DEPARTMENT OF THE ARMY
ST. LOUIS DISTRICT, CORPS OF ENGINEERS
1222 SPRUCE STREET
ST. LOUIS, MISSOURI 63103-2833

REPLY TO
ATTENTION OF:

September 25, 2001

Environmental & Economic Analysis Branch
Project Management Division

Ms. Joyce A. Collins, Field Supervisor
U.S. Fish and Wildlife Service
Marion Illinois Suboffice (ES)
8588 Route 148
Marion, Illinois 62959

Dear Ms. Collins:

Enclosed you will find a Tier II Biological Assessment (BA) for dredging on the Upper Mississippi River during the presumed window of pallid sturgeon reproduction (12 April - 30 June). The BA was prepared to evaluate the effects of dredging during this time frame on pallid sturgeon, as requested by the U.S. Fish and Wildlife Service in their Biological Opinion. Should you have any questions concerning this document, please contact Dr. Thomas Keevin (314-331-8462).

Sincerely,

Owen D. Dutt
Chief, Environmental
Analysis Branch

Enclosure

TIER II BIOLOGICAL ASSESSMENT: EMERGENCY DREDGING

OPERATION & MAINTENANCE OF THE 9-FT NAVIGATION CHANNEL
ON
THE UPPER MISSISSIPPI RIVER SYSTEM

U.S. Army Corps of Engineers, St. Louis District

September 2001

Introduction

The U.S. Fish and Wildlife Service indicated in their Biological Opinion that "Should it become necessary for the Corps to dredge during the presumed window of pallid sturgeon reproduction (12 April - 30 June), reinitiation of formal section 7 consultation will be necessary to address further incidental take of pallid sturgeon. A Tier II will be required to evaluate the effects of dredging during this time frame on pallid sturgeon." The Corps of Engineers (2001) responded to this Term and Condition in a letter dated 11 August 2000, from Major General Phillip R. Anderson to Mr. William Hartwig. The Corps' letter indicated that: "The Corps will prepare a Biological Assessment for use as a basis of formal consultation on this matter during Fiscal Year 2001".

Although dredging during the presumed window of pallid sturgeon reproduction is rare (Table 1), there are times when dredging may be required. The U.S. Fish and Wildlife Service (1998) has developed procedures for such "emergency" situations, pursuant to 50 CFR 402.05. These procedures would allow the St. Louis District to proceed with emergency dredging after seeking advice from the U.S. Fish and Wildlife Service on measures for minimizing effects by either telephone or facsimile. Formal consultation would be initiated after the fact.

The rational for preparing a Biological Assessment for emergency dredging, prior to the actual need for dredging, is to better protect the pallid sturgeon. This allows both the St. Louis District and the U.S. Fish and Wildlife Service to be proactive and to be better stewards of this endangered species.

Pallid Sturgeon: Incidental Take Statement

Section 9 of the Endangered Species Act (ESA) and Federal regulation pursuant to section 4(d) of the ESA prohibit the take of endangered and threatened species, respectively, without special exemption. In their Biological Opinion for the pallid sturgeon, the Service developed an Incidental Take Statement that contained a number of Reasonable and Prudent Measures (RPMs) that would be implemented by the Corps of Engineers during continued Operation and Maintenance of the 9-foot Navigation Project. One of the RPMs dealt with maintenance dredging and potential impacts on eggs and larvae of the pallid sturgeon.

"3. Maintenance dredging will not occur during the presumed window of pallid sturgeon reproduction (12 April - 30 June). The dates may require revision as more information becomes available regarding pallid sturgeon spawning and larval stage development. This RPM addresses incidental take anticipated in 1 and 2 discussed above."

In their Biological Opinion, the Service indicated that in order to be exempt from the prohibitions of section 9 of the Act, the Corps must comply with the following Terms and

Conditions, which implement the reasonable and prudent measures. One of the Terms and Conditions dealt with dredging during the presumed window of pallid sturgeon reproduction.

"5. Should it become necessary for the Corps to dredge during the presumed window of pallid sturgeon reproduction (12 April - 30 June), reinitiation of formal section 7 consultation will be necessary to address further incidental take of pallid sturgeon. A Tier II biological assessment will be required to evaluate the effects of dredging during this time frame on pallid sturgeon. This term and condition addresses incidental take in 3 discussed above."

Analysis of Historical Dredging Frequency and Locations (12 April - 30 June)

The St. Louis District has 39 years of dredging records, dating back to 1963. During that 39-year period, dredging has occurred at 14 locations between 12 April and 30 June (Lance Engle, Personal Communication) (Table 1). One of those dredging events actually began on June 30, the last day of the pallid sturgeon "no-dredge" window and two additional events occurred during the last week of June (June 23 and June 26, 1988).

Table 1 - Dredging Events, Locations, and Dredge Quantities for the Middle Mississippi River Between April 15 and June 30, 1963 -2001 (39-Year Period of Record).

Date	River Mile	Cubic Yards
06-64	13.5	93,600
06-66	65.6	6,600
05-72	66.3	118,000
06-75	183.7	263,400
05-76	66.3	111,200
06-76	183.3	226,600
06-76	183.2	207,000
06-77	161.0	160,800
04-81	183.4	162,500
06-84	176.8	?
06-88	160.5	117,037
06-88	125.0	69,445
06-88	42.3	72,555
06-89	182.4	?

Based on the 39-year period of record, river stage appears to be the major factor responsible for dredging during the pallid sturgeon "no-dredge" window. Nine of the 14 sites (64%) were dredged during "major" drought years (1964-1966; 2 sites; 1976, 3 sites; 1988-1999, 4 sites).

The majority of the dredging locations were either in highly developed areas (7 sites) or chronic dredging problem areas (4 sites). Five of the sites (36%) were in the same general area below the mouth of the Chain of Rocks Canal, an area that will continue to be a dredging problem in the future (Claude Strauser, Personal Communication). Six of the sites (43%), including the five sites below the mouth of the Chain of Rocks Canal, are in the St. Louis Harbor, a highly developed area. Two additional sites are just below the St. Louis Harbor. Four of the dredging events occurred in chronic dredging areas, the Trail of Tears Crossing (R.M. 65.6, 1966-drought year; R.M. 66.3, 1972; 66.3, 1976-drought year) and the St. Genevieve Crossing (R.M. 125, 1988-drought year). Two of the 14 sites are in what current information would suggest is "high quality" sturgeon habitat (R.M. 42.3, 1988-drought year; R.M. 13.5, 1964-drought year). The remaining 12 sites are highly disturbed and do not likely represent potential spawning sites. Although it is reasonable to expect that the majority of dredge locations and conditions will mimic those just described, future conditions and site locations cannot be addressed with certainty and are subject to change. Just as the proposed spawning dates are based on existing data and subject to change, this information is the best available data at the present time.

Literature Review

Reine and Clarke (1998) provided a comprehensive review of the literature on the entrainment of aquatic organisms, including fish, by hydraulic dredges (Provided as Appendix A).

Impact Assessment

There are two major areas of potential concern with respect to dredging during the presumed pallid sturgeon spawning period (April 12 - June 30). The first concern involves entrainment of eggs/larvae/juveniles during dredging. The second concern involves disposal of material on spawning habitat, larvae/juvenile habitat, or feeding habitat.

<u>Entrainment of pallid sturgeon eggs</u>: Pallid sturgeon are thought to spawn over rock, cobble, or gravel substrates (U.S. Fish and Wildlife Service 1993). Dredging occurs in depositional areas to maintain a 9-foot navigation channel. As such, it is not expected that dredging will impact any spawning areas because gravel bars are not usually found in depositional areas.

Entrainment of larval/juvenile pallid sturgeons: Based on the literature review by Reine and Clarke (1998), it appears that there is a potential for entrainment of larval and juvenile pallid sturgeons. Larval fish, the sac-fry larvae drift downstream with the current for 8-13 days (days 11-24 post-fertilization). It is possible that larval fish could be entrained into the dredged material out of the water column. It is impossible to predict the number of drifting sac-fry larvae that might be entrained by dredging. However, based on the suspected number of females in the Middle Mississippi River, the fact that females don't spawn every year, the small fraction of water actually entrained, and the infrequency of dredging during the spawning window, it is anticipated that the number would be small. In addition, the survival rate of larval fish is extremely small and the equivalent adults lost would be at least three to four orders of magnitude smaller than the number of larval fish entrained.

Larval pallid sturgeon have recently been collected from sand/gravel/cobble areas or just below gravel bars (Hrabik et al. 2001) in the main channel border. These are generally not the type of areas that are dredged. Areas with gravel or adjacent to gravel beds are usually in areas of scour and don't require dredging. In addition, dredging to maintain the 9-foot navigation channel occurs in the main channel, not in the main channel border where larval and young-of-year fish have been collected.

Dredged Material Disposal.

A. *Disposal on Spawning Habitat.* Pallid sturgeon are thought to spawn over rock, cobble, or gravel substrates (U.S. Fish and Wildlife Service 1993). The Corps has conducted a survey of gravel bars on the Middle Mississippi River (Laux 2000). This study will be continued in FY 02, if river stage conditions permit. Based on the gravel bar surveys, pre-dredging surveys, and river potomology, the St. Louis District will make every effort to avoid placing dredged material on gravel/cobble/rock outcrops (Conservation Measure 3). The St. Louis District will also make every effort to avoid disposing on areas immediately above these habitats to avoid downstream migration of dredged material. As such, no impacts to spawning habitats are anticipated.

B. *Disposal on Larval Rearing Habitat.* Hrabik et al. (2001) provided the best information on larval pallid sturgeon rearing habitat. "In general, the collection sites were below extensive areas of rock, cobble, or gravel. Nearly all samples were taken in areas that included "quiet" patches of water e.g. eddy pools, which incidentally contained large quantities of detritus." Many of the collection sites were near side-channels or island tips. Based on this information, the Corps proposes to coordinate dredged material disposal sites with the Fish and Wildlife Service (Conservation Measure 2) and to make every effort to avoid disposing on gravel bars (Conservation Measure 3), eddy pools (Conservation Measure 4), or on island tips (Conservation Measure 5). Although every effort will be taken by the St. Louis District to avoid these areas, there may be rare situations when these sensitive habitat areas can't be avoided. Should this be the case, this action will be coordinated with the Service. As such, impacts to rearing habitat are anticipated to be minor or non-existent.

C. Disposal on Larval/Juvenile Feeding Habitat. It is anticipated that feeding habitat and rearing habitats are essentially the same. As such, impacts to larval/juvenile feeding habitats are anticipated to be minor or non-existent.

Conservation Measures

1. Every effort will be made by the St. Louis District to dredge outside the April 12-June 30 pallid sturgeon spawning window. For example, 3 of 14 (21%) historic dredging events (Table1) occurred during the last week of June (June 23, 1988; June 26, 1988; June 30, 1989), and possibly could have been postponed to avoid the spawning window.

2. Emergency dredging (April 12 - June 30) locations and disposal areas will be coordinated with the U.S. Fish and Wildlife Service prior to initiation of dredging.

3. Based on coordination with the U.S. Fish and Wildlife Service (Conservation Measure #2), the District's gravel bar data base (Laux 2000), and pre-dredge surveys, the St. Louis District will make every effort to avoid placing dredged material on gravel bars or rock outcrops that could serve as pallid sturgeon spawning habitat.

4. Based on coordination with the U.S. Fish and Wildlife Service (Conservation Measure #2) and pre-dredge surveys, the St. Louis District will make every effort to avoid placing dredged material in eddy pools that could serve as larval sturgeon rearing areas.

5. Based on coordination with the U.S. Fish and Wildlife Service (Conservation Measure #2) and pre-dredge surveys, the St. Louis District will make every effort to avoid placing dredged material on island tips.

Conclusion

Based on the analysis of past dredging frequency, dredging locations, dredge entrainment impacts and dredged material disposal impacts, it is the St. Louis District's opinion that impacts to spawning sites and larval/juvenile pallid sturgeon range from non-existent to minor. This conclusion is based on both the impact analysis and implementation of Conservation Measures by the St. Louis District. The only potential area of impact is the entrainment of larval pallid sturgeons from the water column by the dredge during the 8-13 days that larval pallid sturgeon sac-fry are part of the drift. The actual number of larval pallid sturgeon that would be lost is not known. However, considering the small fraction of water dredged, the small number of larval pallid sturgeon in the drift, and the equivalent adults that would be lost, it is the opinion of the St. Louis District that impacts would not be significant.

Literature Cited

Engle, Lance. 2001. Personal Communication. Dredging Project Manager, St. Louis District, U.S. Army Corps of Engineers (February 16, 2001).

Hrabik, R. A., D. P. Herzog, and D. E. Ostendorf. 2001. Larval pallid sturgeon and pallid-shovelnose hybrids collected in the Mississippi River. Progress Report, Missouri Department of Conservation, Long Term Resource Monitoring Program.

Laux, E. 2000. Middle Mississippi River Gravel Bar Survey. St. Louis District, Data Base.

Reine, K., and D. Clarke. 1998. Entrainment by hydraulic dredges-A review of potential impacts. Technical Note DOER-E1. U.S. Army Engineer Research and Development Center, Vicksburg, MS (Provided as Appendix A).

Strauser, Claude. 2001. Personal Communication. District Potomologist, St. Louis District, U.S. Army Corps of Engineers (August 14, 2001).

U.S. Army Corps of Engineers. 2000. Letter from Major General Phillip R. Anderson to Mr. William Hartwig (August 11, 2000).

U.S. Fish and Wildlife Service. 1993. Pallid sturgeon recovery plan. U.S. Fish and Wildlife Service, Bismarck, North Dakota. 55 pp.

U.S. Fish and Wildlife Service. 1998. Endangered species consultation handbook: Procedures for conducting consultation and conference activities under Section 7 of the Endangered Species Act. U.S. Fish and Wildlife Service and National Marine Fisheries Service.

APPENDIX A

Reine, K., and D. Clarke. 1998. Entrainment by hydraulic dredges-A review of potential impacts. Technical Note DOER-E1. U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Technical Note DOER-E1
December 1998

Entrainment by Hydraulic Dredges—A Review of Potential Impacts

PURPOSE: This technical note summarizes existing literature regarding potential impacts to aquatic organisms caused by entrainment during dredging and dredged material disposal operations. This information was used to evaluate the current state of knowledge regarding dredge-induced entrainment of commercially and biologically important fish, shellfish, and threatened and endangered species and to identify information gaps where additional research is needed. Specifically, those technical issues related to hypothetical impacts of entrainment that lead to requests for environmental window constraints on dredging operations are given emphasis. Based on the current state of knowledge, future research outlined under the Dredging Operations and Environmental Research (DOER) Program will seek to resolve ambiguity associated with environmental windows linked to entrainment issues and develop operational measures to provide adequate resource protection while maintaining dredging project flexibility.

BACKGROUND/INTRODUCTION: The effects of dredging on aquatic organisms have been a source of environmental concern for several decades. A summary of potential environmental impacts associated with dredging operations can be found in a technical report by LaSalle et al. (1991). One category of concern that has frequently arisen in connection with projects involving hydraulic dredges (e.g., hopper and cutterhead dredges) deals with mortality of fish and shellfish entrained during the dredging process. Entrainment is defined as the direct uptake of aquatic organisms by the suction field generated at the draghead or cutterhead. To a certain degree, this concern is analogous to that of entrainment by power plants withdrawing cooling waters, an issue which has received much scientific and public attention. With respect to entrainment by dredges, several investigations (described below) have sought to determine if absolute entrainment rates and resultant mortalities are meaningful from either broad ecological or fishery population dynamics perspectives. The results of these limited studies have been inconclusive, at least to the extent that findings have seldom been published in the peer-reviewed literature. Thus, the fundamental issues remain subjective. Consequently, state and Federal resource agencies routinely request that dredging operations be restricted when fish or shellfish resources are perceived to be at risk. Entrainment-related restrictions are commonly requested to protect life history stages of many commercially or recreationally important species (e.g., anadromous fishes, oyster larvae), as well as species listed as threatened and/or endangered (e.g., sea turtles).

DREDGING-RELATED ENTRAINMENT: Currently, 49 percent of U.S. Army Corps of Engineers (USACE) Districts (18 districts) report issues related to potential entrainment of aquatic organisms as reasons underlying environmental windows. Entrainment concerns reported in various categories and frequencies by USACE Districts surveyed include: anadromous fishes (19 percent); shellfish (11 percent); and threatened and/or endangered species (32 percent) (Reine, Dickerson, and Clarke 1998). Due to the frequency of entrainment-related issues Corps-wide, an extensive literature review was conducted to examine dredging-related entrainment issues with regard to fish, shellfish, and threatened/endangered species. These studies are summarized with respect to the relative degree of susceptibility to entrainment, operational measures to avoid entrainment, and predictive modeling techniques to assess mortality rates and their population level consequences.

Shellfish. Shellfish studies are summarized as follows:

- **Dungeness crabs:** The Dungeness crab (*Cancer magister*) is a commercially valuable species found in both marine and estuarine waters from central California northward to southeastern Alaska. While Dungeness crabs are found throughout the estuary, they congregate in navigation channels, particularly during times of low tide or while migrating into or out of the estuary. This affinity for navigation channels renders them susceptible to entrainment during channel dredging operations. Dredge-related entrainment of Dungeness crabs has been studied since the late 1970's. Most entrainment studies involving Dungeness crabs have been conducted in Grays Harbor and Puget Sound, Washington, and include: Tegelberg and Arthur (1977); Stevens (1981); Armstrong, Stevens, and Hoeman (1982, 1987); Dinnel, Armstrong, and Dumbauld (1986); Dinnel et al. (1986); McGraw et al. (1988); Dumbauld et al. (1988); Larson and Patterson (1989); and Wainwright et al. (1990, 1992). Entrainment was examined for hopper, pipeline, and clamshell (although mechanical dredges are not generally treated in an entrainment context) dredging and appears to be a function of the type of dredge used. A variety of factors possibly influencing entrainment rates by dredges include bottom depth, hopper dredge speed or cutterhead rates of advance, flow-field velocities generated at the draghead or cutterhead, volume of dredged material, and direction of dredging with regards to tidal flow. Studies yielded little evidence of bivariate correlation between entrainment and any of the parameters tested with the possible exception of direction of dredging with reference to tidal flow. The later relationship was reported by Larson and Patterson (1989), who recorded highest comparative entrainment rates while dredging against the ebb tide during one series of samples. However, this observation was not duplicated in 3 years of follow-up studies.
  - *Entrainment rate*: While most studies have focused on hopper dredging, clamshell and pipeline dredging operations have also been examined. Armstrong, Stevens, and Hoeman (1982) concluded that a strong probability existed that Dungeness crab populations can be negatively impacted by dredging operations unless proper precautions are taken to reduce losses. Larson and Patterson (1989) also concluded that Dungeness crabs are particularly susceptible to entrainment by hopper dredging in estuaries. Mean entrainment rates (for all hopper dredge studies combined) for adult crabs ranged from 0.040 to 0.592 crabs/cubic yard (cy) of dredged material. Juvenile crabs, especially young-of-the-year crabs (7 to 25 mm), were entrained at a significantly higher rate (range 0.32 to 10.78, $\bar{x} = 4.14$ crabs/cy) at an offshore bar station outside Grays Harbor and at the Mouth of the Columbia River (Table 1). Pipeline dredging was also examined by Stevens (1981) and produced an entrainment rate of 0.243 crabs/cy. Clamshell dredging had the least detrimental impacts to Dungeness crabs with "entrainment" rates approximating 0.012 crabs/cy (Table 1). Stevens (1981) stated two possible mitigating factors to account for the reduced mortality by clamshell dredges: avoidance of increased turbidity and suspended sediment concentration as a result of physical disturbance at the bottom; and avoidance of low-frequency vibrations produced from lowering the bucket into the water. These studies indicated that a general linear relationship exists between crab densities and

Table 1
A summary of Dungeness crab entrainment studies conducted in Grays Harbor, Washington, and the Columbia River, Washington and Oregon

Source	Dredge	Study Date	Location	Entrainment Rate (crabs/cy)
Tegelberg and Arthur 1977	Hopper	Mar 1975	Middle and outer estuary	0.131-0.327
	Hopper	Mar 1975	Outer estuary	0.449
Stevens 1981	Clamshell	Oct-Dec 1978	Middle estuary	0.012
	Hopper	Nov-Dec 1978	Outer estuary	0.233
	Pipeline	Sep-Dec 1979	Outer estuary	0.243
		Nov-Dec 1979	Inner harbor	0.0017
	Hopper	Mar 1979	Outer estuary	0.182
Armstrong, Stevens, and Hoeman 1982	Hopper	Jun 1980	Inner harbor	0.079
		Aug 1980	Middle estuary	0.107
		May-Sep 1980	Middle estuary	0.075
Armstrong, Stevens, and Hoeman 1987	Hopper	Oct 1985	Outer esturary	0.046
Dinnel, Armstrong, and Dumbauld 1986	Hopper	Oct 1985	Outer estuary	0.118
Dinnel et al. 1986	Hopper	Aug 1986	Outer estuary	0.135
				0.592
			Middle estuary	0.088
McGraw et al. 1988	Hopper	Aug 1986	Outer estuary	0.155
				0.500
				0.079
			Middle estuary	0.058
Dumbauld et al. 1988	Hopper	Aug 1987	Outer estuary	0.222
				0.397
				0.133
				0.224
			Outer estuary (Bar)	9.367
Larson and Patterson 1989	Hopper	Apr-Oct 1985	Mouth of Columbia River	10.78 (0.04)*
		Apr-Oct 1986		1.12 (0.08)*
		Apr-Oct 1987		3.54 (0.18)*
		Arp-Oct 1988		0.32 (0.03)*
Wainwright et al. 1990	Hopper	Aug 1989	Outer estuary	0.220
				0.325
				0.115
				0.260
				0.40

* Adult crabs only.

entrainment rates. During all studies, entrainment rates for male crabs were twice that for females, probably reflecting female migration out of the estuary before their third year. A summary of relevant data derived from Dungeness crab entrainment studies is given in Table 1.

- *Mortality rate:* Not all crabs entrained during dredging are killed. Mortality rates were found to depend on dredge type, disposal method, season, crab size, and overall condition of the crab (i.e., degree of softness of the shell as related to molting). Postentrainment mortality resulted from physical trauma, burial or crushing under excessive sediment weight, or disposal into a Confined Disposal Facility (CDF) (Wainwright et al. 1992). Mortality during hopper dredging increased with increasing size, from 5 percent for 7- to 10-mm crabs to 86 percent for crabs over 75 mm. Based on limited data, crab mortality rates during clamshell dredging was estimated to be 10 percent for all size classes. When discharge from a pipeline dredging operation occurred directly into a CDF, mortality for all crabs entrained was assumed to be 100 percent. Percent mortality for all age/size classes can be found in Table 2.
- *Draghead modification:* In a comparison of conventional and modified dragheads on the hopper dredge *Yaquina*, the modified draghead was ineffective in reducing entrainment of crabs of any size (McGraw et al. 1988). The modified draghead produced an entrainment rate of 0.054 crabs/cy, while the unmodified draghead entrainment rate was 0.064 crabs/cy. Both dragheads cumulatively produced a mean entrainment rate of 0.118 crabs/cy which was comparable to rates observed in other entrainment studies.

Table 2
Postentrainment mortality rates for Dungeness crab by dredge type, season, and age class (adapted from Wainwright et al. 1992)

Dredge Type	Age Class (yr)	Season	Size Range (mm)	Mortality (%)
Hopper	0+	Apr-May	7-10	5
	0+	Jun-Sep	11-30	10
	0+	Oct-Dec	31-40	20
	0+	Jan-Mar	41-50	40
	1+	Apr-Sep	51-75	60
	1+	Oct-Mar	>75	86
	>1+	All	>75	86
Clamshell	All	All	All	10
Pipeline	All	All	All	100

- **Blue crabs:** Blue crabs (*Callinectes sapidus*) are a commercially important resource that supports a large seafood industry in the Chesapeake Bay and along the southeastern Atlantic and Gulf coasts. Blue crabs have been protected by environmental windows in two USACE Districts (USAED), New York and Baltimore, in an attempt to avoid detrimental effects from dredging operations. Due to its commercial value, this species has been studied extensively with regard to spawning, migration, harvesting, and mortality. Blue crabs have been speculated to be vulnerable to entrainment during dredging activities, particularly during late fall and winter months when egg-bearing females emigrate to deep water and remain buried in surficial sediments until spring. Overwintering crabs may be too lethargic during this period of inactivity to move out of the path of an approaching dredge. Very few references to dredging-related impacts on blue crabs occur in the scientific literature (Wilber and Clarke in preparation), and no studies were found in the present effort from which entrainment rates could be derived.

- **Shrimp:** Entrainment of sand shrimp (*Crangon* spp.) by pipeline and hopper dredges was opportunistically examined during the Dungeness crab studies (Armstrong, Stevens, and Hoeman 1982). Because sand shrimp are important items in the diets of many esturarine organisms, including Dungeness crabs, dredged-related entrainment of large numbers of sand shrimp might reduce their availability as forage (Armstrong, Stevens, and Hoeman 1982). Sand shrimp were the most numerically abundant organism entrained by dredges during the Dungeness crab studies in Pacific northwest estuaries.

  Although pink shrimp, (*Penaeus duorarum*), white shrimp (*P. aztecus*), and brown shrimp (*P. setiferus*) are commercially important species along the Gulf and Atlantic coasts and are protected by dredging restrictions to prevent disruption of migration or detrimental impacts to nursery areas, no references were found in the literature regarding potential entrainment effects.

  - *Entrainment rate:* Sand shrimp had the highest rates of entrainment among all organisms during the Dungeness crab studies. Entrainment rates by pipeline dredges were as high as 3.4 shrimp/cy. Entrainment rates by hopper dredges ranged from 0.063 to 3.38 shrimp/cy. Mean entrainment rates for *Crangon* spp. during pipeline and hopper dredging activities in various locations within Grays Harbor, Washington, can be found in Table 3. Entrainment rates varied significantly during testing of different operating procedures. When pumps were run while the draghead or cutterhead was positioned at or near bottom, the mean entrainment rate was 0.69 shrimp/cy; however, during times when clean water was being pumped to wash out the system and the draghead or cutterhead were not in direct contact with the substrate, the rate of entrainment reached 3.38 shrimp/cy. Based on a calculated annual shrimp population of 80 million, Armstrong, Stevens, and Hoeman (1982) estimated that total loss to the population from entrainment during the course of a "typical" dredging project could range from 1.2 to 6.5 percent.

Bivalves. Bivalve studies are summarized as follows:

- **Oysters:** Currently only the USAED, Baltimore, has environmental windows to prevent hydraulic entrainment of larval oysters. In the 1980's, entrainment of larval oysters by hydraulic dredges in the Chesapeake Bay was recognized as a potentially important issue. Pelagic, essentially passively drifting larvae of the eastern oyster (*Crassostrea virginica*), were hypothesized to be at risk of being entrained, particularly by hydraulic pipeline dredges. Entrained larvae are assumed to suffer 100-percent mortality by smothering under sediment, anoxia, starvation, or desiccation, even if they survive the mechanical forces caused by pumping of the water-sediment slurry. A workshop sponsored by the USAED, Baltimore, and the U.S. Army Engineer Waterways Experiment Station (WES) attempted to resolve the issue by assembling experts in oyster biology. Results of the workshop, summarized in the following text, were published in the peer-reviewed literature.

Table 3
Mean entrainment rates for *Crangon* spp. during pipeline and hopper dredging activities in Grays Harbor, Washington (adapted from Armstrong, Stevens, and Hoeman 1982)

Location	Dredge Type	Total cy	Entrainment Rate	
			Unadjusted	Adjusted*
Inner harbor (summer)	Pipeline	357.0	3.404	—
Outer estuary (winter/spring)	Pipeline	934.5	0.001	—
Middle estuary	Hopper	196.9	0.342	0.124
Middle estuary	Hopper	76.3	0.063	0.079
Middle estuary	Hopper	273.2	0.252	0.109
Inner harbor	Hopper	36.2	3.375	2.344
Middle estuary and inner harbor	Hopper	309.4	0.877	0.280
Outer estuary	Hopper	312.9	0.260	0.232

* Two entrainment rates are given for the hopper dredge. Certain estimates of entrainment were based on relatively small samples of dredged sediment. Samples of less than 10 cy frequently had no shrimp entrained. Unadjusted entrainment values are based on all samples regardless of total yards involved. Adjusted rates are based on these samples in excess of 10 cy (Armstrong, Stevens, and Hoeman 1982).

- *Entrainment rate:* One product of the oyster larvae entrainment workshop was a numerical model described by Carriker et al. (1986). The model utilizes conservative estimates of larval temporal and spatial distributions and densities, the mechanics and hydrodynamics of dredging operations, and appropriate dimensions of the body of water being dredged. The model predicts that late-stage larvae, which are most likely to be affected, would be entrained at a rate between 0.005 and 0.3 percent of the local population, thus having minimal negative effect. Lunz (1985) reached a conclusion of "no significant impact" from entrainment because the dredge entrains a very small portion of the total water volume flowing past the dredge, and larval oysters suffer a high natural mortality rate (99.999967 percent), thereby making the additional influence of entrainment insignificant. An opposing viewpoint was presented by Carter (1986), who estimated that entrainment mortalities could be as high as 25 percent throughout protracted dredging operations during the oyster spawning season. Both viewpoints are summarized by Presant (1986).

Fishes. Studies of fishes are summarized as follows:

Hydraulic entrainment of fishes has been a concern linked to dredging operations in the United States and elsewhere for several decades. Currently, seven USACE Districts report entrainment as a reason used to justify environmental windows on dredging activities. Species frequently cited include: Gulf and shortnose sturgeon, salmonids, American shad, and winter flounder. One of the earliest identified studies of fish entrainment involved juvenile salmon in the lower Fraser River, British Columbia, Canada, which represents a major source of recruitment to Pacific salmon populations (Braun 1974; Dutta and Sookachoff 1975 a, b). Although Braun (1974) found that no salmon fry were entrained by pipeline dredging, Dutta and Sookachoff (1975a) concluded that fry and smolts did suffer high entrainment rates by both pipeline and hopper dredges, particularly when salmon occupied the entire water column in narrow, constricted channels. An additional factor contributing to higher entrainment rates was hypothesized to be the inability of salmon fry and smolts to actively avoid the suction force of hydraulic dredges. Arsenault (1981) estimated that 0.00004 to 0.4 percent of the total out-migration of salmon fry and smolts was entrained by hydraulic dredges. Dutta and Sookachoff (1975a) and Tutty (1976) assessed postentrainment mortality (i.e., at the discharge) to be at or near 100 percent.

In Russia, Veshchev (1981) studied the effects of entrainment on migrating sturgeon larvae (*Acipenser guldenstadti* and *Acipenser stellatus*). Details of the type(s) of dredge plants involved were not provided. Veshchev could not find larvae in the discharge flows from the dredge, but calculated entrainment based on the catch of plankton nets placed upstream from the dredge, and thereby produced estimates of mortality as high as 76.8 percent. The sampling methodology was not described in sufficient detail to gauge the appropriate level of confidence that could be placed in these estimates.

Some of the first records of fish entrainment occurred incidentally during Tegelberg and Arthur's (1977) study of entrainment of Dungeness crabs in Grays Harbor, Washington. They observed entrainment of nine fish species, three of which were anadromous. Additionally, Bengston and Brown (1976) observed the entrainment of adult spiny dogfish (*Squalus acanthias*) during pipeline dredging. While these observations were opportunistic, several studies have since examined the issue in more detail, including Armstrong, Stevens, and Hoeman (1982); McGraw and Armstrong (1990); Larson and Moehl (1990); and Buell (1992).

- **Sport and commercial fishes entrainment rate:** Entrainment rates for 15 species of sport and commercial fishes were reported by Armstrong, Stevens, and Hoeman (1982) (Table 4). Entrainment rates ranged from 0.001 to 0.135 fish/cy for both pipeline and hopper dredging activities. Both small and large fish were entrained in similar proportions; therefore, it was concluded that large fish did not actively avoid the dredge any more effectively than smaller fish. Entrained fish during this study suffered an initial mortality rate of 37.6 percent. McGraw and Armstrong (1990) collected entrainment information on 28 species of fish during a 10- year period (Table 4). Most species (e.g., slender sole, *Lyopsetta exilis*) had relatively low absolute entrainment rates approaching 0.001 fish/cy. Species with the highest entrainment rates during this study were the Pacific sanddab (*Citharichthys sordidus*), Pacific staghorn sculpin (*Leptocottus armatus*), and the Pacific sand lance (*Ammodytes hexapterus*) at 0.076, 0.092 and 0.594 fish/cy, respectively. Larson and Moehl (1990) studied fish entrainment during a 4-year study at the mouth of the Columbia River in Oregon. Entrainment rates ranged from <0.001 to 0.341 fish/cy for 14 species or taxonomic groups of fishes (Table 4). The majority of fishes entrained were demersal; however, a few pelagic species were collected, including anchovy, herring, and smelt (Table 4). Entrainment of anadromous fishes

Table 4
Mean fish entrainment rates by species (fish/cy) for hydraulic dredges (adapted from Larson and Moehl 1990[1] and McGraw & Armstrong 1990[2])

Species	Hopper[1] (fish/cy)	Hopper[2] (fish/cy)	Pipeline[2] (fish/cy)
Anchovy (*Engraulididae*)	0.008	0.001	—
Northern Anchovy (*Engraulis mordax*)	—	0.018	—
Herring (*Clupeiformes*)	0.008	—	—
Arrowtooth Flounder (*Atheresthes stomias*)	—	0.008-0.022	—
Starry flounder (*Platichthys stellatus*)	—	0.001-0.002	—
English Sole (*Pleuronectes vetulus*)	—	0.006-0.035	0.001-0.003
Sand Sole (*Psettichthys melanostictus*)	—	0.001-0.016	—
Slender Sole (*Lyopsetta exilis*)	—	0.001	—
Pacific Sanddab (*Citharichthys sordidus*)	—	0.004-0.076	—
Speckled Sanddab (*Citharichthys sordidus*)	—	0.003	—
Flatfish (*Pleuronectiformes*)	0.008	0.001-0.028	—
Buffalo Sculpin (*Enophrys bison*)	—	0.006	—
Prickly Sculpin (*Cottus asper*)	—	0.020	0.004
Pacific Staghorn Sculpin (*Leptocottus armatus*)	0.003	0.007-0.092	0.001-0.037
Cabezon (*Scorpaenichthys marmoratus*)	<0.001	—	—
Kelp Greenling (*Hexagrammos decagrammus*)	—	0.001	—
Lingcod (*Ophiodon elongatus*)	—	0.001-0.002	—
Poacher (*Agonidae*)	-.009	—	—
Warty Pacher (*Occella verrucosa*)	—	0.009	—
Snailfish (*Cyclopteridae*)	—	0.001	—
Showy Snailfish (*Liparis pulchellus*)	0.002	—	—
Pacific Sandfish (*Trichodon trichodon*)	<0.001	0.002	—
Pacific Sand Lance (*Ammodytes hexapterus*)	0.341	0.036-0.594	—
Saddleback Gunnel (*Pholis ornata*)	—	0.001-0.005	0.023
Snake Prickleback (*Lumpenus sagitta*)	—	0.003-0.135	—
Surfperch (*Embiotocidae*)	<0.001	0.001	—
Eulachon (*Thaleichthys pacificus*)	0.002	—	—
Chum Salmon (*Oncorhynchus keta*)	—	—	0.008
Smelt (*Osmeridae*)	—	0.009	—
Pipefish (*Syngnathidae*)	—	0.008	—
Bay Pipefish (*Syngathus leptorhynchus*)	—	0.006	—
Three-Spined Stickleback (*Gasterosteus aculeatus*)	—	—	0.004
Big Skate (*Raja binoculata*)	<0.001	—	—
Longnose Skate (*Raja rhina*)	—	0.003	—
Pacific Tomcod (*Microgadus proximus*)	<0.001	0.001-0.008	—
Spiny Dogfish (*Squalus acanthias*)	<0.001	—	—

was limited to eulachon (*Thaleichthys pacificus*). Larson and Moehl (1990) concluded that it is unlikely that anadromous fishes are entrained in significant numbers by dredges, at least outside of constricted river areas.

Buell (1992) monitored entrainment by the hydraulic dredge *R. W. Lofgren* by sampling fishes discharged into a containment area and reported that with the exception of white sturgeon (*Acipenser transmontanus*), entrainment involved small numbers of a few fish species. Although substantial numbers of juvenile white sturgeon were entrained, (size class 300 to 500 mm), these were attributed to entrainment at one location referred to as the local "sturgeon hole." The overall rate of entrainment recorded for sturgeon in the Buell (1992) study was 0.015 fish/cy, which is comparable to rates reported for other species of fish.

In the Fraser River, Canada, juvenile salmonids and eulachon were the dominant taxa entrained, whereas at the mouth of the Columbia River and in Grays Harbor, nonanadromous estuarine and marine demersal species were the most frequently entrained (McGraw and Armstrong 1990; Larson and Moehl 1990). One possible explanation in addition to dredge location (the Fraser River site was upstream from the estuary) relates simply to the degree of constriction of the waterway. Juvenile salmon and smelt in the Fraser River case were distributed in closer proximately to the dredge, increasing their relative probabilities of entrainment. In contrast, the mouth of the Columbia River and Grays Harbor are open expanses which allow fish to disperse over a greater area as they migrate through the estuary.

- **Modeling-larval fish entrainment:** Boreman, Goodyear, and Christensen (1981) developed the Empirical Transport Model (ETM) to estimate the conditional mortality rate of aquatic organisms due to water removal. Burton, Weisberg, and Jacobson (1992) utilized the ETM to simulate a "worst case scenario" of entrainment of striped bass (*Morone saxatilis*), herring (*Alosa* spp.), and white perch (*Morone americana*) larvae involving the simultaneous operation of four hydraulic dredges in the Delaware River. For species such as striped bass, the study concluded that less than 1 percent of the total larval population would be entrained by the dredges. Burton, Weisberg, and Jacobson (1992) concluded that the effects of these entrainment rates on larval populations for these and similar species would be minimal.

Marine turtles. Marine turtles studies are summarized as follows:

- **History of dredging effects on sea turtles:** Five threatened or endangered species of sea turtles that occur along the southeastern U.S. coast are potentially affected by hopper dredging activities (Dickerson et al. 1995). Sea turtle mortalities due to entrainment during hopper dredging operations have been documented since 1980. The National Marine Fisheries Service (NMFS) determined that, because of their life history and behavioral patterns, only the loggerhead (*Caretta caretta*), green (*Chelonia mydas*), and Kemp's ridley (*Lepidochelys kempi*) are put at risk from hopper dredging (NMFS, Regional Biological Opinion 1995). Early surveys conducted by Butler, Nelson, and Henwood (1987) demonstrated the presence of sea turtles in several channels along the Florida coast. The Endangered Species Observer Program (ESOP), established in 1980, required observers to quantify entrainment of turtles by screening dredged material from hopper dredge intake structures or overflows. In 1981, a Sea Turtle/Dredging Task Force was formally established to address the issue of sea turtle entrainment.
- **Entrainment rates:** In the decade following the initiation of entrainment monitoring, 174 sea turtles were entrained (0.91 turtles/100,000 cy) in dredging operations conducted in

southeastern U.S. channels (Dickerson et al. 1995). Of these, 159 resulted in mortality, while 15 were classified as live/injured. Entrainment rates ranged from 0.052 turtles/100,000 cy for Brunswick Harbor, Georgia, to 1.68 turtles/100,000 cy for Canaveral Harbor, Florida (Table 5). Canaveral Harbor accounted for 80 percent of all turtle entrainment incidents for the decade with 128 dead and 11 live/injured turtles. Fernandina Harbor, St. Marys River Entrance Channel, Florida, recorded the second highest combined entrainment rate (0.4 turtles/100,000 cy), which accounted for 19 percent of the total "take" (29 dead, 2 live/injured). Mean entrainment rates (turtles/100,000 cy) are given by channel dredged and year in Table 5.

From 1990 through 1997, there have been an additional 105 sea turtles entrained. This reflects a significant reduction in the number of turtle entrainment incidents in years subsequent to 1980 when 71 turtles were entrained during dredging in Cape Canaveral Harbor. However, knowledge gained from studies which focused on relative turtle abundance and specific behaviors, as well as engineering studies on draghead modifications, has not entirely eliminated dredge-related sea turtle entrainment. While entrainment rates may be low for several years, periodically there is a substantial increase in the level of entrainment. An example of this occurred in 1991 when Brunswick and Savannah Harbors, Georgia, experienced a dramatic increase in sea turtle entrainment (34 sea turtles) for an entrainment rate of 1.39 turtles/100,000 cy and 1.55 turtles/100,000 cy, respectively. These two harbors had previously shown low entrainment rates of less than 0.11 turtles/100,000 cy and 0.55 turtles/100,000 cy, respectively. The most plausible explanation for this was that dredging occurred during March through June in Brunswick Harbor and June through August in Savannah Harbor when water temperatures were above 25 °C. This may have been above a temperature threshold at which turtles move into nearshore waters.

Sea turtle entrainment rates remained relatively low in most ship channels after the high level reported in 1991 until 1997 when sea turtle entrainment approached the incidental take level established for the southeast region. The highest entrainment rate for the spring of 1997 was obtained during dredging operations conducted in Morehead City Harbor, North Carolina. During this time, six loggerhead turtles were entrained after the removal of only 120,000 cy of sediment. Although the dredge was operating with sea turtle deflecting dragheads, an entrainment rate of 5.0 turtles/100,000 cy occurred, resulting in the termination of the Morehead City Harbor dredging project. Other channels experiencing higher levels of entrainment include: Fernandina Harbor (Kings Bay), Florida (9 turtles entrained), at a rate of 2.06 turtles/100,000 cy; Charleston Harbor (5 turtles entrained), at a rate of 1.43 turtles/100,000 cy; and Savannah Harbor (3 turtles entrained), at a rate of 0.55 turtles/100,000 cy. In 1997, a total of 28 loggerhead sea turtle entrainment incidents had occurred during hopper dredging activities (Table 5). Contributing factors for these high entrainment rates appear to be an early and unusually high abundance of sea turtles in nearshore and inshore waters; and the reduced efficiency of the draghead deflector under certain dredging conditions.

- **Sea turtle entrainment by species:** By species, loggerheads were the most frequently entrained during hopper dredging, accounting for 67.4 percent of the total entrainment (for turtles identified per species). Green sea turtles and Kemp's ridleys accounted for 11.1 and 2.5 percent of entrainment incidents, respectively. Nineteen percent were unidentified as to species, since only fragments were recovered. Assuming that the majority of unidentified entrained turtles were loggerheads, the overall entrainment rate for this species could account for as much as 86.4 percent of the total.

Table 5
Distribution of quantity of dredged material (cy), entrained sea turtles by species, and rate of entrainment for Atlantic coast ship channels and inlets (adapted from Dickerson et al. 1995)

Channel	Amound Dredged (100,000 cy)	*C. Caretta*		*L. Kempi*		*C. Mydas*		Unidentified Turtles	Total # of Turtles Entrained	Entrainment Rate (turtles/ 100,000 cy)
		Dead	Live/ Injured	Dead	Live/ Injured	Dead	Live/ Injured			
Canaveral Harbor, FL (1980-1994)	85.5	71	4	0	0	11	11	51	148	1.73
Palm Beach Harbor, FL (1995-1996)	3.12	4	0	0	2	1	0	0	7	2.24
Fort Pierce Inlet, FL (1994)	0.62	0	0	0	0	1	0	0	1	1.61
Fernandina Harbor, FL (1986-1997)	123.4	35	0	3	0	3	4	1	46	0.40
Brunswick Harbor, GA (1988-1997)	59.65	20	2	1	0	0	0	1	24	0.40
Savannah Harbor, GA (1989-1997)	56.8	23	2	0	1	0	0	0	26	0.46
Charleston Harbor, SC (1991-1997)	33.8	8	0	0	0	0	0	0	8	0.24
Myrtle Beach, SC (1997)	25	3	0	0	0	0	0	0	3	0.12
Morehead City Harbor, NC (1994-1997)	32	7	0	0	0	0	0	0	7	0.22
Wilmington Harbor, NC (1997)	3	1	0	0	0	0	0	0	1	0.33
Delaware Bay, DE (1994)	12	1	0	0	0	0	0	0	1	0.08

SUMMARY: Effects of entrainment by hydraulic dredging operations on aquatic organisms have been and continue to be an issue of environmental concern. Clearly, assessment of actual impacts due to entrainment pose severe technical challenges. Studies to date illustrate the difficulties in determining precise estimates of absolute entrainment rates and have seldom been able to determine population-level consequences with any degree of confidence. Placing mortalities due to entrainment by dredges into a fishery population dynamic framework, such that dredging can be viewed within the context of other anthropogenic and natural sources of mortality for a resource, would enhance the ability to balance needs for resource protection and dredging project schedules. The persistent lack of quantitative data characterizing effects of entrainment hampers efforts to resolve the issue as it applies to environmental windows. Much of the available evidence suggests that entrainment is not a significant problem for many species of fish and shellfish in many bodies of water that require periodic dredging. Also, many dredging restrictions are based upon limited scientific data, suggesting that well-designed studies and new assessment tools are needed to remove entrainment issues from the realm of subjectivity. In the same regard, however, certain types of dredging operations appear to pose sufficient risk to sensitive resources such that continued application of restrictions is justified. Notably, these exceptions include the conduct of dredging operations in narrow constricted river channels, particularly where sturgeon may be present in appreciable numbers or in channels seasonally occupied by sea turtles or other protected species. Additional studies are definitely warranted to establish the necessity of entrainment-related environmental windows for these resources of concern.

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