International Council for the Exploration of the Sea

CM 1996/E:26
Marine Environmental Quality Comitte

Effects of suspended sediments on cod egg and larvae and on the behaviour of adult herring and cod

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Abstract

The avoidance behaviour of cod and herring to dredging-induced turbidity and the effects of sediment plumes on the buoyancy and mortality of cod egg and larvae have been studied as part of the EIA of the Öresund Link project. The avoidance threshold to suspended sediments of glacial clay or limestone origin was studied in a 15*6 m saltwater flume and was found to be approximately 3 mg/l (or 5 NTU) both for herring and cod. Experiments with cod in the dark showed a similar threshold and the avoidance seems to have an important non-visual component. Exposure of cod eggs to sediment suspensions showed that adhering particles gave a loss of buoyancy which was proportional to the sediment concentration and the exposure time, amounting to 0.02 psu/hour, mg/l. This means that the process can make the eggs sink to the bottom even at relatively low sediment concentrations. Yolk-sack larvae showed an increased mortality on exposure to sediment concentrations of 10 mg/l. The sensitivity to lime particles was higher than to clay.

Keywords: avoidance-reaction, cod, egg-buoyancy, herring, sediments, turbidity.

Introduction

The sea-bed extraction of marine aggregates and the dredging, transport and dumping of sediments related to marine construction work have several adverse environmental effects. One of those is the suspension of fine sediments in the water column, which can spread over large areas. The turbidity in such plumes will affect the primary production by shading (Bach 1992) and increased sedimentation can disturbe the benthic communities (Kenny and Rees 1994 and 1996). The sediment plumes can also have an impact on the fishery through avoidance or decreased gear efficiency due to sediment deposition.

The Öresund Fixed Link project - the construction of a combined bridge and tunnel between Malmö and Copenhagen in the southern Sound - involves the dredging of 7 milj. m^3 of glacial deposits and limestone of Danian age during the approximately 4 year long construction period which started in 1996. The total spillage will be kept below 5 % for the operation as a whole, but the effects of the spreading of sediments is a major environmental concern. The dispersion of turbid water and the effects on macrophytes and benthos is monitored in a comprehensive measurement and modelling program (Anon. 1994). For the effects on fish and fishery two areas of key interest have been subjects to special studies that will be presented here: The avoidance of adult fish from the sediment plumes and the buoyancy effects of sediment adhesion to pelagic fish egg and larvae.

Fish avoidance from areas with suspended sediments is well known to fishermen in the area, the general phenomenon has been reviewed by Moore (1977) and by Appleby and Scaratt (1989). The fishery in the Sound depends mainly on cod and the deeps in the central Sound is an important cod spawning area. A particular concern however is the possible effects on the over-wintering and migration of Rügen herring (Nielsen 1995). Large concentrations of this commersially very important stock are found in the Sound from September to March. During the early spring this herring will pass through the dredging areas on it's spawning migration to the southern Baltic. Little is known about the return migration in the late spring but this probably also takes the route through the Sound. In the southern part of the Sound there are two alternative passages - east or west of the island Saltholm - and the intention is that the dredging operation shall be managed so that sediment plumes never will block both passages simultanously. The quantitative knowledge about avoidance thresholds to sediment suspensions is however limited. Johnston and Wildish (1981) have studied juvenile herring in the laboratory and found a threshold of approximately 10 mg/l, but it was unclear to what extent this threshold was specific to the particular sediment type used in the experiments. No data was available for cod or any other of the main commersial species in the Sound. To get information which was relevant for the kinds of sediment that will be emitted in the Sound experiments were made in a large outdoor saltwater flume whith cod and herring of the Rügen stock.

The deep basins north and south of the island Ven are important spawning grounds for cod, plaice and flounder; all having pelagic eggs. The low salinity of the Baltic water in the surface layer means that the eggs sink and concentrate in the halocline (Westerberg 1994). The deep water in the Sound is of Kattegatt origin and varies widely in salinity; roughly from 18 to 34 psu. Typically the exess buoyancy that keep the pelagic eggs from sinking to the bottom corresponds to only 8 psu. Evidently a deposition of sediment particles on the eggs during the 20-40 days hatching period may result in such a loss of buoyancy and an almost certain mortality due to predation at the bottom. This effect has not been studied before and laboratory experiments using cod eggs were made to quantify the process. Earlier studies have shown that the direct effects of sediment deposition on the excange of oxygen and excretion products are more pronounced for larvae than eggs (Appleby and Scaratt 1989, Auld and Schubel 1978). Experiments were also made to study the mortality of yolk-sack cod larvae at different sediment concentrations.

Methods

Avoidance behaviour

The avoidance studies were made in a large saltwater flume constructed from two adjacent, concrete aquaculture raceway basins at an experimental facility in Ringhals at the Swedish Kattegatt coast. The raceways were 15*3 m large with a depth of 2 m. The separating wall was removed along half the length, creating a 6*6 m arena with two approximately 8 m long entrance channels in one end of the flume (see Figure 1). At the end of each channel salt water was pumped at approximately 500 l/min into vertical, 30 cm diam. pipe with several small nossles at different depths. The jets from the nossles were directed towards the end-wall of the channel and splitting plates were placed to further create a thorough mixing of the incoming water. Approximately 2 m downstream from the inlet a honycomb was built by stacking 10 cm diam. tile pipes. This arrangement dampened the larger eddies very efficiently and the flow in the channels and arena was relatively homogenous and smooth, without large-scale turbulence. A high concentration sediment suspension could be added to one or the other of the inlet pipes using a peristaltic pump with variable volume flow. The stock suspension was kept well-mixed in a 1 m^3 holding

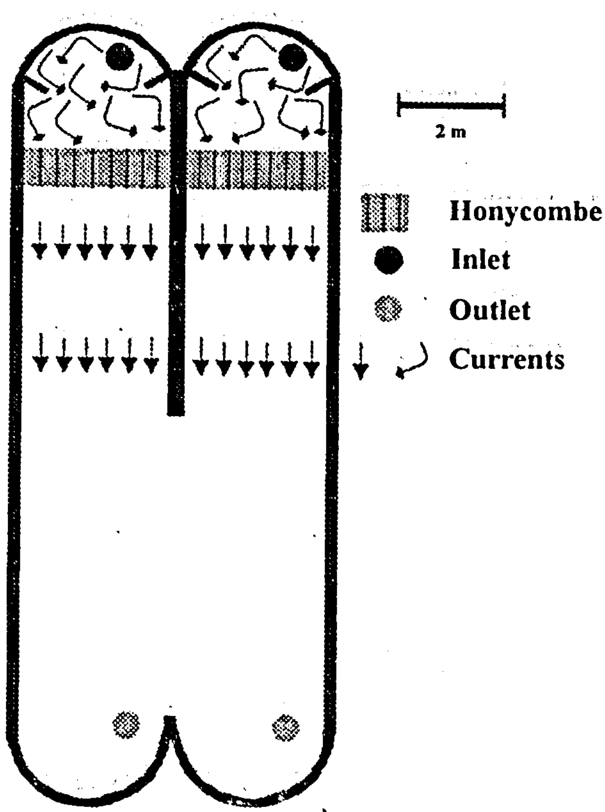


Figure 1. Sketch of the flume used for the avoidance behaviour experiments.

tank adjacent to the flume. The sediment concentration in the flume was varied between experiments by changing the stock concentration or the dose rate. The mean velocity in the flume was approximately 1/3 cm/s at a water depth of 1 m and it took about 20-30 minutes to establish a sediment plume that covered the whole of one side of the flume. Normally a distinct, nearly vertical, separation developed along the middle of the 6*6 m arena.

The behaviour of the fish was monitored from an observation platform placed 3 m above the arena, where the observer had a free view of the whole flume. The observation procedure was based on registrating the position of the shoal of fish every 15:th second continuosly during 20 minutes. The position was given in 3 approximately equal divisions on each side of the central line of the flume. If the fishes were split up in several groups the percentage of the total was noted for each occupied division. One such 20 minutes observation was made prior to starting the addition of sediment suspension. When the plume was established in the whole length of the flume another 20 min. observation period was made. The sediment side was choosen at random for each experiment. To keep external disturbances to a minimum the observer climbed up in the observation tower 30 min. before the start of the first observation period and stayed there to the end of the experiment. A maximum of two trials were made each day.

The experiments were made during the period November 1995 to February 1996 using cod and herring. The cod were caught with fyke nets and brought slowly, in steps, to the surface to avoid rupturing the swim-bladder. A group of 20 fishes were allowed to acclimatize in the flume during 2 weeks prior to the start of the experiments. They were fed daily with mussles or herring after the end of the days trials. Herring was captured with set-nets that were left out for a very short time directly at the place of shoals localized with an echosounder. The herring were shaken loose directly into a waterfilled container without manual handling and brought rapidly to the flume, where they were allowed to acclimatize for 2 weeks. During this time several of the herring with injuries from the net died but the mortality among the remaining, approximately 40, individuals that participated in the experiments was low. The herring fed on the plancton coming with the continous flow trough the flume.

As a measure of avoidance the quotient (T), between the amount of time that the fish spent on the sediment side during the second observation period and the time spent on this side of the flume during the first period, was used. This quotient (multiplied by 100) is in a sense the relative time spent in the sediment exposed water and has an expected value of 100 if the fish behaves randomly and becomes 0 at total avoidance. Ten "blank" experiments without sediment addition were made to establish the natural variability of T. From those experiments the mean T_o and the standard deviation σ_T of the undisturbed condition were calculated and an avoidance reaction was defined as an observed T-value which deviated more than $2*\sigma_T$ from T_o. The actual sediment concentration, salinity and temperature in the flume was measured with a HydroLab Datasonde 3 turbidimeter immediately after the second observation period. The plume concentration was put as the mean of 12 different fixed measurement points spread over the sediment side and at different depths. The turbidity on the clear side was also registred. For some experiments with low concentrations a 30 cm beam attenuation meter was used. This instrument as well as the sond turbidimeter were calibrated both with the sediment suspensions used and with a formazine standard.

Table 1. T-values from 10 control experiments without sediment addition and their mean and standard deviation.

Cod	107,9	68,1	140,7	83,6	102,8	106,9	93,1	91,1	108,4	93,6
Herring	89,6	101	102,9	105,8	96,6	96	102,3	105,6	69,8	98,1

	T_o	σ_T
Cod	99,6	19,1
Herring	96,8	10,7

A series of experiments with cod were made in the dark. To allow observations of the position of the fish five individuals were tagged with a 2*20 mm fluorescent ampulla (Starlite® micro). The ampulla was attached with a piece of rubber tube to a Floy tag that was fastened at the base of the dorsal fin. This tag gave a faint glow which was visible during two nights and could easily be replaced without removing the tag.

Eggs and larvae

The experiments with egg buoyancy were started in June-July 1995 and continued during the spawning season June-Juli 1996 at the laboratory at Ar in northern Gotland. Eggs were obtained from adult cod held in spawning basins at the laboratory. Most of the spawners were of the northern Baltic stock but some originated from the Arkona basin and the Sound also. All experiments were conducted in cold chambers, held at a constant + 7 °C. The incoming sea water was filterd in a 0.2 µm Cartridge filter and held a salinity of 7 psu. Higher salinities were made by adding syntetic sea-salt (Marinemix®).

Two types of sediments dominate in the dredging operation in the Sound - a glacial clay and the so called Copenhagen limestone. Those sediment types were used both in the avoidance experiments above and for the egg studies. Clay samples were obtained from the dredgings at the Kastrup peninsula. The coarser fractions were removed with a 38 µm sieve. This leaves a suspension which approximates the particle content in a plume which is about half an hour old and, at the characteristic current velocities in the area, has travelled 500 m to 1 km from the dredging site. The lime was a commersially available ground product, "Faxe miljöfiller", based on Copehagen limestone. This was also passed through the 38 µm sieve before preparing the experimental solutions.

The change of egg buoyancy was measured in glass cylinders prepared with a linear salinity gradient as described by Combs 1981. The 65 cm high gradient coverd the interval 11 to 27 psu and was prepared using high and low salinity water that both had the sediment concentration to be tested. In each column 30 eggs were allowed to settle. To keep the sediment concentration at a quasi-steady concentration a 15 cm thick layer of sediment suspension in fresh water was added above the salinity gradient. This layer was replaced tree times each day at the same time as the equilibrium level of the eggs was recorded. The initial buoyancy of the eggs varied between 13 and 15 psu. A blank experiment was run in parallell so that a correction could be made for the natural egg buoyancy change with time (Nissling and Vallin 1996).

The sediment samples that were used contains fractions of all particle sizes below 38 µm and those will settle with different velocities. With the 15 cm thickness of the top layer and with the replacement scheme that was used particles less than 1.75 µm (which amounts to 50-65 % of the total concentration) will form a continous rain through the salinity gradient. Coarser particles will fall through the system in intermittent "showers", the duration varying with size. Using the known size distribution and replacement schedule a time integrated mean concentration was calculated for each experiment and this is the value used in presenting the results.

The mortality of eggs and larvae was studied in recirculating sediments suspensions at the salinity 17 psu. The apparatus was a 1100 ml cylinder with a conical bottom. The drain was at the apex of the cone and was covered with a fine-meshed net to avoid circulating the eggs. The inlet was at the top of the cylinder and the trough-flow was 400 ml/minute. To supress the growth of organisms 0.1 g/l doctacillin, 0.05 g/l streptomycine and 2500 IU/l mycostatin was added. The sediment suspension was replaced two times per day to compensate for the sedimentation in the apparatus. The variation of concentration with time was measured by taking water samples that were filtered on 0.7 µm Whatman HF filters and weighted. The concentration which was assigned to the experiment is one which was representative for about 80 % of it's duration. The number of eggs or larvae that were used in each experiment was 100. The initial age of the eggs varied but all experiments with larvae started with newly hatched yolk-sack larvae and the duration was limited to 6 days, before the yolk-sack was depleted. Dead eggs could be readily identified but it was difficult to discriminate between larvae that were in bad condition or dead. A sharp bend on the vertebrate column was used as a definition of a dead larva which probably means that the mortality was underestimated.

Results

Avoidance

A total of 35 trials were made with the group of cod during December and January. The length of the fish was 28 ± 4 cm and the weight 200 ± 100 g. The water temperature varied between -0.4 and +6.2 °C and the salinity between 22.5 and 25.4 psu.

The results of the experiments performed in daylight are summarized in Figure 2. There is a fairly distinct avoidance threshold around 3 mg/l both for clay and lime suspensions. The dottet line is manually fitted to show the variation of T with the sediment concentration.

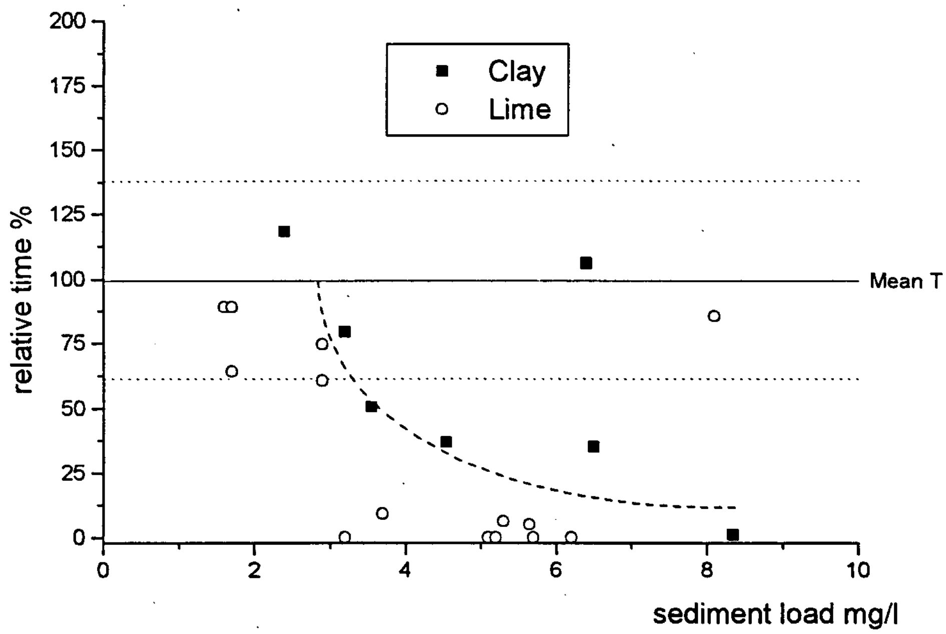


Figure 2. The relaive time spent on the sediment side as a function of the mean particle concentration in the plume for cod tested in daylight. The dotted lines show a 95% confidence interval for the mean of the control experiments.

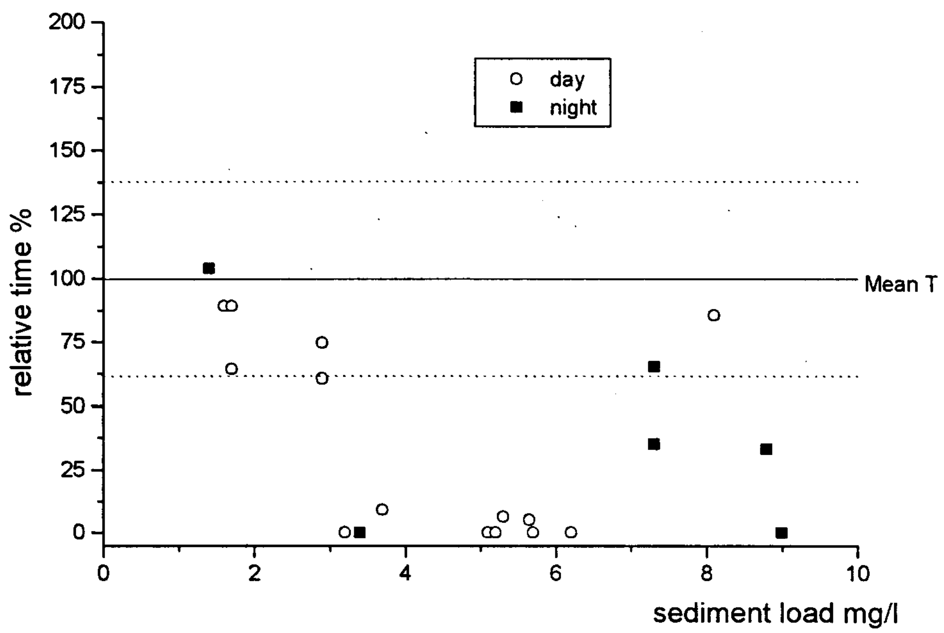


Figure 3. Comparison of cod behaviour to a plume of lime particles in daylight and at night.

The night-time observations are shown in Figure 3. The number is limited and it is difficult to make a precise estimate of a threshold value. One experiment shows a complete avoidance at 3.5 mg/l which indicates that the threshold could be the same as in the light. At higher concentrations, 5-10 mg/l, T=0 for essentially all daylight trials but in the dark the cod spends at least some time (T≅25) in the plume.

The experiments with herring took place in March. The length of the fish was 24 ± 2 cm and the mean weight 114 ± 8 g. A vertebra count gave 55.5 ± 0.7, which together with the fact that they were spring spawners points to that the herring was of the Rügen stock. The water temperature ranged from 5.5 to 8.8 °C and the salinity from 24 to 26.5 psu.

The results are summarized in Figure 4. As for cod there is no evident difference between the two sediment types and the threshold concentration for avoidance seems to be approximately 3 mg/l. The background turbidity in the incoming water corresponds to a sediment concentration between 0.0 and 0.4 mg/l. This was the same during the trials with cod. No correction has been made for the background value.

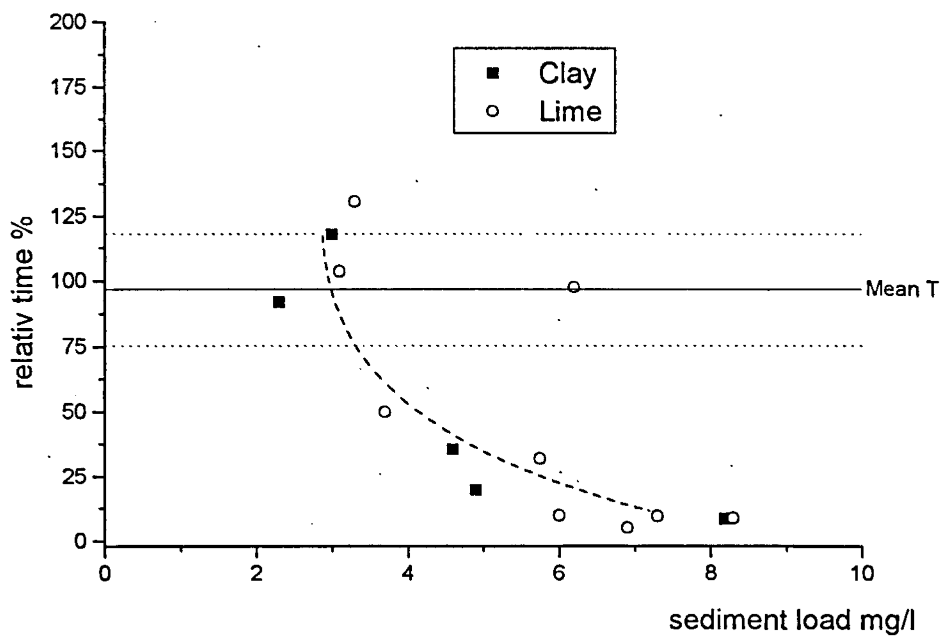
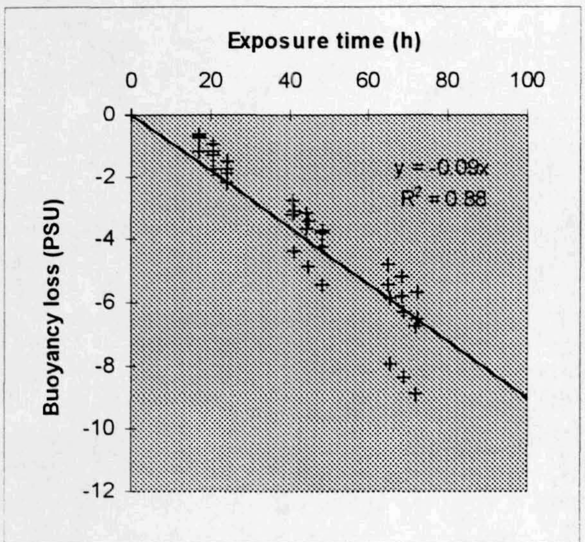


Figure 4. The avoidance behaviour of herring to different concentrations of suspended sediments.

Apart from the calculation of the T-value other observations were made during the experiments. In the early trials both cod and herring seemed curious about the plume and made short, purposeful explorations into it, followed by a rapid withdrawal. There seems to be a learning factor and the withdrawal became slower in the later trials. A recurring behaviour with cod were gill-clensing "coughs" when they came into contact with the plume. At high plume concentrations the general activity level of the fish increased in the presence of the plume. In all trials that were judged to display avoidance the fish entered the plume at one or more occassions during the establishment phase, purely visual avoidance was never seen.

A few trials have been excluded due to the plume becoming stratified when the density of the incoming water slowly decreased, so that the plume spread on top of the clear water. In such conditions it was impossible to tell if the fish was inside or under the plume. In two cases the shoal became trapped between the developing plume and the flume wall, giving a very high T-value. Those cases were excluded but could also be seen as avoidance from the 5-6 mg/l concentration at the time.

Egg and larvae



The gradient column experiments all show a steady loss of buoyancy, which is fairly linear in time. The results are shown in Figure 5 a-c. The rate of buoyancy loss is approximately proportional to the sediment concentration and all the experiments can be contracted in the sinking factor 0.02 psu/hour,mg/l which can be used to calculate the cumulative loss of buoyancy expressed as psu given the exposure time and the prevailing sediment concentration.

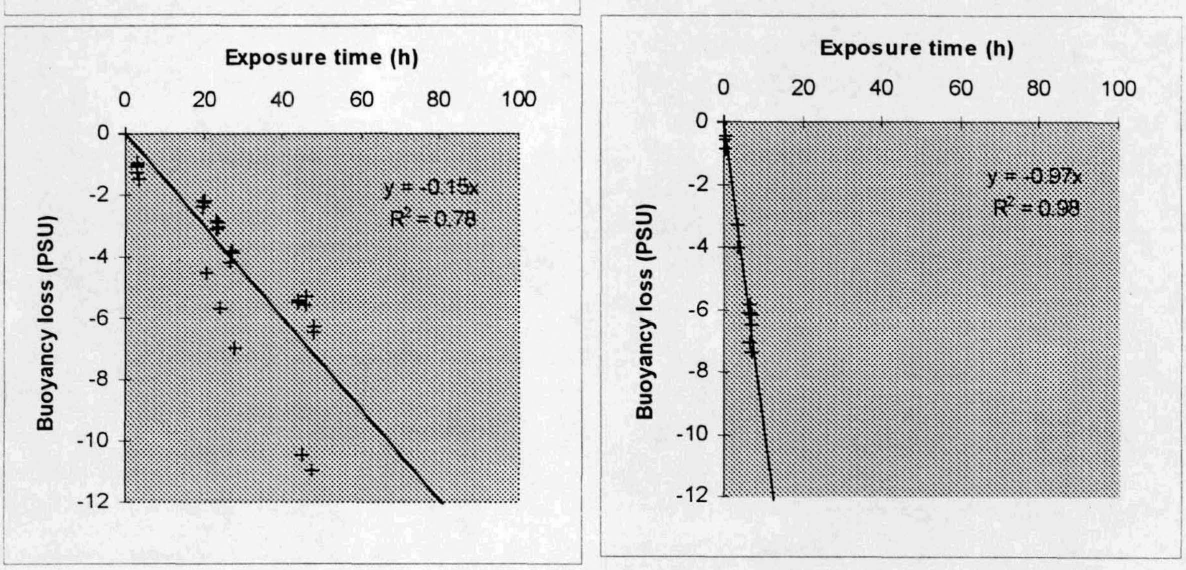


Figure 5. Loss of buoyancy as a function of time at increasing sediment concentrations.
a) 5 mg/l (n=4), b) 16 mg/l (n=5), c) 40 mg/l (n=3).

The results from the mortality experiments are less clear-cut, which is due to a high natural variability of the mortality between egg batches and a contribution to the mortality which depends on the stirring in the apparatus rather than the sediment load.

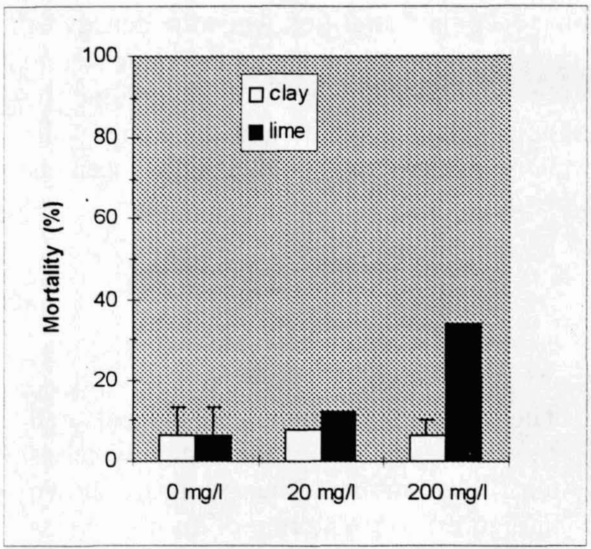


Figure 6. Egg mortality after 3 days exposure to different concentrations of glacial clay and lime sediments.

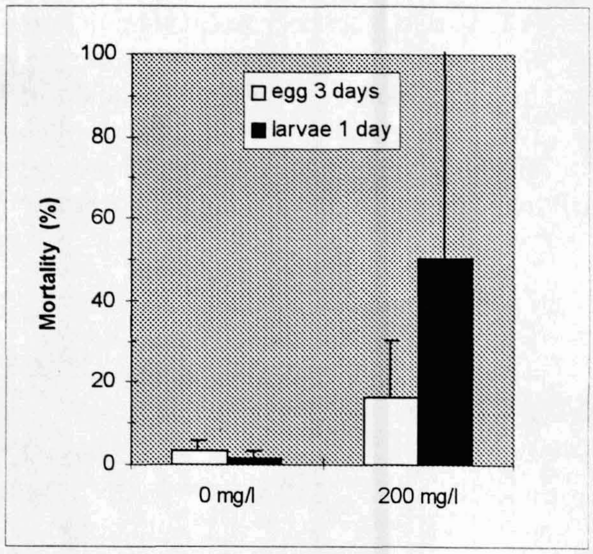


Figure 7. Comparison of mortality of egg and larvae taken from the same batch and exposed to sediments during 3 and 1 day respectively.

The eggs seems rather insensitive to sediment exposure. Figure 6 shows the results from a single batch which was subjected to both clay and lime at different concentrations, where lime at 200 mg/l is the only case giving a significantly increased mortality. Another batch was tested with clay both as egg and newly hatched larvae. In this case (Figure 7) the eggs had an elevated mortality at 200 mg/l for clay also. It is also evident from this experiment that the larvae are more sensitive, showing a three times higher mortality after 1 day than for eggs after 3 days exposure.

A series of experiments using lime at relatively low concentrations are presented in Figure 8-10. The results show an increased mortality in the precense of sediment which increases at longer exposure time, but there is no clear relation to the sediment concentration. In all experiments the stirred blank showed an increased mortality compared to the unstirred controls. A comparison of the condition of larvae from the blank and the sediment exposed groups showed that the latter had a significantly lower activity level and a smaller residue in the yolk-sack at the end of the exposure.

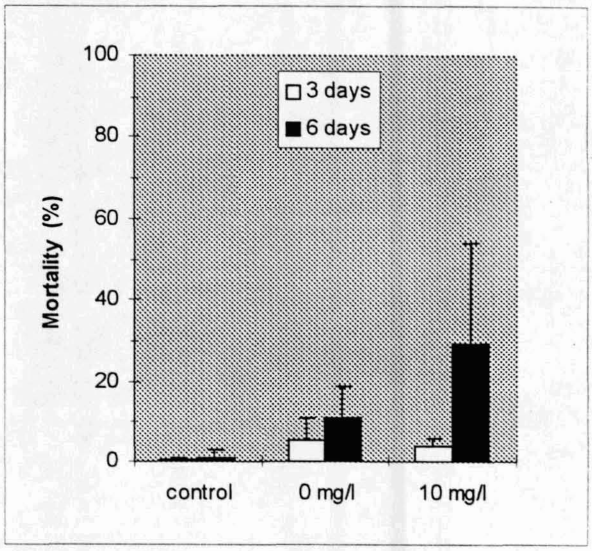


Figure 8. Larval mortality, combined for two batches. Control n=3, 0 mg/l n=8 and 10 n=8.

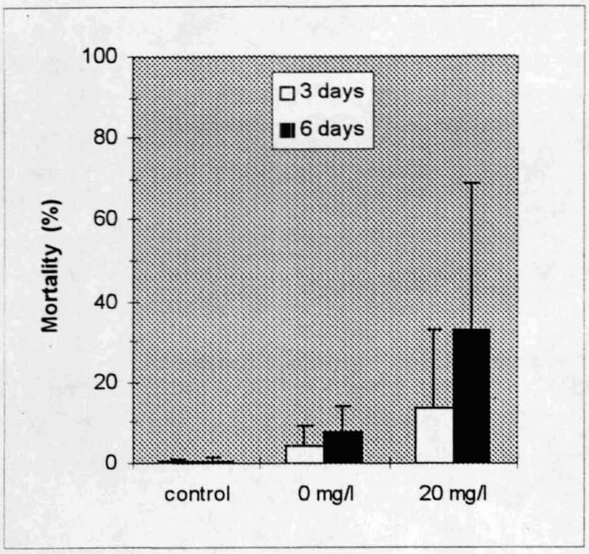


Figure 9. Larval mortality, combined for three batches. Control n=3, 0 mg/l n=10 and 20 n=10.

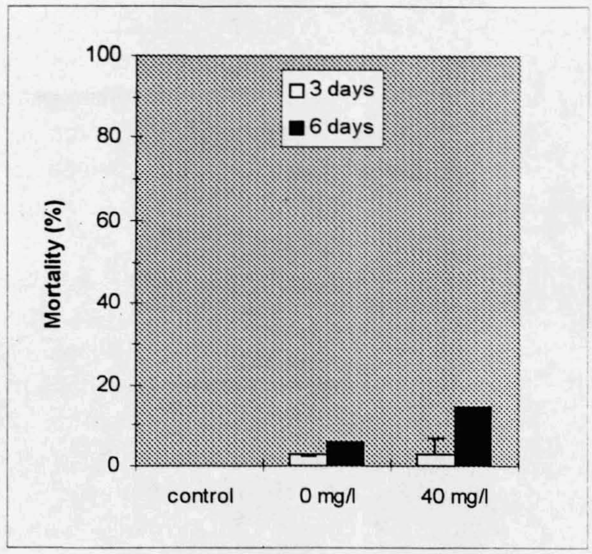


Figure 10. Larval mortality, one single batch. Control n=1, 0 mg/l n=4 and 20 n=4.

Discussion

The avoidance behaviour of both herring and cod showed a very distinct threshold at an unexpectedly low sediment concentration. This threshold was essentially the same for both species and for both the sediment types that were tested. Expressed as turbidity the threshold was approximately 5 NTU and 3 mg/l in terms of sediment concentration. There are few earlier quantitative experiments to compare to. Johnston and Wildish (1981) found a three times higher treshold for juvenile herring. Morinaga *et. al.* (1988) found a threshold of 5 mg/l for the avoidance reaction of the horse mackerel (*Trachiurus japonicus*) to a sand suspension, whereas a parrot fish (*Oplegnathus fasciatus*) showed little or no response at any concentration.

It is noteworthy that in the present experiment there was no difference between the benthic cod and the pelagic herring. The results of the experiments in the dark and the fact that all instances of avoidance were preceded by physical contact with the plume indicate that the avoidance has an important non-visual component.

It is not clear from the present results what will happen in a situation with a weak, gradual horizontal gradient; whether the observed avoidance threshold is absolute or relative. The background turbidity was low throughout the experiment and gives no information about this. In essentially all trials it was noted that the fish had an initial awareness reaction and withdrew from the channel where the sediment addition was just starting. This occurred usually well before any sediment clouding could be seen, at a much lower concentration than in the final plume. This behaviour was seen in cases with end-concentrations below threshold also, where the fish went in and out of the plume freely during the observation period. This can be interpreted so that the experiments measures an absolute threshold. There might however be an adaptation with a longer timescale than the 1 hour duration of the trials.

The effect of dredging-induced turbidity on pelagic eggs has not been investigated earlier. The buoyancy loss seen with cod eggs is rapid enough even at low sediment concentrations to make this effect potentially significant. The process is purely mechanical and will apply to all pelagic egg regardless of species. If an egg sinks to the bottom this will in most cases mean a certain loss to benthic predation so the process will have a direct effect on the reproduction success.

The experiments were made in still water and it is unclear what will happen in a turbulent environment. The deposition is not just a piling of particles on top of the egg but rather an adherence all around the surface. Strong agitation, as in the apparatus used for the mortality studies, dislodges the sediment particles from the eggs to a varying degree. If the turbulence level in the sea will be enough to free the eggs from sediments must vary from time to time. It should be noted that there is a feed-back situation where eggs that happens to accumulate some particles will sink deeper into the pyknocline, where the turbulent intensity will be lower and the chance that they will be cleared from the sediment load is less.

The experiments with yolk-sack larvae show an increased mortality level at a sediment concentration of the order of magnitude 10 mg/l. As has been pointed out by Rosenthal and Alderdic (1976) mortality by itself is a crude measure of environmental stress and is preceded by many important sub-lethal responses that will reduce the longterm survival indirectly. An example of this can be the more rapid consumption of the yolk-sack by the sediment exposed larvae. This decreases the time available for the sensitive transition from endogene to exogene feeding.

The results presented here will give a better foundation for managing the dredging operations of the Øresund Link project in such a way that the blocking effect of the migration of Rügen herring can be minimized. The avoidance of cod from the turbid water, the buoyancy effects on the cod eggs and the increased larval mortality can all combine to give a disturbance of the reproduction of cod in the Sound. The model predictions of the distribution of suspended matter show that the concentration will reach 2-5 mg/l or higher in the cod reproduction area, which is within the concentration range where effects can be expected. What is the case for cod will probably also apply to plaice and flounder, which have a similar spawning area and area of distribution of their egg and larvae.

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