RESULTS OF AN ADAPTIVE ENVIRONMENTAL ASSESSMENT MODELING WORKSHOP CONCERNING POTENTIAL IMPACTS OF DRILLING MUDS AND CUTTINGS ON THE MARINE ENVIRONMENT

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DISCLAIMER

EXECUTIVE SUMMARY

Drilling fluids or "muds" are essential components of modern drilling operations. They provide integrity for the well bore, a medium for removal of formation cuttings, and lubrication and cooling of the drill bit and pipe. The modeling workshop described in this report was conducted September 14-18, 1981 in Gulf Breeze, Florida to consider potential impacts of discharged drilling muds and cuttings on the marine environment. The broad goals of the workshop were synthesis of information on fate and effects, identification of general relationships between drilling fluids and the marine environment, and identification of site-specific variables likely to determine impacts of drilling muds and cuttings in various marine sites.

The workshop was structured around construction of a model simulating fate and effects of discharges from a single rig into open water areas of the Gulf of Mexico, and discussion of factors that might produce different fate and effects in enclosed areas such as bays and estuaries. The simulation model was composed of four connected submodels. A Discharge/Fate submodel dealt with the discharge characteristics of the rig and the subsequent fate of discharged material. Three effects submodels then calculated biological responses at distances away from the rig for the water column, soft bottom benthos (assuming the rig was located over a soft bottom environment), and hard bottom benthos (assuming the rig was located over a hard bottom environment). The model focused on direct linkages between the discharge and various organisms rather than on how the marine ecosystem itself is interconnected.

Behavior of the simulation model indicated relatively localized effects of drilling muds and cuttings discharged from a single platform into open water areas. Water column fate and effects were dominated by rapid dilution. Effects from deposition of spent mud and cuttings were spatially limited with relatively rapid recovery, especially in soft bottom benthic communities which were conceptualized as being adapted to frequent storms. This behavior was generated by the set of assumptions about linkages and functional relationships used to construct the model. Areas of uncertainty included methods for extrapolating 96-hr LC_{50} results to exposures of varying lengths and concentrations; recovery rates of benthic communities; responses to various depths and rates of burial; fate and effects of the plume in relationship to stratification layers; and long-term and sub-lethal effects of slightly elevated concentrations of discharged materials. Evaluation of the assumptions of the Soft Bottom Submodel suggest that the assumptions used may have been relatively liberal estimates of resiliency of these communities.

Discussion of "closed" water bodies such as bays and estuaries indicated several reasons to expect different and more complex fate and effects behavior in these areas. These factors included different species and communities (such as aquatic macrophytes and oyster beds), more complex circulation and stratification patterns, and potentially more active resuspension processes.

Much of the possible difference in behavior in these areas centers around the extent to which they are "closed" or in the relative residence times of water and sediments in these areas as they determine the long-term dispersion of discharged material. Despite the complexity and variability of these areas, a large body of knowledge (such as that concerning fate and physical effects of dredge spoil) that could be effectively employed in analysis of potential fate and physical effects in enclosed areas was identified.

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GLOSSARY

"closed" water body - a salt or brackish water area, such as a bay or an estuary, where exchange of water with surrounding areas is restricted.

dispersion ratio - suspended solids in discharge divided by suspended solids in upper plume.

drilling cuttings - formation solids generated by drilling.

drilling muds - fraction of the drilling mixture that is not formation cuttings; includes drilling fluid additives, formation water, and compounds generated under down-hole conditions.

epifauna - organisms larger than meiofauna living on the substrate surface.

fraction whole mud - fraction of a sediment sample composed of discharged drilling muds, calculated as: [Ba] in sediment/[Ba] in drilling muds.

infauna - organisms larger than bacteria living beneath the substrate surface.

lower plume - plume containing discharged drilling cuttings and mud solids.

macrofauna - general term referring to infauna and epifauna.

meiofauna - microscopic (exclusive of bacteria) and small macroscopic metazoan fauna inhabiting the substrate surface; includes nematodes, ostracods, copepods, tubellarians, gastrotrichs, oligochaetes, etc. (after Pennak 1964).

96-hr EC_{50} - concentration of substance at which 50% of exposed population exhibits an effect from a 96-hr exposure.

96-hr LC_{50} - concentration of substance that produces a 50% mortality in exposed population from a 96-hr exposure.

pycnocline - plane separating two layers of different density.

upper plume - plume containing discharged soluble components and suspended solids (fine-grained particulates).

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We wish to extend special thanks to Dr. T Duke for his sponsorship and coordination of the workshop. We also thank Mrs. P. Wells for her attention to a myriad of organizational details.

Although the above individuals deserve the credit for the accomplishments of the workshop described in this report, the authors take responsibility for any errors the report may contain.

INTRODUCTION

Increased oil and gas exploration/production at offshore sites has generated concern over potential environmental impacts of marine disposal of spent drilling muds and cuttings. This concern has resulted in a broad array of publicly and privately sponsored research beginning in the mid-1970's.

Drilling fluids or "muds" are essential to provide integrity for the wellbore, a medium for removal of drill cuttings, and lubrication and cooling of the drill bit and drill pipe. Study of the environmental effects of drilling muds and cuttings disposal has been particularly difficult for three primary reasons. First, the composition of a drilling mud is tailored to expected or actual down-hole conditions. This means that in addition to the typical base of bentonite or barite, various chemical agents are added as pH modifiers, biocides, corrosion inhibitors, defoamers, emulsifiers, flocculating agents, surfactants, thinners, particle dispersers, and mud weighting agents. Second, many of the chemical ingredients and materials accumulated from cutting through the various formations may undergo change when exposed to bore temperatures and pressures or to each other (especially in deep wells typical of offshore drilling activities). The resulting complexity of discharged materials is reflected in the wide range of concentrations over which effects are observed. Finally, the fate of discharged drilling muds and cutting is extremely hard to predict because localized discharges are subject to highly variable hydrologic conditions.

Although the bulk of drilling muds and cuttings constituents is relatively inert, discharge of this material may constitute a significant perturbation of the physical environment. In addition, some mud additives (e.g., lignosulfonates and formaldehydes) and components of formation cuttings (e.g., heavy metals and petroleum hydrocarbons) have been a source of concern because of toxicity and potential for accumulation and movement through food chains.

OBJECTIVES

To focus available information on these complex, interdisciplinary problems an Adaptive Environmental Assessment modeling workshop was held with the broad goals of information synthesis, identification of general relationships between drilling fluids and the marine environment, and identification of site-specific variables likely to determine the impacts of drilling muds and cuttings on the marine environment. The workshop was sponsored by the U.S. Environmental Protection Agency in conjunction with its research program and regulatory responsibility in the area of environmental effects of drilling muds and cuttings discharges into the marine environment. Specific objectives were:

(a) provide a forum for effective communication between scientists and administrators working with fate and effects of drilling fluids disposal;

(b) begin construction of a simulation model to capture the physical and biological dynamics of drilling fluids disposal in the marine environment;

(c) identify gaps in information on fate and effects of drilling fluids discharged into the marine environment; and

(d) initiate identification of factors determining fate and effects, which will eventually result in guidelines to assist in permit formulation.

The workshop was held September 14-18, 1981 in Gulf Breeze, Florida. It was facilitated by the staff of the Adaptive Environmental Assessment Group of the Western Energy and Land Use Team, U.S. Fish and Wildlife Service and attended by participants representing Federal, State, and private expertise on the fate, effects, and regulation of drilling muds and cutting discharge. This report is a synthesis of workshop activities and results.

THE ADAPTIVE ENVIRONMENTAL ASSESSMENT METHODOLOGY

The Adaptive Environmental Assessment methodology was developed by environmental scientists and systems analysts at the University of British Columbia and the International Institute for Applied Systems Analysis in Austria. The approach is organized around a series of 3- to 5-day workshops that define information needs and promote a common understanding of the issues. These workshops are followed by periods of information collection, analysis, and synthesis. The workshops are attended by groups of participants, drawn from key agencies and interests, who collectively represent a range of scientific expertise, management responsibility, and decisionmaking authority. These individuals are not only involved in the workshops, but undertake some of the key tasks of information collection, analysis, and guidance between workshops.

The focus of AEA workshops is the construction and refinement of a quantitative, dynamic simulation model of the system under study. Early in a particular application, the process of building a model is usually of greater benefit than the model itself. Development of a simulation model enables participants to veiw their expertise in the context of the whole system, thereby promoting interdisciplinary communication and understanding. Simulation models require explicit information; in building a model, participants must thus be precise about their assumptions. Conceptual uncertainties about system behavior are exposed objectively, and questions that must be addressed in order to understand system responses to resource development projects are identified.

A modeling workshop thus provides a good beginning to an environmental analysis. Scientists and policymakers from government agencies, as well as affected private interests are given an opportunity to participate in and contribute to an integrated assessment process. A large part of the value of such a workshop is that it provides a neutral structure or framework for focused communication among this set of participants.

BOUNDING THE DRILLING FLUIDS WORKSHOP MODEL

The analysis of fate and effects of marine discharge of muds and cuttings began by explicitly simplifying the system. Since any simplification of a real system is an abstraction and therefore incomplete, the representation of the system must be detailed enough to address most concerns while remaining understandable to the participants. The process of simplification, or bounding, was accomplished in the workshop by describing management alternatives (actions), identifying performance measures used to evaluate the effects of those actions (indicators), and defining a reasonable spatial and temporal framework.

ACTIONS

Actions, or human interventions, identified at the drilling fluids workshop are listed in Table 1. As one would expect, all of the actions pertained to operations at the drilling site since there is no practical means of altering the fate of the materials once they have been released into the marine environment. Therefore, the general issue addressed at the workshop was the potential environmental effects of various modes of drilling discharge.

Table 1. List of actions developed at workshop.

Alter discharge depth
Alter discharge rate
Dilute prior to discharge
Alter spatial configuration of discharge (i.e., spread out)
Alter mud composition (i.e., light*, medium, heavy*)
Locate the drilling rig over either a soft bottom or a hard bottom
Dispose on land*
Treat drilling fluids before discharge*

*Not explicitly addressed in the model.

INDICATORS

Indicators are defined as those variables used to evaluate the performance or health of a system. They are the links between the simulation model and participants' perceptions of the system. Therefore, it is important to compile a comprehensive set of indicators to represent the concerns of all interests.

Indicators identified at the workshop are listed in Table 2. For purposes of clarity, they have been grouped according to the submodel responsible for producing them. Many of the indicators were judged to be of secondary importance. Others could not be included within the time constraints of the workshop.

Table 2. List of indicators developed at the workshop.

Model component	Indicator
Discharge/Fate	concentration of suspended solids, barium, and chromium in discharged muds and the resulting plume
	depth and area of deposited muds and cuttings
	pH of discharge and plume*
	salinity of discharge and plume*
	DO in plume*
	light transmittance in plume*
	drilling costs*
Water Column Effects	zooplankton mortality rate within plume
	primary and secondary production*
	recruitment to benthos
Soft Bottom and Hard Bottom Effects	population size for coral, microbes, meiofauna, and macrofauna (infauna, epifauna)
	bioaccumulation by benthic organisms
	coral growth rate
	species diversity*
	respiration*
	reproduction*
	disease*
	nutritional status*
	material transfer*
	organism behavior*
	fishery yield*

*Not explicitly addressed in model.

SPACE

For purposes of simulation modeling, two aspects of space are usually defined. First, the boundaries of the total area represented in the model, and second, the degree of resolution or number of smaller subunits considered within the overall boundaries must be specified.

It was decided that a specific geographic location was inappropriate for this model. The model was structured to represent the discharge plume from a hypothetical drilling rig in an "open" water environment in the Gulf of Mexico. Three effects submodels then calculated biological responses for the water column, soft bottom benthos (assuming the rig was located over a soft bottom community), and hard bottom benthos (assuming the rig was located over a hard bottom community). Two spatial resolutions were defined within the plume. The Water Column submodel used a set of plume slices each representing 1 min of discharge (see Water Column submodel discussion), while the Hard and Soft Bottom submodels represented environmental effects in 1-m^2 areas at five distance down current from the discharge (1, 50, 100, 500, and 1500 m)

The workshop simulation model was developed for "open" water environments. Participants felt that modeling fate and effects of discharged drilling muds and cuttings in more enclosed water environments, such as bays and estuaries, would require an effort devoted more completely to those environments. However, because of their importance a subgroup was convened to discuss fate and effects in these areas. This group's objective was to identify factors determining fate and effects in more "closed" water environments, focusing on variables that might produce different behavior from that expected in "open" water environments or that might produce differences among various "closed" water environments.

TIME

There are two aspects of time that must be considered in a simulation model: the time horizon or length of time for which model predictions are desired, and the time step or interval used to calculate changes in variables throughout the length of the simulation.

For example, in a simulation of human population a time horizon of 50 years might be appropriate, indicating that the model would track population size over a 50-year period. An annual time step might be chosen, in which case, annual birth and death rates might be utilized to calculate new values of the population size each year. In contrast, the U.S. Census Bureau's approach to tracking population size has been to utilize a time step of 10 years, updating the value of population size by enumeration every 10 years.

A time horizon of 20-30 years was selected for this model. The participants chose this time horizon so that effects on slow growing corals and their recovery could be simulated. The incremental time step proved to be more troublesome because relevant processes operate at very different time scales. For example, plankton in the water column and microbes in the sediments respond to perturbations in a matter of minutes to hours while response times of organisms such as corals or crabs may be months to years. Because of this disparity, a monthly interval was selected as a reasonable compromise given the degree of knowledge about population dynamics of the indicator organisms and the amount of time available to model these dynamics. The exception to this decision was the 1-minute time step used to represent plankton dynamics.

SUBMODEL DEFINITIONS

The marine system defined by the actions, indicators, spatial scale, and temporal framework described above was divided into four subsystems. The criteria for useful division of a model into submodels at a workshop are:

(a) minimizing information transfers between submodels (each subgroup considers a relatively isolated part of the whole system);

(b) allocating participant expertise efficiently (each submodel represents the concerns and expertise of a set of participants); and

(c) partitioning the workload equally among facilitators so that participants have an opportunity to incorporate an appropriate amount of depth in their area of expertise.

After considerable discussion the following major components (submodels) were selected for the model:

(a) Discharge/Fate - discharge characteristics of oil and gas exploration rigs and production platforms and the subsequent fate of the discharge materials;

(b) Water Column Effects - dynamics of zooplankton and larval forms of benthic organisms within the upper plume;

(c) Soft Bottom Effects - effects of exposure to drilling muds and cuttings on microbes, meiofauna, and infaunal and epifaunal representatives of macrofauna; and

(d) Hard Bottom Effects - responses of coral to exposure to drilling muds and cuttings.

As previously noted, an additional subgroup explicitly considered how the fate and effects of drilling muds and cuttings might differ in more "closed" water bodies such as bays and estuaries. This group did not attempt to build a simulation model treating the components of these systems in the detail that open water systems were being addressed. Instead they focused on identifying the variables or factors that would determine differences in fate and effects between these environments and those for which a simulation model was being developed. The results of these discussions are incorporated in the concluding section of this report.

SUBMODEL INTERACTIONS

Following submodel definition, workshop participants defined the linkages or information transfers between the submodels. These are depicted in a looking outward matrix (Fig 1) in which submodels are arrayed as both row and column headings. For each element of the matrix, participants identified what they needed to know from other submodels in order to meet their responsibilities for quantifying indicators and for providing needed information to other elements of the matrix (i.e., other submodels). In other words, each subgroup was asked to "look outward" to other subgroups for needed information. Note that this is a qualitatively different question than the more common one of what information can be provided, rather than what information is needed.

Identification of the information transfers in a looking outward matrix is valuable in several ways. First, the exercise promotes interdisciplinary communication and broadens participants' understanding of the system. Second, the looking outward matrix lays the foundation for building a simulation model Submodel construction quantifies how the information requested in the matrix affects the variables of a particular submodel. If sufficient information exists, such relationships can usually be formulated. If not, an information gap or research need is identified. Third, the resulting simulation model can be used to test the sensitivity of the information transfers. Sensitive transfers can be noted for further, more detailed, investigation.

The looking outward matrix constructed during the workshop contains relatively few entries (Fig 1). This reflects a focus on direct linkages between the discharge (Discharge/Fate submodel) and various organisms rather than on how the marine ecosystem itself is interconnected (e.g , how corals are dependent on plankton or how pelagic fish are dependent on benthic fauna).

Figure 1. Workshop looking outward matrix of information transfers between submodels.

TO

FROM	DISCHARGE/FATE	WATER COLUMN EFFECTS	SOFT BOTTOM EFFECTS	HARD BOTTOM EFFECTS
DISCHARGE/FATE		- Discharge characteristics 1. Plume and concentration gradients at 10 minutes, 1 hour, and 2 hours for typical discharge 2. # discharges/month	- Sediment deposition 1. Depth at given distances 2. Composition (% whole mud) at given distances	- Discharge characteristics 1. # discharges/month 2. Maximum concentrations at given distances 3. Duration of typical discharge - Sediment deposition 1. Depth at given distances 2. Composition (% whole mud) at given distances
WATER COLUMN EFFECTS			- % reduction in benthic recruitment from water column	- % reduction in benthic recruitment from water column
SOFT BOTTOM EFFECTS				
HARD BOTTOM EFFECTS				

SUBMODEL STRUCTURES

DISCHARGE/FATE SUBMODEL

Responsibilities

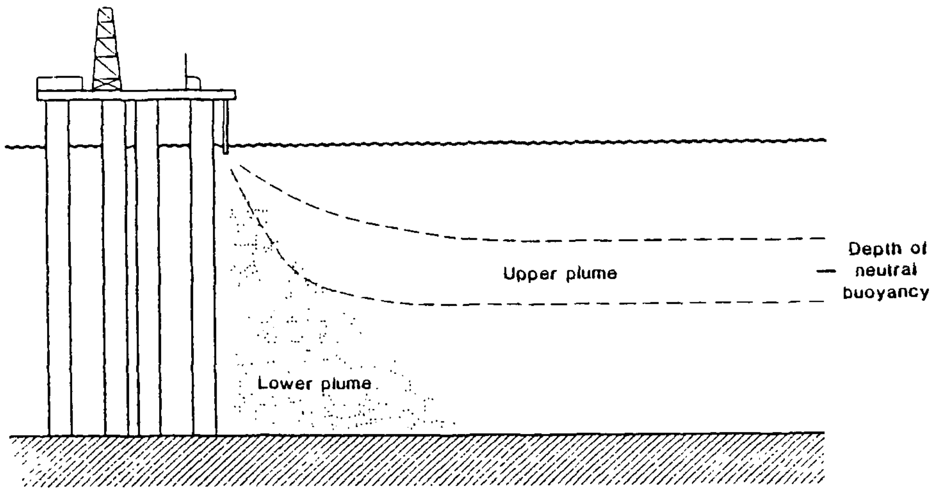
The Discharge/Fate submodel was responsible for determining characteristics of drilling muds and cuttings discharge plumes and fates of various materials in those plumes. Specific indicators of interest included discharge frequency and duration and associated plume size, dispersion ratios, concentrations of soluble and solids fractions at different distances from the platform, and both the depth of sediment added and fraction whole mud in sediments at different distances. Actions of interest included variations in discharge rate and amount, predilution, and shunting. The submodel could also respond to differences in site characteristics such as current velocity, water depth, depth of neutral buoyancy (an approximation for density stratification), and storm frequency and severity.

Structure

Quantitative prediction of the fate of ocean discharged drilling materials generally requires extremely complex mathematical models. This complexity arises from temporal and spatial variation in current velocity and density stratification, the highly variable composition of drilling muds, and the chemical and physical interactions of mud components following discharge. A number of complex mathematical ocean discharge models have been developed over the last 10 years (e.g., Koh and Chang 1973; Teeter and Baumgartner 1979; Brandsma et al. 1980; Houghton et al. 1980). Time during the workshop did not permit such a complex treatment of plume dynamics; therefore, a more empirical approach was taken.

Drilling rigs typically have continuous discharges of solids at low rates (1-10 bbl/hr) while actually drilling, and periodic bulk discharges at higher rates (100-1,000 bbl/hr). The continuous discharges primarily contain cuttings that are separated from the mud before it is reused, while the bulk discharges contain some cuttings but are primarily spent muds that have lost their efficiency. These discharges were conceptualized as separating into two components (Fig. 2); an upper plume containing the liquid fractions of the mud as well as solids such as fine-grained silts and clays, and a lower plume containing cuttings and most of the other discharged solids. Since the continuous, low-rate discharge is primarily cuttings, only lower plume dynamics were modeled for the continuous discharge. Both upper and lower plume dynamics were modeled for bulk discharges.

Figure 2. Idealized drilling platform discharge.



Upper Plume

The upper plume of liquid mud fractions and fine-grained materials was conceptualized as 20 m thick, spreading at an angle of 53° for the first 10 min of transport time (a function of current velocity), and maintaining a constant width subsequently. The plume was assumed to be at a depth of neutral buoyancy, specified for each model run. While plume characteristics can vary greatly, these assumptions seemed reasonable based on observations and measurements by subgroup participants on plumes in the Gulf of Mexico, Southern California, and the Mid-Atlantic. They represent an empirical alternative to the complex mathematics required to model explicitly the convective descent, dynamic collapse, and passive diffusion phases of a plume. In actuality, the plume would be spread out in a wider, thinner layer following its dynamic collapse phase, but the assumptions above yielded reasonable plume characteristics for purposes of this model.

Plume volume (m^3), dilution and concentration of the soluble fraction (mg/l or ppm), and dispersion ratio and concentration of the solids fraction (mg/l) were calculated at distances of 1, 50, 100, 500, and 1,500 m from the drilling rig. Soluble fraction dilution occurs by entrainment of seawater into the plume and was calculated as the volume of liquid discharged divided by the plume volume at each distance. Soluble fraction concentration was calculated as initial concentration divided by the dilution factor. Dispersion of the solids fraction occurs through entrainment of seawater as well as particulate settling. The dispersion ratio (suspended solids in discharge/ suspended solids in plume) was calculated from a multiple regression using transport time and the inverse of discharge rate as independent variables:

$$DISPR = 10^{4.4495} * (1/DSCHR)^{0.35674} * (TT)^{1.1001} \quad (1)$$

where DISPR = dispersion ratio

DSCHR = discharge rate (bbl/hr)

TT = transport time (min)

This regression was based on measured dispersion ratios from wells in the Gulf of Mexico, Tanner Bank, and the mid-Atlantic summarized in Petrazzuolo (Table 6-4, 1981). The squared correlation coefficient (R^2) for this regression was 0.74.

Lower Plume

It was assumed that, over a sufficiently long time period, solids from the lower plume (cuttings and spent muds) would be deposited evenly over a circular area around the platform. In actuality, solids from individual discharges are deposited primarily in one direction away from the platform by prevailing currents. As currents change through the life of a platform, a starburst depositional pattern is often produced with greater sediment depths nearer the platform. An attempt was made to incorporate varying sediment depths based on Petrazzuolo's (1981) empirical model of fraction of whole muds in surface sediments; however, an adequate formulation could not be derived in the time available. Although discussed during the workshop, time also did not permit incorporation of horizontal spreading of the descending plume near the sea bed or resuspensive spreading of deposited materials in this first cut model. The approximation of even deposition over a circular area, therefore, did not completely reflect the spatial variability of deposition or severity of impact. The circular area and depth of added sediment were, however, useful indicators for comparing scenarios and for use by other submodels. The radius of this circle was calculated as:

$$RADIUS = tangent\ (ANGLE) * (DEPTH) \quad (2)$$

where RADIUS = radius of deposition (m)

ANGLE = angle of drift

DEPTH = depth from discharge to bottom (m)

The angle of drift was calculated as:

$$ANGLE = \text{arc tangent } (CURR/PSR) \qquad (3)$$

where ANGLE = angle of drift

CURR = current velocity

PSR = particle settling rate

A portion of this circle could be specified to receive the total deposition, thus simulating situations where currents are predominantly in one direction. Depth of added sediment (cm) was calculated by dividing the total volume of discharged solids by the area covered. These added solids can also change the sediment particle size distribution which may in turn affect indigenous benthic organisms and recruitment of benthic organisms. Particle size effects were not incorporated in the workshop model.

The fraction of a sediment sample that is whole drilling muds has been used as an indicator of toxicity to benthic organisms. This is usually measured by sediment barium concentrations. In the Discharge/Fate submodel, excess barium added to the sediment from each well at different distances from a drilling rig was calculated from the following empirical relationship modified from Petrazzuolo (1981):

$$EBAR = (50,000 * e^{-.003 * DIST})/(10 + DIST^{.5}) \qquad (4)$$

where EBAR = excess barium (mg/kg)

DIST = distance from rig (m)

The fraction of whole muds was calculated as excess barium in the sediment at each distance divided by the concentration of barium in whole muds.

Sediments near drilling rigs are also affected by periodic severe storms that can displace the upper 1 cm or more of sediment and thereby eventually eliminate any indication of drilling solids deposition. In the Discharge/Fate submodel, the average time between such major storms and the amount of sediment displaced could be specified to represent different geographical locations. The effect of these storms in the submodel was to reduce added sediment and associated excess barium.

Behavior

The Discharge/Fate submodel could be parameterized to simulate either an exploratory rig or a production platform. It was assumed that an exploratory rig would drill a single well over a 3-month period with bulk discharges of 600 bbl every 3 days and a total solids discharge of 2,250 metric tons. A production platform was assumed to drill 20 wells consecutively at 6 weeks per well with similar bulk discharge characteristics but a total of only 1,500 metric tons of solids per well. For purposes of model runs, characteristics of a 13 lb/gal mud were assumed.

A production platform scenario was run to demonstrate behavior of the Discharge/Fate submodel. Assuming a 10 m/min current and a total discharge of 600 bbl, upper plume characteristics were calculated for discharge rates of 30, 100, 275, 500, 750, and 1,000 bbl/hr. Results are shown in Table 3. Assuming the same current, an 80-m depth from the discharge to the bottom, and no periodic severe storms; sediment buildup was calculated as 17 cm over a circular area of radius 154 m (Fig. 3). Figure 3 also shows the effects of periodic storms; which occur on the average every 6-months and remove either 1 cm or 2 cm of sediment per storm. Assuming no periodic severe storms, sediment buildup characteristics for water columns 20 m and 80 m deep with currents of 1, 5, and 10 m/min are presented in Table 4.

Limitations

The Discharge/Fate submodel provided reasonable plume characteristics for use by other submodels. However, the lack of explicit mathematical treatment of detailed physical and chemical plume dynamics, spatial and temporal variability in currents, and density stratification precluded addressing certain important questions. For example, plume constituents may become concentrated at stratification layers where certain life stages of some species are found. This possible concentration and its effects on organisms could not be explored with the submodel structure described above. Another question that was not addressed concerns potential integrated or cumulative effects of multiple platforms in close proximity. Another topic of discussion was the effect of shunting. The purpose of shunting discharges to the bottom is to limit the area impacted by cuttings and solids and to keep the liquid fractions and fine silts and clays below the pycnocline. Shunting in the submodel did limit bottom areas impacted, but assumed the liquid and fine-grained fractions would rise to the specified level of neutral buoyancy and therefore potentially still affect the pycnocline. The fate of these shunted upper plume components under actual discharge conditions (staying approximately at shunted depth vs. rising to pycnocline) was discussed at the workshop but not resolved. To address questions such as the ones posed above, a much more detailed, mechanistic modeling approach would be required.

Table 3. Upper plume characteristics at various discharge rates.

$(xEy = x * 10^y)$

Table 3. Upper plume characteristics at various discharge rates. $(xEy = x * 10^y)$

Discharge rate (bbl/hr)	Plume volume (m^3)					Dilution factor for soluble fraction					Dispersion ratio for solids fraction				
	1m	50m	100m	500m	1500m	1m	50m	100m	500m	1500m	1m	50m	100m	500m	1500m
30	9.9	2.5E4	1.0E5	9.0E5	2.9E6	1.6E3	7.9E4	1.6E5	2.8E5	3.1E5	6.6E2	4.9E4	1.1E5	6.2E5	2.1E6
100	9.9	2.5E4	1.0E5	9.0E5	2.9E6	4.7E2	2.4E4	4.7E4	8.5E4	9.2E4	4.3E2	3.2E4	6.9E4	4.0E5	1.4E6
275	9.9	2.5E4	1.0E5	9.0E5	2.5E6	1.7E2	8.6E3	1.7E4	3.1E4	3.3E4	3.0E2	2.2E4	4.8E4	2.8E5	9.4E5
500	9.9	2.5E4	1.0E5	8.9E5	1.3E6	9.5E1	4.7E3	9.5E3	1.7E4	1.8E4	2.4E2	1.8E4	3.9E4	2.2E5	7.6E5
750	9.9	2.5E4	1.0E5	8.6E5	0.6E5	6.3E1	3.2E3	6.3E3	1.1E4	1.1E4	2.6E2	1.6E4	3.3E4	2.0E5	6.6E5
1,000	9.9	2.5E4	1.0E5	6.2E5	6.2E5	4.7E1	2.4E3	4.7E3	8.2E3	8.2E3	1.9E2	1.4E4	3.0E4	1.8E5	5.9E5

Figure 3. Depth of spent mud solids and cuttings under various conditions.

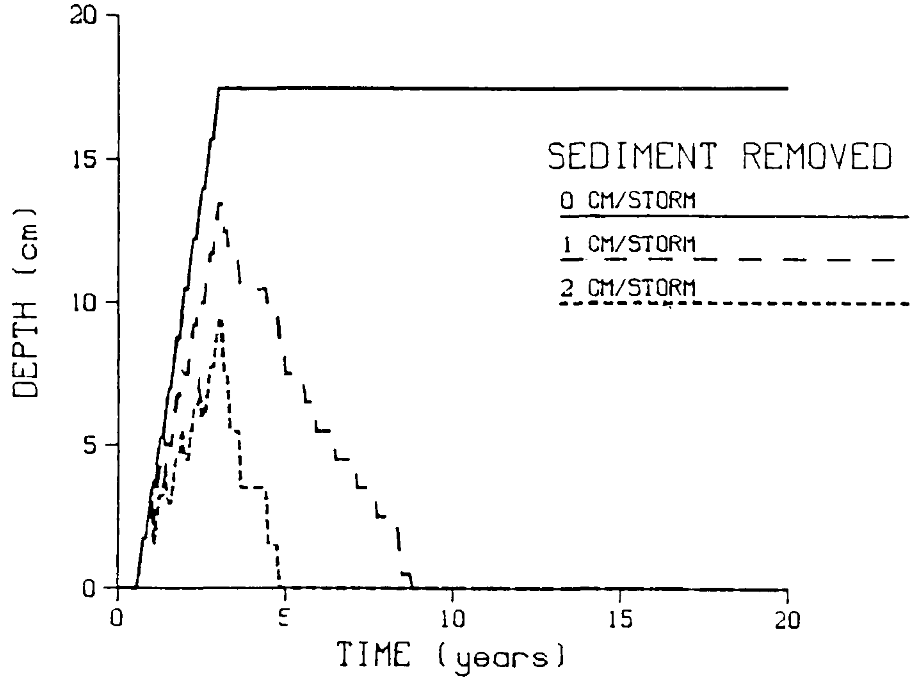


Table 4. Deposition radius and total deposition of drilling muds and cuttings.

Water depth (m)	20			80		
Current velocity (m/min)	1	5	10	1	5	10
Deposition radius (m)	3.4	17.0	34.0	15.4	77.0	154.0
Total deposition (cm)	35906	1436	359	1750	70	17

WATER COLUMN EFFECTS SUBMODEL

Responsibilities

The prime indicators of water column "health" were considered to be primary and secondary production. The Water Column Effects submodel focused, however, on estimating the proportion of planktonic animals within the plume that might be killed by a single discharge of drilling fluids. Subgroup participants felt that this would be a sensitive and tractable indicator of water column effects, given the spatial and temporal scales of the discharge from a single rig. Zooplankton mortality in the plume was used to estimate the percentage loss in monthly recruitment of larval forms to the benthos, considering the number of discharges per month and duration of each discharge. Zooplankton mortality was calculated separately for the discharge and post-discharge phases of the plume. Development and movement of the plume during these two phases is depicted in Figure 4.

Structure

Mortality during discharge phase. The form of the plume assumed by the Discharge/Fate submodel was divided into slices, each representing 1 minute's discharge (Fig. 5). Since the plume was assumed to remain at constant width after 10 minutes, organisms were entrained only within slices 1 to 10. The submodel considered only the "area" of organisms entrained, since plume depth was assumed to be constant. Zooplankton populations were thus represented by areas (m^2), which could be converted to more conventional measures of number of individuals or biomass by utilizing the constant depth of the plume and a site-specific estimate of zooplankton density. The area entrained within a given slice "i" was simply the area of slice i minus the area of slice (i-1). It was assumed that animals entrained at a given point within the plume (i.e., somewhere in slices 1 through 10) would be carried with the current and thus exposed to a declining concentration gradient (Fig. 6). The duration of a subpopulation's exposure to this gradient during the discharge phase depended upon which slice entrained it and how long the discharge continued after the subpopulation was entrained. For example, within a 36-minute discharge, there were 315 different subpopulations with different exposure "schedules".

The concentrations of solubles in the slices (calculated as outlined in the Discharge/Fate submodel description and shown for a test run in Fig. 6) were used to compute an average concentration (c_{st}) for the period of exposure (t) of each subpopulation:

$$c_{st} = \frac{\sum_{i=s}^{s+(d-t)} c(i)}{(d-t+1)} \qquad (5)$$

Figure 4. Top view of assumed development and movement of upper plume at several times during discharge and post-discharge phases.

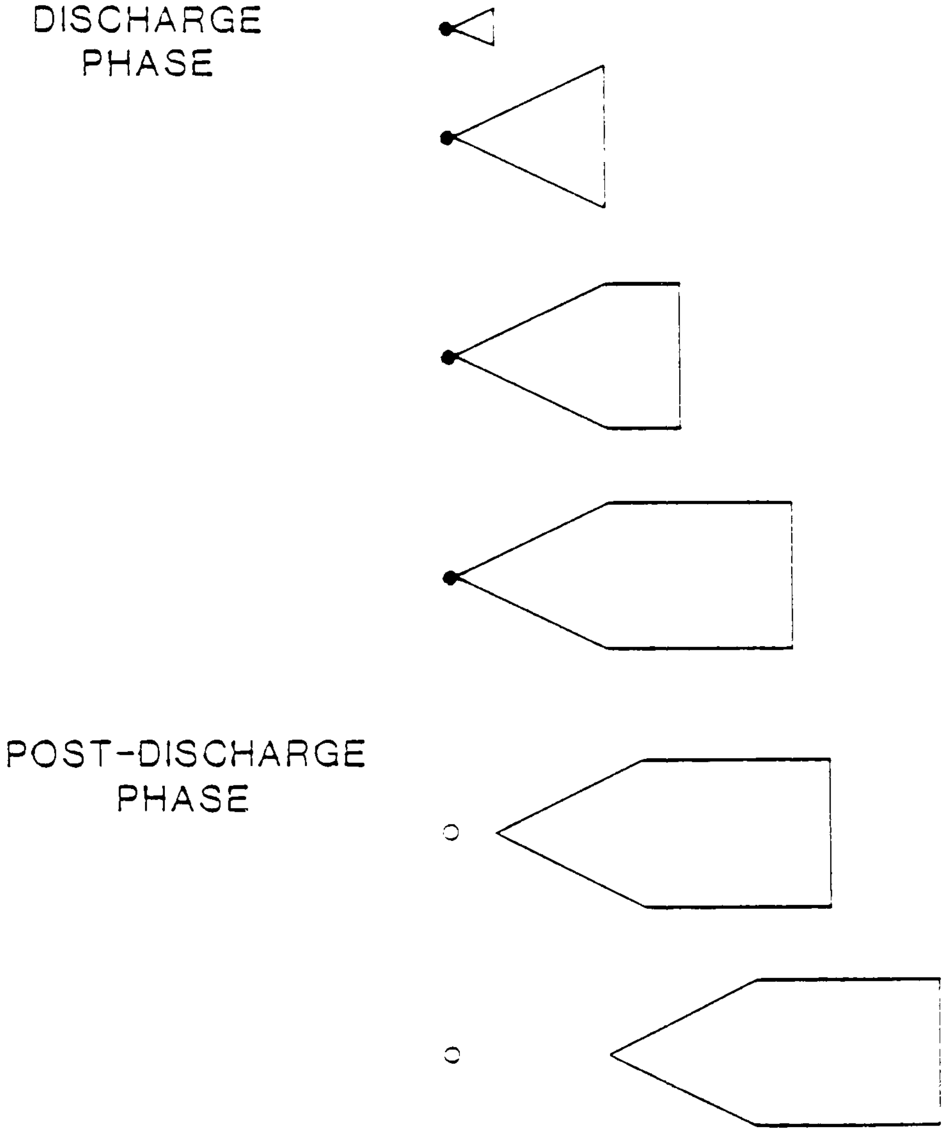


Figure 5. Top view of upper plume slices used in water column submodel calculations.

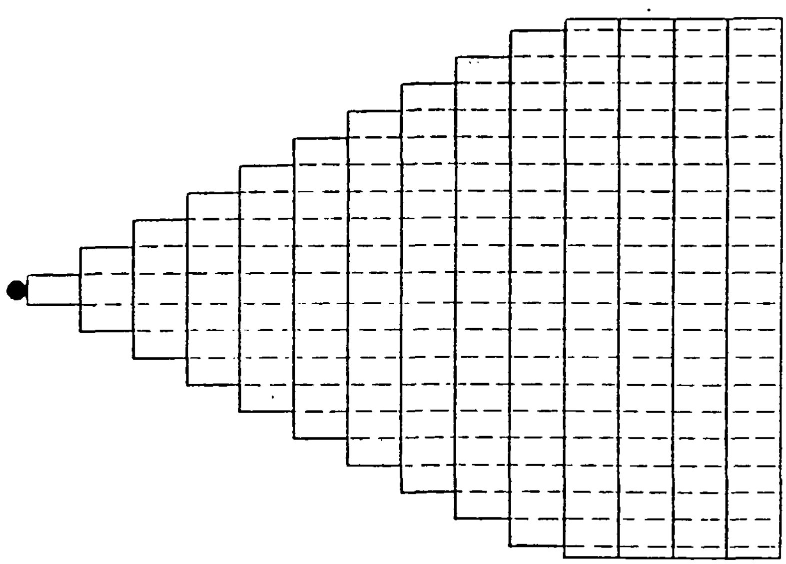
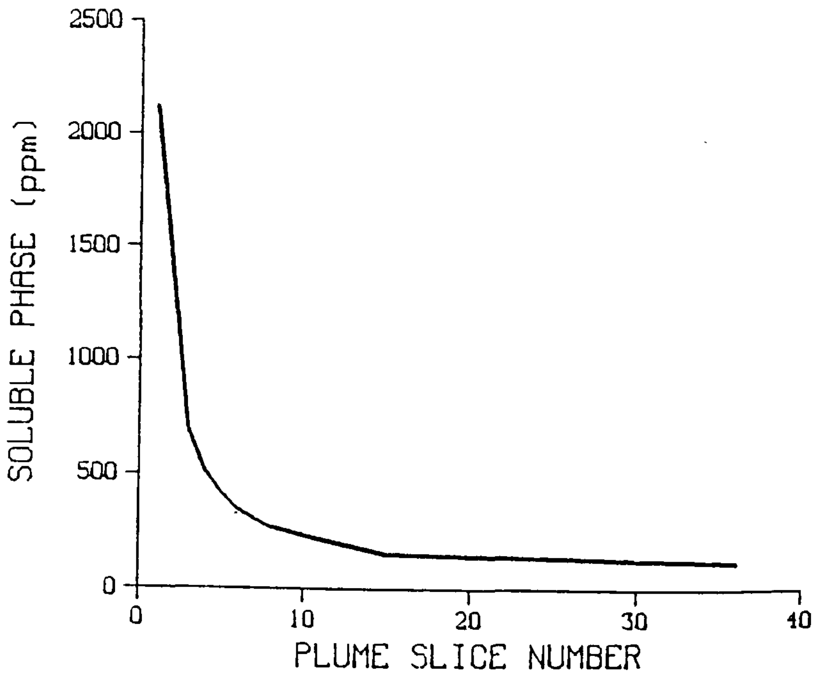


Figure 6. Concentration gradient of soluble phase in discharge plume at 1000 bbl/hr discharge rate.



where c_{st} = mean exposure concentration for organism entering slice "s" at time "t" (where t=1 is first minute of discharge)

$c(i)$ = concentration of solubles (ppm) in slice "i"

d = total duration of discharge (min)

Following Petrazzuolo (1981), an LC_{50} value appropriate to each subpopulation's "t" minutes of exposure was estimated for the discharge phase by converting the 96-hr LC_{50} according to:

$$\text{t-minute } LC_{50} = \text{96-hr } LC_{50} * \left(\frac{96 \text{ hr}}{t \text{ min}} * \frac{60 \text{ min}}{\text{hr}} \right)^{\frac{1}{2}} \tag{6}$$

Using equation 6, 60 "toxicity curves" were constructed for 1 to 60-min exposures, assuming that the general sigmoid shape of Figure 7 applied in all cases. A 96-hr LC_{50} of 50 ppm was assumed in the right hand side of equation 6. This is a conservative value for 96-hr LC_{50} since a value of 100 ppm whole mud is reported as the 96-hr LC_{50} for the most sensitive species tested (Petrazzuolo 1981) The survival rate of each subpopulation was then calculated and used to compute the total loss of plankton, expressed as a top view area of plume (m^2), during the discharge phase (TLDP):

$$TLDP = \sum_{j=1}^{n} A_j(1-SD_j)$$

where A_j = area of subpopulation j (m^2)

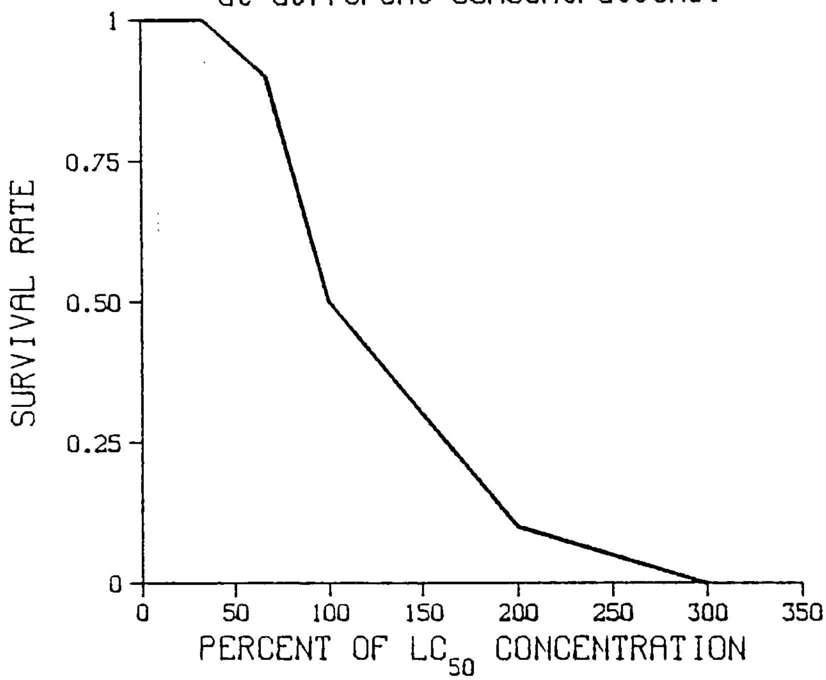
j = subpopulation index

n = total number of subpopulations (= 10d-45)

d = total duration of discharge (min)

SD_j = survival of subpopulation j in discharge phase

Figure 7. Generalized toxicity curve used to calculate survival rates in the water column at different concentrations.



Mortality following discharge. Although observed concentrations from the upper plume gradually decline over several hours following the discharge, the model assumed that exposure during the post-discharge period could be represented by an exposure at the concentration found at the end of the discharge; rather than a series of decreasing concentrations resulting from continued dilution. The plume was thus assumed to remain the same size throughout the post-discharge period (Fig. 4). This assumption was necessary since the dynamics of the upper plume during the dynamic collapse phase were not explicitly represented in the Discharge/Fate submodel. For discharges less than 1 hour in length, the post-discharge period was assumed to be 2 hours long. Exposures during discharges greater than 1 hour duration were (for ease of computation) divided into a discharge phase 1 hour long (at declining concentrations) and a "post-discharge phase" with exposure in the "post-discharge phase" fixed at the concentrations existing after 1 hour. This simplifying assumption is reasonable due to the slow rate of change in concentrations after 1 hour. A survival rate for the post-discharge period was computed for each subarea (or subpopulation), following the same procedure as outlined for the discharge period, but substituting t=120 minutes or more in equation 5.

Total plume mortality and potential monthly benthic recruitment losses. Total plume mortality rate (TPM) over the two phases was calculated as:

$$TPM = \sum_{j=1}^{n} A_j * (1-SD_j) * (1-SPD_j)/(FPA) \qquad (8)$$

where SPD_j = survival of subpopulation j, during the post-discharge phase

FPA = final area of plume (m^2)

j, n, A_j, and SD_j are as defined in equation 7

The relative loss in monthly recruitment to the benthos (RLOSS) was then computed (on a scale from 0 to 1) by:

$$RLOSS = \frac{NDIS * DDIS * TPM}{30(days/month) * 24(hrs/day) * K} \qquad (9)$$

where NDIS = number of discharges per month

DDIS = duration of discharge and post-discharge phases (hr)

TPM = total plume mortality rate as defined in equation 8

$$K = \frac{\text{depth of water column}}{\text{depth of plume}}$$

Equation 9 illustrates that even with 100% mortality in the plume, the monthly reduction in potential benthic recruits would be very small. Assuming 10 discharges per month, each lasting 2.5 hours (discharge + post-discharge phase) and causing 100% mortality, benthic recruitment would be reduced by only 1 7% in a 40-m water column:

$$RLOSS = \frac{10 * 2.5 * 1.0}{30 * 24 * 2} = 0.017 \qquad (10)$$

Behavior

Normal discharge rate. The water column concentrations of solubles for a 36-minute, 1000 bbl/hr discharge at a 10 m/sec current velocity were as shown in Figure 6. Although concentrations of solubles in the post-discharge phase were generally lower than in the discharge phase, survival rates in the post-discharge phase were also generally lower. Lower survivorship in the post-discharge phase was due to longer exposure times. The total mortality under these conditions over the two phases was 8.2%, with 96% of this mortality occurring in the post-discharge phase.

Although survival rates during the post-discharge phase were lowest in the slices nearest the rig, as shown in Figure 8, the highest plankton losses occurred in slice 5 (Fig. 9). This is because the total losses depend upon both the survival rates (a function of concentration and exposure time) and the size of the exposed population (area of plankton) that are in a given slice. As one moves away from the rig, these variables change at different rates, producing the largest total losses in slice 5.

Decreased discharge rate. When the discharge rate was reduced from 1,000 bbl/hr to 30 bbl/hr the water column concentrations dropped from the levels shown in Figure 3 to those in Figure 10. Total plankton mortality per discharge fell from 8.2% to 0.003%.

Figure 8. Survival in post-discharge phase versus position in plume.

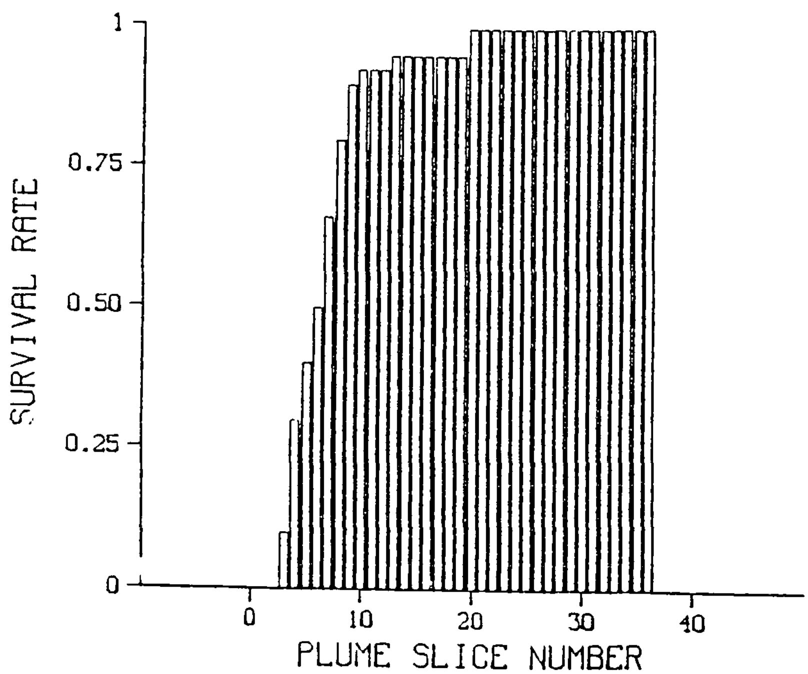


Figure 9. Total loss of plankton in post-discharge phase versus position in plume.

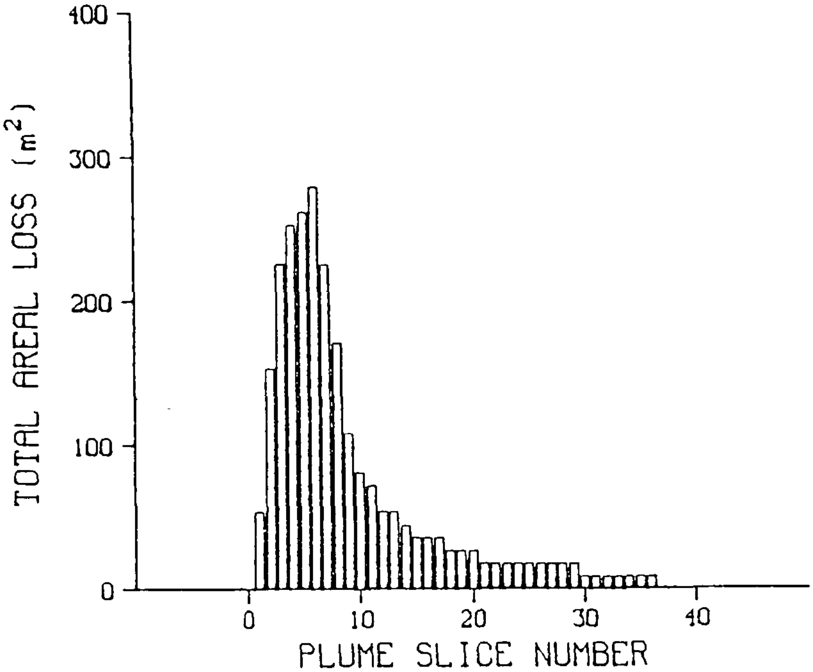
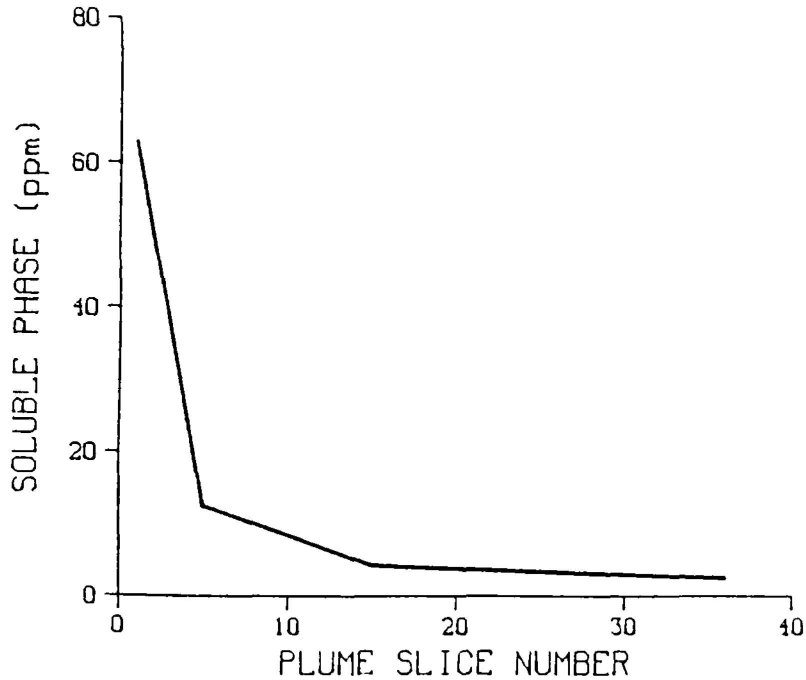


Figure 10. Concentration gradient of soluble phase in discharge plume at 30 bbl/hr discharge rate.



Limitations

The Water Column Effects submodel consists of a collection of hypotheses about exposure and effects of drilling muds. These hypotheses need to be stated explicitly and criticized to reveal the uncertainties associated with model predictions and the priorities for information needs. This section of the report challenges the basic hypotheses of the Water Column Effects submodel as a means of discussing the major difficulties with effects prediction.

It was clear at the workshop that 96-hr toxicity tests at constant concentrations do not accurately simulate the exposures experienced by organisms in the field. Equation 6, used to convert 96-hr LC_{50} values to shorter periods of exposure, assumes that the LC_{50} for a shorter period should be increased by a factor equal to the square root of the relative exposure time (e.g., $\sqrt{96/1}$ for a 1-hour exposure). For example, equation 6 predicts that a population exposed to a toxicant for 1 hour rather than 96 hours would require a concentration equal to about ten times the 96-hr LC_{50} to kill 50% of the exposed population. Estimates of mortality in the plume itself are quite sensitive to the assumptions used to apply 96-hr tests to other time periods. Although assumptions used in the LC_{50} extrapolation produce large differences in mortality within the plume, they do not have a large overall effect on a variable such as benthic recruitment because the bulk discharge plumes occur a relatively small fraction any month as indicated in equations 9 and 10.

A second problem with assessment of plankton survival is the assumption that survival through an exponentially decreasing series of concentrations over the discharge can be estimated by survival at the mean concentration over this period. An alternative approach to this problem would be to use only 1-min toxicity curves, and use the product of the respective survival rates to estimate survival over the whole discharge period. This method potentially runs into other conceptual difficulties, namely, the issues of variability (within a subpopulation) in individual organisms' sensitivity to the toxicant, and selection for tolerant individuals over the duration of the plume.

To clarify this conceptual problem, consider a series of two exposures (of equal duration) at 50 ppm and 100 ppm to an initial population of 100 individuals. Survival using the "non-selective" toxicity curve shown in Figure 11 for both exposures would yield 5 individuals at the end of the second test (0.5 survivorship in first exposure * 0.1 survivorship in second exposure * 100 = 5) However, if one assumes that the first exposure removes the 50 <u>most sensitive</u> organisms, then the toxicity curve for the remaining 50 individuals might be as shown in the "selective" curve of Figure 11. Under this toxicity curve, exposures of 50 ppm or less have no effect, because the population receiving such exposures consists of the more tolerant individuals from the original population. The second exposure of 100 ppm would only cause 20% of these hardy organisms to die (Fig. 11), leaving 40 individuals at the end of the second exposure. Table 5 summarizes these calculations. Though consideration of selection for toxicant resistance is probably unnecessary for very short exposures, it may be important if longer term survival is to be considered as the result of a large number of such exposures as might be the case in more "closed" water bodies or multiple platform fields.

Figure 11. Selective and non-selective toxicity curves.

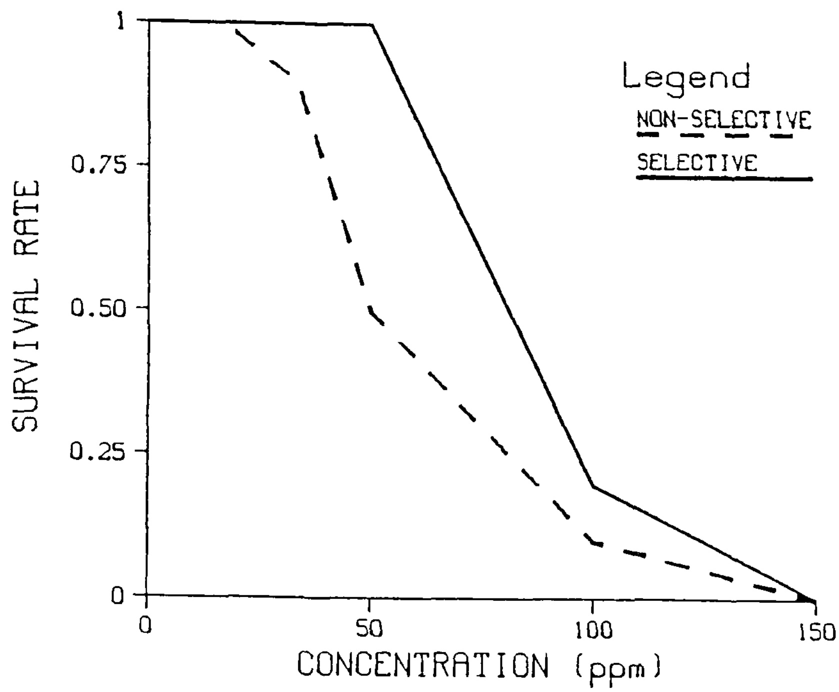


Table 5. Effects of assumptions on population variability in sensitivity and selectivity of toxicant.

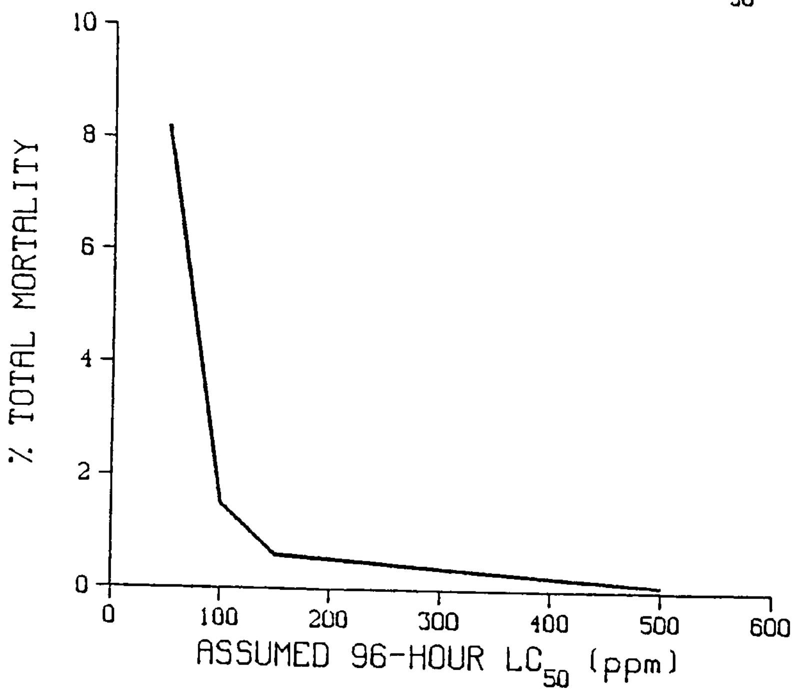
Time	Number of animals remaining	
	No selection (using Fig. 11 "Non-selective" curve in both exposures)	With selection (using Fig. 11 "Selective" curve in second exposure)
Start of 1st exposure	100	100
End of 1st exposure	50	50
End of 2nd exposure	5	40

It would be interesting to do some 2-hr toxicity tests with exponentially decreasing concentrations of drilling muds, using organisms that have previously been extensively tested at constant concentrations.

The assumption that the 96-hr LC_{50} of 50 ppm is representative of most zooplankton seems unduly conservative. Measured EC_{50} values of 50 ppm were attained for scallop larvae using relatively toxic Mobile Bay muds, but values are as high as 50,000 ppm for low density muds (Tom Gilbert, see ACKNOWLEDGEMENTS Section). Similar ranges in toxicity have been found for grass shrimp larvae and copepods. When the assumed 96-hr LC_{50} was varied in the model, the total plankton mortality under normal discharge (1000 bbl/hr, 36 min) decreased according to Figure 12. At 96-hr LC_{50} values greater than 930 ppm there was zero mortality.

The assumption that concentrations in the plume remain constant during the post-discharge phase and return to background levels after 2 hours may have led to either an overestimation or underestimation of post-discharge phase mortality. The direction of error depends upon the extent to which the real world decreases in concentrations over those two hours compensate for the fact that parts of the plume may remain above background concentrations for longer than 2 hours.

Figure 12. Sensitivity of total plankton mortality of exposed population to assumed 96-hr LC_{50}.



The estimation of water column effects depends on the assumptions used to represent plume dynamics. The behavior of the plume in relation to water column stratification (the pycocnline and more subtle stratification layers of particulates) is especially important. A relative concentration of discharged material, and perhaps of the biota (such as larval stages), in these zones might lead to greater effects than those indicated by the assumptions used here.

Notwithstanding the above uncertainities about zooplankton mortality within the upper plume, the relatively rapid return of water column concentrations to background levels suggests that the impact of a single drilling rig on benthic recruitment in the open ocean is likely to be negligible. The impact might be more serious with multiple drilling rigs, in enclosed areas, or in situations where a species is present in the water column for a very short time (e.g., as a larval stage) or in a restricted location (such as a particular stratification layer) that coincides with high concentrations of discharged materials.

SOFT BOTTOM EFFECTS SUBMODEL

Responsibilities

This submodel had a deceptively simple set of responsibilities. The first was to represent population levels, expressed as g/m^2 or $numbers/m^2$, of microbial, meiofaunal, infaunal, and epifaunal components of a hypothetical benthic community. The second responsibility was to produce an index of bioaccumulation levels and sublethal effects due to exposure to sediments containing a fraction of deposited spent mud and cuttings.

Addressing these responsibilities required considerable simplification of complex biological processes. However, subgroup members, after much agonizing, decided that the general behavior of the separate components of a generic soft bottom benthic community could be reasonably represented although such a model would be highly deficient in explicit representation of interactions between benthic components.

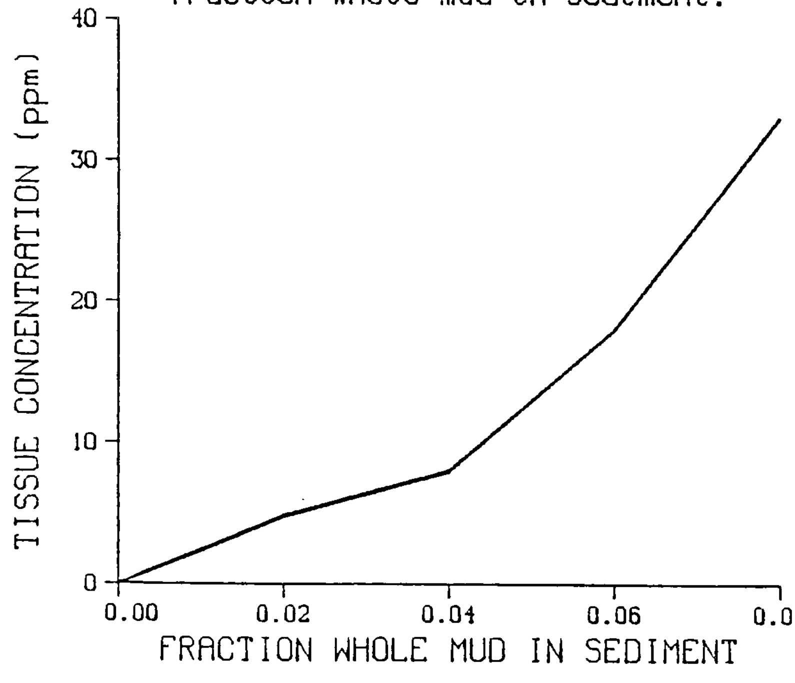
One of the consequences of construction of such a general conceptutal model was that specific examples could not always be used to define the responses of the hypothesized community. For example, recolonizaton by infauna and epifauna or redevelopment of the oxygenated zone were generalizations developed from the collective input of the subgroup participants. If another type of community had been hypothesized, it may have been equally valid to use the results of specific experiments (i.e., Boesch and Rosenberg 1981 or Cantelmo et al. 1979) to derive appropriate response behavior The main point is not how accurately the submodel portrays a particular site, but what has been learned about the information needed if a credible predictive model of soft bottom benthos is to be constructed.

Structure

The subgroup members first emphasized that the basic assumption underlying this particular submodel is that the soft bottom ecosystem represented by the model is dominated by storm events. Therefore, the resulting community is composed of "invader" species. The lack of stability in the substrate structure means short recovery/colonization times often characterized by overcompensation (increases) in the biomass of microbes and meiofauna. If a different type of benthic community (i.e., one from a stable substrate) had been modeled, the above characteristics would certainly be very different. The submodel dealt with bioaccumulation, survival, and sublethal responses of four indicator groups (expressed as g biomass/m^2 or numbers/m^2).

Bioaccumulation of chromium depended on exposure to deposited sediments expressed as fraction whole mud (Fig. 13). Tissue buildup continued until all of the drilling mud was removed by storm events. Estimates of tissue concentration of chromium (in oysters), in this case ppm above background, were derived by the subgroup members based on work by McCulloch et al. (1980). The subgroup was presented with the dilemma of how to deal with the ability of the organism to flush excess chromium from its system while accounting for exposure on a monthly time step. Oyster flushing rate was considered sufficient to reduce tissue concentrations to ambient levels in less than one month. Therefore, the subgroup concensus for the modeling approach was that if more than four drilling fluid discharges occurred in a month, the tissue concentration of chromium would be that which would be expected from exposure to the sediment input during that month (i.e., additional exposure).

Figure 13. Epifaunal tissue concentration of chromium (above background) as a function of fraction whole mud in sediment.



Mortality of soft bottom organisms was caused by burial with spent mud and cuttings (Fig. 14), by toxicity of the spent mud (Fig. 15), and by removal of deposited sediments by storms (Fig. 16). Burial survival rates were estimated using data collected by U.S. Army Corps of Engineers (CE) in the Great Lakes. Toxicity estimates due to exposure to barium concentration in the sediments were derived by Petrazzuolo (1981). When interpreting the responses of the soft bottom community it must be kept in mind that use of the Petrazzuolo (1981) toxicity responses assumes that the community represented in the submodel is not qualitatively or quantitatively different from those used by Petrazzaolo to derive the toxicity responses. Storm events only affected deposited sediments. Population changes due to storm intensity were indexed according to the amount of sediment removed by each storm. Sublethal effects were derived from Petrazzuolo (1981) and expressed as the percentage of organisms showing altered physiological indicators in response to various fractions of whole muds (Fig. 17) Although it was recognized that sublethal effects will, in part, govern such things as recovery rates and population levels, the functional relationships were unknown and therefore not incorporated into the submodel. Therefore sublethal effects stand as an unconnected indicator.

Population recovery, or colonization, was affected by the depth of deposited sediments, the fraction whole mud, and the time required for re-establishment of the layer of oxygenated sediment. In the cases of microbes and meiofauna, population response due to addition or removal of sediments resulted in considerable overshoot in the populations in the month of the disturbance (Figs. 18 and 19) before settling back to original biomass levels after 2 months. Recovery to original population levels was modified by the time required for re-establishment of the oxygenated layer. The rate at which the oxygenated layer was reformed depended on the degree of disturbance, which was estimated by the ratio of the post-disturbance population to the pre-disturbance population. Therefore, the original 3-cm oxygenated layer was re-established according to the formula:

$$\text{OXYGENATED LAYER (cm)} = M + (P_d/P_s)(K-M) \qquad (11)$$

where M = minimum depth of reoxygenated sediment (cm) regardless of degree of disturbance (set at 1.0 cm for all model runs)

P_d = population size after disturbance (note: this may be a partially recovered population)

P_s = population size before disturbance

K = maximum depth (cm) of undisturbed oxygenated layer (set at 3.0 cm for all model runs)

Figure 14. Monthly survival rate of soft bottom fauna as a function of sediment depth.

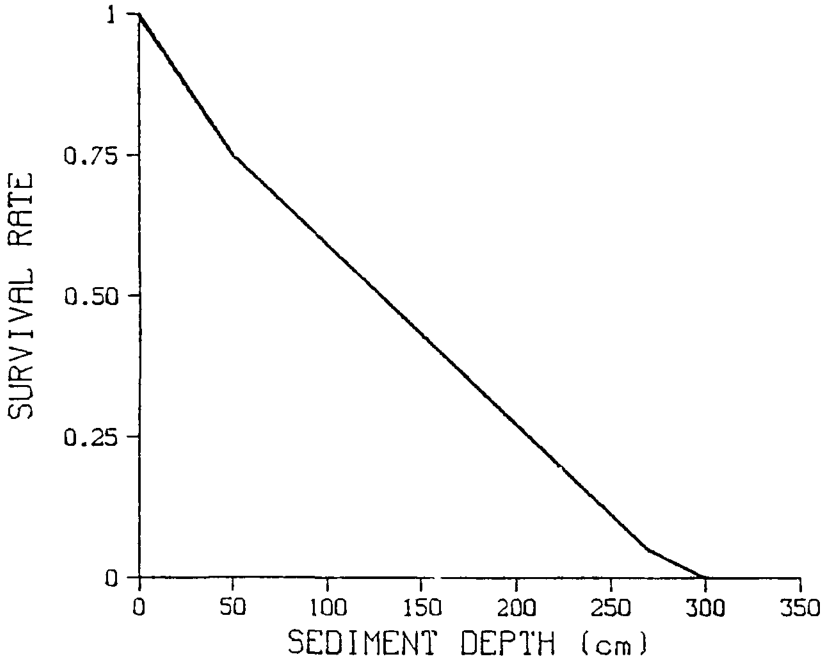


Figure 15. Monthly survival rate of infauna and epifauna as a function of the toxicity of the fraction whole mud in the sediment.

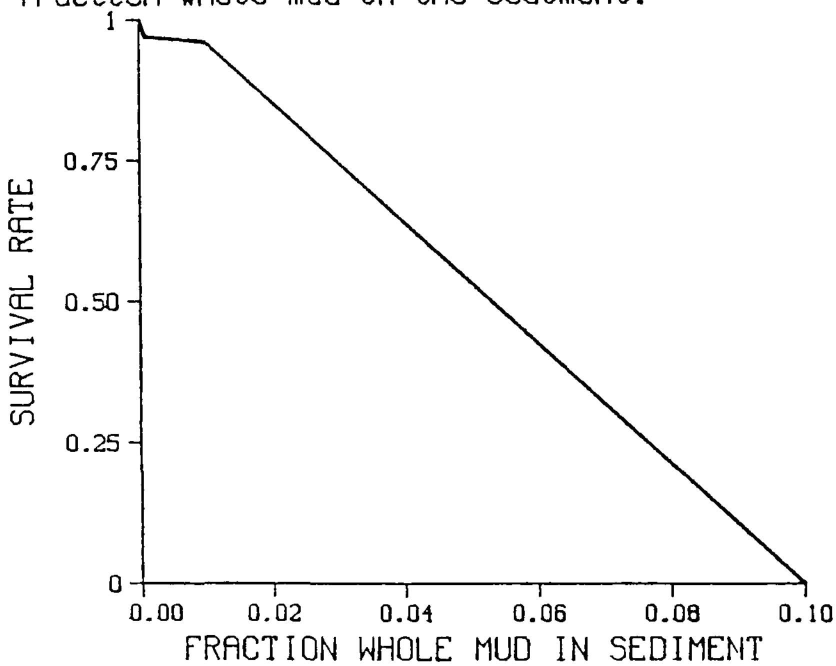


Figure 16. Monthly survival rates of soft bottom fauna as a function of sediment removal by storms.

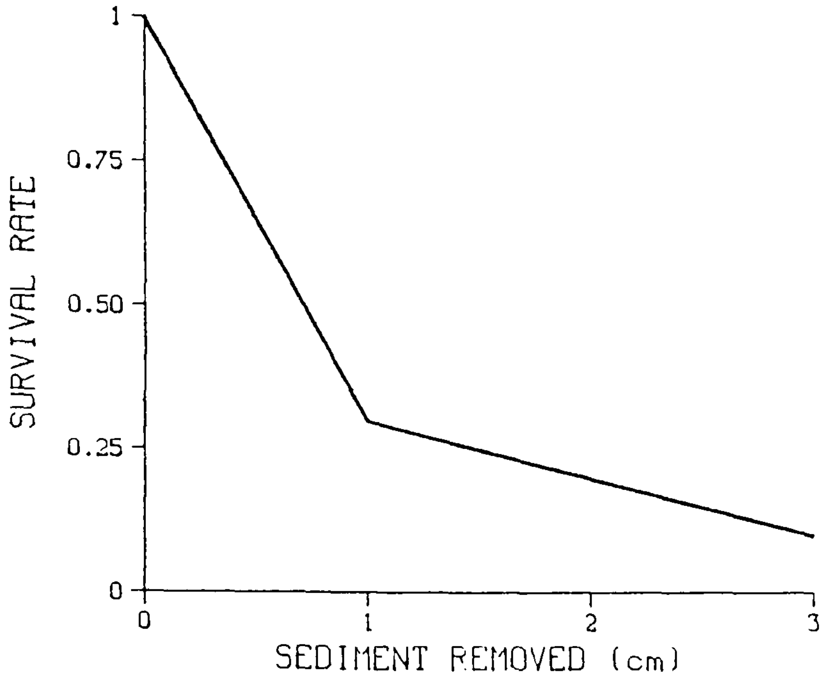


Figure 17. Fraction of soft bottom fauna exhibiting sublethal response as a function of fraction whole mud in sediment.

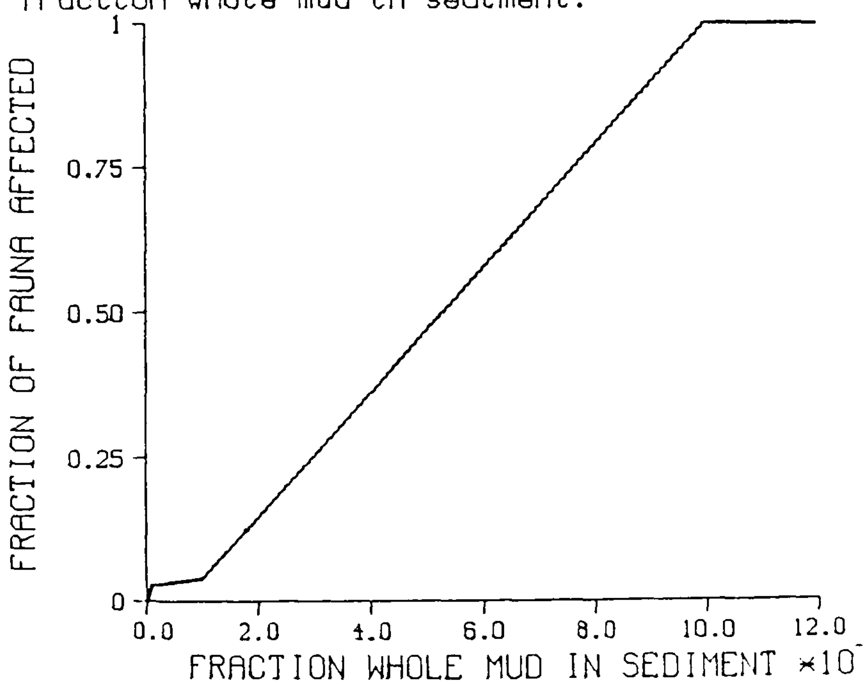


Figure 18. First month recolonization response of microbes to change in fraction whole mud.

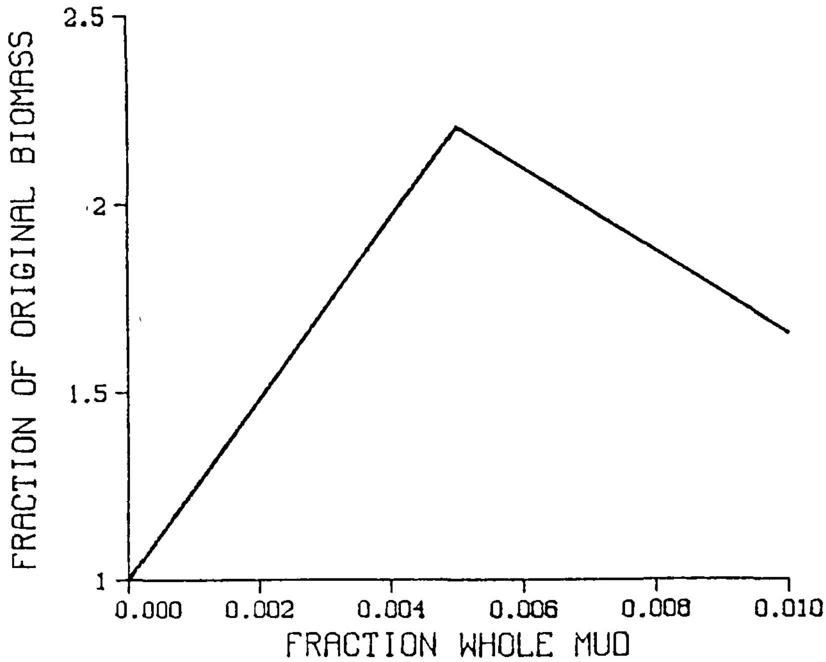
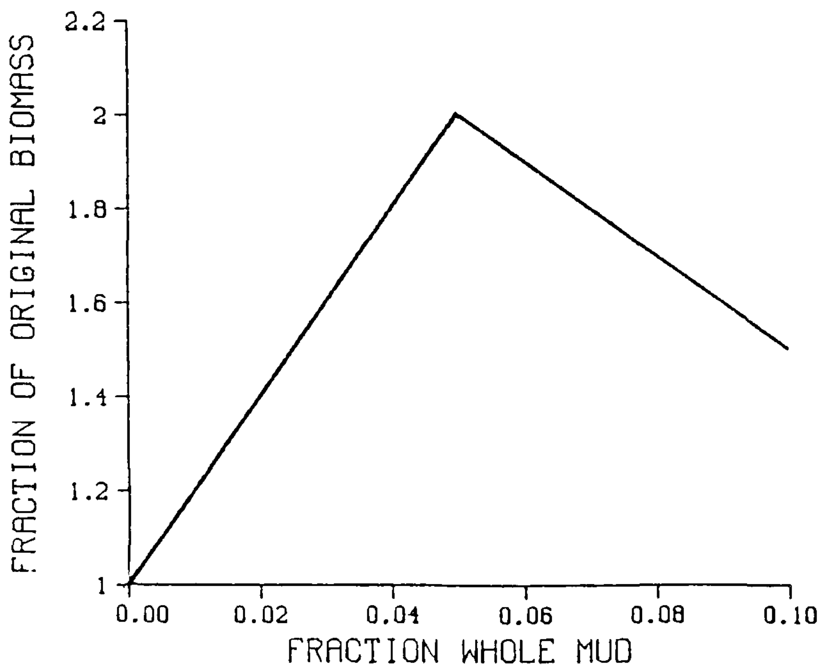


Figure 19. First month recolonization response of meiofauna to change in fraction whole mud.



The potential increment of recovery of the infaunal and epifaunal components of the macrofaunal group was decremented by residual toxicity of the sediments as represented by the fraction whole mud (Fig. 20).

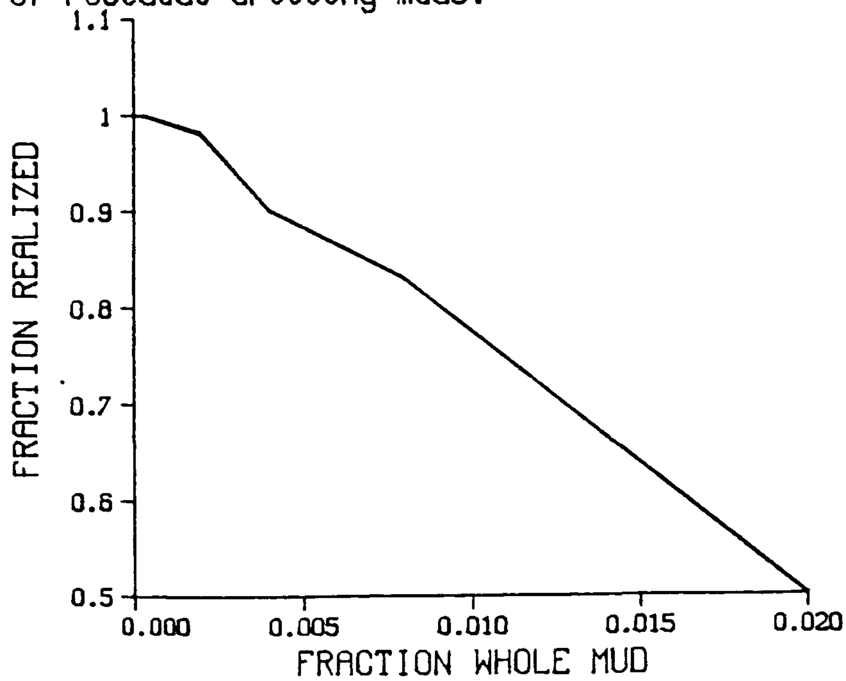
Limitations

Comments by Donald Boesch, a workshop participant, on the approaches taken in the Soft Bottom Submodel are attached as an appendix.

One major deficiency in the submodel was that there was no interdependency between the faunal groups. While such interactions obviously exist, the relative importance of their omission on the qualitative behavior of the submodel was unknown. A second major problem was the necessity for using short-term toxicity information to predict effects of longer-term chronic exposure. This probably resulted in an overestimate of survival of soft bottom organisms. Finally, there were no vertebrates included in the submodel because of a lack of information.

Use of burial survival rates based on experience in the Great Lakes probably represents extreme tolerance to burial. While this is not inconsistent with expected behavior in a storm dominated system, it indicates how model behavior would be altered by using different assumptions of community composition. There was some evidence that population recovery times may be as much as six times longer than those currently incorporated in the model

Figure 20. Fraction of first month potential recolonization increment realized due to toxicity of residual drilling muds.



(Fredette 1980; Tagatz et al. 1980; Boesch and Rosenberg 1981; Shaffner et al. 1981). Although there was insufficient time at the workshop to investigate the effects of this assumption on model behavior, examination of variation in natural community recovery rates and the factors influencing that variation is an important area of further investigation in predicting effects of drilling muds and cuttings discharges on these communities which was not fully addressed due to time constraints at the workshop.

HARD BOTTOM EFFECTS SUBMODEL

Responsibilities

The Hard Bottom Effects subgroup was responsible for representing the potential impacts of various discharge patterns of drilling muds and cuttings on the dynamics of a "typical" hard bottom community in the Gulf of Mexico. Basic information available from other subgroups included sediment depth, concentrations of various constituents in the sediments, and concentrations of drilling muds in the water column (both solid and soluble fractions). The task of the Hard Bottom Effects subgroup was to formulate mathematical expressions describing how hard bottom organisms might respond to these discharges as reflected in indicators such as biomass, growth rate, mortality rate, and recruitment.

Structure

In an attempt to simplify the task into something manageable in the time available, the subgroup made several initial assumptions.

(1) While other organisms (e.g., sponges or gorgonians) may well dominate a typical hard bottom community, corals were used as an indicator. This decision was necessitated by the lack of data on the toxicity of drilling muds to other hard bottom organisms.

(2) Corals were considered in a nonreef situation to reduce complications caused by the dynamics of a plume striking an irregularity in the ocean bottom.

(3) Coral dynamics were represented in biomass units of grams carbon per square meter (gC/m^2).

(4) Coral biomass was represented only at discrete distances (0, 50, 100, 500, and 1500 m) down current from a drilling rig.

(5) The drilling rig was located on the hard bottom community.

(6) Uncertainties were, insofar as possible, resolved in favor of a worst case assumption.

Initial subgroup discussion highlighted four major potential impacts of drilling fluids on nonreef corals: direct mortality due to sediment deposition; direct mortality due to plume toxicity; reduced growth due to plume toxicity; and reduced recruitment due to burial of appropriate substrate by sediments. Several other possible mechanisms were discussed at length and, for the purposes of the modeling exercise, ignored on the basis of having lower potential for significant effects than the four listed above. For example, there was considerable discussion concerning the possibility that light attenuation by a discharge plume passing over, but not in contact with, corals would significantly reduce photosynthetic activity. Such a mechanism was eventually discarded on the basis that plumes would simply not be present for a significant fraction of the daylight hours, and that photosynthesis recovers rapidly following periods of reduced light. Possible growth rate reductions due to temperature variations were ignored for similar reasons. In addition, larval mortality due to plume toxicity was discussed as a factor having potential for reducing recruitment of new corals. In the context of the spatial and temporal scales of the model, however, this factor was judged to be relatively insignificant for organisms (such as coral) with planktonic larval forms, since the moving water mass would likely replace the larval community in a matter of hours. The significance of this factor for organisms having nonplanktonic larval forms may deserve further attention.

Biomass dynamics of coral were thus conceptualized in the framework of the following equation:

$$C_{t+1} = C_t - S^*C_t - P^*C_t + G + R \qquad (11)$$

where C = coral biomass (gC/M^2)

S = mortality due to burial (%)

P = mortality due to toxicity of plume (%)

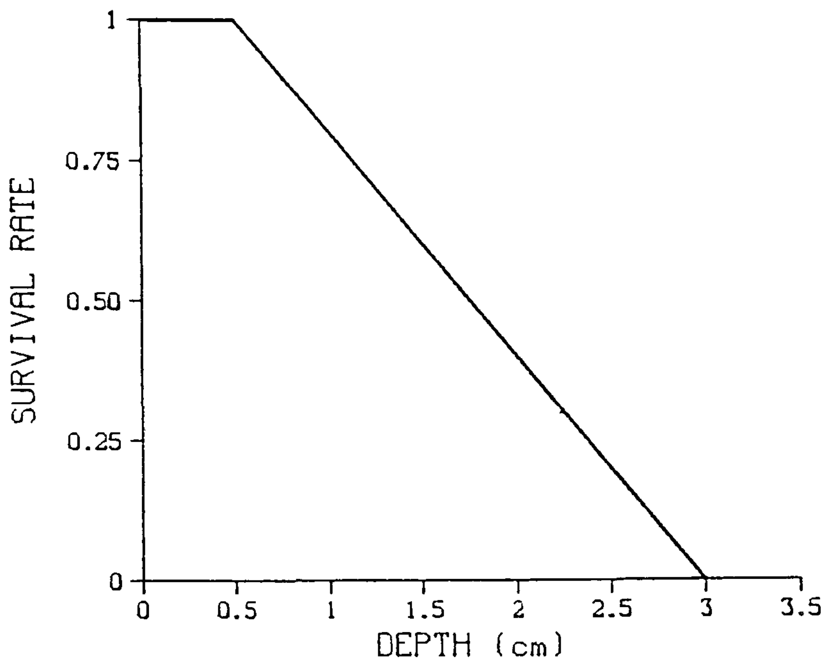
G = growth (gC/m^2)

R = recruitment (gC/m^2)

The following sections discuss model formulations for each of these factors.

Sediment deposition. Sediment depths at each of the five distances downcurrent from the simulated rig were calculated by the Discharge/Fate submodel. Corals were assumed to be uniformly covered with sediment of those depths, and resulting survival reductions were computed using the relationship shown in Figure 21. Data values for Figure 21 were extrapolated by subgroup

Figure 21. Coral monthly survival rate as a function of depth of muds and cuttings.



members from information given by Thompson (1980). Lack of information prevented consideration of other aspects of sediment deposition, such as growth rate reduction and recovery following incomplete burial, and effects of repeated intermittent burials followed by flushing or clearing.

Plume toxicity. Coral survival was further reduced due to toxicity of the plume. Maximum concentrations reached at each of the five locations downcurrent during any single discharge were generated by the Discharge/Fate submodel. These maximum concentrations were modified by a multiplier (nominally set at 0.5) designed to reduce the maxima to average concentrations to which corals might be exposed over the course of a discharge.

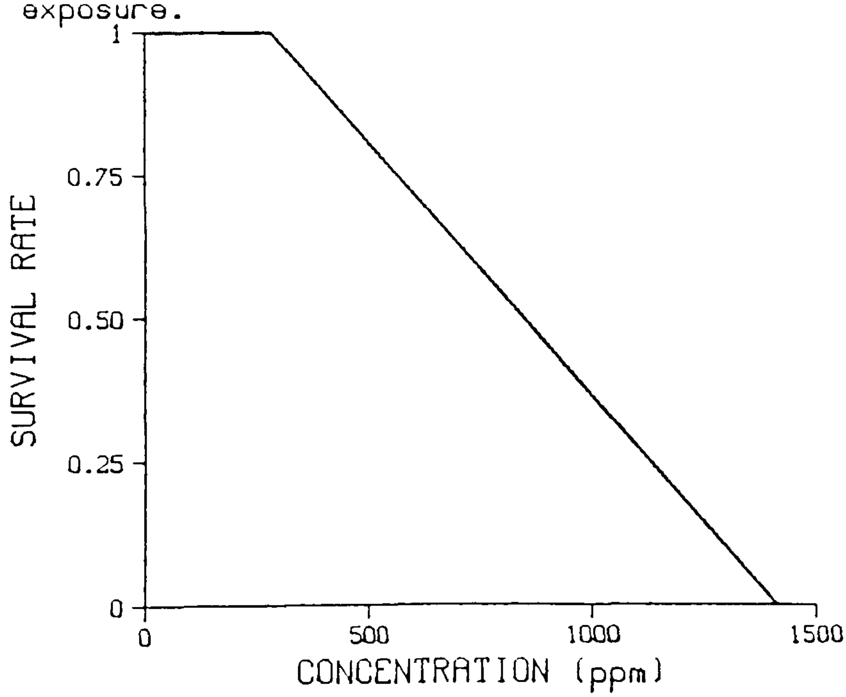
Survival rates were calculated for these average concentrations using duration of discharge, number of discharges per month (both supplied by the Discharge/Fate submodel), and unpublished toxicity data contributed by Eric Powell (see ACKNOWLEDGEMENTS section). Powell found that *Acropora cervicornis* suffered no mortality and no obvious zooxanthellae loss during a 24-hour exposure to 100 ppm whole drilling mud, and total zooxanthellae loss after a 24-hour exposure to 500 ppm. It was assumed, based on visual and biochemical data, that the corals exposed to 500 ppm drilling mud were dying and would have suffered 100% mortality. These experiments used a Mobile Bay drilling mud judged by Conxlin et al. (1980) to be more toxic than most to *Plaemonetes pugio*. An LC_{50} of 300 ppm was therefore arbitrarily assumed for purposes of the workshop model. Concentrations likely to produce 0, 50, and 100% mortality for discharges for durations other than 24 hours were calculated using equations of the following form (after Petrazzuolo 1981):

$$3\text{-hr } LC_{50} = 24\text{-hr } LC_{50} * (24/3)^{\frac{1}{2}} \qquad (15)$$

The results of these calculations for a 3-hour discharge are depicted as survival rates in Figure 22. A new curve was calculated for each simulation using the duration of discharge provided by the Discharge/Fate submodel Survival rate for a particular average concentration was then interpolated from the curve and applied repetitively for as many discharges as occurred during the month.

Growth. Growth of the coral remaining after mortality due to sediment deposition and plume effects was treated using a density-dependent potential growth rate and a proportion of the potential growth rate realized due to plume concentrations. Formulation of the growth rate as a density-dependent function prevented unlimited exponential growth of corals in the model.

Figure 22. Coral monthly survival rate as a function of solids concentration for a 3-hr exposure.



The density-dependent potential growth rate (Fig. 23) was derived in the following manner. An estimate of the biomass of the coral Montastrea annularis in gC/m^2 of tissue was obtained from unpublished data contributed by Alina Froelich (see ACKNOWLEDGEMENTS section). She found an average of about 65 µg atoms N/cm^2 of tissue. Assuming a carbon/nitrogen ratio of approximately 7, and adjusting for the molecular weight of carbon, this translates to about 54.6 gC/m^2 of tissue. An annual linear growth rate of 5 cm was assumed and, using a hemisphere as an approximation of the growth form of this coral, annual increases in surface area were computed for corals ranging from 5 to 50 cm radius (Table 6). Increases in surface area were converted to gC added annually by multiplying by 54.6, and expressed as a percentage of the biomass present at the start of the year. The resulting values, plotted as a function of biomass present, are shown in Figure 23. Monthly growth rates were obtained simply by dividing values interpolated from Figure 23 by 12.

Figure 23. Potential coral annual growth rate. Biomass in gC/m^2.

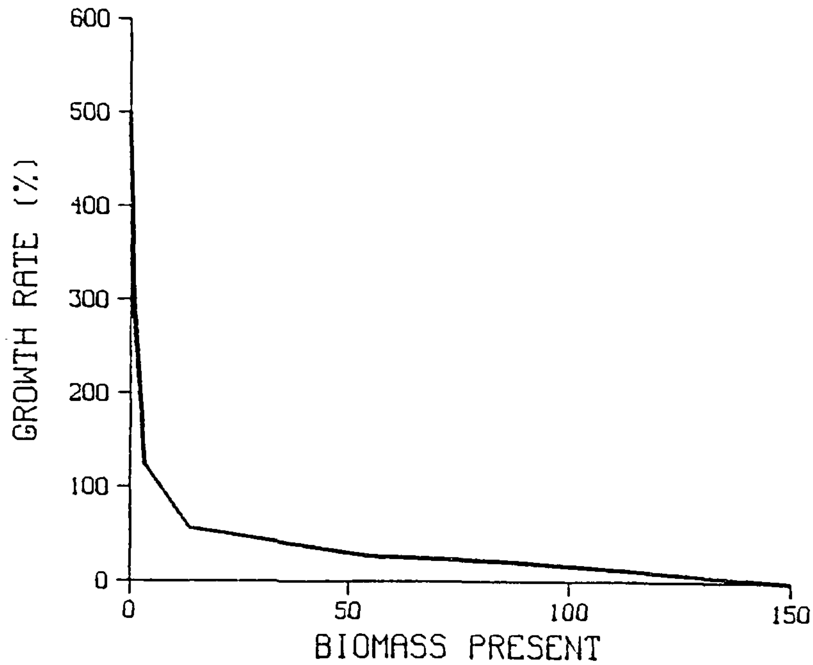


Table 6. Derivation of a density-dependent coral growth rate, assuming a hemispheric growth form.

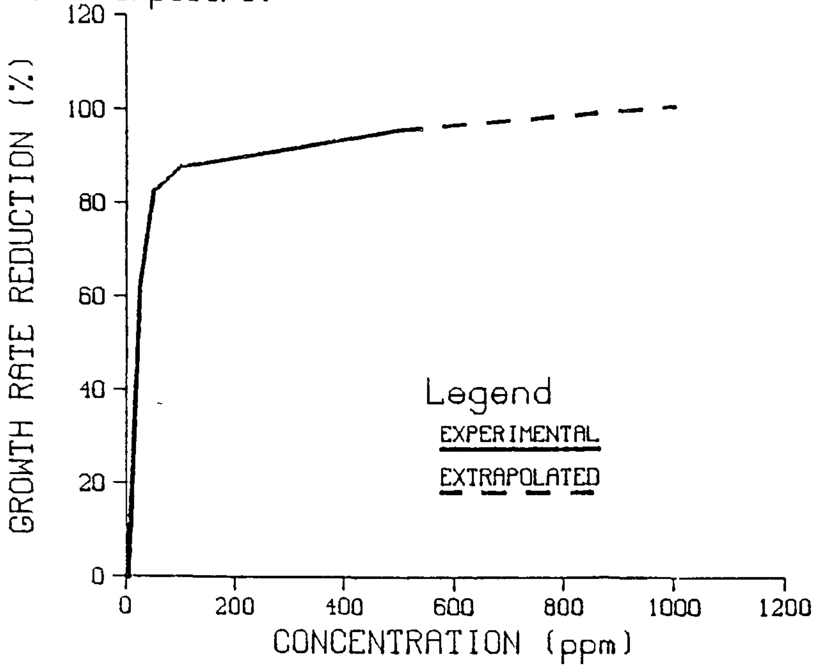
Radius of hemisphere (cm)		Surface area(m^2)[1]		Biomass(gC/m^2)			
Start of year	End of year	Start of year	End of year	Start of year	End of year	Biomass added (gC/m^2)	Growth rate (%)
0				0[2]			500[2]
5	10	0.016	0.063	0.86	3.43	2.57	300
10	15	0.063	0.141	3.43	7 72	4 29	125
20	25	0.251	0.393	13.72	21.44	7 72	56
40	45	1 005	1.272	54.87	69.45	14.58	27
50	55	1.571	1.901	85.78	103.78	18.00	21
>50				150.00[2]			0[2]

[1]Assuming annual growth of 5 cm.
[2]Arbitrarily assigned value.

Potential monthly growth rates were treated as maxima and reduced according to drilling fluids concentrations produced by the Discharge/Fate submodel. A concentration/growth response curve was derived from unpublished data contributed by Eric Powell for 24-hour exposures of *Acropora cervicornis* to various concentrations of whole drilling mud (Fig. 24). The mud and corals used were the same as those mentioned earlier in the discussion of mortality data. Growth rate reductions for exposures of durations other than 24-hour were simply calculated as proportions of the 24-hour reduction; that is, a 12-hour exposure to a given concentration resulted in half the growth rate reduction caused by a 24-hour exposure. Multiple exposures in any month resulted in continued reduction of the growth rate. Recovery of the growth rate was allowed only in months without discharge. In the first such month, recovery halfway to the maximum was allowed. A second consecutive month without discharge resulted in complete restoration of the maximum growth rate. These assumptions concerning growth rate recovery and reductions in growth rate for exposure durations less than 24 hours were arbitrary, there being little or no information of this kind available for corals.

Recruitment. Recruitment of new coral was allowed only at times and locations where: (a) no larger coral was present; and (b) sediment depth was zero. This aspect of coral biomass dynamics was included only to illustrate the potential for recovery following episodic events (such as the storms generated by the Discharge/Fate submodel) that remove sediment and expose substrate suitable for establishment of corals. Data on larval settlement rates were unavailable for this situation. Spat set was therefore arbitrarily designated as 0.05 gC/m^2 for locations meeting the conditions listed above, and reduced by the percent reduction in benthic recruitment calculated in the Water Column Effects submodel.

Figure 24. Reduction in coral growth rate as a function of solids concentration for a 24-hr exposure.



SYSTEM MODEL

STRUCTURE

For each monthly iteration, the Discharge/Fate submodel calculated upper plume characteristics and deposition of drilling muds and cuttings. The Water Column Effects submodel next calculated impacts of the upper plume on zooplankton and benthic recruitment. Information from these two submodels was then used by the Soft Bottom and Hard Bottom Effects submodels to calculate potential benthic impacts.

BEHAVIOR

In the following section we present sample output generated with the workshop model. The output is organized into four scenarios which differ in water depth and discharge rate. The baseline scenario represents a production platform in 80 m of water, sequentially drilling a total of 20 wells at 6 weeks per well, with bulk discharges of 600 bbl every 3 days at a rate of 1,000 bbl/hr, and a total discharge of 1,500 metric tons of solids per well. Each model run represents 20 years with drilling initiated halfway through the first year and ending in year 3. Results from this scenario are presented in some detail to establish baseline conditions. Discussion of subsequent scenarios focuses on those variables that show large differences from the baseline scenario.

The scenario results are presented in terms of absolute quantities (depth of added sediment, coral density). In so doing, we run the risk of inputing greater accuracy to this initial model than is justified. We present the results in this form not because we necessarily believe them to be entirely accurate, but rather in the hope of promoting constructive discussion. Models cannot be validated; like hypotheses, they can only be invalidated. Only by subjecting the model and its results to criticism can we establish the limits of its credibility. In comparing scenarios, it should therefore be remembered that qualitative changes and general trends probably have greater meaning than actual numbers. The numbers are included only as points of reference and discussion.

Scenario I

Under baseline drilling and discharge conditions, drilling muds and cuttings built up to a maximum depth of 15 cm over a circular area of radius 154 m (Fig. 25). This added sediment was completely dispersed by periodic storms 6 years after drilling stopped. The fraction whole mud in the sediment at various distances from the platform showed a similar temporal pattern (Fig. 26). At 50 m from the platform, the maximum fraction whole muds was

Figure 25. Scenario I: depth of deposited spent mud and cuttings at three distances from platform.

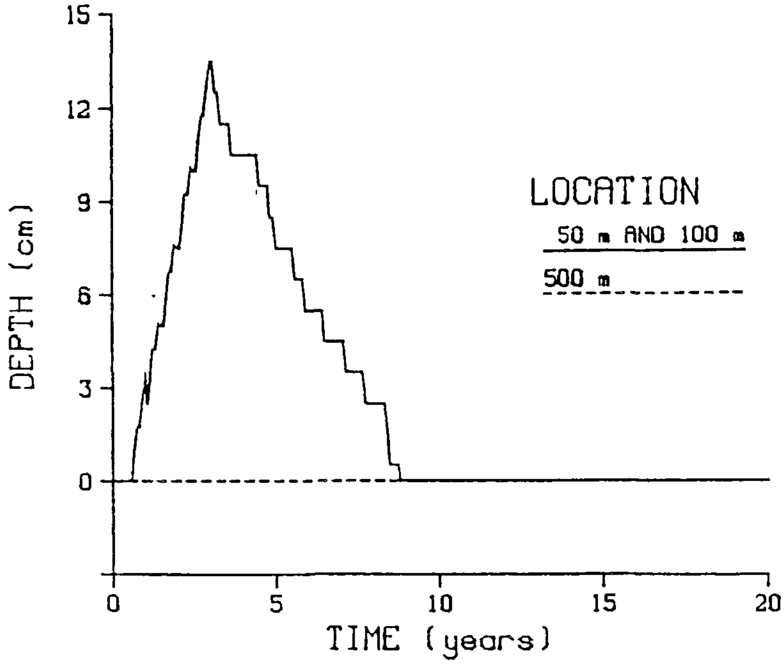
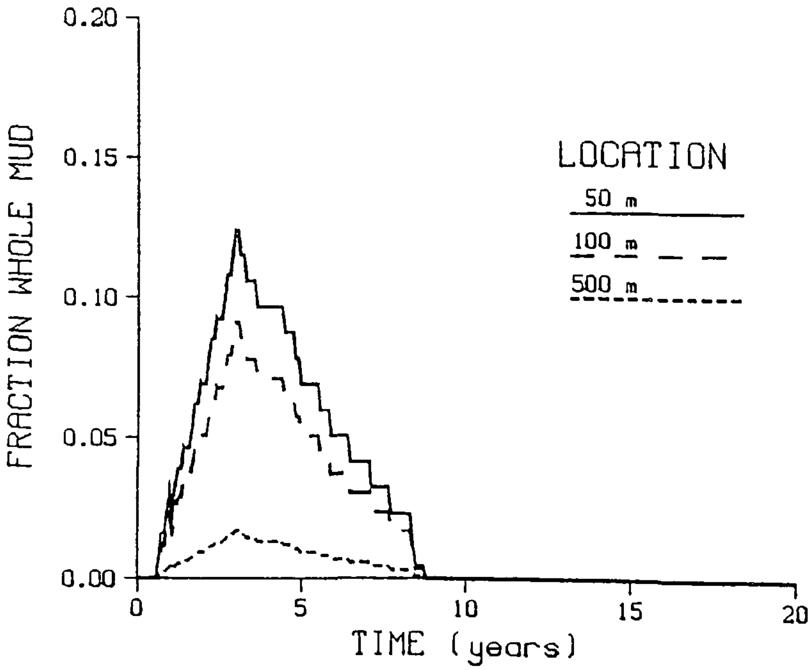


Figure 26. Scenario I: fraction whole mud at three distances from platform.



0.12, which also decreased to zero 6 years after drilling stopped. Figure 27 shows the concentration of fine-grained particulates in the upper plume at 50, 100, and 500 m from the platform.

With high rate of discharge and relatively deep water, coral is not subjected to toxic materials in the soluble fraction of the upper plume. However, all coral at 50 and 100 m was smothered by cuttings and spent mud and they had not fully recovered by the end of the 20-year model run (Fig. 28). At 50 and 100 m, microbes and meiofauna showed very little response because the stimulation to the population from deposition of new substrate was only slightly overridden by the toxicity of the deposited materials (Fig. 29). Macro-infauna showed severe reductions in their populations during the period of drilling and continued population oscillations until all of the deposited cuttings and spent muds had been removed by storm action (Fig 30). Epifaunal tissue concentrations of chromium, above background, were less than 2 ppm at 50 and 100 m, and 0 ppm at 500 m (Fig 31). Change in recruitment to the soft bottom communities was insignificant as 99.98% of the organisms survived.

Figure 27. Scenario I: concentration of fine grained particulates in the upper plume at three distances from platform.

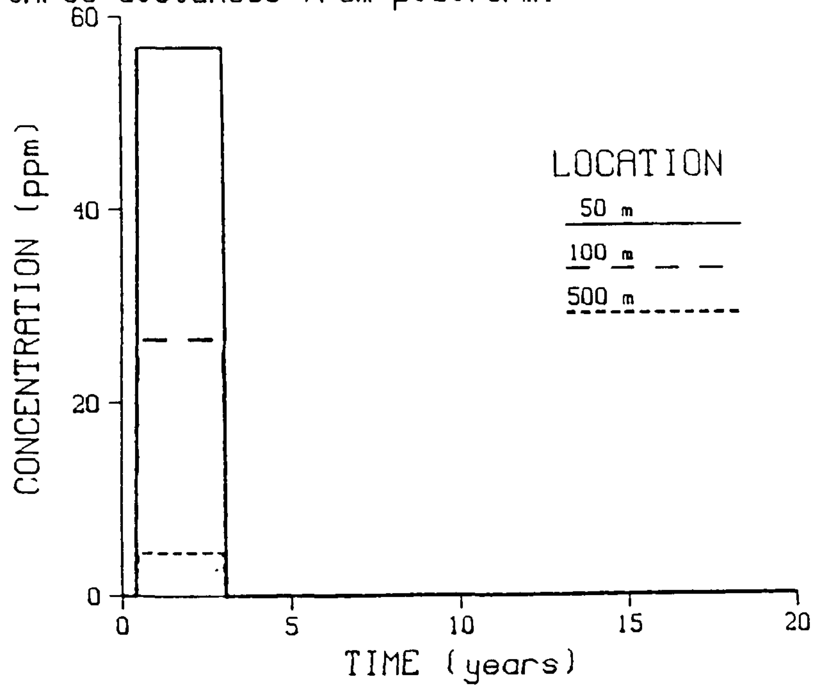


Figure 28. Scenario I: coral biomass at three distances from platform.

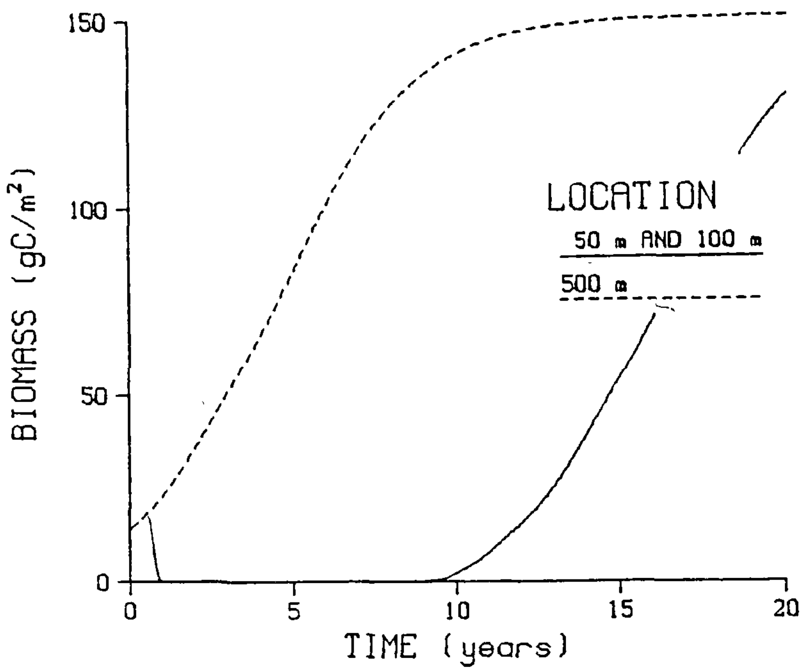


Figure 29. Scenario I: microbial biomass at two distances from platform.

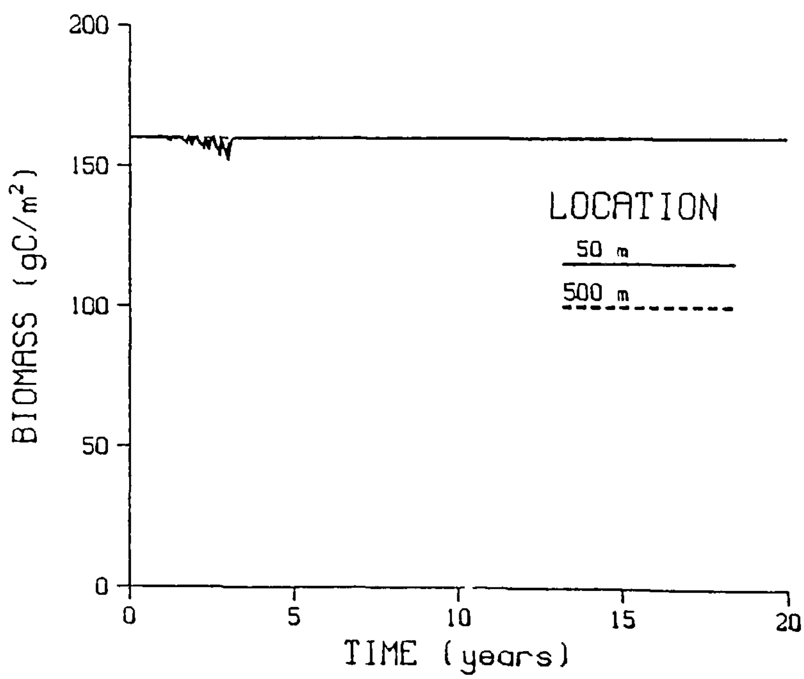


Figure 30. Scenario I: macro-infaunal biomass at two distances from platform.

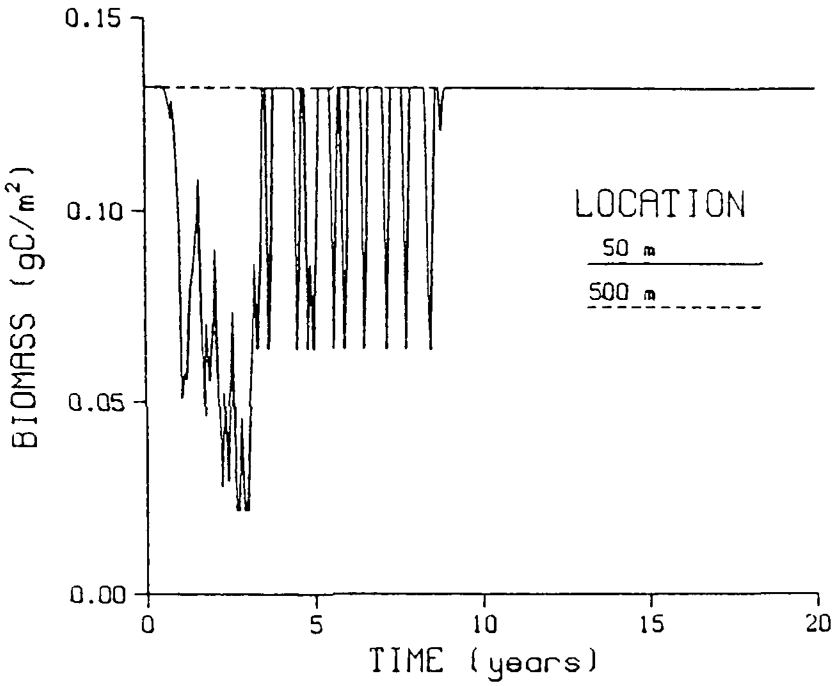
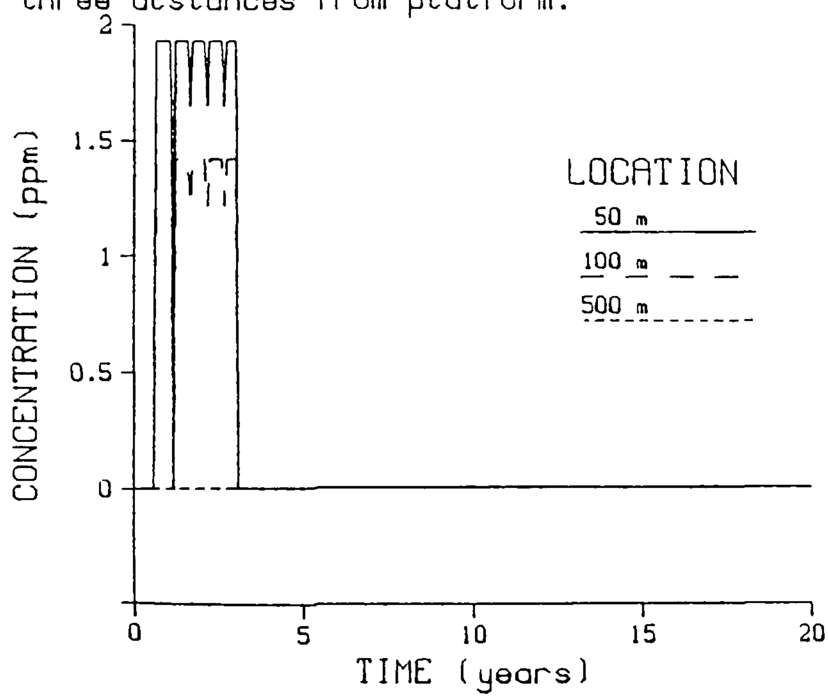


Figure 31. Scenario I: epifaunal tissue concentrations of chromium (above background) at three distances from platform.



Scenario II

In the second scenario, the rate of bulk discharge was decreased from 1,000 to 30 bbl/hr. All other drilling and discharge characteristics remained the same. Decreasing the discharge rate affected concentrations in the upper plume but had no affect on the lower plume. Therefore, added sediment and fraction whole mud were the same as the baseline scenario. The lower discharge rate resulted in concentrations of fine-grained particulates at 50, 100, and 500 m from the platform that were approximately 1/3 of baseline levels.

With the exception of survival rate in the water column (essentially 100%), the biological response was identical to that seen in Scenario I. This was due to the time step selected for the model runs. For example, despite the fact that the discharge rate was much lower, the total amount of material discharged during a month was the same.

Scenario III

The third scenario had the same discharge characteristics as the baseline, but it was assumed that drilling occurred in only 20 m of water. Upper plume characteristics were unchanged from the baseline scenario because discharge characteristics were identical. The shallower water depth resulted in greater maximum sediment build up (34 cm) over a much smaller area (33-m radius). The fraction whole muds was therefore higher than in the baseline scenario and dispersed much slower (Fig. 32).

Corals had a very different response than in the baseline scenario, Scenario I, (Fig. 33) with the dominant effect in this scenario due to the toxicity of the solids fraction of the upper plume rather than burial. Therefore, colonization can begin as soon as drilling is completed without having to wait for sediment removal from the substrate. This resulted in total recovery of the coral after about 16 years. The reduction in organisms available for recruitment to the soft and hard bottom communities was somewhat greater but still relatively insignificant (99.81% survival). There were no effects on the soft bottom community at any of the distances chosen for display because there was no sediment buildup. Note that the soft bottom submodel did not respond to the toxicity of sediments (i.e., fraction whole mud) in the absence of a change in sediment depth.

Scenario IV

Scenario 4 assumed a 20-m water depth and a 30-bbl/hr discharge rate. Upper plume characteristics were the same as Scenario II (also 30 bbl/hr) while added sediment characteristics were the same as Scenario III (also 20-m depth).

Coral response at 50 and 500 m was identical to that of Scenario III. The difference (at 100 m) between these two sets of discharge conditions is that the lower discharge rate allowed sufficient dispersion of the toxic portion of the plume so that there was no coral mortality at 100 m. The rest of the biological behavior was the same as that of Scenario III.

Figure 32. Scenario III: fraction whole mud at three distances from platform.

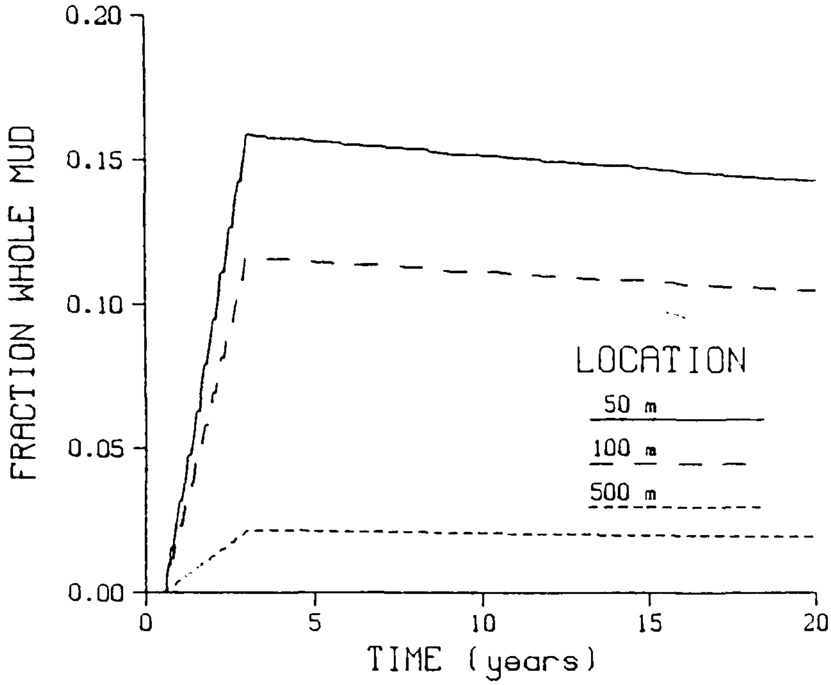
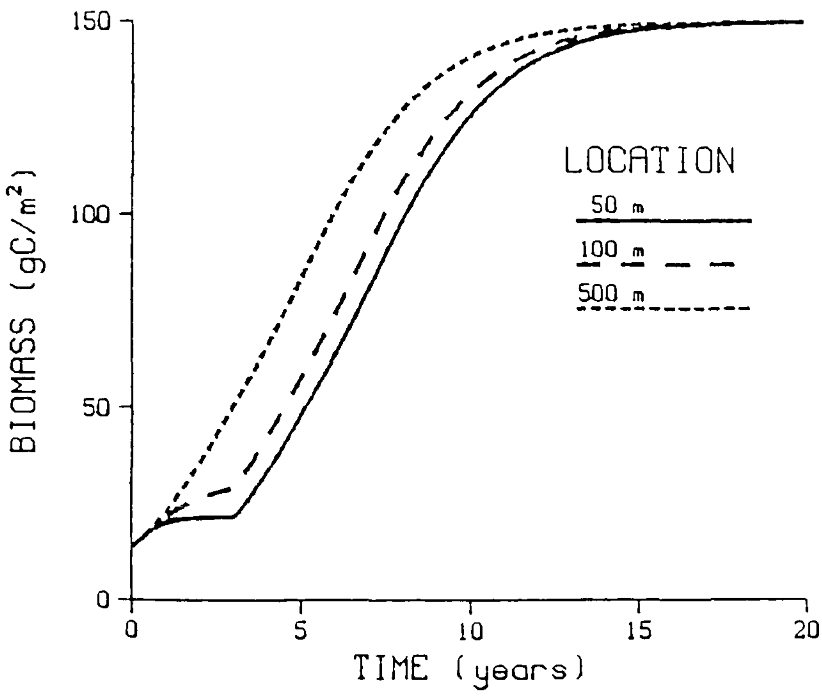


Figure 33. Scenario III: coral biomass at three distances from platform.



WORKSHOP RESULTS

COMMUNICATION

The workshop was effective in providing a forum for communication among the participants on the somewhat controversial topic of the fate and effects of discharged drilling muds and cuttings. In large part this was due to the interest, expertise, and openness of individual participants. It resulted in broadened individual perspectives of the issue, exchange of data and insight, and plans for future cooperative activity. These aspects are difficult to document for any workshop; however, they are extremely valuable to the extent that the participants represent a community that will continue to be involved with the issue of marine discharge of drilling muds and cuttings.

Construction of a simulation model focused discussion on a number of critical areas. Some of the most useful discussions concerned composition of discharged materials and linkages between the processes influencing fates and the processes determining effects. Several examples of these discussions are presented below.

One subgroup concentrated on identification of factors that might produce differences in the fate and effects of drilling muds and cuttings discharged into more "closed" bodies of water, such as bays and estuaries. Results of these discussions are highlighted in this section on communication and also formed much of the basis of a later section summarizing general factors determining fate and effects of marine drilling discharges.

Composition

Uncertainty about the composition of discharged drilling muds and cuttings has complicated analysis of their fate and effects in the marine environment. However, they are not unknown substances. The vast majority (by weight) of the material is relatively inert and only a small fraction of the many compounds available as additives are actually used at a given site. It is also possible to identify muds that are characteristic of a mud type representing the probable combination of materials that would be used in a majority of similar sites.

Discussion centered around the extent to which it was possible to define the composition of the material as it is discharged. The two initial sides to this question were:

(1) Drilling muds are closely controlled mixtures tailored to meet specific performance criteria. Materials used at a particular location can be exactly specified, and in fact are specified in the drilling log. The substrate that produces the cuttings can be defined. The composition of the material being discharged is, in principle, absolutely predictable and is, in fact, measurable with respect to elemental composition.

(2) There is much variation in materials added and the composition of cuttings at different locations and over time and depth at one location. This uncertainty is aggravated by the complexity of possible reactions among components and in the breakdown of components, variations in temperature and pressure within the "reaction vessel" (drilling apparatus and mud circulation system), and the possibility that the mixture is not at equilibrium. In combination, these factors make it practically impossible to specify the composition of material as it is discharged at the level of chemical resolution appropriate for investigation of chemical toxicity

There was some resolution of this question through the perspective of drilling muds and cuttings as a dynamic chemical system. There was then better acceptance of the levels at which this system could be specified and the levels at which uncertainty exists. It was possible to phase meaningful statements about the muds and cuttings system from a toxicity standpoint. One example was the statement that the bulk of the toxic materials seemed to settle out in a relatively unavailable form, bound to clays and fine sediments; whereas a large part of the toxicity of the discharge seemed to be associated with materials in the more available soluble phase. The actual availability and toxicity of particulate and bound materials in "relatively unavailable forms" remains uncertain, especially with respect to long-term behavior in the bottom sediments. The question of composition was resolved in the model itself by specifying a 13-bbl/gal mud with toxicological properties expressed in terms of the ppm or fraction of this whole mud present. Considerable concern remained, however, over how various environmental fractions of the discharge, such as solubles in the upper plume, corresponded to various fractions utilized in laboratory experiments.

Fate and Effects

Expected exposure levels. The modeling effort provided a logical structure for discussing expected concentrations over time at various distances from the rig. This discussion and the results of simulation runs were effective in indicating to biologists involved with toxicity testing the approximate levels of environmental concentration that might be expected in the field.

Toxicity evaluation. A considerable amount of discussion occurred among the group as a whole and within subgroups on the relationship between the results of defined toxicity tests such as a 96-hr LC_{50} and the effects of time-varying field concentrations on individuals and populations. The problem was basically how to convert results from fixed length and concentration to exposures of variable concentration over much shorter and longer times.

Suggestions included using the integral of concentration over time or a time-averaged concentration with an algorithm to account for differing lengths of exposure. The types of functional relationships utilized, in fact, differed somewhat among submodels, reflecting both uncertainty about the correct form and perhaps organismal differences in the relationship.

Short of extremely complex and expensive toxicity tests, there seemed to be no highly accurate way of connecting predictions of variable field concentrations to results of laboratory toxicity tests. Utilization of laboratory toxicity results in the workshop model was more in the mode of indicating where toxicity problems might be encountered, rather than quantitative accuracy in prediction of effects.

Worst case sediment deposition. The Discharge/Fate submodel required that some assumptions be made concerning patterns of sediment deposition. There was some uncertainty about what constituted a "worst case" assumption about the pattern of sediment deposition from the platform. A given quantity of mud solids and cuttings deposited in a deep layer over a small area would kill a high proportion of the benthic organisms in that area, whereas a shallow layer over a larger area would kill a smaller proportion of the benthic organisms in a larger area. The "worst case" pattern or maximum number of benthic organisms killed thus depends on organisms' responses to sediment depostion. This response most likely has a strong threshold component with organisms able to survive a certain depth of burial depending on the natural sedimentation regime to which they are adapted. The workshop did not resolve a clear "worst case" pattern and, in fact, the "worst case" is likely to be species-specific, since it is critically dependent on organisms' ability to tolerate burial.

Shunting. Shunting, or discharging at some greater depth than the surface (e.g., below the pycnocline), is considered as a management action to produce the following results:

(a) reduce the visible plume;

(b) entrap discharge in nephloid layer minimizing impacts above discharge depth;

(c) avoid a potential buildup of material as the discharge encounters a diffusion barrier at the pycnocline; and

(d) minimize the area of deposition for material settling out (i.e., mud solids and cuttings).

There were questions raised about some of the benefits of shunting, despite its value in routing the plume away from features that rise above the bottom. As noted above, it was not clear that minimizing the area of sediment deposition minimized the total impact on benthic organisms. There was also uncertainty about the behavior and importance of the plume encountering the pycnocline. It is also possible that shunted soluble material might rise above the depth of discharge, possibly encountering the pycnocline, as the upper plume moved to a level of neutral bouyancy.

"Closed" water bodies. Fate and effects of discharged drilling muds and cuttings in closed water bodies such as bays and estuaries was felt to be considerably different and more complex than that in more "open" water environments such as those treated in the simulation model Many of the critical variables producing these differences have been incorporated in the following section (Factors Determining Fate and Effects). Conceptual models of fate and effects in these areas would contain components similar to those utilized in the open water simulation model with several modifications.

(1) Additional communities, such as aquatic macrophytes and oyster beds, would have to be treated.

(2) The importance of "closed" water bodies as food production and rearing areas would necessitate more detailed incorporation of population-level processes and trophic interactions.

(3) Many of the processes represented in the open water simulation model, such as plume dynamics, sediment deposition, and sediment redistribution, would require fundamentally different mathematical treatment due to shallower water and more complex circulation and stratification patterns.

(4) The importance of resuspension in shallower water and slower long-term dispersion would necessitate more detailed consideration of long-term effects of slightly elevated concentrations.

In addition to these considerations complicating the extension of open water analyses to closed water environments, participants felt that a general analysis or model was less appropriate for closed water environments because of the large amount of variability among these areas in factors strongly influencing fate and effects (such as circulation and salinity patterns, community composition, and natural sedimentation regimes).

Much of the possible difference in behavior centers around the extent to which these areas are "closed" or the relative residence time or amount of net exchange in water and sediment between these areas and surrounding areas. This is a critical factor in determining long term dispersion of discharged material. It was suggested that indices expresssing residence or turnover time of water and material in the surficial sediments might be useful in evaluating differences in fate and effects in "closed" areas, and that such indices might be calculated from information on freshwater inputs, circulation pattern, volume of the basin, and natural sediment loadings.

Although enclosed areas were considered more complex and variable than those treated in the model, a large base of knowledge and understanding does exist for many well-studied bays and estuaries. Information and models developed by the U.S. Army Corps of Engineers with respect to fate and effects of dredge spoil disposal were identified as being particularly relevant to discharge of drilling muds and cuttings.

INFORMATION INTEGRATION

A simulation model is a structure for representing the net result of a series of statements about how the system operates. A number of assumptions are often necessary to integrate more well-established individual relationships and linkages. Some set of assumptions (often unstated and relatively crude) is used in any integrated statement or management criteria on the fate and effects of drilling muds and cuttings into the marine environment. The value of a simulation model is that it forces an explicit statement of what assumptions are being used.

The simulation model developed at the workshop for open water environments in the Gulf of Mexico indicated relatively localized effects of drilling muds and cuttings discharge (see SYSTEM MODEL section). Water column fate and effects were dominated by relatively rapid dilution. Deposition of spent mud solids and cuttings was localized spatially with relatively rapid recovery especially in soft bottom benthic communities.

This is the behavior generated by the set of assumptions about linkages and functional relationships used to construct the model. There are two general ways in which such a model can be inadequate. The first is that linkages and processes included in the model may have been poorly represented. Areas of uncertainty in the workshop model included the relationship between time-varying exposures and 96-hr LC_{50} results, recovery rates of benthic communities, and responses of organisms to various depths and rates of burial.

The second area is that important aspects of the system may not have been included in the model. Many potential linkages and processes are excluded from a simulation model because they are judged to be of secondary importance, such as the effect of light attenuation from the plume passing over corals on annual coral growth. Others are excluded because they are unknown or not currently tractable within the modeling constraints. They could very well be critical in the behavior of the real world system. Some of the interactions and processes not incoporated in the model included density stratification and possible dispersion barriers it might create, long-term effects of slightly elevated concentrations, potential food chain transfers, and the interactions that might occur among discharges from multiple platforms. Some of these limitations could be partially addressed through model refinements. Some, however, reflect lack of current understanding rather than lack of ability to integrate existing information.

INFORMATION GAPS

A number of information gaps were identified at the workshop in the process of constructing the simulation model and in discussing factors determining fate and effects in enclosed areas. These represent areas of uncertainty where additional information would be desirable. This does not necessarily mean that no work has been done in these areas. It may merely indicate that participants were not fully aware of the relevance of completed work or that additional analysis needs to be undertaken to interpret that work more fully in terms of its relevance to fate and effects of discharged drilling muds and cuttings.

These information gaps are detailed throughout the report in the descriptions of the simulation model and discussions of enclosed areas, such as bays and estuaries. The following list is a summary of the more important of these areas of uncertainty identified at the workshop:

(1) The extension of 96-hr LC_{50} results (or any fixed-concentration, fixed-interval toxicity test) to other exposure times at other, perhaps time-varying, concentrations was a central problem in estimating effects on field populations from predictions of environmental fate. The relatively simple algorithms utilized for this extension involve considerable extrapolation and interpolation from observed cases.

(2) The relationship between variation in composition of discharged drilling fluids and cuttings (variation in additives, different sites, and across time and depth at one site) and variation in toxicity does not seem to be well-established. Current research (Thomas Duke, ACKNOWLEDGEMENTS section) is addressing this question through a series of standardized tests on a large set of drilling fluid samples.

(3) There seems to have been little explicit consideration of indirect or community-level effects (such as accumulation of materials through food chains, indirect effects on a secondary species through direct effects on a competing, predator, or food-source species). Detailed prediction of effects at this level may, in fact, be beyond the state of the art with respect to analysis methods and knowledge of the relevant marine systems. It may be possible, however, to strengthen the value of toxicity tests on individual species and life history stages by more consideration of the position and importance of these species in the communities of which they are a part. One example in terms of life history stages is the possible importance of effects on benthic larval stages of benthic organisms

on these populations, which may be more severe than the generally very small effects on recruitment due to effects on planktonic larval stages.

(4) Variations in the rate of recovery of disturbed benthic communities, sensitivity of these communities and their recovery rates to altered particle size distributions, and sensitivity to depth and rate of burial are all areas where additional quantitative information was needed in model construction. These areas are amenable to experimental investigation and it may be possible to make considerable progress through synthesis of existing information. Recovery rates for corals after exposure to drilling fluids are now being investigated (Eric Powell, ACKNOWLEDGEMENTS section).

(5) Little information was available on long-term effects of slightly elevated concentrations and sub-lethal effects (such as growth rate depression) in general.

(6) Information on hard bottom community effects seemed to be concentrated on several species of coral. A broader set of species and hopefully community-level indicators would be especially desirable for these areas.

(7) There was considerable uncertainty about behavior of the plume at water stratification layers and possible effects of a potential higher concentration of discharged materials in areas where organisms might also tend to be concentrated.

(8) The interaction among discharges from multiple platforms is not explicitly treated by current plume models, including the workshop simulation model This interaction, if important, would require a much more complex mathematical treatment to address integrated or cumulative effects in densely utilized lease area.

(9) A resolution of the relative advantages of shunting at different depths would be very useful from a management perspective. Questions were raised at the workshop about the benefits of some of these alternatives. Clear resolution will depend on better understanding of the movement of the upper plume from various density points (including efficiency of entrapment in nephloid layer) and as it encounters the pycnocline, effects at the pycnocline, and the optimum pattern of sediment deposition. The optimum patter of deposition may be dependent on avoiding impacts on features rising above the surface, such as coral reefs, as well as minimizing impacts on benthic communities.

(10) Finally, there seemed to be a major need to synthesize information concerning fate and effects to be expected in enclosed areas. A number of factors limit the applicability of open water results to these areas. The potential sensitivity of these areas argues for more detailed consideration of fate and effects. Several factors were identified that could support such an effort. A number of bays

and estuaries have been extensively studied. Many of the toxicity tests have, in fact, been conducted on estuarine organisms. In addition, models and a relatively large body of data are available on the fate and effects of dredge spoil in enclosed water bodies which should have considerable relevance to fate and effects of drilling discharges.

FACTORS DETERMINING FATE AND EFFECTS

Discharge of drilling muds and cuttings into a marine ecosystem is a perturbation of that system. A number of factors interact to determine the fate and effects of any particular drilling mud and cuttings discharge, and thus need to be considered as a whole in a scientific evaluation of the system's response to the perturbation and in management decisions concerning an acceptable level of perturbation.

The workshop addressed identification of these variables and their interactions through two complementary activities. The first approach was construction of a simulation model of the fate and effects of drilling muds and cuttings discharged into several types of open water environments in the Gulf of Mexico. This activity identified a set of important variables and their interactions for each environment. Discussions were also held to identify features of "closed" water environments, such as bays and estuaries, which would need to be considered in evaluating fate and effects in these areas.

The factors identified at the workshop are discussed below in terms of three broad categories; discharge characteristics, physical/chemical characteristics, and biota. The list represents a guideline of variables that need to be considered in evaluating and/or regulating the discharge of drilling muds and cuttings at any particular site. The list is an attempt to synthesize discussions of the workshop participants as to what should be considered. It is not intended to substitute for detailed synthesis of the scientific literature as it relates to these variables, nor does it imply that all variables need to be given equally detailed consideration in all management decisions concerning discharge of drilling muds and cuttings.

Discharge

Composition. The drilling muds and cuttings discharge is itself a complex and dynamic chemical system varying across different drilling locations and over time and drilling depth at a particular location. Mud components are adjusted to meet local conditions as they occur. Composition can be defined in terms of materials added and in terms of elements and major compounds for the actual discharged mixture. Precise composition and activity of discharged material (in terms of the exact chemical compounds and chemical associations resulting from breakdown of added components, reactions occurring in the well at elevated temperatures and pressures, and complexing and sorption processes) are more elusive.

Aspects of drilling muds and cuttings composition that most directly determine differences in fate and effects following discharge into the marine environment are density, particle size distribution, and toxicity. Density and particle size distribution are important determinants of the transport of various fractions of the discharge. Particle size distribution of deposited material in relation to the particle size distribution of existing sediments can influence the recovery time and composition of benthic communities.

Generalization about the toxicity of drilling muds and cuttings discharges is difficult due to their variability and complexity. Approaches have included toxicity measurements, such as the 96-hr LC_{50}, utilizing "typical" whole mud samples or fractions of such samples, as well as toxicity measurements of individual additives, such as biocides. Although a large proportion of the material (by weight) is relatively inert, little progress has been made in multivariate approaches for isolating the compositional determinants of variations in toxicity. A series of reasonable "worst case" extrapolations from defined toxicity measurements appears to be the only currently feasible approach.

In addition to the relatively short-term, high-concentration toxicity associated with the immediate discharge plume, possible long-term effects of slightly elevated concentrations of stable constituents, such as heavy metals, were raised as a point of concern at the workshop. These potential effects were not incorporated into the simulation model primarily due to lack of quantitative information. It was pointed out that they might be expected to be more important in a "closed" water body such as a bay where long-term dispersion of discharged material would be less rapid.

Delivery. The rate and amount of discharge are principle parameters determining the extent and dynamics of the discharge plume. Predilution of the discharge was discussed as a management action that would ameliorate toxic effects, especially in the immediate vicinity of the discharge point, by reducing concentrations.

Location and configuration of the discharge port or ports is also an important factor in determining discharge plume behavior. Discharge from a series of ports could reduce maximum concentrations by distributing the discharge over a wider area. The location of the discharge port in the water column in relation to the total depth and stratification layers in the water column can strongly affect the resulting discharge plume. Shunting, by locating the discharge port below a stratification layer, has been proposed to avoid impacts to features above the discharge depth (e.g., coral reefs, pychnocline) by entrapping the discharge in a deeper layer. Shunting should also tend to localize the area of cuttings and mud solids deposition and minimize aesthetic impact by reducing the visible plume.

Location of the discharge port close to the bottom sediments, as would be unavoidable in a shallow-water environment, produces a fundamentally different plume behavior. Unless overt action is taken to redirect the discharge, plume dynamics in these situations involve a "rebound" component as the discharge hits the bottom and require basically different mathematical treatments than those utilized to represent the dynamics in deeper water situations.

Physical/Chemical Environment

Salinity and temperature regimes. Salinity and temperature are important factors for several reasons. Stratification of the water column affects plume dynamics and resuspension from bottom sediments, which can be especially important in shallow water areas. Salinity can significantly influence flocculation of drilling fluids and solids with resulting effects on the proportions of various components that remain suspended in the upper plume. In addition, temperature and salinity are important determinants of the biota and its sensitivity, especially in areas such as near-shore environments where there are strong temperature and salinity gradients.

Depth. Water column depth and its relation to depth of the discharge port is a parameter of the representation of plume behavior used in the workshop simulation model for open water environments. Discussion of how more "closed" water environments might differ suggested that some qualitatively different types of behavior would be expected in the shallower water columns generally associated with such environments. Depth would be a very important varaible in such systems through its influence on circulation within the system, expected short-term dilution of the discharge, stratification of the water column, and resuspension from sediments.

Water movement. Current velocity and direction are two of the primary parameters governing short-term dilution and direction of discharge. Long-term dispersion of the dissolved or suspended fraction and movement of deposited sediments are also critically dependent on the intensity and pattern of water movement. Turnover time or exchange rate for water in "closed" water bodies was identified as an important factor distinguishing these environments. Long-term dispersion of discharged materials would be reduced to the extent that these bodies of water were "closed" Effects of wind and wave action on resuspension of deposited material would also be expected to be higher in these generally shallower areas.

Sedimentation regime. The nominal or natural sedimentation regime is another site-specific factor determining the effects of sediments introduced by drilling solids discharge. Higher natural sedimentation rates result in a relatively lower level of perturbation from additional sediment. Differences in particle size distribution between drilling mud solids and cuttings and naturally occurring sediments could increase the perturbation since particle size distribution is an important determinant of benthic community composition. Benthic communities might thus recolonize at a different rate and recover to an altered state that could be maintained for as long as particle size distributions remained different.

Frequency and severity of storms play a major role in redistributing sediments. The long-term fate of sediments added to a particular area would be influenced by these events much as natural sediments are. Drilling mud solids and cuttings might thus be expected to accumulate in certain areas as a result of bottom topography, water movement patterns and velocities, and storm events. To the extent that these factors influence the movement of natural sediments in the same manner, there is reason to expect that this will result in a net dilution of drilling materials with natural sediments in comparison to the initial area of deposition.

Biota

Composition and sensitivity of the biota in a particular area determine, in large part, effects of a given drilling fluids and solids discharge into that area. Laboratory toxicity tests such as 96-hr LC_{50} experiments can provide indicators of sensitivity, especially with respect to short-term effects in the immediate discharge area. As discussed earlier, direct connection of this information to population level effects from various discharge scenarios is complicated by temporal variation in actual field concentrations. In addition to toxicity, sensitivity to burial mortality, growth reduction due to sediment deposition, and recolonization rates of benthic communities are important factors in assessing effects of a given discharge.

Discussions at the workshop indicated several areas of special concern where significant, and possibly larger than expected, effects might occur. These included oyster bed, coral reef, and submergent or emergent aquatic macrophyte communities. Concern was also expressed about possible effects on endangered species and critical life history stages. If sensitive species or life stages of species concentrate in portions of the environment, such as the pycnocline, where discharged material also tends to concentrate, it might lead to greater effects than would be predicted based on assumptions of more even exposure.

Little information was available at the workshop that quantitatively addressed the potential long-term effects of relatively low environmental concentrations that might result from drilling mud and cuttings discharge. The possibility of indirect effects through trophic interactions was identified in cases of a depression of primary production affecting higher trophic levels, potential for bioaccumulation and transport of toxic materials by rooted aquatic macrophytes, and possible transfer of introduced materials such as heavy metals through a food web with resulting increase in effective dose for certain species over what would be estimated based on general environmental concentrations. It is unlikely that effects in these areas will ever be completely predictable in the general case, due to the variety and complexity of drilling mud and cuttings discharges and of the marine environments into which they might be discharged. They thus represent a responsibility for continued attention and monitoring especially in conjunction with discharge operations in those areas in close proximity to sensitive and "important" biological communities.

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APPENDIX

Workshop participants raised a number of important and valid points in their comments on this workshop report. These points included concern over the extrapolation of fixed-length, fixed-exposure toxicity tests to field conditions; observations that shunting has been successful in routing plumes away from coral reefs; identification of the importance of considering fate and effects in "closed" water bodies; and concern over consideration of discharged material at density stratification layers where sensitive organisms might also concentrate. In addition, Donald Boesch provided a detailed critique of the Soft Bottom Effects Submodel. Although the submodels developed in a 1-week workshop are often of limited value in themselves, the structured modeling approach does provide a well-focused framework for discussing the relevant mechanisms and relationships. In this spirit, Dr. Boesch's comments are included here as an appendix to the report.

COMMENTS ON THE SOFT BOTTOM EFFECTS SUBMODEL

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Comparison of the Water Column Effects Submodel and the Soft Bottom Effects Submodel illustrates the strengths and weaknesses of the adaptive environmental assessment approach. The physics of dispersion of contaminants in the water column is better known than that of deposited particulate material. Bioassay procedures, although not without limitations, more reasonably simulate the conditions of exposure of pelagic organisms to contaminants than those experienced by benthic organisms exposed to a complex sediment medium. Consequently, the water column fate and effects submodels are more richly supplied with observations which allow for development of models with variable parameters. This permits the heuristic use of sensitivity analysis, thus identifying which factors might realistically influence the effects predicted and which processes deserve further research.

The contributors to the Soft Bottom Effects Submodel were evidently deterred because a lack of data or sound conceptual framework in which to consider variable conditions and used a rather narrow set of assumptions, most of which are relatively liberal, in the sense of diminishing the extent of expected effects. This is unfortunate because the majority of drilling fluid solids are deposited on the seabed rather rapidly, the benthic organisms are exposed to them for longer periods of time relative to pelagic organisms, and it is only with the soft bottom benthos that effects of drilling fluid discharge have been detected in nature.

The Lower Plume Submodel is based on unrealistic assumptions concerning the settling of particles as individuals, whereas actual observations indicate a negatively bouyant jet with horizontal spreading near the seabed. Also resuspensive or bed load spreading are not dealt with except as a source of dilution. The spurious nature of this model is illustrated by the prediction of confinement of particle accretion to extremely small radii (as little as 3.4 m in 20 m of water with a 1 m/min current; Table 4) and the counter-intuitive prediction that deposited muds are dispersed much more slowly in waters 20 m deep than in waters 80 m deep.

The assumptions of the Soft Bottom Effect Submodel regarding the life history characteristics ("invader" species) of constituent organisms and their resistence to burial restrict the potential relevance of this model to, at best, a few extreme environments. Continental shelf benthic communities, particularly those on the outer shelf, include many "equilibrium" species which have long generation times and are slow to recruit. Also, the assumption of 50% survival following burial by more than a meter of sediment is probably in error by an order of magnitude or two for continental margin macrobenthos, although relevant data do not exist. In environments characterized by a low rate of sediment flux (resuspension plus net deposition), such as the continental slope, tolerance to burial is probably very low.

Additional problems relate to the use of Petrazzuolo's (1981) model for predicting toxicity effects on soft bottom benthos. Petrazzuolo used two approaches: Type I Analysis based on published LC_{50} values with an application factor of 0.01, and Type II Analysis based on the relationship of sediment barium concentration to community development in laboratory experiments conducted on the Florida Gulf coast. It is unclear which of Petrazzuolo's analyses were applied, although there are serious limitations to the application of either First, the LC_{50} data represent aqueous concentrations in the sediment medium in which the benthos lives. Petrazzuolo's analysis is based on a tenuous inference that "benthic impacts of drilling fluids were thought likely to correspond to dispersions of these fluids in the water column." In fact, both field data and the upper plume and lower plume submodels contradict this assumption. Petrazzuolo's Type II Analysis is based exclusively on a series of experiments conducted at Gulf Breeze assessing the effects of drilling fluids and barite on community development in aquaria through which sea water was pumped. Benthic colonists of laboratory aquaria represent species predisposed for rapid recruitment rather than natural communities.

As in the case of tolerance to burial, the mortality induced by storms is also likely to vary for different habitats. Natural communities are, however, adapted to storms and other sediment disturbances which are normal features of their environments. Although severe storms undoubtedly cause heavy mortalities, many continental shelf communities (e.g., Middle Atlantic Bight) undergo resuspension or erosion of 1 cm or more of sediment with greater than 25% survival (Fig. 16).

The variable to which the predictions of effects is most sensitive is perhaps the recovery time or resilience of benthos. The justification for the model predicting enhanced populations of meiobenthos one month after additions of drilling fluids is not supported. As indicated above the estimated macrofaunal colonization rates are based on experiments in laboratory aquaria through which estuarine water flows and are unrealistically rapid for continental shelf macrobenthos. Data now exist to show that "recovery" of macrobenthos following its annihilation ranges from weeks to several years depending on the habitat and the adaptation of its community and populations to disturbance (Boesch and Rosenberg 1981). Model predictions incorporating a range of colonization rates could easily have been included in this assessment.

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16. ABSTRACT

This publication summarizes findings of a workshop held September 14-18, 1981, under a Federal Interagency Energy/Environment Agreement (EPA-81-D-X0581) between the U.S. Environmental Protection Agency and the U.S. Fish and Wildlife Service. The U.S. EPA Environmental Research Laboratory, Gulf Breeze, Florida, was host for the sessions held on Pensacola Beach, FL. Discussions focused on information pertaining to fate and effects, identification of general relationships between drilling mud fluids and the marine environment, and identification of site-specific variables likely to determine impacts of drilling muds and cuttings in various marine sites. The workshop was structured around the construction of a model simulating fate and effects of discharges from a single rig into open waters of the Gulf of Mexico. Factors that might produce different fate and effects in enclosed areas such as bays and estuaries also were discussed. Considerable knowledge (such as that concerning fate and physical effects of dredge spoil) that could be effectively employed in analysis of potential fate and physical effects in enclosed areas was identified.

17. KEY WORDS AND DOCUMENT ANALYSIS

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