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PHYSICAL EFFECTS OF SUSPENDED SOLIDS ON MARINE AND ESTUARINE FISH AND SHELLFISH, WITH SPECIAL REFERENCE TO OCEAN DUMPING: A LITERATURE REVIEW

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CONTENTS

LIST OF TABLES

ABSTRACT

Appleby, J.P. and D.J. Scarratt. 1989. Physical effects of suspended solids on marine and estuarine fish and shellfish with special reference to ocean dumping: A Literature Review. Can. Tech. Rep. Fish. Aquat. Sci. 1681:v + 33 p.

Literature concerning the lethal and sublethal effects of suspended solids on marine and estuarine fish and shellfish is reviewed, with reference to ocean and coastal zone dredging and dumping where applicable.

Experiments indicate that many species of adult fish and shellfish survive in concentrations of suspended solids far greater than those commonly observed in nature. Eggs and larvae are less tolerant to suspended solids than are adults, and larvae are more sensitive than eggs. Tolerance varies between species and between particle type. Particles in the larger size range or having the greater angularity have been shown to be more lethal than smaller or smoother particles.

Histological and hematological evidence of suspended sediment damage to fish and shellfish is explored, and some mechanisms by which such effects are realized are outlined. Observations pertaining to behavior, feeding, growth, fishing success, and habitat alteration are included. Several conclusions regarding current ocean-dumping and dredging practices are presented.

RÉSUMÉ

Appleby, J.P. and D.J. Scarratt. 1989. Physical effects of suspended solids on marine and estuarine fish and shellfish with special reference to ocean dumping: A Literature Review. Can. Tech. Rep. Fish. Aquat. Sci. 1681:v + 33 p.

On procéde à une étude de la documentation concernant les effets létaux et sublétaux des solides en suspension sur les poissons, les crustacés et les mollusques marins et estuariens, en s'attachant aux cas de dragage et de déversements dans les zones océaniques et côtiéres.

Les expériences rélèvant que de nombreuses espèces de poissons, de crustacés et de mollusques adultes survivent dans des concentrations de solides en suspension beaucoup plus élevées que celles que l'on trouve couramment dans la nature. Les oeufs et les larves tolèrent toutefois moins bien ces matières en suspension, les secondes encore moins que les premiers. La tolérance varie d'une espèce à unde autre; elle varie aussi selon le type de particule en suspension. Les particules les plus grosses ou celles à grande angularité se sont avérées plus néfastes que les particules plus petites ou moins anguleuses.

On examine les preuves histologiques et hématologique des dommages causés aux poissons, aux mollusques et aux crustacés par les sédiments en suspension, ainsi que certains de mécanismes de détérioration. On présente aussi des observations au sujet de comportement, de l'alimentation et de la croissance des poissons, des mollusques et des crustacés, du succés de leur pêche et des changements touchant leur habitat. Plusieurs conclusions sont offertes à propos des pratiques actuelles de déversement et de dragage en mer.

INTRODUCTION

SOURCES OF SUSPENDED SEDIMENTS

Sources of suspended sediments in estuarine and marine environments are well known and have been discussed by several authors eg. Guilcher 1967; Freitag 1960; Moore 1978; MacLaren Plansearch/Lavalin 1984. This section provides a summary of these and other publications (below), and the reader is referred to bibliographical citations for a more complete account.

The distance travelled by various particle types depends primarily on the size and density of the material, current velocities and weather patterns. Table I provides critical transportation velocities for particles of various sizes.

Residence time in the water column varies enormously for particles of different sizes, and it is generally true that the smaller the particle, the longer will be its time in suspension. This paper deals primarily with those particles which remain in suspension long enough to have potential biological impacts upon fish and shellfish, namely; the finer grained sands and clays.

A primary source of suspended solids in coastal zones in land-base erosion (Schubel 1971; Anderson et al. 1973). Much of the release of sediments from river systems is seasonal during spring freshets, wet seasons and severe storm events, although virtually all rivers discharge varying amounts of sediments into estuaries on a continuous basis. Sediment and particulate matter discharge from freshwater sources is greatly enhanced by watershed-specific activities such as agriculture, forestry, highway and road construction, building construction, surface mining, and urbanization.

Coastlines characterized by sedimentary rock and rising sea levels are typified by relatively high levels of wave-eroded suspended solids in adjacent waters. Bay of Fundy waters receive a large portion of suspended solids in this fashion (C. Amos, pers. comm.), as does the much-studied coastal zone between Sydney and Point Donkin, Cape Breton Island (Dobrocky-Seatech 1984/85).

A substantial proportion of particles in estuarine waters come from the resuspension of fine, unconsolidated sediments and detritus by wave action and currents.

In some areas (eg. Minas Basin), tidal currents are sufficient to produce daily elevated SS episodes directly attributable to tidal flux and amplitude (G. Daborn, pers. comm.). Krone (1972), noted that for the San Francisco Bay area, winds in excess of 16 km/hr were sufficient to resuspend up to 2200 mt of sediment per day and to result in suspended solids concentrations of up to 1,000 mg l^{-1}. Similarly, increased suspended sediment concentrations have been recorded for the Mirimichi estuary in New Brunswick in windy conditions.

Non-coastal areas characterized by shallow-water reaches of ocean bottom are also subject to substantial resuspension of sediments, particularly during storm events (eg. shallow areas of offshore banks, Sable Island area, Magdalene Island area).

Turbidity maxima are a common estuarine phenomenon, and can locally concentrate suspended solids in the water column to levels far in excess of those coming from (parent) freshwater sources or measured in the seaward portion of an estuary. The existence of turbidity maxima has been attributed to hydrodynamic conditions as well as the flocculation and deflocculation of river borne sediment (Schubel, 1968). The process is initiated by a portion of river borne sediments descending into the (higher density) saline water below the halocline at the saltwater/freshwater interface. The saltwater component has a net upstream movement and particles are then resuspended in the upper (fresh) water layers by vertical mixing. The process repeats itself and localized high concentrations of suspended material result. Suspensions of up to 1,200 mg l^{-1} have been reported.

A major source of turbidity in marine and aquatic systems are phytoplankton blooms. The intensity of such episodes depends on a number of environmental factors, including light, temperature, and inorganic and organic nutrient availability. However, phytoplankton are not considered to be, at least within the scope of this paper, suspended solids, and most of the ensuing discussion will deal directly with inorganic suspensions, or inorganic suspensions containing various amounts of organic, non-living material.

A fifth source of suspended sediments is ocean and coastal zone dredging and dumping. The contribution of materials from related activities to aquatic and marine environments in Canada has been discussed in a recent review of disposal alternatives for dredged materials (MacLaren Plansearch, 1984, Vol. I).

Dredging in Canada is composed primarily of "baseline" and maintenance activities, consisting of a few large-scale projects carried out on a yearly basis (eg. St. Lawrence and Fraser Rivers) and a large number of projects involving less than 100,000 m^3 (most often connected with small craft harbour improvements). There are also occasional major capital works such as the Vancouver-Roberts Bank and Mirimichi River projects (MacLaren Plansearch, 1984, Vol. I). Table II summarizes dredging activities in Canada from 1976 to 1984 registered and processed through Environment Canada's Ocean Dumping Control Act referral mechanism. While the overall trend for dredging volumes since 1980 has been a decreasing one, total figures show an incomplete picture. Of primary importance to environmentalists are the site-specific characteristics of individual projects such as the total amount of material to be disturbed, its particle size distribution, organic content and associated pollutants, and the presence of sensitive biological resources in the area. Existing recreational or commercial use patterns are also analyzed to predict what effect proposed dredging and dumping activities will have on traditional activities.

The Environmental Protection Service (EPS) of Environment Canada administers the Ocean Dumping Control Act, and acts as the lead agency for the Ocean Dumping Referral System. In the Atlantic Provinces, the review mechanism is composed of member agencies of the Regional Ocean Dumping Advisory Committee (RODAC), including EPS (Atlantic Region), and the Scotia-Fundy, Gulf and Newfoundland Regions of the Science Sector, Federal Department of Fisheries and Oceans (DFO). While EPS assesses Ocean Dumping applications primarily through RODAC, provincial agencies and other experts are also consulted as required.

This review of the physical effects of suspended solids on marine and estuarine fish and shellfish has been prepared to aid in the comprehensive review and assessment of Ocean Dumping and Dredging project applications and other related issues. Funding for the project was provided in part by the Ocean Dumping Research Fund, administered by Environment Canada, and in part by the Scotia-Fundy Region of the Science Sector.

TURBIDITY VERSUS SUSPENDED SOLIDS

The literature concerning the effects of suspended solids (SS) on fish is extensive, although many earlier studies did not relate animal response to actual concentration of particles in suspension. Jackson (1962), Larimore and Smith (1963), Mills et al. (1966), and others, after conducting extensive sampling on several major river systems, concluded that turbidity from suspended soil is the single-most important factor affecting fish. However, results from these studies provided little in the way of qualitative and quantitative data.

Turbidity has been defined as a condition in water (or other liquid) resulting from the presence of suspended material, such as clay, silt, finely divided organic and inorganic particles, plankton and microscopic organisms, and dissolved substances which cause light to be scattered and absorbed, rather than transmitted (APHA 1976). The size, shape, and refractive index of particulate material determined the overall turbidity of a given suspension. However, turbidity values by themselves do not provide quantitative information concerning the concentration or specific gravity of suspended solids. Therefore, while the term turbidity is suitable for describing water clarity, it is not in itself a complete description of those properties of suspensions which result in physical impacts on aquatic organisms.

More recent authors (e.g. Peddicord et al. 1975; O'Connor et al. 1977), suggest it is unlikely that the light absorption and diffusing properties of suspended solids directly affect fish or invertebrates, but may have indirect effects through behavioral modification and through reduction in photosynthetic activity and subsequent related food chain effects if suspended solids episodes are chronic in nature (Sherk 1972; Stern and Stickle 1978; O'Connor et al. 1976; 1977). However it is the intent of this paper to concentrate on the direct lethal and sublethal physical effects of suspended solids on organisms, and not on the indirect effects.

Several reviews of the indirect effects of SS on fish are available, two good ones being Stern and Stickle (1978), and Moore (1978).

SOURCES OF VARIATION IN BIOLOGICAL EFFECTS OF SUSPENDED SOLIDS

Cairns (1968), listed four primary mechanisms by which suspended solids affect living organisms as follows:

(a) Mechanical or abrasive action;
(b) Reduction of light penetration;
(c) Availability as a growth surface for bacteria and fungi; and
(d) Absorption and adsorption of chemicals.

Insofar as the physical effects of suspended solids on marine and estuarine fish and shellfish are concerned, mechanical or abrasive action is the most important. Reduction of light penetration is also considered to be fairly important as it affects avoidance responses, prey capture efficiency, prey selection and feeding mode.

Lethal levels of suspended solids vary with species (Table III) (Herbert and Richards 1963; O'Connor et al. 1976; Alabaster and Lloyd 1980; Stern and Stickle 1978), particle density and subsequent residence time in the water column (Carritt and Goodgal 1954; Richards 1969; Schubel and Kana 1972; Sherk 1972), particle size distribution and angularity (Rogers 1969; O'Connor et al. 1976; 1977; Goldes 1983) mineralogy (O'Connor et al. 1976; 1977; Ruttner 1963; Gustafson 1972; Garritt and Goodgal 1954) sorptive properties (Ruttner 1963; Richards 1969; Gustafson 1972; O'Connor et al. 1976; 1977; Stern and Stickle 1978; Eisma 1980) and oxygen and temperature (Brown and Clark 1968; Carriker 1967; O'Connor et al. 1976; 1977; Huet 1965; McNulty et al. 1962). Because of the variety of determinant parameters, it is not rare when reviewing the literature to find substantial variation between laboratory and field experiments, and between laboratory experiments using similar levels of suspended solids and experimental methodologies. The following review of pertinent literature reflects this.

LETHAL EFFECTS - FISH

The largest body of information concerned with the lethal effects of suspended solids on fish has been provided by laboratory bioassays performed under controlled conditions. A summary of results from several pertinent works is provided by Table III.

Rogers (1969) noted that the lethality of individual test materials seems to depend in large part on the shape, and in particular on the angularity of the particles. In exposing Apeltes quadracus (ocean perch) to (in order of decreasing angularity) glass powder, diatomaceous earth, glass spheres and powdered charcoal, it was found that glass powder and diatomaceous earth killed all test animals within 24 hours at 10 mg l^{-1}. By contrast suspensions of glass spheres and powdered charcoal proved to be only slightly lethal at 10 mg l^{-1}.

Rogers (1969) testing Tautogolabrus adspersus (fourspine stickleback) and A. quadracus, found that particles having the largest median grain size exhibited the greater relative lethality. However, the mummichog (Fundulus heteroclitus) exhibited less tolerance to diatomaceous earth than to Kingston silt, a reverse situation. It appears then, that when particles of equivalent texture or shape are employed, animals exhibit less tolerance to larger size particles, but that angular particles may prove more toxic than relatively larger but "smoother" material.

O'Connor et al. (1976), exposed eleven species of estuarine fish to suspensions of kaolinite of up to 140,000 mg l^{-1} concentration and observed no mortalities at 24 and 48 hour observation intervals. However, when exposed to suspensions of (more angular) fullers earth, all eleven species showed significant mortalities within 24 hours at concentrations exceeding 6,500 mg l^{-1}. Natural sediments were less harmful than mineral solids for all species tested.

Two hypotheses are commonly presented concerning the reasons why fish may be able to tolerate greater concentrations of natural sediments than mineral solids. One supposes that the abrasive mineral particles in natural sediment are diluted by other less angular particles, and may also be coated by organic material which reduces angularity. The other suggests that trapped larger size-fraction particles allow water to flow through the larger interstices and reach the gill surface (Cameron and Davis, 1970; Muir, 1969).

Several investigators have concluded that suspended particulate matter is lethal to fish only at concentrations well in excess of those normally found in nature (Wallen 1951; Legore and Desvoigne 1973; Muir 1969; Cameron and Davis (1970); Rogers 1969; EIFAC 1964; O'Connor 1976; Sherk 1972; Cronin 1970). Wallen (1951) exposed 16 species of fish to montmorillonite clay up to an equivalent of 225,000 mg l^{-1} silica flour and observed no symptoms until a level of about 20,000 mg l^{-1} was reached, and no mortalities attributable to experimental conditions until concentrations of 175,000 mg l^{-1} were reached. Unfortunately, this study did not include any salmonids. Similarly, O'Connor et al. (1976) noted no mortalities in toadfish (Opeanus tau), cusk eel (Brosme brosme) and hogchoker (Trinectes maculatus) after 24 h exposures to 140,000 mg l^{-1} fullers earth (above). These investigators also determined LC_{50}s for Atlantic Silverside (Menidia menidia), Bay Anchovy (Anchoa mitchilli), White Perch (Morone americanus) and Mummichog to be 2400, 4710, 9850 and 39,000 mg l^{-1} respectively.

Rogers (1969) determined 24 h LC_{50} values for four species of estuarine fish to range from 2500 mg l^{-1} to in excess 300,000 mg l^{-1}. Sherk et al. (1972, 1974) determined the 24 h LC_{10} for silversides to be 580 mg l^{-1}, while that for mummichog was 24,500 mg l^{-1}.

Peddicord et al. (1975), in testing for the effect of suspended bentonite under laboratory conditions on English sole (Perophrys vetulus), found no mortalities at concentrations of 70,000 mg l^{-1}, and 80 percent mortality at 117,000 mg l^{-1} after 10 days.

O'Connor et al. (1976), using natural resuspended harbour sediments, recorded 24 h LC_{50} values for spot (Leiostomus xanthurus) and white perch of 88,000 mg l^{-1} and 9,850 mg l^{-1} respectively. In another experiment, contaminated harbour sediments containing oil, grease, heavy metals and organic matter produced no observable adverse effects on stickleback or coho salmon fry in four day exposure periods at concentrations up to 28,000 mg l^{-1} (LeGore and DesVoigne 1973).

Based upon these and other studies, O'Connor et al. (1976) have placed fish into 3 categories: tolerant species (24 h LC_{10} greater than 10,000 mg l^{-1}), including mummichog, striped killifish (Fundulus majalis) and spot; sensitive species (24 h LC_{10} between 1000 and 10,000 mg l^{-1}) including white perch and bay anchoy; and highly sensitive species (24 h LC_{10} less than or equal to 1,000 g l^{-1}, including the silversides. However, it should be noted that silversides can be very difficult to work with and often die in the laboratory for no obvious reason.

Suspension-tolerant species commonly inhabit waters where suspended solids are naturally high (Masch and Epsev 1969) or frequent the sediment/water interface. For example, killifish and cusk frequently burrow into the bottom and remain buried for long periods of time (Hildebrand and Schroeder 1928). Similarly, the English sole is a demersal fish, frequently in contact with bottom sediments. Mummichog can be found under a wide range of SS concentratrations, and typically show no aversion to highly turbid water.

Habitat correlations for suspension-sensitive and highly sensitive species have not been made. However, filter feeders have been shown to be relatively less tolerant of suspended solids than other species (O'Connor et al. 1976; Sherk 1972; Herbert and Richards 1963; McFarland and Petticord 1980; and Stern and Stickle 1978). The general conclusion reached by these authors is that fish which inhabit relatively clear waters are less tolerant to suspended solids than those fish normally frequenting waters high in suspended solids.

Ellis (1937) described several ways in which particles could cause asphyxiation in fish (e.g. coating by fine particles and clogging by larger particles such as those found in natural mud). Virtually all researchers and reviewers have noted similar phenomena (Goldes 1983; Alabaster and Lloyd 1980; Slalina (in: Alabaster and Lloyd 1980; Cairns 1967; O'Connor et al. 1976; Sprague and Logan 1979; Stickney 1979). At very high levels, the opercular cavity may become blocked (Sprague and Logan 1979), and at lower concentrations, particles tend to coat the gill surface and inhibit gaseous diffusion, nitrogenous excretion and ion exchange (Stern and Stickle 1978; Goldes 1983; Cairns 1967).

Histological examinations of dead and moribund fish show moderate to extensive gill damage. Observed effects include epithelial and mucus cell hyperplasia (Goldes 1983), hyper-secretion of mucus (Slalina in: Alabaster and Lloyd 1980; Cairns 1967), fusion of gill filaments and lamellae (Slalina in: Alabaster and Lloyd 1980; Goldes 1983; Cairns 1967), thickening of gill lamellae (Stern and Stickle 1978), and overall respiratory distress (Stern and Stickle 1978; Wallen 1951).

While the effects of elevated levels of suspended solids on fish are somewhat varied (above), the overall cause of death is usually due to oxygen starvation from disruption or damage to respiratory tissue. Wallen (1951) recorded his observations concerning fish behavior in high levels of SS and noted that their behavior was very similar to that of oxygen starved fish. Rogers (1969) completed a series of similar observations and concurred.

DISSOLVED OXYGEN

Not surprisingly, dissolved oxygen concentration has been shown to play a major role in determining the tolerance of fish to elevated suspended solids levels (Rogers 1969; Peddicord et al. 1975; O'Connor et al. 1976; Stern and Stickle 1978). Rogers (1969) noted markedly increased LC_{50}s for *A. quadracus* and *T. adspersus* when supplementar (pure) oxygen was bubbled through test silt suspensions. Peddicord et al., (1975) observed an increase in the tolerance of *C. nigricauda* to suspended sediments when oxygen concentrations were high, but the data were too erratic to quantify. O'Connor et al., (1976) noted an increased 24 h LC_{50} for silversides when bubbled air was incorporated into the experimental design.

Several researchers have noted that the resuspension of sediments high in organics can have an effect on levels of dissolved oxygen in the water column. Isaac (1965) estimated that for sediments with a measured BOD of $0.05gO_2M^{-2}$ day when resuspended, exerted a BOD of $0.4gO_2M^{-2}$ day $^{-1}$ (or eight times that of the parent bottom sediments). Brown and Clark (1968) studied the dissolved oxygen levels following resuspension of bottom sediments by dredging in several tidal bays between Staten Island, New York and the New Jersey shoreline and found that oxygen levels at dredge sites were 16-83 percent lower than during non-dredging periods at the same sites. Berg (1970) determined that suspension of bottom sediments through agitation increased the oxygen demand by 10 times that of stabilized sediments, and studies in San Francisco and San Pablo Bays by the U.S. Fish and Wildlife Service (1970) indicated a reduction of dissolved oxygen from 8.0 to 0.1 ppm at dredge disposal sites. It is generally believed that reductions occur through adsorption of O_2 molecules onto silt particles, or because of oxygen uptake by organic acids. However, studies have also shown that most oxygen depletion occurs near the bottom in the vicinity of a spoil pile (Lee et al. 1985; May 1973), and that oxygen depletions are usually transitory and of short duration, at least in open water (Stern and Stickle 1978; U.S. fish and Wildlife Service 1970; Lee et al. 1975.

Based on the above, lowered oxygen levels due to the resuspension of sediments during dredging and dumping operations may conceivably contribute to fish mortality. This would be particularly true for extremely high levels of SS where fish are undergoing respiratory distress from the physical impacts of particulate matter, and during warmer months of the year when O_2 levels are already low and bacterial and chemical action on newly exposed organic material would be more rapid. This is a more important consideration where relatively low energy environments are concerned. It is also possible that avoidance of oxygen poor water may occur (author's note).

TEMPERATURE

Temperature changes also have an effect on the tolerance of fish to sediment loading. Rogers (1969) found that mortalities among three species of fish were directly proportional to temperature. Peddicord et al. (1975) reached a similar conclusion using striped bass (Morone saxitalis), English sole and shiner perch. Several authors have concluded from these and other studies (eg. Cronin 1970; Cairns 1968) that high suspended solids concentrations from dredging would be more likely to produce either lethal or sublethal effects on fish during summer months when water temperatures are high, independent of oxygen concentrations. Already-stressed fish are less tolerant of other extreme conditions.

FISH EGGS - LARVAE

The lethal effects of suspended solids on fish change with different stages of life history. Table IV summarizes much of the available information as outlined by the ensuing text.

Sherk and O'Connor (1977) noted decreased tolerances to SS by juvenile bluefish, menhaden and young-of-the-year white perch when compared with adult members of the same species. All juveniles exhibited mortalities in SS concentration below 1,000 mg l^{-1}, placing them in the highly sensitive category (O'Connor et al. 1976). Adult white perch, by contrast, are categorized as sensitive (24 h LC_{10} between 1000 and 10,000 mg l^{-1}).

Dovel (1970) found no indication of mortality attributable to dredging and spoil disposal activities in fish eggs and larvae in Chesapeake Bay. However, Dovel noted several limitations concerning the detection of egg and larval mortalities in the field, suggesting the need for follow-up laboratory studies to determine specific tolerance limits for individual species and developmental stages. During the study, 95% of the eggs and larvae of estuarine and marine species sampled were found in waters of 11% salinity or less. Dovel (1970) stressed the importance of low salinity feeding and nursery areas in estuarine environments, and recommended that dredging and spoil disposal operations should not be carried out in shallow, low salinity waters during spring and summer months.

Schubel and Wang (1973) conducted laboratory experiments using eggs of yellow perch, white perch, striped bass and alewife incubated in suspensions of natural, fine-grained sediments from Chesapeake Bay. Concentrations of SS up to 500 mg l^{-1} had no statistically significant effect on the hatching success of all four species. However, concentrations over 100 mg l^{-1} delayed for 24 h at 4,000 mg l^{-1}. In the same study, 48 h LC_{50} striped bass and white perch larvae were 3,411 mg l^{-1} and 2,679 mg l^{-1}, respectively.

Mansueti (1961) has postulated that many activities carried out by man may in fact be "compatible" with survival of eggs and larvae which are pelagic, at least over the course of their initial developmental periods. He states that "the chances of survival are higher for floating eggs and larvae over areas of low light penetration, high turbidity, low dissolved oxygen and excessive sedimentation than for demersal or semi-demersal eggs deposited by most other species using the same spawning area". However, this statement does not appear to take into account the myriad of other factors which may determine egg and larvae survival, nor does Mansueti discuss the possibility of fish avoiding such areas for use as spawning habitat. The statement was probably made prematurely.

In general, larvae are less tolerant to high concentrations of suspended sediments than are eggs of the same species. Auld and Schubel (1978) exposed eggs and larvae of six species of anadromous and estuarine fish to concentrations of natural sediment ranging from 1 to 1,000 mg l^{-1}. Concentrations of up to 1,000 mg l^{-1} did not significantly affect the hatching success of blueback herring, yellow perch, alewife or American shad eggs. Beyond 1,000 mg l^{-1}, hatching success of white perch and striped bass eggs was significantly reduced. In the same set of experiments, concentrations of 500 mg l^{-1} significantly reduced the survival of striped bass and yellow perch larvae over 48-96 h exposure times. Survival of American shad larvae was significantly reduced at concentrations greater than 100 mg l^{-1}.

Experimental results published to date show widely divergent threshholds of SS concentrations producing sublethal effects on fish eggs. Morgan et al. (1973) found no significant increase in the mortality of striped bass eggs in natural sediment suspensions up to 2,200 mg l^{-1} and the corresponding value for white perch eggs was 5,250 mg l^{-1}. In the same experiment, decreased developmental times were noted for eggs of both species when concentrations exceeded 1,500 mg l^{-1}. Contrasting results were reported by Schubel and Wang (1973), where a hatching delay of several hours was noted for eggs of white perch and striped bass in sediment concentrations of 500 mg l^{-1}. Such variable results are no doubt due in part to differences in light, temperature, oxygen and particle size regimes, and it would appear that further standardization of experimental techniques is necessary before reliable comparison of results may be made.

There is a paucity of data concerning the effects of suspended solids on marine and estuarine fish eggs and larvae. However, it is clear that many researchers and reviewers agree that eggs and icthyoplankton are more sensitive to elevated levels of suspended solids than are adults (O'Connor et al. 1976 and 1977; Sherk 1972; Stern and Stickle 1978; Cairns 1968). While the causes of such age-specific differences are poorly known, two hypotheses are popular. One is that when fish are exposed to lethal levels of suspended sediments, the 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). The physical dimensions of the gills are proportional to the size of the fish (Muir 1969 in: O'Connor et al. 1976). As fish increase in size, so do the sizes of openings in the gill filter. Large fish may therefore trap fewer particles, and experience less respiratory trauma than smaller fish of the same species.

The second hypothesis which may explain greater tolerance of larger fish to suspended solids is the fact that metabolic rates decrease as size increases. Small fish require more oxygen per unit body weight than large fish (O'Connor, Newmann, and Sherk 1977), and are therefore less tolerant to gill damage and clogging.

Auld and Schubel (1978) have discussed possible reasons why larvae are nonetheless able to survive suspended sediment loads greater than those found in nature. At hatching, the gills of most larvae are not fully developed, and the absence of full operculum cover renders the gills less susceptible to clogging and abrasion. Furthermore, at early larval stages, much of the oxygen demand is supplied via the general body epithelium (Blaxter 1969), enabling larvae to meet individual oxygen requirements independently of gills and regardless of any gill tissue damage inflicted by particles. Stuart (1953, in: Auld and Schubel 1978) found that trout larvae were able to keep the respiratory apparatus clear of fine sediment by setting up so-called "respiratory currents" using the pectoral fins, and later in their development, when the gills become more important, through the use of a 'coughing' reflex, and agglomeration of particles with mucus.

SUBLETHAL EFFECTS OF SUSPENDED SEDIMENT ON FISH

HEMATOLOGICAL RESPONSES

O'Connor et al. (1977) studied the sublethal effects of SS on seven estuarine fish species (white perch, spot, striped bass, hogchoker, mummichog, striped killifish, and oyster toad fish). White perch exposed to 650 mg l^{-1} for five days showed significant increases in microhematocrit (packed red blood cell volume), hemoglobin concentration and red blood cell counts. Hogchokers exposed to 1,240 mg l^{-1} fullers earth showed similar responses, and the striped killifish, when exposed to 960 mg l^{-1} for 5 days, showed 29.7 percent increase in microhematocrit measurements over that of the control group. All test concentrations were previously determined by O'Connor et al. (1976), and were equal to that sufficient to achieve a 24 h LC_{10} for each species.

Similarly, mummichogs exposed to 1,600 mg l^{-1} fullers earth showed elevated microhematocrit values, as did striped bass at 1,500 mg l^{-1}. However, striped bass also underwent an increase in osmolality (ionic concentration of the blood), and elevated microhematocrit counts may have been the result of water loss and subsequent concentration of blood components. No significant differences were noted in hematological parameters for spot or toadfish at concentrations of 16,960 mg l^{-1} and 14,600 mg l^{-1}, respectively.

White perch and striped bass tested in resuspended natural sediments showed no significantly different hematological responses over those observed in the control groups.

HISTOLOGICAL EVIDENCE

O'Connor et al. (1977) also conducted histological examinations of the gills of fish exposed to sublethal concentrations of suspended solids. Gills of white perch subjected to 650 mg l^{-1} for 5 days developed several mucous goblet cells on the anterior margins of the gill filaments (the first section of the gill to come into contact with the water). Further examination showed swollen secondary lamellae, a separation of pilar cell tubes from epithelial cells, enlargement of epithelial cells (forming a thick covering, and occasional pilar cell disruption.

Similar histological effects have been noted for rainbow trout exposed to diatomaceous earth (Southgate 1962) and for brown trout exposed to low levels of china clay mining wastes (Herbert et al. 1961; Herbert and Merkens 1961) and to high levels of china clay (Southgate 1960).

Ritchie (1970) hypothesized that the type of gill damage caused by particles in suspension effectively reduces the respiratory surface area. However, there was little in the way of support data provided.

PHYSIOLOGY

Many species of fish have been shown to survive for long periods in highly turbid conditions (EIFAC 1964; Stern and Stickle 1978; Melay 1973, Martin et al. 1984; Brannon et al. 1981), suggesting that compensatory mechanisms may exist which enable fish to survive gill damage.

Randall (1970) hypothesized a "shunt" mechanism, whereby not all of the gill is used for respiration. By using a "reserve surface area," fish may have sufficiently functional, though damaged, gas exchange surface to survive prolonged exposure to elevated suspended solids levels. It is also possible that a functional decrease in gill surface area caused by abrasion and clogging may be offset by compensatory increases in the gas exchange capacity of the blood (O'Connor et al., 1977).

Rates of glycogen mobilization in fish have been used to estimate energy utilization rate during starvation (Beamish 1968; Swallow and Fleming 1969). O'Connor et al. (1977) noted rapid glycogen utilization in hogchokers exposed to fullers earth, and suggested that stress-related compensatory mechanisms resulted in an increased energy requirement. This was supported by studies showing elevated oxygen consumption rates for striped bass and white perch exposed to elevated levels of SS (O'Connor et al. 1977). These results tend to support the hypothesis that sediment-related stress may induce greater energy requirements in fish. However, exact reasons for this are not clear. Elevated energy consumption may be caused by hematological responses (as previously noted), by increased movement and subsequent energy expenditure by fish exposed to highly turbid conditions, or by a combination of the two. Further, as oxygen exchange capacity across the gills is reduced, a greater demand may be exerted on body energy stores (Stern and Stickle 1978).

It has been previously noted that many experimental results show that some fish species which live in habitats characterized by high turbidity levels (eg. demersal or turbidity maxima environs) show a much higher tolerance to elevated levels of suspended solids than do others. However, results from O'Connor et al. (1977) suggest that even tolerant species may be subject to sublethal effects at non-lethal concentrations of SS. For example, the sediment-tolerant hogchoker (LC_{10} greater than 10,000 mg l^{-1}) showed a significant increase in energy utilization during a five day exposure to 1,240 mg l^{-1} fullers earth (O'Connor et al. 1976).

Melay et al. (1973) found that grayling exposed to greater than 300 mg l^{-1} suspended solids showed a much reduced tolerance to a reference toxicant and decreased times to death in sealed jar bioassays (i.e. increased oxygen uptake rates). This suggests that fish may be less tolerant to other environmental contaminants under conditions of high suspended solids. Melay et al. (1973) also found that grayling showed impaired feeding ability, reduced growth rates, downstream displacement, and decreased scope for activity in SS concentration ranging from 100 to 1,000 mg l^{-1}.

BEHAVIOR

Several examples of avoidance of highly turbid waters by fish are described in the literature, although the majority cite freshwater species. Hofbauer (1963, in: Alabaster and Lloyd 1980) noted that the tendency for Barbus barbus to migrate decreased with increasing water turbidity. Summer and Smith (1939, in: Alabaster and Lloyd 1980) observed king salmon to avoid "muddy" water and to enter clean tributaries at the earliest opportunity. These same fish chose "clear streaks" in muddy water in which to spawn.

Concentrations ranging from 27 mg l^{-1} of suspended soapstone particles to 1,500 mg l^{-1} of kaolin have elicited strong avoidance, or "fright," responses on the part of rainbow trout (Guebitz 1966). Strong avoidance responses have also been reported for trout using various concentrations of clay mining wastes (Ingle et al. 1955; Saunders and Smith 1960 in: Stern and Stickle 1978).

Wildish et al. (1977) in laboratory experiments using fine and coarse grained sediments, found that juvenile herring tended to avoid suspended solids at threshhold levels of 13 · 5 mg l^{-1} and 35 · 5 mg l^{-1}, respectively. Additions of 1 ppm PCb or 1 ppm hexadecane did not alter results. Wildish and Power (1985) also tested avoidance behavior for American smelt in a "single fish" laboratory apparatus. They found that smelt spent significantly less time in water bearing a suspended sediment load of 21.8 mg l^{-1} or greater ($p= 0.05$). However, the authors cautioned that while the results indicate that smelt may avoid areas high in suspended solids, extrapolation of laboratory results to the field is difficult because of the apparatus-specific nature of the results and because of the variety of environmental and innate behavioral factors operating in field conditions. Surprisingly, this point is very often not mentioned by other researchers.

Messieh et al. (1981) repeating experiments by Wildish et al. (1977) and using sediment taken from the Miramichi River estuary, found that the threshhold for avoidance by juvenile herring lay between 9.5 and 12 mg l^{-1}. This compared closely with results obtained by Wildish et al. (1977) using sediments taken from the Digdequash Estuary in New Brunswick. Johnson and Wildish (1981) and Wildish and Power (1985) tested the preference/avoidance responses of herring and smelt (respectively) to changes in light intensity. Smelt showed a clear reduction in activity under conditions of reduced (red) lighting, as did herring. Both publications suggest that if a learning process is involved in avoiding sediment suspensions, then suspended sediments would represent the unconditioned stimulus, and that light and possibly other sensory cues would be the conditioning stimuli. Messieh et al. (1981) have stated that the threshhold response concentrations thus determined are probably dependent upon the degree of lighting as well as the geometry of the experimental apparatus, and that the visual cues available to assist learning would be affected to some extent. Because of this, Messieh (1981) also cautions against extrapolating laboratory results to the field. Johnson and Wildish (1981) have suggested that unconditioned stimuli involved in an avoidance response by herring involves both tactile and chemical factors.

Collette and Talbot (1971) noticed that increases in concentrations of suspended solids tended to delay nocturnal-diurnal rhythms for fish inhabiting coral reefs. Changeover activity was delayed and extended when high waves and land-base runoff increased suspended solids levels over the reef. However, such was not the case for all species studied, and the authors suggest that fish which delayed their behavioral rhythms would depend largely on external stimuli for control. Other species not affected by the suspended loading are thought to have activity cycles under endogenous control.

Other behavioral responses to changes in suspended solids levels have been noted. Woodhead (1966 in: Moore 1978) has suggested that since the extent of vertical migration of herring is related to light intensity, changes in water clarity will affect activity patterns. Blaxter and Parrish (1965) also maintain that changes in water clarity will affect the schooling ability of species such as herring and other clupeids using visual schooling cues. Similarly, Reintjes and Pacheco (1966) have noted that school size in menhaden varies with turbidity. Presumably, sight-dependent schoolers lose track of each other when water clarity is reduced.

From this, one may infer that a consequence of increased sediment loading in the water column will be decreased effectiveness of fishing gear when the target species relies primarily on vision to either school or locate prey. For example, decreases in the size of herring or capelin shoals will detrimentally affect the catch per unit of effort of seining or stern and side trawling operations. However, this may be offset in part by a decrease in the ability of such fish to avoid fishing gear in turbid waters. Murphy (1959, in: Moore 1978) showed that numbers of albacore (a visual predator) taken by trolling were greatly reduced under turbid conditions. He also noted that catches of albacore taken by gill net in turbid waters increased when compared to catches from clear water.

A further implication of the effect of suspended solids on fishing success is avoidance of affected waters by some species. In Turkish waters, the disappearance of mackerel was attributed to the presence of dredge spoil in the Sea of Marmara, a primary spawning area for the species (G.F.C.M., 1972: in: Moore 1978). In the Miramichi estuary in New Brunswick, several successful claims were made by local trap net fishermen for losses attributed to a major channel dredging project. Given that trapnets should work better in turbid waters, any noted decreases in catch in the latter case may be owing in part to disruptions in schooling behavior and/or outright avoidance response by gaspereaux, tomcod, and smelt. Shelton (1973) presented data showing the avoidance of a china clay disposal site in the U.K. by herring juveniles and sprat.

However, it seems clear in some cases that not all fish avoid highly turbid waters, at least over the short term. Ritchie (1970) found no gross physical effects of shallow water overboard spoil disposal in Chesapeake Bay on 44 species of fish sampled, and no changes in catch rates attributable to disposal activities were detected.

Ritchie (1970) also caged several species of fish in the vicinity of a dredge disposal effluent pipe and was unable to separate cage-related mortality from mortality caused by suspended solids. However, no damage to gill epithelia was noted during subsequent post-mortem examination.

Similarly, Ingle (1952) found no mortality of fish or motile shellfish at a dredging site in Mobile Bay, Alabama. In the same field study, no net migration away from the site was detected. Similar findings were presented by Saila et al. (1968) from field investigations at a sediment dumpsite in Rhode Island Sound.

INVERTEBRATES

INTRODUCTION

The largest single cause of mortality in invertebrates associated with sediments is attributable to the effects of sediment deposition, and not from suspended solids per se. The most obvious effect of deposited sediments is that of smothering non-motile species. Another major effect is that of delaying or prevention of larvae settlement through substrate alteration. A sampling of relevant publications is as follows: Brever, J.P. (1962); Buelow, R.W. (1968); Butler, P.A. (1965); Bybee, J.R. (1969); Chapman, C. (1968); Chesapeake Biological Laboratory, (1970); Copeland, B.J. and F. Dickens (1969); Dodgen, H.D. and Baughman, J.L. (1949); Flemer, D.A. et al. (1968); and Lunz, G.R. (1942).

The remainder of this text describes influence of suspended particles on invertebrates. With a few exceptions, these effects are of a sublethal variety only.

Several publications discuss the effects of suspended solids on the rate of feeding in bivalve molluscs. Feeding in suspensions has been estimated by measuring pumping (or water clearance) rates, and/or the production of feces. Pseudo-feces production has been measured in an effort to determine the clearance rate of inorganic particles by a given animal (Loosanoff and Tomers 1948; Loosanoff 1961; Gustofson 1972; Lund 1957; Chiba and Oshima 1957).

Different species of bivalves respond differently under similar suspended solids regimes. Part of the reason is that pumping rates of some species are dependent upon food particle size and concentration, whereas others pump water at rates independent of particle size or concentration. Also worth mentioning is the fact that very often an animal will increase water pumping rates in response to increased suspended particle concentrations regardless of the nutritional value of the particles presented.

BIVALVES

Loosanoff and Tommers (1948) observed an 80 to 94% reduction in the pumping rate of oysters exposed to concentrations of silt, kaolin, and powdered chalk ranging from 250 to 4,000 mg l^{-1} for durations of up to six hours. Loosanoff (1961) found that while small concentrations of natural silt, kaolin, and Fullers earth often stimulated pumping rates in Crassostrea virginica and Mercenaria mercenaria, rates were significantly reduced for both species at concentrations greater than 100 mg l^{-1}. That a slow down in pumping, with eventual cessation, occurs at increased levels of SS is supported by Gustofson (1972), who found that Mya arenaria ceased water clearance altogether after five days in a turbidity regime 20 times above ambient.

However, pumping rates may not in fact be the best variable to measure in such experiments. Lund (1957) has suggested that the quantitative measurement of castings, or (pseudofeces), is a more reliable measure of feeding than water propulsion because pumping may continue after feeding has stopped.

Chiba and Oshima (1957) found that the pumping rates of four species of bivalves (Venus semidecussata, M. meretrix, Crassostrea gigas and Mytilus edulus) were not reduced in concentrations of bentonite up to 1,000 mg l^{-1}. However, V. semidecussata and Mya meretrix increased the production of pseudofeces, while true feces production did not increase at higher concentrations. Jorgensen (1955), in a discussion of the quantitative aspects of filter feeding in invertebrates, concluded that pumping rates in lamellibranchs are independent of particle concentration only when small (normal) amounts of SS are present; at higher levels, lamellibranchs decrease pumping rates.

Moore (1978) suggests that since turbidity in nature is primarily due to clay-sized particles, and since it seems that many lamellibranchs are unselective of nutritious particles, then food value (sic) may be diminished in some cases in proportion to the inorganic constituents, with corresponding reductions in individual weights or growth rates. There may also be utilization of stored energy reserves to maintain a basal metabolic rate when the ratio of food to inorganic particles is low. Winter (1972) suggested that weight loss may also be attributable in part to the increased production of pseudofeces, which represent a further drain on energy reserves.

Pratt and Campbell (1956) found that growth rates of Mercenaria mercenaria were reduced in sediments with a high silt-clay content. They suggested that lowered growth rates were a function of the additional expenditure of energy required for frequent clearing of the feeding apparatus. Similarly, Stone et al. (1974) found that scallops and quahogs increased mucus production when clearing gills of kaolin, and suggested that increased production of mucus resulted in the utilization of stored energy reserves which would normally be used for other functions such as gametogenesis.

In field observations, Barnett (1973 in: Moore 1978) noted that the body weight of Tellina tenuis was reduced in warmer waters owing to an increased metabolic rate. The body weight was further reduced during an interval when suspended solids were increased.

That a relationship exists between particle size fraction and effects on lamellibranch feeding was documented by Jorgensen and Goldberg (1953), and Jorgensen (1955), who reported that oysters filtered and cleared graphite particles in the 2-3 μm size range 5 to 10 times faster than particles less than 2 μm in size.

Laboratory experiments confirm that a wide range of sensitivities to suspended solids exists among different bivalve species. Peddicord et al. (1975), found that Trapezium japonica showed no mortality after 10 days in 100,000 mg l^{-1} kaolin, but that Mytilus edulis averaged 10 percent mortality for two age cohorts after 5 and 11 day exposures at the same concentrations. In the same set of experiments, they found the 200 h LC_{50} for M. californianus to be 96,000 mg l^{-1}. Hughes (1969) found that V. mercenaria, M. edulis and Cardium edule, all relatively clear water species, were characterized by high pumping (water clearance) rates. He contrasted this with Scrobocularia plana and Mya arenaria, both of which exhibit relatively low pumping rates per unit of gill area and utilize the layer of water at the (fine) sediment-water interface, characterized by higher levels of SS. However, Hughes failed to account for the exploitation (in some cases) of relatively highly turbid environments by Mytilus edulis. Further, finely divided particles tend to be hydrodynamically stable, thus (possibly) negating the suggestion that relatively higher turbidities persist at some sediment-water interfaces such as tidal flats.

Jorgensen (1966) has suggested that in some cases morphological differences may play a role in determining individual species tolerance levels and thus habitat selection. For example, oysters of the genus Crassostrea inhabit inshore waters which are often typified by high suspended silt concentrations. Ostrea species, on the other hand, frequent waters which are relatively clear. Jorgensen (1966) suggests that these organisms may exploit different environments because of fundamental differences in body plan. In Crassostrea species, the right mantle lobe is separated from the visceral mass forming a promyal chamber. The chamber increases the volume of water which can be introduced into the dorsal part of the mantle cavity. The water may then be used for cleansing a portion of the mantle cavity through contraction of the adductor muscle. In *Ostrea* species, the animals are much more vertically compressed. The narrower parts of the dorsal mantle may therefore be more susceptible to particle accumulation, since relatively little water is available for flushing (Elsey 1935; Yonge 1960).

TEMPERATURE AND OXYGEN

Peddicord et al. (1975) subjected *M. edulis* to several temperature and dissolved oxygen regimes in varying concentrations of bentonite. A greater mortality was observed at higher temperatures, and the authors suggested that although the animals remained closed during the initial stages of the tests, a higher metabolic rate at higher temperatures forced the mussels to open sooner, thus increasing the time period during which the gills were exposed to suspended particles.

Peddicord et al. (1975) noted that *M. edulis* lose byssal attachments in suspended bentonite after substantially shorter exposure times than those causing significant mortality. Low dissolved oxygen concentrations have also been shown to result in the loss of byssal attachments (Reish and Ayers, 1968). Peddicord et al. (1975) have suggested that the loss of byssal attachments may be an early indicator of effective death.

DREDGING AND DUMPING

Much of the work on marine and estuarine bivalves concerning the effects of suspended material has consisted of field studies in the vicinity of dredging and dumping activities. Lunz (1938 *in*: Moore 1978) noted no mortality among American oysters adjacent to a dredge site off the coast of Florida, nor was the dredging activity believed to have affected subsequent spawning or larvae settlement. Mackin (1956) studied the effects of dredging on oysters over a three year period and found that mortality actually decreased as turbidity increased. However, results were variable and were believed to be dependent at least in part to differences in salinity regimes. Mackin (1956) also tested feeding in oysters in the laboratory and noted no change up to 700 mg l^{-1} suspended sediment.

Ingle (1952) observed oysters in suspended baskets adjacent to an operating dredge and did not find significant mortality rates. It was suggested that organic particulate matter in the resuspended sediment actually enhanced feeding and growth in this particular case. Exploitable quantities of shrimp appeared to be attracted to the immediate area of dredging as well.

Flemer et al. (1968) could detect no adverse affects on benthic invertebrates at a dredge site in Chesapeake Bay, beyond that of smothering of some species in the immediate disposal area. Neither species diversity nor biomass were affected outside of a 550 meter radius, and re-population within the area began soon after deposition occurred.

White et al. (1968, *in*: Sherk and Cronin 1970) conducted a literature review and found no reported adverse (physical) effects on marine biota from dredge-related SS excepting reduced pumping rates in oysters and oyster mortality caused by complete burial. However, Wilson (1950, *in*: Sherk and Cronin 1970) found that dredged "beach material" in concentrations from 4,000 to 32,000 mg l^{-1} were detrimental to oyster growth and eventually resulted in death. This may have been due in part to coarser sand grains with increased angularity predominating in the beach material (reviewers' note). No effects were noted on animals beyond 275 meters of the site.

Pfitzenmeyer (1970, in: Chesapeake Biological Laboratory 1970), during a three year study of benthic populations in the vicinity of a dredge site in Chesapeake Bay, noted a 71% reduction in the number of animals per unit area, and a 65% reduction in benthic biomass in the area. Levels returned to normal within one and a half years. However, direct sedimentation was undoubtedly the primary causative agent, with highly turbid waters near the bottom perhaps contributing, but to an unknown extent.

From the foregoing, it appears that ample evidence exists suggesting that adult bivalves also survive suspended sediment loading at levels far in excess of those commonly observed in nature, at least for relatively short time periods. It also appears that suspended sediments from dredging activities may not have detrimental impacts upon adult bivalves in the short term.

INVERTEBRATE EGGS AND LARVAE

David (1960) subjected eggs and larvae of *Mercenaria mercenaria* to suspended clay, chalk, Fuller's earth and silt at levels up to 4,000 mg l^{-1}. Eggs developed normally (no significant difference from controls) in silt at levels up to 4,000 mg l^{-1}. Eggs developed normally (no significant difference from controls) in silt concentrations up to 750 mg l^{-1}, but beyond this normal development decreased. No eggs developed normally during 48 h exposures beyond 3000 mg l^{-1}. Clam larvae were observed to cease growing at concentrations exceeding 250 mg l^{-1} chalk and 500 mg l^{-1} clay and Fuller's earth. Beyond these levels, mortality exceeded 90%. Experiments employing natural silt showed that growth rates of exposed larvae exceeded those of controls at levels up to 750 mg l^{-1}, at which point growth rates were equal. Growth rates were decreased by silt concentrations between 1,000 and 2,000 mg l^{-1}, and no growth occurred at 3,000 and 4,000 mg l^{-1}. No significant larval mortality occurred in any of the treatments.

Millar and Scott (1968) noted that the growth of *Ostrea edulis* larvae was faster in water pretreated with (so-called) adsorbing agents (e.g. Fullers earth, magnesium trisilicate). The suggested reason was that these substances chelated toxins (such as microbial waste products) and removed them from the water. Because of this, the authors suggested that such adsorbants should be used as a treatment process to remove toxins from algal or microbial blooms in continuous culture systems to eliminate seasonal inhibition of bivalbe larval growth.

Davis and Hidu (1969) conducted similar experiments using eggs and larvae of American oysters (*Crassostrea virginica*), European oysters (*Ostrea edulis*) and quahogs (*Arctica islandicus*). They found a significant decrease in the number of normally developing oyster eggs in concentrations of silt exceeding 188 mg l^{-1}. Similarly, decreased normal development occurred at 3,000 mg l^{-1} and 4,000 mg l^{-1} kaolin and Fuller's earth respectively. Survival of European oyster larvae were found to be less affected by silt, kaolin, and Fuller's earth suspensions than were larvae of the American oyster and quahog.

In tests using suspensions of silicon dioxide particles, Davis and Hidu (1969) found that particles of less than 5 microns in size had the greatest deleterious effect on survival and growth of clam and oyster larvae. Davis and Hidu (1969) also found that the growth of European oyster larvae was less affected by kaolin and Fuller's earth than were the other two species, but were more strongly affected by natural silt. Bivalve larvae were seen to grow faster in low concentrations of suspended particles than in clear sea water.

Davis and Hidu (1969) also noted that many clam larvae eventually lost their ability to reject smaller particles of kaolin and Fullers earth. The stomach eventually became packed, and the larvae died. Both American and European oyster larvae were better able to reject smaller particles, and showed correspondingly lower mortalities.

A previous experiment by Loosanoff (1961) found that concentrations of 250 mg l^{-1} silt adversely affected egg development in C. virginica. Similarly, M. mercenaria egg development was retarded at silt concentrations greater than 2000 mg l^{-1}. Oyster larvae growth was significantly affected at a lower concentration of silt (750 mg l^{-1}) than clams (2000 - 3000 g l^{-1}). Oyster larvae were, however, less affected by kaolin suspensions (1000 to 2000 mg l^{-1}) than were clam larvae (500 mg l^{-1}).

Harrison and Farina (1965) observed egg laying and development in three species of gastropods exposed to elevated levels of suspended solids. Although freshwater species were used (L. natalensis, B. globosus and B. pfeifferia), it is worth noting that similar responses to high SS were observed, along with markedly different sensitivities between species. For example, L. natalensis developed normally up to 360 mg l^{-1} while B. globosus suffered high mortalities in the 190 to 360 mg l^{-1} range. B. pfeifferia layed eggs in 190 mg l^{-1}, but layed none in 360 mg l^{-1}.

From the foregoing it can be seen that a great range of tolerances to suspended particle concentrations have been observed for eggs and larvae, both between species and between particle types. A less-than-clear picture of the effects of suspended solids on eggs and larvae emerges from the literature. However, general statements can be made to the effect that eggs and larvae are more sensitive to inorganic suspensions than are adults of the same species. Similarly, suspended solids adversely affect egg development, and larvae are generally affected through their inability to feed successfully beyond threshold concentrations of suspended solids.

CONCLUSIONS

High concentrations of suspended solids have the potential to adversely affect marine and estuarine fish and shellfish. This is especially true when suspended particles are highly angular, when particularly sensitive species are present, when an abundance of larvae is present and when water temperature is high and oxygen concentrations are correspondingly low. Resuspended sediments high in organics have the potential to greatly reduce oxygen concentrations over the short term, particularly in shallow, poorly flushed areas.

The Ocean Dumping and Dredging review process currently assesses applications based on a number of factors, including contaminant concentration, particle size distribution and site specific geography and use patterns. However, it is currently not common practice to examine spoil or dredge material for particle angularity. It is recommended that an attempt be made to develop criteria by which the abrasive potential of materials may be evaluated. In particular, dredge and spoil material should be examined for diatomaceous components and for relatively unweathered crystalline fractions.

Currently, (RODAC) reviews conducted by the Regional Ocean Dumping Advisory Committee routinely consider flushing rates at a proposed dredge or dump site. This is particularly important given the potential for high levels of BOD in shallow, low energy environments such as estuaries, and should be given special attention.

Reviewers should also pay special attention to the presence (or absence) of fish or invertebrate larvae at a proposed site. Of particular importance are estuaries which serve as major nursery or rearing areas. Dredging and dumping activities should be timed to avoid critical periods. Dredging and dumping activities should be timed so as not to correspond with the presence of large numbers of visually-dependent schoolers such as herring, mackerel, smelt or gaspereaux. Peak arrival times for such species are usually predictable and of short duration, and should not be difficult to "work around."

Evidence from the Mirimichi dredging program showed that dumped material was resuspended by storm events up to several months after the program was completed. Dumpsites should ideally be selected where resuspension is unlikely to occur. However, efforts to find a solution to resuspension problems are not always straightforward. Suitable dumpsites need to be either sheltered and poorly flushed, in deep water, or terrestrial. However, BOD is a problem in poorly flushed water, and the latter two dumpsite categories are not always viable options because of economic or logistic limitations.

Whenever probable, dredging and dumping activities should be timed to avoid periods of peak invertebrate larval occurrence, including periods of bivalve "spatfall."

Dredging and dumping activities should not be carried out close to aquaculture emplacements. Actual distance restrictions should be based upon local current patterns, the material to be deposited, time of year, and site-specific flushing rates.

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Table I. Critical transportation velocities for particles of various sizes (from: Stern and Stickle, 1978).

Particle	Mean diameter (mm)	Current velocity (m/sec)
Clay	0.004	0.08
Sand	0.5	0.28
Granule	4.0	0.63
Pebble	7.0	0.86
Gravel	54.0	1.62
Boulder	409.0	4.87

Table II. Volumes of dredge material (Canada) approved through the Ocean Dumping Control Act, 1979-1984.

Year	Volume (metric tons)
1976	5.7
1977	5.1
1978	11.0
1979	19.6
1980	17.9
1981	14.0
1982	11.6
1983	6.5
1984	6.9

Table III. Summary of experimental results of: Lethal Effects - Fish.

Species	Parameter	Test mg l^{-1}	Result	Reference
Apeltes quadracus	24 h M	glass powder/10 mg l^{-1}	100% M	Rogers (1969)
Apeltes quadracus	24 h M	diatomaceous earth/10 mg l^{-1}	100% M	Rogers (1969)
Apeltes quadracus	24 h M	glass spheres/10 mg l^{-1}	low % M	Rogers (1969)
Apeltes quadracus	24 h M	powdered charcoal/10 mg l^{-1}	low % M	Rogers (1969)
Tautogolabrus adspersus	M	grain size (g.s.)	M g.s.	Rogers (1969)
A. quadracus	M	grain size	M g.s.	Rogers (1969)
Fundulus heteroclitus	M	grain size	M g.s.	Rogers (1969)
Eleven Estuarine Spp.	M	140,000 mg l^{-1} Kaolinite	0% M	O'Connor et al. (1976)
Eleven Estuarine Spp.	M	6,500 mg l^{-1} Fullers Earth	Significant M	O'Connor et al. (1976)
Sixteen Estuarine Spp.	M	Up to 75,000 mg l^{-1} Montmorillonite	0% M	Wallen (1951)
Atlantic Silverside	LC_{50}	Fullers Earth	2400 mg l^{-1}	O'Connor (1976)
Bay Anchovy	LC_{50}	Fullers Earth	4710 mg l^{-1}	O'Connor et al. (1976)
White Percy	LC_{50}	Fullers Earth	9850 mg l^{-1}	O'Conner et al. (1976)
Mummichog	LC_{50}	Fullers Earth	39,000 mg l^{-1}	O'Connor (1976)
English Sole	10 day M	Bentonite	0% M at 70,000 mg l^{-1}	Peddicord et al. (1975)
English Sole	10 day M	Bentonite	80% M at 117,000 mg l^{-1}	Peddicord et al. (1975)
Spot	24 h LC	Natural Sediment	88,000 mg l^{-1}	O'Connor et al. (1976)
White Perch	24 h LC	Natural Sediment	9,850 mg l^{-1}	O'Connor et al. (1976)
Stickleback	4 day M	28,000 mg l^{-1} Contaminated Harbour Sediment	0% M	Le Gore and DesVoigne, 1973
Coho Salmon fry	4 day M	28,000 mg l^{-1} Contaminated Harbour Sediment	0% M	

Key:

M = mortality
LC_{50} = Concentration at which 50% mortality occurs
S = significant

Table IV. Summary of lethal effects, fish eggs and larvae.

Species	Parameter	Test	Result	Reference
Bluefish J	M	SS	SM below 1000 mg l^{-1}	O'Connor et al. 1977
Menhaden J	M	SS	SM below 1000 mg l^{-1}	O'Connor et al. 1977
White Perch J	M	SS	SM below 1000 mg l^{-1}	O'Connor et al. 1977
Yellow Perch E	hatching success	natural sediment	No S up to 500 mg l^{-1}	Schubel and Wang, 1973
White Perch E	hatching success	natural sediment	No S up to 500 mg l^{-1}	Schubel and Wang, 1973
Striped Bass E	hatching success	natural sediment	No S up to 500 mg l^{-1}	Schubel and Wang, 1973
Alewife E	hatching success	natural sediment	No S up to 500 mg l^{-1}	Schubel and Wang, 1973
White Perch E	hatching success	natural sediment	No S up to 1,500 mg l^{-1}	Morgan et al., 1973
Striped Bass E	hatching success	natural sediment	No S up to 1,500 mg l^{-1}	Morgan et al., 1973
White Perch J	48 h LC_{50}	natural sediment	3,411 mg l^{-1}	Morgan et al., 1973
Striped Bass J	48 h LC_{50}	natural sediment	2,679 mg l^{-1}	Morgan et al., 1973
Blueback Herring E	hatching success	natural sediment	No S up to 1000 mg l^{-1}	Auld and Schubel, 1978
Yellow Perch E	hatching success	natural sediment	No S up to 1000 mg l^{-1}	Auld and Schubel, 1978
Alewife E	hatching success	natural sediment	No S up to 1000 mg l^{-1}	Auld and Schubel, 1978
American Shad E	hatching success	natural sediment	No S up to 1000 mg l^{-1}	Auld and Schubel, 1978
White Perch E	hatching success	natural sediment	No S up to 1000 mg l^{-1}	Auld and Schubel, 1978
Striped Bass E	hatching success	natural sediment	No S up to 1000 mg l^{-1}	Auld and Schubel, 1978
Striped Bass J	M	natural sediment	SM at 500 mg l^{-1}	Auld and Schubel, 1978
Yellow Perch J	M	natural sediment	SM at 500 mg l^{-1}	Auld and Schubel, 1978
American Shad J	M	natural sediment	SM at 100 mg l^{-1}	Auld and Schubel, 1978

Key:

J = juveniles
E = eggs
S = significance
M = mortality
LC_{50} = Concentration at which 50% mortality occurs