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ASSESSMENT OF THE EFFECTS OF SUSPENDED DREDGE MATERIAL ON AQUACULTURE ORGANISMS

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ABSTRACT

Several Atlantic Canadian aquaculture species were exposed to suspended particulate material (SPM) in laboratory and field experiments to investigate the effects of SPM concentrations typical of dredging operations on growth, length, weight, condition and mortality. In general, either no effect or slight negative effects were observed. The study also reviewed literature on effects of SPM on aquatic biota and includes data on SPM concentrations in the Maritimes.

A 30-day exposure of 100 g rainbow trout (Onchorhynchus mykiss) to fluctuating SPM concentrations (11-356 mg L-1) from an addition of silt once a day to continuous flow experimental chambers, resulted in no difference in growth rate, condition index, and average weight and length compared to a control group. A 6-day exposure to continuous SPM concentrations (180 mg L-1), resulted in a large proportion of the trout in both experimental and control showing negligible weight gains, indicative of a failure to feed. The proportion of trout demonstrating negligible weight gains was larger in the SPM exposure group. No acute mortality (96 hours) was observed for rainbow trout exposed to an average SPM concentration of 360 mg L^{-1} (range 100-658 mg L^{-1}).

A 35-day laboratory exposure of blue mussels and European oyster to an average SPM concentration of 157 mg L^{-1} led to smaller tissue weights and condition index than control for the oyster, but no differences for mussels. No acute mortality (96 hours) was observed for blue mussels and European oysters at concentrations ranging from 91-258 mg L^{-1}.

Two size classes each of blue mussel (Mytilus edulis), European oyster (Ostrea edulis), and sea scallop (Placopecten magellanicus) deployed beside a channel dredging project in Pugwash Harbour, Nova Scotia, showed no effect except for a slight reduction in condition index near the dredged channel (indicative of a negative effect) for small mussels and large oysters. Lobster (Homarus americanus) held in cages in the area and at a control site did not differ in weight and incidence of particles on the gills.

Weight and condition index of blue mussels suspended from a wharf in Souris Harbour, Prince Edward Island, were less than in mussels moored in the outer harbour where SPM concentrations were lower, indicating a slight negative effect of SPM. Mussels and American oyster (Crassostrea virginica) hung from one part of the wharf had a smaller condition index than those hung from a part of the wharf where SPM was lower. Bay scallops (Argopecten irradians), however, did not differ significantly in weight and condition index between the two locations on the wharf.

RÉSUMÉ

Plusieurs espèces aquicoles typiques de la côte Atlantique canadienne furent exposées à différentes concentrations de matière en suspension (MES) afin de vérifier, sur le chantier et en laboratoire, l'impact sur leur croissance, longueur, poids ainsi que sur leur indice de condition et leur taux de mortalité. En général, l'incidence négative était absente ou très faible. On a aussi effectué un relevé des travaux publiés sur les incidences des MES sur la faune aquatique et on présente des données sur les concentrations en MES dans divers secteurs des Maritimes.

Des truites arc-en-ciel (Oncorhynchus mykiss) de 100 g exposées pendant 30 j à des concentrations variables de MES (11-356 mg/L) par ajout de limon, une fois par jour, aux bassins expérimentaux à débit continu n'ont pas montré de variations de leur taux de croissance, de leur indice de condition et de leurs poids et longueur moyens par rapport à un groupe témoin. Une exposition à des concentrations soutenues de MES (180 mg/L) pendant 6 j s'est traduite par un faible gain de poids chez la plupart des truites du groupe expérimental et du groupe témoin, gain indicateur d'une alimentation insuffisante. Le pourcentage d'individus montrant un faible gain de poids était plus élevé dans le groupe exposé à des MES. Par contre, les truites exposées à une concentration moyenne en MES de 360 mg/L (écart: 100-658 mg/L) n'ont pas montré un taux de mortalité aigu (96 h).

Chez les moules bleues (Mytilus edulis) et les huîtres plates (Ostrea edulis) exposées pendant 35 J à une concentration en MES de 157 mg/L, on a observé que le poids de la masse corporelle et l'indice de condition étaient plus faibles chez les huîtres, mais n'avaient pas varié chez les moules. De plus, aucune mortalité aigue (96 H) n'a été observée chez ces espèces à des concentrations variant de 91 à 258 mg/L.

Il n'y a eu aucun impact sur deux groupes de taille différente de moules bleues, d'huîtres plates et de pétoncles géants (Placopecten magellanicus) déposés près du projet de dragage du chenal de Pugwash (Nouvelle-Ecosse) sauf pour une légère baisse de l'indice de condition (indicatrice d'une incidence négative) chez les petites moules et les grosses huîtres. Des homards (Homarus americanus) gardés en cages dans cette région et à un site témoin n'ont pas montré de variations de poids et d'incidences de particules sur leur ouies.

Le poids et l'indice de condition des moules bleues suspendues au quai de Souris (Ile-du-Prince-Édouard) sont moindres que ceux observés chez des individus immergés dans l'avant-port où les concentrations en MES étaient moins élevés: cette différence révèle une légère incidence négative des MES. Des moules et des huîtres creuses américaines (Crassostres virginica) suspendues au quai ont montré un plus faible indice de condition que les individus immergés à un endroit où les concentrations en MES étaint moins élevées. Toutefois, le poids et l'indice de condition des pétoncles de baie (Argopecten irradians) immergés à ces deux endroits n'ont pas montré de différences significatives.

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Executive Summary

EXECUTIVE SUMMARY

This study was supported under the Unsolicited Proposals Program of Supply and Services Canada and the Ocean Dumping Research Fund, administered by Environment Canada, Environmental Protection. Chapter 1 is an overview of the literature on the effects of suspended particulate matter (SPM) on marine and freshwater organisms, and contains a summary of marine SPM concentrations in the Canadian Maritimes. Chapter 2 contains an assessment of effects of field and laboratory experimental exposures to elevated SPM of rainbow trout (Onchorhynchus mykiss)[1] and a variety of shellfish, including lobster (Homarus americanus), blue mussel (Mytilus edulis), European oyster (Ostrea edulis), American oyster (Crassostrea virginica), sea scallop (Placopecten magellanicus) and bay scallop (Argopecten irradians). Chapter 3 contains conclusions of the study.

The major results are summarized in Table 1. One exposure was carried out at Pugwash, Nova Scotia, in the vicinity of a 56,000 m^3 channel dredging project using a bucket dredge. Mussels, European oysters and sea scallops were deployed for three weeks in hanging nets, and lobsters were deployed in bottom cages, at a control site and at two sites near the dredging operation. The dredging activity did not result in elevation of SPM over the area as a whole, although elevated SPM (mean 45 mg L^{-1}; maximum 88 mg L^{-1}) was observed in the dredge plume and likely was experienced at the experimental sites when the dredge operated near them. Few clear differences attributable to the dredging were observed in size, weight, and condition index for bivalves, and no differences were noted in weights and particle incidence on the gills in lobster. An exception, indicating a potential effect in the sites near the dredging, was noted for small mussels and large European oysters which had lower condition indices near the dredging operation than at the control site. Results with small oyster and scallop, although suggestive of enhanced growth for one or more of the deployment sites in the vicinity of dredge, may be suspect due to problems with shell

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[1] Onchorhynchus mykiss is the new scientific name for rainbow trout (Salmo gairdneri).

TABLE 1.

SUMMARY OF RESULTS

Study Component		Conclusion
Pugwash Harbour, N.S.	o	SPM never greater than about 100 mg L^{-1} near, and in the plume of, a bucket dredging operation.
	o	SPM concentrations were highly localized; no differences in SPM observed between sites near an operating dredge and a control situation.
	o	Possible negative effects of dredging on condition index for blue mussel (*Mytilus edulis*) and European oyster (*Ostrea edulis*). No effects on sea scallop (*Placopecten magellanicus*) and lobster (*Homarus americanus*).
Souris Harbour, P.E.I.	o	Exposure to turbid water (SPM > 10 mg L^{-1}) at a wharf caused reduced growth or changes in condition in blue mussel (*Mytilus edulis*), bay scallop (*Argopecten irradians*) and American oyster (*Crassostrea virginica*).
Laboratory Experiments	o	No effect on shell growth and tissue weight for blue mussels (*Mytilus edulis*), and reduction in tissue weight and condition index relative to controls in European oysters (*Ostrea edulis*) during 35-day exposure to SPM (157 mg L^{-1}).
	o	Respiration rate reduction, and decreased O/N ratio and growth, indicating reduced food availability in softshell clam (*Mya arenaria*) during 35-day exposure to SPM (157 mg L^{-1}).
	o	Inhibition of feeding in rainbow trout *Onchorhynchus mykiss* at constant SPM (178 mg L^{-1}) through delayed recovery from handling stress or interference with food finding.
	o	No effect on growth of rainbow trout from a 30-day exposure on a pulsed daily SPM regime ranging from 11-356 mg L^{-1}.
	o	No acute mortality (96 hours) to blue mussels and European oysters (91-258 mg L^{-1}), and rainbow trout (360 mg L^{-1}).

abrasion during deployment. No significant mortality was observed among the three sites.

The Souris, PEI, exposure consisted of two moorings of lantern nets in the outer harbour (controls) and cages suspended from a wharf in higher SPM environments in the inner harbour. Mussels (Mytilus edulis), bay scallop (Argopecten irradians) and American oyster (Crassostrea virginica) were exposed. The experiment detected reduced weight and condition in mussels in the inner harbour sites, representing a possible effect of elevated SPM there. Little difference between sites representing low and high SPM in the inner harbour, was noted for all test organisms, although there was a tendency for reduced weight and condition at the high SPM site. Other factors affecting feeding and growth were assumed to be comparable for the sites.

A 35-day laboratory exposure to SPM at concentrations averaging 157 mg L^{-1} resulted in reduced tissue weights and condition index of European oyster but had no effect on growth and condition parameters or mortality of blue mussels. There was a suggestion that growth rate, as measured by shell growth increment, was smaller in mussels exposed to the high SPM, and a parallel study which used a laser technique to measure microgrowth, also detected slight, though statistically insignificant reduction in growth rate in the exposed animals. Oxygen consumption and the ratio of oxygen consumption to ammonia excretion (O/N ratio) in softshell clams exposed with the mussels and oysters showed evidence of reduced filtration and ingestion of food when exposed to SPM, as indicated by decreased respiration rate and decreased O/N ratio in the experimental group.

Rainbow trout showed no effect in growth resulting from exposure to cyclic SPM concentrations of 10.7 to 355.8 mg L^{-1} for 30 days. Exposure to average concentrations of 361 mg L^{-1} (96 to 658 mg L^{-1}) for 4 days caused no mortality. Continuous SPM at a concentration of about 180 mg L-1 for six days decreased the proportion of fish feeding, possibly by causing additional stress which inhibited feeding and by preventing the fish from seeing the food. Fish in the control also showed inhibition in feeding

during the 6-day experiment, probably as a result of stress during handling, but the proportion was smaller.

In general, either no effect or small to moderate negative effects of SPM at concentrations of from 100-200 mg L^{-1} were observed, a finding which agrees with findings of the effects of SPM on molluscs in the literature. Rainbow trout exposed for as little as six days showed feeding reductions, although the fish later recovered and fed normally.

To avoid negative effects of SPM resulting from dredging it is suggested that SPM concentrations in the vicinity of a dredging operation not be allowed to continuously exceed the approximate peak natural levels in the area, approximately 200 mg L^{-1} in high turbidity environments (in erosional areas) and 100 mg L^{-1} in normally low turbidity environments (rocky coastlines). Where salmonid aquaculture is concerned, any situation in which SPM exceeds 100 mg L^{-1} on a continuous basis should probably be avoided.

1. Literature Survey

CHAPTER 1

LITERATURE REVIEW

EFFECTS OF SUSPENDED SEDIMENT FROM DREDGING ON AQUACULTURE ORGANISMS

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1.0 INTRODUCTION

Dredging, the removal of bottom material for channel and harbour maintenance or construction activity, is one of the most common human impacts in coastal and estuarine environments. The activity may have a variety of effects, including introducing a wide variety of organic and inorganic, suspended and dissolved compounds, as well as suspended particulate matter (SPM) into the water column, potentially impacting local biota and perturbing water quality. With increasing use of coastal and estuarine areas for aquaculture, particularly of shellfish and salmonids, conflicts of dredging operations and aquaculture facilities are bound to arise.

There is little information on effects of SPM on aquaculture organisms. SPM effects have been studied for decades, however, on a wide range of fish and invertebrates, both from an ecological and toxicological point of view. Some of the studies have focused on the acute effects of suspended sediment on organisms through short term toxicological tests using high, and often unnatural, concentrations of suspended material. This acute testing has indicated a wide range in response, sometimes indicating a surprising tolerance for suspended sediment, but also some toxicity. Most always there is some damage to the organism.

Lower levels of suspended sediment (even at or near ambient), however, can also affect organisms in a variety of ways, which influence their fitness by interfering with physiology, energetics, predator-prey relationships, and food availability. Although many have adapted or have the ability to acclimate to elevated suspended sediment concentrations in their normal habitat, suspended sediment, even at ambient concentrations, usually has some cost to the organism.

This review will consider both acute and sublethal effects of suspended particulate matter on invertebrates and fish in general, and on aquaculture organisms in particular. It puts particular emphasis on sublethal effects, which are most likely to occur given the moderate levels of SPM to which Maritime aquaculture organisms are likely to be exposed during dredging activity. Levels of SPM, both natural and those to be expected as a result of dredging activity, are discussed to a limited extent.

2.0 SUSPENDED PARTICULATE MATERIAL (SPM) IN THE MARINE ENVIRONMENT

2.1 Natural Suspended Particulate Matter

General

Moore (1977) has summarized the range of SPM levels observed in marine environments (Table 1). Suspended matter concentrations in inshore waters often amount to several milligrams per litre with an overall average of 1.0 mg L^{-1} (Chester and Stoner 1972) (from Moore 1977). Typical nearshore levels are illustrated by several studies. Resuspended matter levels in Buzzards Bay, Massachusetts, were 35 mg L^{-1} (Rhoads 1973). In central Long Island Sound SPM levels are 10 - 40 mg L-1 (Rhoads et al 1984). Particulate inorganic matter concentrations in a Norwegian fjord were 3.3 to 9.4 mg L-1 (Wallace and Reinsnes 1985) and the particulate organic matter levels ranged from 0.7 to 3.9 mg L^{-1} with particulate inorganic matter concentrations from 2 to 5 times higher. Winter levels of SPM in a river estuary in southwest England were from 20 to 35 mg L^{-1} (organic content 6%) and in summer were less than 5 mg L^{-1} (organic content, 25%) (Widdows et al 1979).

Table 1. Levels of Suspended Particulate Matter in the Marine Environment (mg/L). From Moore (1977)

Reference	Locality	Comments	Dry wt seston
Buchan, Floodgate & Crisp (1967)	Menai Strait (U.K.)	Inshore (inorganic)	0·5–50
Postma (1961a)	Wadden Sea	Coastal	80
Manheim, Hathaway & Uchupi (1972)	Gulf of Mexico	Surface (inshore)	64
		Surface (offshore)	0·125
Young (1971)	Buzzards Bay (U.S.A.)	Epibenthic nepheloid layer	1·4–3·4
Bond & Meade (1966)	Chesapeake Bay	Surface	
		(estuarine)	3–8
		(coastal)	0·5–2
Chave (1965a)	S.W. Florida, Caribbean	Surface	5
Kajihara, Inoue & Nakamura (1972)	Yoshioka River (Japan)	Coastal	1–10
Gibbs (1974b)	Amazon shelf, tropical Atlantic	Within 100 km of shore at high river discharge	2·0
Drake (1971)	Santa Barbara Channel—shelf edge	After floods, 1 m above bottom	8–10
Drake (1974)	Submarine canyons (S. California)	Canyon floor	0·4–6
Wolff (1973)	North Sea	Offshore	10
Drake, Kolpack & Fischer (1972)	Santa Barbara—Oxnard shelf (during floods)	Near bottom (offshore)	2
		Near bottom (inshore)	50
Pierce, Nelson & Colquhoun (1972)	Continental shelf (Chesapeake Bay, Savannah, Georgia, U.S.A.)	—	0·5–8·44
Vityuk (1975)	Black Sea	—	0·12–2·8
Chester & Stoner (1972)	English Channel	Surface	1·719
	Irish Sea	Surface	1·680
	Inland Sea (Japan)	Surface	1·452
Folger *et al.* (1972)	Somes Sound, Maine (U.S.A.)	Nr. surface and near bottom	0·6–4·1
Roy & Smith (1971)	Fanning Island Lagoon, C. Pacific	Turbid area	3·5
		Clear area	1·0
		Outside fringing reef	0·3
		Open ocean	0·03
Pak (1974)	Equatorial Pacific	Surface	0·11–1·76
		Below 25 m	0·04–0·092
Buss & Rodolfo (1972)	Continental shelf off Cape Hatteras, U.S.A.	Surface (inshore)	2 (11·8 max)
		Surface (offshore)	0·1
		Mid-depth	1–2
		Nr. bottom	0·5–2
Emelyanov & Shimkus (1972)	Mediterranean	Surface	0·2–2·3
		100–3,000 m	0·4–1·0
Zeitschel (1970)	Gulf of California	Surface-50 m	0·11–1·4
Harris (1972)	Gulf of Mexico	Shelf (0–100 m)	0·149–2·38
		Open Gulf (surface)	0·063–1·63
		Open Gulf (deep)	0·022–0·64
Harris (1972)	Indian Ocean	(after Lisitsyn)	1·06
	N. Atlantic	(after Vikhrenko & Nikolaeva)	1·26
	S. Atlantic	(after Gordeyev)	0·88
	N. Atlantic	(after, Folger)	0·87
Ingle (1966)	Suspended sand	In breaker zone	27,000
	Suspended sand	Immediately seawards of breaker zone	1,000–4,000
Schubel (1974)	Chesapeake Bay	During hurricane	10,000
Purchon (1937)	Bristol Channel U.K.	Estuarine	5,700
Evans & Collins (1975)	The Wash (U.K.)	Intertidal flats	< 1,200
Halliwell & O'Connor (1967)	R. Mersey (U.K.)	Estuarine	1,000
Kendrick (1972)	R. Thames (U.K.)	Estuarine mud reaches	2,000
Jackson (1964a)	R. Humber (U.K.)	Estuarine	≈ 150–≈ 900
Gallene (1974)	R. Loire (France)	Estuarine turbidity maximum	≈ 1,000
Meade (1969b)	Savannah River (U.S.A.)	Estuarine	25–8,900
Bassindale (1943)	Bristol Channel (U.K.)	At Weston-Super-Mare	30–900
Wolff (1973)	Rivers Rhine, Meuse, and Scheldt	Estuarine	50–1,000
Postma (1961b)	Wadden Sea	Coastal	1,000
Scruton & Moore (1953)	Off Mississippi delta	Inshore (surface)	260–640
Kester & Courant (1973)	Chesapeake Bay	During spring freshet	
		(head of Bay)	140
		(mid Bay)	20
Moore (1972)	N. Yorkshire (U.K.)	Coastal	8·4–314·4
Patten (1966)	York River (U.S.A.)	Estuarine	
		(inorganic)	0–224
		(organic)	0–27
Patten, Young & Roberts (1966)	Lower York River (U.S.A.)	Estuarine (inorganic)	0·6–192·4
Schubel (1971)	Chesapeake Bay	Turbidity maximum	10–300
Schubel (1974)	Chesapeake Bay	Normal background	100
Melbourne & Metropolitan Board of Works (1973)	Port Phillip Bay, Australia	Coastal	2·4–32·0
Verwey (1952)	Wadden Sea	Average	25
McCarthy, Pyle & Griffin (1974)	Anchote estuary (U.S.A.)	Estuarine	22·1–47·2
Sharma & Burbank (1973)	Port Valdez, Alaska	Surface-10 m	2–600
		10 m–100 m	2–5
Ouellette (1970)	Mississippi River (South Pass)	Inshore (various depths)	5–125
Persoone & De Pauw (1968)	Ostend Harbour	Inshore	75–150
	Westerschelde	Estuarine	20–70
	Lower Elbe	Estuarine	50–200
Newton & Gray (1972)	N. Yorkshire (U.K.)	Inshore	3–50
Gopinathan & Qasim (1971)	Cochin Backwater, India	Pre-monsoon (surface	1–10
		Monsoon (surface)	30
		Monsoon (middle)	50–60
Garcia de Ballesteros & Larroque (1974)	Gulf of California	Inshore (surface)	1–100
Harris (1972) *contd*	N. Indian	(after Gordeyev)	0·178
	Pacific	(after Lisitsyn &	0·957
		Bogdanov)	0·957
	N. Atlantic	(after Jacobs & Ewing)	0·049
	S. Atlantic	(after Jacobs & Ewing)	0·051
	N. Pacific	(after Jacobs & Ewing)	0·038
	S. Pacific	(after Jacobs & Ewing)	0·030
	Indian	(after Jacobs & Ewing)	0·072
	Gulf of Mexico	(after Jacobs & Ewing)	0·066
	N. Atlantic	(after Gordon)	0·155
	Atlantic	(after Svirenko)	0·58
Chester & Stoner (1972)	N. Atlantic	Surface (average)	0·467
	S. Atlantic	Surface (average)	0·15
	Indian	Surface (average)	0·066
	China Sea	Surface (average)	0·127
	Oceanic deep-sea	Average (incl. N. Atlantic)	0·199
	Oceanic deep-sea	Average (excl. N. Atlantic)	0·110
	Java Sea	Surface (average)	0·747
	S. Japanese coast	Surface (average)	0·245
	S. African coast	Surface (average)	0·456
L. A. Hobson (1967)	N.E. Pacific	Below 250 m	0·03–1·0
Baker, Sternberg & McManus (1974)	Nitinat Fan, off Continental slope, Washington, U.S.A.	Bottom nepheloid layer (inorganic)	0·02–0·08
Ichiye, Bassin & Harris (1972)	Caribbean Sea	Surface	≈0·10
		Below 300 m	0·05
Jacobs, Thorndike & Ewing (1973)	N. & S. Atlantic	Nepheloid water	0·45–0·56
		Mid-Atlantic ridge	0·03–0·24
Jacobs & Ewing (1965)	Arctic Ocean	—	0·006–0·049
Bassin, Harris & Bouma (1972)	Caribbean Sea	Mean surface	0·135
		Below 100 m average	0·047
Riley & Chester (1971)	Deep Sea	—	0–0·05
Manheim, Meade & Bond (1970)	Atlantic Continental margin (Cape Cod–Florida Keys)	Surface (offshore	0·1
		Surface (inshore)	0·1
Copin-Montegut & Copin-Montegut (1972)	Northeast Atlantic	Down to 150 m	0·035–0·23
		Below 200 m (average)	0·027
Meade *et al.* (1975)	Middle Atlantic Bight	Various depths	0·028–3·3

Suspended sediment loads in natural waters are generally highly variable (Sherk 1972). In Chesapeake Bay, seston levels ranged from less than 20 to more than 100 mg L^{-1} (Sherk 1972) where mean grain size was 1.3 um. Storm waves and wind-induced current was responsible for the extreme range of SPM concentrations, and tidal scour for maintaining background. Tidal resuspension accounted for changes in seston of 20 to 40 mg L^{-1} in that study.

Resuspended Matter

Resuspension by storms, waves, currents and tides, and input from terrestrial sources, are the major sources of natural suspended matter in inshore marine areas. A given site can have considerable variability throughout the year and on the short term, due to physical processes such as tides, waves and currents, leading to resuspension. Bricelj et al (1984) noted order of magnitude changes in SPM concentration at a site in Great South Bay, New York, with storm resuspension resulting in levels of 126 mg L^{-1} against a background of about 10 mg L^{-1}. This was in quite shallow water (mean depth 1.3 m) in a wind-driven system. Cundy and Bohlen (1980) indicated that suspended particulate concentrations near a clamshell dredge operation were smaller than those typically associated with storm events. The concentration of suspended solids in many estuaries and embayments increases with depth, reaching maximum values near the bottom. A near bottom high turbidity layer has been reported in estuarine and in poorly stratified or non-estuarine environments (Rhoads 1973). The matter resuspended in this manner probably differs from that resulting from dredges, containing richer microbial fauna and organic content. Resuspended sediment from storms in nearshore environments is not likely, however, to extend far from the site of resuspension (Bohlen et al 1979).

Suspended Particulate Matter Levels in the Maritimes

Concentration - No comprehensive surveys of SPM have been conducted in nearshore areas of New Brunswick, Prince Edward Island, or Nova Scotia. SPM has been measured sporadically as a variable in other research or dredging studies. For instance SPM was measured as part of studies of dredging effects in the Miramichi River, New Brunswick (Maclaren Plansearch 1983). SPM levels from several studies are presented in Table 2.

SPM concentrations in the Miramichi River estuary are commonly 2 to 20 mg L^{-1}. Short-term, non-tidal perturbations due to storms and the passage of ships elevated SPM concentrations to 200 mg L^{-1} and to 90 mg L^{-1} respectively (Maclaren Atlantic Limited 1978). SPM concentrations of up to 47 mg L^{-1} have been observed near bottom under normal conditions. Tides can induce variations in SPM concentrations from 10 to 60 mg L^{-1} near the turbidity maximum (Winters 1981). Over 50 per cent of the SPM in the Miramichi River estuary comes from freshwater runoff (MacLaren Plansearch 1983). Extremes of SPM concentration have been reported in the Bay of Fundy (up to 11,000 mg L^{-1})(Amos and Asprey 1981).

Composition - SPM from nearshore environments has both an inorganic and organic component. The organic component consists of both living material (chiefly phytoplankton) and detritus. The organic component of natural background SPM in Lunenburg Harbour taken as part of a pre-dredge sampling accounted for from 64 to 98 per cent of the total SPM (Seatech unpublished data, 1988). Industrial effluent and domestic sewage outfalls situated on this heavily utilized harbour contributed to some of the background organic particulate concentrations. Widdows et al (1979) noted the organic component of seston in an English estuary to be from 6 to 25 per cent.

2.2 Dredging Effects on SPM Levels

Dispersal of SPM

Evaluation of dredging impacts requires an understanding of spatial distribution of sediments entrained in the water column during the operation (Cundy and Bohlen 1980). Once particulate matter is placed in the water column, it begins to settle. How fast it settles (or whether it will settle) depends on grain size and density of constituent particles and water column turbulence (which is a function of water velocity). The distance SPM will

Table 2. SPM Concentrations for locations in the Maritimes.

LOCATION	DATE	DEPTH (m)	CONCENTRATION (mg L^{-1})				COMMENT	REFERENCE
			Mean	S.D.	Range	N		
Lunenburg, N.S.								
Harbour	Sept.7/88	1	15.5	5.9	6.0 - 22.4	6	Pre-dredge	Seatech MS 1988
		b - 1	19.3	7.2	10.8 - 29.2	6	"	"
	Sept.29/88	1	22.7	9.5	4.8 - 30.8	6	Dredge	"
		b - 1	28.9	6.8	23.1 - 41.6	6	Vicinity	"
		1	36.5	24.2	16.8 - 63.6	3	Background	"
		b - 1	25.7	6.5	18.8 - 31.6	3	"	
	Oct.6/88	1	30.9	12.8	15.2 - 53.6	10	Dredge	"
		b - 1	26.8	9.9	12.0 - 40.8	10	Vicinity	"
		1	30.7	4.2	26.8 - 35.6	4	Background	
		b - 1	36.4	8.0	29.2 - 47.6	4	"	
Harbour Mouth	Sept.7/88	1	48.4	N/A	N/A	1	Pre-dredge	Seatech MS 1988
		b - 1	27.2	N/A	N/A	1	"	
Miscou Harbour, NB	July/87	< 2 m	8.2	5.5	5 - 30	24	Inorganic material,	Environment Canada, 1987 MS
Strait of Canso, NS								
North of Causeway	N/A	Surface	0.8	-	-	-		Buckley et al (1974)
		Bottom	1.3	-	-	-		"
South of Causeway	N/A	Surface	4.0	-	-	-		"
		Bottom	0.7	-	-	-		"
Donkin-Morien, Cape Breton	June/81	1-3 m	3.5	1.9	1 - 7	28	Nearshore,	MacLaren Plansearch 1982
	Nov/81	1-3 m	13.1	3.7	4 - 37	23	natural SPM	
New Waterford, Glace Bay, Cape Breton								
Nearshore	Aug/88	0-7 m	11.8	6.4	5 - 32	24	Natural SPM, nearshore	Matt Blais, DEVCO
		0-16 m	10.8	7.4	1 - 32	24	Natural, 300 m offshore	" "
Miramichi River, Inner Bay, New Brunswick								
	Sept-Oct/73	Bottom	47	31	—	12	Natural, Predredging	Kranck, 1981
	Feb/77	Bottom	10	7	—	16	Natural, Predredging	Winters, 1981
	May/76	Bottom	28	11	—	15	Natural, Predredging	" "
		Surface	25	16	—	—	Natural, Predredging	" "
	Nov/77	Water Col.	59	22	—	5	Effect of Ship	Maclaren Atlantic, 1978

disperse when released in the water depends on the settling rate and water velocity. Different settling rates of particles in currents too small to keep them in suspension tend to sort them on the basis of settling rate. For example, in a river estuary in Connecticut, Bohlen (1979) (from Cundy and Bohlen 1980) found that 90% of particles with a settling rate of 4.8 cm sec-1 settled within 100 metres of a dredge while the remainder had a substantially lower settling velocity (less than 0.9 cm sec-1) and dispersed farther. Background was reached roughly 700 metres downstream. Cundy and Bohlen (1980) note, however, that settling velocity in the natural environment cannot readily be established using laboratory analysis of grain size characteristics.

In a New England estuary, the plume of SPM from a dredge site extended more than 1000 metres and particles remained in suspension for more than half the tidal period (Cundy and Bohlen 1980). The plume could be divided into three primary regions: an initial mixing zone adjacent to the dredge where concentration levels and mixing were dominated by vertical motion of the dredge bucket; a secondary zone where concentration rapidly decayed under the influence of gravitational settling; and a final zone within which levels approached background and were dominated by settling and turbulent diffusion (Cundy and Bohlen 1980).

Dredging activity may, however, result in measurable elevation of water column SPM at a substantial distance from the site of dredging. Biggs (1970) (from Sherk 1972) observed increased turbidity within a 5 km radius of the site of overboard disposal in Upper Chesapeake Bay.

Gordon (1973) (from Bohlen et al 1979) found the plume from a large volume clamshell dredge (11 m^3) was a relatively small-scale feature, extending only 1000 metres downstream. About 2.5 per cent of dredged sediment volume was introduced into the column adjacent to the dredging operations and subsequently advected or dispersed downstream.

Dredging operations with a clamshell dredge result in a narrow, well-defined plume (Bohlen et al 1979). The initial mixing zone of a clamshell dredge is a cylindrical wake produced by the bucket passing through the water column. Sediment is entrained into this zone by the impact of the bucket with the bottom and leakage from the ascending bucket (Cundy and Bohlen 1980). Columns of suspended sediment are introduced into the water column as a series of distinct pulses which coalesce downstream into a plume (Cundy and Bohlen 1980). The initial field of suspended sediment concentration decreases from the bottom to the surface.

Elevated levels of SPM from dredging operations frequently do not extend as far at the surface as at mid depth and near the bottom. In an Alabama hydraulic shell dredging operation, surface SPM levels less than 100 mg L^{-1} were observed beyond 400 feet and at mid depth up to 800 feet from the dredge. SPM concentration in mid water at distances of from 200 to 800 feet of the dredge was about 60 mg L^{-1}, and the dredging operation resulted in a bottom mud flow in which concentrations of SPM of 1000 mg L^{-1} could extend up to 1000 feet (May 1973). In the same study, hydraulic channel dredging resulted in comparable levels of SPM to the shell dredging operation, with levels of more than 100 mg L^{-1} limited to within 400 feet of the dredge at the surface and in mid water. SPM concentrations of 50 mg L^{-1} were observed to 1200 feet from the dredge (May 1973).

Concentration and Composition of Dredge-Induced SPM

Clamshell or bucket dredges have been shown to create plumes of suspended sediment with concentrations below 500 mg L^{-1} and mean concentrations less than 100 mg L^{-1} (Barnard 1978) (from Peddicord 1980). Hydraulic cutterhead, or pipeline dredges do not generally create concentrations above a few hundred mg L^{-1}, and concentrations arising from hopper dredges are probably less than 1000 mg L^{-1} (Ibid).

Yagi et al (1977) and Koiwa (1977) (both from Bohlen et al 1979) found maximum concentrations of 400 mg L^{-1} in the vicinity of a dredging operation moving silty clay. The dredging operation studied by Bohlen (1979) (from Cundy and Bohlen 1980) had suspended concentrations from 500 to 1000 mg L^{-1} in the immediate vicinity of the dredge with maxima near bottom. Bohlen et al (1979) reported suspended particulate loads of 200-400 mg L^{-1} while dredging fine grained silts and sand, resulting from loss of 1.5 to 3 per cent of sediment from each bucket on each pass of a clamshell dredge.

Extremely high levels of suspended material have been observed in the near bottom layer near dredging operations. Masch and Espey (1967) (from Sherk 1972) noted concencentrations up to 150,000 mg L^{-1} six inches off bottom in a Galveston Bay dredging operation (dredge type not specified), and concentrations of 20,000 mg L^{-1} were observed in a fluid mud layer 1 to 2 metres above the bottom in a hopper dredging operation in San Francisco Bay (U.S. Army Corps of Engineers 1976) (from Peddicord 1980). Although these high concentrations are not uncommon in dredge discharges, the levels observed in surface waters are usually considerably lower.

In one study (Bohlen et al 1979), SPM resulting from a dredging operation raised the percentage of inorganic matter and median grain size of the suspended material.

Physical/Chemical Effects of Dredge-Induced SPM

Dredging activity frequently results in depression of dissolved oxygen concentration in the water (Sherk 1972, from Moore 1977; May 1973). The effect is due to a combination of metabolism of microorganisms attached to particles and reduction in light penetration affecting photosynthesis in some cases (see Moore 1977).

Clamshell dredging, however, did not result in measureable changes in pH, and dissolved oxygen was lowered significantly only in the mobile, near-bottom suspended density flow (May 1973). Dissolved oxygen was not significantly lowered in surface and mid-water but was reduced in the bottom layer as the result of channel dredging (May 1973).

Transfer of contaminants to the water column during dredging has not proven to be a major concern in dredging operations, although it was early considered a possibility (Maurer et al 1986). Transfer of PCBs and pesticide material to the water column was found to be negligible and chlorinated hydrocarbons associated with the suspended solids reached background or near background after settling periods of 5 - 24 hours (Folk et al (1975) (from Maurer et al 1986). Little change in levels of dissolved heavy metals were observed in an Alabama estuary as a result of channel dredging (May 1973). After monitoring dispersion of trace metals in sediments dredged in southeastern U.S. estuaries, it was concluded that dredging of polluted sediments doesn't necessarily impair water quality in estuarine environments (Windom 1972) (from Maurer et al 1986).

Relative Impact of Dredge-Induced SPM

Concentration - Many factors induce suspended sediment levels above background. Storms caused estuary-wide variations in suspended material concentrations in a Connecticut estuary, increasing the mass of material in suspension by at least two times. This was an order of magnitude larger than levels produced by a clamshell dredge (Bohlen and Tramontano 1977) (from Bohlen et al 1979).

Composition - Bohlen et al (1979) found a distinct similarity between dredge and storm induced resuspension. Particulate inorganic matter typically is a dominant constituent of SPM, making up 70 - 80 % (Oviatt and Nixon 1975; Biggs 1978) (both from Bricelj and Malouf 1984).

3.0 BIOLOGICAL EFFECTS OF SPM

3.1 Introduction

The abundant literature on the effects of inorganic suspended sediments on marine organisms has been the object of a number of reviews, cited in a comprehensive review by Moore (1977) and a recent review done for Environment Canada (Appleby and Scarratt 1989). Effects of suspended sediment have been noted in virtually all marine invertebrate groups and also in fish (Moore 1977). There is general agreement that particulate material in suspension or settled on the bottom can affect aquatic organisms both directly and indirectly (Sherk 1972). Due to the interaction of organisms in communities, it seems likely that suspended particulate matter

(SPM) can have complex effects beyond those on single groups. Frequently organism distribution or abundance has been used, indirectly, as an indicator of SPM effects. The diverse kinds of effects possible are summarized from Moore (1977) in Tables 3 & 4. The complex kinds of interactions possible in a single taxonomic group are illustrated in Figure 1, which shows the ways in which inorganic particulate suspensions can affect metabolic processes in bivalves. Sherk (1972) notes that "most certainly some aspects of mortality, decreased yield, or at least interference with energy flow are implied. These may be related to growth, survival, or reproductive aspects of various life cycle stages."

In addition to these effects are those resulting from interactions of suspended material with contaminants. Surface adsorption reactions may be important in concentrating a wide range of pollutants and exposing them to organisms (Moore 1977).

Organisms are exposed naturally to elevated SPM levels caused by storms, sediment load in rivers entering the ocean, and catastrophic events such as landslides and turbidity flows. The highest values of turbidity or SPM generally derive from high energy environments. But frequently SPM levels are raised by the activities of man (e.g. harbour construction or dredging).

Important physical effects of elevated SPM include depression in dissolved oxygen content as the result of dredging and depression of light transmission affecting photosynthesis. High temperature can be deleterious in association with low dissolved oxygen, due to the resultant elevation in metabolic rate of organisms.

Marine organisms living on or near the bottom in coastal areas are exposed naturally to elevated suspended particulate matter concentrations as a result of currents, tides or storm activity. Many bottom organisms rework sediments, making them easier to erode and to enter suspension (Rhoads 1973).

TABLE 3. EFFECTS OF SUSPENDED PARTICULATE MATERIAL ON AQUATIC INVERTEBRATES (from Moore 1977)

	Effects Mechanism	Taxon
1.	Ingestion of particles increases specific gravity and affects movement patterns and transport of organism by waves.	Protozoa
2.	Acceptance of inorganic particles as food leads to growth reductions because of wasted effort in food handling.	Foraminifers
3.	Affects juvenile settlement. Thus sponges are found on vertical overhanging rock faces and not on horizontal ones in turbid areas.	Porifera
4.	Deposition of silt may bury young organisms.	Porifera
5.	Suspended sediment may clog pores, affecting respiration and feeding.	Porifera,
6.	Reduction in light penetration.	Hydroids
7.	Scouring of attached species from surfaces by suspended sand.	Oyster spat, corals, tube-dwelling polychaetes on rocks
8.	Abrasion of tissues by suspended particulates.	Ctenophores
9.	Smothering.	Hydrozoa (corals)
10.	Incorporation of particulates into tube.	Polychaeta
11.	Forming impermeable envelope with mucus and smothering organism.	Polychaeta
12.	Contaminating and rendering inedible mucus feeding net.	Polychaeta

TABLE 3 (Cont'd). EFFECTS OF SUSPENDED PARTICULATE MATERIAL ON AQUATIC INVERTEBRATES (from Moore 1977)

	Effects Mechanism	Taxon
13.	Sand in suspension encourages metamorphosis of larvae in organisms normally living in unstable environments.	Polychaeta
14.	Adsorption of toxic metabolites, thus lowering inhibition.	Polychaeta
15.	Clogging of filtering structures.	Crustacea
16.	Diluting nutritious particles in proportion to the relative concentration of suspended sediment, particularly in filter feeding species.	Crustacea (Copepoda)
17.	Reduced light penetration affects photosynthesis, primary production, and the number of nutritious cells available to filter feeders.	Crustacea (Copepoda)
18.	Suspended sediment interferes with respiration.	Brachyura
19.	Adsorbing to organism surface and preventing clearance.	*Daphnia*
20.	Diminishing activity and consequently increasing susceptibility to predation.	Copepoda
21.	Triggering light-controlled or other movement patterns (i.e. offsetting diel cycles).(Can be positive or negative)	Crustacea, amphipoda
22.	Interfering with larval settlement to differentially favour particular organisms.	Sedentary organisms

TABLE 3 (Cont'd). EFFECTS OF SUSPENDED PARTICULATE MATERIAL ON AQUATIC INVERTEBRATES (from Moore 1977)

	Effects Mechanism	Taxon
23.	Loss of organic material from tissues as a result of stimulation of digestive cells by indigestible material.	Bivalves
24.	Reduction in dissolved oxygen in the water.	All groups
25.	Increased pseudofeces production in response to suspended sediment in bivalves may result in accumulations which smother the organism (i.e. oysters).	Oysters
26.	Interfere with development and survival of eggs and juvenile stages.	Bivalves
27.	Increased pseudofeces production consumes energy which may otherwise be used for growth.	Suspension-feeding bivalves
28.	Failure of the mantle edge to extend in the face of impacts from mineral particles results in less growth and stunted animals.	Oysters
29.	Direct abrasion of shell edges in sufficiently energetic conditions, resulting in reduction in linear shell dimensions.	Oysters
30.	Turbidity affords protection from predation.	Cockles
31.	Deposited sediment made substrate unsuitable for egg laying.	Gastropods

TABLE 3 (Cont'd). EFFECTS OF SUSPENDED PARTICULATE MATERIAL ON AQUATIC INVERTEBRATES (From Moore 1977)

	Effects Mechanism	Taxon
32.	Interferes with orientation mechanisms (taste,smell) of predators to prey.	Sea stars
33.	Choking feeding structures results in mucus production which lessens ability to burrow in sediment.	Sea urchin

TABLE 4. EFFECTS OF SUSPENDED PARTICULATE MATERIAL ON FISH

(From Moore 1977)

1. Clogging of gill structures, affecting metabolism.

2. Reductions in oxygen availability leads to changes in blood characteristics.

3. Tissue disruption and increased mucus production.

4. Leads to increased energy requirements.

5. Induction of escape or inactive behaviour.

6. Interfere with spawning and spawning beds.

7. Interfere with visual orientation in feeding, schooling or escape. Influence fishing catch.

8. Altering diel cycles by changing the time of diurnal changeover.

9. Physical damage through sand accumulation in gill chambers.

10. Damaging gill structures and increasing susceptibility to infection and parasites.

11. Adherence of suspended sediment to eggs, inhibiting gas exchange and retarding embryonic development.

12. Reduce food perception by fry.

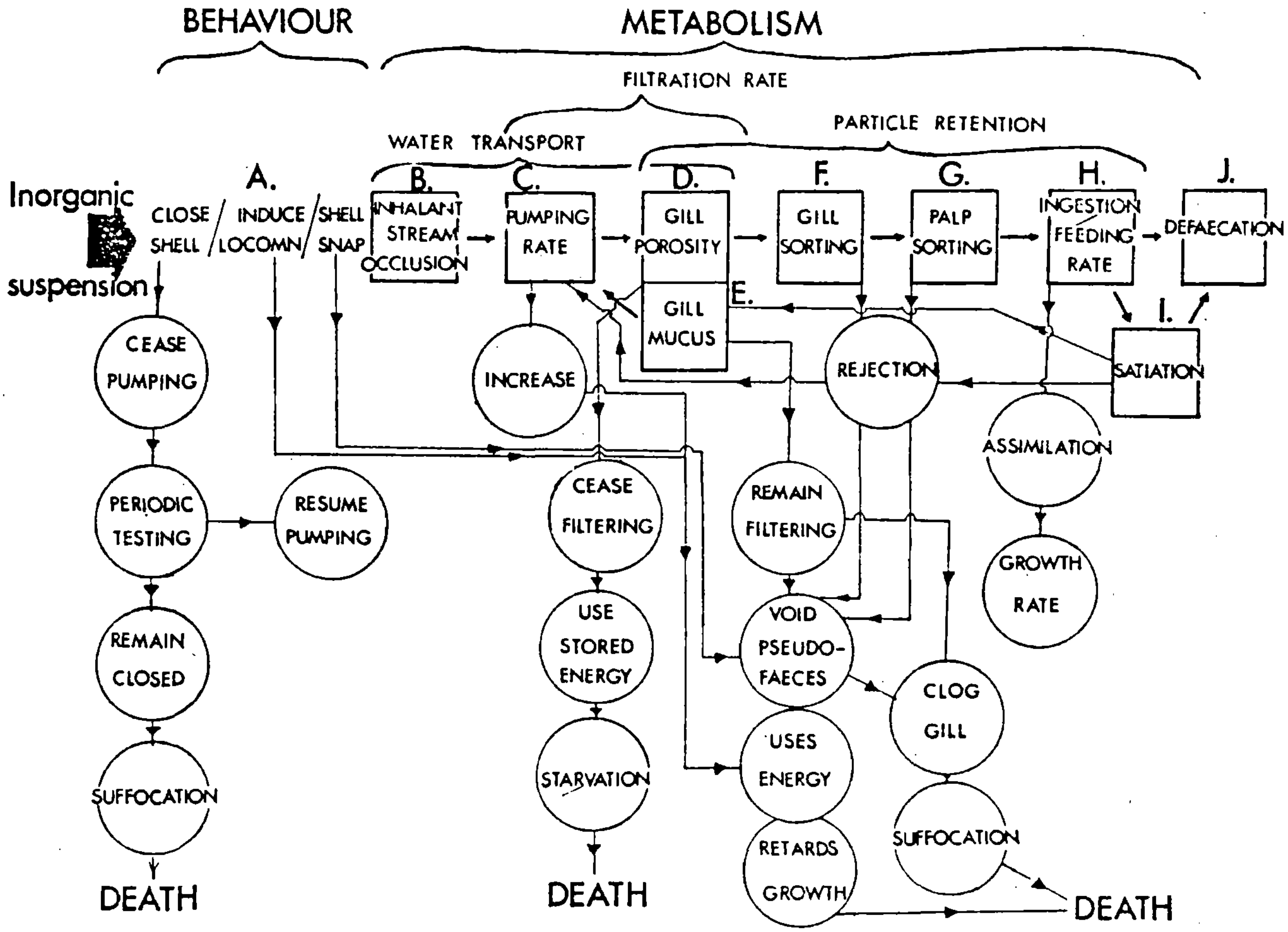

Figure 1. Effects of inorganic particulate suspensions on metabolic processes in bivalves (from Moore 1977).

Resuspended matter often has a beneficial effect on organisms. Mercenaria mercenaria held just off the bottom (where concentrations of resuspended material were expected to be high) in Buzzards Bay, Massachusetts, grew faster than their counterparts in the intertidal zone (Rhoads and Pannella 1970). Rhoads (1973) transplanted Crassostrea virginica to racks 20 cm off soft bottom in Long Island Sound in an area of bottom resuspension (estimated SPM concentration of 10 - 35 mg L^{-1}), and observed larger meat volumes than in oysters grown in commercial beds in shallow water.

Sedimentation rate may be more important than suspended sediment per se in affecting occurrence of organisms in bottom communities (Farrow et al 1983) although it is relevant to aquaculture only in possibly affecting spatfall under certain circumstances. Sedimentation is a major limiting factor for larval settlement on the bottom but is unlikely to affect spatfall on collectors (Farrow et al 1983). Larvae of many epilithic (living on rocks) invertebrates avoid silted surfaces (Withers and Thorpe 1977) (from Farrow et al 1983) and others may die after metamorphosis (Davis and Hidu 1969).

Various studies cited in Farrow et al (1983) have shown that filter feeders including sponges, ascidians, and bivalves have a lowered tolerance for highly turbid environments. However the mussels Mytilus and Modiolus do well in high turbidity areas (Dodgson 1928) (from Farrow et al 1983). Peddicord (1980) found short term tolerance in the tunicate, Ascidia ceratodes, to suspended sediment. The 21-day LC_{50} was 10,000 mg L^{-1} and the organisms survived concentrations of sediment up to 20,000 mg L^{-1} for three days (Peddicord 1980).

Sellner and Bundy (1987) observed that population success of the copepod Eurytemora affinis was reduced at 350 mg L^{-1} of a clay suspension (particle diameters less than 3 um) compared with concentrations of 50 and 100 mg L^{-1} and clean water. The measures they used were rate of nauplii produced, number of adults produced, and low reproductive potential of adults (number of eggs/initial nauplii present).

Moore (1977) summarized the physical and chemical effects of SPM, some of which directly or indirectly affect organisms. The effects include:

- depressing the dissolved oxygen level (Sherk 1972) through a combination of increased oxygen demand of the SPM and a reduction in photosynthetic production of oxygen;

- affecting oxygen solubility, diffusivity coefficient and rate of transfer in aqueous solutions;

- reducing light penetration and shifting spectral composition, favouring red over blue;

- affecting the albedo of the water mass;

- adsorption of detritus, dissolved organic matter, and colonization by microorganisms.

Moore (1977) concluded that "the concept of a simple, inert, inorganic suspension in nature is naive."

Most studies on SPM used to assess dredge effects, however, have examined only direct or acute effects. These have led to conclusions that the impacts of suspended sediment caused by dredging are likely to be minor. Fish and invertebrates have a surprisingly high tolerance for suspended sediment. There is a large literature on this type of effect. For example, Ritchie (1970) (from Appleby and Scarratt 1989) found no gross physical effects of shallow water overboard spoil disposal on 44 species of fish in Chesapeake Bay, and no changes in catch rates attributable to disposal activities. That author also noted no damage to gill epithelia from caging several species in the vicinity of a dredge disposal effluent pipe. Ingle (1952) (from Appleby and Scarratt 1989) found no mortality of fish or shellfish at a dredge site in Mobile Bay, Alabama, and no migration from the site. Saila _et al_ (1968) had similar findings at a sediment dump site in Rhode Island Sound.

Stern and Stickle (1978) (from Peddicord 1980) concluded from a literature review that typical dredging-related suspended sediments do not cause irreversible ecological impacts. Peddicord (1980) concluded that effects of dredging, apart from near bottom, would be minor given the comparatively low and transient nature of suspended particulate concentrations resulting from dredging, and the low acute toxicity of SPM. These authors, however, based their judgement only on measurements of mortality in response to high concentrations of suspended sediment for short periods.

3.2 Effects on Invertebrates

Apart from acute lethality, SPM at low concentrations can affect invertebrates in the following main ways:

Growth

Growth has only been recently widely used to assess effects of suspended sediment on organisms. Prior to 1971 there were no studies on final body size reached by marine animals in relation to turbidity (Wilber 1971). Body weight of a standard size suspension feeding bivalve Tellina tenuis was reduced relative to a control area, in an area receiving warm water effluent, due to increased metabolic rate. The reduction was augmented during an interval when the water was turbid from nearby construction (Scottish Marine Biological Association 1973) (from Moore 1977). Reviewing several studies on bivalves, Moore (1977) noted that dry flesh weight of a standard animal may be lowered during a period when the water is turbid with inorganic material, presumably because of a depression of feeding activity and/or feeding efficiency together with the cost in energy and hence of storage products of excessive pseudofecal expulsion.

SPM may result in either positive or negative effects on growth in bivalves. M. edulis grew more at natural concentrations of SPM (up to 20 mg L^{-1}), than on a pure algal culture (Kiorboe et al 1981). Clearance increased 32-43 per cent, and ingestion and growth rate were increased, by the addition of 5 mg L^{-1} silt. In fact, only with silt added did the growth of the lab cultures approach the maximum in situ growth rates (Kiorboe et al 1981). The authors suggest that natural suspended matter serves as an additional food source. Winter (1976) observed similar growth enhancement in M. edulis when oxidized silt was added to an algal diet. Widdows et al (1979) also suggest that the organic component of natural silt is a food source for Mytilus. Murken (1976) (from Bricelj et al 1984) found that growth of M. edulis increased on a diet of fish waste, water, and algae when silt was added. Ali (1981) (from Bricelj et al 1984) noted increased growth in C. virginica at the highest algal ration used, though no effect was observed at low and medium algal rations.

In contrast, Bricelj et al (1984) found that low concentrations of silt (less than 25 mg L^{-1}) mixed with algal food did not enhance the growth rate of juvenile quahogs (M. mercenaria) and that growth reduction occurred at 44 mg L^{-1}. The surf clam Spisula solidissima showed no growth during short exposures (3 and 21 days) to attapulgite clay suspensions of up to 1.0 g L^{-1} (Robinson et al 1984) but digestive efficiency and amount of algae ingested were progressively lower with increased clay concentration. The authors concluded that turbidity as low as 100 mg L^{-1} may have adverse effects. The clams apparently acclimated somewhat to the high suspended sediment by increasing pseudofeces production, a strategy used by Mytilus. Suspended inorganic particulate matter can reduce or stop feeding with consequent reductions in growth in Chlamys islandicus (Wallace and Reinesnes 1985). Consequently these authors concluded that culture of the species high in the water column (where SPM is lower) would result in a longer growing season and enhanced growth relative to bottom culture (Wallace and Reinsnes 1985). Vahl (1980) noted that seasonal changes in relative concentrations of particulate organic and inorganic matter in the seston can explain the seasonal pattern of growth of Chlamys. Through much of the year, particulate inorganic material dilutes organic material available to Chlamys and limits food absorption and growth.

Behaviour

Shell-snapping in bivalves is commonly observed during exposure to elevated suspended sediment concentrations, presumably to facilitate removal of pseudofeces and to dislodge silt accumulated on the shell (see Moore 1977). The bay scallop (*Argopecten irradians*) reduced its gape and overlapped its guard tentacles in the form of a screen when exposed to moderate to high concentration algal suspensions versus low concentrations (Palmer and Williams 1980).

Energetics and Digestive Physiology

There have been numerous studies of effects of SPM on feeding, energetics, and activity of bivalves, particularly suspension feeders, since they filter the water and would be directly impinged by SPM. In general the SPM/organism interaction is complex; many bivalves have strategies for processing the excess inorganic material to which they are exposed, while others may lack compensatory mechanisms. Thus, for example, *Mytilus* can compensate for SPM concentrations much above ambient by selecting food particles from a particle suspension of inorganic and food particles (Kiorboe and Mohlenberg 1981). *M. edulis* rids itself of particulate material at concentrations above approximately 5 mg L^{-1} by the production of pseudofeces (ibid.). By increasing the amount of water filtered, this species can stabilize its food intake to some extent. Other bivalves are unable to rid inorganic material and so are forced to reduce consumption in inorganic suspensions.

Inorganic SPM reduces or dilutes the amount of usable organic matter from a particle suspension, and some suspension feeders have developed mechanisms, including particle selection, to counteract the food diluting effect (Kiorboe and Mohlenberg 1981). *Crassostrea virginica* and the Bay Scallop *Argopecten irradians* can respond to variations in natural seston by changing retention efficiency of the gill, through increasing pseudofecal production and regulating the size of openings in the gill respectively (Palmer and Williams 1980). Both *Argopecten* and *Crassostrea* formed only feces at low concentrations and pseudofeces at higher concentrations. These changes were observed at comparatively low concentrations of particulate matter (from less than 1 mg L^{-1} to 11 mg L^{-1}) (Palmer and Williams 1980).

Suspended matter may also affect absorption efficiency. In *Chlamys islandicus*, absorption efficiency decreases with increasing dilution (Vahl 1980). Higher assimilation efficiencies in suspended sediment regimes have been noted (e.g. *Spisula subtruncata*, Mohlenberg and Kiorboe 1981) (from Robinson *et al* 1984). Growth rate increased with algal concentration and was further increased by 10 to 110 % with the addition of suspended bottom material. The positive effect was due to the increased efficiency of assimilation of ingested algae and to the utilization of organic matter from the suspended material (Mohlenberg and Kiorboe 1981). Increased concentrations of spent drill mud suspensions increased pseudofeces production, and decreased chlorophyll consumption and digestive efficiencies of adult *Spisula solidissima* (Robinson *et al* 1984). Those authors suggested that prolonged exposure to drill mud suspended matter would result in decreased amounts of energy available for growth and reproduction. Levels of SPM in the range of 100 to 1000 mg L^{-1} would likely be deleterious to this species.

The reduction in energy intake may force the organism to utilize stored energy reserves. Winter (1972) suggested that weight loss may also be attributable in part to increased production of pseudofeces, which represent a further drain on energy reserves. Pratt and Campbell (1956) (from Appleby and Scarratt 1989) found that growth rates of *Mercenaria* were reduced in sediments with high silt/clay content, suggesting that lowered growth rates were due to additional expenditure of energy required for frequent cleaning of the feeding apparatus. Stone *et al* (1974) (from Appleby and Scarratt 1989) found scallops and quahogs increased mucus production when clearing gills of kaolin and suggested that increased production of mucus resulted from utilization of stored energy reserves which would normally be used for other functions. Barnett (1973) (from Moore 1977) noted that while *Tellina tenuis* body weight was reduced in warmer waters due to an increased metabolic rate, it was further reduced during an interval when suspended solids increased.

Bricelj et al (1984) found at low concentrations (up to 25 mg L^{-1}) of suspended particulate matter (modal size 6.3 um), that growth rate expressed as ash-free tissue dry weight in the quahog Mercenaria mercenaria was not significantly affected by sediment concentrations. At concentrations as low as 44 mg L^{-1}, however, there was a significant growth reduction (16 % relative to controls grown on phytoplankton) resulting from dilution of the algal food by the inorganic matter and the failure of Mercenaria to compensate by increasing ingestion. That study found no evidence that suspended sediment could stimulate growth of Mercenaria, but high levels inhibited it. Ali (1981) (from Bricelj et al 1984) reported an increase in growth in Crassostrea at the highest algal ration of a mixed suspension of oxidized silt, though no effect was noted at low and medium algal rations. Bricelj and Malouf (1984) found that clearance rate and algal ingestion rate of Mercenaria declined significantly with increasing sediment loads.

Other effects of SPM on bivalves include changes in pumping rate, pseudofecal production, shell closing, shell deposition etc. The high rate of pseudofecal expulsion required of animals embedded in fine sediments (which are resuspended by currents and taken in with the inhalent siphon) interrupts feeding and consumes energy which may otherwise be used for growth.

Few studies have been carried out on the effect of inorganic turbidity on the respiration of bivalves. Widdows et al (1979) noted no effect of elevated seston levels (from 100 to 280 mg L^{-1}) on oxygen consumption of M. edulis.

3.3 Effects on Fish

General

Moore (1977) notes considerable information on the effects of turbidity and siltation on fish. The types of effects are presented in Table 4. In general, turbidity and siltation can affect growth of adults, spawning success, hatching rate, larval mortality, spawning bed destruction, gill pathology, behavioural avoidance of turbid areas, and species composition.

Aquaculturists in general are not concerned with suspended sediment effects on fish eggs and larvae and consequently these effects have not been considered extensively in this review.

Adult fish and shellfish can survive in concentrations far greater than those commonly observed in nature (Appleby and Scarratt 1989) and it is generally acknowledged that high, short-term concentrations are not lethal to fish. Many species of fish have been shown to survive for long periods in highly turbid conditions. McKee and Wolf (1963) tested the effects of turbidity on 16 species of freshwater fish. Fatal turbidity in montmorillonite clay varied from 40,000 mg L^{-1} for rock bass, Ambloplites rupestris (84 hours), to greater than 200,000 for black bullhead, Ictalurus melas exposed for an average of 17 days. Harmful effects on fish were observed at concentrations near 20,000 mg L^{-1}. Wallen (1951) investigated the effect of erosion silt (mostly montmorillonite clay) on some species of North American fish. Most endured for a week exposed to intermittant concentrations of 100,000 ppm, but died within 2 hours when the concentration was raised to 175,000 to 225,000 ppm.

Cole (1935) found that a 2 per cent suspension of wood fibres (20,000 ppm) was not harmful to healthy fish but hastened the death of unhealthy or moribund individuals.

Fish eggs and larvae are less tolerant to suspended sediment than adults, and larvae are more sensitive than eggs (Appleby and Scarratt 1989). Undoubtedly similar effects would be observed in salmonids in aquaculture and hatchery facilities.

A guideline for water quality (EIFAC 1965) (from Moore 1977) states that fisheries were unlikely to be harmed at SPM concentrations below 25 mg L^{-1}, good or medium fisheries would be sustainable at 25-80 mg L^{-1}, and that good fisheries would be unlikely at 80-400 mg L^{-1}. Above 400 mg L^{-1}, poor fisheries are expected. Nikolsky (1963) (from Moore 1977) considered that 4% V/V solids has the greatest effect on fish. High tolerance limits for fish under various circumstances are illustrated by the work of Wallen (1951), who found that concentrations of clay below 55 g L^{-1} were not acutely toxic (one week exposures) to 16 warm water fish species from Oklahoma and Michigan.

Behaviour

Suspended sediment can affect fish behaviour, though effects have not been reported in an aquaculture setting. Turbidities have evoked fright responses and avoidance by rainbow trout (Guebitz 1966; Saunders and Smith 1960; Stern and Stickle 1978; and Ingle _et al_ 1955) (from Appleby and Scarratt 1989). Wildish _et al_ (1977) found herring avoided suspended sediment at a threshold of 13 ± 5 mg L^{-1} of fine sediments and 35 ± 5 mg L^{-1} in coarse sediments. Natural sediments were also used. Messieh _et al_ (1981) repeated the experiments of Wildish _et al_ (1977) using sediments from the Miramichi estuary and found the avoidance threshold to be between 9.5 and 12 mg L^{-1}. Blaxter and Parrish (1965) (from Appleby and Scarratt 1989) maintained that changes in water clarity affect schooling ability in species such as herring which use visual schooling cues. Reintjes and Pacheco (1966) (from Appleby and Scarratt 1989) noted that school size in menhaden varies with turbidity. Given that fish in aquaculture facilities frequently exhibit schooling patterns, changes in turbidity may result in subtle effects if schooling behaviour is disrupted. Ritchie (1970) (from Appleby and Scarratt 1989), however, was unable to separate cage-related mortality from mortality caused by suspended sediment, after caging fish in the vicinity of a dredge disposal effluent pipe. Noggle (1978) noted that salmonids do not avoid water with suspended sediment levels several times greater than natural levels, but that feeding is reduced at relatively low turbidities.

Physiology

Suspended sediment can effect respiration of fish. The effects may be due to oxygen reductions resulting from BOD of the material, and also to changes in the physico-chemical regime near the gills, affecting oxygen transport (Moore 1977). Brown and Clark (1968) (from Appleby and Scarratt 1989) studied dissolved oxygen levels following resuspension by dredging in tidal bays between Staten Island and New Jersey, and found a 16-83 per cent reduction in dissolved oxygen from non-dredging periods. The US Fish and

Wildlife Service (1970) (from Appleby and Scarratt 1989) cited reductions of dissolved oxygen from 8 to 0.1 ppm at dredge spoil disposal sites. In contrast, May (1973) noted only slight declines in dissolved oxygen concentration and then only in a mobile near-bottom suspended sediment density flow in the vicinity of shell dredging in Alabama estuaries. As a result of channel dredging, oxygen concentrations were not significantly reduced in surface and mid-water but lowered in the near-bottom layer (May 1973). Channel dredging also resulted in slightly lower pH (May 1973). Stern and Stickle (1978) (from Appleby and Scarratt 1989) note that oxygen depletions resulting from dredging are transitory. The effects of suspended material on respiration and oxygen levels would be seasonally variable, depending on water temperature and water column conditions which control oxygen demand and production.

Physiological responses to suspended sediments, chiefly increases in oxygen exchange capacity, have been noted in a number of species of fish (Sherk _et al_ 1972) (from Moore 1977). Those authors monitored blood cell count, hemoglobin level, blood ionic composition, carbohydrate utilization and gill histology in three fish species and noted similar responses. The results suggest that interference with oxygen and carbon dioxide transport may be an important effect of SPM. Some of the sublethal effects occurred at concentrations as little as 650 mg L^{-1} Fuller's earth (white perch), and included significant increases in hematocrit, hemoglobin and red blood cell count. Rates of liver glycogen depletion were increased in one species, indicating an increased carbohydrate utilization during sublethal sediment stress and a drain on metabolic resources (Sherk _et al_ 1972) (from Moore 1977). Mullen (1951) and Rogers (1969) (both from Appleby and Scarratt 1989) noted that fish exposed to high suspended sediment levels showed behaviour similar to that of oxygen-starved fish. Fourspine stickleback, _Apeltes quadracus_, tended to gulp air at the surface when placed in sublethal concentrations of suspended sediment (Rogers 1972) (from Moore 1977). Rogers (1969) (from Appleby and Scarratt 1989) noted increased LC_{50}s for _Apeltes quadracus_ and _Tautogolabrus adspersus_ when oxygen was bubbled through test silt suspensions. Peddicord _et al_ (1975) (from Appleby and Scarratt 1989) noted increased tolerance of suspended sediment by one fish species when oxygen concentration was high. O'Connor _et al_ (1976) (from Appleby and

Scarratt 1989) noted increased 24-hour LC_{50} for silversides by bubbling air. Plasma glucose levels rose in coho salmon exposed to high suspended sediment (Noggle 1978). Hematocrit showed no relation to suspended sediment for concentrations approaching the LC_{50} (Noggle 1978). Stern and Stickle (1978) (from Appleby and Scarratt 1989) suggested that suspended sediment could increase energy requirements of fish and consequently place a greater demand on energy stores, by stimulating hematological responses, increasing motility, or both. In contrast, short-term (96 hour) exposure to high suspended sediment levels didn't affect blood characteristics or gill structures in _Fundulus heteroclitus_ (Berry and Baily 1973) (from Moore 1977). By and large, according to Moore (1977):

> " fish exposed to sublethal levels of suspended solids show the same hematological (and behavioural) responses as fishes deprived of sufficient oxygen, namely, increased red cell counts, increased hematocrit, and increased concentration of hemoglobin in the peripheral blood. Since sublethal exposure resulted in tissue damage to the gill epithelia, it would seem that oxygen availability at the gill surface is reduced by partial non-functioning of the gill..."

Tests of toxicity of suspended sediments to fish often show an age specific difference in toxicity, related to the size-related abilities of gills and gill structures to clear suspended sediment impinging on them. Gill filaments and secondary lamellae act as a sieve to trap particles which interfere with gaseous and ionic exchange mechanisms across the gill surface (Ellis 1937) (from Appleby and Scarratt 1989). The physical dimensions of the gills are proportional to the size of the fish. As fish increase in size, so do the gill filter openings. Large fish may then trap fewer particles and experience less respiratory trauma than smaller fish of the same species.

A second hypothesis for size dependent differences in mortality is decreased metabolic rates with increasing size (less oxygen consumption per unit weight) (O'Connor _et al_ 1977) (from Appleby and Scarratt 1989). Large fish are thus more tolerant to respiratory stress resulting from gill damage and clogging. Temperature apparently contributes to mortality of fish in some cases during exposure to suspended sediment, probably contributing additional stress (e.g. Cronin 1970; Cairns 1968) (from Appleby and Scarratt 1989).

Although there have been suggestions that fish may show compensatory mechanisms to suspended sediment exposure (i.e. shunt mechanisms) (Randall 1970) (from Appleby and Scarratt 1989) and increased gas exchange capacity (O'Connor _et al_ 1977) (from Appleby and Scarratt 1989), these most likely result in added energetic expenditure which would be detrimental to the fish. Rates of liver glycogen mobilization have been used to estimate energy utilization rate during starvation (Beamish 1968; Small and Fleming 1969) (from Appleby and Scarratt 1989). O'Connor _et al_ (1977) (from Appleby and Scarratt 1989) showed rapid glycogen utilization in hogchoker exposed to Fuller's earth suspensions "suggesting a stress-related compensatory mechanism resulted in an increased energy requirement." They suggested that even tolerant species may be subjected to sublethal effects at non-lethal concentrations of suspended sediment.

Suspended sediment may induce mucus secretion by gills. Development of mucus-secreting goblet cells has been noted to occur on the anterior gill filament margin of white perch (O'Connor _et al_ 1977) (from Appleby and Scarratt 1989). Other histological effects on fish gills have also been noted. Suspended sediment may also increase stress and affect response to a toxicant (Melay _et al_ 1973) (from Appleby and Scarratt 1989).

3.4 Effects on Aquaculture Species

Salmonids

In experiments running for a maximum of 3 months, Herbert and Merkens (1961) found an increase in the incidence of fin-rot in rainbow trout, _Onchorhynchus mykiss_, exposed to suspensions of 270 ppm of either kaolin or diatomaceous earth. A variable mortality, usually more than 50 per cent, was observed at concentrations above 270 ppm. Histological changes such as fusion of adjacent gill lamellae and thickened respiratory epithelia were found in fish dying in concentrations of 270 and 810 ppm. After several weeks at concentrations above 270 ppm, fish were white in color. At the lower concentration of 30 ppm, mortality was the same as in controls, and at 90 ppm there was some mortality. Gills were normal after exposure for 2 months to a concentration of 30 ppm. It was concluded that trout were harmed if exposed to kaolin or diatomaceous earth in suspended concentrations above 270 ppm.

Suspended sediment levels in nature rarely approach lethal levels (Noggle 1978). 96-hour LC_{50}s for coho and chinook salmon and 'steelhead' (Onchorhynchus mykiss) are presented in Table 5. Values range for coho from 1,198 to 35,000 mg L^{-1}, and for chinook and steelhead, 2,586 and 10,233 mg L^{-1} respectively (Noggle 1978).

Slanina (1962) (from Wilber 1971) found no mortality of rainbow trout kept in suspended mineral solids for 8 days at concentrations between 1 and 100 g L^{-1}, and the same species also survived at 300 g L^{-1}. Increased mucilagination in the gill lamellae and proliferation of gill epithelial cells were observed at concentrations as low as 20 g L^{-1}.

Griffin (1938) (from Van Oosten 1945) reported that salmon and trout fingerlings survived for 3 to 4 weeks when exposed to suspended silt concentrations of 300 - 750 ppm which were raised briefly each day to 2,300 - 6,500 ppm.

Average values of 100 ppm suspended particulates for surface waters containing trout and other fish have been reported (Ward 1938). Schnedeberger and Jewel (1928) found an increase in fish production when turbidity in ponds decreased to an average of 100 ppm.

Herbert et al (1961) (from Wilber 1971) noted that studies of brown trout, Salmo trutta, exposed naturally to turbid waters resulting from china clay wastes, indicated no measureable effect on fish length. Condition indicated that trout from turbid waters grew normally and apparently found adequate food. Concentrations of 1 g L^{-1} reduced the abundance of brown trout (ibid).

Table 5. Acute toxicity of suspended sediments to salmonids (from Noggle 1978)

Date	Species	Origin	Length (mm)	Fish/Tank	Grams/Liter	Temp (°C)	No. of Tanks	96 hr LC50	0.95 Conf. Int.
5/1	coho	wild	132	10	4.13	7	6	4,420	2,739-7,327
5/20	chinook	wild	51	50	0.85	11	10	2,586	2,391-2,803
7/7	coho	wild	62	10	0.85	14	17	1,927	912-4,422
8/6	coho	wild	75	10	0.92	15	5	1,198	591-2,622
9/13	coho	hatchery	62	10	0.53	12	3	1,500	*
9/13	coho	wild	72	10	0.85	12	3	15,000	*
11/13	coho	wild	83	10	1.05	8	11	35,000	*
12/6	steelhead	hatchery	140	5	2.50	6	10	10,233	6,774-16,222

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*LC50 estimates too approximate to estimate 0.95 confidence intervals.

Rainbow trout Onchorhynchus mykiss (30 to 65 mm in length) and coho salmon (Oncorhynchus kisutch) exposed to continuous clay turbidities, grew less well than in clear water (Sigler et al 1984). As little as 25 Nephelometric Turbidity Units of turbidity caused growth reduction. Noggle (1978) noted a steady decline in the ability of coho salmon smolts to feed as suspended sediment concentration increased. Feeding stopped at 300 mg L^{-1}.

Lobster and Crustaceans

Effects of SPM on American lobster, Homarus americanus, have been noted in artificial situations with high turbidities, though not in natural turbidity situations. H. americanus exposed to dredge spoils and sewer sludge in well-aerated circulating aquaria, developed eroded areas of the outer covering of the carapace and appendages as well as the cuticular gill within 6 weeks after initial exposure (Pearce 1972). In contrast, Saila et al (1968) (from Moore 1977) found that adult H. americanus from Rhode Island Sound were tolerant of turbidity.

Cobb (1972) exposed H. americanus larvae to kaolin mud and quartz "flour" (maximum particle size ranges 15, 44, 74 and 105 um) at concentrations ranging from 1000 ppm to 50,000 ppm by weight. Quartz particles 30-50 um in diameter blocked gill filaments so that finer particles normally passing through were retained on the gill. Finer particles (smaller than 15um) seemed to have no effect on larvae in the absence of larger particles regardless of concentration. On exposure to kaolin mud, high mortality occurred after several days at higher concentrations of 10,000 and 50,000 ppm. In shorter experiments, mortality was low and no particle accumulation was found on the gills. An explanation given was the possible failure of a gill cleaning mechanism due to fatigue.

In contrast, Peddicord (1980) found juvenile H. americanus (3-4 cm) to be tolerant of SPM, with no mortality or abnormal molting at up to 20 g L^{-1} of contaminated Oakland Bay sediment in suspension for 25 days. The same sediment caused greater mortality in the sand shrimp Crangon nigromaculata than uncontaminated sediment. Uncontaminated sediment resulted in 21 %

mortality of the latter species at 19.7 g L^{-1} over a 21 day exposure. As for the lobster, the related sand shrimp species (Crangon nigricauda) showed no indication of mortality linked to clean suspended sediment at concentrations up to 19.7 g L^{-1} (Peddicord 1980).

Sand shrimp (Crangon crangon) survived suspensions of red mud, a residue of the production of aluminum from bauxite, at concentrations up to 33 mg L^{-1} (Blackman and Wilson 1973) (from Moore 1977). In these exposures the shrimp became coated, particularly where there were fine setae, and on the gills. Particles on the exoskeleton were lost soon after transfer to clean water. Mud on subchelae and gills remained until the animals molted (Blackman and Wilson 1973) (from Moore 1977). Greve and Kinne (1971) (from Moore 1977) found similarly that red mud sticks to the gills of Pagurus bernhardus and resists removal even after transfer to clean water.

Pearce (1972) found that Cancer irroratus died when migration took them into the New York sludge disposal area. After exposure to sludge sediments for six weeks in well-aerated, circulating aquaria, the gill chambers had become filled with fine debris characteristic of sediments in the area. Erosion of the carapace and cuticular gill covering was noted both in C. irroratus and H. americanus. Peddicord (1980) found that Dungness crab, Cancer magister, showed significant mortalities when exposed to high concentrations of suspended contaminated sediment. Concentrations of 4.3 g L^{-1} were not lethal during 25 day exposures but 15 % of the crabs showed abnormalities upon molting. Mortalities were observed after a week of exposure to 9.2 g L^{-1} (Peddicord 1980).

Moore's review (1977) found no studies on effects of suspended particulate matter on respiration of crustacea. The present review did not find any recent papers on this subject.

American and European Oyster and Quahog

Adults - Numerous studies have been carried out to assess effects of suspended particulate material on adult oysters.

The American oyster, C. virginica, has been viewed as being silt tolerant. Mackin (1961) found no significant mortality of C. virginica kept in suspended sediment concentrations as high as 700 mg L^{-1}, and studies by Lunz (1938) (from Sherk 1972) also showed that Crassostrea was silt tolerant.

Crassostrea responds, however, in several ways to elevated suspended sediment levels. Hsaio (1950) (from Moore 1977) allowed suspended silt to settle on C. virginica and found shells remained closed for 16-19 hours. Later they attempted to open and closed again. Oysters recovered if the silt was removed after 2 days, but all died if the silt remained for more than 3 days. Oysters previously exposed even to highest concentrations of suspended material recovered quickly when returned to clear sea water. Loosanoff and Tommers (1948) observed reduced pumping rates at high suspended sediment levels and reported C. virginica stopped feeding in highly turbid waters. Some would close for several weeks, opening from time to time. Some would pump even at 4 g L^{-1}. In experiments lasting 6 hours in concentrations ranging from 0.1 to 4.0 g L^{-1} silt or kaolin, the pumping rate decreased an average of 57 % and as much as 87 % at an SPM concentration of 0.1 g L^{-1}. Pumping rate was reduced by 80 % of initial at a concentration of 1 g L^{-1} and by 94 % at 3 - 4 g L^{-1}. No significant difference was found between the effects of silt and kaolin. One experiment using Fuller's earth (a mixture of bentonite and montmorillonite clays and some silica) at 0.5 g L^{-1} caused a reduction in pumping rate of 60 per cent. This study also showed a change in amplitude and pattern of shell movements in oysters kept in turbid waters. In contrast, Chiba and Oshima (1957) (from Moore 1977) found that bentonite suspensions of from 500 to 1000 mg L^{-1} did not lead to pumping rate reductions in Venerupsis semidecussata, V. meretrix, Ostrea gigas, Mytilus edulis, and Scrobicularia plana. Concentrations of SPM less than 100 mg L^{-1} may often induce more rapid pumping in oysters (Moore 1977).

Oysters have been reported to be capable of feeding in turbid water (Nelson 1960) (from Moore 1977). C. virginica can continue to feed in a mixture of inert Fuller's earth suspension and chloroplasts by increasing the volume of pseudofeces produced (Lund 1957a from Moore 1977). Urban and

Langdon (1984) suggested that kaolin may be a good additive to food for oysters grown in hatchery conditions.

According to Yonge (1966) (from Moore 1977), *Ostrea* is likely to have a greater susceptibility to suspended sediment than *Crassostrea*. Basically *Ostrea* is a clear water species while *Crassostrea* species inhabit inshore waters which are typified by high suspended silt concentrations. The latter has relatively restricted pseudosiphonal openings often screened with tentacles, more discriminating palps selecting quantitatively as well as qualitiatively, a more efficient routing of pseudofeces away from the gills, and more efficient muscular development for snapping of valves to rid pseudofeces. In support of this, Waugh (1954) (from Moore 1977) observed that flood-induced suspended sediment levels killed more *Ostrea* than *Crassostrea angulata*. Similarly *C. gigas* withstood turbid water better than *O. lurida* (which ressembles *O. edulis*) (Moore 1977).

In some cases, oysters raised above the bottom can survive high levels of suspended sediment compared with those on the bottom which may be smothered by accumulated silt or pseudofeces. Thus, although they can cope with high SPM levels, they cannot survive smothering. The restriction of some oysters to clearer waters may thus not be a simple reaction to suspended solids in the water but rather a response to the resultant of a complex of interactive requirements (Moore 1977).

Since most lamellibranchs are non-selective or only slightly capable of selection of particle food content, changes in feeding rate would provoke use of stored reserves, reducing flesh weight and growth rate (Moore 1977). *Crassostrea virginica* grown on metal racks supporting them above the bottom in water with a maximum turbidity of 10 to 35 mg L^{-1}, had a higher meat yield than those grown on commercial beds in shallow water (Rhoads 1973). However Haven and Andrews (1957) (from Moore 1977) found lower rates of growth of *Mercenaria* planted on natural bottoms instead of racks. There is little evidence for beneficial effects of turbidity, according to Moore (1977) who states that Rhoads' (1973) data appear to be the exception to the rule in describing the beneficial effects of turbidity on post-larval lamellibranch growth rates.

Growth rates and degree of shell thickening in C. gigas were related to the amount of fine (smaller than 15 um) inorganic material in suspension (Key et al (1976) (from Moore 1977). In extreme cases of suspended load, Waugh (1958) (from Moore 1977) showed that bombardment by suspended mineral particles contributed to a limitation in shell growth of Ostrea edulis.

Larvae and Spat - Davis (1960) and Davis and Hidu (1969) evaluated the effects of suspended materials of several types in different size ranges on eggs and larvae of Ostrea, Crassostrea and Mercenaria. Their general conclusion was that:

> ...bivalve larvae can tolerate turbidities higher than those normally encountered in natural waters, and under special circumstances low concentrations of turbidity-producing materials may be beneficial. Nevertheless, higher silt concentrations, such as those produced by dredging or filling operations, could be detrimental to bivalve larvae, both as a direct effect of the particulate matter and, indirectly, as a result of lowered pH (caused by silt addition).
>
> Davis and Hidu (1969)

Ostrea edulis larvae could reject small particles of kaolin, Fuller's earth, and silica (smaller than 5 um) and suffered little mortality from exposure to suspensions of these materials. In silt, larval growth was impaired at 0.75 g L^{-1} and stopped at 3 g L^{-1}. O. edulis larvae survived concentrations of 4 g L^{-1} silt though growth was significantly impaired. At low silt concentrations, however, slight beneficial effects were observed (Davis 1960). Growth of O. edulis larvae was faster in water pre-treated with adsorbents (Fuller's earth or magnesium trisilicate) (Miller and Scott 1968) (from Moore 1977).

In contrast, Utting (1988) found particulate inorganic matter (PIM) may adversely effect growth of Ostrea edulis spat through decreased assimilation efficiency over a period of 7 months where PIM was less than 1 um in size and the concentration of SPM ranged from 15.88 - 88.05 mg L^{-1}. Shelbourne (1957) (from Moore 1977) concluded that turbidity and associated scour could be important in physically removing newly-settled Ostrea spat.

Crassostrea virginica could reject small particles of kaolin and Fuller's earth but suffered severe mortality from small silica particles (below 5 um) at comparatively low concentrations (0.5 g L^{-1}). Crassostrea could withstand comparatively high concentrations (up to 4 g L^{-1}) of larger silica particles (5-50 um). Growth showed a similar pattern, with least growth in the smallest fraction and greatest in the larger size groups, although some growth reduction was noted as a result of exposure to silica grains 5-25 um. Kaolin did not reduce growth in Crassostrea at concentrations up to 2 g L^{-1} (Davis and Hidu 1969).

Silt at concentrations as little as 0.75 g L^{-1}, however, reduced growth of C. virginica larvae; at 2 g L^{-1} growth stopped; at 3 g L^{-1} and above, all larvae died. Concentrations of silt below 0.5 g L^{-1}, however, increased the growth rate. Loosanoff (1962) (from Moore 1977) noted silt at concentrations less than 0.1 g L^{-1} could stimulate activity in Crassostrea.

Mercenaria mercenaria larvae could withstand silt concentrations up to the maximum of 4 g L^{-1} with only slight mortality. In the presence of fine particles of kaolin and Fuller's earth, however, larvae lost the ability to reject the particles, stomachs became packed, and the larvae died (Davis and Hidu 1969). Mercenaria also suffered mortality from exposure to low concentrations (0.5 g L^{-1}) of small (below 5um) silica particles, but not when exposed to high concentrations (4 g L^{-1}) of particles in the 5-50 um size range. Kaolin and Fuller's earth induced greater mortality than small silica particles (below 5um).

Growth was not impaired in Mercenaria at concentrations below 1 g L^{-1} and reduced only slightly until beyond 2 g L^{-1}. Growth was negligible at 4 g L^{-1} of silt (Davis 1960). Exposed to Fuller's earth, growth was reduced markedly at 0.5 g L^{-1} and larvae died at 1 g L^{-1}. In contrast, very low concentrations of silt, kaolin and Fuller's earth, had a beneficial effect (Davis 1960).

Eggs - Davis (1960) and Davis and Hidu (1969) studied the effects of silt, kaolin and Fuller's earth on eggs and larvae of Ostrea edulis and Crassostrea virginica. Silt was more harmful to eggs of C. virginica than either kaolin or Fuller's earth. As little as 0.188 g L^{-1} of silt significantly reduced the number of eggs reaching the straight-hinge stage. Fuller's earth and kaolin had no significant effect at concentrations less than 1 g L^{-1} and 2 g L^{-1}, respectively. A maximum of only 3 % developed normally in 1 g L^{-1} silt, whereas the number was 76 % and 26 % respectively in 4 g L^{-1} of kaolin or Fuller's earth. No effects of silica particles from less than 5 um to 50 um in size at concentrations up to 4 g L^{-1} were observed.

Loosanoff (1962) found that 0.25 g L^{-1} of silt reduces C. virginica egg survival to 73 per cent of controls kept in clear water. At a silt concentration of 0.5 g L^{-1}, 30 per cent of the eggs developed; at 1 or 2 g L^{-1} silt, almost all died.

Mercenaria mercenaria eggs developed in silt concentrations as high as 0.75 g L^{-1} but all died at concentrations of 3-4 g L^{-1}. Concentrations of Fuller's earth of 0.125 g L^{-1} and of kaolin of 0.5 g L^{-1} also reduced significantly the numbers developing (Davis 1960), although some survived even at the highest concentration (4 g L^{-1}). Egg development was impaired at high concentrations (2-4 g L^{-1}) of small silica particles (smaller than 5 um).

Blue Mussel

Acute toxicity of SPM to mussels appears to be low. Peddicord et al (1975) found Mytilus edulis had 10 per cent mortality for two age cohorts after 5 and 11 day exposures at 100,000 mg L^{-1} kaolin. The 200 hour LC_{50} for M. californianus was 96,000 mg L^{-1}. The 21-day LC_{50} of 1.5 - 2.5 cm M. californianus exposed to contaminated sediment with a high proportion of silt was about 10,000 mg L^{-1} (Peddicord 1980). Mortality on clean sediment at concentrations up to 19,500 mg L^{-1} was 35% after a 21 day exposure. That author also noted that neither contaminated nor uncontaminated sediment exposures up to 19,500 mg L^{-1} resulted in loss of byssal attachment during exposure and depuration up to 25 days. M. edulis showed significant long-term mortalities which appear to be related to concentration from exposures to ferric hydroxide flakes (Winter 1972) (Table 6).

Table 6. Mortality of Mytilus edulis exposed to ferric hydroxide suspensions. (From Winter 1972)

CONCENTRATION	TIME (months)				
(mg L^{-1} ferric hydroxide)	1 mo.	2 mo.	3 mo.	4 mo.	5 mo.
0 (control)	1%	4%	8%	12%	20%
0.74	3%	13%	17%	29%	40%
0 (no food)	5%	20%	33%	75%	
3.68 (no food)	2%	30%	55%	75%	
7.36	6%	40%	75%		
1.84	29%	70%	75%		
2.0	18%	69%	75%		

Purchon (1937) (from Moore 1977) found Mytilus edulis unaffected by 440 mg L^{-1} of suspended solids, but all died after 13 days exposure to 1,220 mg L^{-1} suspended mud.

SPM has been shown to interfere with energetics and feeding in M. edulis. Winter (1972) found a reduction in soft tissue dry weight of Mytilus edulis exposed to suspensions of ferric hydroxide flakes for 5 months compared to starved mussels. Mussels exposed to 7.36 mg L^{-1} ferric hydroxide and 1.59 mg L^{-1} algal food (giving a suspended load of 8.95 mg L^{-1}), showed a 60 per cent reduction in soft tissue dry weight in 3 months. Starved M. edulis in the absence of ferric hydroxide flakes had a higher soft tissue dry weight than those given the suspended flakes and food if the flake concentration was greater than 1.0 mg L^{-1} iron.

Widdows et al (1979) found that the inert component of natural silt diluted the amount of algal food ingested by Mytilus, but that at low concentrations of suspended material there was a potential for growth enhancement. Kiorboe et al (1980) note that M. edulis is well adapted to silt concentrations up to 55 mg L^{-1} and can benefit from concentrations up to 25 mg L^{-1}.

Similarly, Winter (1976) noted that filter feeding activity, amount of food ingested and growth observed in Mytilus edulis was stimulated when the diet consisted of an optimal food concentration and small amounts of suspended silt (12.5 mg L^{-1}) for 26 days. There was an increase of 32 per cent in dry tissue weight over M. edulis fed only algae at the same concentration. The largest increase in dry tissue weight (88.8 % after 26 days) was in 12.5 mg L^{-1} suspended silt and 40 x 10^3 cells L^{-1}.

Increased production of pseudofeces with associated increased mucus secretion (which may clog gills and impair respiration), must represent a significant drain of organic substance as far as the animal is concerned, especially when this occurs over a long period of time (Winter 1972) (from Moore 1977).

Foster-Smith (1975) found assimilation efficiency of Mytilus edulis decreased with increasing concentration of algae mixed with alumina. Neither type of particle was preferentially selected at any concentration. Ingested material contained the same proportions as the suspension. Foster-Smith (1975) concluded that particulate inorganic matter limits by dilution the amount of food absorbed by Mytilus edulis. The filtration rate of M. edulis was not affected markedly by the range of concentrations used. M. edulis rejects a large proportion of the material as pseudofeces (Moore 1977).

Chiba and Oshima (1957) (from Moore 1977) found the feeding rate and rate of pseudofeces production of M. edulis increased with increased concentration of bentonite after 1 hour exposures. Dodgson (1928) (from Moore 1977) noted that Mytilus will feed and pass a maximum of true feces when immersed in extremely turbid water.

Winter (1973) found filtration rate (the volume of water filtered free of particles per unit time) of Mytilus edulis decreased with increasing cell concentration. When the maximum ingestion rate was reached, the filtration rate decreased to keep the amount of food ingested constant. At higher concentrations filtration and ingestion rates were drastically reduced and pseudofeces production began.

The filtration rate of M. edulis doesn't appear to be affected markedly by a range of suspended material concentrations as in several other suspension feeders. Chiba and Oshima (1957) (from Moore 1977) found that pumping rate was not reduced in response to high concentrations (500-1000 mg L^{-1}) of bentonite. Mytilus, Crassostrea, and Mercenaria have been reported not to close their shell in turbid waters (Rice and Smith 1958; Fox 1942, from Moore 1977).

Feeding and respiratory movements in Mytilus were more irregular when exposed to high suspended sediment levels, decreasing both in duration amplitude in suspended sediment levels up to 15 g L^{-1} (Hsiao 1950) (from Moore 1977).

Mussels can pick up sediment and sand suspended by storm activity (De Vooys 1987). Commercially fished mussels in the Wadden Sea, Netherlands, contained an average of 8.9 g of sand (range 4 - 16.8) for 5 kg of mussels (De Vooys 1987). Mytilus edulis has physical mechanisms to both reduce the influx of sand and to eliminate excess sand from the mantle cavity. These mechanisms include ciliary tracts on the foot and visceral mass and cilia on the mantle surface which can transport particles to the mantle edge. Some of the material transported on the mantle goes into the inhalent siphon (De Vooys 1987). De Vooys (1987) found that Mytilus voids sand particles for approximately 48 hours after fishing but that 99 per cent of particles are voided within 24 hours, and 93 per cent within four hours.

Mytilus may also be exposed to material adhering to the shell through deposit feeding and shell cleaning behaviours. Theisen (1972) from Moore (1977) described shell-cleaning behaviour and deposit-feeding in young

Mytilus and Blackman and Wilson (1973) have made similar observations (Moore 1977).

Sea Scallop and Bay Scallop

No published work was found dealing with turbidity effects on Placopecten magellanicus. This species generally lives in clear waters and is not expected to have great tolerance to suspended material compared to mussels or oysters. Placopecten appears to produce pseudofeces at relatively low seston levels (visually clear waters) and would show reduced ingestion rates in turbid waters (Dr. J. Grant, Dalhousie University, personal communication). Drilling mud SPM has been shown to be toxic to scallop adults and larvae (Texaco Canada Limited, personal communication).

Kaolin at a concentration of 0.5 g L^{-1} reduced filtration rate in Placopecten magellanicus (Stone, Palmer and Chen (Unpublished report, 1974); Stone and Palmer 1975).

Carriker (1959) (from Moore 1977) found pseudofecal accumulation would smother bay scallop unless material was washed away or compacted. Castanga (1975) (from Moore 1977) found small Argopecten (less than 10 mm) do not survive well when exposed to silt.

Stone and Palmer (1975) measured oxygen consumption in adult Argopecten irradians exposed for 7 to 14 days to 0.25, 0.5 and 1.0 g L^{-1} kaolin. Those exposed to 0.5 and 1.0 g L^{-1} kaolin showed increased oxygen consumption compared to controls, but exposure to 0.25 g L^{-1} kaolin had no effect after 14 days. Seed scallops increased oxygen consumption at all three concentrations.

4.0 CONCLUSIONS AND SUMMARY

This chapter has provided an overview of suspended particulate matter in marine and estuarine waters, concerning its concentration, effects of dredging on its levels, and its effects on biological organisms, in particular those important in aquaculture in Atlantic Canada.

Natural levels of suspended particulate matter (SPM) in marine and estuarine nearshore areas in Atlantic Canada and other areas are generally less than 100 mg L^{-1}. This concentration may be exceeded in situations in which bottom sediment is resuspended by storms, or where river discharge has a high suspended load. Even under these circumstances, concentrations generally do not exceed about 200 mg L^{-1}. Extremely high SPM concentrations occur rarely, typically in environments with high tidal currents or in surf zones.

Dredging activity causes locally high concentrations of SPM in the vicinity of the dredge but concentrations fall within a short distance to within the normal range. Concentrations may range from less than 100 mg L^{-1} up to 1000 mg L^{-1} near a dredge, but within 500 metres can be expected to fall to below maximum values naturally experienced at a site. Elevated SPM concentrations extend further from the dredge in mid-water than at the surface and further near bottom than in mid-water.

Elevated SPM concentrations can have a variety of generally minor effects on biological organisms, although chronic exposures can have serious detrimental effects. Extremely high SPM concentrations are not generally acutely toxic to fish and invertebrates. Effects on marine and estuarine organisms and aquaculture species of contaminants associated with SPM resulting from dredging are not well documented.

Adult stages of Atlantic Canadian aquaculture species are generally tolerant of elevated SPM levels. Salmonids can withstand short term exposures to high SPM concentrations from a few hundred to a few thousand mg L^{-1} and do not suffer mortality from chronic exposures at levels of a few hundred mg L^{-1}, although they may suffer physiological effects and reduced growth. Molluscan aquaculture species such as the blue mussel, European and American Oyster, and Bay Scallop do not suffer mortality from short-term exposure to concentrations of SPM of several hundred to a thousand mg L^{-1} but physiological parameters and growth may be affected. The effects of exposure of sea scallops to elevated SPM concentrations are not known. Lobster larvae and juveniles are tolerant of elevated SPM although extremely high concentrations can result in larval mortality.

The observed low degree of effect of elevated SPM concentrations on aquaculture organisms, combined with the highly localized, short-term and often intermittent distribution of SPM resulting from dredging, suggests that this should be a comparatively minor concern in the evaluation of the hazards of dredging operations.

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2. Experimental Studies

CHAPTER 2

EXPERIMENTAL STUDIES

EFFECTS OF SUSPENDED SEDIMENT FROM DREDGING ON AQUACULTURE ORGANISMS

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1.0 INTRODUCTION

Every year a substantial amount of dredging of harbours and channels is carried out in Canadian coastal waters in the interest of maintaining transportation corridors and for coastal engineering development. Dredged material must be moved and dumped where it will not interfere with transport and harborage or natural resources. In 1987 approximately 5.3 million cubic metres of dredged material were dumped in Canadian coastal waters (Environment Canada 1989).

Dredging and disposal of seabed materials poses a number of environmental problems which frequently require mitigation. Included are release into the water of contaminants from the sediments; displacement and physical removal, by the dredging process, of resource species such as fish and lobster; burial of resource species at dump sites; alteration of water chemistry and physical properties such as turbidity; and socioeconomic effects such as interference with fishing patterns and activities.

In the last decade, conflict of dredging activity with marine aquaculture has also become an area of concern. The aquaculture industry, particularly the coastal sea-farming of species such as Atlantic salmon, mussels, and oysters, has been growing rapidly. In Atlantic Canada, value of aquaculture products doubled from 1980-82, manifesting a worldwide upward trend. These operations, which include bottom leases, pounds for temporary holding, or raft and cage facilities (salmonids, mussels, oysters, scallops and other species), are, of necessity, located in coastal areas. Furthermore, many of the characteristics of coastal areas which make them ideal as harbours and sites for human habitation, also make them suitable for aquaculture (Aggett and McIver 1987). In recent years aquaculture operators have become increasingly concerned over potential conflicts with dredge spoil dumping. The current expansion of the aquaculture industry has been leading, and will continue to lead, to dredging operations being viewed with increased concern.

Effects on aquaculture organisms, particularly from SPM caused by dredging, are, however, as yet largely conjectural. Three general areas of concern regarding dredging conflicts with aquaculture operations have been identified (Aggett and McIver 1987):

1) Concerns over mortality of aquaculture organisms resulting from dredging operations;

2) Concern over effects on palatability, market acceptability, or safety of cultured organisms; and

3) Public perceptions of effects.

The main objective of the present study is to provide information which will assist in managing these concerns.

Dredging is thought to impact aquaculture operations largely as a consequence of increasing the suspended sediment load in the water. Organisms may be affected through physical contact with high suspended loads or through contact with contaminants chemically associated with the suspended particulate fraction. Parameters such as growth, behaviour and stress on adults and juveniles of aquaculture species may have an impact on the viability and profitability of the aquaculture operation and all are potentially affected by suspended particulates.

A body of evidence has accumulated, however, that suspended particulates have limited impacts on marine organisms, and probably on aquaculture organisms as well. It is difficult, however, to extrapolate these findings to aquaculture activities, partly because of the narrow focus of some of the studies or broad general conclusions of others. Aquaculture operations also pose special conditions of holding which differ from organisms in the natural environment, and further, aquaculture has requirements for quality and commercial rates of production quite unlike natural populations. Only a small number of studies has examined the impact of suspended sediments in terms which can be related to aquaculture.

This study has examined the effects of suspended sediments, in some cases associated with dredge spoils, on several key Atlantic aquaculture species. It uses available literature on effects of suspended sediments on marine organisms in general, and assesses effects both through laboratory and on-site exposures of the organisms to suspended particulate matter.

2.0 METHODS

2.1 Field Exposures

2.1.1 Pugwash Harbour

Field Exposure Conditions

A variety of aquaculture species were deployed in the vicinity of a 56,000 m^3 channel dredging project using a bucket dredge in Pugwash Harbour, Nova Scotia, on Northumberland Strait, in late September-early October, 1988. The site was chosen because it had relatively low contamination and reasonably high levels of silt. Large and small blue mussels (Mytilus edulis), European oysters (Ostrea edulis), and sea scallops (Placopecten magellanicus) along with canner lobsters (Homarus americanus) were deployed in cages and lantern nets at three sites (Figure 1). The mooring arrangement and positioning of the animals in the water column is illustrated in Figure 2. Two of the exposures (1 & 2) were along the dredged channel and were as close as possible to the dredge track without interfering with the operation. The third site (control) was situated 2 km from the other sites in an area which was not dredged until after the experiment. Sediment traps and recording thermographs were placed at each site and each site was visited three times a week for the three-week duration of the exposure. At each visit, vertical profiles of transmittance, salinity and temperature were taken. Water samples were taken to determine SPM concentration and to calibrate the transmissometer. SPM concentration was determined gravimetrically.

Biological Effects

Lobster - Canner lobster (69 mm carapace length and 250 gm wet weight) from a pound in Pugwash, Nova Scotia, were used in experiments. Carapace length to the base of the rostrum, and wet weight were determined after exposure. Length/weight regressions on Log_{10} transformed measurements were determined

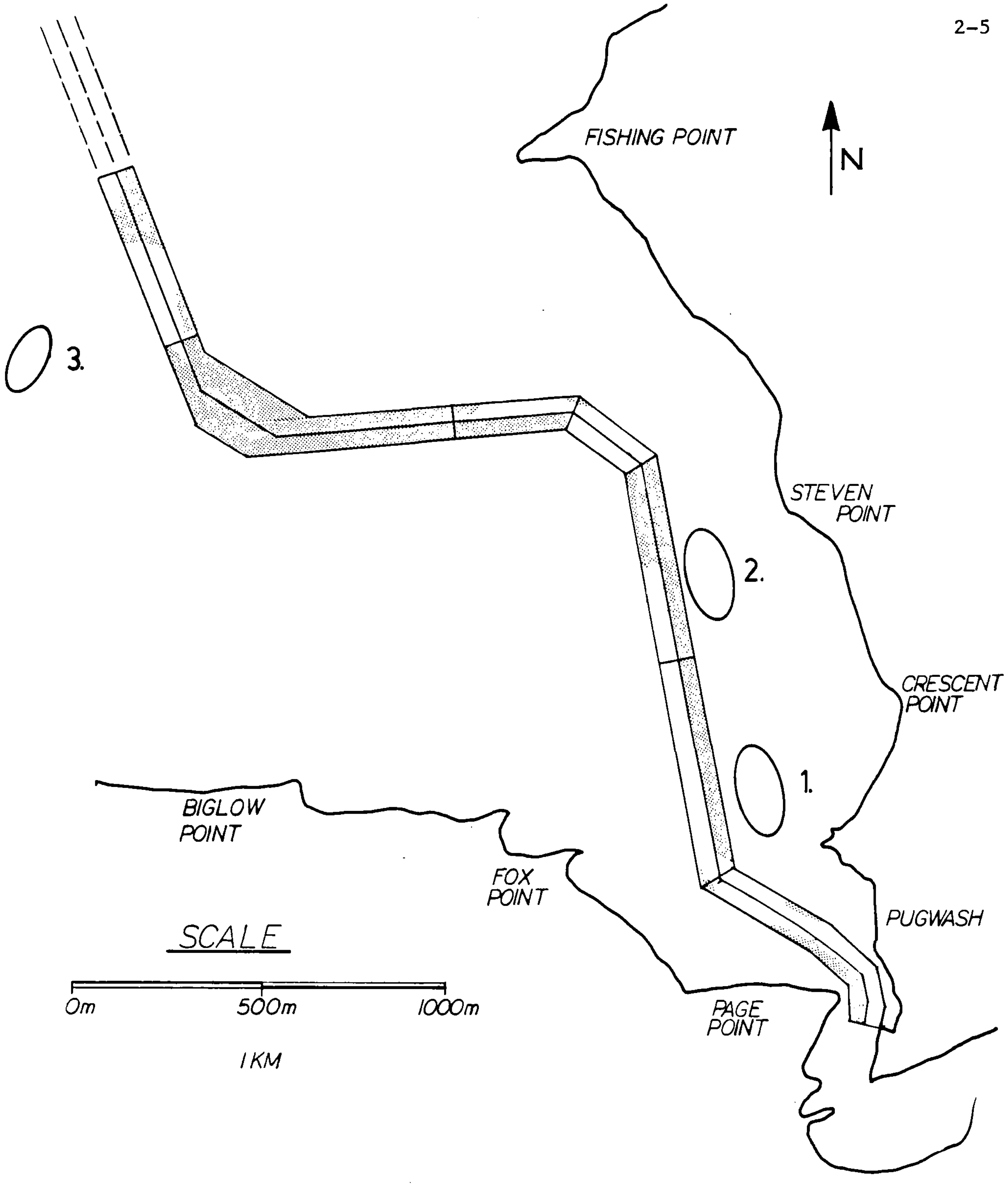


Figure 1. Pugwash Harbour, Nova Scotia, and exposure sites, September-October 1988. Shading represents areas designated for dredging. Site 3 is the control site.

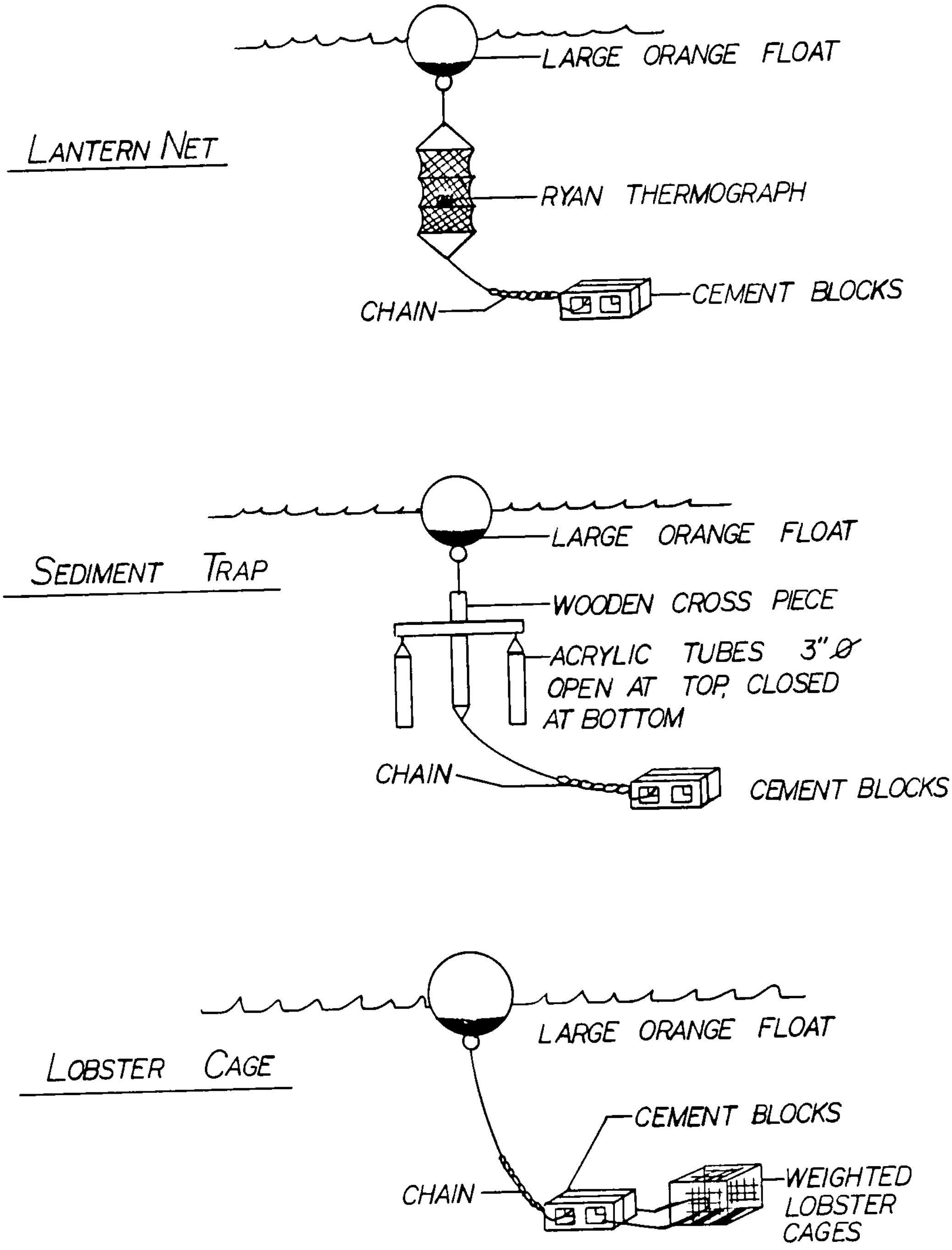


Figure 2. Field exposure apparatus, Pugwash, Nova Scotia.

and adjusted mean weight for each treatment compared by covariance analysis. In addition, the gill from each of the first two right walking legs was removed, stored in formalin, and observed later under a stereo dissecting microscope for evidence of damage, particle accumulation and the occurrence of parasites, chiefly bivalve larvae, attached to the gills.

Mussels - Large and small blue mussels (Mytilus edulis) (66.4 mm ± 7.4 and 43.1 mm ± 5.6, shell length respectively) were purchased from commercial suppliers, and were allocated randomly to an initial, control and two treatment groups. In addition, a number of the small mussels from each treatment were etched with a number to enable later identification and estimation of growth during the experiment. This technique was not wholly successful as in most cases the etching could not be read, but a number of growth measurements were obtained in this manner. All animals were shucked into pre-weighed tinfoil dishes prior to weighing. Dry weights of tissue and shell were determined after drying for 24 hours at 60° C. Wet weight was determined after blotting to remove excess liquid. Shells were measured with digital calipers at the point of greatest length and weights were measured to the nearest milligram. A condition index was calculated by dividing the dry flesh weight by the shell weight (Freeman 1974). Depending on contingency, the mussels were either measured fresh, or were frozen for later analysis. Tissue ash-free dry weight (AFDW) was estimated for about half of the individuals but had high variability and was not used further. Treatment effects were compared by covariance analysis on log-transformed weight and length measurements. Only the mussels and small European oysters had sufficiently good length-weight relationships for this analysis to be used.

Mortality rate in each treatment was noted and we attempted to estimate outmigration of large mussels from experimental socks as a further comparison among treatments. The latter initiative was dropped as losses from the socks occurred during handling.

Oysters and Scallops - The approach was similar to that for the mussels. Large and small European oysters (Ostrea edulis) (82.5 mm ± 4.9 mm and 29.6 mm ± 2.7 mm, shell length respectively) and large and small sea scallops

(Placopecten magellanicus) (97.6 mm ± 5.2 mm and 27.6 mm ± 3.3 mm, shell length respectively) were used. Small oysters were marked with an indelible marker for growth estimates. Only a small number of large oysters and scallops were available for deployment in the study.

2.1.2 Souris Harbour

Field Exposure Conditions

The exposure design consisted of two moorings with suspended Japanese lantern nets located in outer Souris Harbour adjacent to an ocean dumpsite used by a harbour dredging operation, and at a distant control site (Figures 3 & 4). A secondary exposure was put in place to provide additional data regarding effects of high turbidity in the vicinity of the boat harbour (Figure 3). The dredging program was abandoned prematurely at the beginning of our exposure period, however, and the secondary exposure design became the sole source of data from the site.

For the secondary exposure, two metal lobster cages were suspended from a breakwater (Figure 3), one in an exposed area with visibly high turbidity and the second on the protected side where the water was visibly clear. In each cage we placed synthetic mesh bags (6 mm openings) containing 40 each of blue mussels (52.3 mm ± 4.0 mm shell length) and bay scallops (Argopecten irradians) (34.6 mm ± 3.4 mm shell length) as well as 12 preweighed and labelled clumps of small American oyster (Crassostrea virginica). Mussels, scallops and oysters deployed in lantern nets in the outer harbour served as controls and 35 organisms of each species brought back to the laboratory served as initials. Organisms in the outer harbour deployment were individually numbered with plastic label tape affixed to the shell with epoxy. All organisms were obtained from New Wave Shellfish Farm, Mount Stewart, PEI, and were kept in running sea water for a day prior to deployment. Shell and weight measurements were made as for other experiments, after freezing. Periodic water samples were taken during the exposure period and SPM concentration was measured gravimetrically.

The exposure lasted 28 days (September 14 to October 12) and the

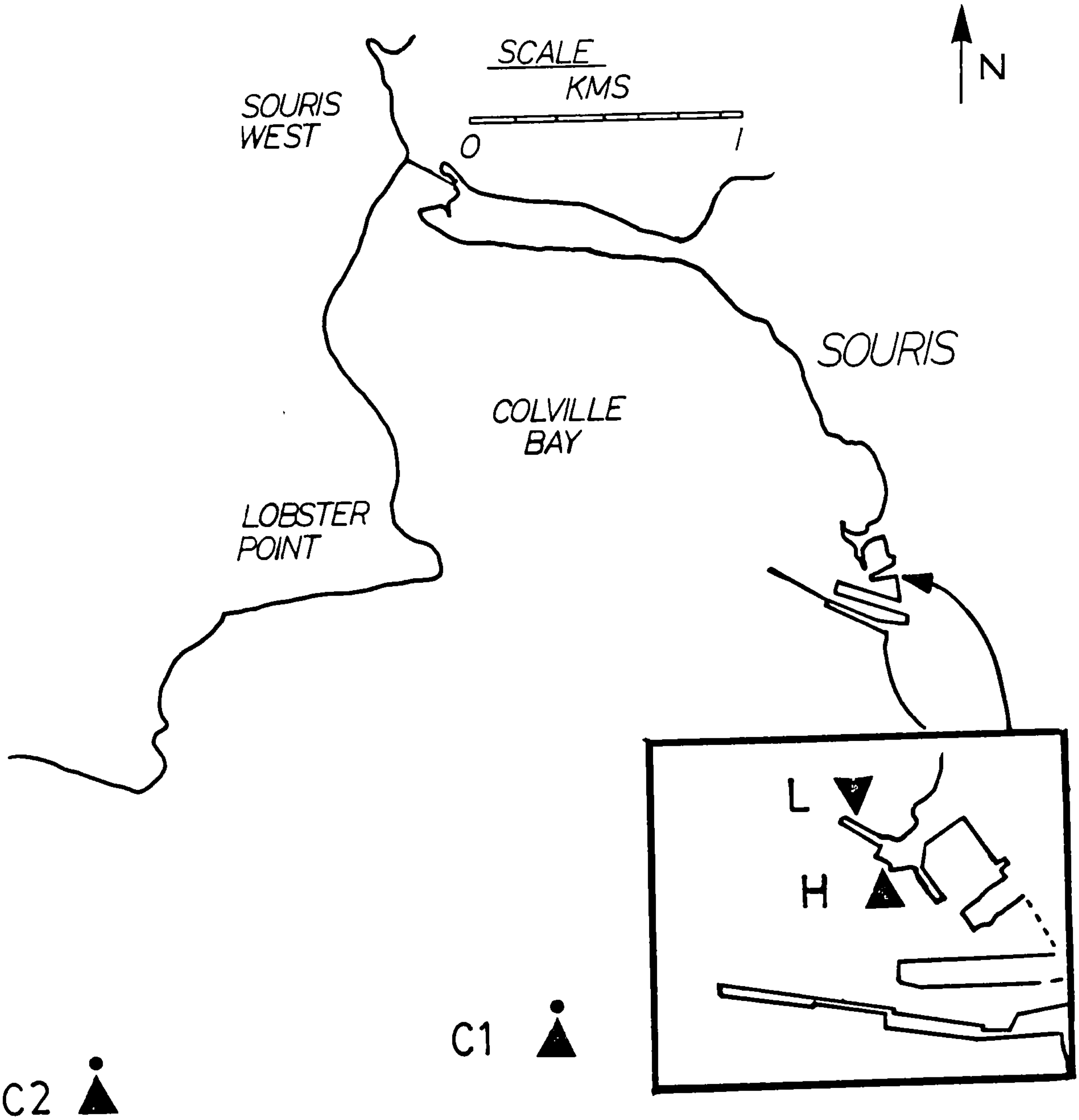


Figure 3. Souris Harbour, Prince Edward Island, and exposure sites, September-October 1989. C_1 and C_2, Outer Harbour; L, Inner Harbour, low SPM; H, Inner Harbour, high SPM.

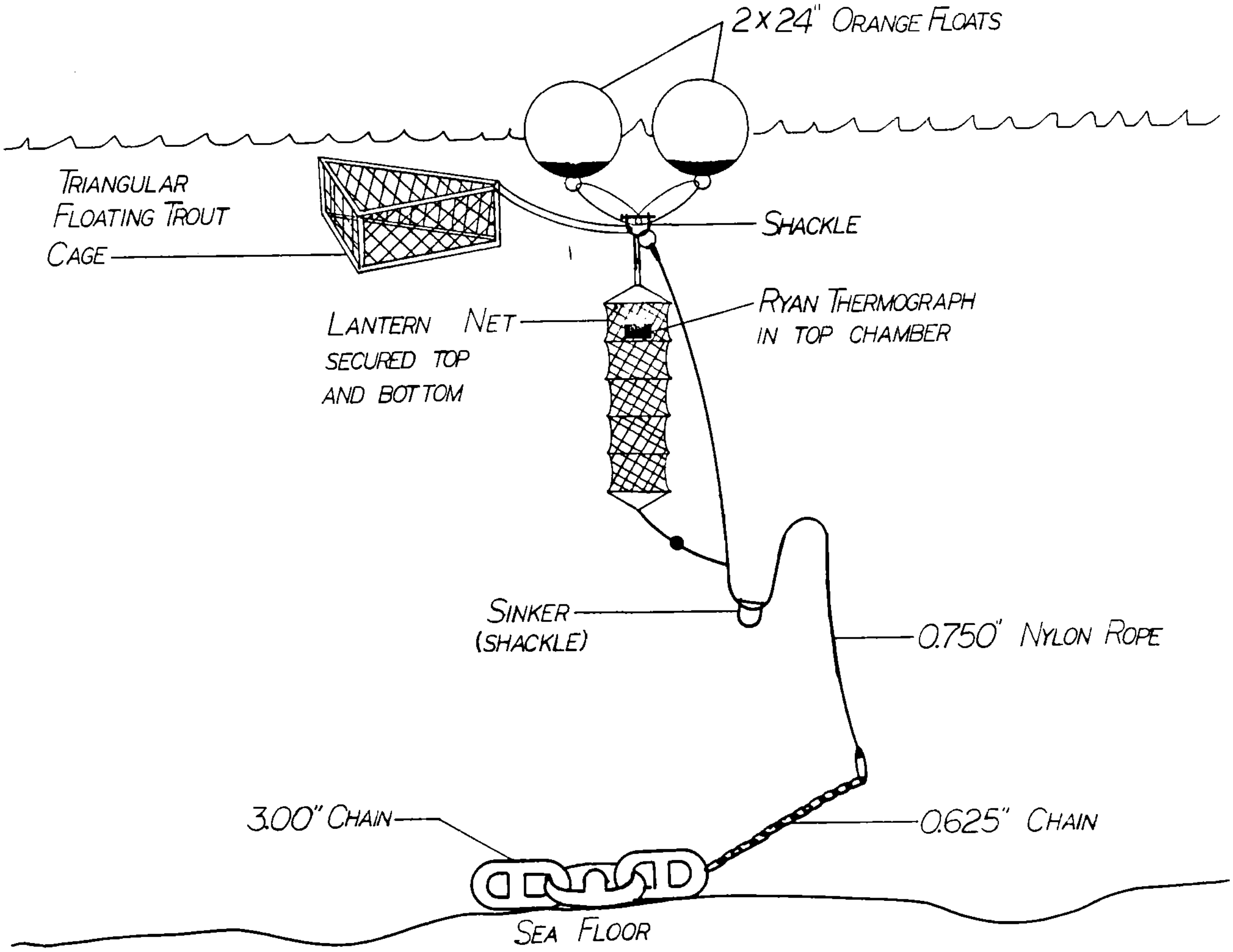


Figure 4. Field exposure apparatus, Outer Harbour, Souris, PEI.

majority of the organisms survived deployment. The shell edges of American oyster and bay scallop deployed in the outer harbour became abraded by knocking against one another through wave activity. Consequently individuals of these species from the outer harbour deployment were not used in further analysis.

2.2 Laboratory Exposures

2.2.1 Blue Mussel and European Oyster

The SPM exposure system was set up as shown in Figure 5. Cold, sand-filtered seawater at 6-10° C flowed into an aerated head tank and the overflow was divided, with half directed into the control tank and the other half to the SPM mixing tank. A stock supply of intertidal mud containing some silt and clay, obtained from Burntcoat Head, Minas Basin, Nova Scotia, was used to generate SPM concentrations for the experiments.

To obtain target concentrations of from 100 to 200 mg L^{-1}, one liter of mud was added to the mixing tank twice daily. The overflow from the mixing tank (carrying the SPM) passed through a settling bucket equipped with a baffle to allow the heavier sediments (mostly fine sand) to fall from the stream before passing into the exposure tank. Concentrations fluctuated somewhat, both during the day and from day to day, and levels were regulated by slight alterations in the amount of mud added.

Thirty numbered and measured mussels (Mytilus edulis, 35-60 mm) and European oysters (Ostrea edulis, 30-45 mm) were placed in separate plastic mesh baskets and hung in the control and exposure tanks (sea scallops Placopecten magellanicus were also included initially but were discontinued when they became unhealthy, evidently due to elevated copper levels from an unpainted cooling coil). With the exception of the scallops, all organisms appeared healthy as evidenced by normal feeding activity. Approximately 1.8 gm of algal diet (Chaetoceros sp and Isochrysis sp) in 2 L of seawater was added daily. Algae was provided by Mr. Ken Freeman of the Department of Fisheries and Oceans in Halifax, and maintained in aerated and illuminated 20 L buckets covered with cellophane wrap. Flows were first set at about

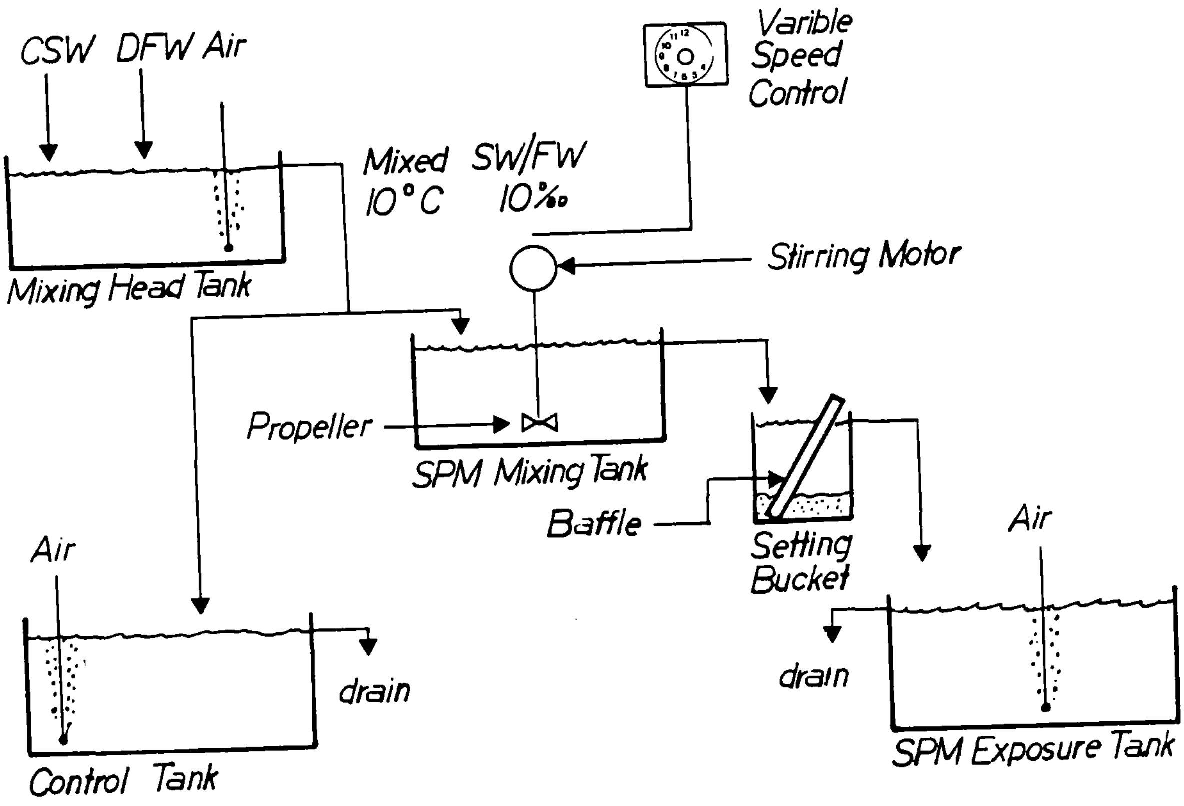


Figure 5. Laboratory exposure system for tests of effects of suspended particulate matter (SPM) on blue mussels, European oysters and rainbow trout.

500 mL/minute, but were increased after 15 days to about 700 mL/minute to reduce slightly elevated ammonia levels. Chilling units were placed in each tank to maintain temperature at 10° C.

Thirty animals of each species were randomly removed from the holding tanks and frozen for measurement of initial weight and length, and a final length was determined for animals after exposure. Body parameters were determined as indicated for animals in the Pugwash field exposure. The exposure lasted 35 days.

Softshell clams (Mya arenaria) were also placed in the experimental apparatus in a parallel experiment conducted by Dr. Jon Grant of the Department of Oceanography, Dalhousie University, Halifax, Nova Scotia. Weight-specific oxygen consumption rate and ammonia excretion rate were determined throughout the exposure, to detect changes in physiology of the organisms through the experiment.

Growth increments in Mytilus edulis exposed experimentally to elevated SPM concentrations were also measured by a laser diffraction technique (Stromgren 1975; 1984) with the cooperation of the Department of Fisheries and Oceans, Mr. Ken Freeman. The experiment was carried out by a work term student, and the complete project report is presented in Appendix 1.

2.2.2 Rainbow Trout

The SPM exposure system for trout was the same as for the mollusc exposures (Figure 5), except that approximately two parts dechlorinated fresh water were mixed with one part cold seawater to give a mixture of 10 ppt salt water, as measured by refractometer.

Juvenile rainbow trout (Onchorhynchus mykiss) from Merlin Fish Farms Ltd., Wentworth Valley were anaesthetized (MS222, 0.5 g in 10 L for 2 - 3 minutes) weighed, measured and individually identified with a series of Alcian Blue fin marks injected by tagging gun. Fish were allowed to recover for two days before being assigned to treatments. During exposures fish were held in fibreglass tanks covered with mesh screen to prevent them from jumping out, and a twelve hour light/dark cycle was used.

The exposure consisted of two parts, an initial six-day exposure to continuously elevated SPM at an average concentration of about 180 mg L^{-1}, followed by an eleven-day recovery period, and then a 30-day exposure to concentrations which had a pronounced high-low cycle through the day, from as little as 20 to more than 200 mg L^{-1}. For the continuous exposure, about 1 L of mud was added to the mixing tank twice daily, with a flow rate of about 750 ml per minute. Fifty fish between 75 and 115 grams were measured and randomly distributed into control and exposure tanks. Fish were fed Corey brand sinking pellets, and the bottom of the tanks were siphoned daily to remove fish wastes and any settled SPM from the exposure tank. Feeding was on a "demand" basis, with feed containers weighed before and after feeding to calculate the amount fed. The fish exposed to SPM fed poorly, which we attributed to the high SPM preventing them from seeing the food. This exposure was, therefore, terminated after six days. All fish were weighed and measured and allowed to recover for 11 days.

Subsequently a 30-day exposure was begun in which the SPM concentration was allowed to drop during part of the day to levels at which the fish could see the food and feed. Food was switched to a floating variety. One litre of mud was added to the mixing tank once per day, with the flow set at 2 liters per minute. This resulted in an SPM regime highest after the mud addition and decreasing until the next addition. Fish were reweighed and remeasured, and half from each of the previous control and exposure groups were assigned to the same treatment and half to the opposite treatment. This arrangement enabled us to look for differences resulting from the new SPM exposure, as well as to evaluate any prolonged effects of the earlier six-day SPM exposure. Feeding was done by preweighed ration, based on a ratio of 1.2% of total tank fish weight per day, which was added prior to the daily addition of mud. Fish were again weighed and measured at the end of the experiment.

3.0 RESULTS

3.1 Field Exposures

3.1.1 Pugwash Harbour

Exposure Conditions

SPM distribution in the vicinity of the dredge was patchy and SPM was quickly dispersed by the strong tidal current. Transmissometer measurements at the three study sites (control plus two experimental) were similar, and gave an estimate of about 12 mg L^{-1} SPM (Table 1). Concentrations in the dredge plume or in the immediate vicinity of the dredge were generally higher (Table 2) with the highest measured SPM occurring there (88 mg L^{-1}). Each of the experimental sites is expected to have been exposed to concentrations similar to these when the dredge was operating near them. The physical oceanographic information gathered at the time indicated that all three sites had similar physical conditions during the experiment, and no differences in turbidity were noted with depth at any of the stations. Temperatures recorded by continuous thermograph were similar between control and experimental sites, and showed a gradual decline from about 15° C to 10° C during the 21 days of the exposure. The weather during the exposure period included several windy days which resuspended bottom sediments and created turbid conditions throughout the harbour.

Table 1. SPM concentration during Pugwash field exposure, September-October 1988, determined from transmittance measurements. SPM (mg L^{-1}) = (1345.9 x 1/T) - 8.34, $r^2 = 0.91$, N = 28.

	Transmittance (%)			Estimated SPM (mg L^{-1})	
Treatment	$\bar{x}$	S.D.	N	$\bar{x}$	S.D.
Control	70.4	9.2	54	11.1	2.5
Site 1	66.7	8.3	53	12.1	2.6
Site 2	69.4	9.4	53	11.4	2.8

Table 2. Direct measurements of SPM in the vicinity of experimental moorings and dredging operations, Pugwash Harbour, September-October, 1988.

	N	$\bar{x}$	S.D.	Maximum
Control	22	12.6	6.4	30.0
Site 1	20	16.3	9.0	39.7
Site 2	17	12.4	3.6	18.4
Near Dredge	14	45.8	22.0	88.1

Biological Effects

Lobster - The mean weights and lengths of lobster in each treatment were similar (Table 3) and means adjusted for carapace length were not significantly different (Analysis of Covariance). The lobster at Site 2, however, appeared to have a higher slope of the length-weight regression than the other treatments (Table 3) but the difference was not statistically significant.

Types and abundance of particles on the gills of lobster from different exposures were similar (Table 4). Fewer of the lobster from Site 1 had an increased frequency of isolated particles and particle aggregates on the gills compared with control and Site 2. The control appeared to have a higher number of bivalve larvae attached to the gills (Table 4).

The gills of both control and exposed lobster showed occasional darkened lamellae, particularly the tips, though occasionally the shaft of the lamellae was darkened. Many of the darkened tips appeared encapsulated. The observations were verified by the Fish Health Unit of DFO in Halifax (Dr. John Cornick). The phenomenon has been observed before in lobster under stress, including lobster with Gaffkemia, and may be a mechanism for isolating parts of lamellae which have been exposed to harmful substances. The condition in our experimental lobster may have resulted from holding in a pound prior to testing.

Table 3. Weight, length, and weight-length relationship for canner lobster exposed to dredge-suspended sediment in Pugwash Harbour, Nova Scotia. Length-weight relationship: Log_{10} W (g) = b + (m x Log_{10} L (mm))

Treatment	N	Mean Length (mm)	S.D.	Mean Weight (g)	S.D.	Regression Parameters	
						b	m
Control	12	68.8	2.7	259.8	28.1	-2.308	2.569
Site 1	11	69.7	2.3	262.8	21.1	-1.853	2.318
Site 2	11	67.6	1.9	246.2	23.8	-3.650	3.301

Table 4. Observations of particles on gills of the first two walking legs of <u>Homarus</u> <u>americanus</u> in field exposures. Data for two gills have been summed. Proportions are in brackets.

	Control	Low	High
N =	12	11	12
Number with isolated particles	10 (0.83)	3 (0.27)	11 (0.92)
Average number of particles	3.8	2.7	3.4
Number with particle aggregates	11 (0.92)	8 (0.73)	11 (0.92)
Number with aggregate accumulation at base of lamellae	4 (0.33)	3 (0.27)	7 (0.58)
Number with darkened lamellae	7 (0.58)	8 (0.73)	6 (0.50)
Average number of darkened lamellae	1.4	1.9	2.7
Number with attached bivalve larvae (average)	3 (3.0)	1 (2.0)	2 (1.0)

Mussels, Oysters, and Scallops - Measurements for each of the species are summarized in Tables 5-7 and Figures 6-8. Weight-length relationships and statistical comparisons of adjusted means for large and small mussels and small oysters are presented in Appendix 2.

Adjusted tissue weights (dry and wet) for large mussels did not differ significantly between control and experimental sites, but were significantly higher at the beginning of the experiment than at the end (Figure 6), suggesting that conditions were less favourable to their growth in the field situation than at the site from which they had been acquired. Shell weight of the large individuals measured at the start of the experiment was similar to that in the treatments, and no difference between treatments was noted (Figure 6). No differences in condition index (CI) were observed between treatments (Figure 9), but CI at the beginning of the experiment was significantly greater than in all groups deployed in the field.

Tissue wet and dry weight for small mussels also did not differ significantly between control and experimental sites, although the control appeared to be highest in both these measures. Small mussels also showed higher adjusted tissue wet weights at the beginning of the experiment than at the end (Figure 7), and shell weight at the start of the experiment was significantly smaller than at the end. Since shell weights have been adjusted to a common size, the result suggests a shell thickening in the animals placed in the field. Condition index (CI) was larger in the control than experimentals (Mann Whitney U test, $p < 0.05$) (Figure 9), possibly indicating an effect of dredging. As observed in the large mussels, CI at the beginning of the experiment in small mussels was significantly higher than for treatments, reflecting the higher tissue weights, and suggesting tissue weight loss in the field deployment. Growth increments in marked small mussels were similar between treatment sites (Table 8).

The small European oysters showed high variability between treatments for all measures and no clear patterns were evident. Highest tissue weight

Table 5. Measurements of *Ostrea edulis* in field exposures to dredge-induced SPM, Pugwash Harbour.

Species/Exposure		Wet Weight (g)		Meat Weight (g)		Tissue Dry Weight (g)		AFDW (g)		Shell Weight (g)		Shell Length (mm)		Condition Index (AFDW)		Condition Index (Dry Weight)	
	N	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.
Ostrea edulis - Large																	
Initial	9	62.86	9.49	10.75	2.16	1.89	0.42	0.194	0.034	52.11	7.99	82.51	4.85	—	—	0.036	0.007
Control	5	55.00	10.94	6.94	1.66	1.73	0.44	0.194	0.034	48.06	9.81	—	—	—	—	0.036	0.008
Site 1	5	52.04	11.77	5.39	1.27	1.31	0.35	—	—	46.65	10.51	—	—	—	—	0.028	0.003
Site 2	5	51.98	11.85	6.16	2.68	1.52	0.69	—	—	45.82	9.24	—	—	—	—	0.032	0.009
Average	24	56.7	11.21	7.88	3.01	1.65	0.5	0.194	0.034	48.82	8.96	82.51	4.85	—	—	0.034	0.007
Ostrea edulis - Small																	
Initial	10	1.00	0.24	0.13	0.04	0.023	0.01	0.004	0.001	0.87	0.20	29.58	2.69	0.005	0.002	0.026	0.006
Control	25	0.74	0.29	0.17	0.06	0.023	0.01	0.005	0.002	0.57	0.23	25.55	2.50	0.009	0.005	0.041	0.006
Site 1	15	1.14	0.35	0.34	0.11	0.034	0.01	—	—	0.80	0.26	29.21	2.69	—	—	0.044	0.006
Site 2	15	1.01	0.30	0.24	0.07	0.03	0.01	0.003	0.001	0.76	0.23	29.35	2.47	0.006	0.002	0.037	0.006
Average	65	0.93	0.33	0.22	0.11	0.027	0.01	0.005	0.002	0.71	0.26	29.70	3.12	0.007	0.004	0.038	0.008

Table 6. Measurements of *Mytilus edulis* in field exposures to dredge-induced SPM, Pugwash Harbour.

Species/Exposure		Wet Weight (g)		Meat Weight (g)		Tissue Dry Weight (g)		AFDW (g)		Shell Weight (g)		Shell Length (mm)		Condition Index (AFDW)		Condition Index (Dry Weight)	
	N	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.
Mytilus edulis - Large																	
Initial	10	16.04	7.62	9.08	4.37	1.79	1.01	0.144	0.067	6.96	3.43	64.28	10.06	0.020	0.004	0.249	0.066
Control	30	16.24	5.75	8.20	3.05	1.58	0.67	0.126	0.049	8.04	2.94	66.88	6.70	0.016	0.005	0.199	0.053
Site 1	30	16.12	6.10	8.39	3.42	1.47	0.75	0.135	0.037	7.73	3.00	67.15	7.10	0.017	0.003	0.193	0.057
Site 2	30	15.34	5.81	7.95	3.18	1.49	0.71	0.138	0.071	7.35	2.84	65.92	7.69	0.019	0.005	0.203	0.052
Average	100	15.92	5.99	8.27	3.31	1.54	0.74	0.135	0.055	7.64	2.95	66.41	7.43	0.018	0.004	0.203	0.057
Mytilus edulis - Small																	
Initial	10	3.51	1.08	2.17	0.72	0.38	0.12	0.03	0.017	1.34	0.41	41.10	4.17	0.022	0.008	0.291	0.063
Control	30	4.31	1.48	2.50	1.04	0.53	0.28	0.052	0.023	1.81	0.52	44.86	4.93	0.026	0.004	0.281	0.086
Site 1	29	3.74	1.91	2.07	1.15	0.41	0.24	0.034	0.017	1.67	0.78	41.93	6.39	0.018	0.010	0.239	0.043
Site 2	30	3.90	1.46	2.19	0.92	0.40	0.17	0.035	0.016	1.71	0.56	43.14	5.63	0.017	0.008	0.234	0.051
Average	99	3.94	1.58	2.24	1.01	0.44	0.23	0.037	0.019	1.69	0.62	43.1	5.62	0.020	0.009	0.256	0.067

Table 7. Measurements of <u>Placopecten magellanicus</u> in field exposures to dredge-induced SPM, Pugwash Harbour.

Species/Exposure		Wet Weight (g)		Meat Weight (g)		Tissue Dry Weight (g)		AFDW (g)		Shell Weight (g)		Shell Length (mm)		Condition Index (AFDW)		Condition Index (Dry Weight)	
	N	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.
Placopecten magellanicus - Large																	
Control	5	138.82	23.83	46.24	8.00	8.51	1.80	0.94	0.16	90.73	16.76	98.82	7.35	0.010	0.002	0.096	0.011
Site 1	5	130.78	17.78	44.59	10.92	8.20	1.41	0.80	0.16	84.20	9.98	94.96	4.56	0.010	0.002	0.099	0.014
Site 2	5	132.41	23.16	48.87	12.11	8.08	2.84	0.71	0.09	87.05	15.45	98.87	4.42	0.009	0.000	0.094	0.029
Average	15	134.12	20.24	46.56	9.88	8.26	1.96	0.83	0.16	87.33	13.59	97.55	5.23	0.010	0.001	0.096	0.018
Placopecten magellanicus - Small																	
Control	15	1.80	0.67	0.89	0.33	0.13	0.05	0.024	0.008	0.904	0.346	—	—	—	—	0.137	0.013
Site 1	30	1.89	0.67	0.98	0.34	0.13	0.05	0.025	0.008	0.908	0.342	—	—	—	—	0.147	0.015
Site 2	25	2.26	0.72	1.22	0.39	0.16	0.05	—	—	1.042	0.337	—	—	—	—	0.150	0.015
Average	70	2.00	0.71	1.05	0.37	0.14	0.05	0.025	0.008	0.955	0.342	—	—	—	—	0.146	0.015

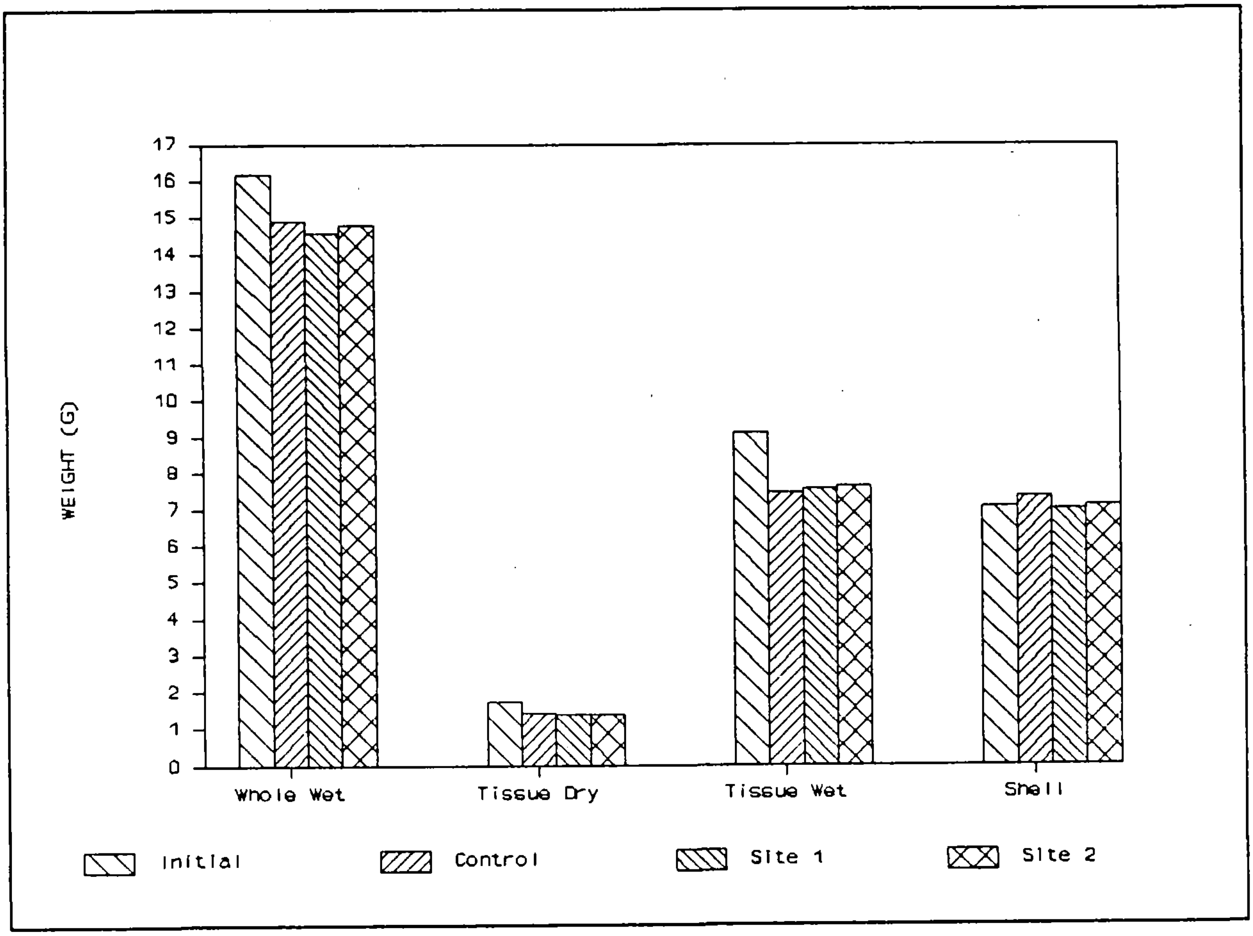


Figure 6. Adjusted mean weight (g) for large mussels (shell length = 66.4 mm ± 7.4 mm) deployed near a bucket dredge operation, Pugwash, Nova Scotia.

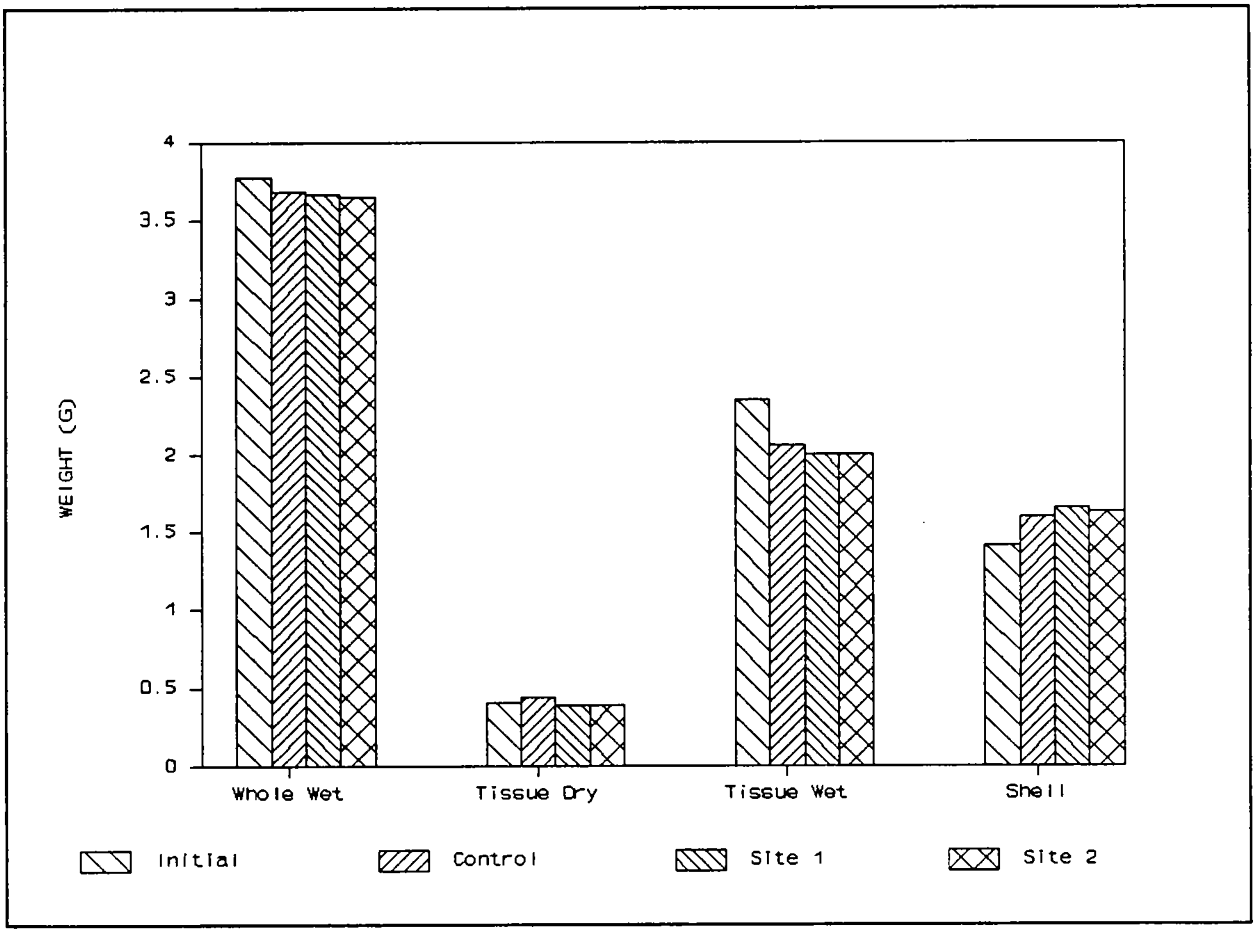


Figure 7. Adjusted mean weight (g) for small mussels (shell length = 43.1 ± 5.6 mm) deployed near a bucket dredge operation, Pugwash, Nova Scotia.

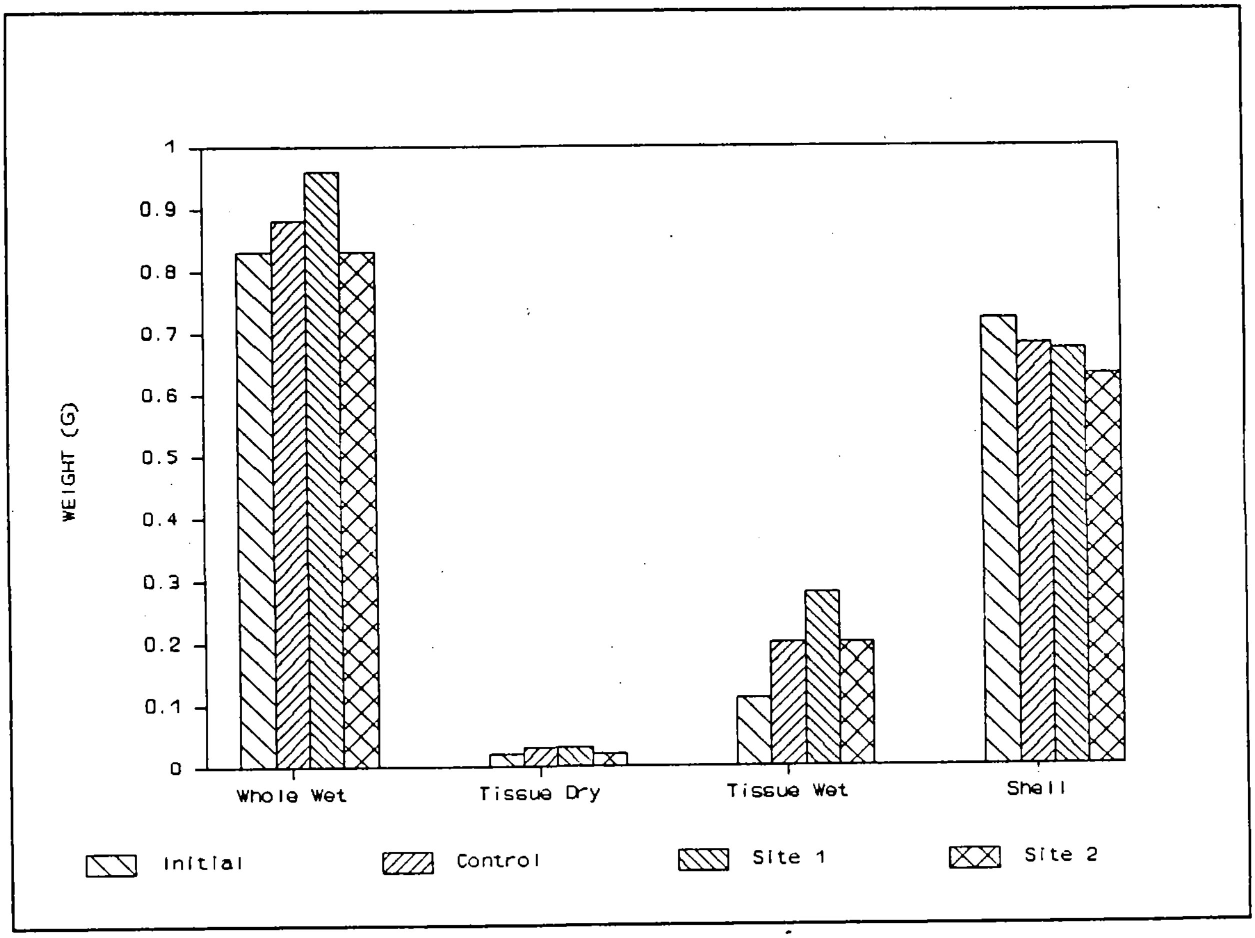


Figure 8. Adjusted mean weight (g) for small oysters (shell length = 29.7 ± 3.1 mm) deployed near a bucket dredge operation, Pugwash, Nova Scotia.

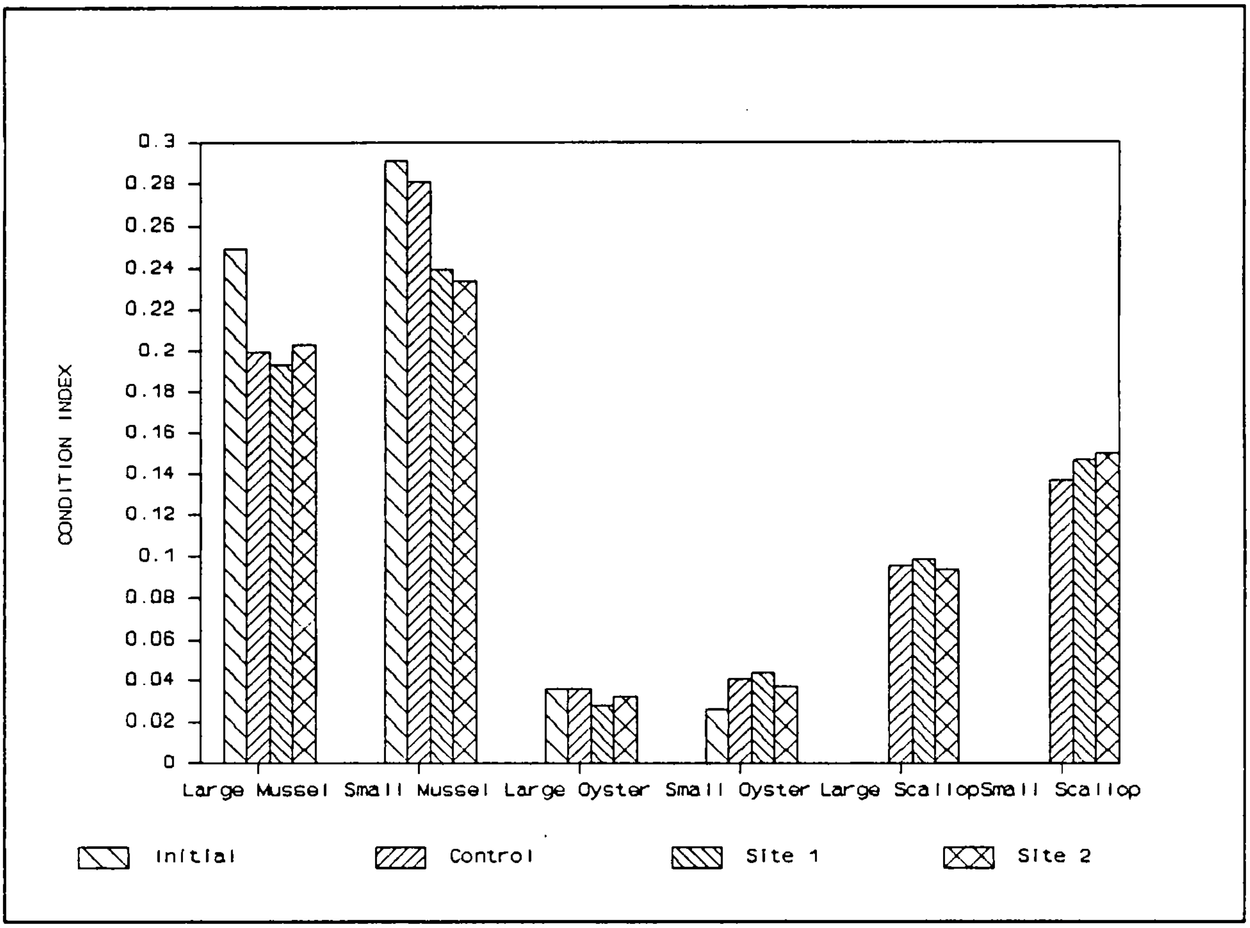


Figure 9. Condition indices of bivalves deployed near a bucket dredge operation, Pugwash, Nova Scotia.

Table 8. Growth increments in marked animals deployed near a bucket dredging operation, Pugwash Harbour, Nova Scotia.

		Control		Site 1		Site 2	
Species	Average Length (mm)	Increment (mm)	N	Increment (mm)	N	Increment (mm)	N
Oysters	29.7	- 0.52	5	1.58	4	0.20	2
Mussels	43.1	0.72	15	0.41	14	0.70	15
Scallops	27.6	0.08	2	- 0.62	4	0.97	5

occurred in the Site 1 exposure with tissue weights in the other treatments similar to each other (Figure 8). Small oysters showed highest condition index in control and Site 1 groups (Figure 9). Some of the variability in the results may be due to variability in shell dimensions resulting from abrasion of the shell edge during deployment (see Section 3.1.2, Souris exposure). Loss in shell length was noted in marked individuals of all species but more than half (6 out of 10) of the marked small oyster and 5 of 11 small scallops listed in Table 8 had negative increments (only 3 of 45 small mussels had negative increments). The results with oysters and scallops should thus be viewed with caution due to the potential error introduced by differences in shell length caused by shell edge loss during deployment.

Too few of the larger oysters were available to enable detailed statistical comparisons, but CI was significantly higher in the initials and control exposure than at the sites near the dredge (Mann Whitney U test, $p < 0.05$) (Figure 9). This result contrasts with the tentative result for the smaller oysters but would support a suggestion that the dredging activity had affected the oysters.

Small scallops did not have good enough length/weight relationships to compute adjusted weight and length parameters for statistical comparison.

Condition index of small scallops was significantly lower in the control than the two sites near the dredging operation (ANOVA, $p < 0.05$). As noted for small oysters, the small scallops also demonstrated some loss in shell length, possibly the result of shell abrasion, and this conclusion should be viewed with caution. Condition indices of the larger scallops were similar for controls and the two exposure sites (Figure 9).

Exposure mortality was insignificant for all species. Three of twenty large scallop (6 %) died in the control and one of thirty small oysters (1.3 %) at Site 2 (Table 9). Large mussels experienced about 10 % mortality in all treatments and small mussels had a mortality of between < 1 % and 2 % (Table 9). These levels were similar to those experienced prior to deployment.

Summary

In summary, most of the evidence from the Pugwash, Nova Scotia, field exposure suggests that the dredging activity may have had no major negative effects on tissue weight or condition. Mussels showed little difference in weight and condition parameters between the control site and sites near the dredge, although animals exposed in the field had less tissue weight and a reduced condition index compared with their condition at the beginning of the experiment. Small mussels, however, had a higher condition index at the control site than at sites near the dredge, indicating a possible negative effect of the dredging activity. Small European oysters deployed in the field demonstrated ambiguous results, while the occurrence of elevated condition indices in large European oysters at the control site tended to support a negative effect on growth at the dredge sites. Small scallops, in contrast, appeared to have smaller condition indices at control site than at the dredge site, indicative of a possible positive effect of dredging. Large scallop showed similar condition between control and exposure sites. Overall, the absence of effect may be attributed to the comparatively low levels of SPM caused by the dredge and the moderate size of the operation (56,000 m^3).

Table 9. Mortality data for mussels, oysters and sea scallops deployed near a dredging operation in Pugwash Harbour, Nova Scotia.

Organism		Treatment								
		Control			Site 1			Site 2		
		N_f	N_m	P	N_f	N_m	P	N_f	N_m	P
Scallop	- Large	17	3	0.176	11	0	0.00	11	0	0.00
	- Small	43	0	0.00	52	0	0.00	46	0	0.00
Oyster	- Large	17	0	0.00	17	0	0.00	17	0	0.00
	- Small	25	0	0.00	30	0	0.00	29	1	0.034
Mussel	- Large	188	20	0.106	185	15	0.081	186	17	0.091
	- Small	150	1	0.006	148	3	0.020	150	2	0.013

N_f Total number of organisms at end of exposure
N_m Number of mortalities
P N_m/N_f

3.1.2 Souris Harbour

Exposure Conditions

Temperature at the outer harbour mooring, measured by thermograph, decreased gradually through the exposure from 17° C to 11.5° C. A severe storm, 10 days after the beginning of the exposure, caused the temperature to drop briefly to 8° C. SPM concentrations were low, with smallest levels recorded at the outer harbour site and slightly larger values at the inshore sites. SPM concentrations ranged from less than 10 mg L^{-1} in the inner harbour to about 1 mg L^{-1} at the outer harbour mooring (Figure 10). Measured SPM did not appear to differ substantially between the inshore sites, but the water was visibly more turbid at the high SPM site, and we suspect the SPM concentration was higher than 10 mg L^{-1} during the exposure. In support of this, the test organisms from the high site had a coating of mud at the end of the exposure while animals from the low SPM site did not.

Growth and Condition

Mussels - Measurements of mussels used in the experiment are presented in Table 10 and adjusted means are shown in Figure 11 and Table 11. The outer harbour group had generally higher adjusted body weight parameters than either low or high SPM treatments or initials. Whole wet weight was significantly greater in the outer harbour group than in both high and low treatments (Analysis of Covariance, $p < 0.05$), while tissue wet weight was significantly larger than in the low treatment (the outer harbour also appeared to be larger than in the high treatment group (Table 11) but the difference could not be compared statistically because of inequality of slopes of the length-weight relationship). Tissue dry weight in the outer harbour group was significantly greater than in the high SPM treatment group but not in the low SPM treatment (Analysis of Covariance, $p < 0.05$). The outer harbour group grew significantly during the experiment, having higher whole wet weight, tissue dry weight and shell weight than initials (Analysis of Covariance, $p < 0.05$).

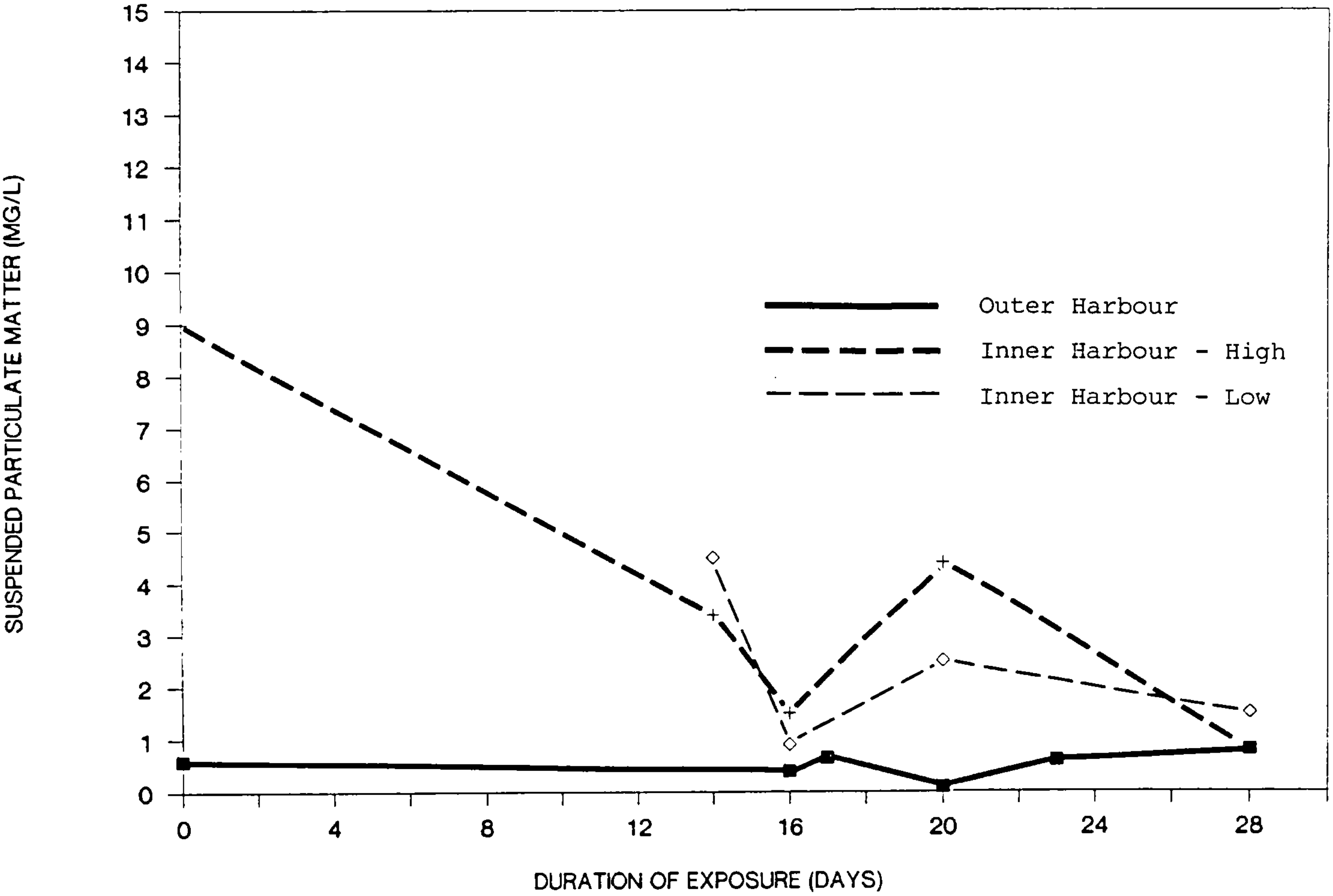


Figure 10. SPM concentrations at experimental sites, Souris, Prince Edward Island, 1989.

Table 10. Growth parameters for blue mussel (Mytilus edulis), bay scallop (Argopecten irradians), and American oyster (Crassostrea virginica) from Souris Harbour, PEI, deployments, September-October, 1989.

		Whole Wet Weight (g)		Tissue Wet Weight (g)		Tissue Dry Weight (g)		Shell Weight (g)		Shell Length (mm)		Condition Index	
Species/Exposure	N	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.
Mussel													
Initial	40	10.23	2.21	6.65	1.73	1.17	0.25	3.58	0.60	49.84	3.44	0.326	0.044
Outer Harbour	39	12.24	2.56	7.74	1.64	1.46	0.35	4.50	1.02	52.35	3.81	0.326	0.045
Inner Harbour													
- Low SPM	38	12.90	2.62	8.04	1.75	1.54	0.37	4.86	1.04	54.51	3.69	0.320	0.055
- High SPM	40	11.92	2.62	7.37	1.94	1.31	0.35	4.55	0.79	52.64	3.87	0.285	0.041
Average	157	11.81	2.678	7.44	1.83	1.37	0.36	4.37	1.00	52.31	4.03	0.314	0.049
Bay Scallop													
Initial	50	7.47	1.76	3.97	1.06	0.57	0.15	3.50	0.76	32.88	2.71	0.161	0.018
Inner Harbour													
Low SPM	39	8.98	2.19	4.77	1.32	0.66	0.18	4.22	0.94	34.59	3.09	0.155	0.015
High SPM	35	10.24	2.43	5.43	1.44	0.75	0.19	4.81	1.06	36.95	3.27	0.157	0.020
Average	124	8.73	2.38	4.63	1.39	0.65	0.19	4.09	1.05	34.56	3.41	0.158	0.018
American Oyster *													
Inner Harbour													
Low SPM	10	20.59	6.29	6.74	2.18	0.73	0.24	13.85	4.18	---	---	0.053	0.006
High SPM	12	21.15	8.08	6.71	2.74	0.67	0.29	14.45	5.38	---	---	0.046	0.004

* Oyster clumps

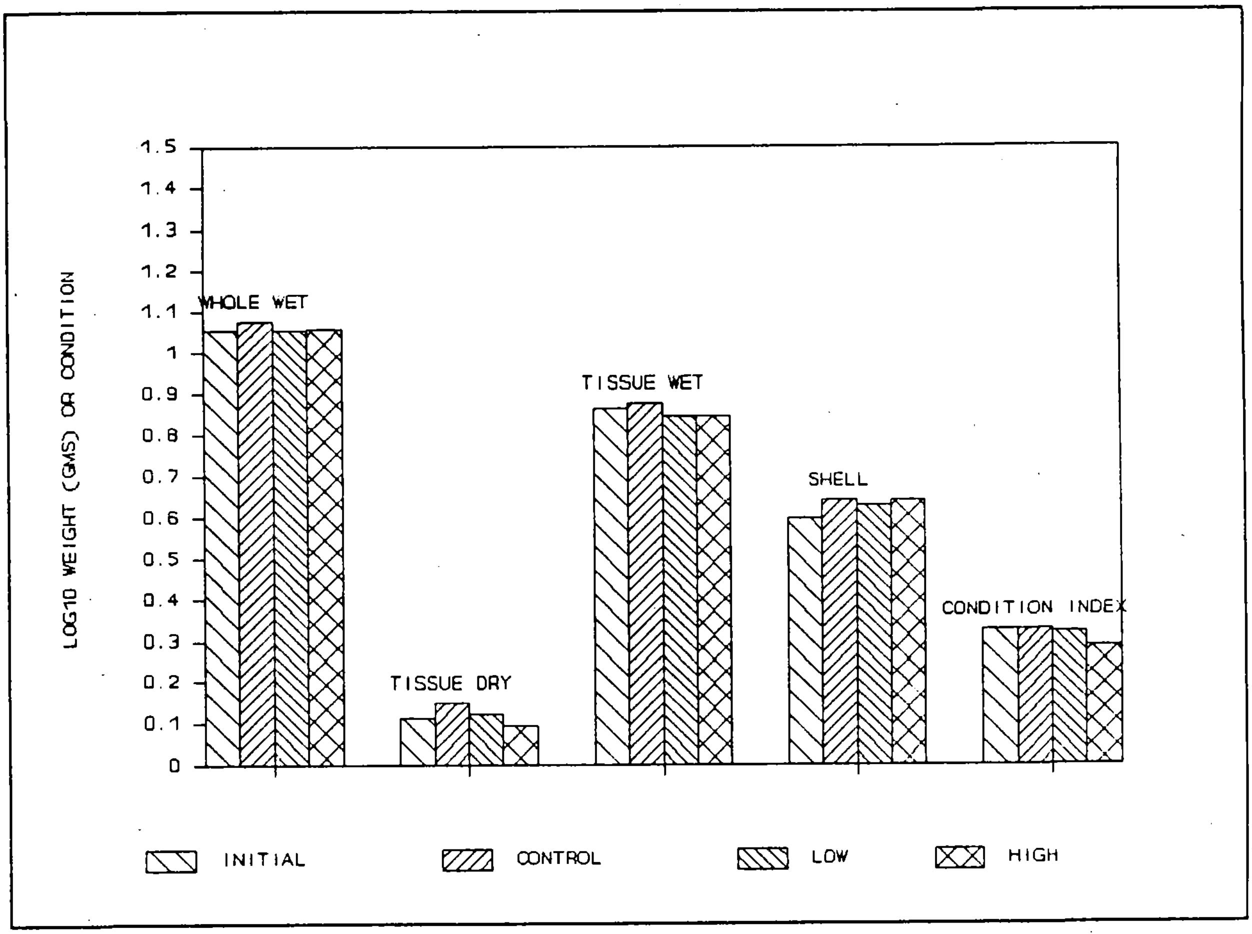


Figure 11. Adjusted mean growth and condition parameters for mussels exposed to elevated SPM, Souris Harbour, PEI, 1989.

Table 11. Adjusted mollusc growth parameters, Souris, PEI, exposures.

Species/Exposure	N	Whole Wet Weight (g)	Tissue Wet Weight (g)	Tissue Dry Weight (g)	Shell Weight (g)
Mussel					
Initial	40	11.22	7.24	1.29	3.98
Outer Harbour	39	12.02	7.59	1.41	4.37
Inner Harbour					
- Low SPM	38	11.22	7.08	1.32	4.27
- High SPM	40	11.48	6.92	1.23	4.37
Bay Scallop					
Initial	50	8.32	4.37	0.63	3.89
Inner Harbour					
Low SPM	39	8.71	4.57	0.63	4.07
High SPM	35	8.32	4.37	0.60	3.98

The inner harbour high and low SPM treatments did not differ in any of the measures except condition index, which was lower in the high SPM treatment group (t, $p < 0.01$). Condition index in this group was also significantly smaller than in the outer harbour group and the initial (t, $p < 0.01$). All other groups had similar condition indices. The low condition index in the high SPM treatment reflects a low tissue dry weight. All treatment groups had similar adjusted shell weights, which were greater than the initial (Analysis of Covariance, $p < 0.05$). This observation suggests that shell thickening occurred during field deployment. The high SPM treatment also had a significantly lower tissue wet weight than the initial (Table 11), although tissue dry weight appeared to be similar to initials.

Mussels at the outer harbour mooring increased in shell length during the exposure by about 3 % (1.55 mm ± 0.85, n = 16). Comparable measurements on individual animals were not available for the inshore mussels.

Bay Scallops - The shells of most of the Bay Scallops (82%) at the outer harbour site decreased in shell length due to abrasion. Consequently this group was not used in further analysis. Of the six that gained shell length, the average increment was 1.54 ± 0.03 mm.

Bay Scallops showed no differences in whole wet weight, tissue wet weight, and tissue dry weight between inshore low and high SPM sites (Analysis of Covariance, $p < 0.05$), although all parameters appeared to be larger in the low than in the high SPM group. These measures were also not significantly different than initials except for whole wet weight, which was larger in the low treatment than in the initial (Analysis of Covariance, $p < 0.05$). Both the inshore low and high SPM groups had significantly larger shell weights than the initial (Analysis of Covariance, $p < 0.05$) (Table 11; Figure 12). Condition index also did not differ significantly between treatment groups (t, $p < 0.05$).

American oyster - Whole wet weights were greater in the high SPM group than in the low SPM group, reflecting a greater shell weight (Table 10). Condition index was significantly higher in the low SPM group (t, $p < 0.05$).

Summary

Mussels deployed at inshore sites with elevated turbidity at Souris, PEI, showed reductions in tissue weight and condition compared with mussels exposed to lower SPM concentrations in the outer harbour. In contrast, mussels did not differ significantly in body weight between inshore high and low SPM sites, but had a lower condition index in the high SPM exposure. Bay Scallops did not differ significantly in weight parameters between inshore high and low SPM sites, although measures in the low SPM sites tended to be higher than in the high SPM exposure. American oysters showed higher condition indices in the lower SPM exposure group. These observations suggest that conditions at the outer harbour site may have been more favourable for growth of mussels than at the inshore sites, but that the inshore sites were not appreciably different in favouring growth of mussels or Bay Scallops. In contrast, the low SPM site may have been more favourable for growth of American oyster than the high SPM site.

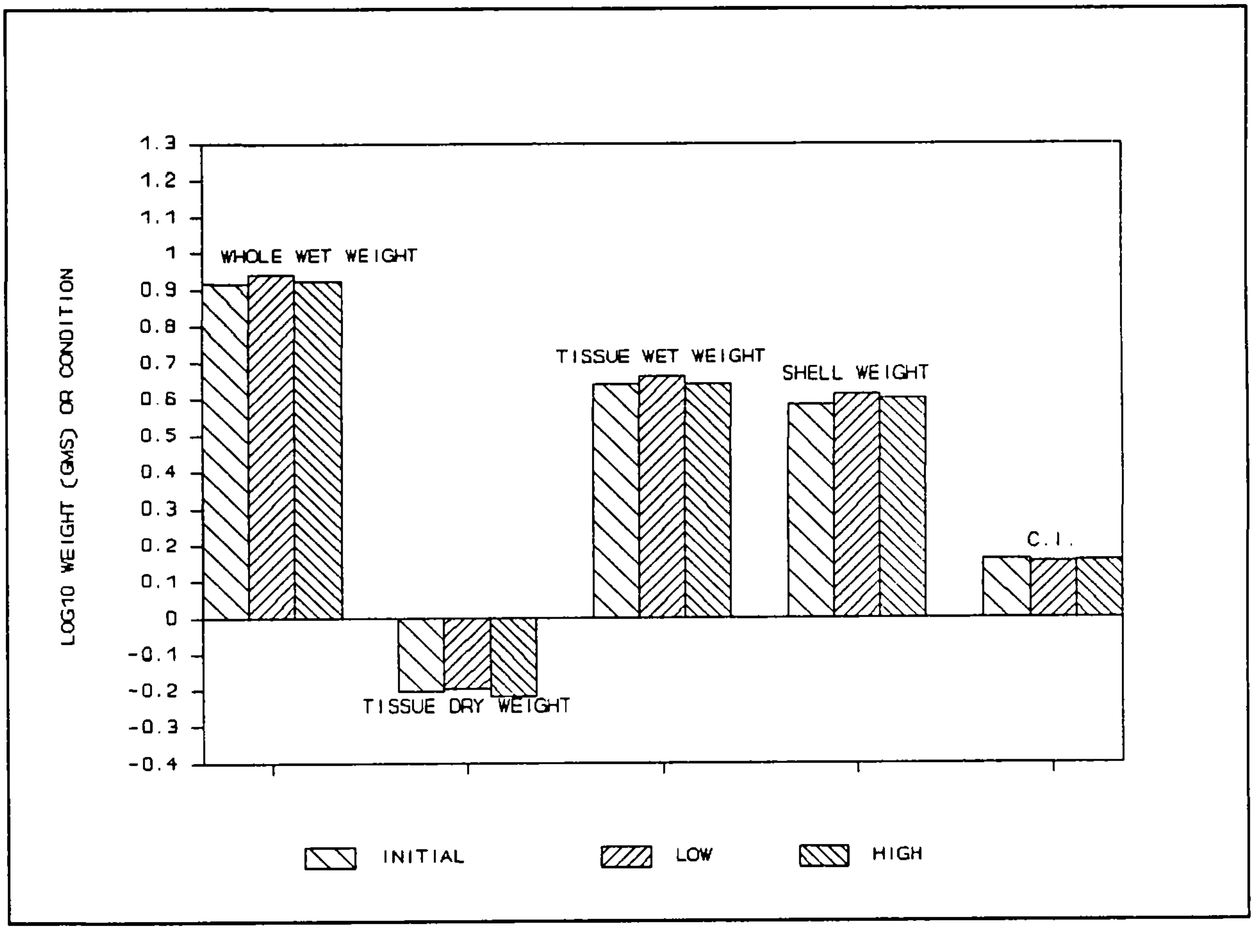


Figure 12. Adjusted mean growth and condition parameters for bay scallops exposed to elevated SPM, Souris Harbour, PEI, 1989.

3.2 Laboratory Exposures

3.2.1 Blue Mussel and European Oyster

Exposure Conditions

SPM concentrations fluctuated during the 35-day exposure (Figure 13), with much of the variation due to the daily pattern of mud addition. Mud was added once a day, usually in the morning, resulting in a cyclic fluctuation in SPM concentrations during a 24-hour period (Figure 14). The time-weighted mean SPM concentration for the experiment was 156.9 mg L^{-1} and concentrations ranged from 21.4 to 520 mg L^{-1}.

Temperature was maintained between 8.0 and 11.5° C for most of the experiment, except for the first four days where it was from 13 to 14.5° C. Salinity was not measured but ambient seawater at the facility has a salinity of 28 to 31 °/oo.

The organisms were exposed to elevated levels of copper because of a defective cooling unit for at least part of the experiment. Both oysters and mussels did not show outward differences in behaviour, signifying toxic effects, from controls. In contrast the sea scallops were affected to a much greater degree, showing mantle retraction and suffering excessive mortality and as a consequence were dropped from the experiment.

Biological Effects

Mussels - No significant differences in tissue dry weight, shell weight, shell length, and condition index were noted between controls and experimentals (Table 12). The experimental group had a slightly larger mean shell length than the control and consequently might have been expected to have a higher average weight. In fact it had slightly smaller adjusted tissue dry weights and shell weights (Table 13, Figure 15). This difference in adjusted tissue dry weight between treatments was about 5 %.

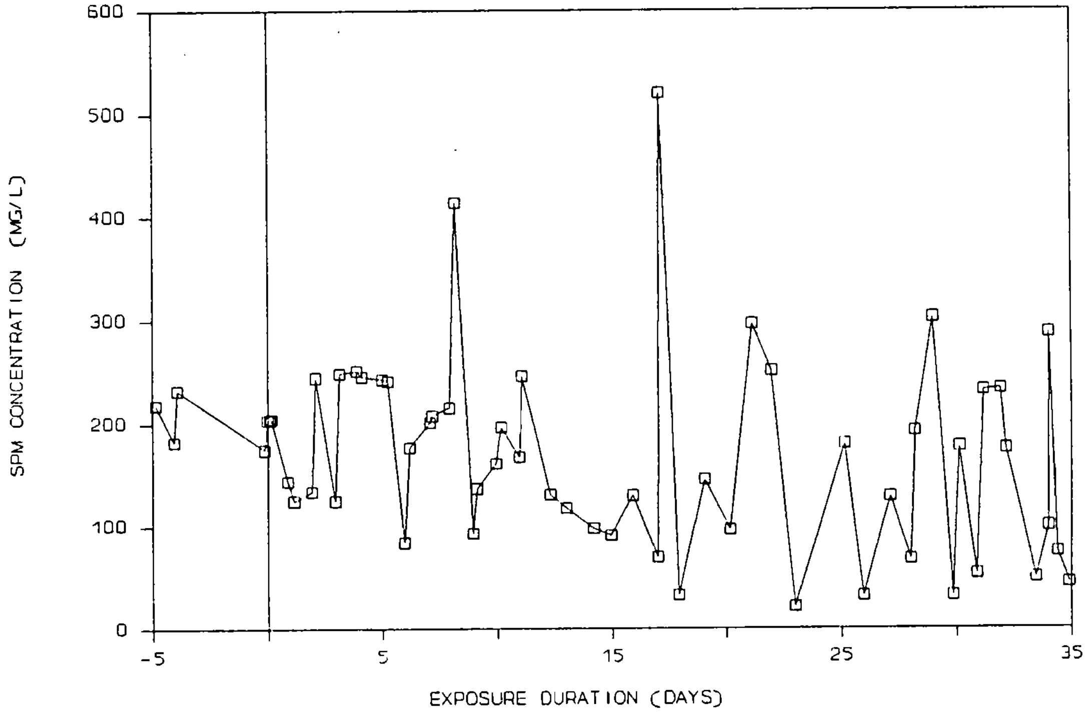


Figure 13. SPM concentrations in experimental tank, long-term exposure of mussels and European oyster, December, 1988.

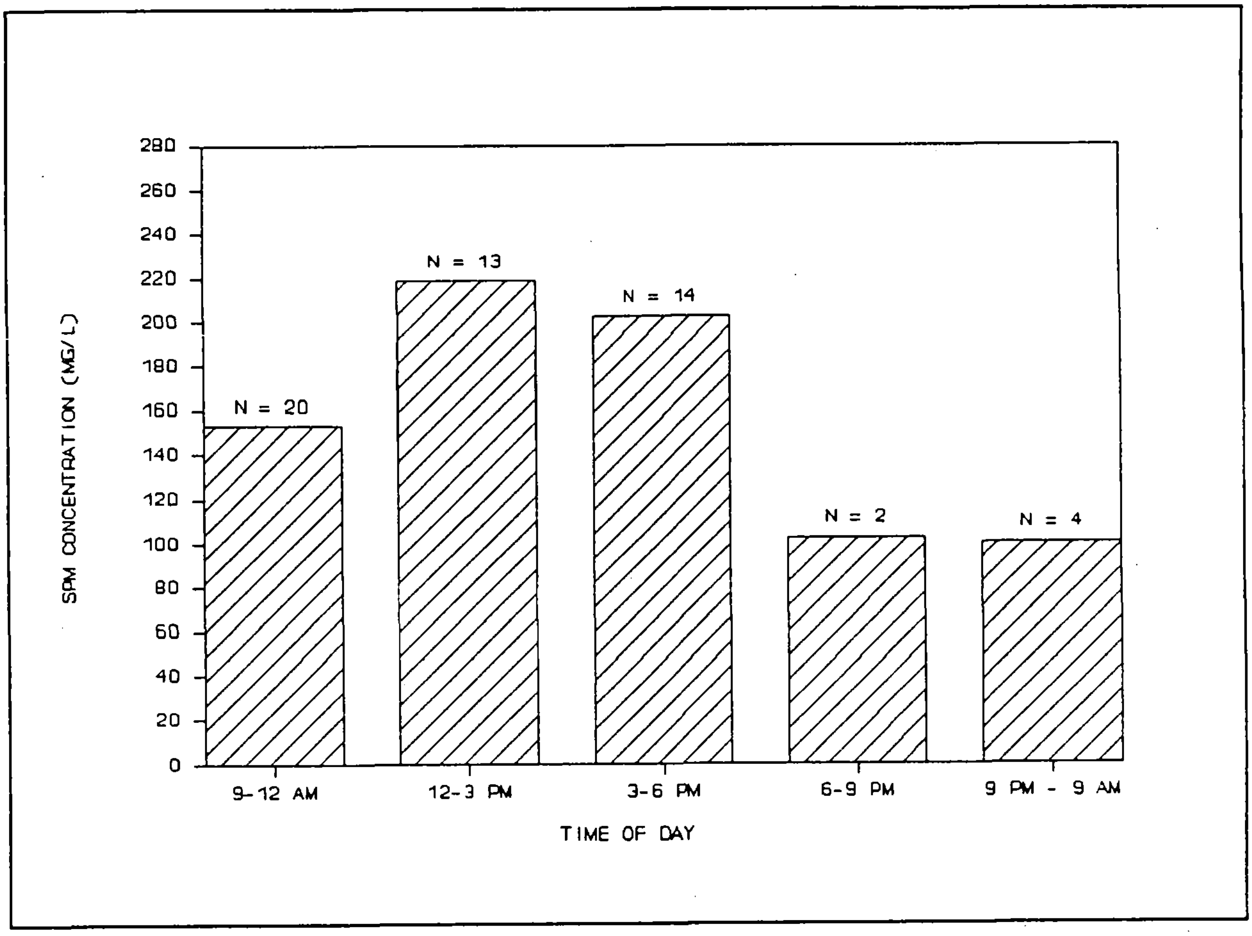


Figure 14. Daily SPM cycle in experimental tank, long-term exposure of mussels and European oyster, December, 1988. Derived from data presented in Figure 13. The 9-12 o'clock group includes values before and after the daily mud addition and thus is elevated over the evening and overnight levels.

Table 12. Body parameters and condition index for mussels and oysters exposed experimentally to elevated suspended particulate matter for 35 days.

		Whole Wet Weight (g)		Tissue Dry Weight (g)		Shell Weight (g)		Shell Length (mm)		Condition Index	
Species/Exposure	N	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.	$\bar{x}$	S.D.	x	S.D.
Mussel											
Control	30	4.827	1.601	0.466	0.209	2.158	0.881	47.92	5.40	0.225	0.088
Experimental	29	4.890	1.251	0.453	0.152	2.137	0.592	49.43	4.10	0.218	0.065
Average	59	4.858	1.428	0.459	0.182	2.148	0.747	48.66	4.83	0.222	0.077
Oyster											
Initial	30	1.557	0.452	0.042	0.019	1.224	0.331	35.03	3.26	0.034	0.011
Control	30	1.604	0.432	0.038	0.012	1.343	0.352	35.14	3.14	0.028	0.005
Experimental	30	1.587	0.428	0.030	0.010	1.360	0.370	35.63	2.79	0.022	0.004
Average	90	1.582	0.433	0.037	0.015	1.309	0.353	35.26	3.04	0.028	0.009

Table 13. Adjusted mollusc growth parameters, laboratory exposures to SPM.

Species/Exposure	N	Whole Wet Weight (g)	Whole Dry Weight (g)	Tissue Dry Weight (g)	Shell Weight (g)
Blue Mussel (*Mytilus edulis*)					
Control	30	4.77	2.58	0.44	2.11
Experimental	29	4.54	2.41	0.41	1.98
European Oyster (*Ostrea edulis*)					
Initial	30	1.52	1.24	0.39	1.20
Control	30	1.57	1.35	0.37	1.32
Experimental	30	1.50	1.31	0.28	1.28

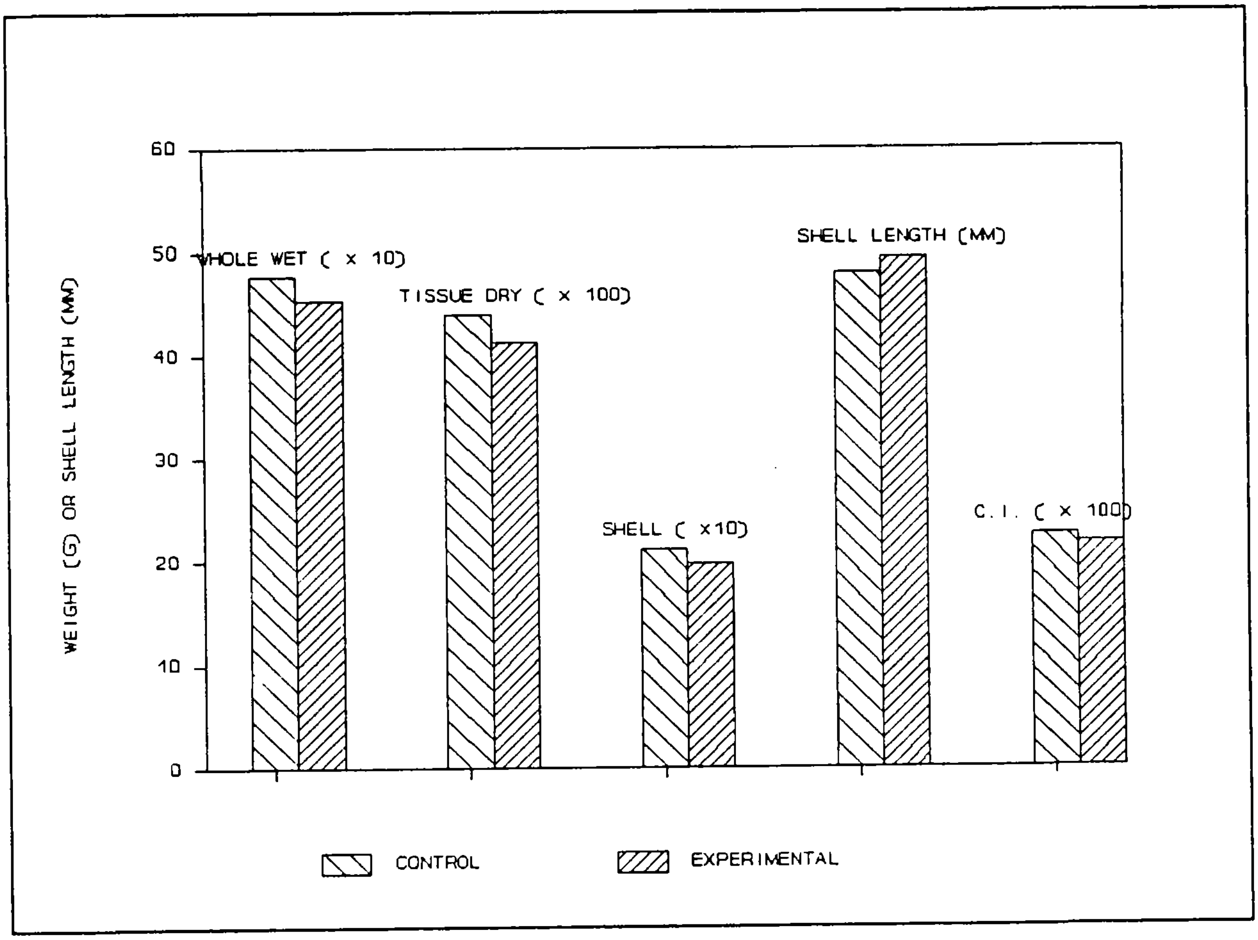


Figure 15. Body and condition parameters for blue mussel in a 35-day laboratory exposure to high SPM, average concentration 157 mg/L.

A small positive increment in length was observed in both control and experimental (Table 14), with the growth increment for the control slightly larger, though the difference was not statistically significant. A difference of this magnitude would account for a negligible weight difference.

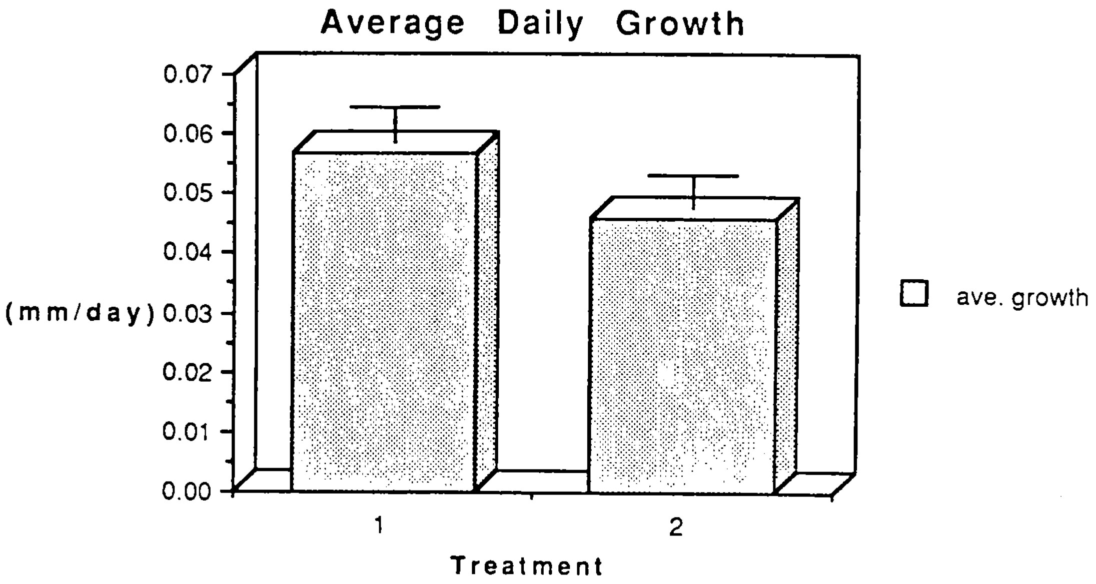
Table 14. Mean growth increment of mussels (Mytilus edulis) in laboratory exposure to SPM.

	$\bar{x}$ (mm)	S.D.	N
Control	0.08	0.09	30
Experimental	0.05	0.11	29

Microgrowth measurements of Mytilus edulis over five days at an average daily SPM concentration of 225 mg L^{-1} showed a trend towards reduced growth compared with controls (Figure 16) but the differences were not statistically significant. The full report of the work term student who carried out this phase of the study is presented in Appendix 1.

Oysters - Tissue dry weight and condition index were smaller in the experimental than in the control (t, $p < 0.01$) and as well were smaller than the initial group (Kruskal-Wallace test, $p < 0.05$) (Tables 12 & 13; Figure 17). In contrast, shell length, shell weight, and whole wet weight were not significantly different among controls, experimentals and initials (Kruskal-Wallace Test). Tissue dry weight for experimentals was approximately 76% of controls.

Growth increments from marked animals had a broad range and as well included negative values in both experimental and control. We attribute the variation to the irregularity and fragility of the shell. As such they were not documented here or compared further.



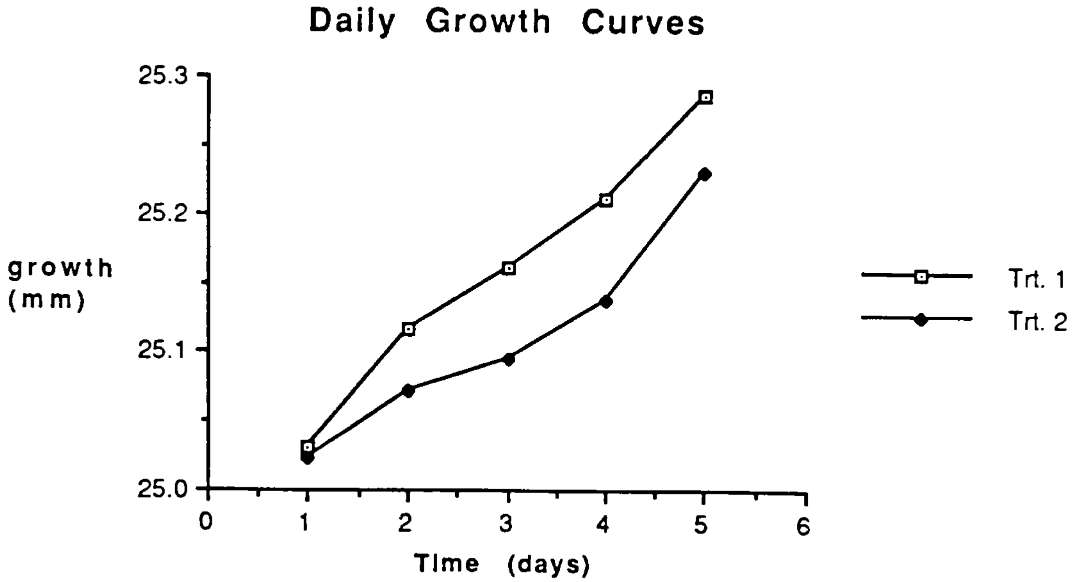


Figure 16. Average daily growth of blue mussel *Mytilus edulis* exposed to SPM for five days, measured by a laser diffraction technique. Average concentration was 225 mg/L. Treatment 1 = control; Treatment 2 = experimental.

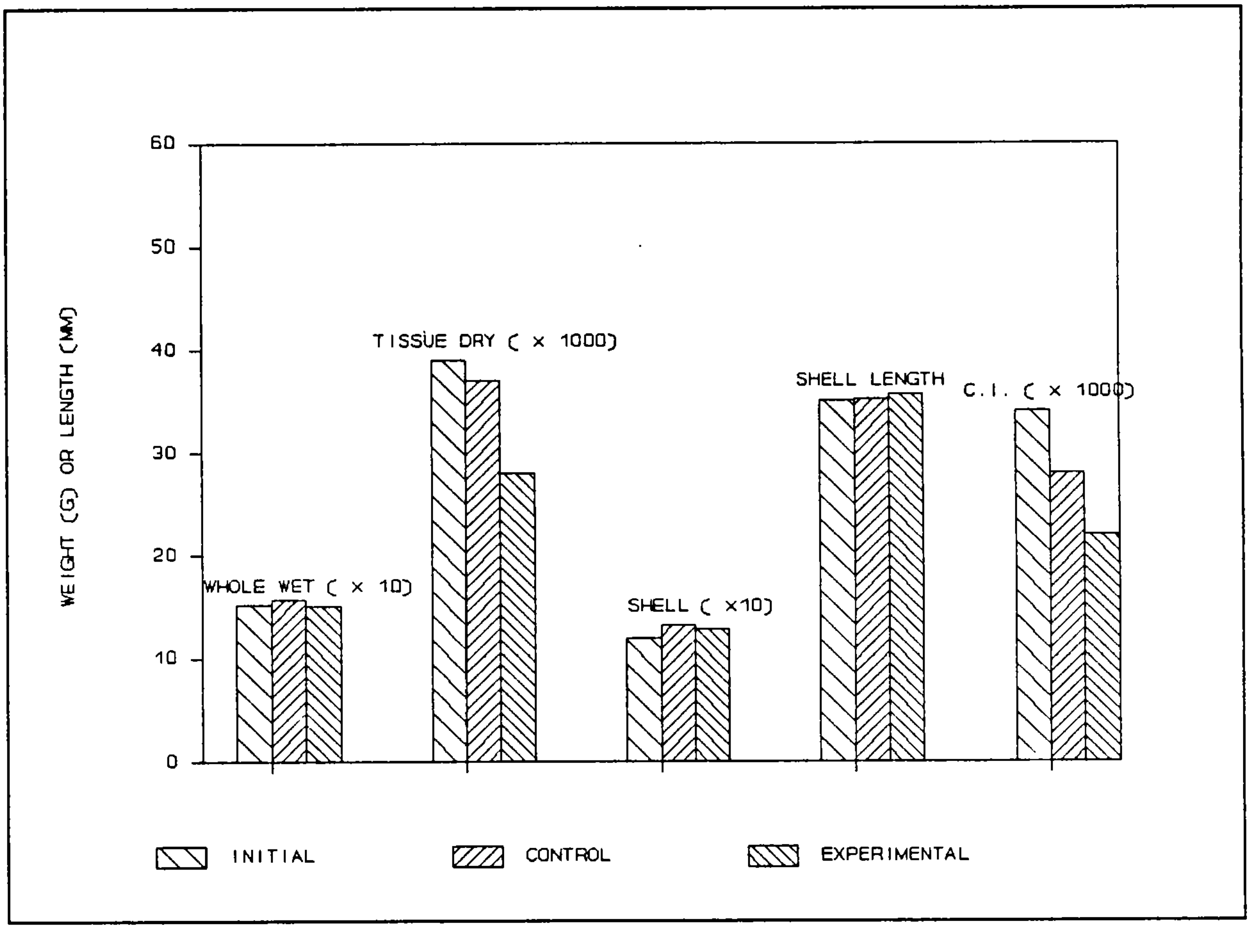


Figure 17. Mean body and condition parameters for European oyster in 35-day laboratory exposure to high SPM, average concentration of 157 mg/L.

Physiological Effects

Respiration and ammonia excretion rates of softshell clams (*Mya arenaria*) exposed in the experiment were measured in a parallel study by Dalhousie University Department of Oceanography. The results are due for publication and are summarized here. Softshell clams exposed to the high SPM regime showed a gradual decrease in oxygen consumption rate to near basal levels, and an increase in ammonia excretion. The initial respiration decline could be attributed to the clams shutting down their filtration activity, but the prolonged decline was suggested to be due to a reduction in food availability as a result of the SPM. The O/N ratio decreased through the experiment, a further indication that the clams were not getting enough food for growth. O/N ratio is a measure of the relative amounts of carbohydrate and protein metabolized by the mussels, with a low ratio indicating metabolism of body protein, a shift which occurs when there is an inadequate food supply.

Mortality

No mortalities attributable to SPM were noted for mussels, oysters or softshell clams during the chronic exposures. This was also true of a preliminary 4-day test with similar concentrations. These SPM concentrations are clearly not acutely toxic to either blue mussels or European oysters. The scallops sustained greater than one-third losses due to presumed copper toxicity problems.

3.2.2 Rainbow Trout

Chronic Exposures

Exposure Conditions - The batch nature of mud addition to the exposure system resulted in a peak in SPM concentration shortly after mud addition followed by an exponential drop-off with time, illustrated in Figure 18. In the 6-day exposure, two mud additions were spaced through working hours, resulting in a bimodal pattern with visibly high concentrations through most

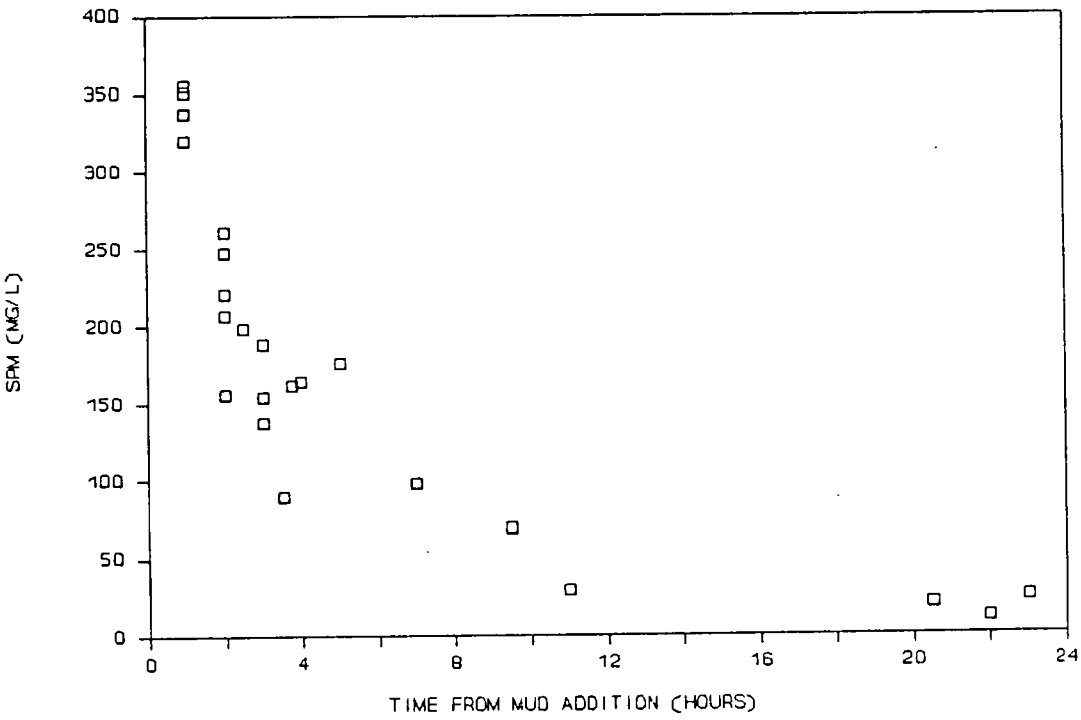


Figure 18. SPM cycle, using single daily mud addition. Data derived from 30-day laboratory exposure of rainbow trout.

of the day. The 30-day exposure had a single daily mud addition and the pattern of daily SPM fluctuation was as shown in Figure 18. Most of the time the SPM obscured the fish but they were usually visible before the first mud addition of the day.

The concentration during the 6-day exposure averaged 178 mg L^{-1} (range 99.4 to 203.0 mg L^{-1}) and during the 30-day exposure was 355.8 mg L^{-1}, measured an hour after mud addition. Sampling was not at the same time after mud addition and consequently these values only give a rough idea of true SPM levels. Trout were also exposed for four days to concentrations ranging from 96 to 658 mg L^{-1} (weighted average 361.8 mg L^{-1}), and exhibited no mortality. In the four-day exposure, the turbidity level fluctuated less during the day than in the other cases.

Behaviour - During the 6-day exposure we noted that only a small proportion of trout in the experimental tank were feeding. We attributed the inhibition to their inability to see the food, which at the time was a sinking variety. The failure to feed accounted for differences in growth (see next section). In the 30-day experiment we allowed the SPM to drop to a low level for part of the day and then fed the fish, resulting in good feeding. Floating food was used in the 30-day experiment.

Growth and Mortality - No fish died during the experiment. Weight and length measurements on marked fish before and after treatment, enabled an estimate of growth and condition for each individual. For the 6-day exposure, a large proportion of the trout in both treatment and control showed either no appreciable growth in weight or weight loss (Table 15; Figure 19).

Table 15. Proportion of rainbow trout (*Onchorhynchus mykiss*) with either no growth or weight loss.

Treatment	Control	Experimental	
6-day	0.44	0.88	N = 25
30-day	0	0.04	N = 25

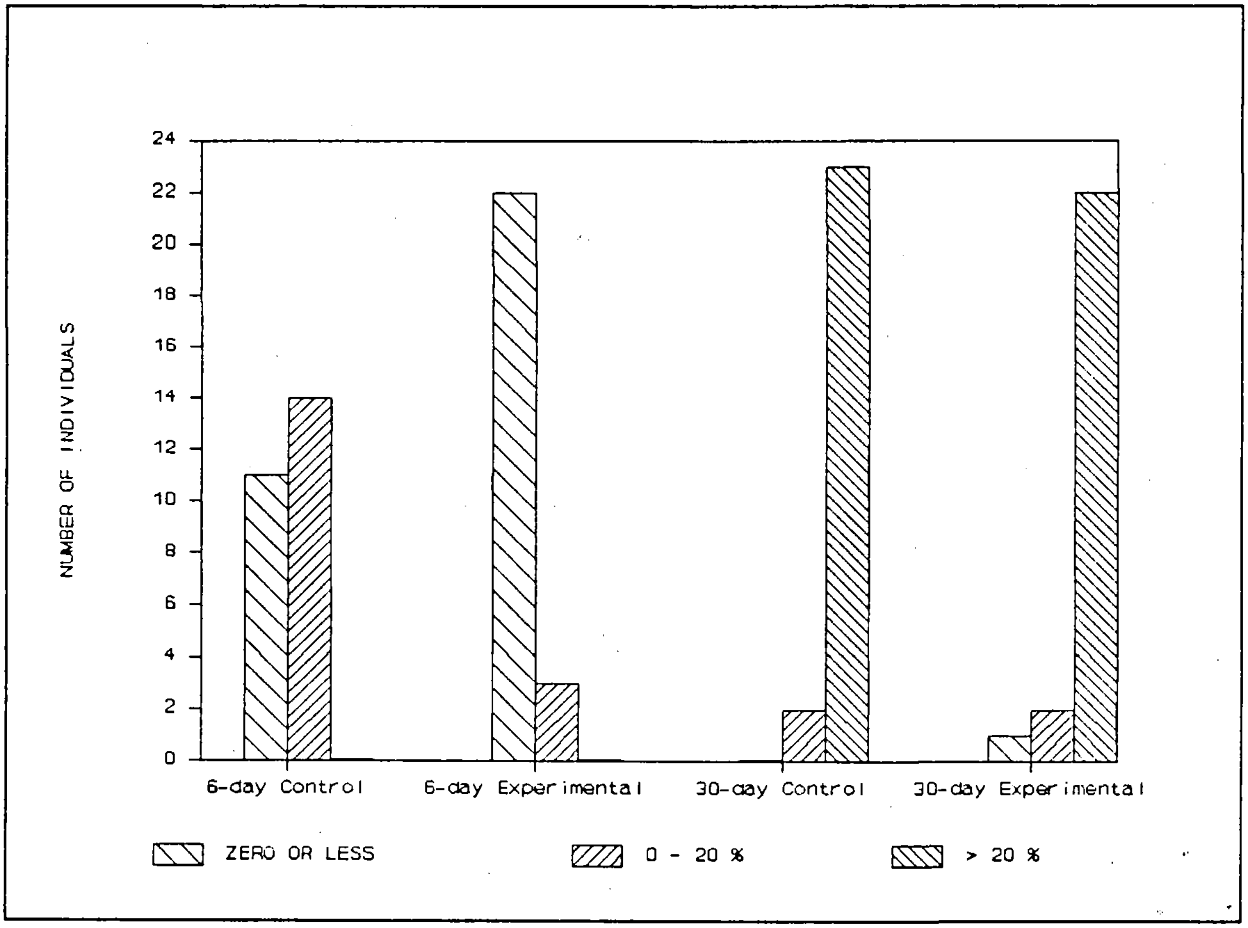


Figure 19. Number of rainbow trout (Onchorhynchus mykiss) versus growth category in 6- and 30-day laboratory exposures to elevated SPM.

Because failure to feed was noted for the experimental trout, it is probable that these fish were either not feeding or feeding at a low level. Although feeding was apparently inhibited in both groups, the rate of non-feeding was twice as high in the SPM treatment (Table 15), a statistically significant difference (Z, $p < 0.001$). In contrast, only one 'non-feeder' was observed in the 30-day exposure (in the experimental) and there was no weight loss. A small proportion of fish with low growth was noted in both groups.

Of trout with positive growth in the 6-day exposure, the controls had a significantly greater weight increase (12.4 versus 6.4 %, Table 16, Figure 20) (t, $p < 0.05$) and a greater, though not statistically significant, length increase (2.7% versus 1.5%, Figure 21). Controls and experimentals were initially not significantly different in weight or length (Table 16).

For both experimental and control treatments, the groups with zero weight increase or weight loss showed a similar, small increase in length of less than 1% (Figure 21).

In the 30-day exposure all but one of the trout showed positive growth in weight. Fish exposed to the elevated SPM had a slightly larger percentage weight gain than controls. The experimentals were initially heavier and larger than controls and maintained the difference through the experiment. Experimentals in the second experiment which had also been experimentals in the 6-day exposure showed the highest percentage weight gain of any of the four treatment combinations (see Methods), but the difference between the smallest and largest groups was not statistically significant.

At the start of the 6-day exposure both experimental and control groups were similar in condition (Table 16). In fish with positive growth, no condition differences were detected during the experiment and condition had increased at the end of the exposure. Fish with no growth or weight loss showed a decrease in condition index (reflecting the loss in weight without a loss in length). The weight loss of the experimentals appeared to be greater than in the controls. In the 30-day exposure, the condition index of both groups increased substantially and there were no significant differences between them (Table 16).

Table 16. Growth parameters of rainbow trout exposed to continuously high SPM for 6 days and to a cycled daily SPM regime for 30 days. Fish with positive growth in the 6-day exposure are grouped separately from those which had zero growth or weight loss during the experiment.

Exposure Regime	Control	Experimental
6-day exposure, positive growth	N = 14	N = 3
Weight gain (%)	12.4 ± 4.0	6.4 ± 5.2
Initial Weight (g)	97.0 ± 11.7	102.8 ± 4.3
Length Gain (%)	2.7 ± 1.1	1.5 ± 1.4
Initial Length (cm)	19.9 ± 1.0	20.2 ± 0.8
Initial Condition Index	4.8 ± 0.4	5.1 ± 0.1
Final Condition Index	5.3 ± 0.5	5.4 ± 0.2
6-day exposure, zero or negative growth	N = 11	N = 22
Weight loss (%)	2.0 ± 1.1	3.6 ± 4.6
Initial Weight (g)	102.5 ± 10.9	96.0 ± 10.3
Length Gain (%)	0.8 ± 0.6	0.7 ± 0.9
Initial Length (cm)	20.6 ± 0.8	20.1 ± 0.9
Initial Condition Index	5.0 ± 0.4	4.8 ± 0.4
Final Condition Index	4.8 ± 0.4	4.6 ± 0.4
30-day exposure	N = 25	N = 24
Weight gain (%)	46.0 ± 14.7	47.9 ± 18.4
Initial Weight (g)	114.4 ± 17.5	118.6 ± 18.3
Length Gain (%)	11.4 ± 4.0	11.4 ± 4.6
Initial Length (cm)	20.8 ± 0.9	21.0 ± 0.9
Initial Condition Index	5.5 ± 0.7	5.6 ± 0.7
Final Condition Index	7.4 ± 1.4	7.1 ± 1.0

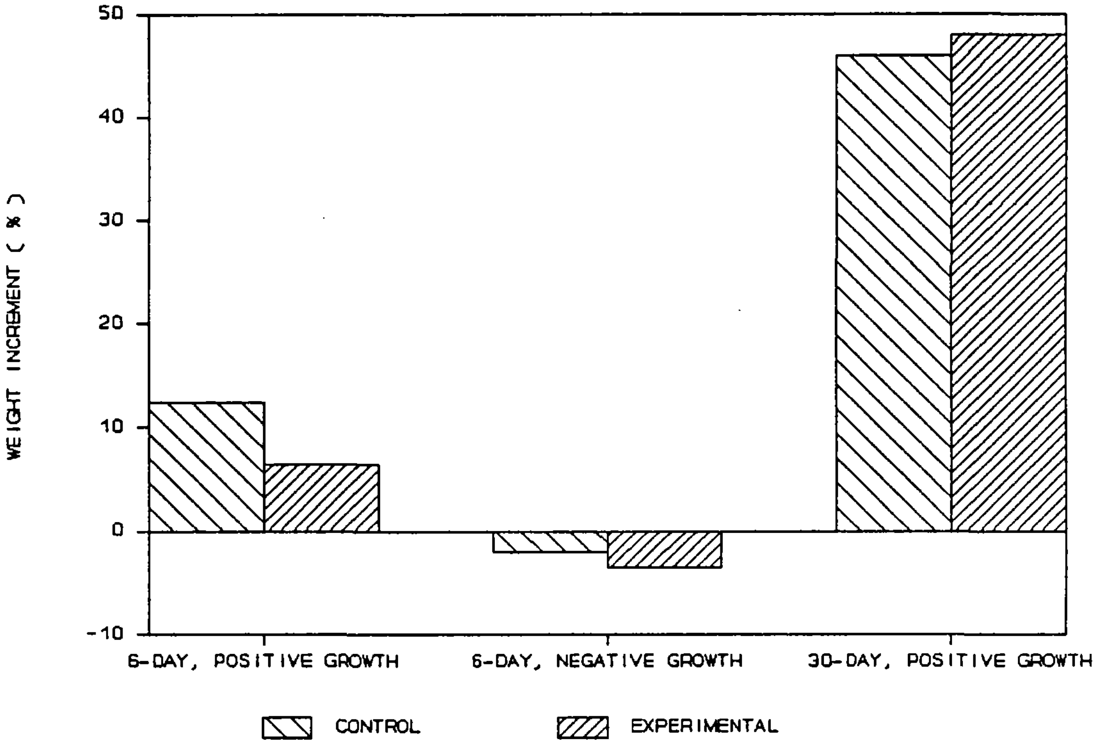


Figure 20. Weight increment (%) of rainbow trout (Onchorhynchus mykiss) for individuals with positive growth and zero growth or weight loss, 6- and 30-day laboratory exposure to elevated SPM. In the 30-day exposure, growth was noted in all individuals.

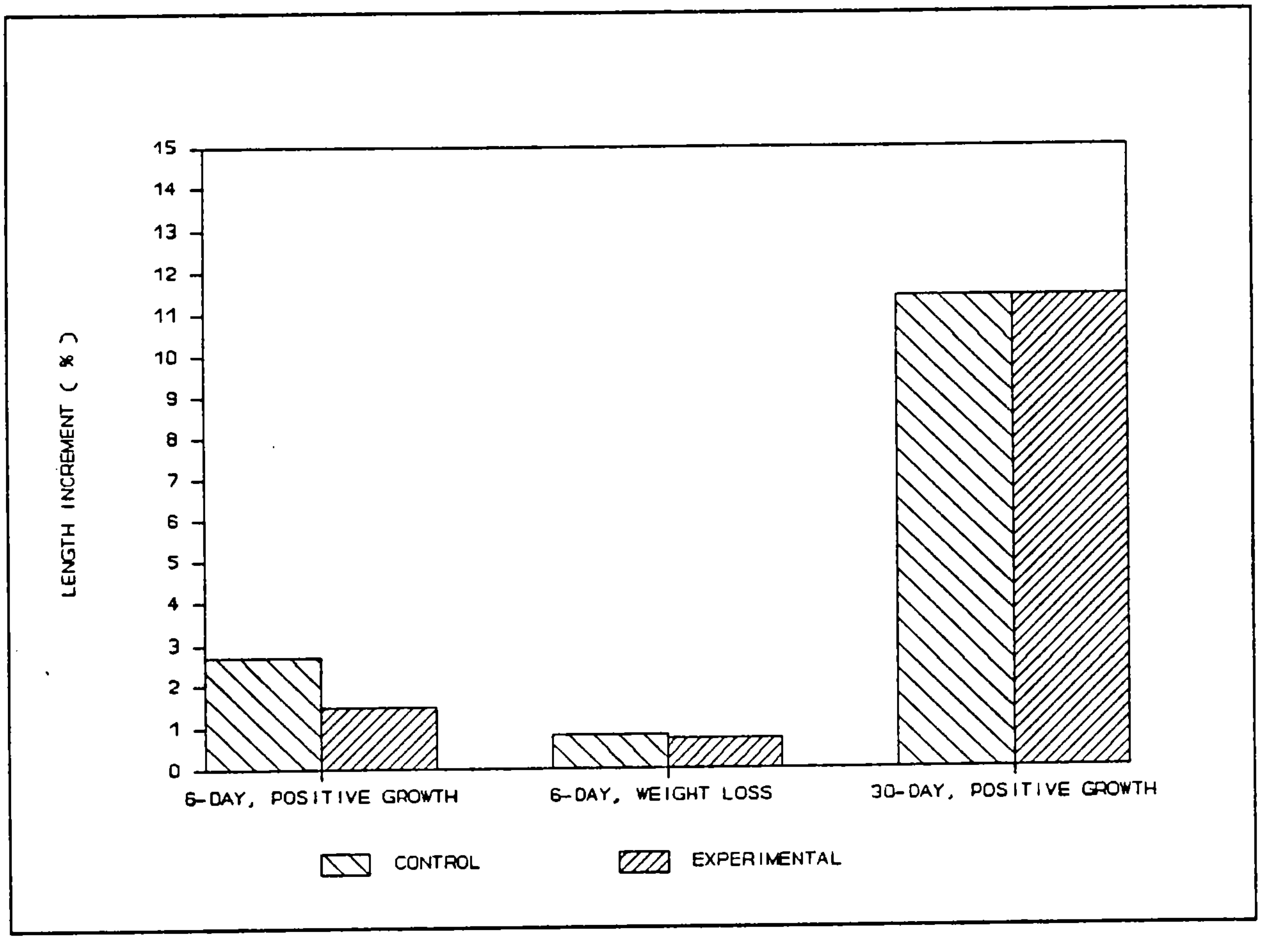


Figure 21. Length increment (%) of rainbow trout (Onchorhynchus mykiss) for groupings based on growth, 6- and 30 -day laboratory exposure to elevated SPM. In the 30 -day exposure, growth was noted in all individuals.

Two fish exposed to SPM in the experimental treatment and which were submitted to post-mortem examination by the Department of Fisheries and Oceans Fish Health Unit, were normal and showed no signs of damage which could be attributed to elevated SPM.

Acute Exposure

Exposure Conditions - Concentrations for the first day of the acute exposure were from 100-200 mg L^{-1} but a change to direct addition of the mud/water slurry to the exposure tank resulted in a gradual increase in concentration (Figure 22). The concentrations of SPM did not fluctuate as much on a daily basis as in the chronic exposure, since some of the slurry deposited on the bottom and served as a source for resuspension by bubbling throughout the day. For most of the time the fish were completely obscured by this level of SPM.

Mortality - No mortalities were noted in this experiment.

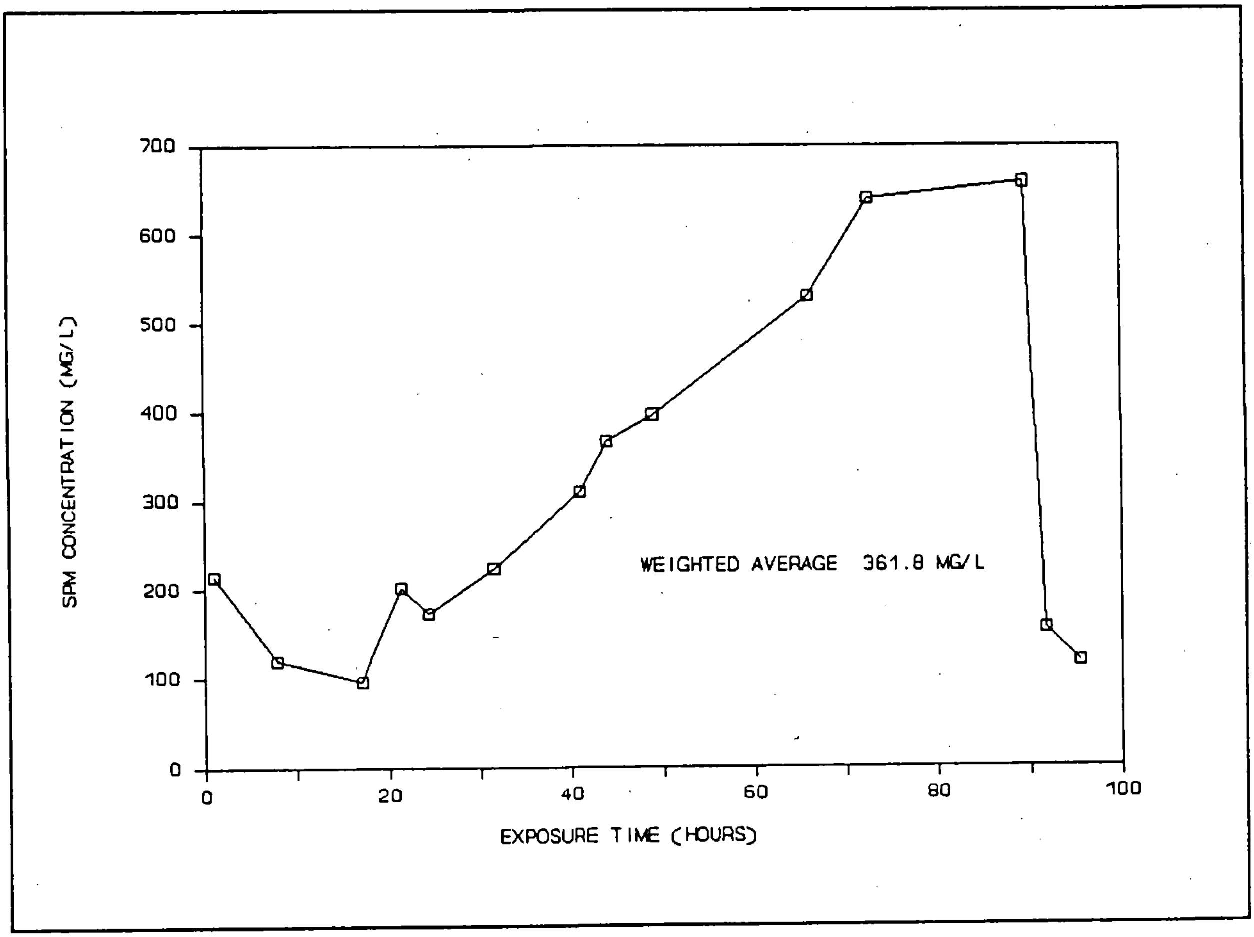


Figure 22. SPM concentration, 96-hour exposure of rainbow trout (Onchorhynchus mykiss) to SPM.

4.0 DISCUSSION

4.1 General

The object of this study was to determine whether suspended particulate matter (SPM) from dredging projects could affect growth, condition and mortality of typical aquaculture organisms from the Canadian Maritimes. The approach included exposure of several bivalve aquaculture species and lobster in the vicinity of a Nova Scotia dredging operation, as well as laboratory exposures of bivalves and rainbow trout to elevated SPM. We were also aware of a need to assess acute toxicity of SPM to aquaculture organisms and the study included exposures of several species to relatively high SPM concentrations in the laboratory.

Growth was the simple, integrated measure of response chosen for the study. All molluscan aquaculture species are filter feeders and the main effect of elevated SPM concentrations resulting from dredging activities, based on a variety of studies in the literature, was expected to be a reduction in food availability through clogging feeding structures and dilution by SPM. Variations in food supply would affect growth, with changes in tissue weight being an indicator of effect. Condition index, the ratio of tissue weight to shell weight, is a sensitive indicator of changes in body mass which might result from changes in feeding or reproductive status. Some filter feeders, however, benefit from the presence of SPM, and we were aware that there might be some intraspecies variability in response. The literature review (Chapter 1) discusses in more detail the effects of SPM on growth in bivalves.

The likely effects on salmonid aquaculture species of suspended particulate matter at concentrations likely to be encountered in a dredging operation were not readily apparent at the beginning of the study. Consequently, our experiments with rainbow trout included an approach similar to that for the molluscan aquaculture species, using weight, length and growth measurements as an integrated measure of response.

4.2 Effects on Bivalves and Lobster

The exposure carried out at Pugwash, Nova Scotia, in the vicinity of a channel dredging operation using a bucket dredge, was the only experiment in the present study involving an actual dredging operation. In the Pugwash exposure, blue mussels, European oysters, and sea scallops, as well as caged lobster, were placed as close as possible to an active dredging operation for three weeks.

SPM concentrations arising from dredge operations are usually localized and short-term in nature. In the Pugwash study, SPM concentrations in the water column, even beside the dredge, did not exceed 88 mg L^{-1}, and concentrations dropped steeply with increasing distance from the dredge. As a consequence, SPM concentrations measured at the control and exposure sites were similar. The sites nearest the dredge, however, might be expected to experience SPM concentrations higher than the control for short periods, perhaps on the order of hours, when the dredge is at its closest approach, but levels would never be expected to be greater than that measured at the dredge. It is possible that our sampling program failed to detect such differences.

In general, the measures we used, including tissue weight and condition index, showed a lack of biological effect of deployment near the dredging operation in all measures for blue mussels, European oysters, sea scallops, and canner lobster. Small mussels and large oyster, however, had a higher condition index at the control site than at sites near the dredged channel, which would suggest a slight dredging effect. In contrast, in some instances small scallop and small oyster showed possible positive effects for one or more of the deployment sites in the vicinity of the dredge. Caged lobster showed no mortality or changes in growth parameters, and as well had clean gill surfaces, showing no overall effect.

A second field exposure in the present study, at Souris, Prince Edward Island, provided some data on effects on aquaculture organisms of SPM, although the primary purpose of assessing an active dredge operation at the site was not achieved. Data on SPM at the site were not good and there is only circumstantial evidence that SPM concentrations were higher at one of the inshore sites than at the other, allowing some basis of comparison. The site chosen to represent high SPM concentrations was visibly more turbid (less than 1 m visibility) and there was noticeable deposition of sediment on shells, in contrast to the other site. The high SPM site was more exposed and near shallows, suggesting that during storm activity it would be exposed to higher levels of resuspended material than at the protected site. Both inshore sites, however, had higher SPM concentrations than the outer harbour site.

There appears to be some evidence in the Souris experiment for an effect of SPM, although slight, on the bivalves studied. Both inshore sites appeared to be less favourable for mussels, as evidenced by weight and condition differences, than the outer harbour sites. Furthermore, although few differences were observed in weight and condition between low and high SPM sites, the high SPM site had lowest tissue dry weight and condition for mussels, and a significantly lower condition index for American oysters. In addition, Bay Scallop appeared to have lower weight parameters at the high SPM site compared with the low SPM site although they had similar condition indices. Other factors, in addition to SPM concentration, may be important in determining the differences observed, including food supply, which may have differed between sites. We have assumed that because of the closeness of the sites, they would be exposed to similar water characteristics including food regime and temperature.

The laboratory exposures of bivalves yielded the most quantitative information on response to elevated SPM, showing a small negative effect for mussels and a significant negative effect on European oyster at average concentrations of 157 mg L^{-1}. As well, this component demonstrated tolerance of this SPM concentration by the test organisms and no mortality resulted from them. The component of this study involving measurement of microgrowth in mussels exposed to elevated SPM also showed a small, though not statistically significant, growth reduction in the SPM treatment group.

The small or negligible effect of SPM in mussels is not unexpected. Exposure to low concentrations of natural SPM (up to 20 mg L^{-1}) has been reported to have positive effects on growth of Mytilus edulis (Kiorboe et al 1981), and Kiorboe et al (1980) have noted that M. edulis is well-adapted to silt concentrations up to 55 mg L^{-1} and can benefit from concentrations up to 25 mg L^{-1}. Evidently M. edulis can withstand the high concentrations to which it was exposed in the present study. In other organisms, concentrations as little as 100 mg L^{-1} can cause growth or feeding reductions in quahogs and surf clams (Robinson et al 1984) and Iceland scallops Chlamys islandica (Wallace and Reinsnes 1985).

In contrast, significantly lower tissue dry weight and condition index of European oysters exposed to high SPM concentrations was noted in the laboratory study. Reduced feeding leading to reduction in tissue weight is a likely explanation. The American oyster Crassostrea virginica has been shown to reduce pumping rate at SPM concentrations as little as 100 mg L^{-1} (Loosanoff and Tommers 1948) and European oyster Ostrea edulis (used in this study) has been suggested to be more sensitive than Crassostrea to water column SPM. The parallel study of respiration and ammonia excretion rates of softshell clams tended to support the observations with European oyster, suggesting that animals in the treatment group were not getting adequate food and were not growing.

Our study did not examine the effects of SPM on other life stages of the aquaculture species considered. Particulate organic matter at concentrations from 15 to 88 mg L^{-1} adversely affected growth of European oyster larvae (Utting 1988). Growth in larval Crassostrea virginica was impaired at concentrations greater than 500 mg L^{-1} (Davis and Hidu 1969).

4.3 Effects on Rainbow Trout

Our study demonstrated no physical effects of elevated SPM (up to about 650 mg L^{-1} for short periods) on rainbow trout, in keeping with literature observations which show generally that fish can tolerate high concentrations of SPM (See Chapter 1 and Appleby and Scarratt (1989)). The study revealed, however, that SPM concentrations about 200 mg L^{-1} can interfere with feeding in rainbow trout, and that the interaction appears to be more complex than simple visual impairment, being effected possibly by stressing the trout in some way. In the first part of the experiment, we noted that some fish in both the experimental and control treatments had neglible growth or weight loss, but that the proportion was significantly higher in the SPM exposure group. We attributed this observation to failure of the trout to feed, and had some supporting observations that feeding activity in the SPM exposure group appeared to be reduced over the control treatment. We suggest that the effect may be due in part to inability to see the food and in part to stress caused by the high SPM, leading to slower recovery from handling stress.

There are suggestions from the literature both for and against the effect of turbidity on the ability of fish to see food. Increased turbidity has been noted to decrease the reaction distance of fish to prey of all sizes (Vinyard and O'Brian 1976). In contrast, Wilson and Connor (1976) (from Seavey and Pratt 1979) noted that visually acute fish such as mackerel would enter and feed in water made opaque by china clay wastes. Our study would tend to support the latter view, since some of the fish in the high SPM treatment demonstrated equivalent weight gains to the fish in the control.

Handling stress can interfere with feeding in trout. Wedemeyer (1976) observed that rainbow trout ceased feeding for a day after gentle handling and Pickering _et al_ (1982) noted that brown trout receiving only minimal handling underwent physiological changes and refused to feed for three days. Our procedure, which involved anaesthetizing the fish, weighing and measuring them, and placing a dye mark on the fins, is possibly more traumatic than gentle handling and would result in a greater inhibition of feeding. In addition, elevated SPM concentrations appear to be responsible for stress responses in rainbow trout. Ross _et al_ 1985 noted that short term (1 hour) exposures of rainbow trout to silt in concentrations of 10, 100 and 1000 mg L^{-1} caused increased ventillation rate, incidence of coughing, and increased respiration rate. The effects were not necessarily related to concentration and all measures dropped to normal one hour after exposure. These parameters are stress indicators and the results suggest that at least short-term exposure to elevated SPM is a stressor in trout. In the present study, this stress acting in concert with handling stress, could have been responsible for our observations. As a consequence of our experimental design, which involved handling the trout, we do not know with certainty if SPM concentrations in the absence of handling would have resulted in feeding inhibition.

In the second experiment (30-day exposure) feeding appeared to be the same between control and experimental tanks and the trout showed similar growth and condition at experiment end. As in the first part of the experiment, however, some of the fish in both groups showed poor growth. This part of the experiment differed from the first part in that fish were exposed to an intermittent regime with low SPM at feeding time and also were exposed for much longer. It is possible that the extended period of exposure allowed the trout to overcome any inhibition of feeding imposed by handling, and, as well, they may have overcome SPM-induced stresses.

The SPM exposure regime during this exposure, in which the fish were allowed to feed normally, clearly did not interfere with growth of trout. This is an indication that the SPM, at least at the levels used in this study, does not appear to have a major effect on the physiology of the fish. It would appear that intermittent or pulsed exposures to SPM, such as would be encountered by trout in aquaculture facilities as the result of dredging operations using grab or bucket type dredge, would not be harmful.

Other literature suggests that SPM can have both positive and negative effects on growth in trout. Herbert _et al_ (1961) (from Wilber 1971) noted that brown trout exposed naturally to waters made turbid by china clay wastes, grew normally and apparently found adequate food. In contrast, rainbow trout exposed in streams to continuous clay turbidities grew less well than in clear water (Sigler _et al_ 1976). Noggle (1978) noted a steady decline in the ability of coho salmon smolts to feed as SPM concentration increased, and feeding stopped at concentrations of 300 mg L^{-1}.

Our results cannot be extrapolated, however, to a situation where SPM level is continuously elevated for extended periods. The best approach to avoid possible impacts of dredging operations would be to avoid and minimize the duration of exposure of salmonids in aquaculture facilities to continuous conditions of elevated SPM.

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3. Conclusions

CHAPTER 3

CONCLUSIONS

Our study confirmed that suspended particulate material (SPM) can have slight to moderate negative effects on growth, but no physical effects, in rainbow trout and several bivalve species commonly or likely to be cultured in the aquaculture industry in Atlantic Canada. These findings are in agreement with the literature which generally demonstrates effects, particularly in growth, in bivalves, and in stress and feeding in trout, at high SPM concentrations. At the same time, the SPM concentrations to which these organisms were exposed in the present study, and the duration of exposure, was greater than aquaculture operations are likely to encounter as a result of typical dredging operations. It therefore seems unlikely that, except in cases of extremely large and/or lengthy dredging projects, that SPM concentrations would ever reach these levels or that major impacts would occur.

The effects of SPM on growth of rainbow trout were observed only during exposure to continuous concentrations (178 mg L^{-1} average) at which SPM hindered trout feeding, possibly through stress and interaction with other factors. Exposure to fluctuating concentrations, during which the levels of SPM fell to low levels, did not result in growth effects. It is thus possible that continuously high SPM concentrations, even for periods of several days, could have more significant effects if it coincided with times when aquaculture species are exposed to stress, such as during handling or when they are transferred to new facilities. In light of this possible effect, it would not seem appropriate to permit SPM concentrations resulting from a dredging activity to reach continuous levels of more than 100 mg L^{-1} (the range at which effects were reported in this study) at any time in the vicinity of a fish farm.

Aquaculture organisms are exposed naturally to high levels of SPM during storms and periods of high runoff. The levels are typically higher than would be experienced 500-1000 metres from a dredging operation (the distance within which SPM falls to background levels (Sosnowski 1984)), and the duration is generally shorter than the average period of storm disturbance. Natural levels of SPM in most areas of the Maritimes do not exceed approximately 200 mg L^{-1} (maximum concentrations in the upper Bay of Fundy are much higher), with the highest concentrations associated with eroding coastlines and the mouths and estuaries of large rivers (for example the areas bounding the southern Gulf of St. Lawrence), while rocky coastlines and coastal environments open to the ocean would have lower levels. **We would recommend that for regulatory purposes, concentrations of SPM resulting from a dredging operation in Atlantic Canada should not be allowed to exceed 200 mg L^{-1} in normally highly turbid environments, and perhaps 100 mg L^{-1} in normally less turbid environments for prolonged periods. Situations should be avoided in which fish aquaculture operations are exposed to continuous SPM concentrations of more than 100 mg L^{-1} for more than a day in any environment.** These recommendations are in accord with our findings of low severity effects in these SPM ranges and also agrees with the recommendations of Lunz et al (1984) that 'acceptable' concentrations of SPM used to regulate dredging operations should be related to the ambient seasonal suspended sediment concentration maximum (SSSCM). The levels recommended here are roughly equivalent to or slightly in excess of the expected naturally-occurring SPM maxima in most areas. Ultimately the decision on an acceptable level should be based on measurements of the SSSCM for the area and season in question. There is a need for a database on SSSCMs and seasonal variability in the Maritimes to aid in dredging regulation in future. The practise of monitoring SPM concentrations in dredging projects, as is carried out at present, would seem to be advisable, both to permit efficient regulation and to establish a bank of background data on SPM in coastal areas.

Key periods for aquaculture production in Atlantic Canada coincide with desirable times for dredging, which usually takes place in the late spring to late fall. There appears to be no ideal time apart from the late fall to winter period in which dredging activities will not overlap with critical periods for salmonid aquaculture. In most of Atlantic Canada, trout and Atlantic salmon aquaculture is concentrated in the May to November period, with some Atlantic salmon overwintered in certain areas. The spring-fall period is also a critical period for molluscan aquaculture, with peak growth of species such as oysters, mussels and scallops.

SPM potentially can affect other stages in the life cycle of aquaculture organisms, such as planktonic larvae and newly settled spat. Peak larval abundance in the water column and spatfall tends to be in mid summer. Late fall and winter are quiescent periods for molluscan aquaculture, and in some areas salmonid aquaculture is not carried out in the winter. Thus although little dredging takes place then, operations are least likely to be exposed to impact.

Field moorings of test organisms, such as used in the present study, appear to be a useful protocol for monitoring impacts of dredging. We recommend that in dredging projects where conflicts with molluscan aquaculture are expected, test moorings and a growth and condition measurement protocol, such as we used, be placed between the dredge site and any aquaculture sites. A suitable test organism would be the blue mussel, <u>M. edulis</u>, because of its aquaculture importance, and tendency to attach to nets by byssus threads, preventing shell abrasion and permitting the collection of satisfactory growth data even in exposed environments. We also believe it is feasible to deploy test cages containing rainbow trout in sheltered areas where dredging activities conflict with salmonid aquaculture facilities.

Use of field experiments to assess the effects of suspended dredge material proved to be difficult due to the differing suitability and availability of dredge sites. Other options for future studies assessing the effects of SPM include laboratory studies or large volume microcosm or tank experiments. Experimental studies should use bottom material from environments that typify those to be dredged.

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Appendices

APPENDIX 1

The Effects of Suspended Dredge Material on the Shell Growth of Mussels, *Mytilus edulis*, Measured by Laser Diffraction

by Halia Sushko

THE EFFECTS OF SUSPENDED DREDGE MATERIAL ON THE SHELL GROWTH OF MUSSELS, *Mytilus edulis*, MEASURED BY LASER DIFFRACTION

BY: HALIA SUSHKO

MARCH,1989

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ABSTRACT

A deficiency of data on the effects of dredge material and wastes, on marine organisms has become apparent. Literature on this subject was scattered and fragmentary. In this study, the growth in shell length of *Mytilus edulis* when exposed to simulated dredge material was measured using a laser diffraction technique every twenty-four hours for five consecutive days to detect growth differences between exposed and unexposed experimental populations. Statistical analyses of the five- day comparative growth test demonstrated that exposure to an average daily concentration of 224.75 mg/l of particulate inorganic material was not sufficient to cause a statistically significant decline in shell growth rate, although the data did exhibit a trend of reduced growth in the exposed population. This method of measuring the incremental shell deposition in mussels could prove to be valuable to aquaculturists as an expedient test to determine the effects on growth of various environmental stressors. Details of the laser diffraction method are provided within this report.

1.0 INTRODUCTION

It has been established that suspended solids have important effects on the biology of marine animals (Moore, 1977). Growing concern over the integrity of the inshore environment by aquaculturists has more recently focussed attention on the biological effects of suspended material on commercial species. Dredging and ocean dumping activities which cause high concentrations of suspended solids of questionable nature have the potential to perhaps more adversely affect certain marine organisms than others, in particular shellfish at aquaculture sites (Appley, 1987). The reasons are as follows : (a) shellfish such as mussels and oysters are filter feeders and depend on filtration for their respiration as well, (Baynes, 1976) and (b) the much heavier loading of a given area by cultured stocks compared with the density of natural populations increases their vulnerability to concentrations of extraneous or deleterious products which may be found in the environment (Heral, 1987). Therefore, there is a need to ensure ready accessibility to existing knowledge when decisions on the acceptability of turbidity levels are required.

A recent court case in New Brunswick, involving the effects of suspended dredge material on mussel cultures in Neguac Bay, has clearly emphasized that data from controlled experiments is deficient in this area of study. The outcome in court held that the mussel cultures were killed by re-suspended dredge spoils without definitive proof being presented that this was the case. Freeman (pers. comm.) concludes that "... in the absence of a controlled experiment to test the specific influence of varying degrees of siltation on the viability of the mussel stock used, it would be impossible to ascribe a cause-effect relationship between recent ocean dumping at Neguac Bay and summer die-off in the lease."

By using the optical technique, laser diffraction, to measure linear growth of living shells, of *Mytilus edulis*, this study attempts to determine whether suspended particulate matter can interfere with mussel physiology in a manner sufficient to be detectable in a changed growth rate. The living shell can be measured frequently with this method without mechanical damage or exposure to environmental conditions which would adversely affect growth or survival (Stromgren, 1975)

2.0 PROBLEM STATEMENT

The controversy over the effect of suspended particulate matter on cultivated mussels in Neguac Bay, N.B. has led to a general awareness of the need for understanding the effects of suspended and/or re-suspended particulate matter on shellfish.

3.0 BACKGROUND

The importance of particulate matter on water quality in freshwater environments has long been established (Brehmer, 1965; Federal Water Pollution Control Administration, 1968). Since dumping dredge materials and wastes into the sea has become a matter of concern, as in the Soleiko case at Neguac Bay, N.B., a deficiency of data on the effects of turbidity on marine organisms has become apparent. There is an immediate need for an overall synthesis of available knowledge as well as for controlled experiments to determine what levels of turbidity interfere with aquaculture organisms such as mussels.

4.0 THE PURPOSE

Major losses of mussel stocks at aquaculture sites may occur in the absence of man-made perturbations at the site (Mallet et al., 1987). Without a controlled experiment to test the specific influence of suspended dredge material on the viability of mussels it would be impossible to show cause-effect relationships between suspended particulate matter and mussel mortality. By applying a sensitive method for detecting short term growth in mussels, a technique will be made available to allow rapid testing for effects of suspended and re-suspended sediment. Thus, tests of sites intended for use could be made and tests of sites affected by dredge spoils could be quickly done to prove or disprove claims of adverse effects.

5.0 SIGNIFICANCE OF RESEARCH

This method of measuring the incremental growth of mussel shells could prove to be valuable to aquaculturists as an expedient test to determine the effects of suspended dredge spoils and other environmental stressors on mussel stocks. It follows that laser diffraction could also be a useful measuring technique in short term bioassays.

6.0 NATURE OF THE STUDY

The growth in length of mussels exposed to suspended dredge material was measured by laser diffraction every twenty-four hours for five days. This technique was used to attempt demonstration of growth differences between two lots of experimental animals.

7.0 LITERATURE REVIEW

Suspended sediments in seawater are held to be derived from: (a) suspended river material, (b) eolian material, and (c) colloid or solid precipitated substances (Moore, 1977). Since the sources of the materials are various, their relative concentrations will vary from place to place. This study will deal with the finer grained sand and clays that remain in suspension long enough to potentially have a biological impact on shellfish.

The majority of land-derived material is estimated to be transported to the oceans from inland sources by freshwater run-off. The rate at which this occurs depends upon climate, the configuration of the relief, the presence of vegetation and the land utilization regime. Human activities are modifying the natural particulate regime to a greater extent, especially in coastal waters. (Moore, 1977)

Eolian (wind transported) material can be divided into three types, as follows (Moore, 1977): biological material originating from the continents, (2) inorganic solids including, volcanic debris, originating from the continents, and (3) man-made contaminants. Millions of tons of dust are transported in eolian suspension (Moore, 1977).

The ultimate fate of insoluble particles suspended in the sea is sedimentation which may involve a lengthy process (Moore, 1977). It has been estimated that a 10 micron particle settling according to Stoke's Law would take two years to reach a depth of 4,000 meters, which is the average Pacific deep sea depth (Rex and Goldberg, 1962; In Moore, 1977).

High suspension silt levels may be found with effluent discharge or dredging activities. Extremely high levels may be reached from time to time, depending upon a number of factors, including the tidal cycle, seasons of the year, and stormy conditions. Larger particles (sand) cause scouring effects and smaller particles (clay and silt) create turbidity. The mobility of suspended material depends upon grain size, particle shape, and density and water movement. (Moore, 1977)

Experiments involved in determining the metabolic effects of suspended particulate matter on marine animals confront the problem of how to keep the particles in suspension over lengthy periods of time in the laboratory. These difficulties would seem proportional to the experimental duration. In view of the potential effects of water movement *per se* on animal metabolism and behavior, sea water controls that are clear and contain only nutrients are necessary. (Moore, 1977)

Basically the process of feeding in suspension-feeding bivalves can be summarized, as follows (Moore, 1977):

> "...the inhalant stream carrying suspended particles (which may have undergone primary screening at the inhalant siphonal aperture or mantle edge brought about by variously disposed marginal tentacles) impinges against, and passes through, a gill of characteristic and alternate porosity, which strains off suspended matter. The filtered water is expelled to the exterior and the particulate matter retained on the gill is bound by mucus and conveyed by ciliary action towards the mouth (usually undergoing size/weight selection during entrainment, with only the smaller and lighter material being directed to the mouth) where it undergoes further selection by the labial palps. Material accepted by the palps is ingested and its residuum

eventually voided as faeces, whilst material rejected by the palps and gills is accumulated and rejected as pseudofaeces."

It appears that particles are discriminated on the basis of size and weight rather upon nutritional quality. Each measurable aspect of the feeding process has received attention e.g. rate of pumping, rate of water transport, filtration rate, efficiency of particle retention relative to pore size of gill ostia, and rate of faecal and pseudofaecal expulsion. (Moore, 1977)

Two distinct mechanisms have been defined by which the amount of material ingested is restricted when concentrations of suspension increase, described as follows (Foster-Smith, 1975): (1) by a reduction of the filtration rate, to restrict the amount of material filtered at high concentrations of suspension, and (2) by increasing the proportion of material rejected without reducing the filtration rate.

A variety of investigators have shown that ingestion of suspended material by bivalves continued in turbid conditions (Moore, 1977). *Mytilus edulis* was noted to feed and pass a maximum of faeces when immersed in water so turbid with added river mud, clay, chalk, flour, and similar materials, that the mussels were invisible at a depth of two or three inches (Dodgson, 1928; In Moore, 1977).

Turbidity in nature is largely attributable to clay sized particles, which are relatively efficiently filtered out by bivalves. Thus, these particles play a significant role in bivalve nutrition causing a resultant "dilution" of food quality in turbid water, as particles are discriminated on the basis of size and weight and not upon nutritional quality. This would be expected to provoke the utilization of stored reserves (to maintain metabolism at a certain rate) which would result in a decrease in individual flesh weight and reduction in growth rate. The presence of silt in water can also reduce the quantity of dissolved oxygen through oxidation reactions of organic matter; therefore, adding to the stress on the organism as the passage of large volumes of water may become a respiratory necessity. (Moore, 1977)

Bivalve growth involves two aspects which are shell growth and soft-tissue proliferation. Shell growth which is measured as increase in linear dimensions was shown to be reduced in particle-laden waters (Gruffyd, 1974; In Moore, 1977). This may be due to the mantle margin contracting away from the shell edge in the presence of a bombardment of mineral grains (Rhoads and Pannella, 1970; In Moore, 1977). A reduction in linear dimensions may also occur due to the direct abrasion of the shell edge under sufficiently energetic conditions (Walne, 1958; In Moore, 1977).

Different species require different conditions which contributes to their ecological separation in the field (Moore, 1977). *Mytilus edulis* is comparatively tolerant of turbidity and siltation. It will thrive in conditions inimical to the majority of suspension-feeders (Moore, 1977). It has been shown that *Mytilus edulis* was unaffected by 440 mg/l suspended solids, although the animals died after 13 days when the experimental concentration was brought up to 1,220 mg/l (Purchon, 1937; In Moore, 1977).

Mytilus edulis also has the ability to clean its shell. This has been described as follows (Theisen, 1972; in Moore, 1977): A "licking" movement of the dorso-ventrally flattened foot over the outer surface of the shell valves, with both the organic and inorganic particles cleaned from the surface of the shell, and then transported by ciliary action into the mantle cavity.

When feeding in high concentrations of suspension, *Mytilus edulis*, maintains a steady rate of ingestion when the maximum or satiation level is reached, with increased production of pseudofaeces (Moore, 1977). Thus, efficient shell-cleaning behavior and pseudofaecal expulsion, contribute to the common blue mussel's success in surviving turbidity and siltation. In spite of its byssal attachment, *Mytilus edulis*, is not immobile (Paine, 1974; In Moore, 1977) so that it may also be possible for it to avoid inappropriate conditions in certain circumstances (Moore, 1977).

8.0 HYPOTHESIS

The null hypothesis is that suspended dredge material does not affect mussel shell growth.

9.0 DEFINITION OF TERMS

Definitions are given below for terms often used in connection with this topic, as follows (Moore, 1977; Standard Methods, 1985; Stromgren, 1975):

SUSPENDED PARTICULATE MATTER (SPM) - total particulate matter suspended in sea water; sum of plankton, detritus, and inorganic solids.

PLANKTON - floating plants and animals with limited powers of effective independent locomotion.

DETRITUS - decaying debris of dead organisms, often consisting of large quantities of inorganic material which is firmly bound to organic substances.

TURBIDITY - in general, the situation in fluids where minute particles are in suspension causing an obvious cloudiness. In reference to this study involving marine sediments, it is the experimental condition where sediments are re-suspended in sea water and maintained that way in a more or less stable state.

RESPONSE - the measured biological effect of the material tested. In acute toxicity tests the effect is usually death; whereas, in biostimulation tests it is biomass increase.

CONTROL - test organisms exposed to dilution water alone and/or the natural water to which they are normally exposed.

TOXICITY - adverse effect to a test organism caused by "pollutants", which in this study will involve suspended particulate matter (SPM).

EXPOSURE TIME - time of exposure of test organism to test solution.

LETHAL CONCENTRATION (LC) - toxicant concentration producing death of test organism. Usually defined as median (50%) lethal concentration, LC50 i.e. concentration killing 50% of exposed organisms at a specific time of observation.

SUBLETHAL CONCENTRATION - a concentration of toxicant which at higher levels will kill an organism or group of organisms.

NUTRIENT - a nutritive ingredient (of food) required to maintain cellular integrity.

RECIRCULATION TEST - static test with circulation of test solution through an experimental chamber. Test solution may be treated by aeration, filtration, sterilization, or in other ways to maintain water quality.

10.0 ASSUMPTIONS

In this study, it has been assumed that:

(a) in previous studies using laser diffraction, the method was accurate in measuring the incremental shell growth of mussels.

(b) "inter-operator" variability may exist; therefore, the method will be tested using non-filtering shells, in addition to the live animals.

(c) closure of shells can also affect the accuracy of the measurements by the laser diffraction technique. Optimum measuring conditions are obtained when the shells are completely closed. Since individual mussels can exhibit varying closure responses, tests will be conducted to find which mussels show greater variability of shell closure and those showing greater variation during repeated testing will be rejected before the commencement of the experimental run.

(d) the experimental design including the grazing chamber design will replicate the turbid conditions of the field (eg. dredging operations).

(e) the conditions in the experiment where shell length may be affected, also, reflects a change in soft tissue

11.0 SCOPE OF RESEARCH

This study investigated the sub-lethal effects on the mussels (as opposed to the lethal effects) of suspended particulate matter at levels which are typically found at dredging operations.

12.0 RESEARCH APPARATUS DEVELOPMENT OF THE LASER DIFFRACTION METHOD

The growth of shellfish can be recorded as an increase in length along a defined axis. For the mussels under consideration in this study, growth rates of 50 microns per day are typical. Since mechanical measurements with sliding rules and micrometer screws may easily damage the growth zones of shellfish, and are only sensitive to several days cumulative growth, optical methods using microscopes or phototechniques are preferable. The length growth of the mussel can be measured relatively accurately by a new modification of a non-destructive optical method, laser diffraction, which is sensitive enough to detect daily growth. (Stromgren, 1984)

The posterior edge of the shell of *Mytilus edulis* and a thin plate of an inert material are arranged to form a slit (Fig. 1A); when a laser beam is passed through the slit, a diffraction pattern is produced which is proportional to the slit width. By measuring the distance between the center of the two adjacent light spots, or light maxima, of this diffraction pattern, the slit aperture (a) can be calculated from the formula, as follows (Stromgren, 1975):

$a = (\lambda * s)/ d$

where, s = the vertical or horizontal distance from the slit to the diffraction pattern;

d = the distance between two adjacent light maxima;

λ = the wavelength of the laser light

The diffraction pattern can be photographed and the average distance between two adjacent light maxima are measured under magnification. Reduction of the slit aperture width over time is equivalent to the growth in shell length of the mussel. Before measurement the mussels are permanently fixed in position by glueing one valve of the mussel to an acrylic frame. For stable positioning, a bed is formed with a cement-like substance and the mussel is glued on the top of this mount with cyanoacrylate glue. (Stromgren, 1984)

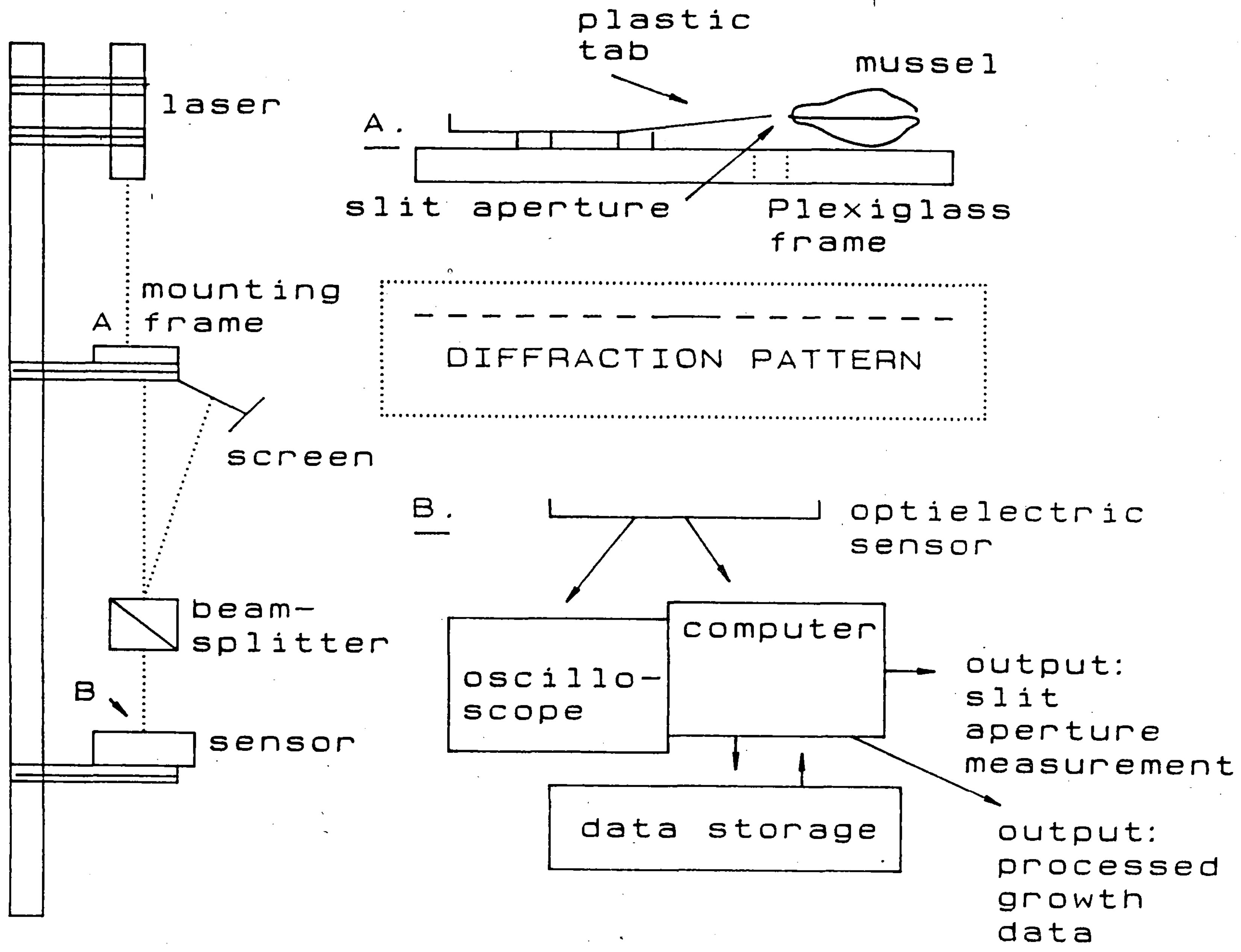

FIG.1 Design of the laser diffraction system (Stromgren, 1984

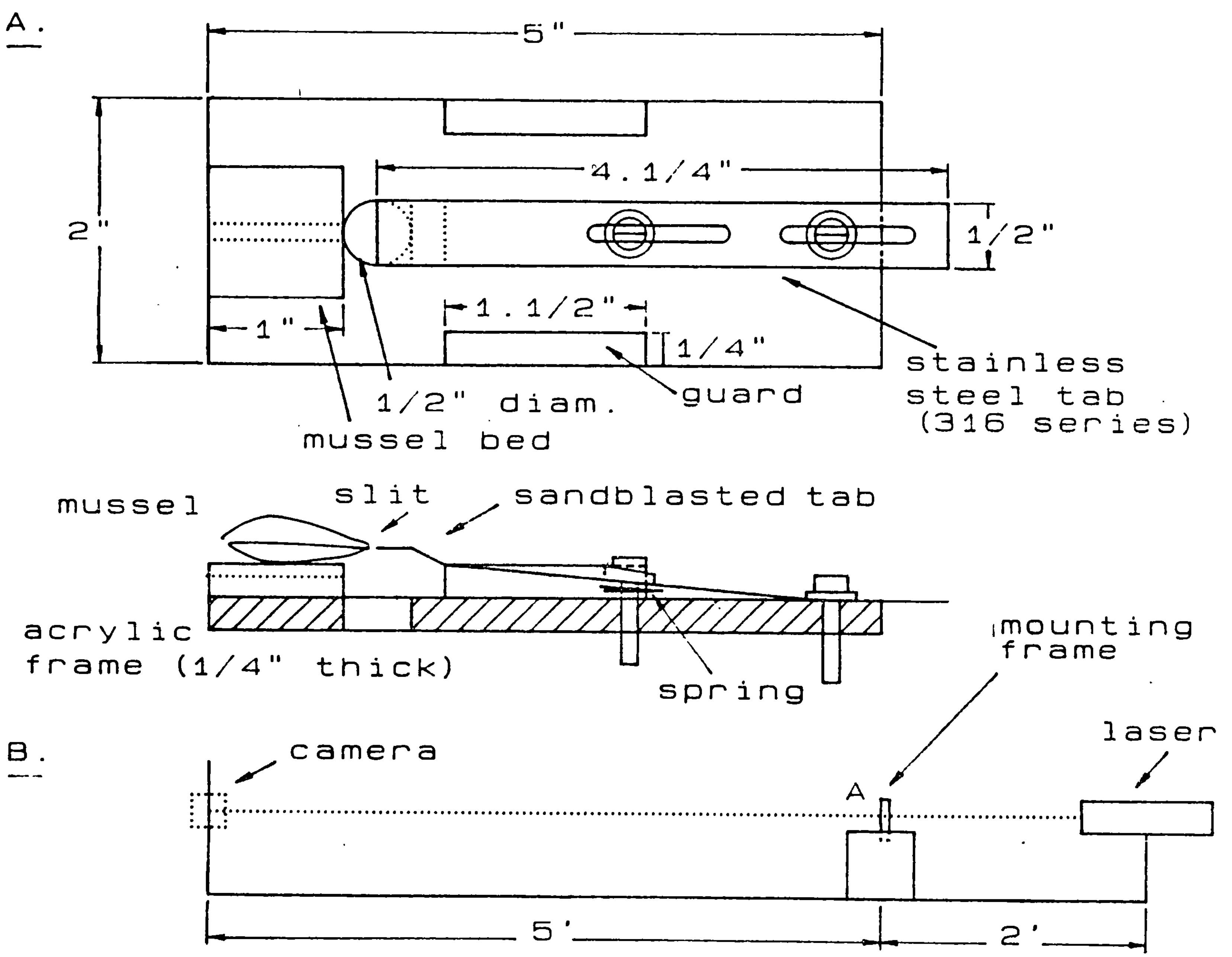

FIG.2 Design of laser diffraction system (Sushko, 1988)

Since the laser diffraction technique permits linear growth measurements of the living shells with high accuracy (SD = 7um) over short intervals, it was selected as the optimum method for this short-term study. This method for measuring shell growth was initially developed in 1975 by Tor Stromgren who further refined the technique in 1984.

12.1 SLIT APERTURE ESTABLISHMENT

In Stromgren's modified version of the laser diffraction method, the plastic edge of a regular tab is arranged with the growing edge of the mussel to form a slit; whereas, in the original version a thin plate of silver was used as the tab. For the purposes of this study, the inert material for the tab was a 316 series, stainless steel which was suitable for exposure to saltwater without deterioration. Since the tab must be positioned along the same horizontal plane as the shell edge, the stainless steel plate or tab was mounted on a acrylic base using stainless steel bolts, through tapped holes drilled in the acrylic. The stainless steel tab was slotted to permit movement on a horizontal plane and stainless stell springs were used to permit movement in the vertical plane. This is in contrast to Stromgren's two approaches where in the original version, the silver plate was mounted with acrylate glue or soldered to a small plate which is brought into position by two adjusting screws and fixed tightly by a setscrew. Stromgren's modified version utilized a Plexiglass frame upon which a plastic tab is mounted. The shape of the tab is also modified from a flat thin plate to one which is bent at an angle which allows the tab to lie in the same horizontal plane as the shell edge.

The shape of the stainless steel tab used in this study was modified from the simple bend approach used by Stromgren (Fig. 1A), which required bevelling of the tab to obtain a 90 degree angle parallel to the growing edge of the mussel shell. The final shape of the tab used in the present study was modified such that bevelling of the tab edge was not required. This was accomplished by bending the tab twice to form an "S" shape (Fig. 2A). Initially, a stainless steel spring was installed on each bolt and used to adjust the height of the tab, but it was subsequently found that only one bolt/spring assembly was required to set the height of the tab. Thus, the bolt at the farthest end was fastened tightly without a spring, to rigidly hold that end of the tab. Springs were selected as an alternative to shims which were initially found to be impractical in adjusting the height of the tab.

Temperature changes may cause corresponding changes in length and volume of the apparatus, which would affect the slit opening. Stromgren (1975) tested this effect in water baths from 8 degrees up to 22 degrees Celsius, in steps of 2 degrees, and observed a linear increase in the slit of about 10 microns from the low to the high temperature. Thermal expansion was not a factor in this study as the mussels were held in the grazing chambers at room temperature and subsequently measured at essentially the same temperature.

Mytilus edulis fixes itself in position on the acrylic base of the mounting frame with the foot and byssus threads. The shell can marginally shift position being affixed to the frame by tightening its byssus threads, but the drag of the byssus threads and of the foot was not considered to give a measurable response in the slit width determinations (Stromgren, 1975).

12.2 MUSSEL ATTACHMENT

In Stromgren's original technique, the mussel was fastened with a stable acrylate material used in dental work and, after hardening, the space between the lower shell half and the steel plate was filled with aluminate cement to increase stability. The modified version involved forming a bed with plastic cement and the mussel being glued on top of that with cyanoacrylate glue. In the present study, a bed was formed using marine epoxy resin. As well, a putty was made by adding microspheres to form a soft plastic material. After the bed hardened, a space was carved into it, to conform with the shape of the mussel shell and the mussel was glued into place with a cyanoacrylate glue.

12.3 RECORDING AND MEASURING OF DIFFRACTION PATTERN

In Stromgren's original version of the method, the diffraction pattern was photographed and the average distance between the light maxima was measured under magnification. The procedure was then greatly simplified by exposing the diffraction pattern on an array of 256 photocells linearly arranged over approximately 6.3 mm (Fig. 1B). After optimizing the slit opening by using direct visual observation of both the diffraction pattern on a screen and its energy distribution at the optielectric sensor (using an oscilloscope), the slit aperture was automatically calculated by a microcomputer. Since such equipment as utilized in Stromgren's later version of recording and measuring diffraction patterns was not available for this study, the diffraction was recorded directly on photographic film. This technique was enhanced by removing the camera lens. Negatives of the diffraction pattern were then developed and measured under magnification using an ocular micrometer.

13.0 PROCEDURE

One hundred three month old mussels (20 30 mm in length) were taken from a culture line at Mountain Island Hatchery at Blandford, N.S.. From this stock, separate subgroups (populations) were established by randomly selecting two lots of fifteen animals which were used in the experiment (control and experimental groups).

Mixtures of *Chaetocerogracilis* and *Isochrysis galbana* (independent variable) were fed daily to both lots of mussels, using an air-lift injection system leading into grazing chambers where the animals will be held. One group was also fed sediment which was mixed with the food. The sediment was obtained from the Bay of Fundy region and concentrations of suspended particulate matter were measured following the procedure for measuring total suspended solids found in the Standard Methods For the Examination of Water and Wastewater (Sixteenth Edition, 1985). The suspended particulate phase was mixed as follows: one parts of seawater to nine parts sediment was stirred for one-half hour and allowed to settle for one-half hour (the seawater was pre-mixed to contain one part of the algae mixture to nine parts of seawater); the liquid phase was then siphoned off and kept aerated in a carboy. The grazing chambers were based on the principle of the classic air-water lift which allowed the continuous recirculation and aeration of the seawater, food and sediment. The system kept food particles and suspended particulate matter in suspension and evenly distributed, and the necessary aeration was provided without injuring the animals. Shell growth (dependent variable) was measured daily in both lots of mussels by the laser diffraction method.

The growth of shells may be recorded as an increase in length along a defined axis. The laser diffraction technique measures the shell length increase, as a decrease of a slit formed by affixed stainless steel edge and the growing edge of the shell (Fig 2A). A monochromatic light is passed through the slit aperture. The slit has an opening of the order of the wavelength of light so that a diffraction pattern is produced, consisting of dark and light spots. Laser light is coherent and produces regular diffraction patterns. A small Ne-He gas laser with a wavelength of 6.328 * 10^-7 m and an output of 0.8 mW is used with no health risk for the observer and harmful effects on the animal are assumed to be negligible. (Stromgren, 1975)

The distance between two spots on the diffraction pattern (d) is inversely proportional to the width of the slit (a), which can be calculated from the formula: a = (wavelength of the light * s)/d, where (s) is the distance from the slit to the diffraction pattern. The diffraction pattern was recorded on film using a 35mm camera and the negatives were developed and viewed with an ocular micrometer to measure the distance (d) between two maxima (from the center of one maximum to the center of the next maximum). An average was taken of 10 maxima measured in the diffraction pattern. An alternate record was made by marking the distance (d) with calipers on paper, onto which the diffraction image was projected. For further details on the laser diffraction method refer to the preceding section on Research Apparatus Development of the Laser Diffraction Method.

The distance between the tab and growing edge of the mussel shell measured from 0.10 mm to 0.60 mm. Although the stainless steel edge is linear and the edge of the shell is curved, it has been observed by Stromgren (1975) that a good diffraction pattern can be obtained when the tangent of the shell edge is parallel to the stainless steel edge. Only under these conditions can a good diffraction pattern be obtained; therefore, refinding the same part of the slit is easy. Errors due to variable closing of the shells were reduced by a test procedure and adequate irritation of the animal. Inadequate stability of the shell closing was detected by observing the diffraction pattern during such irritation. The most important precautions to maintain accuracy were to make the slit as stable as possible and to ensure that the shells were firmly closed. (Stromgren, 1975)

In this experiment, the classification variable was shell length change, and the comparison of shell length change between groups of experimental mussels allowed inferences about effects, of suspended particulate matter on the animals. Length change data was analyzed by standard parametric statistics.

14.0 RESULTS:

14.1 STATISTICAL ANALYSIS:

Wilk's - Lambda test, a criterion of general use in multivariate analysis for testing hypotheses concerning multivariate Normal populations, was chosen as the test statistic, as described in General Linear Models Procedure from SAS - Series in Statistical Applications. Experimental factors of interest are related to the dependent variables by a linear model, and functions of sums of squares are computed to test hypotheses of these factors. A significance level of 0.05 (ie. 95% confidence interval) was used to determine the acceptance or rejection of null hypotheses. The raw data, derived from diffraction pattern measures, is summarized in Table 1. (SAS, System for Linear Models, 1986)

14.2 WILK'S - LAMBDA STATISTIC used to test:

(1) The null hypothesis which was "no time effect"; ie. there was no difference in the amount of growth over time. The Wilk's - Lambda test was significant at $p=0.0001$ indicating that the null hypothesis should be rejected or that there was a difference in the amount of growth over time

(2) The null hypothesis which was "no time - by - treatment effect"; ie. there was no difference in growth over time among treatments. The Wilk's - Lambda test was not significant ($p=0.0387$) indicating that the null hypothesis should be rejected or that growth varied through time (both treatments didnot grow in a similar fashion).

(3) The null hypothesis which was "no time - by - treatment - by - replicate effect"; ie. there was no difference in growth over time among replicates within a treatment. The Wilk's - Lambda test was significant ($p=0.3158$) indicating that the null hypothesis should be accepted or that replicates within each treatment showed that they did behave the same way through time.

14.3 ANALYSIS OF VARIANCE

Repeated measures of variance were used to determine whether there was a significant difference between the experimental treatment and the control treatment (SEE TABLE 2):

(1) The null hypothesis was that of no difference in shell growth between treatments. The null hypothesis was accepted ($p=0.3896$) indicating that there was no significant difference in shell growth between the control group and experimental group of mussels.

(2) The null hypothesis was that of no difference in shell growth among replicates within a treatment. The null hypothesis was accepted ($p=0.0532$) indicating that the replicates within a treatment did not behave differently.

TABLE 1- DAILY SHELL GROWTH

Fri, Feb 24, 1989 19:41

	OBSERVATIONS	TREATMENTS	REPLICATES	MUSSEL ID	DAY 1	DAY 2	DAY 3	DAY 4	DAY 5
1	1.000	1.000	1.000	1.000	0.006	0.033	0.083	0.005	0.098
2	2.000	1.000	1.000	2.000	0.030	0.109	0.006	0.100	0.100
3	3.000	1.000	1.000	3.000	0.026	0.013	0.051	0.000	0.058
4	4.000	1.000	1.000	4.000	0.009	0.081	0.065	0.054	0.025
5	5.000	1.000	1.000	5.000	0.007	0.021	0.019	0.003	-0.010
6	6.000	1.000	1.000	6.000	0.030	0.109	0.069	-0.042	0.013
7	7.000	1.000	2.000	7.000	0.006	0.110	0.025	0.010	0.000
8	8.000	1.000	2.000	8.000	0.011	0.070	0.063	0.035	0.098
9	9.000	1.000	2.000	9.000	0.070	0.119	0.092	0.087	0.122
10	10.000	1.000	2.000	10.000	0.112	0.023	0.057	0.060	0.195
11	11.000	1.000	2.000	11.000	0.017	0.157	0.003	0.069	0.060
12	12.000	1.000	2.000	12.000	0.068	0.085	0.033	0.079	0.160
13	13.000	1.000	2.000	13.000	0.012	0.129	0.005	0.063	0.013
14	14.000	1.000	2.000	14.000	0.013	0.133	0.030	0.121	0.098
15	15.000	1.000	2.000	15.000	0.043	0.133	0.055	0.114	0.087
16	16.000	2.000	1.000	16.000	0.023	0.041	0.046	0.052	0.115
17	17.000	2.000	1.000	17.000	0.031	0.056	0.006	0.023	0.103
18	18.000	2.000	1.000	18.000	0.021	0.037	0.016	0.107	0.079
19	19.000	2.000	1.000	19.000	0.011	0.046	0.062	0.004	0.159
20	20.000	2.000	1.000	20.000	0.014	0.047	0.009	0.068	0.111
21	21.000	2.000	1.000	21.000	0.000	0.014	0.004	0.033	0.053
22	22.000	2.000	1.000	22.000	0.074	0.116	0.010	0.117	0.110
23	23.000	2.000	2.000	23.000	0.015	0.052	0.004	0.011	0.078
24	24.000	2.000	2.000	24.000	0.032	0.070	0.005	0.025	0.146
25	25.000	2.000	2.000	25.000	0.018	0.012	0.002	0.003	0.028
26	26.000	2.000	2.000	26.000	0.024	0.023	0.014	0.021	0.077
27	27.000	2.000	2.000	27.000	0.008	0.061	0.052	0.067	0.124
28	28.000	2.000	2.000	28.000	0.027	0.062	0.034	0.068	0.072
29	29.000	2.000	2.000	29.000	0.024	0.096	0.076	0.018	0.120
30	30.000	2.000	2.000	30.000	0.016	0.003	0.006	0.017	0.024

TABLE 2 : GENERAL LINEAR MODELS PROCEDURE

REPEATED MEASURES ANALYSIS OF VARIANCE

TESTS OF HYPOTHESES FOR BETWEEN SUBJECTS EFFECTS

Source	DF	Mean Square	F Value	Pr > F
TRT	1	0.00216508	0.77	0.3896
TRT (REP)	2	0.00930944	3.29	0.0532
Error	26	0.07351954		

14.4 MEASUREMENT OF SUSPENDED PARTICULATE MATTER

Throughout the five-day experiment the average suspended particulate inorganic matter concentration was 224.75 mg/l, with a range of 147 mg/l to 357 mg/l. (TABLE 3)

TABLE 3 - SPM MEASUREMENTS (mg/l)

Day	1. SPM-initial	1. SPM-final	2. SPM-initial	2 SPM-final	Ave. SPM
1	206.000	147.000	264.000	158.000	193.750
2	217.000	215.000	251.000	241.000	231.000
3	227.000	217.000	208.000	203.000	213.750
4	357.000	262.000	233.000	207.000	264.750
5	229.000	209.000	229.000	215.000	220.500
				Total ave.	224.750

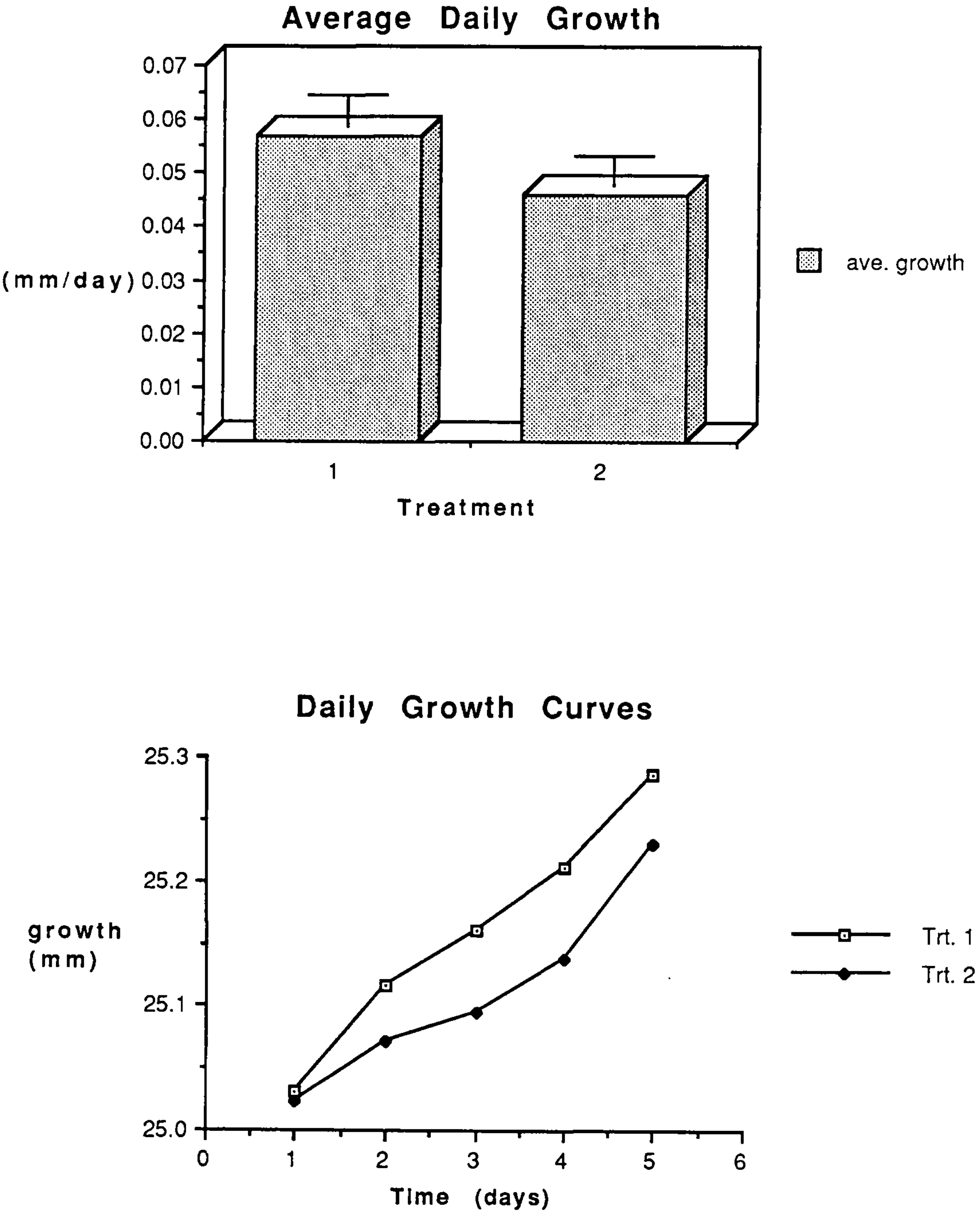
Average Daily Growth
0.07
0.06
0.05
0.04
(mm/day) 0.03
0.02
0.01
0.00
1
2
Treatment
▨ ave. growth
Daily Growth Curves
25.3
25.2
growth (mm)
25.1
25.0
0
1
2
3
4
5
6
Time (days)
Trt. 1
Trt. 2

Figure 3.

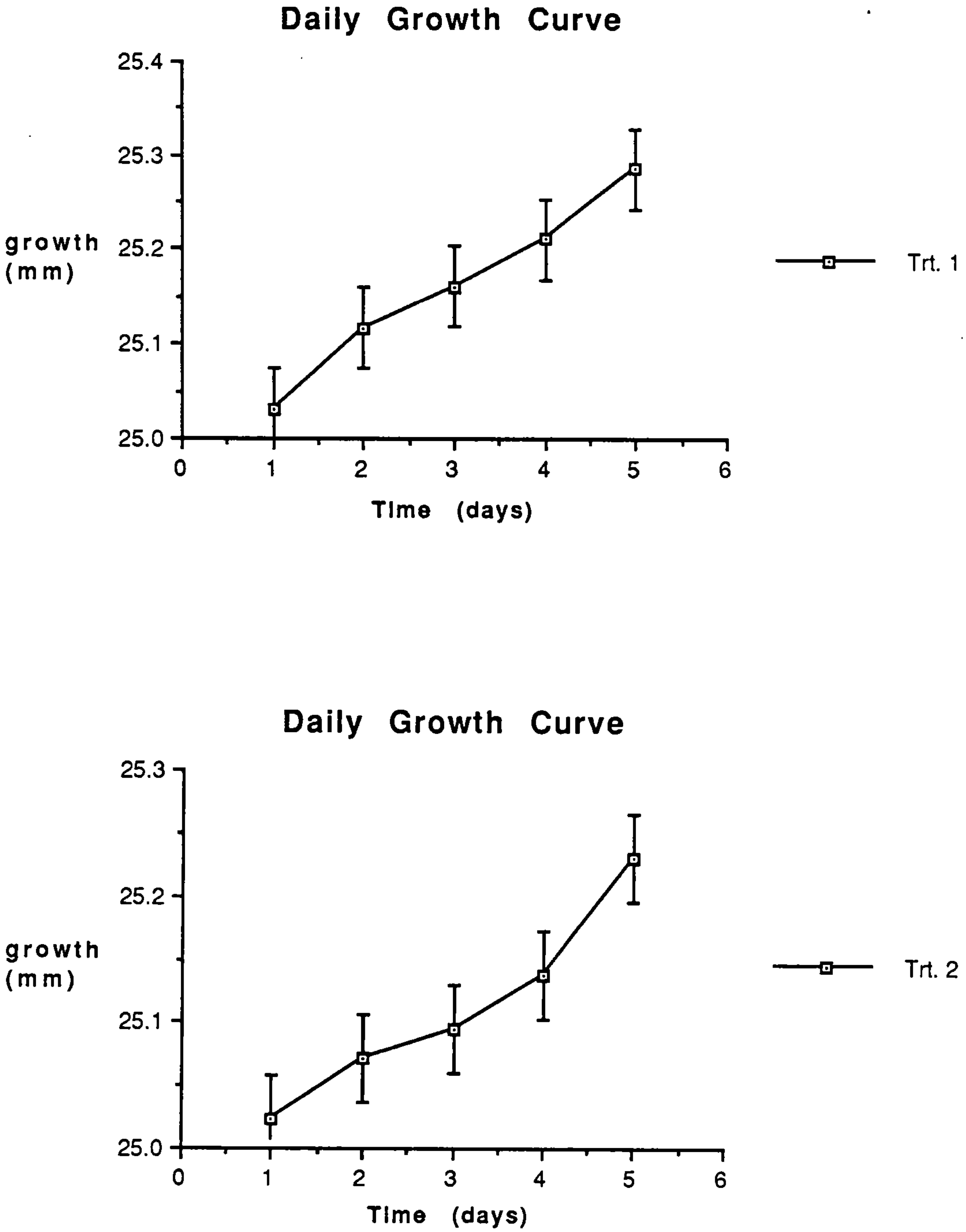
Daily Growth Curve
25.4
25.3
25.2
25.1
25.0
growth (mm)
0
1
2
3
4
5
6
Time (days)
Trt. 1
Daily Growth Curve
25.3
25.2
25.1
25.0
growth (mm)
0
1
2
3
4
5
6
Time (days)
Trt. 2

Figure 4.

15.0 DISCUSSION:

15.1 SUMMARY

The study was done as a result of increasing interest in environmental perturbation of aquaculture leases through industrial and domestic influences. Dredge spoils plus other discharges into the sea represent the continuation of decades of pollution and the effects of settlement pressures upon large areas of sheltered coastline. As nearshore activity increases through a combination of both industry and population expansion, the pollution problem and resulting negative impact on aquaculture is increasing. Recent litigation in New Brunswick concerning a mussel lease exposed to dredge spoils demonstrates this trend and underscores the need for a wide data base derived from scrupulousexperimentation.

The attempt to show the presence or absence of short-term negative effects of suspended particulate material on mussel shell growth through the use of the laser diffraction technique is a response to the need for bioassay type tests which can be applied to assess damage, or to predict the likelihood of damage, to shellfish aquaculture. Statistical analyses of the data obtained from a five-day comparative growth test demonstrated that an exposure to an average daily concentration of 224.75 mg/l of particulate inorganic material was not sufficient to cause a statistically significant decline in shell growth rate, although the data did exhibit a trend of reduced growth in the exposed population. The control group (TRT 1) grew more than the experimental group (TRT 2) and this trend was consistently observed over a four-day period, however, on day five, the trend was reversed. The conditions under which statistically significant differences between the two treatments may be detected would include: (a) increasing the duration of exposure while maintaining the same average concentrations of SPM or (b) increasing the concentrations of SPM over a five-day period of exposure.

Mussels are widely distributed in the marine environmrnt and are of great value as food for man; therefore, they are suitable for toxicity evaluation in short-term and long-term tests. As toxicants can affect bivalves by interfering with growth (shell deposition), these toxic effects are the basis for short- and long-term toxicity tests. (Standard Methods for the Examination of Water and Wastewater, Sixteenth Edition, 1985). For a given test, increasing the number of test organisms increases precision. As a general rule, Standard Methods for the Examination of Water and Wastewater (Sixteenth Edition, 1985), recommends the use of no less than ten test organisms and preferably, the use of twenty or more. In the statistical analysis of the study, logistical limitations occurred due to the number of mussels that could be measured in the laboratory in one day and accomodated in the grazing chambers where the animals were held.

15.2 RECOMMENDATIONS

Due to the short duration of the experiment, coupled with the necessarily small numbers of test animals, the laser diffraction technique should be re-applied in further investigations involving: (a) larger numbers of animals (including other measurable genera ie. scallops) and (b) a longer duration of exposure to suspended sediment; where more than one type of sediment could be used, including one which was shown to contain noxious chemical substances, and (c) higher concentrations of sediments could also be used.

15.3 CONCLUSIONS

During a five-day toxicity test, using the Bay of Fundy sediment at an average concentration of 224.75 mg/l, it is not possible to demonstrate a significant effect on shell growth in *Mytilus edulis* The experiment confirms earlier work (Purchon, 1937, In Moore, 1977) which suggests that the blue mussel is tolerant of even much higher concentrations of suspended material than that used in this experiment. The laser diffraction technique for measuring short-term length changes in blue mussels shows promise as a tool, to be used to perform bioassays on pollutants potentially harmful to mussels leases. The method of holding test animals in this experiment is such that minor changes in deployment would enable "in situ" bioassays to be performed or allow the survey of growth potential in unused nearshore areas which might be exploited for aquaculture.

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APPENDIX 2

Regression Relationships and Miscellaneous Data Tables

Table A2-1. Regression relationships and adjusted means, small oysters, Pugwash, Nova Scotia. Log weight (g) = M x log length (mm) + b

	M	b	Adjusted Means Log10 (x)		Significant Difference
			Log10	g	
Whole wet weight					
Initial	2.10	-3.09	-0.08	0.83	
Control	3.04	-4.43	-0.05	0.88	
Site 1	2.59	-3.75	-0.02	0.96	
Site 2	3.23	-4.74	-0.08	0.83	
Overall	2.76	-4.04	-0.06	0.88	** p < .05
Tissue dry weight					
Initial	2.93	-5.98	-1.73	0.02	
Control	2.76	-5.54	-1.58	0.03	
Site 1	2.08	-4.52	-1.53	0.03	
Site 2	2.75	-5.60	-1.63	0.02	
Overall	2.22	-4.81	-1.60	0.02	** p < .001
Tissue wet weight					
Initial	2.63	-4.76	-0.96	0.11	
Control	2.82	-4.76	-0.71	0.20	
Site 1	1.99	-3.41	-0.55	0.28	
Site 2	3.04	-5.09	-0.69	0.20	
Overall	2.54	-4.37	-0.71	0.20	** p < .001
Shell dry weight					
Initial	2.02	-3.03	-0.15	0.72	
Control	3.10	-4.62	-0.17	0.68	
Site 1	2.83	-4.26	-0.17	0.67	
Site 2	3.28	-4.95	-0.20	0.63	
Overall	2.80	-4.21	-0.17	0.67	Test not possible as slopes were not equal

* Treatments significantly different

Table A2-2. Regression relationships and adjusted means, large mussels, Pugwash, Nova Scotia. Log weight (g) = M x log length (mm) + b

	M	b	Adjusted Means Log10 (x)		Significant Difference
			Log	g	
Whole wet weight					
Initial	2.84	-3.96	1.21	16.18	
Control	3.23	-4.71	1.17	14.90	
Site 1	3.02	-4.33	1.16	14.57	
Site 2	2.80	-3.93	1.17	14.80	
Overall	2.94	-4.17	1.17	14.87	N.S.
Tissue dry weight					
Initial	3.41	-5.97	0.24	1.73	
Control	3.27	-5.81	0.15	1.40	
Site 1	3.53	-6.29	0.14	1.37	
Site 2	3.09	-5.48	0.14	1.38	
Overall	3.24	-5.75	0.15	1.42	N.S.
Tissue wet weight					
Initial	2.89	-4.30	0.96	9.09	
Control	3.28	-5.10	0.87	7.45	
Site 1	3.13	-4.83	0.88	7.55	
Site 2	2.71	-4.05	0.88	7.61	
Overall	2.93	-4.45	0.88	7.66	$p < .10$
Shell dry weight					
Initial	2.75	-4.16	0.85	7.06	
Control	3.23	-5.01	0.87	7.33	
Site 1	2.86	-4.36	0.84	6.97	
Site 2	2.81	-4.27	0.85	7.08	
Overall	2.92	-4.46	0.85	7.10	N.S.

Table A2-3. Regression relationships and adjusted means, small mussels, Pugwash, Nova Scotia. Log weight (g) = M x log length (mm) + b

	M	b	Adjusted Means Log10 (x)		Significant Difference
			Log	g	
Whole wet weight					
Initial	2.61	-3.68	0.58	3.77	
Control	2.47	-3.46	0.57	3.68	
Site 1	2.74	-3.90	0.56	3.66	
Site 2	2.56	-3.62	0.56	3.65	
Overall	2.61	-3.70	0.56	3.67	N.S.
Tissue dry weight					
Initial	2.01	-3.67	-0.39	0.41	
Control	2.98	-5.22	-0.36	0.44	
Site 1	2.98	-5.27	-0.40	0.39	
Site 2	2.61	-4.66	-0.41	0.39	
Overall	2.89	-5.11	-0.39	0.41	N.S.
Tissue wet weight					
Initial	2.57	-3.82	0.37	2.35	
Control	2.69	-4.07	0.31	2.06	
Site 1	3.06	-4.68	0.30	2.00	
Site 2	2.91	-4.44	0.30	2.00	
Overall	2.88	-4.39	0.31	2.05	N.S.
Shell dry weight					
Initial	2.69	-4.23	0.15	1.41	
Control	2.18	-3.35	0.20	1.59	
Site 1	2.38	-3.66	0.22	1.65	
Site 2	2.14	-3.27	0.21	1.63	
Overall	2.29	-3.53	0.20	1.59	$p < 0.10$

Table A2-4. Regression parameters of log transformed variables on log length for *Mytilus edulis* and *Ostrea edulis* in laboratory exposures to SPM. Regression equation: Log_{10} Weight (g) = m x Log_{10} Length (mm) + b.

Blue Mussel (*Mytilus edulis*)		r^2	m	b	Adjusted (g)
Tissue Dry Weight					
Overall	N = 59	0.313	2.177	-4.039	
Control	N = 30	0.390	2.448	-4.479	0.440
Experimental	N = 29	0.172	1.794	-3.403	0.413
Shell Weight					
Overall		0.623	2.303	-3.569	
Control		0.606	2.242	-3.452	2.114
Experimental		0.677	2.599	-4.084	1.980
Whole Wet Weight*					
Overall		0.702	2.403	-3.381	
Control		0.749	2.418	-3.395	4.773
Experimental		0.631	2.508	-3.569	4.537
Whole Dry Weight*					
Overall		0.681	2.321	-3.512	
Control		0.684	2.321	-3.497	2.584
Experimental		0.708	2.505	-3.839	2.412
European Oyster (*Ostrea edulis*)					
Tissue Dry Weight					
Overall	N = 90	0.360	2.945	-6.020	
Initial	N = 30	0.506	3.846	-7.355	0.039
Control	N = 30	0.258	2.217	-4.864	0.037
Experimental	N = 30	0.534	3.141	-6.412	0.028
Shell Weight					
Overall		0.557	2.385	-3.585	
Initial		0.716	2.627	-3.981	1.197
Control		0.425	1.972	-2.931	1.315
Experimental		0.506	2.487	-3.737	1.284
Whole Wet Weight*					
Overall		0.568	2.471	-3.636	
Initial		0.701	2.840	-4.209	1.515
Control		0.423	2.028	-2.941	1.567
Experimental		0.541	2.540	-3.753	1.500
Whole Dry Weight*					
Overall		0.560	2.401	-3.599	
Initial		0.720	2.668	-4.029	1.239
Control		0.424	1.976	-2.925	1.351
Experimental		0.511	2.501	-3.750	1.313

* sum of shell weight plus either tissue wet or tissue dry weight.