Final Report

A Review of Scientific Information on the Effects of Suspended Sediments on Pacific Herring (*Clupea pallasi*) Reproductive Success

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1. Introduction

Pacific herring (*Clupea harengus pallasi* Valenciennes) support an important commercial roe fishery and sportfishery in San Francisco Bay. Because of their economic and recreational value, there are significant management efforts in place to maintain the health and abundance of the San Francisco Bay herring. The CA Department of Fish and Game (DFG) manages the fishery based on an extensive research program that collects data to assess the herring population on an annual basis. This data is used to set quotas and gauge the overall health of the population, which helps guide the regulation of this important fishery resource.

There has recently been some concern about the potential effects of dredging and dredge materials disposal on herring spawning activity and on the hatching and survival of the eggs and larval fish (Turner 1993). This has resulted in the implementation of a "fish window" for herring that prevents or limits dredging activities in Central San Francisco Bay (and Richardson Bay) from December 1 through February 28. Ideally, all of the necessary dredging in San Francisco Bay could be completed consistent with this fish window. However, logistical problems such as variable weather and the availability of the dredgers can make this difficult to accomplish.

Fish windows are based upon available scientific information. And while scientists have generated and collected an abundance of data on Pacific herring, there is little known available information regarding the effects of dredging activity, sediments, and related contaminants on herring spawning and herring early life stages in San Francisco Bay. As a result, there is some degree of uncertainty whether or not the limits imposed by the 'windows' are indeed protective or necessary to maintain the health and well-being of the herring population.

As a first step towards addressing this issue, the Long Term Management Strategy (LTMS) Science Assessment and Data Gaps Workgroup Herring Subcommittee has identified a review of the available scientific information regarding the effects of dredging-related suspended sediments of Pacific herring as an important data gap. To address this need, the U.S. ACOE has contracted this review of effects of suspended sediments on the spawning and early life stages of Pacific herring. It is expected that this review will serve as a resource to facilitate subsequent research efforts that may follow.

2. Potential Effects of Suspended Particulates on Key Reproduction Stages

Successful reproduction by Pacific herring involves many distinct processes, or stages, each of which is essential, and many of which are potentially subject to effects resulting from exposure to dredging-related suspended sediments:

- Survival
- Growth
- Reproduction
    1. Gonad growth
    2. Gonad maturation

3. Migration to spawning site(s)
4. Exhibition of appropriate spawning behavior
5. Adhesion of eggs to appropriate substrate
6. Fertilization of eggs
7. Development, survival, and hatching of embryos
8. Survival of larval fish
9. Exogenous feeding by larval herring

With the exception of gonad growth, Pacific herring are potentially susceptible to exposure to dredging-related suspended sediments while these important processes are occurring (Figure 1). Based upon an earlier preparation of a bibliography of available scientific papers relevant to Pacific herring (and Atlantic herring), scientific papers relevant to the reproduction processes listed above were obtained and reviewed. It should be noted that due to the relative limited number of relevant publications, a definitive evaluation of potential impacts on these reproductive processes is simply not possible, although additional review of related scientific information may allow a preliminary assessment of sorts. Similarly due to the dearth of information specific for Pacific herring, relevant information for Atlantic herring was also reviewed for this report. The information gleaned by this review follows.

2.1 Effects of Suspended Sediments on the Final Gonadal Maturation of Pacific Herring

It is presumed that most of the gonadal growth of Pacific herring occurs during the pre-spawning period while still in the Pacific Ocean. However, it has been reported that upon migration into San Francisco Bay, the pre-spawning adult herring will hold in deep water (>18 m) for several days as their gonads ripen for spawning (Watters and Oda 2002).

To the best of our knowledge, there is no information available with which to assess the potential effects of dredging-related suspended sediments upon this final gonad maturation.

2.2 Effects of Suspended Sediments on Migration of Pacific Herring to Spawning Site(s)

The San Francisco Bay population(s) of Pacific herring spend most of their adult life in the Pacific Ocean (Barnhart 1988), with sexually-maturing adults migrating into the Bay in early winter, reportedly holding in deep water (>18 m) for several days as their gonads ripen for spawning (Watters and Oda 2002) before migrating into the shallower intertidal and subtidal areas of the Bay to spawn, primarily in the northern Central Bay and San Francisco regions (Watters et al. 2004).

There have been no studies that directly address the potential for dredging-related suspended sediments to affect migration of Pacific herring to their spawning sites. In a worst-case scenario, mature Pacific herring might exhibit an avoidance response to the presence of a dredging-related plume of suspended sediments in the vicinity of their intended spawning site. Johnston and Wildish (1981) reported that juvenile **Atlantic herring** did exhibit avoidance responses to

Figure 1. A conceptual model of how Pacific herring might be exposed to dredging-related suspended sediments during critical reproductive life stages.

suspended sediments, with a threshold avoidance response at 9-12 mg/L suspended sediments, and the magnitude of the avoidance response increasing as the suspended sediment concentration increased. This suggests that adult Pacific herring may well exhibit a similar avoidance response to dredging-related suspended sediments.

However, the presence of a dredging-related plume of suspended sediments should not be expected to persist beyond a few days, at worst. Hay (1986) performed experiments in which sexually-mature Pacific herring were prevented from spawning for certain intervals of time, after which the fish were allowed to spawn, and the effects of the delayed spawning on hatching and larval fish survival determined. It was observed that delays in spawning of up to two weeks had no affect on fertilization, embryo survival, or hatching success. These findings suggest that temporary delays in the onset of spawning caused by avoidance of desired spawning sites by the presence of dredging-related suspended sediments should not be expected to adversely affect reproductive success.

2.3 Effects of Suspended Sediments on Exhibition of Appropriate Spawning Behavior

The stimuli that initiate spawning by Pacific herring are not completely understood, although temperature and salinity are almost certainly important factors. It has also been suggested that a sexual pheromone present in male herring milt is the actual "trigger" that starts a mass spawning event (Stacey and Hourston 1982).

Furthermore, it has been reported that immediately prior to spawning, the adult herring will interact closely with the intended spawning substrate, with the texture and rigidity of the substrate being 'tested' using the tips of the pectoral and pelvic fins (Stacey and Hourston 1982), and it has been hypothesized that the presence of sediment on the substrate may inhibit spawning (Stacey and Hourston 1982).

However, our review of the literature revealed no information with which to assess the potential effects of dredging-related suspended sediments upon spawning behavior.

2.4 Effects of Suspended Sediments on Adhesion of Eggs to Appropriate Substrate

Arguably, the key characteristic of herring eggs is their adhesion to submerged substrates, and it has been hypothesized (Cherr 2004, personal communication) that the siltation of spawning substrate and/or the egg surfaces might impair the successful adhesion of herring eggs to the desired substrate.

However, our review of the literature revealed no information with which to assess the potential effects of dredging-related suspended sediments upon adhesion of herring eggs to the intended spawning substrate.

2.5 Effects of Suspended Sediments on Fertilization of Eggs

Upon initiation of spawning, there remain several critical processes that must be completed successfully before the eggs can become successfully fertilized:

1. The herring sperm must become "activated". At the initial release of milt by males, the sperm are still immotile. The sperm require contact with egg chorion-derived proteins for initiation of motility (Vines et al. 1996b);
2. Upon activation, the now motile sperm must find and enter the egg micropyle;
3. Upon entry of sperm into the micropyle, the egg is activated to 'plug' the micropyle to prevent further sperm entry (e.g. polyspermy).

Studies have suggested that particulate material might adhere to the sperm surface and subsequently prevent activation (Vines et al. 1996a). However, our review of the literature revealed no information with which to definitively assess the potential effects of dredging-related suspended sediments upon these critical sperm-egg interactions.

2.6 Effects of Suspended Sediments on Embryo Development, Survival, and Hatching

2.6.1 Messieh et al. (1981) conducted experiments in which **Atlantic herring** embryos were exposed to sediments or suspended sediments and effects on embryo development, survival, and successful hatching were determined. Three sets of experiments were performed:

1. In the first set of experiments, herring eggs were fertilized with milt, and glass slides were inserted into the resultant egg mass so that a 2.5 cm length of one end of the slides were coated with multiple layers of the adhesive eggs. The eggs on one set of these slides were covered by burial with fine-grained sediment (median grain size = 4-4.5 μm) to a depth of ~1 cm; the eggs on a second set of slides were completely coated with the sediment, but were not buried; a Control treatment consisted of a similar set of egg-slides with no added sediment. These egg-slides were maintained under flow-through seawater conditions at ~10˚C until the control treatment embryos had developed pigmentation of the eyes, at which time the number of live embryos and total number of eggs were determined.

   The survival of eggs at the Control treatment was highly variable (mean = 55%), with all subsurficial eggs (i.e., those layers of eggs below the superficial layer of eggs) being dead. For the "coated" but unburied eggs, there was 15% survival, with those the surviving embryos being observed to be the most superficial eggs with no attached sediment. None of the buried embryos survived.

2. In the second set of experiments, egg-slides were prepared as described above, and were suspended in funnels containing seawater and sediments that were maintained in suspension via aeration. The test treatment TSS concentrations were ~700, ~6000, and ~19,000 mg/L, and the suspension media were renewed every 48 hrs for the 14-d test duration. Upon development of eye pigmentation, the embryos were examined every 48 hrs for determination of successful hatch and size of the hatched larvae.

   Due to the variable number of eggs on the slides at the various test treatments, percent successful hatch could not be determined. Of the larvae that did hatch, there was an apparent reduction in the number of live larvae at the ~6000 mg/L treatment, and no live larvae at the ~19,000 mg/L treatment. It was also observed that there was a trend for decreasing larval fish length as the suspended sediment concentration increased, although it was unclear whether this was statistically significant.

3. In the third set of experiments, herring eggs were mixed with milt within a plastic bucket to which seawater was added; the bucket was then cut into pieces, each piece having an attached monolayer of eggs that were counted. These egg substrates were then suspended in funnels containing seawater and sediments that were maintained in suspension via aeration. The test treatment TSS concentrations were ~10, ~1000, and ~7300 mg/L, and the suspension media were renewed daily for the 15-d test duration. Upon development of

eye pigmentation, the embryos were examined daily for determination of successful hatch and size of the hatched larvae.

There was no apparent impairment of the suspended sediment treatment on the successful hatching of the herring eggs. There appeared to be a slight reduction in the time to hatch at the highest sediment treatment, although it was unclear whether this was statistically significant. Similarly, there appeared to be a slight reduction in the larval fish length as the concentration of suspended sediments increased.

2.6.2 Kiorboe et al. (1981) conducted experiments in which **Atlantic herring** were spawned onto sections of 1 mm mesh net, and the resulting embryos incubated in test replicates containing 15 ppt seawater at 12.5˚C for ~10 days until hatching occurred. Two different types of experiments were performed:

1. In the first set of experiments, very fine-grained silt (median diameter of ~10 μm, obtained from an estuarine sediment after sieving and settling out larger particles) was added to the experimental replicate containers within 3 hrs of egg fertilization; the suspended particulate concentrations ranged from 5-300 mg/L, and were maintained in suspension in each replicate via magnetic stirrers. The herring embryos were examined regularly until all of the larvae had hatched (11-d post-fertilization).

   There were no effects of the suspended silt exposures on the survival and successful hatch of the herring embryos, nor upon the size of larvae at hatch.

2. In the second set of experiments, the fine-grained silt was added to the experimental replicate containers at 2, 4, or 6 days post-fertilization; the initial suspended particulate concentration was 500 mg/L, which was maintained in suspension in each replicate for 2 hrs and then allowed to settle. The herring embryos were examined regularly until all of the larvae had hatched (11-d post-fertilization).

   There were no effects of the suspended silt exposures on the development, survival and successful hatch of the herring embryos, nor upon the size of larvae at hatch.

2.6.3 Boehlert et al. (1983) performed experiments in which adult **Pacific herring** were spawned in the laboratory, and the eggs allowed to attach in a monolayer upon glass microscope slides. Two different types of experiments were then performed:

1. In the first experiment, the egg-slides were placed horizontally within a tank containing suspensions of volcanic ash or estuarine sediment at TSS concentrations of 500, 1000, 2000, 4000, and 8000 mg/L. The suspension was static so that the particulate material was allowed to settle onto the eggs. The test solutions (including fresh suspended material) were renewed every 72 hrs through the exposure period of 9 days (post-fertilization to first

hatch), after which the egg-slides were transferred into tanks of clean seawater for an additional 3 days for determinations of successful hatch and embryo mortality.

There was no significant effect of suspended sediment exposure on embryo mortality or successful hatch rate at the 500 mg/L treatment; however, embryo mortalities increased as the suspended sediment concentration increased, and there were significant reductions in successful hatch at the 1000 and 2000 mg/L treatments, and complete hatch failure at the 4000 and 8000 mg/L suspended estuarine sediment. The authors observed that the embryos at the higher exposure treatment exhibited physical characteristics consistent with lack of oxygen.

There was also no apparent effect of the suspended sediments on embryonic deformity rate up through the 500 mg/L estuarine sediment treatment, with an increase the percentage deformed as the suspended sediment concentration increased.

2. In the second set of experiments, the Pacific herring eggs were exposed to sediments that were maintained in suspension (via a re-circulating mixing system) during the exposure period. The egg-slides were placed horizontally within a tank containing suspensions of volcanic ash or estuarine sediment at TSS concentrations of 500, 1000, 2000, 4000, and 8000 mg/L. The test solutions (including fresh suspended material) were renewed once during the exposure period (8 days post-fertilization to first hatch for the estuarine sediment and 9 days for the ash treatments), after which the egg-slides were transferred into tanks of clean seawater for an additional 4 days (sediment treatments) or 3 days (ash treatments) for determinations of successful hatch and embryo mortality.

   There was no significant effect of suspended sediment exposure on embryo mortalities, deformities, or successful hatch rate at any of the suspended particulate treatments for both ash and sediment.

2.6.4 Morgan and Levings (1989) performed experiments in which adult **Pacific herring** were spawned in the lab, with their eggs allowed to attach to pieces of 63-μm mesh Nitex netting. The test sediment materials were obtained from a "clean" site and a "contaminated" site (note – subsequent chemical analyses revealed that the "clean" sediment did have elevated levels of cadmium); each sediment was sieved, with the <63 μm fractions (silts and clays only) being used in the experiments. The test treatments consisted of these sediments, kept in suspension (via aeration) at TSS concentrations of 500, 4000, and 10,000 mg/L for each sediment type, in addition to the Control treatment (= no suspended sediment). Small pieces of Nitex holding one-day old eggs were then placed into 20 L tanks containing 12 L of seawater at the various suspended sediment exposure treatments, with the experimental exposures lasting until all hatching was completed and through to larval survival at 96 hrs post-hatch (i.e., to exhaustion of the yolk-sac).

There was a delay of ~3 days in the 'time-to-hatch' in the 10,000 mg/L "contaminated" suspended sediment treatment; the authors concluded that this delay may have been the result of the layer of silt that covered the eggs at this treatment inhibiting oxygen diffusion into the eggs, thereby slowing the development of the embryos.

There was a statistically significant reduction in percent hatch at the 10,000 mg/L "contaminated" sediment suspension; otherwise, there was no significant effect of suspended sediment exposure on embryo mortalities or successful hatch rate at any of the suspended particulate treatments for either sediment, although there was a general trend for decreases in both responses as the suspended sediment concentration increased.

2.6.5 Costello and Gamble (1992) – While not true suspended sediment exposures, Costello and Gamble (1992) performed experiments in which **Atlantic herring** embryos were exposed to suspensions of sewage sludge and effects on embryo development, survival, and hatching determined. Mature Atlantic herring were spawned onto glass slides, and the resulting embryos incubated in test replicates containing full-strength seawater at 8-10˚C until the resulting hatched larvae had absorbed their yolk-sacs. In these experiments, wet sewage sludge at exposure concentrations of approximately 100, 200, 1000, 2000, and 10,000 mg/L (the sewage sludge was actually dosed on a volume-to-volume basis; 0.01% is presumed to be ~ 100 mg/L) was introduced into the test containers 10-d post-fertilization. Although the test replicates were aerated to prevent hypoxia, there was no indication by the authors that the sewage sludge particulates were maintained in suspension. The herring embryos were examined regularly until all of the larvae had hatched.

There were no effects of the sewage sludge exposures on the survival and successful hatch of the herring embryos at concentrations up through the 2000 mg/L (=0.2% V/V) treatment. There was a significant (~35%) reduction in successful hatching at the 10,000 mg/L treatment, with much of the unsuccessful hatching attributed to partially-hatched larvae (the egg case was ruptured but there was a dead larvae wholly or partially inside); however, due to the elevated concentrations of ammonia and metals associated with the high sludge concentration treatment, that cause(s) of the reduction in hatchability could not determined.

2.6.6 Summary of Suspended Sediment Effects on Herring Embryos – The survival of Pacific herring eggs is dependent upon the availability of oxygen to each egg to support respiratory activities (Alderdice and Hourston 1985). When oxygen is unavailable to the egg due to a "smothering" or burial of the eggs by the settling of suspended sediments onto the eggs (or in the case of subsurficial eggs, the inhibition of interstitial water exchange), embryo mortalities will result, as was observed in the Messieh et al. (1981) study (and perhaps in Boehlert et al's [1983] first set of experiments in which the suspended sediments were allowed to settle onto horizontally-oriented eggs substrates). This is clearly a worst case scenario, and may not be a prevalent response to dredging-related suspended sediments given the apparent tendency of Pacific herring to preferentially spawn on vertically-oriented substrate.

Barring burial by the sediments, there is a consensus among these studies that suspended sediments do not adversely affect herring embryo development or hatching at TSS concentrations as high as 500 mg/L, and perhaps as high as 6000-10,000 mg/L (Table 1).

2.7 Effects of Suspended Sediments on Survival of Larval Herring

2.7.1 Boehlert (1984) **–** performed experiments in which newly-hatched **Pacific herring** larvae were exposed to varying concentrations of suspended estuarine sediment (or volcanic ash) for 24 hrs, after which the effects of the exposure on larval survival and on the epidermis of the larvae were determined. Prior to use in these experiments, the larger particulates were removed from the sediment (or ash) via hydraulic settling, such that 96% of the test material was between 3 and 19 μm. The sediment exposure treatments were 0 (control), 500, 1000, 2000, 4000, and 8000 mg/L. The sediment (or ash) particulates were not maintained in suspension such that the exposure concentration decreased to 25% of the initial levels after ~2 hrs, and the test solutions were replaced every 2 hrs during the tests such that the larval fish were exposed to 'pulses' of sediment (or ash) suspensions during the tests. At the end of the 24-hr test duration, the survival of the larval fish was determined, and the fish were preserved for later microscopic analysis of the epidermal tissues.

There was no effect of the suspended sediment (or ash) exposures on larval fish survival (the mean mortality rate was <6% for all test treatments). However, there were significant increases in the degree of epidermal damage at the 4000 and 8000 mg/L sediment treatments; the damage caused by the volcanic ash was more severe, with significant increases in the degree of epidermal damage at the 1000 mg/L ash treatments. The author hypothesized that this epidermal damage may have been sufficient to result in later mortality of the larval fish.

2.7.2 Morgan and Levings (1989) - performed experiments in which **Pacific herring** eggs were exposed to continuous suspensions of "clean" and "contaminated" sediments until all hatching was completed and through to larval survival at 96 hrs post-hatch (see Section 2.5.4 for greater detail of the experimental design for this study).

After 96 hrs exposure, there was 76% survival of the larval herring at the Control treatment. Survival of larval herring was reduced to 10% in the 500 mg/L "clean" suspended sediment treatment, 6% survival at the 4000 mg/L treatment, and <1% survival at the 10,000 mg/L treatment; larval herring survival was reduced to <1% at all "contaminated" suspended sediment treatments. Morgan and Levings (1989) concluded that the larval fish life stage was much more sensitive to suspended sediments than the embryo stage, although they could not rule out that the reduced survival was not the result of the chemical contamination.

2.7.3 Costello and Gamble (1992) **–** While not true suspended sediment exposures, Costello and Gamble (1992) performed experiments in which larval **Atlantic herring** were exposed to suspensions of sewage sludge and effects on survival determined. Larval Atlantic herring (20-d post-hatch) were maintained in test replicates containing full-strength seawater at 8-9˚C for 9 days. In these experiments, wet sewage sludge at exposure concentrations of approximately 100, 200, 1000, 2000, and 10,000 mg/L (the sewage sludge was actually dosed on a volume-to-volume basis; 0.01% is presumed to be ~100 mg/L) was introduced into the test containers. Although the test replicates were aerated to prevent hypoxia, there was no indication by the authors that the sewage sludge particulates were maintained in suspension. The herring larvae were examined regularly during the test. Additional evaluation of effects on survival of herring larvae included assessment of the survival of the larvae that had hatched in the previously described embryo studies (see Section 2.5.4).

The authors reported that there were no effects of the sewage sludge exposures on herring larvae survival at concentrations up through the 2000 mg/L (=0.2% V/V) treatment (in fact, there was some indication of improved survival at the 100, 200, and 1000 mg/L treatments). There was a significant increase in larval mortality at the 10,000 mg/L treatment; however, due to the elevated concentrations of ammonia and metals associated with the high sludge concentration treatment, that cause(s) of the reduction in larval survival could not determined.

2.7.4 Summary of Suspended Sediment Effects on Larval Herring – Morgan and Levings (1989) reported that survival of larval Pacific herring was reduced to 10% in their 500 mg/L "clean" suspended sediment treatment, and concluded that the larval fish life stage was much more sensitive to suspended sediments than the embryo stage, although they could not rule out that the reduced survival was not the result of the chemical contamination present in the sediment. These findings are in contrast to the other larval fish studies indicating that there were no adverse effects of suspended sediments to larval herring at TSS concentrations as high as 2000 mg/L. Additional study may be needed to resolve this apparent discrepancy.

2.8 Effects of Suspended Sediments on Exogenous Feeding by Larval Fish

2.8.1 Boehlert and Morgan (1985) – Larval Pacific herring were maintained in tanks of 15 ppt seawater at 10˚C. During the pre-test acclimation period, the larval fish were fed rotifers (*Brachionus plicatilis*) and cultured algae (*Isochrysis sp*.). Two different types of experiments were then performed:

1. In the first experiment, 10-d old larval herring were transferred to experimental tanks of water, and volcanic ash or estuarine sediment was added to each tank to provide an initial suspended sediment concentrations of 500, 1000, 2000, 4000, and 8000 mg/L. The suspension was static so that the particulate material was allowed to settle. The tests were initiated with the immediate addition of rotifers at a density of 5 organisms per mL, with manual re-suspension (via stirring) of the particulate material every 15 minutes. After a 2-hr exposure period, the larval fish were collected and preserved. The larval fish were later examined to determine the percentage of the exposed fish that had fed, and the number of prey consumed by those fish that had fed.

For both ash and estuarine sediments, exposure to the suspended particulates resulted in dramatic increases in the percentage of fish that fed at the 500 and 1000 mg/L treatments, with a gradual decline thereafter as the suspended particulate concentration increased. There was similarly a dramatic increase in the number of organisms consumed by those fish that did feed at the 500 mg/L treatment for both ash and sediment, with a gradual decline thereafter as the suspended particulate concentration increased.

2. In the second set of experiments, 22-d old Pacific herring larvae were exposed to suspended sediments that were maintained in suspension during the exposure period. The larval fish were placed in replicate tanks containing suspensions of volcanic ash or estuarine sediment at TSS concentrations of 500, 1000, 2000, 4000, and 8000 mg/L. After a 2-hr exposure period, the larval fish were collected and preserved. The larval fish were later examined to determine the percentage of the exposed fish that had fed, and the number of prey consumed by those fish that had fed.

   For both ash and estuarine sediments, exposure to the suspended particulates resulted in dramatic increases in the percentage of fish that fed <u>and</u> in the number of prey consumed for those fish that did feed at the 500 mg/L treatment, with a decline to levels that were less that the Control at higher suspended sediment concentrations.

2.8.2 Johnston and Wildish (1982) – Larval **Atlantic herring** (>2 weeks old) were fed *Artemia* at a concentration of 4 organisms/mL while being exposed to TSS concentrations of 4, 8, and 20 mg/L for 3 hrs, after which the number of consumed *Artemia* was determined.

At 20 mg/L suspended sediments, there was a significant reduction in the number of *Artemia* consumed by the larval herring. It was also observed that the larval herring tended to migrate to the upper part of the exposure tanks in the suspended sediment tests and it was hypothesized that the effects of the suspended sediments were affected via reduction of light levels, although the authors reported that the increased turbulence that resulted from the water inflow at the bottom of the tanks may have contributed to the absence of fish in the bottom part of the tanks. The authors also cautioned that this study did not provide “conclusive evidence” that suspended sediments impair larval herring feeding due to reduced vision of predators.

2.8.3 Utne-Palm (2004) – Larval Atlantic herring, 20, 23, and 29 mm total length (42, 53, and 62 days posthatch), were exposed to suspensions of diatomaceous earth at concentrations of 0, 35, and 80 Jackson Turbidity Units (JTU), with repeated addition of diatomaceous earth every 20 minutes to replace settled material. *Acartia tonsa* were added to each test replicate at a concentration of 20 nauplii/L, and the effect of turbidity on the feeding behavior of the larval herring was determined.

In accordance with earlier studies, the 20-mm larvae exhibited fewer attacks than did the larger fish larvae, presumably due to improved visual acuity in the larger fish. In general, there was an increase in attack rate as turbidity increased to 35 JTU, although this increase was only statistically significant for the 20 mm fish. Further increase to 80 JTU resulted in a significant decrease in attack rate for all three fish age groups.

2.8.4 Summary of Suspended Sediment Effects on Larval Herring Feeding

Boehlert and Morgan (1985) suggested two possible mechanisms for enhanced feeding in turbid waters:

1. the presence of suspended particulates may enhance the visual contrast, allowing the larval herring to better perceive prey organisms (i.e., the relatively transparent *Brachionus* may have been better contrasted against a background of suspended particulates);
2. the back-scattering of light in turbid waters may help to disperse the light in all directions (thus, illuminating prey organisms from all directions), effectively decreasing their transparency.

It has also been suggested that increased feeding activity by short ‘reaction distance’ predators (i.e., larval fish) at intermediate turbidity levels may result from a lowered risk of predation by large reaction distance predators (Gregory and Northcote 1993; Utne-Palm 2004)

These hypotheses may help explain the apparent discrepancy between Johnston and Wildish’s (1982) observations of decreased feeding in much low suspended sediment concentrations: the low levels of TSS (4-20 mg/L) in the Johnston and Wildish study may have been below optimal contrast levels or optimal back-scattering levels. This is compounded by Johnston and Wildish’s use of *Artemia* nauplii as the test prey organism: relative to *Brachionus*, *Artemia* nauplii are highly pigmented (McGurk 1984) which should be expected to effectively negate the mechanisms for beneficial effects of sediment suspensions put forth by Boehlert and Morgan.

Bollens and Sanders (2004) recently reported that the primary prey for larval herring in San Francisco Bay were tintinnids (ciliated protozoa) and copepods, and it is uncertain as to whether or not the presence of suspended sediment might similarly enhance the ability of larval Pacific herring to ‘perceive’ these prey organisms. However, even if impairment of feeding by larval Pacific herring by suspended sediments were to occur, the exposure to any dredging-related suspended sediments not be expected to persist beyond a few days, at worst. McGurk (1984) reported that the feeding by Pacific herring can go up to 6-8 days post yolk-sac exhaustion before survival becomes impaired; these findings suggest that any temporary inhibition of feeding by larval Pacific herring caused by the presence of dredging-related suspended sediments should not be expected to adversely affect survival of the larval fish.

3. Summary and Conclusions

The reported effects thresholds of suspended sediments on key life stages of Pacific herring (and Atlantic herring) are summarized in Table 1.

3.1 Characterization of Ambient Suspended Sediment Concentrations

To the best of our knowledge, there are no available data characterizing TSS specific to herring spawning sites at the time of the herring spawning events or during the subsequent periods of embryo development and early larval survival. Recent studies have indicate that the majority of spawning by Pacific herring takes place in the northern Central Bay and San Francisco regions with significant spawning in the Oakland-Alameda region in some years (Watters et al. 2004). Arguably, one of the best sets of TSS data for this use are the San Francisco Estuary Regional Monitoring Program (RMP) status and trends data collected during the months of January through March during the period of 1993-2001 (Table 2); these data should be qualified as consisting of one grab sample during the three month period of January-March each year, with most sites located in the main channels of the Bay. As such, these data sets may not reflect the extremes that occur following stormwater runoff events (Cloern et al. 2000), nor capture the higher TSS levels that might be expected along the shorelines due to expected greater wave action (Schoellhamer [2002] reported that wind-wave resuspension is the major factor in affecting TSS levels in the Bay, with wind-wave resuspension decreasing as depth increases).

Table 1. Summary of reported effects thresholds of suspended sediments on key life stages of Pacific herring.

Referenced Study	Response	Suspended Sediment Concentration (mg/L)	Comments
Gonad maturation			
No information		unknown	
Migration to spawning site(s)			
Johnston and Wildish (1981)	Avoidance	9-12 mg/L	Hay (1986) reported that delays in spawning of up to 2 weeks had no affect on fertilization, embryo survival, or hatching success, suggesting that temporary delays in spawning caused by avoidance of desired spawning sites by the presence of dredging-related suspended sediments should not be expected to adversely affect reproductive success.
Exhibition of appropriate spawning behavior			
Stacey and Hourston (1982)	Tactile acceptance of spawning substrate	unknown	Stacey and Hourston (1982) hypothesized that the presence of sediment on the substrate may inhibit spawning.
Adhesion of eggs to appropriate substrate			
No information		unknown	
Fertilization of eggs			
Vines et al. (1996a)	Sperm activation	unknown	Vines et al (1996a) reported that particulate material might adhere to the sperm surface and prevent activation.
Development, survival, and hatching of embryos			
Messieh et al. (1981)	No effect on successful hatching	~7300 mg/L (highest concentration tested)	There appeared to be a slight reduction in the time to hatch at the highest suspended sediment treatment.
Kiorboe et al. (1981)	No effect on embryo survival, successful hatch, or size of hatched larvae	300 mg/L (highest concentration tested)	Continuous exposure to sediment suspension during the 11-day embryonic period.
		500 mg/L (highest concentration tested)	2-hr exposure to sediment suspension at various points during the 11-day embryonic period.

Table 1 (continued). Summary of reported effects thresholds of suspended sediments on key life stages of Pacific herring.

Referenced Study	Response	Suspended Sediment Concentration (mg/L)	Comments
Development, survival, and hatching of embryos			
Boehlert et al. (1983)	No significant effect on embryo mortality, successful hatch rate, or embryonic deformities	500 mg/L	Repeated renewals of static sediment suspensions that were allowed to settle onto horizontally-oriented egg substrates may have facilitated mortalities.
		8000 mg/L (highest concentration tested)	Sediment maintained in suspension during exposure.
Morgan and Levings (1989)	No significant effect on embryo mortalities or successful hatch rate	4000 mg/L	Both test sediments used in this study were acknowledged as being contaminated.
Costello and Gamble (1992)	No effects on the survival and successful hatch of herring embryos	2000 mg/L	Test media consisted of sewage sludge, not sediment.
Survival of larval fish			
Messieh et al. (1981)	No effect on larval fish	700 mg/L	Reported for the 2nd set of experiments in Section 2.6.1
	Reduced survival of larval	6000 mg/L	
Boehlert (1984)	No effect on larval fish survival	8000 mg/L (highest concentration tested)	There were significant increases in the degree of epidermal damage at the 4000 and 8000 mg/L sediment treatments; the author hypothesized that this epidermal damage might result in later mortality of the larval fish.
Morgan and Levings (1989)	Significant reductions in larval herring survival	500 mg/L (the lowest concentration tested)	Both test sediments used in this study were acknowledged as being contaminated.
Costello and Gamble (1992)	No effects of on larval fish survival	2000 mg/L	Test media consisted of sewage sludge, not sediment.

Table 1 (continued). Summary of reported effects thresholds of suspended sediments on key life stages of Pacific herring.

Referenced Study	Response	Suspended Sediment Concentration (mg/L)	Comments
Exogenous feeding by larval herring			
Boehlert and Morgan (1985)	increase in the percentage of fish that fed	500 and 1000 mg/L	2-hr exposure of 10-22 day old larvae. Consumption decreased as the higher sediment concentration increased.
	increase in the number of organisms consumed	500 mg/L	
Johnston and Wildish (1982)	Reduction in feeding	20 mg/L	
Utne-Palm (2004)	Increase in prey attack rate	35 JTU	At intermediate turbidity levels, there was an increase in prey attack rates, with the increase in feeding activity being greater for smaller (i.e., younger) herring larvae.
	Decrease in prey attack rate	80 JTU	At higher turbidity levels, there was a decrease in prey attack rates, for all larval herring age groups.

JTU – Jackson Turbidity Unit.

Table 2. Characterization of ambient TSS concentrations in the primary Pacific herring spawning areas	
RMP Station ID	TSS (mg/L, mean ± SD)
Red Rock	17.2 ± 9.2
Point Isabel	14.8 ± 15.6
Richardson Bay	8.0 ± 3.6
Yerba Buena Island	11.7 ± 10.1
Alameda	11.7 ± 5.1
Oyster Point	15.1 ± 13.4
USGS Transect Set[a]	Peak TSS (mg/L)
Central Bay	~50

a – from Cloern et al. (2000).

3.2 Characterization of Dredging-Related Suspended Sediment Concentrations

There have been several reviews of the suspended sediments that might be associated with dredging-related activities (see review by Anchor 2002); an analysis of the cumulative percent TSS concentrations that results from hydraulic or mechanical dredging indicates that the 90th percentile is <200 mg/L (see Figures 2 and 3, Anchor [2002]). However, there are very few data that are specific to dredging in San Francisco Bay. An earlier evaluation of the suspended sediments associated with mechanical dredging in San Francisco Bay reported a "mid-range" TSS of 90 mg/L, and a maximum TSS of 200 mg/L at 160 ft from the dredging activities (Barnard [1978], as cited in Anchor [2002]).

A more recent study characterized the sediment plume(s) associated with mechanical dredging in the Outer Oakland Harbor (MEC 2003). Ambient suspended sediment concentrations were reported as high as 100 mg/L in the deeper, central channel bottom waters, with concentrations generally below 25 mg/L in the 0-8 ft depth profile. Characterization during an ebb tide indicated that at >200 m from the dredging activity, the suspended sediment profile generally reflected ambient conditions; at 200 m downstream from the dredging activity, there is the first indication of a plume of increasing suspended sediments, although the TSS concentrations were still generally <50 mg/L. The dredging-related sediment plume becomes more distinct at closer distances, reaching maximum concentrations of 150 mg/L, and then declining to background levels at 200 m upstream of the dredging.

Characterization of the suspended sediment plume during the flood tide revealed similar results (MEC 2003), although the TSS concentrations of 125 mg/L at 200 m downstream of dredging were clearly elevated above background levels. A second flood tide survey reported maximum TSS concentrations of 150 mg/L at 200 m upcurrent of the dredging, with peak TSS concentrations of 225 mg/L along the channel bottom at closer distances to the dredging, and then returning to ambient concentrations at 200 m downcurrent of the dredging.

3.3 Is Dredging-related Suspended Sediment Adversely Affecting Pacific Herring?

While acknowledging that there remain significant data gaps in the potential effects thresholds suspended sediment concentration, the available information does allow for some preliminary conclusions. The maximum TSS concentration of 225 mg/L suspended sediments reported by MEC (2003) for the recent characterization of dredging-related sediment plumes is consistent with the maximum TSS of 200 mg/L that had been previously reported by Barnard (1978, as cited in Anchor [2002]). Comparison of these peak TSS concentrations with the reported effects threshold concentrations summarized in Table 1 should allow for assessment of whether or not some of the Pacific herring reproduction-related life stages are being impaired by dredging-related suspended sediments:

- The peak TSS concentration of 200-225 mg/L dredging-related suspended sediments is well below the effects threshold concentrations reported for effects on embryo development and hatching (Table 1),
- This peak TSS concentration of 200-225 mg/L is also well below most of the reported threshold concentrations for effects on larval herring survival, with the possible exception of the findings reported by Morgan and Levings (1989); their observation of significant larval mortality at 500 mg/L TSS, which was the lowest concentration that they tested, suggests that the actual threshold for impaired survival may occur at even lower TSS concentrations, suggesting that this is an area of uncertainty that should be addressed by additional study,
- The observation of enhanced feeding by larval Pacific herring at 500 mg/L suspended sediments reported by Boehlert and Morgan (1985) suggests that dredging-related activities may actually be beneficial to the Pacific herring population(s); it is important to note that these findings appear to be contradicted by Johnston and Wildish (1982), again suggesting that this is an area of uncertainty that should be addressed by additional study.

Resolution of these uncertainties, along with evaluation of some of the potential effects for which there are currently no data (e.g., effects of suspended sediments on adhesion of eggs to spawning substrate) are important next steps in determining whether or not the limits currently imposed by the ‘windows’ are indeed protective or necessary to maintain the health and well-being of the Pacific herring population(s) in San Francisco Bay.

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