Scientific Considerations and Research Results Relevant to the Review of the 1996 Offshore Waste Treatment Guidelines

Peter J. Cranford, Kenneth Lee, John W. Loder, Timothy G. Milligan, D. K. Muschenheim, and Jerry Payne

Department of Fisheries and Oceans
Bedford Institute of Oceanography
P.O. Box 1006
Dartmouth, Nova Scotia B2Y 4A2

Institut Maurice-Lamontagne
Mont Joli, Quebec G5H 3Z4

Northwest Atlantic Fisheries Centre
P.O. Box 5667
St. John's, Newfoundland A1C 5X1

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Scientific Considerations and Research Results Relevant to the Review of the 1996 Offshore Waste Treatment Guidelines

by

Peter J. Cranford[1], Kenneth Lee[2], John W. Loder[1], Timothy G. Milligan[1], D. K. Muschenheim[1] and Jerry Payne[3]

[1]Department of Fisheries and Oceans
Maritimes Region
Bedford Institute of Oceanography
P.O. Box 1006
Dartmouth, Nova Scotia B2Y 4A2

[2]Laurentian Region
Institut Maurice-Lamontagne
Mont Joli, Quebec G5H 3Z4

[3]Newfoundland Region
Northwest Atlantic Fisheries Centre
P.O. Box 5667
St. John's, Newfoundland A1C 5X1

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ABSTRACT

This report has been prepared by DFO scientists from the Maritimes, Laurentian and Newfoundland Regions in response to a request by DFO senior management for scientific advice to support recommendations for changes to the *1996 Offshore Waste Treatment Guidelines*. The purpose of this document is to provide a summary of current DFO research results on the transport, fate and biological effects of operational drilling and production wastes on the eastern Canadian continental shelf.

The Department of Fisheries and Oceans, assisted by funding from the Program for Energy Research and Development, has been conducting research on the transport, fate and effects of drilling wastes and the development of oil spill countermeasures since the late 1980's. During this time, international research has addressed continuing controversies regarding the impact of the offshore oil and gas industry. There is growing concern that produced water discharges may be causing contamination and effects on fish and fish habitat. The environmental data on production water are limited and few studies have been conducted on lethal and sub-lethal effects on marine organisms. The particulate fraction of discharged operational drilling wastes is also of concern because their drift, dispersion and dilution are generally lower than those of dissolved or buoyant discharges.

The collection and interpretation of physical, chemical, geological, and biological oceanographic data have provided insight into the processes that influence drilling waste deposition on the seafloor and their subsequent redistribution. This research indicates that drilling waste discharges do not always disperse to negligible concentrations on the continental shelf, but can become concentrated in the near-seabed region (benthic boundary layer). Comprehensive three-dimensional models, developed to improve our capability for estimating the geographic 'zone of influence' of discharged drilling wastes, indicate that the exposure of organisms to potentially deleterious drilling waste concentrations can be expected to vary substantially between drilling sites.

An important environmental concern related to the impact of offshore oil and gas developments is the consequence to resident organisms of long-term exposure to low-level contaminants. Only a very small fraction of marine organisms and life stages have been studied with respect to the potential for chronic lethal and sublethal effects at low waste levels. DFO studies on the chronic biological effects of production drilling wastes has focused on determining dose-response relationships in order to provide an estimate of the potential size of impact zones associated with spills or discharges from rig sites. Laboratory studies with flounder and sea scallops indicate little potential for drilling waste toxicity beyond 1-2 km from a production drilling sites. A low level of MFO enzyme induction in American plaice taken near the Hibernia development site was observed. Prolonged or repeated induction of MFO especially to high levels, has the potential to produce a variety of physiological and pathological conditions in fish. Although observed impacts of drilling wastes have generally been attributed to chemical toxicity or organic enrichment effects of associated oil- and synthetic-base fluids, there is increasing field and laboratory evidence to indicate that fine particles in drilling wastes contribute greatly to the effects observed around drilling platforms. The studies with sea scallops indicate that physical interference by bentonite and barite particles in drilling wastes can significantly affect growth and reproduction at environmentally relevant concentrations. Modelling studies of the fate and effects of drilling wastes on scallops suggest there exists a small probability of detectable and significant population and ecosystem level effects of exploration drilling in some areas of the eastern Canadian shelf.

The volume of produced water discharges will undoubtedly increase with the expansion of offshore oil

and gas production operations in Atlantic Canada. While rapid dilution of the effluent stream is likely to reduce the concentrations to levels which are not acutely toxic to marine organisms, the possibility of chronic long-term effects cannot be excluded. Preliminary results have demonstrated a high level of spatial and temporal variability for contaminants within produced water samples recovered from the Atlantic Region. Furthermore, there is evidence that produced water contaminants may become concentrated within environmental compartments of known ecological importance (e.g. surface microlayer, benthic boundary layer).

Important gaps in knowledge remain with respect to factors affecting dispersion of drilling discharges and chronic ecotoxicological effects of offshore oil and gas activities. An important step in addressing uncertainty is to have in place rigorous monitoring programs which take an ecosystem approach to provide early warning of any adverse environmental impacts. Environmental monitoring and protection plans should address site- and project-specific elements and the potential for impacts from other sources. Overall, oil fields situated on major fishing grounds that discharge large quantities of production waters and drilling wastes within an area that is impacted by discharges from adjacent fields, present the most concern for potential cumulative impacts on fish and fish habitat.

RÉSUMÉ

Le présent rapport a été établi par des scientifiques de la Région des Maritimes, de la Région Laurentienne et de la Région de Terre-Neuve du MPO, à la demande de la haute direction du MPO, qui sollicitait un avis scientifique pour étayer ses recommandations de changements aux *Lignes directrices relatives au traitement des déchets dans la zone extracôtière (1996).* Il a pour but de résumer les résultats des travaux de recherche actuels du MPO sur le transport, le devenir et les effets biologiques des résidus du forage opérationnel et de la production dans l'est du plateau continental canadien.

Grâce au financement du Programme de recherche et de développement énergétiques, le ministère des Pêches et des Océans effectue depuis la fin des années 1980 des recherches sur le transport, le devenir et les effets des résidus de forage ainsi que sur l'élaboration de mesures de lutte contre les déversements d'hydrocarbures. La recherche internationale s'est, quant à elle intéressée parallèlement aux controverses constantes sur l'impact de l'industrie du pétrole et du gaz extracôtiers. On s'inquiète de plus en plus de ce que les eaux résiduaires évacuées puissent contaminer le poisson et son habitat, et avoir sur eux d'autres effets. Les données environnementales sur les eaux résiduaires sont limitées et il y a eu peu d'études au sujet de leurs effets létaux et sublétaux sur les organismes marins. La fraction particulaire des résidus de forage évacués inquiète aussi parce que sa dérive, sa dispersion et sa dilution sont généralement plus profondes que celles des résidus dissous ou flottants.

La collecte et l'interprétation de données d'océanographie physique, chimique et biologique ont permis de comprendre les phénomènes qui influent sur le dépôt des résidus de forage sur le fond marin et sur leur redistribution subséquente. Les recherches révèlent que les résidus de forage évacués ne se dispersent pas toujours en concentrations négligeables sur le plateau continental, mais qu'ils peuvent au contraire se concentrer à proximité du fond marin (couche limite de la zone benthique). Des modèles exhaustifs en trois dimensions, élaborés pour améliorer notre capacité d'estimer la « zone d'influence » des résidus de forage évacués, indiquent qu'on peut s'attendre à ce que l'exposition des organismes à des concentrations de résidus de forage susceptibles d'être délétères varie considérablement d'un lieu de forage à un autre.

L'exposition à long terme des organismes résidants à de faibles concentrations de contaminants représente une inquiétude majeure associée à la mise en valeur du pétrole et du gaz extracôtiers. Les risques des effets létaux et sublétaux chroniques de faibles concentrations de résidus n'ont été étudiés que sur une très petite partie des organismes marins et de leurs stades biologiques. Les études du MPO sur les effets biologiques chroniques des résidus de forage ont surtout porté sur l'établissement d'une relation dose-réaction, parce qu'on cherchait à estimer la grandeur possible des zones d'impact des déversements ou rejets des lieux d'exploitation. Des études réalisées en laboratoire sur les plies et le pétoncle géant révèlent qu'il y a peu de risques de toxicité des résidus de forage au-delà d'un rayon de 1 à 2 km des zones de forage de production. Un faible niveau d'induction enzymatique d'OFM a été observé chez des plies canadiennes prélevées près du site de mise en valeur d'Hibernia. Une induction prolongée ou répétée d'OFM, en particulier à de hauts niveaux, risque de produire diverses conditions physiques et pathologiques chez le poisson. Bien que les impacts observés des résidus de forage aient en général été attribués à la toxicité chimique ou aux effets de l'enrichissement organique des fluides connexes d'origine pétrolière ou synthétique, il y a de plus en plus de preuves, sur le terrain et en laboratoire, que les fines particules des résidus de forage contribuent grandement aux effets observés alentour des plates-formes de forage. Les études sur le pétoncle géant révèlent que l'interférence physique des particules de bentonite et de baryte présentes dans les résidus de forage peut influer considérablement sur la croissance et la reproduction, si ces particules sont présentes dans le milieu en quantité suffisante. Des études de modélisation du devenir et des effets des résidus de forage sur le pétoncle semblent indiquer qu'en ce qui concerne le forage exploratoire dans certains secteurs de l'est du plateau canadien, il existe une faible probabilité d'effets décelables et importants à l'échelle des populations et de l'écosystème.

Le volume d'eaux résiduaires produit augmentera sans aucun doute avec l'expansion des opérations de production de pétrole et de gaz extracôtiers au Canada atlantique. Quoique la dilution rapide des matières en suspension dans les effluents diminuera vraisemblablement les concentrations à des niveaux qui n'ont pas d'effets toxiques aigus pour les organismes marins, on ne peut exclure la possibilité d'effets chroniques à long terme. Les résultats préliminaires ont révélé une forte variabilité spatiale et temporelle des contaminants dans des échantillons d'eaux de production résiduaires prélevées dans la Région de l'Atlantique. De plus, il a été prouvé que les contaminants des eaux de production résiduaires peuvent se concentrer dans des parties de l'environnement qui sont notoirement importantes (p. ex. mince couche de surface, couche limite de la zone benthique).

Il subsiste des lacunes importantes dans les connaissances des facteurs qui influent sur la dispersion des résidus de forage et des effets écotoxicologiques chroniques des activités pétrolières et gazières dans les eaux extracôtières. La mise en place de programmes de surveillance rigoureux, axés sur une approche écosystémique permettant de prévenir à l'avance les impacts environnementaux néfastes, constitue un moyen important de composer avec les incertitudes. La surveillance environnementale et les plans de protection devraient porter sur des éléments propres au lieu de forage et à l'activité ainsi que sur le risque d'impacts d'autres sources. De façon générale, les champs pétroliers qui sont situés dans des lieux de pêche importants et qui déversent de grandes quantités d'eaux de production résiduaires et de résidus de forage dans une zone exposée aux déversements de champs adjacents sont ceux qui risquent le plus d'occasionner des effets cumulatifs

1. Purpose and Scope of DFO Review

The *Offshore Waste Treatment Guidelines* (OWTG) describe minimum standards for the treatment and/or disposal of wastes associated with routine offshore oil and gas drilling and production operations in Canada. The Canada-Newfoundland Offshore Petroleum Board (C-NOPB), the Canada-Nova Scotia Offshore Petroleum Board (C-NSOPB) and the National Energy Board (NEB) are conducting a review of the current *Offshore Waste Treatment Guidelines* document published in September 1996.

This report has been prepared for DFO senior management in response to a request for scientific advice to support recommendations for changes to the *1996 Offshore Waste Treatment Guidelines.* Scientists from the Maritimes, Laurentian and Newfoundland Regions (DFO Atlantic Zone) contributed to the preparation of this report. Focus has been given to the recent results of research funded by DFO and the Program for Energy Research and Development (PERD).

The purpose of this document is to provide a summary of the most current information on the transport, fate and effects of operational drilling and production wastes on the eastern Canadian continental shelf. Much of the scientific information in this document is based on data that have only recently or have yet to be published by DFO scientists.

2. Background and Context

The development of environmental standards and regulations for the offshore oil and gas industry must consider economic, environmental and social issues. Based on the socioeconomic desirability that sustainable commercial fisheries coexist with the offshore petroleum industry, pollution prevention and environmental protection measures, such as those defined in the *Offshore Waste Treatment Guidelines*, need to be commensurate with the risk of environmental impacts at each drilling site.

A viewpoint commonly held until recently was that impacts of the offshore oil and gas industry on commercial fish and shellfish could be limited to the immediate vicinity of production drilling platforms. However, recent laboratory and field observations indicate that impacts on fisheries can occur at much greater distances than originally envisaged. For example, studies in the North Sea, using extensive sampling and detailed statistical techniques now indicate that the area of biological effects can, in some instances, be greater than 60 km^2 around a production platform and that pollution from drilling wastes can cause reductions in food for bottom dwelling fish through changes in benthic communities. Sub-lethal effects have also been observed in both adult fish and larvae at varying distances from some platforms in the North Sea. There are additional concerns about the potential for heavy metal pollution at petroleum exploration and development sites. Metals of environmental concern, including cadmium, lead and mercury, are found in drilling wastes. Sources include production waters and drilling mud additives and trace contaminants (e.g. barite). Recent studies in the Gulf of Mexico have indicated that trace metals can accumulate in sediments and exceed levels associated with biological effects. North Sea studies also indicate the possibility of barium and heavy metals having effects on the benthos. Produced water, the largest volume waste stream from oil and gas production activities, contains oil, several potentially toxic metals, small amounts of radionuclides as well as industry additives (e.g. biocides, oxygen scavengers, scale inhibitors and corrosion inhibitors). The environmental data on production water are limited and few studies have been conducted on lethal and sub-lethal effects on marine organisms. There is growing concern that produced water discharges may be causing contamination and effects on fish and fish habitat.

3. Overview of DFO Research Programs

The exploration, development and production of offshore oil and gas production on the eastern Canadian continental shelf resulted in a need to collect direct scientific information on the environmental consequences of these activities. The Department of Fisheries and Oceans, assisted by funding from PERD, has been conducting research on the transport, fate and effects of drilling wastes and the development of oil spill countermeasures since the late 1980's. The initial focus of the program was on Georges Bank to investigate concerns raised about potential impacts on fisheries, especially sea scallops. With time, the geographic coverage of the program expanded to oil and gas development and production sites on Sable Island Bank, and the Grand Banks. The scientific collaboration includes scientists from DFO laboratories in Dartmouth, St. John's and Mont-Joli as well as Natural Resources Canada scientists from the Geological Survey of Canada (Atlantic) and universities (Acadia, Dalhousie, and Memorial).

Collectively, these studies were designed to provide sound scientific information and technologies that can form a basis for informed advice and management decisions. This information can also assist with the formulation of environmentally responsible drilling practice regulations and environmental monitoring standards for offshore oil and gas developments. Research studies included physical, chemical, geological, and biological oceanography, sedimentology, instrument development, contaminant analysis, toxicology, numerical circulation and dispersion modelling, and biological risk assessments. The following sections provide an overview of this program and the major conclusions to date that are relevant to the review of the *Offshore Waste Treatment Guidelines*.

3.1. Transport and Fate of Drilling Wastes

Discharged drilling wastes are of concern because their particulate fraction tends to settle on the seafloor so that its drift, dispersion and dilution are therefore generally lower than those of dissolved or buoyant discharges. Studies of the dispersion and distribution of drilling wastes are essential for understanding the factors that determine their deposition and subsequent re-distribution due to current and wave stresses. The four main objectives of this component have been:

- to advance knowledge of transport processes affecting the dispersion of discharged drilling wastes, especially the fine particulate fraction;
- to study the change in dispersive capacity caused by flocculation between discharged drilling wastes and naturally occurring organic matter and to assess the microbial processes that likely mediate the interaction;
- to provide technology transfer of new instrumentation designs for the recovery of benthic boundary-layer samples for use in research and industry environmental effects monitoring programs; and
- to develop drilling waste dispersion models as a generic tool for predicting the zone of influence for drilling wastes.

An important aspect of this component has been the collection and interpretation of physical oceanographic data to provide insight into the processes that influence the deposition and subsequent redistribution of drilling wastes. This has included moored current measurements, drifter tracking, turbulence profiles, and detailed hydrographic surveys, as well as collaboration with industry in the interpretation of current measurements collected during industry Physical Environmental programs. These studies have provided a quantitative description of spatial structure in the physical environment, and information on the potential trajectories of oil spills and the dispersion of drilling wastes. The observational data are being used for the forcing and validation of comprehensive three-dimensional circulation models of the eastern Canadian continental shelf (e.g. Han *et al.* 1997; Hannah *et al.* 2001b). A comparison of modelled and observed tidal ellipses and seasonal-mean currents for the Scotian Shelf is shown in **Figure 1**. This modeling approach provides high spatial resolution in key areas, which is important for applications on specific oil and gas activities.

In the past it has been assumed that material such as drilling mud, that consists of very small particles with settling velocities <0.01 cm s^{-1}, would readily dissipate to negligible concentrations on the energetic offshore banks of the Canadian east coast. Ongoing laboratory studies by DFO have shown that drilling wastes readily flocculate in seawater to form aggregates on the order of 0.5-1.5 mm in diameter with settling velocities > 0.1 cm s^{-1}. The fragility of natural flocs makes it impossible to sample them using conventional methods. However, high resolution colour video images obtained during one research survey showed dark flocculated material on the seabed as far away as 15 km from the platform at the CoPan field. While this type of material can occur naturally, the highest concentrations were observed within 3 km from the Rowan Gorilla III platform (**Fig. 2**). The production drilling platform was also found to be the geographical centre of a water column turbidity field.

A complication to studying the fate of particulate wastes in nature is the difficulty in differentiating drilling waste particles/flocs from naturally occurring material. The principal components of all currently utilized drilling muds are fine silts and clays (bentonite and barite). Particle size analysis of disaggregated inorganic drilling mud shows a very distinct size distribution with a modal diameter <1 μm (bentonite). When plotted as log concentration versus log diameter, a steep negative slope between 1 and 10 μm was observed (Muschenheim *et al.* 1995, Muschenheim and Milligan, 1996). A comparison of the grain size of particles in discharged drilling muds with naturally occurring suspended particulate material (SPM) shows that the fine bentonite particles can be used as a tracer of drilling wastes since they were not observed in SPM on the Georges, Sable Island or Grand Banks.
These particle size distribution data have been used to confirm the presence of drilling wastes at the CoPan field in the surface discharge plume, in flocs on the seabed surface as far as 8 km from the platform, and also in the benthic boundary layer. Observations have indicated that these flocculated drilling wastes were alternately resuspended and deposited over a tidal cycle and during storms. The new sampling methods developed during research projects on Georges Bank and Sable Island Bank are now being used to study drilling waste dispersion at Hibernia. Early results have revealed the presence of flocs on the seafloor near the production platform, but it has not yet been determined if they contain drilling mud.

The results of these physical oceanographic and drilling waste behaviour studies have been used in the application of plume descent models for discharged wastes (Andrade and Loder 1997), and in the development and application of a novel model for drilling waste dispersion and drift in the benthic boundary layer. The latter is referred to as a *bblt* (benthic boundary layer transport) model (Hannah *et al.* 1995). The plume descent model simulations have confirmed rapid initial dilution of discharged wastes, but have also indicated that the fraction reaching the benthic boundary layer can vary strongly with location depending on local oceanographic conditions such as currents, stratification and water depth. The *bblt* model can provide site-specific estimates of the subsequent suspension, drift, dispersion and concentration of drilling wastes in the benthic boundary layer, for various oil and gas exploration and production drilling scenarios. The predictive modelling capability provided to government and industry through these studies has been effective in producing realistic 'zone of influence' estimates for drilling wastes, as evidenced by the application of *bblt* in environmental impact assessments for the Sable Offshore Energy Project and the Georges Bank Review Panel hearings (Boudreau *et al.* 1999), and in the environmental assessment of exploration drilling off Nova Scotia (LGL, 2000). Simulations for Georges Bank predict that regional and temporal variations in physical oceanographic processes have a large influence on the potential zone of influence of discharged drilling wastes (**Fig. 3**). Continued development and application of the dispersion models, and of numerical circulation models that provide estimates of currents and bottom stress, are providing an improved capability for estimating the fate of discharged drilling wastes at other eastern frontier sites, where differences in depth and oceanographic conditions can affect suspension, drift and dispersion (Hannah *et al.* 2000a; Xu *et al.* 2000).

Similarly large spatial variations in the drilling waste zone of influence have been predicted for other sites on the Atlantic shelf (LGL, 2000). The application of circulation and dispersion models,

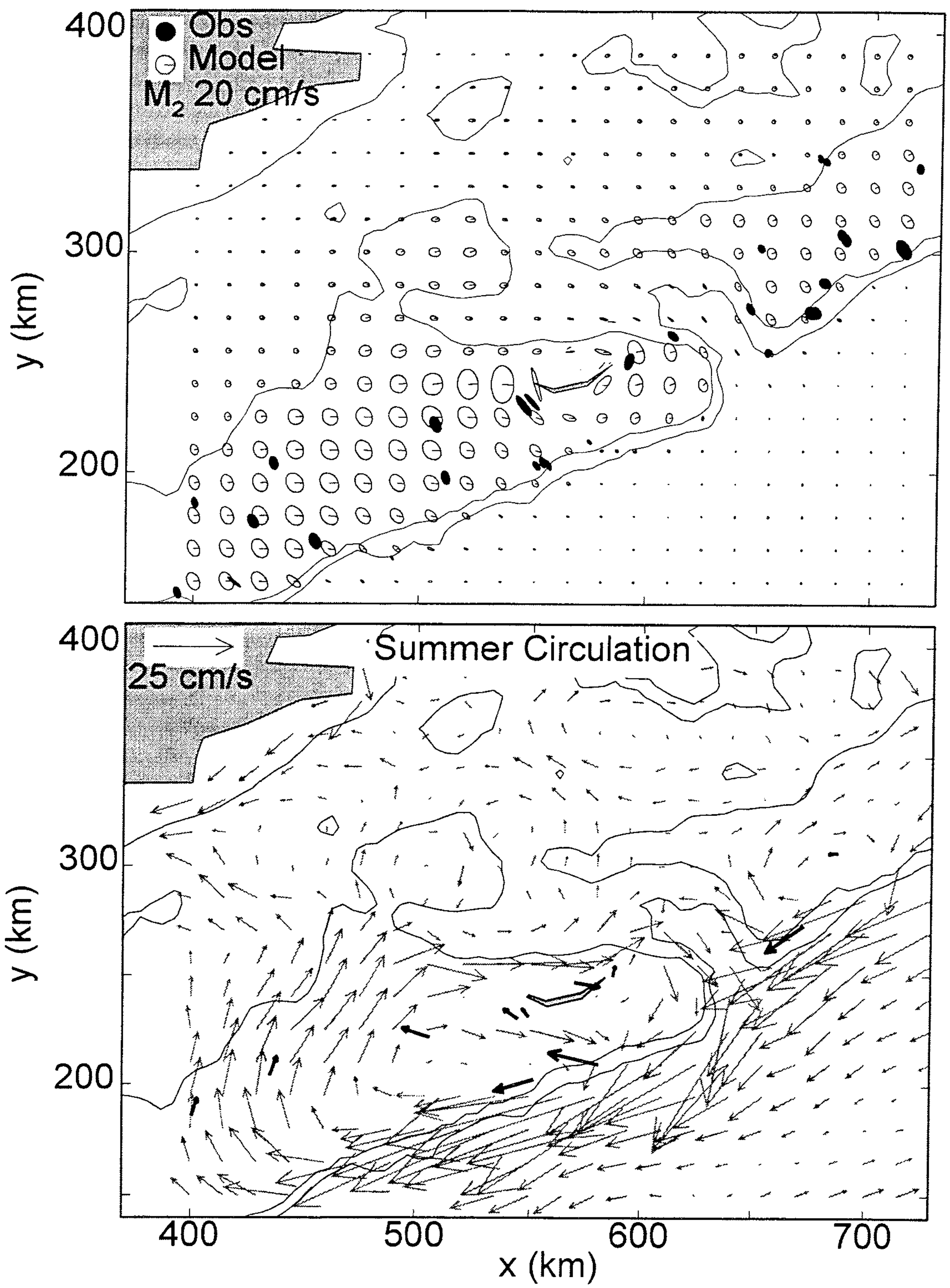


Figure 1. Upper panel: Modelled and observed M2 tidal ellipses on Sable Island Bank illustrating the spatial variability, with generally larger currents in shallow water. **Lower panel:** Modelled (thin, grey arrows) and observed (thick, black arrows) mean summer circulation. A clockwise flow around the bank and a branch of the shelf-edge flow following the topography into and out of the Gully (to the east of Sable Island) is predicted (Han and Loder 2000).

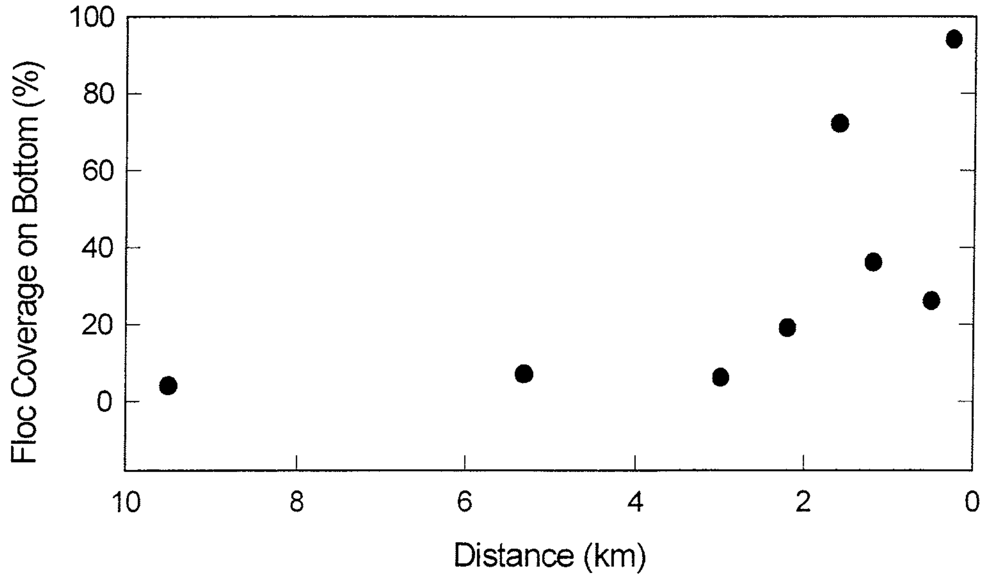


Figure 2: Graph showing the % of seabed covered by floc along a video transect running west from the Rowan Gorilla III drilling platform on Sable Island Bank. .

in conjunction with model validation studies, provide a means of classifying much of the eastern Canadian continental shelf with respect to the potential spatial scale of biological effects from drilling waste discharges. However, it is important to note that models often do not fully represent all of the processes occurring in nature and they require reliable data on physical forcings and properties of the discharges, so they should be used with caution. For instance, the *bblt* models are sensitive to uncertainties in the settling rates of the discharges and in the near-bottom currents and stresses such that further validation studies are desirable.

Conclusions from DFO Studies of the Fate of Drilling Wastes:

- Drilling waste discharges do not always disperse to negligible concentrations on the continental shelf.
- Drilling wastes readily flocculate in seawater in laboratory experiments and form fragile aggregates on the order of 0.5-1.5 mm in diameter with high settling velocities > 1 mm s^{-1}.
- Flocs containing drilling wastes have been observed to accumulate on the seabed at distances up to 8 km away from an active drilling platform.
- Drilling waste particles can be concentrated in the benthic boundary layer associated with flocculated wastes being alternately resuspended and deposited over the tidal cycles.
- Physics-based numerical models have provided a tool to estimate the zone of influence for drilling waste at specific drilling sites and for specific discharge scenarios, but further validation studies are desirable.
- Regional and temporal variations in physical oceanographic processes, that determine the degree of initial dilution and waste suspension, dispersion and drift in the benthic boundary layer, have a large influence on the potential zone of influence of discharged drilling wastes.
- The exposure of organisms to potentially deleterious drilling waste concentrations can be expected to vary substantially between drilling sites.

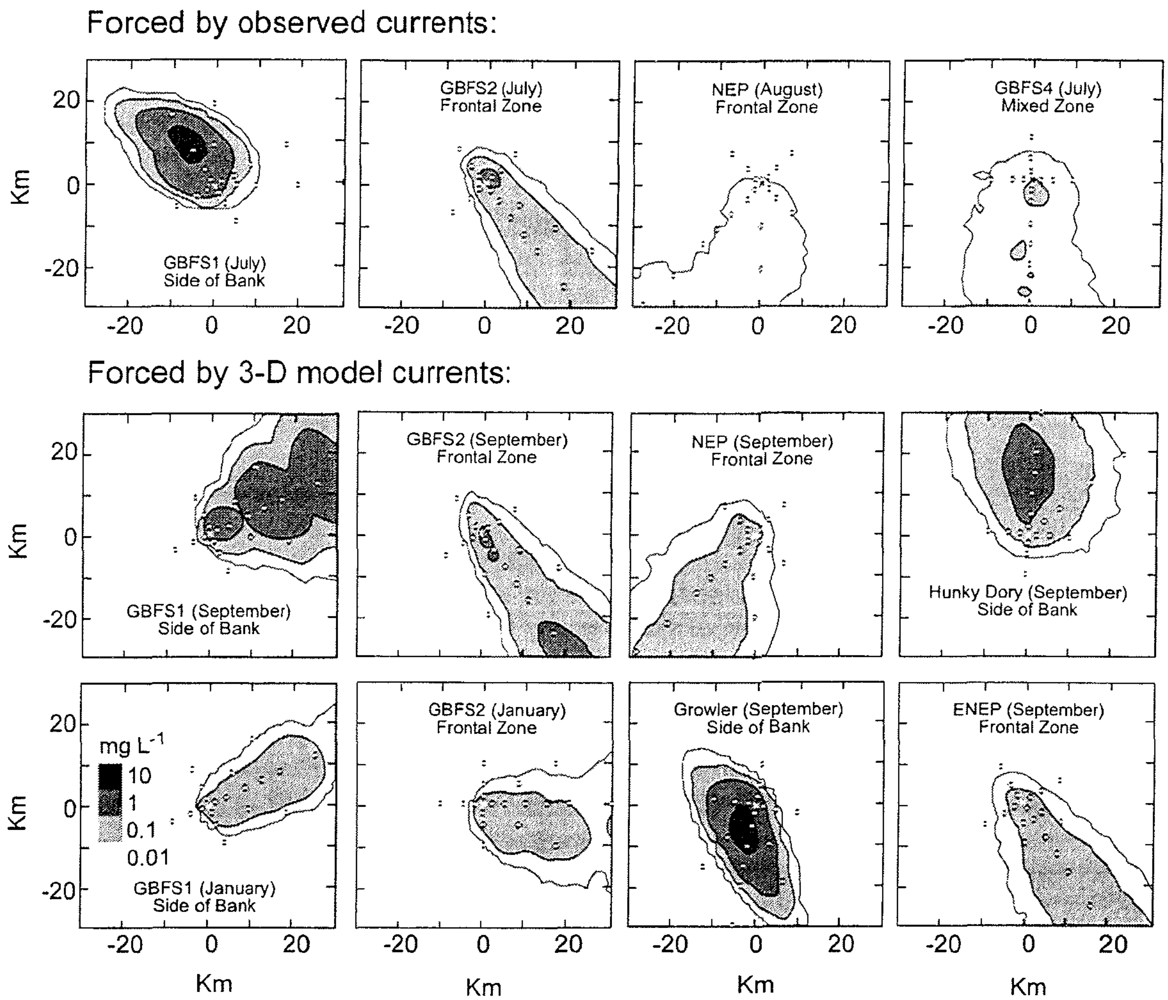
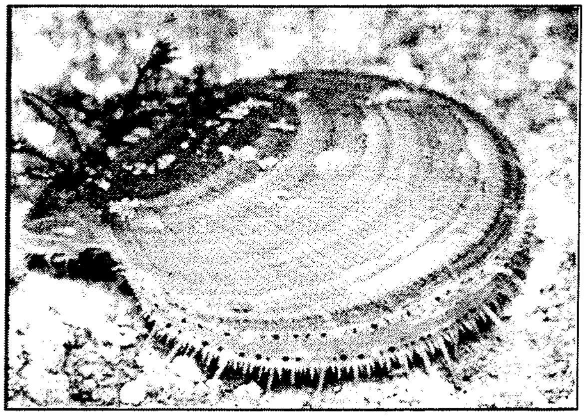


Figure 3. Model (*bblt*) predictions of near-bottom drilling mud concentrations (mg l^{-1}) during simulated exploration drilling on Georges Bank. Application sites in different oceanographic regions (mixed, frontal and side) of Georges Bank are shown for different times of the year (Gordon *et al.* 2000). See Loder *et al.* (2000) for site locations and further information on how these estimates were derived.

3.2. Biological Effects of Drilling Wastes

In a major review of oil pollution carried out under the auspices of the Royal Society in the United Kingdom in the early 1980's, reference was made to "the apparent paradox that it is the unknown, the suspected but hard-to-detect chronic effects, that are the real cause for concern". The Interagency Committee on Ocean Pollution Research in the United States and later a group of experts convened by NOAA and NSF stated similar concerns. One of the most important environmental concerns related to the impact of offshore oil and gas developments is the consequence to resident organisms of long-term exposure to low-level contaminants. Studies on the chronic lethal and sublethal biological effects of production drilling wastes are being conducted by DFO to assess the potential environmental hazard associated with the discharge to the marine environment of specific used drilling muds and additives. Emphasis has been placed on determining dose-response relationships in order to provide an estimate of the potential size of impact zones associated with spills or discharges from rig sites.

3.2.1. Toxicity Studies with Sea Scallops



The sea scallop, *Placopecten magellanicus,* has been one of the primary study species for drilling mud toxicity studies. Sea scallops are a widely distributed offshore resource species, the bulk of particulate drilling waste discharges rapidly reaches the seabed, and they are sedentary and unable to escape chronic exposure. Scallops also obtain their food (phytoplankton and detritus) by filtering particulate matter from the benthic boundary layer, where resuspension/deposition processes concentrate drilling waste particles (Muschenheim and Milligan 1996).

Research has focused on assessing the potential for impairment of productivity and reproduction as these types of impacts are considered, from both ecological and fisheries perspectives, the most important sublethal effects on adult organisms (Capuzzo, 1988). Chronic toxicity studies, in which scallop cohorts were exposed under environmentally relevant conditions to low levels of suspended aqueous and non-aqueous drilling muds for up to 72-days, showed that low levels of drilling wastes can influence food utilization, growth, reproduction and survival (Cranford and Gordon 1992; Cranford 1995; Cranford *et al.* 1999). The chronic lethality of low levels (<10 mg l^{-1}) of water-based muds (WBM), and pseudo-oil-based muds (although operational definitions vary, we will refer to these as synthetic-based muds or SBM), including a new low viscosity ester-based mud, was very low and scallop mortality in these exposures were similar to the controls (no drilling wastes added) (**Fig. 4**). However, drilling mud containing a low-toxicity mineral oil (LTMO; Shell SOL DMS) caused high mortality at concentrations greater than 0.5 mg l^{-1} (Cranford *et al.* 1999).

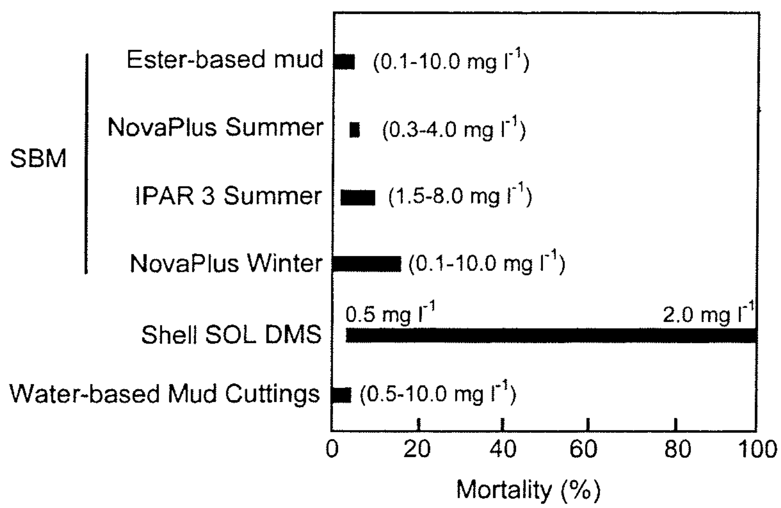


Figure 4. Mortality of adult sea scallops during chronic exposure to different types and concentrations of drilling muds. Horizontal bars show the range of mortalities observed over the concentration range tested (Cranford and Armsworthy, unpublished data). See text for abbreviations.

Threshold drilling waste concentrations causing significant impacts on scallop tissue growth varied between 0.07 and 10 mg l^{-1} (Cranford and Gordon, 1992; Cranford *et al.* 1999; Cranford and Armsworthy, unpublished data). Toxicity was assessed from chronic lethal and sublethal (somatic and reproductive tissue growth, and physiological condition) effects on sea scallops during summer and winter. Growth effects from the drilling fluid containing the Shell SOL DMS base oil were the most severe among all the wastes tested as indicated by the lack of any tissue growth at 0.5 mg l^{-1} (the lowest concentration tested), the resorption of gonad tissue, the cessation of feeding and the inability to recover feeding activity during periods when this LTMO was not present (Cranford *et al.* 1999). Tissue growth was significantly impacted by the three SBM formulations (Novaplus®, IPAR-3®, and a low viscosity ester-based fluid) at 1.0 mg l^{-1} concentrations (**Fig. 5**). Significant growth effects of the Novaplus SBM were detected at 0.07 mg l^{-1} during winter the exposure (**Fig. 5**). Growth reductions resulted primarily from reduced energy intake through feeding (clearance rate) and digestion (absorption efficiency), but increased energy losses to respiration and excretion also contributed. Clearance rate was particularly sensitive to suspended drilling wastes and an EC_{50} (concentration resulting in 50% reduction in response) value for each SBM was indicated between 0.5 to 1 mg l^{-1}. Exposure to a mixture of WBM and fine cuttings particles (<50µm diameter) significantly enhanced scallop growth rates at concentrations below 10 mg l^{-1} owing to the adsorption of organic matter onto the cuttings particles and the subsequent increase in food availability.

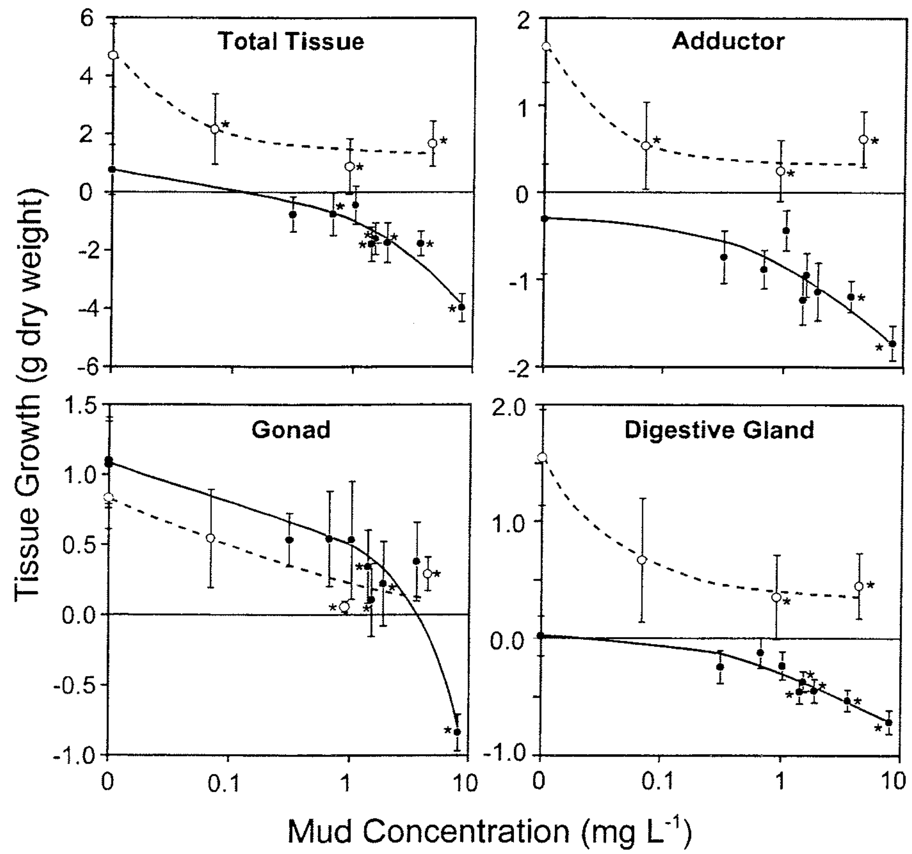


Figure 5. Mean growth (±2SE) of scallop dry tissues during summer (•, solid line) and winter (o, broken line) chronic exposures to SBM (Novaplus and Ipar 3). Curves were fit by eye and treatments displaying significant growth reduction, compared to the controls (0 mg L^{-1}), are indicated by asterisks ($P < 0.05$)(Cranford and Armsworthy, unpublished data).

All of the drilling wastes tested have previously been characterised as slightly toxic (1,000-10,000 ppm [mg l^{-1}]) to practically non-toxic (>10,000 ppm) according to 96-h LC_{50} acute toxicity standards employed by the Joint Group of Experts on the Scientific Aspects of Marine Pollution (GESAMP, 1993). The results of the DFO studies, however, show that these same wastes can significantly affect somatic and reproductive tissue growth, and survival of adult sea scallops at concentrations that are between three to five orders of magnitude lower than the acute lethal concentration. Although acute toxicity testing of drilling fluids and components is valuable for assessing relative toxicity, chronic lethal/sublethal effects studies conducted under environmentally representative conditions are most critical to our understanding of the consequences of pollution to marine organisms. The following ranking of the drilling wastes studied, in order of increasing chronic detrimental effects, was observed: water-based mud and cuttings < bentonite < barite = synthetic-based mud < mineral oil-based mud. Observed effects of drilling wastes on benthic fauna have generally been grouped as being caused primarily by the following combination of factors:

- chemical toxicity from hazardous pollutants and biodegradation products (e.g. hydrocarbons, heavy metals, sulfides);
- organic enrichment of sediment that may produce anoxia; and
- physical smothering.

DFO research on the effects of drilling wastes on the sea scallop shows that an additional, and potentially more important, source of toxicity exists that could have consequences at the population and ecosystem level. Although the chemical toxicity of the base fluid was identified as the primary cause of the high chronic toxicity of the LTMO drilling mud tested (Cranford *et al.* 1999), the biologically inert components in all drilling fluids (e.g. bentonite and barite) also contributed to the impacts and were the major cause of the observed effects from the three SBMs tested. Physical inhibition of somatic and reproductive growth by bentonite and barite particles was apparent in these treatments as these materials interfere with feeding/digestion processes. For example, the impact of different wastes on clearance rate is shown in **Figure 6**. Data from the LTMO exposures are not shown as the LTMO had a much greater impact on clearance rate owing to it's combined physical and chemical toxicity (Cranford *et al.* 1999). Barite had a greater impact on scallop growth than bentonite as evidenced by the complete cessation of gonad growth at the lowest concentration tested (0.5 mg l^{-1}). Given the relatively large effect of barite, chronic effects would certainly occur at even lower concentrations. The effect of barite on scallop growth appears to result from tissue abrasion and/or nutritional stress from adsorption to barite of mucus secretions, which are critical to normal feeding and digestion processes (Cranford *et al.* 1999). The lack of any deleterious physical effects during the WBM exposures can be explained by the absence of barite in the formulation tested. Barite is generally a required component in drilling fluids. The WBM exposure was primarily conducted to observe the impact of cuttings particles, which are larger than the operational solid components of drilling fluids. Concentrations of suspended cuttings particles below 10 mg l^{-1} did not interfere with the physiological processes controlling growth.

Numerous chronic lethal/sublethal effects studies have been carried out with a variety of marine organisms exposed to different drilling wastes. Sublethal effects have been observed at drilling fluid concentrations up to two orders of magnitude lower than acutely lethal concentrations (Neff, 1987). Our work on scallops has documented sublethal effects at waste concentrations that are generally much lower than previously observed. However, recent observations of barite effects on other suspension- and deposit-feeding bivalve species tend to confirm our observations with scallops and provide new insights into the potential effects on other species and on the biological impact mechanism (Barlow and Kingston, 2001). There is much field and laboratory evidence to indicate that oil- and synthetic-base fluids are not the prime factor causing the far-field effects observed around drilling platforms (Cranford *et al.* 1999, Barlow and Kingston 2001). Also recent dose-response studies carried out on Hibernia SBM with sediment monitoring surrogates indicate that sediment impact zones should be less than 500m in radius (Payne *et al.* 2001a), a distance which is inconsistent with that found for impacts on benthic communities in most monitoring programs. Greater attention needs to be focused on the physical effects of materials such as bentonite and barite.

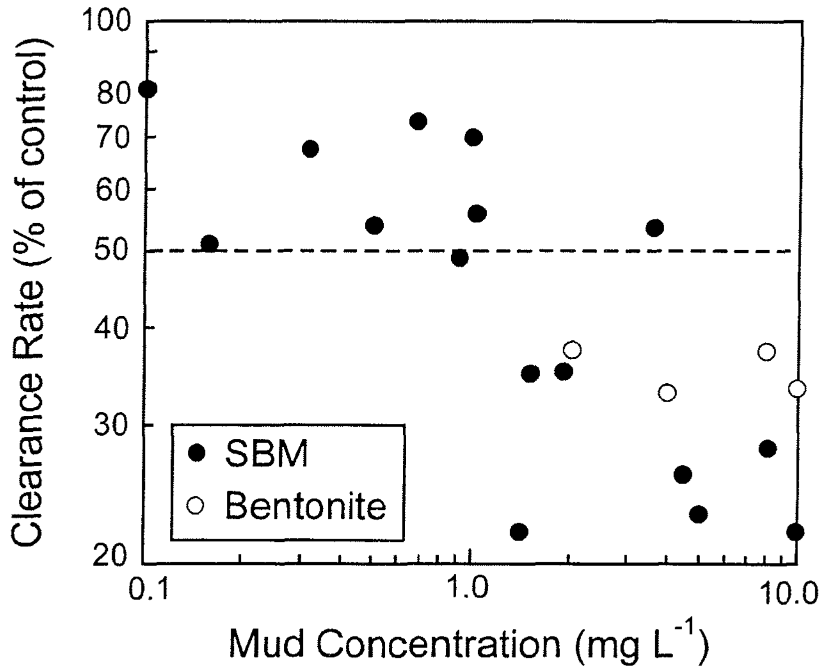


Figure 6. Effect of synthetic-based drilling wastes on average sea scallop clearance rates, expressed as a percentage of the average rate measured for control animals (Cranford and Armsworthy, unpublished data).

3.2.2. Chronic Toxicity and Field Studies with Fish

The results of DFO chronic toxicity studies on commercially important finfish have contributed to the review of environmental impact statements and the provision of Departmental position statements on offshore development. New knowledge from our scientific studies have influenced the design and implementation of industry environmental assessment/monitoring

Chronic ecotoxicological effect studies usually rely on the quantification and interpretation of biotests having multiple endpoints at the biochemical, physiological and histological levels of biological organization. While more difficult to conduct, these studies have a higher level of ecological relevance.

Sub-lethal effects have been observed in flounder chronically exposed to sediment containing aromatic hydrocarbons as low as 1 ppm (Payne *et al.*, 1988).. However similar studies with sediments contaminated with an aliphatic hydrocarbon based drilling mud indicated little potential to affect fish health. The indices studied included organ and body condition indices, muscle and liver energy reserves, blood parameters, liver and gill histopathology and mixed-function oxygenase enzymes (Payne *et al.*, 1995). A similar long-term chronic toxicity study has been carried out with cuttings from the Hibernia site. These cuttings contain an aliphatic drilling fluid (IPAR®) also slated for use at Terra Nova and White Rose. The histopathological studies for this exposure are incomplete, but studies on organ condition indices and energy reserves indicate little potential for toxicity beyond 1-2 km from rig sites. A variety of short and long term studies on different species also indicate that IPAR has a very low acute toxicity potential (Payne *et al.*, 2001a, Payne *et al.*, 2001b). Laboratory studies also indicate that IPAR can be substantially degraded in sediments after 4 months.

Petroleum hydrocarbons include aliphatic and aromatic compounds and their N, S and O substituted analogs. Sources of petroleum hydrocarbons in waters and sediments around petroleum development sites include cuttings from either synthetic or water-based muds (during development drilling), production waters and displacement waters. Chronic toxicity studies with flounder indicate that concentrations of petroleum hydrocarbons commonly found in sediments around petroleum development sites can potentially affect fish health. The sensitivity of fish gills to hydrocarbons has been noted in chronic toxicity studies with codfish (Khan and Kiceniuk, 1984) and flounder (Payne *et al*, unpublished). However concentrations producing effects may be more or less confined to areas within a few km of rig sites. The biological effects indices studied included organ condition indices, energy reserves, levels of mixed-function oxygenase enzymes and selected aspects of liver and gill histopathology (Payne *et al.*, 1988; Payne and Fancey, 1989; Payne *et al*, unpublished).

Fundamental studies on mechanisms of toxicity indicate that aromatic hydrocarbons have a higher toxicity potential than aliphatic hydrocarbons (e.g. Payne *et al.*, 1987a). Chronic toxicity studies with flounder showed limited bioaccumulation of polycyclic aromatic hydrocarbons (PAH) in fish exposed to sediments containing very high concentrations of petroleum hydrocarbons. (Hellou *et al.*, 1994). This is presumably due to enzyme-linked detoxification capacities. These results are of importance with respect to concerns about the potential for PAH impairing fish quality and marketability.

MFO enzyme induction is a sensitive early warning indicator for assessing the impacts of selected organic contaminants on fish (e.g. Payne *et al*, 1987b; Porter *et al.* 1989) and has been accepted by eight of the contracting parties to the Oslo Paris Commission, as well as other agencies, for use in monitoring programs. With respect to petroleum development, studies carried out by Stagg *et al* (1995) in the East Shetland Basin demonstrated significant induction of enzyme activity in dab caught within several km of three oil platforms. Moreover, Stagg and McIntosh (1996) have also reported elevated MFO enzyme levels in fish larvae at significant distances from rig sites. Water column concentrations of aromatic hydrocarbons in the ppb range have also been linked in other environmental studies to enzyme induction and histopathological lesions in fish (e.g. Spies *et al.*, 1996). Preliminary information has been obtained by DFO indicating a low level of enzyme induction in American plaice taken near the Hibernia development site. These results are of interest given the early phase of development. Prolonged or repeated induction of MFO especially to high levels, has the potential to produce a variety of physiological and pathological conditions in fish (e.g. Stegeman and Hahn, 1993).

3.2.3. Chronic Toxicity to other Species

The chronic toxicity studies with fish and scallops also indicate the importance of carrying out studies with drilling muds on other key species. Chronic toxicity studies with lobster indicate that relatively low concentrations of petroleum hydrocarbons in water (0.04-0.05 ppm range) can affect animal health. Crab is presently the main fishery on the Grand Banks and these observations are of interest with respect to assessing potential effects on crabs from any petroleum enriched drilling muds in the near vicinity of development sites such as White Rose. A suite of 56 different parameters, including biochemical, physiological and morphological indices were investigated in the lobster study (Payne *et al.*, 1983). One of the pathological effects observed was gill melanization, which markedly increased in oil exposed animals indicating its potential use as a simple monitoring index.

Conclusions from DFO Studies on Biological Effects of Drilling Wastes

Sea Scallops

- Chronic exposure of sea scallops to different drilling wastes can significantly affect growth and reproduction at environmentally relevant concentrations (< 10 mg l^{-1}).
- A waste containing a mineral oil-based fluid was highly toxic to scallops.
- Chronic sublethal effects of SBM and WBM exposures are similar as the toxicity of the base-fluids was generally low. Significant impacts on scallop growth and reproduction from SBM and WBM formulations were attributed to physical interference .
- The drilling wastes tested have detrimental effects in the following order of increasing chronic effects: water-based mud and cuttings (impact threshold >10 mg l^{-1}) < bentonite (>2 mg l^{-1}) < barite ≈ synthetic-based mud (> 0.07 mg l^{-1}) < mineral oil-based mud.

Finfish

- Chronic toxicity studies with flounder indicate that aliphatic hydrocarbon-based drilling fluids have little potential to affect fish health.
- Studies on organ condition indices, energy reserves and MFO in flounder indicate little potential for toxicity beyond 1-2 km from rig sites.
- Sub-lethal effects have been observed in flounder exposed to sediments containing aromatic hydrocarbons as low as in the 1ppm range.
- Laboratory studies indicate that very high concentrations of petroleum hydrocarbons in sediment result in little bioaccumulation of polycyclic aromatic hydrocarbons (PAH) in fish tissues.
- A low level of enzyme induction in American plaice taken near the Hibernia development site was observed. Prolonged or repeated induction of MFO especially to high levels, has the potential to produce a variety of physiological and pathological conditions in fish.

Other Species

- Chronic toxicity studies with lobster indicate that relatively low concentrations of petroleum hydrocarbons in water (0.04-0.05 ppm range) can affect animal health.
- Only a very small fraction of marine organisms and life stages have been studied with respect to the potential for chronic sublethal effects at low waste levels.

3.3. Risk of Waste Discharges to Populations

Numerous studies on the potential hazard of operational drilling wastes to marine organisms have been conducted through toxicological assessments (Neff 1987; GESAMP 1993). Environmental risk assessment requires the integration of these data with information on the concentration, spatial extent and persistence of the waste. Numerical models are valuable tools for evaluating the potential environmental impact of drilling activities as they provide a quantitative framework for integrating knowledge on the intrinsic physico-chemical properties of the different contaminants and the extrinsic processes that control their transport and fate in the environment. The risk to the sustainability of commercial scallop stocks on offshore banks has been assessed by integrating laboratory toxicity data (Section 3.2.1) with information on the spatial distribution, and transport of drilling wastes in the environment (Section 2.1), and the distribution of scallop stocks.

The *bblt* numerical models were used to simulate the dispersion of drilling wastes around drilling platforms under typical exploration drilling scenarios on Georges Bank (Hannah *et al.* 1995; Loder *et al.* 2001). Predictions of the potential spatial and temporal extent of drilling waste concentrations were coupled with the biological effects information to explore site-specific impacts on sea scallop populations (Boudreau *et al.* 1999; Gordon *et al.* 2000a). At some sites, waste concentrations known to affect scallops were predicted to extend over large areas (**Fig. 3**), particularly during the first drilling section when wastes are released directly at the seabed, and after bulk WBM dumps. The highest near-bottom concentrations of WBM discharged from a typical 92-day exploration well were predicted to occur in relatively-deep stratified water along the side of Georges Bank (>100m depth). Information on toxicity threshold concentrations indicated a potential for 0-48 days of growth inhibition depending upon the site, settling velocity of the mud, and area over which results are averaged. Scallop stocks on the side of the bank are relatively small, but dense aggregations are found in some areas and it is possible that changes in reproductive output could have detectable effects at the population level. Growth inhibition in the shallower tidal front region, which has the densest scallop stocks, is predicted to be more localized and confined to a range of 0-15 days. Growth loss in the energetic central mixed region (<65 m) is predicted to be negligible (<2 days). It was concluded that there exists a small probability that exploration drilling could have population and ecosystem level impacts. The actual impact is predicted to depend on the location of the drilling, timing of activities and properties of the discharge.

Similar *bblt* applications for hypothetical oil and gas exploration sites have been conducted for the Sable Island Bank, the northern Grand Bank, Laurentian Channel and the St. Pierre Bank (MacLaren Plansearch 1997; LGL, 2000; Hannah *et al.* 2000a). Differences in the local oceanography and water depth have resulted in a range in the predicted zone of influence for drilling wastes, and similarly large differences in the biological effects zone would be expected. All of the *bblt* applications performed to date illustrate the importance of site location and waste settling velocity in defining the zone of potential sublethal population effects. The implications of the potential loss of reproductive output (e.g. reduced size of the population gene pool) by organisms over the spatial scales of the population should be considered from resource sustainability and ecological perspectives.

Conclusions of Population Risk Assessments

- Numerical dispersion models, used in conjunction with laboratory data on sublethal effects and field information on population distributions, are valuable tools for evaluating the risk of potential population-level impacts of discharged drilling wastes.
- Near-seabed waste concentrations of WBM have been predicted to extend for large areas around single exploration platforms at levels that are known to adversely affect scallops.
- The predicted biological effects zone can vary greatly with location and season.
- There exists a small probability that changes in reproductive output resulting from exposure to fine particle in WBM could have detectable and significant population and ecosystem level effects in some areas of the eastern Canadian shelf.

3.4. Water-Based versus Synthetic Drilling Muds

DFO studies on the fate and effects of water-, oil- and synthetic-based muds provide a means of assessing the relative potential environmental impact that each poses to sensitive benthic organisms. SBMs are currently the most reliable method for managing hole stability and provide required lubricity to lower string torque and drag. Owing to the operational advantages of their use compared with WBM, a scientific assessment of SBM discharges associated with cuttings needs to be conducted given that the majority of SBM is separated from cuttings and recycled while all the used WBM is discharged to the marine environment. A hypothetical WBM release scenario for the first 60 days of exploration drilling is used in this assessment (**Fig. 7**).

Drilling of the upper well sections is typically

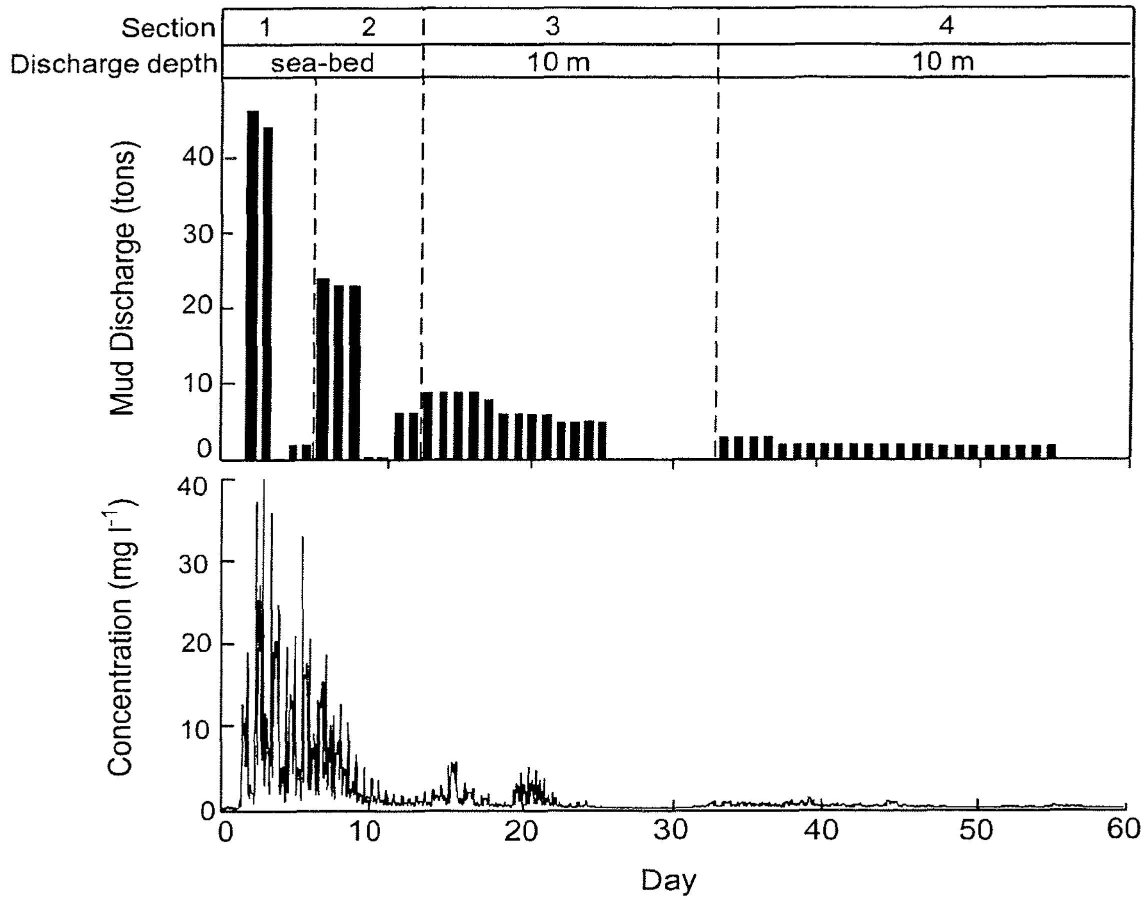


Figure 7. Top: Hypothetical WBM releases scenario for the first 60 days of exploration drilling. **Bottom:** Example of predicted near seabed WBM concentrations near one of the *bblt* model application sites on Georges Bank (adapted from Gordon *et al.* 2000a).

performed with WBM as the casing, riser and blow-out preventer are not installed and the mud and cuttings cannot be returned to the platform. Use of an SBM for drilling the top part of the well would therefore be costly and may not be practical. Model (*bblt*) predictions of WBM concentrations near the seabed are generally highest during the first 10 days of drilling (**Fig.** 7), including during bulk WBM dumps after Day 60 (not shown). Predicted waste concentrations vary widely between application sites and the estimates shown in **Figure** 7 are used only to illustrate the general temporal trend. Predicted impacts on scallops are largely associated with large WBM waste releases during the initial part of drilling, and after bulk dumps. The use of a low toxicity SBM for the deeper well sections would eliminate bulk WBM dumps and mitigate some of the predicted effects on marine organisms caused by the physical effects of elevated turbidity (see Section 3.2). This assumes that the SBM is recycled and is not permitted to be dumped at sea as is permitted for WBM in the *OWTG*.

The use of SBM over WBM comes with the additional risk of organic enrichment impacts from SBM contaminated cuttings and the potential that synthetic-based fluid biodegradation products may be persistent or toxic. However, these risks must be weighed against the benefits that the elimination of bulk WBM dumps would have on turbidity levels and the discharge of heavy metals often associated with barite. Unlike the synthetic-based fluids that biodegrade rapidly, heavy metal contamination becomes more or less permanent with dispersion and dilution being the primary mechanisms for reducing potential problems. North Sea studies suggest that these metals may be involved in benthic impacts and contamination of finfish and shellfish.

The risk of organic enrichment impacts on the benthos may be mitigated by employing the best practicable technology for reducing retention of SBM on cuttings prior to discharge. Currently technology exists to obtain synthetic-based fluid retention values under 5% (e.g. cuttings dryers). Reducing the amount of synthetic fluid on cuttings has been shown to promote biodegradation, reduce the build-up of deleterious cuttings piles and mats, and to improve the dispersion of deposited cuttings. Sea water flushing of cuttings is also reported to help disperse synthetic-based cuttings like water-based cuttings, and would reduce the flocculation and settling rates of waste particles. High settling rates tend to trap drilling wastes near the seabed, where they concentrate and can impact some benthic and demersal organisms.

Conclusions on the Relative Environmental Impacts of WBM and SBM

- Exposure of demersal and benthic organisms to drilling wastes is greatest during the initial part of drilling, and after bulk dumps.
- The use of SBM over WBM comes with the additional risk of organic enrichment impacts from SBM contaminated cuttings.
- Use of SBM for deeper sections would eliminate bulk WBM dumps that can cause physical effects and heavy metal contamination. Higher concentrations of particulate and heavy metal contaminants are introduced into the environment from drilling with WBM than for SBM.
- Unlike synthetic-based fluids which biodegrade rapidly, heavy metal contamination from WBM dumps can be more or less permanent.
- SBM impacts can be mediated by pretreatment of cuttings.

3.5. Produced Water

Water brought up from the hydrocarbon bearing strata during the extraction of oil and/or gas is termed produced water. It is primarily composed of formation-water that is, in effect, a brine which derives its salinity from the major ions found in seawater (GESAMP, 1993). In addition, it can also include flood water (injected into the formation to maintain reservoir pressure), condensed water (in the case of gas production) and trace amounts of treating chemicals (e,g, bactericides, corrosion and scale inhibitors). As a result, produced water contains a number of constituents of environmental concern including hydrolysis metals, heavy metals, nutrients, radionuclides, petroleum hydrocarbons, and chemical agents.

Produced water is the highest volume waste generated in association with oil and gas operations. Over the life of a typical oil field, as much or more water than oil is likely to be produced. For current offshore operations within eastern Canada, it is estimated that both the Cohasset and Hibernia fields have or will produce greater than twice the volume of water over oil (Ayers and Parker, 2000).

Produced water from Canadian offshore operations is discharged into the sea after hydrocyclone treatments that reduce its dispersed oil and grease content below regulatory limits (30 day average of <40mg/L) defined by *the Canadian Offshore Waste Treatment Guidelines (OWTG).* Approval for the disposal of residual treatment chemicals within the produced water discharge stream is granted under the *Guidelines Respecting the Selection of Chemicals Intended to be used in Conjunction with Offshore Drilling and Production Activities (Offshore Chemical Screening Guideline - OCSC).*

With the lack of direct evidence for acute toxicity in produced water plumes there has been little demand for more rigorous protocols to monitor the discharge of contaminants in the produced water discharge stream. However, recent studies in the North Sea have suggested that environmental impacts may be attributed to constant exposure to produced water discharges. As a result, some regulatory agencies and members of the environmental community are now requesting a zero discharge limit for produced water.

Reinjection has been proposed as an alternative to produced water discharge. For offshore operations, this control system is not supported by industry due to cost considerations and the enormous level of logistics involved. To address this issue in an environmentally sound manner, scientific research within DFO and elsewhere is being conducted to identify acceptable disposal limits for produced water. Data from these programs may justify a reduction in the level of produced water treatment prior to discharge and/or the need for disposal by re-injection.

Since the composition of produced water between different sources and geological formations can vary by orders of magnitude on a constituent-specific basis, a regional study has been initiated by DFO to address:

- the chemical characteristics of the produced water;
- the significance of flocculation processes in the transport of produced water contaminants;
- the identification of potential impacts of produced water, if any, on commercial species and other marine biota;
- methods to identify and trace the impact zone of produced water discharge; and
- the application of numerical models to interpret and predict the distribution of produced water from offshore hydrocarbon platforms.

An ecological risk assessment will be provided once all data are collected, but initial results are of relevance to improving the current OWTG.

A preliminary multidisciplinary study has been conducted with samples of produced water collected by PanCanadian from the Cohasset offshore production well on the Scotian Shelf to understand the mechanisms controlling the transport, fate and biological effects of discharged produced water. In addition to petroleum hydrocarbons (within current waste treatment guideline limits), elevated concentrations of Al, Cd, Co, Cu, Fe, Pb, Mn, Ni, and Zn were measured in total, particulate and dissolved phases. Within the Cohasset field alone, the concentrations of both inorganic and organic contaminants have been found to be highly variable over temporal and spatial scales. Furthermore, other offshore gas wells on the Scotian Shelf, such as those operated by Sable Offshore Energy Incorporated (SOEI), have been reported to produce condensed water without the high concentration of brines traditionally reported in produced water. Due to this inherent level of variability in the composition of discharged produced waters, it is very difficult to predict accurately the level of environmental impacts within the Atlantic Region associated with produced water discharges.

Biological effects may be induced by produced water containing hydrocarbon levels deemed acceptable by the current *Offshore Waste Treatment Guidelines.* These include both stimulatory and inhibitory effects. For example, the high concentration of inorganic nutrients in produced water may alter the rates of primary production and/or changes in microbial community structure in offshore waters. The potential toxicity of produced waters from the Cohasset site has been demonstrated with a number of biotests with various endpoints including MFO induction in fish, sea urchin fertilization success, amphipod survival and growth, inhibition of bacterial bioluminescence and productivity, and survival of larval commercial fisheries species. Results from the Microtox® assay (inhibition of bacterial bioluminescence) showed that produced water toxicity changed with time as a result of chemical kinetics following its discharge into open ocean waters. Furthermore, toxicity was associated with both dissolved and particulate fractions (Lee et al., 2000).

Numerous research studies from other offshore oil and gas sites around the world have concluded that produced water discharges to the open ocean cause little or no measurable effects in marine organisms within the pelagic zone. This is primarily because the toxicity of produced water is relatively low and dilution rates are high. Recent DFO studies on surrounding water at the Hibernia site have supported this conclusion. No significant changes (either stimulatory or inhibitory) were observed between depth profiles of microbial activity with distance from the Gravity Base Structure (**Fig. 8**). Additional DFO studies have also shown that

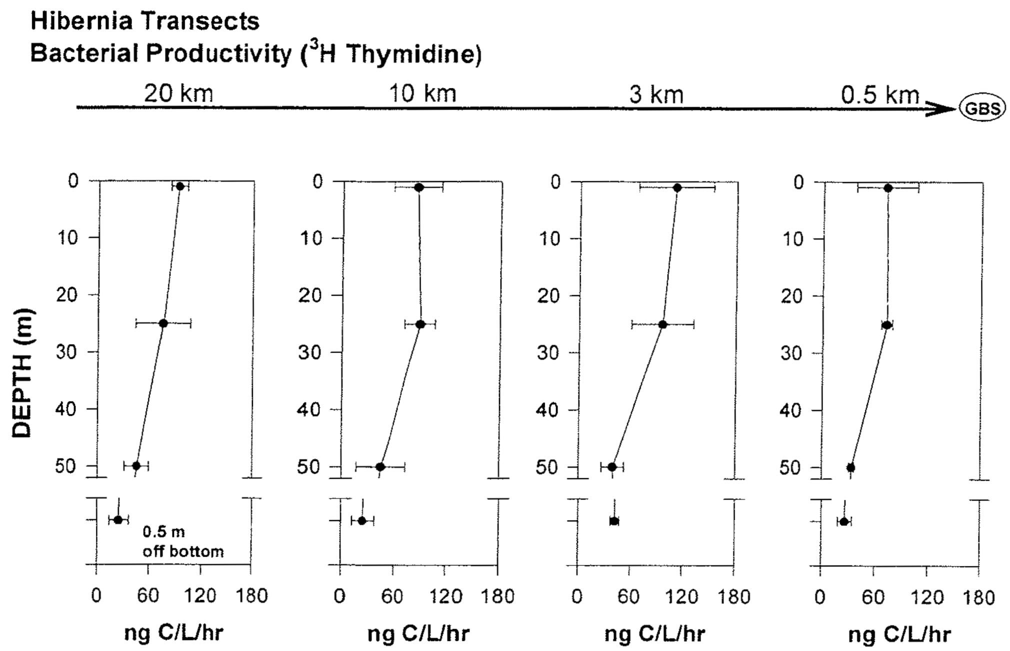


Figure 8. Rates of bacterial production over depth with distance from the Hibernia Gravity Base Structure (GBS). Productivity rates were determined by the measurement of 3H-thymidine incorporation into DNA.

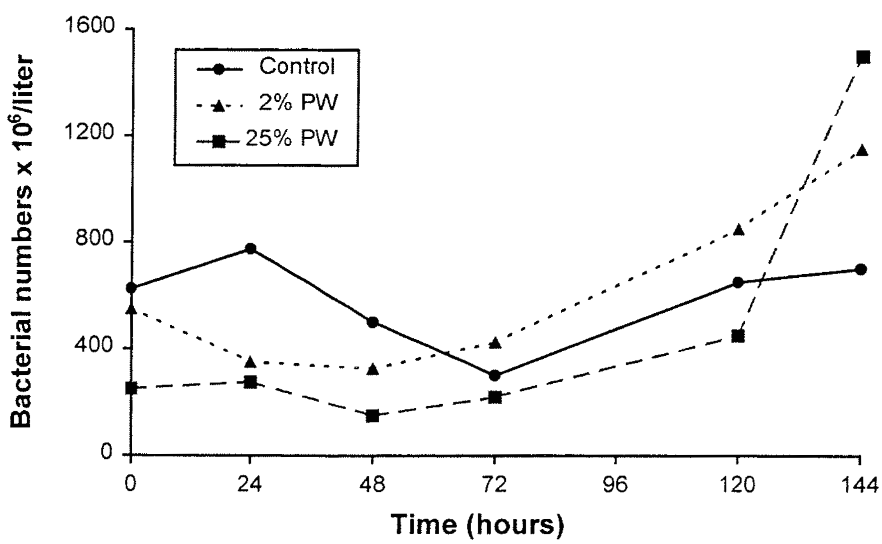


Figure 9. Changes in bacterial numbers over 144 hours in response to produced water exposure at 2 and 25% levels. The results illustrate a stimulatory response after an adaptation period for indigenous bacteria during which some volatile hydrocarbons may have also been lost as a result of physical processes (evaporation). Gas chromatograpy/mass spectroscopy analysis confirmed that bacteria significantly degraded the hydrocarbon constituents within produced water.

predominant organic constituents (organic acids, phenols and hydrocarbons) in produced water are effectively biodegraded by indigenous microorganisms following a period of adaptation.(**Fig. 9**). While this stimulation of bacterial activity is generally considered positive, it must be noted that such changes may alter the food web that regulates all living resources.

In terms of the particulate fraction of contaminants in produced water, laboratory studies have shown that the heavy metals in produced water samples from the Cohasset site were rapidly transformed from a dissolved to particulate form and the majority of these precipitates flocculated into large particles that settled rapidly (>100 m d^{-1}). Positively buoyant oil droplets that sequestered particles on their surface were also observed. Such flocculation processes can mediate the rapid transport of contaminants to the surface microlayerand the benthic boundary layer of the seabed. The environmental significance of these contaminant transport and concentration mechanisms has not been evaluated. Their occurrence may help to explain the results of North Sea investigations that indicate potential effects of offshore drilling activities on fish, larvae and benthic organisms around platforms at considerable distances. Furthermore, considering the potential ability of these mechanisms to transport produced water contaminants, a reliable prediction of impact zones for produced water discharges cannot be based on simple plume dispersion models for the water column.

The concentration of natural radionuclides (^{226}Ra, ^{228}Ra, ^{210}Pb) has been determined for produced waters recovered from the Scotian Shelf. While compounds such as ^{228}Ra have enrichment factors as high as 20,000; they are not considered to be a human health risk. However, these compounds may be used to follow the partitioning of components in produced water following its discharge. Since Ra tends to remain in solution it can be used to track the dispersion of the produced water effluent. Daughter products such as ^{210}Pb and ^{210}Po rapidly associate with fine-grained particles in seawater and can thus be used to track the behavior of particle-reactive compounds.

The volume of produced water discharges will undoubtedly increase with the expansion of offshore oil and gas production operations in Atlantic Canada. Overall, oil fields situated on major fishing grounds that discharge large quantities of production waters within an area that is impacted by discharges from adjacent fields, present the most concern for potential cumulative impacts of production water on fish and fish habitat. Of special importance in this regard are sites with limited dispersion potential on an annual or seasonal basis.

Conclusions from Produced Water Studies

- Produced water (PW) contains a number of contaminants of environmental concern including; hydrolysis and heavy metals, petroleum hydrocarbons, nutrients, radionuclides, and treating chemicals.
- Heavy metals in PW can rapidly transform from a dissolved to particulate form in seawater and these precipitates can flocculate into large particles that settle rapidly.
- Toxicity has been correlated with both dissolved and particle fractions produced during the discharge of produced water.
- The toxicity of discharged PW is variable over spatial and temporal scales due to source variations and chemical kinetics.
- There is concern that PW contaminants may become concentrated in benthic and surface microlayers.
- The chronic toxicity potential of long term exposure of marine organisms to low levels of production waters is relatively unknown.
- As a result of chemical kinetics that facilitates contaminant partitioning between the surface microlayer, water column and sediments, current model predictions of PW dispersion do not adequately describe the potential exposure of marine organisms to associated contaminants.
- Produced waters extracted from the Scotian Shelf contained natural radionuclides at concentrations below that of human health risk concern.

4. Monitoring and Protection Programs

Important gaps in knowledge remain with respect to factors affecting dispersion of drilling discharges and chronic ecotoxicological effects of offshore oil and gas activities. An additional important step in addressing uncertainty is to have in place rigorous monitoring programs which will provide early warning of any adverse environmental impacts. An ecosystem approach should be taken. This program should include studies to monitor potential alterations in trophic level dynamics as well as specific impact studies on fish (including shellfish), fish larvae, plankton and bottom sediment communities in sensitive areas. In addition to compliance monitoring goals, environmental monitoring program objectives should include:

- establishing a basis for assessing temporal and spatial trends in contaminant distributions and effects on the fisheries and fish habitat in relation to discharges from oil and gas installations;
- assessing the predictions of environmental impact assessments, and identifying areas of concern;
- detection of unforseen effects; and
- contributing to the identification of cause-effect relationships.

Environmental monitoring and protection programs should be developed in consultation with all stakeholders and should address site- and project-specific elements including the potential for cumulative impacts in conjunction with other sources (Gordon *et al.* 2000b). Site specific oil and gas monitoring programs should be coordinated regionally so that interactions between drilling/production sites may be detected. The program design must take into account both scientific and statistical principles of analysis. To take into account the level of natural variation in measured parameters; initiation of a monitoring program is recommended prior to project operations. The monitoring should continue through and beyond the decommissioning phase to assess recovery time. The exact nature and extent of compliance and environmental effects monitoring should be proportional to the predicted level for environmental impacts. Stakeholder advisory committees, such as the Sable Offshore Energy Environmental Effects Monitoring Advisory Group (SEEMAG), should be established for oil and gas production projects, wherein EEM data reports can be scientifically reviewed using an adaptive management framework. This approach is flexible and responsive to issues arising at a particular locale or region.

Monitoring programs should use an ecosystem-based approach and consider physical, chemical, biological and social conditions. Studies should be focused on the assessment of potential biological impacts to organisms at all trophic levels. An accurate environmental risk assessment cannot be made on the basis of results from single species tests. The significance of impacts on trophic level dynamics must be recognized. A change to one trophic level within the ecosystem will be reflected to all others. For the prediction of long-term effects, studies on the chemical and environmental persistence of the contaminants must also be made.

To ensure the co-existence of the fishing and offshore oil and gas industry, the program should have an emphasis on the nature and extent of any unanticipated adverse effects on fish and fish habitat. Thus, the program should include monitoring of effects on fish health, including early and adult life stages, as well as tainting and contamination. This is particularly important given studies on MFO enzyme levels (stress response) in adult and larval fish in the North Sea, as well as our chronic toxicity studies with American plaice captured around the Hibernia platform, and studies that predict reproductive inhibition in scallops on Sable Island and Georges Banks. Effects on fish have been demonstrated with exposures to aliphatic hydrocarbon based drilling fluids including the potential for reproductive dysfunction at higher exposure levels (e.g. Idler *et al.*, 1995). Fish health measures suggested for monitoring programs include MFO enzyme levels, histopathology and reproductive status. Investigations of zones of impact on benthic communities are necessary to assess the degree of fish habitat loss/alteration. It is important that observations on COSEWIC-listed species, marine mammals and birds also be included.

Identification of the zone of chemical contamination (i.e. hydrocarbons and heavy metals) in sediments and biota remains an important means of testing hypotheses and model predictions made in environmental impact assessments. However, these do not replace the need for measures of fish health as there are few studies that link environmental and body-burden chemical concentrations to health effects. The use of sensitive health indicators in monitoring programs, particularly those that integrate effects across all classes of potential contaminants (e.g. changes in primary metabolic processes, fish histopathology and shellfish growth and reproductive output) provide an early warning system for detecting problems that may not have been anticipated. Histopathology is being used increasingly in monitoring programs, and has been adopted by the Oslo-Paris Commission for environmental quality studies in the North Sea. Histopathology provides a tool for investigating the potential cumulative effects of various contaminants whether they be related to drill cuttings, production waters, etc.

Physiological/pathological indicators can play a valuable role in defining (a) the degree and nature of impacts at petroleum development sites, (b) whether effects might be negligible or significant, and (c) whether further regulatory actions might be required. Bioindicators should be used in combination with contaminant body burden measurements to provide insight into causal relationships.

Essential Elements of Environmental Monitoring and Protection Plans

- The degree of environmental monitoring required should be proportional to the potential for environmental impacts associated with the specific drilling site.
- The program should address site- and project-specific elements and the potential for impacts from other sources.
- The program needs to be scientifically and statistically sound and in place before project start-up so that baseline conditions are known.
- The program should include monitoring of physical, chemical, and biological variables.
- Emphasis should be placed on determining the nature and extent of any adverse effects on biota and fish habitat, including unanticipated effects.
- The program should utilize sensitive health indicators that integrate effects across all classes of potential contaminants to provide an early warning system for detecting problems.
- The risk assessment should take an ecosystem approach. The monitoring program should include biotests for all trophic levels and incorporate a component to identify potential changes to trophic level dynamics.
- Long term chronic toxicity studies with fish reinforce the need to include studies on effects on fish in monitoring programs, with choice of species being related to development site.

5. Implications for Offshore Waste Treatment Guidelines

Offshore Waste Treatment Guidelines should be reviewed and revised on a regular basis to incorporate new scientific knowledge and experience gained by scientists, operators and regulators on unanticipated impacts from waste discharges to the offshore environment. The major conclusions of the DFO research programs summarised herein should be presented by senior DFO management to the Guidelines Review Group for their consideration in the interest of further reducing the risk that unanticipated environmental impacts may be occurring.

The potential for environmental impacts from drilling and production waste discharges is related to both the concentration of contaminants in the effluent and the rate at which they are released. The product gives the total release of the contaminant in a given time period. A low concentration released at a high rate can cause as many problems as a high concentration released at a low rate. The present guidelines deal only with concentrations (or particle size in the case of sanitary and food wastes) of wastes and there is no consideration of the rate of release or the presence of multiple contaminants in different waste streams (e.g. hydrocarbons, metals, fine particles, etc.) that may vary in concentration over different time scales. There are currently no limits on the total amount of discharge allowed per unit time and this is a serious omission.

The strategy used in the current *OWTG* assumes that all contaminants below a concentration threshold will be dispersed regardless of discharge rate. Model predictions of environmental waste concentrations during typical exploration drilling operations indicate that bulk discharges of WBM may permit contaminants (fine particulate matter) to exceed concentrations that have been shown to impact the health and reproductive potential of sensitive marine organisms (e.g. scallops). Model-based risk assessments suggest that this practice could result in detectable and significant population and ecosystem level effects in some areas of the eastern Canadian shelf. Mitigation measures are available to industry to prevent such biological effects thresholds from being exceeded. One such measure is the utilization of a non-toxic synthetic-oil-based drilling fluid. DFO and worldwide research has confirmed that suitable alternative drilling fluids are now available and are already in use in Canada. Owing to the high cost of these fluids, they are recycled, eliminating the need for bulk WBM dumps and removing the identified environmental risk associated with this operational activity. Alternatively, if WBM is to be used, discharge strategies that maximize dispersion, such as pre-dilution and discharge into the strongest available current regime, have the potential to keep environmental concentrations below toxic threshold levels.

A second major outcome of our research, that stems from physics-based model predictions of drilling waste transport and dispersion, is that there are large spatial variations in the capacity of the receiving environment on the eastern Canadian shelf to disperse wastes. As a result, some offshore regions are inherently more susceptible to environmental impacts than others. The current *Offshore Waste Treatment Guidelines* provide the same level of environmental protection for all regions. A more flexible waste treatment guidelines approach that permits the implementation of different guidelines and standards under different environmental conditions could be cost-effective. It could also provide an even greater level of marine ecosystem protection for particularly vulnerable or unique fish and fish habitats while not placing undue limitations on industry wishing to drill in highly dispersive areas where effects are predicted to be less. Ecological risk assessment tools, including the *bblt* model, could serve to provide objective and conservative (i.e. precautionary principle) estimates of the potential sensitivity of each location to operational discharges from oil and gas exploration, development and production activities.

The ecological effects of wastes associated with production operations is the focus of a new DFO study funded by PERD The volume of produced water discharged into the marine environment will increase in the future. The discharge of produced water is a continuous process during the life of a production facility. While rapid dilution of the effluent stream is likely to reduce the concentrations to levels which are not acutely toxic to marine organisms, the possibility of chronic long-term effects cannot be excluded. Preliminary results of our studies have demonstrated a high level of spatial and temporal variability for contaminants within produced water samples recovered from the Atlantic Region. Furthermore, there is evidence that produced water contaminants may become concentrated within environmental compartments of known ecological importance (e.g. surface microlayer, benthic boundary layer).

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