The box corer sampling was carried out throughout the area before and after the disturbance in order to conduct biological and sediment grain size analyses.

In Summer 1994 recolonization by the benthic organisms and the reestablishment of the sediment structure was observed, and current meter moorings were collected.

The deposition monitoring was appropriate to find out about the redeposition pattern. However, the sediment traps were located comparatively high (2 mab), so that the load in the densest, near-bottom plume parts went probably undetected. Since the experiment was restricted to the resulting redeposition, monitoring of the concentration and distribution of the bottom plume was not sufficiently taken into account. The nephelometer signals indicated that the near-source plume consisted of isolated clouds or bands. The nephelometers were also located at 2 mab, so no information on vertical plume profile is available. Probably, the main difference between the disturber discharge and a real collector plume lies in the temporal development of the sediment cloud and its deposition. The disturber worked discontinuously in an irregular way for total 98 hours during 19 days of deployment. The envisioned collectors produce a continuous discharge, and follow a pattern at the bottom avoiding coming back to the already mined areals.

No attempt was made to follow the plume at some distance from the tracks. There were uncertainities regarding the source strength, since only estimates from samples collected at the outlet of the discharge pipe were available.

JET. In summer 1994 the Metal Mining Agency of Japan (MMAJ) has conducted Japan Deep Sea Impact Experiment (JET) in cooperation with CGGE and NOAA in the Japanese mining claim in the CCFZ, at a depth of 5300 m depth in an abyssal valley with comparatively smooth topography. In this area MMAJ had been collecting baseline data since 1991. The objectives and methodology were similar to those used in BIE experiment (MMAJ, 1994; Fukushima, 1995).

The benthic disturber uf the US BIE experiment was used again. The disturber was towed in alternate directions (SW-NE) only 19 times from 50 planned. Two parallel tracks were laid in order to make sure that a region of heavy deposition was located between them. The discharge parameters are given in Table 2. The discharged dry sediment mass was estimated by analyzing the slurry samples from the rossette sampler at the top of the discharge pipe (Barnett and Yamauchi, 1995). These samples were used for estimating the sediment settling velocity. Before the experiment, sediment samples were collected, and the currents were measured during 76 days at 5 and 50 mab, with an additional sediment trap at 30 mab.

Table 2. A brief comparison BIE/JET.

Parameter	BIE	JET
mean site depth	4800 m	5300 m
disturber deployment	19 d	14 d
disturber action	98 h	20.5 h
towing area	150×3000m	two tracks 150×2000m
number of tows	49	19
discharge rate	125 L/s	125 L/s
discharge height	5 m	4 m
wet sediment discharge vol. (after 24h settling)	4888 m^3	2475 m^3
dry weight discharged	1450 t	352 t
aimed deposition area	ca. 2 km^2	ca. 2 km^2(?)
maximum deposition thickness	10 mm	1.9 mm
sediment traps	18+4	12+2
current meter moorings during experiment	2	5
pre/post observations current meter moorings	2/4	2/1
nephelometer deployed/failed	2/0	4/2
pre/post sediment sampling stations	3/7	13/14

Throughout the experiment numerous mooring systems were deployed to monitor the current and sedimentation conditions (sediment traps with two tubes and nephelometers) around the disturber tracks. Two systems were deployed at some distance from the area in order to observe the current near the bottom, and the current assumed to be unaffected by the bottom topography. Two current meter systems with transmissometers and sediment traps were located NW, and towards the ends of the device tracks, in order to describe exactly the conditions in these places, where the greatest disturbance occured (turning points of the device). Two other systems with sediment traps were also equipped with current meters and transmissometers, and were placed centrally on the both sides of the tracks. This array was completed by ten sediment traps at 2 mab, placed very close to the disturber tracks.

During the experiment (after 11 tows) two moorings were recovered to check the current, indicating a significant current reversal during the experiment. To clarify the reason of the current reversals, the post-disturbance survey was continued for over a year with one mooring consisting of 6 current meters at different water depths and two sediment traps.

The results from the numerous sediment traps were interpolated in the entire experimental area, yielding blanketing thicknesses up to 1.91 mm. In addition, different geo- and radiochemical estimations of the blanketing thickness were made.

Pre- and post-disturbance surveys using sediment sampling and an underwater camera with CTD sensors were carried out in order to produce a photographical documentation of the bottom, and estimate the bottom blanketing thickness.

Most of the comments regarding the BIE apply to the JET as well. The strong side of this experiment was the description of the sediment deposition at the bottom together with the near-bottom currents. By concentrating, as BIE, on documenting the deposition, the suspended plume was observed rudimentarily. Therefore, the JET yields no additional information on the plume drifting away from the experimental area. Information concerning the bottom boundary layer characteristics is much better than during BIE (moorings in different places provided measurements at various heights above the bottom), but no information on the vertical structure of the plume is available. Again, no continuous plume was produced. Due to technical problems the discharge could be carried on for no longer than total 20.5 h (discontinuously) during 14 days.

Synthesis. A simple quality estimate on the model data acquisition in the four discussed experiments is given in Table 3. During the mining tests, efforts were made to monitor not only the bottom blanketing, but also the plume in its different stages. The later experiments neglected the drifting plume. These experiments concerned only two aspects of the impact, i.e. bottom destruction and plume deposition at the bottom. Direct comparison between the disturbances caused by a plow-harrow or the disturber to the impact caused by real mining devices cannot be made. The main difference is that the nodules in the experiments were not removed from the bottom. Other obvious differences are due to scale, spatial and temporal development of the produced discharges. The discharge components may be also different, because in the case of real mining the separation of nodules from surrounding sediments is a process which probably increases heavy metal mobilization, and introduces also nodule fines into the water column. The experiments did not consider the possible effects caused by the diluted plumes drifting away from the source, the modellers are left alone with theoretical concepts. Already in the DOMES conclusions this aspect was pointed out as a field for future research. Although the resuspension experiments give a chance to estimate the sediment settling velocity in situ, and to clear the uncertainities connected with the density effects, these aspects were not considered.

Existing models and their validation

A number of computer models applied to deep-sea material transport are available. They were applied to the natural sediment transport phenomena, as well as to the environmental impact assessment of human activities (e.g. Marietta and Simmons, 1988; Gross and Dade, 1991).

The first attempts to model the deep sea mining plumes were made by Hess and Hess (1976) and Ichiye and Carnes (1977). Further, Lavelle et al. (1981) developed an analytical model for the bottom plume and for the surface discharge (Lavelle and Ozturgut, 1981), based on an analytical solution of the sediment transport equation in a uniform velocity field. Actually, the analytical model of the bottom plume was used to estimate the unmeasured parameters during the OMI test. Although the authors were aware that the chances of verification were limited, they tried to extrapolate the test results to industrial scale mining in both bottom and surface plume cases (Ozturgut et al., 1981; Lavelle et al., 1982).

A few years later, Lavelle reanalyzed the problem using a two-dimensional numerical finite-difference model, in order to include the effects of the bottom boundary layer, particle scavenging by marine snow, and new settling velocity laboratory analyses (Ozturgut and Lavelle, 1986; Lavelle, 1987).

Table 3. Data acquisition in the field studies

Parameter	DOMES	DISCOL	BIE	JET
long-term current	+	+	+	+
current during exp.	+/–	+	+	++
BBL characteristics	–/+	–/+	–/+	+/–
current vert. resol.	+/–	+/–	–/+	+/–
current hor. resol.	–	–	+	+
diffusivity	–	+/–	+/–	+/–
bathymetry	–/+	+	++	++
salinity, temp., turb.	+/–	+	+	+
scavenging	–	–	–	–
discharge charact.	+/–	–	+	+
deposition	–/+	–/+	+	++
sed. particle charact.	+	+/–	+	+
settling vel. in lab.	+	+/–	+	+
settling vel. in situ	–	–	–	–
cohesivity in lab.	–/+	–/+	–	–
cohesivity in situ	–	–	–	–
heavy metal mobil.	–	+/–	–	–

++ good, + satisfactory, +/– partly usable
–/+ unsatisfactory, – not addressed

Taguchi et al. (1995) developed a three-dimensional finite-difference model applied to the JET experiment. The current measurements were incorporated directly into the model yielding the velocity field. For model validation well-documented resedimentation data from the comparatively small JET area were used, and the effective settling velocity was compared with laboratory values.

Within the TUSCH group, a three-dimensional, finite element, mesoscale model (Jankowski et al. 1994, 1995) and a large-scale model with finite-differences (Segschneider and Sündermann 1995, 1996, Zielke et al. 1995) were developed. The TUSCH modelling efforts concentrate on parameter sensivity studies and scenario computations. The input data used came mainly from the DISCOL experimental area. The main problem encountered is connected with missing validation data. The large-scale hydrodynamics can only be compared with known patterns of global circulation (Segschneider and Sündermann 1995, Zielke et al. 1995). The group intends to formulate an extrapolation to the industrial recovery level. Both models include dispersion of particle-reactive effluents (as heavy metals), with input data from systematic DISCOL experimental campaigns (Segschneider and Sündermann, this issue, Koschinsky et al., this issue).

The existing models are listed chronologically in Table 4. While the early models were specifically dedicated to deep-sea mining discharges alone, the latest are adjustments of generic, complex models for this particular application. There is a tendency to include all relevant physical phenomena.

As can be expected, most of the models related to deep-sea mining are rather strictly connected with particular experimental activities. Although most of these models can be adapted to different mining areas, they were applied for a given experimental area only. They differ also greatly in basic assumptions as to the conceptual model and the included physical phenomena, as well as the application domain scale. While the models are

Table 4. Existing models of the deep sea mining discharge impact.

Name	Year	Type, Method	Data	Comments
Hess and Hess	1976	analytical		surface plume
Ichiye and Carnes	1977	analytical		surface plume
Lavelle et al.	1981	analytical	OMI/OMA	bottom plume and deposition
Lavelle et al.	1981	analytical	OMI/OMA	surface plume
Lavelle	1987	numerical, finite differences	OMI/OMA, settling velocity measurements	2D, bottom plume, < 20 km
Jankowski et al.	1993-5	numerical, finite element	DISCOL	3D, mesoscale, bottom plume and deposition
Segschneider et al.	1993-5	numerical, finite differences	DISCOL	3D, large-scale, geostrophic, both plumes, deposition
Nakata (unpubl.)	1994	numerical, finite differences	BIE	3D, for BIE area, bottom plume
Taguchi et al.	1995	numerical, finite differences	JET	3D, for JET area, bottom plume and deposition

usually well verified using measurements or analytical solutions (in order to test if the effects of the included physical phenomena are reproduced properly), their validations were not possible.

The sensitivity studies with the models point out that the crucial parameter for the model reliability and accuracy is the settling velocity of the cohesive deep-sea sediments. Most of the studies use constant mean sediment settling velocities. Tests with a broad range of constant settling velocities are performed in order to detect the inaccuracies. A theoretical flocculation model was discussed, but not applied, due to the data situation (Jankowski et al., 1995). Other domains, where uncertainities affecting model reliability exist, are listed under conclusions. In contrast, the reproduction of the hydrodynamics with simple bottom boundary layer descriptions and topographic influences is usually satisfactory.

Conclusions

1. Numerical models are quite advanced with regard to the physical processes which govern the sediment plume resulting from deep sea mining. Recent models include real bathymetry, variability of currents, bottom boundary layer, density changes induced by suspended sediment and resulting currents. Even flocculation and scavenging have been included, in spite of the fact that they have been only scarcely investigated in the deep sea.
2. There is a lack of input data to operate the models and an even greater lack of calibration and validation data. Therefore a formal process of model calibration and succeeding validation is not possible at the present time.
3. It seems that present models are capable of reliable prediction of the deposition in the experimental areas, on the experimental scale, provided sufficient input data are provided.
4. Sensitivity studies with a model allow the selection of those parameters which are crucial for its predictive capability. In addition to the current data, the most important parameter is the settling velocity of the cohesive deep-sea sediments.
5. The uncertainties in model parameter values, influencing model reliability and accuracy and defining future research requirements, concern the modelling of the following phenomena:
    (a) cohesive sediment properties including sediment settling velocity,
    (b) exact discharge characteristics, especially for the near-bottom plume,
    (c) scavenging of the plume particles by external particles (as marine snow),
    (d) density currents and stratification induced by suspended sediment in the vicinity of the source,
    (e) the bottom boundary layer (shear-induced mixing),
    (f) the role of effluents, such as heavy metals,
    (g) global circulation features enhancing vertical transport.
6. The available data sets are insufficient for the validation of the predictions of the plume development and sedimentation at a distance from its source, i.e. in the mesoscale (< 500 km), where a major impact is to be expected, and in the large-scale (> 500 km), where also long-term effects may occur. No validation of the models on these scales has been performed.
7. Past experiments such as DISCOL, BIE and JET, as well as the pre-pilot mining operations (PPMT), as the OMI and OMA tests in 1978, were limited in scale. They allowed determination of only some of the parameters needed by models. Actually, some parameters can be obtained even without generating any impact. It seems that only appropriate monitoring of pilot mining operations (PMO) may bring a chance to estimate the full scope of needed parameters. These operations are envisioned as longer (a few months) tests of commercial mining. The PMO's may also allow efficient collection of the validation data.

Recommendations

1. The validation of impact modelling can be conducted only during appropriately monitored longer pilot mining opera-

tions in future. The most challenging task (from the experimental point of view) is to provide the models with input and validation data in appropriate spatial and temporal scales and resolutions. The transient, three-dimensional dispersion data together with the current and deposition flux measurements are needed for the model validation. Additionally, information on in-situ particle characteristics in different transport stages are essential for the modelling of the settling velocity.

2. The experimental and model activities should be concentrated in reference areas in the regions of potential deep seabed mining, where the baseline data are systematically sampled and where the future mining tests will probably be carried out. Models of appropriate resolution and transport scales should be adapted or developed for these regions, using all available data, so that they are suitable for predictions of the future mining impacts.
3. The challenge remains to extend modelling of physical processes to ecological modelling.
4. At present, research groups work independently in different areas, with almost identical subjects and goals. Cooperation should be increased.

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