DELAWARE RIVER
ADULT AND JUVENILE
STURGEON SURVEY
WINTER 2005

Prepared for

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Contract No. DACW61-00-D-0009
Delivery Order No. 0068

September 2005

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1.0 INTRODUCTION

1.1 BACKGROUND

The Delaware River Basin Fish and Wildlife Management Cooperative has established dredging restrictions for the protection of fisheries resources that restricts blasting in the Delaware River to the winter months (1 December to 15 March). This restriction was primarily imposed to protect springtime anadromous spawning fish and summer spawning and nursery activity in the river. The U.S. Army Corps of Engineers has been working on plans to deepen the Delaware River to 45 feet below mean low water from the Philadelphia port facilities to the sea. If the Delaware River Main Channel Deepening project proceeds as planned in future years, blasting will be needed to remove rock outcrops located in the Marcus Hook, Chester, Eddystone and Tinicum ranges of the channel (Figures 1-1 and 1-2). While blasting in the winter months should protect most fish species that use the Delaware River in the spring and warmer months, Atlantic sturgeon (*Acipenser oxyrinchus*) and Shortnose Sturgeon (*Acipenser brevirostrum*) may be susceptible to blasting mortality if they use the Marcus Hook area during winter.

Shortnose Sturgeon occur throughout the Delaware River estuary and may occur in the nearshore ocean (Brundage and Meadows 1982). The abundance of adults is greatest in the tidal river from Trenton. New Jersey, to Philadelphia, Pennsylvania (Hastings et al. 1987). Spawning occurs primarily in the lower non-tidal Delaware River during April (Brundage 1986). After spawning, adult Shortnose Sturgeon disperse and spend the summer and early fall foraging throughout the tidal river, with some fish moving into Delaware Bay (Brundage and Meadows 1982; O'Herron et al. 1993; ERC, unpublished data). Adult Shortnose Sturgeon are known to over winter in dense aggregations in the Bordentown, New Jersey, to Trenton reach of the river (O' Herron et al. 1993). It is believed that some shortnose sturgeon over winter in the lower tidal Delaware River, although areas of aggregation have not been identified.

Analysis of the movements of acoustically-tagged adult Shortnose Sturgeon during April through December 2003 indicate that the Marcus Hook to Tinicum reach of the Delaware River is used as a short-term migratory route and, to a lesser extent, a summer/fall foraging area (ERC 2004).

Little is known regarding the occurrence and distribution of juvenile shortnose sturgeon in the Delaware River. In other rivers, shortnose sturgeon are known to occur upstream of the freshwater-saltwater interface during summer. Depending on river discharge, this zone can variably occur from Wilmington, Delaware, to Philadelphia, including the Marcus Hook to Tinicum reach of the river.

The Atlantic Sturgeon is an anadromous species variously utilizing oceanic, estuarine, and riverine habitats depending on its life stage. The location of spawning grounds in the Delaware River are not known, but based on information from other estuary systems, they would occur in the middle estuary, probably north of Wilmington, Delaware (RM 71), but may extend

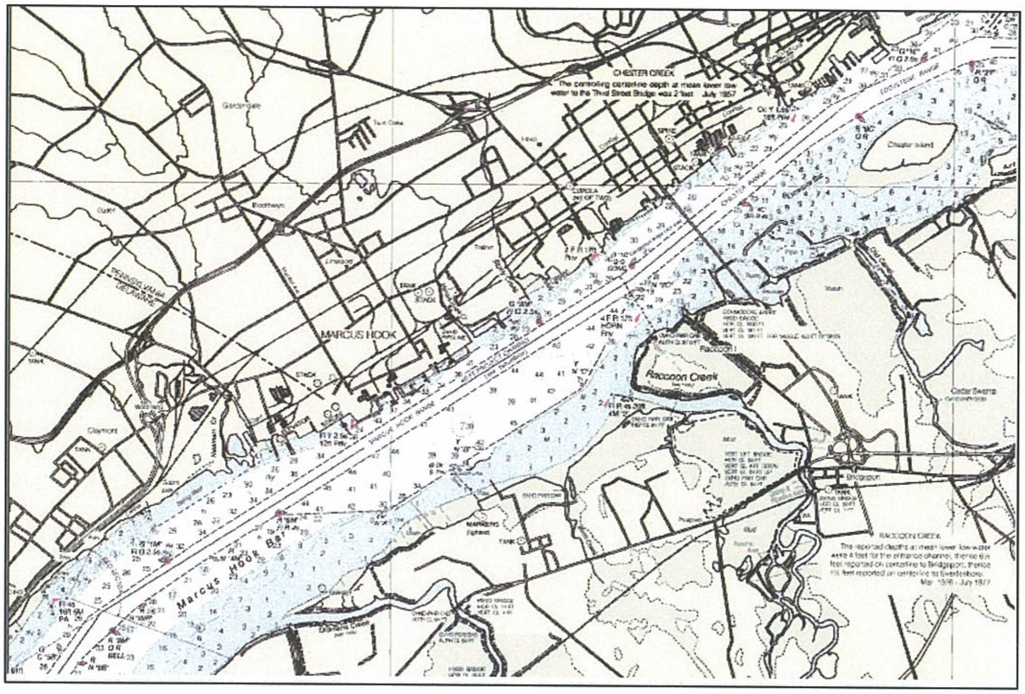

Figure 1-1. Location of the Marcus Hook and Chester Navigational Ranges

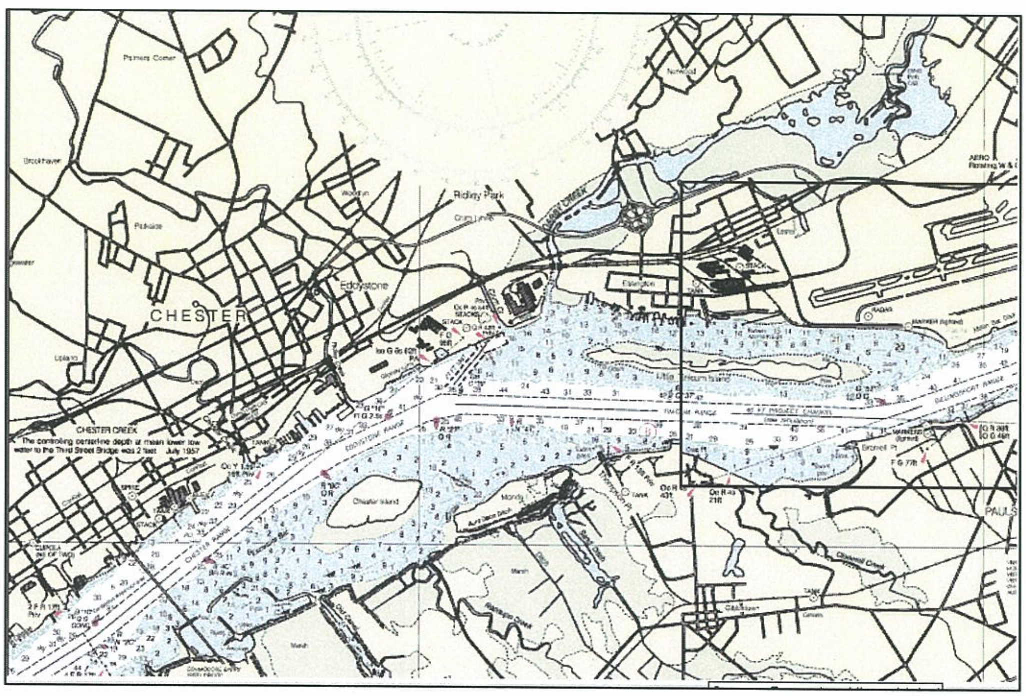

Figure 1-2. Location of the Eddystone and Tinicum Navigational Ranges

from Bombay Hook, Delaware (RM 34) to Chester, Pennsylvania (RM 83). Spawning occurs from late April to early June in moving water over hard bottom substrate. After spawning, the adults move seaward over the course of the summer and fall. Juveniles utilize the estuary year-round for several years after hatching, and may migrate annually to the lower estuary and immediate oceanic waters during fall and winter (O'Herron. et al. 1995). Atlantic Sturgeon spawn in deep water and are likely to use the navigation channel for this purpose, although no gravid adults have been recently collected. The critical reach of river for spawning is believed to be from Artificial Island (RM 55) to Chester, Pennsylvania (RM 80), from early April to mid-June. Although the Federal government does not presently list this species as endangered, the Atlantic States Marine Fisheries Commission has recently adopted Amendment 1 to the Atlantic Sturgeon fisheries management plan. The ASMFC plan recommends that a coast-wide moratorium on sturgeon landings be implemented by all member states. This recommendation has been adopted and the moratorium is expected to last a minimum of 40 years. NOAA Fisheries is currently conducting a status review for the Atlantic Sturgeon that could result in the species being listed as threatened or endangered.

Assuming that the Main Channel deepening proceeds, blasting the rock outcrops in the Marcus Hook area during the winter period could pose unacceptable risks to sturgeon adults and juveniles that may use the area in winter. However, little historical data on sturgeon use of this part of the river exists, particularly during winter. The lack of information on sturgeon populations in the Marcus Hook region is partially a function of the difficulties the physical conditions the area poses to routine fisheries survey techniques (i.e., trawling and gillnetting). The Delaware River near Chester, Pennsylvania is subject to high tidal currents (4-5 knots), and heavy commercial tanker traffic, and has rocky bottom features and other snags that make trawling with nets and other traditional sampling devices extremely difficult and dangerous.

The challenge for this project was to design an effective method to survey the project area for sturgeon. In association with two local experts on Delaware River sturgeon (Harold M. Brundage III and John C. O'Herron, Environment Research and Consulting, Inc.) a unique survey method employing the use of a Video Ray® submersible underwater video system was devised.

1.2 STUDY OBJECTIVE

The purpose of this study was to determine if sturgeon adults and juveniles inhabit the Marcus Hook to Tinicum reach of the Delaware River during the winter blasting period, and if so, to evaluate the abundance of sturgeon in the project area relative to that in known upriver over wintering habitats near Trenton, New Jersey (Figure 1-3 and 1-4).

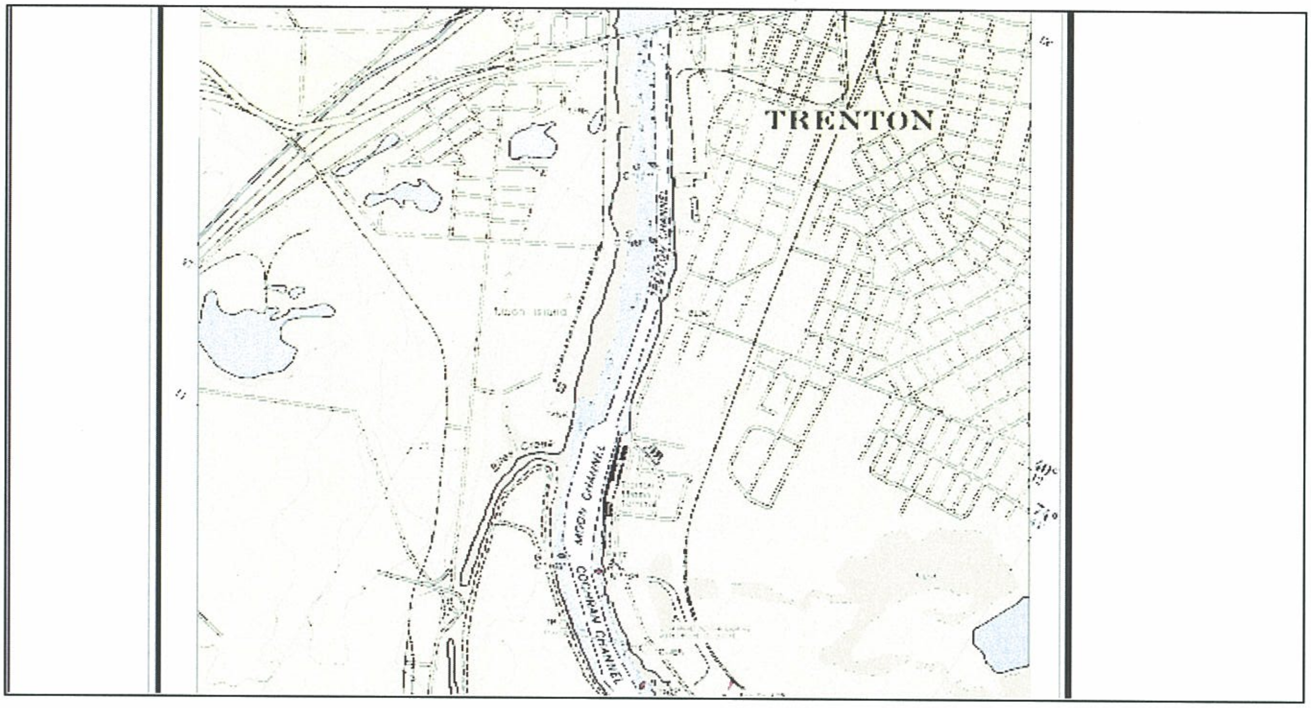

Figure 1-3. Location of the navigational channel near Trenton, New Jersey

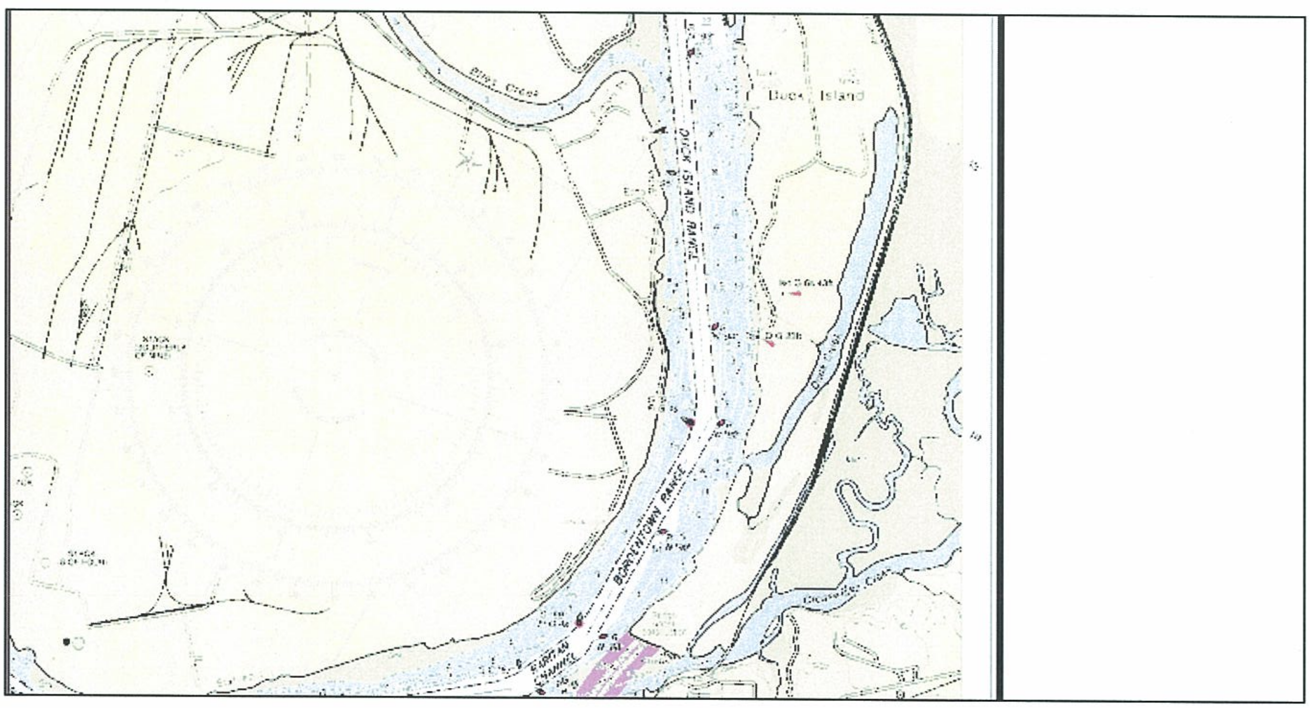

Figure 1-4. Location of the Bordentown and Duck Island Navigational Ranges

2.0 METHODS

2.1 FIELD

Surveys for the presence of Atlantic and Shortnose Sturgeon were conducted between March 4 and March 25, 2005 primarily using a Video Ray® Explorer submersible remotely operated vehicle (ROV). The Video Ray® was attached to a 1.0 x 1.0 x 1.5 meter aluminum sled which was towed over navigational channel bottom habitats behind Versar's 25-foot research boat the R/V Integrity (Figures 2-1 and 2-2). All images captured by the underwater camera were transmitted through the unit's electronic tether and recorded on 60-minute Mini Digital Video Cassettes with a Sony GV-D1000 NTSC Digital Video Cassette Recorder. The recorded images were captured through the video monitor feed on the control unit of the ROV. A total of 43 hours of bottom video were collected on 14 separate survey days. Twelve days of survey work were conducted in the project area, specifically the Marcus Hook, Eddystone, Chester, and Tinicum navigational ranges (Figure 2-3), while two separate days of survey work were conducted up river near Trenton, New Jersey, at an area known to have an over wintering population of Shortnose Sturgeon (Figure 2-4; Table 2-1).

After deploying the sled and bottom contact was confirmed, the recording of digital video was initiated. The sled was generally towed on the bottom parallel to the centerline of the channel and into the current at 0.8 knots. Tows were attempted with the current to reduce the amount of "snow" created in the recordings from passing particles. This tow method was abandoned after hanging the sled up on debris and determining that the speed over the bottom could not be properly controlled. Tow track logs were maintained throughout the survey and any fish seen on the ROV monitor was noted. Boat position during each video tow was recorded every five minutes with the vessel's Furuno Geographic Positioning System (GPS). The Sony digital recorder recorded a time stamp that could be matched with the geographic coordinates taken from the on-board GPS.

Limited 25-foot otter trawling and gillnet sets were conducted initially to provide density data, and later to provide ground truth information on the fish species seen in the video recording. Large boulders and other snags that tore the net and hung up the vessel early on in the study prompted us to abandon this effort for safety reasons given high degree of tanker traffic in lower Delaware River. The trawl net was a 7.6-m (25-foot) experimental semi-balloon otter trawl with 44.5-mm stretch mesh body fitted with a 3.2-mm stretch mesh liner in the cod end. Otter trawls were generally conducted for five minutes unless a snag or tanker traffic caused a reduction in tow time. Both Versar and Environment Research and Consulting, Inc. (ERC) staff deployed experimental gillnets periodically throughout the survey period in the Marcus Hook area. Versar's experimental gillnets were 91.4-m in length and 3-m deep and were composed of six 15.2-m panels of varying mesh size. Of the six panels in each net, two panels were 50.8-mm stretch mesh, 2 panels were 101.6-mm stretch mesh and two panels were 152.4-mm stretch mesh. ERC's gillnets were 100 m in length and consisted of four 25 x 2-m panels of 2.5-10.2-cm stretched monofilament mesh in 2.5 cm increments. Gill nets were generally set an hour

Figure 2-1. Video Ray® Explorer attached to bottom sled

Figure 2-2. Versar's 25-foot R/V Integrity at the base of the Commodore Barry Bridge in Chester, Pennsylvania

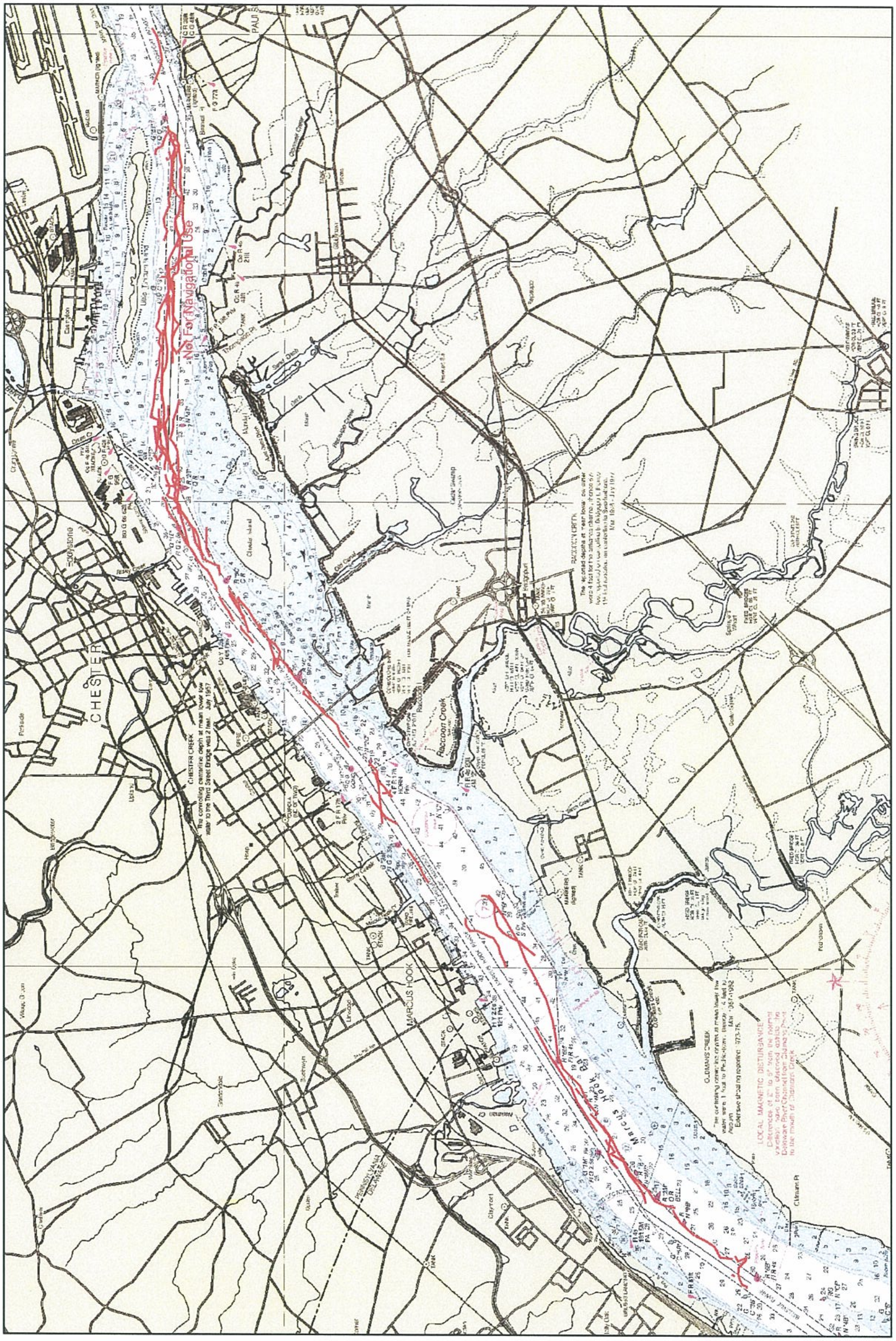

Figure 2-3. Tow tracks for bottom imaging surveys for sturgeon in the Marcus Hook project area

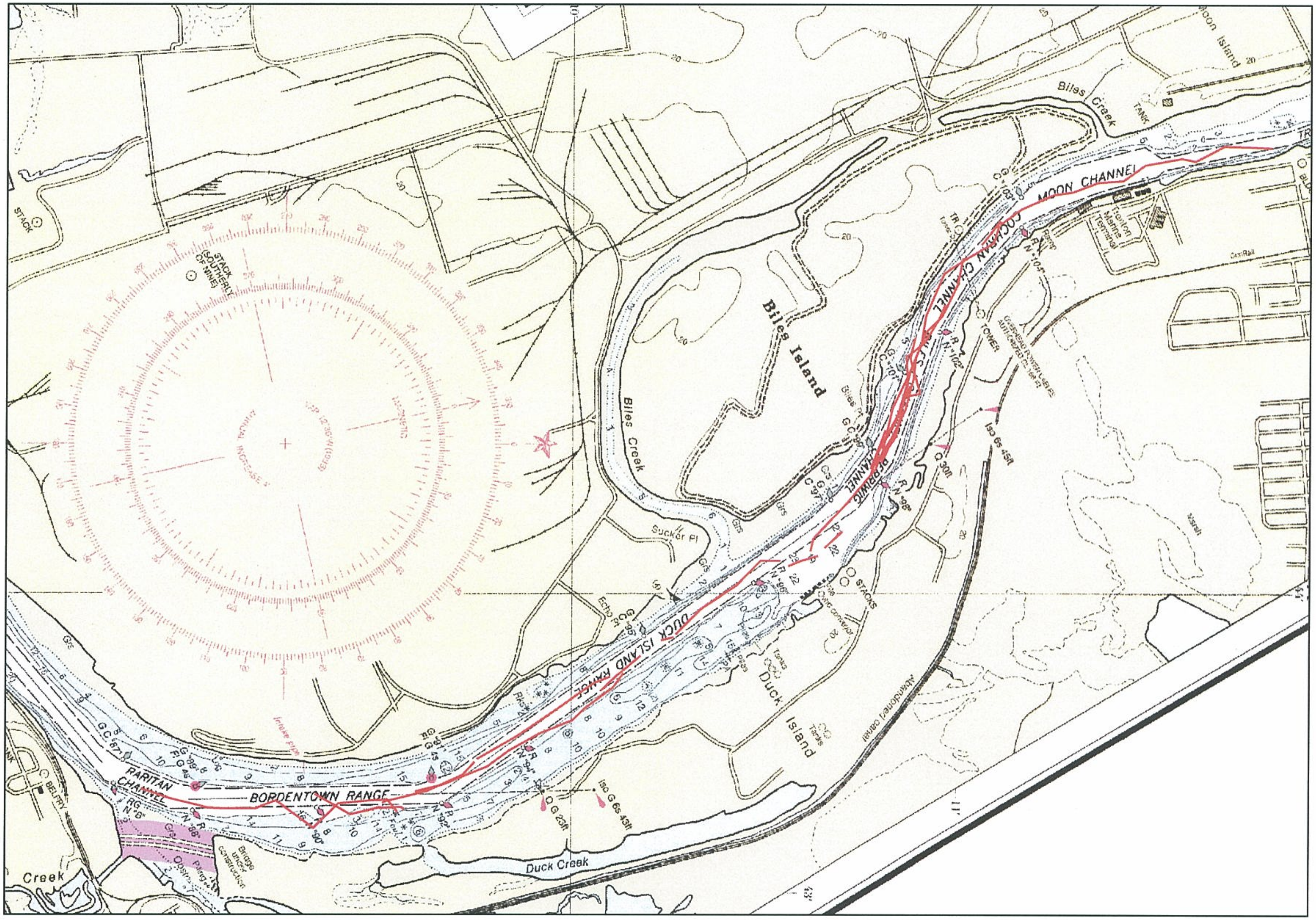

Figure 2-4. Tow tracks for bottom imaging surveys for sturgeon near Trenton, New Jersey.

Table 2-1. Summary of bottom imaging video tow distances by survey date and navigational range

Date	Navigational Range	Tow Distance (meters)
03/04/2005	Chester	3543
03/05/2005	Chester	4151
03/05/2005	Tinicum	3199
03/07/2005	Marcus Hook	1101
03/10/2005	Eddystone	5281
03/10/2005	Marcus Hook	467
03/10/2005	Tinicum	1417
03/11/2005	Marcus Hook	1798
03/13/2005	Eddystone	1297
03/13/2005	Marcus Hook	2280
03/13/2005	Tinicum	823
03/14/2005	Duck Island	3567
03/14/2005	Perring Channel	2884
03/15/2005	Marcus Hook	8981
03/16/2005	Chester	4111
03/16/2005	Marcus Hook	387
03/16/2005	Tinicum	2462
03/17/2005	Marcus Hook	3121
03/21/2005	Duck Island	1659
03/21/2005	Perring Channel	1719
03/21/2005	Trenton Channel	2919
03/22/2005	Chester	440
03/22/2005	Eddystone	2003
03/22/2005	Tinicum	1137
03/24/2005	Marcus Hook	1103
03/24/2005	Tinicum	6086
03/25/2005	Chester	1368
03/25/2005	Eddystone	6146

before slack high or low water and allowed to fish for two hours as the nets had to be retrieved before maximum currents were reached. Table 2-2 summarizes the number and locations of the trawl and gillnet sets deployed during the survey.

All sampling was performed in accordance with Permit to Take Endangered Species No. 1486, issued to Harold M. Brundage III (Environmental Research and Consulting, Inc.).

Table 2-2. Trawl and gillnet sampling dates, times, and coordinates for the sturgeon survey conducted in the Delaware River during February and March 2005

Date	Range	Time	Sample Number	Latitude		Longitude	
				Degrees	Minutes	Degrees	Minutes
Trawl							
02/09/2005	Marcus Hook	16:27	1	39	48.324	75	24.736
02/09/2005	Marcus Hook	14:15	2	39	47.209	75	26.035
02/09/2005	Marcus Hook	13:48	3	39	47.362	75	26.684
02/09/2005	Marcus Hook	12:15	4	39	47.615	75	26.218
02/09/2005	Marcus Hook	11:50	5	39	47.646	75	28.228
02/14/2005	Marcus Hook	12:53	6	39	47.018	75	27.303
02/14/2005	Marcus Hook	12:35	7	39	47.205	75	27.108
02/14/2005	Marcus Hook	12:18	8	39	47.316	75	26.839
02/14/2005	Marcus Hook	11:43	9	39	47.54	75	26.372
02/14/2005	Marcus Hook	14:30	10	39	46.97	75	27.32
02/14/2005	Marcus Hook	14:13	11	39	46.552	75	28.897
02/15/2005	Marcus Hook	15:34	12	39	47.067	75	26.276
02/15/2005	Marcus Hook	12:07	13	39	46.802	75	27.617
02/15/2005	Marcus Hook	11:41	14	39	47.201	75	27.025
02/15/2005	Marcus Hook	11:16	15	39	47.482	75	26.474
Gillnets							
02/09/2005	Marcus Hook	12:48	1	39	47.525	75	26.347
02/14/2005	Marcus Hook	11:14	2	39	47.611	75	26.202
02/15/2005	Marcus Hook	11:00	3	39	47.552	75	26.327
02/15/2005	Marcus Hook	11:30	4	39	48.685	75	23.294
02/15/2005	Marcus Hook	12:00	5	39	48.585	75	23.448
02/15/2005	Marcus Hook	12:26	6	39	49.129	75	22.984
02/16/2005	Marcus Hook	12:00	7	39	48.529	75	23.554
02/16/2005	Marcus Hook	12:26	8	39	48.57	75	23.456
02/16/2005	Marcus Hook	12:45	9	39	48.618	75	23.349
03/04/2005	Marcus Hook	11:55	10	39	48.657	75	23.314
03/04/2005	Marcus Hook	12:12	11	39	48.574	75	23.497
03/04/2005	Marcus Hook	12:36	12	39	48.414	75	23.96
03/06/2005	Tinicum	8:45	13	39	51.006	75	16.234
03/06/2005	Tinicum	9:05	14	39	50.986	75	16.773
03/06/2005	Tinicum	9:25	15	39	51.037	75	17.514
03/17/2005	Marcus Hook	10:50	16	39	46.968	75	27.74
03/17/2005	Marcus Hook	10:25	17	39	47.303	75	27.154
03/17/2005	Marcus Hook	10:40	18	39	47.104	75	27.523
03/18/2005	Marcus Hook	10:16	19	39	48.92	75	23.185
03/18/2005	Marcus Hook	10:44	20	39	48.662	75	23.344
03/18/2005	Marcus Hook	11:05	21	39	48.586	75	23.617

2.2 LABORATORY

Digital tapes were reviewed in a darkened laboratory at normal or slow speed using a high quality 28-inch television screen as a monitor. When a fish image was observed the tape was slowed and advanced frame by frame (30 images per second were recorded by the system). The time stamp where an individual fish was observed was recorded by the technician. Each fish was identified to the lowest practical taxon (usually species) and counted. A staff fishery biologist reviewed questionable images and species identifications. Distances traveled by the sled between time stamps were calculated based on the GPS coordinates recorded in the field during each tow. Total fish counts between the recorded coordinates within a particular tow were converted to observed numbers per 100 meters of tow track.

3.0 RESULTS

Turbidity in the Marcus Hook region of the Delaware River limited visibility to about 18 inches in front of the camera. However, despite the reduced visibility, several different fish species were recorded by the system including sturgeon. In general, fish that encountered the sled between the leading edge of the sled runners were relatively easy to distinguish. The major fish species seen in the video images where confirmed by the trawl and gillnet samples (Tables 3-1 and 3-2). In the Marcus Hook project area, a total of 39 survey miles of bottom habitat were recorded in twelve separate survey days. Eight different species were observed on the tapes from a total of 411 fish encountered by the camera (Table 3-3; Figure 3-1). White perch, unidentified catfish, and unidentified shiner were the most common taxa observed. Three unidentified sturgeon were seen on the tapes, two in the Marcus Hook navigational Range, and one in the Tinicum navigational range (Figure 3-2). Although we could not determine if these sturgeon were Atlantic or Shortnose, gillnetting in the Marcus Hook anchorage produced one juvenile Atlantic Sturgeon (Figure 3-3) that was 396 mm in total length, 342 mm in fork length, and weighed 250 g.

Water clarity in the Trenton survey area was much greater (about 6 feet ahead of the camera) and large numbers of Shortnose Sturgeon were seen in the video recordings. In a total of 7.9 survey miles completed in two separate days of bottom imaging, 61 Shortnose Sturgeon were observed (Figure 3-4; Table 3-3). To provide a comparative measure of project area density (where visibility was limited) to up river densities (where visibility was greater), each of the 61 sturgeon images were classified as to whether the individual fish was observed between the sled runners or whether they were seen ahead of the sled. Real time play backs of video recordings in the upriver sites indicated that the sturgeon did not react to the approaching sled until the cross bar directly in front of the camera was nearly upon it. Thirty of the 61 upstream sturgeon images were captured when the individual fish was between the runners. Using this criterion, approximately 10 times more sturgeon were encountered in the upriver area relative to the project site near Marcus Hook where three sturgeon were observed (Table 3-3). Using the number of sturgeon observed per 100 meters of bottom surveyed, the relative sturgeon density in the project area was several orders of magnitude less than those observed in the Trenton area. The relative density of unidentified sturgeon in the Marcus Hook area was 0.005 fish per 100 meters while the densities of Shortnose Sturgeon between the sled runners in the upriver area was 0.235 fish per 100 meters.

Table 3-1. Summary of 25-foot trawl catches taken in the Marcus Hook study area during the March 2005 sturgeon survey

Date	Range	Sample Number	Species	Total Caught
02/09/2005	Marcus Hook	1	Channel Catfish	4
			Eastern Silvery Minnow	14
			White Perch	12
02/09/2005	Marcus Hook	2	Eastern Silvery Minnow	2
			White Perch	19
02/09/2005	Marcus Hook	3	Channel Catfish	5
			Eastern Silvery Minnow	7
			White Perch	24
02/09/2005	Marcus Hook	4	American Eel	1
			Channel Catfish	5
			Eastern Silvery Minnow	8
			White Perch	3
			White Sucker	1
02/09/2005	Marcus Hook	5	Eastern Silvery Minnow	12
			White Perch	4
02/14/2005	Marcus Hook	6	Eastern Silvery Minnow	5
			White Perch	2
02/14/2005	Marcus Hook	7	American Eel	2
02/14/2005	Marcus Hook	8	Channel Catfish	1
			Eastern Silvery Minnow	1
			White Perch	6
02/14/2005	Marcus Hook	9	Eastern Silvery Minnow	2
			White Perch	15
02/14/2005	Marcus Hook	10	American Eel	1
			Channel Catfish	3
			Eastern Silvery Minnow	4
			Tessellated Darter	1
			White Perch	1
02/14/2005	Marcus Hook	11	Eastern Silvery Minnow	9
			White Perch	2

Table 3-1. Continued

Date	Range	Sample Number	Species	Total Caught
02/15/2005	Marcus Hook	12		0
02/15/2005	Marcus Hook	13	American Eel	1
			Channel Catfish	1
			Eastern Silvery Minnow	2
			White Perch	23
02/15/2005	Marcus Hook	14	Channel Catfish	1
			Eastern Silvery Minnow	4
			White Perch	28
02/15/2005	Marcus Hook	15	Channel Catfish	6
			Eastern Silvery Minnow	6
			White Perch	16

Table 3-2. Summary of experimental gillnet catches taken in the Marcus Hook study area during the March 2005 sturgeon survey

Date	Range	Sample Number	Species	Total Caught
02/09/2005	Marcus Hook	1		0
02/14/2005	Marcus Hook	2		0
02/15/2005	Marcus Hook	3		0
02/15/2005	Marcus Hook	4	Atlantic Sturgeon	1
02/15/2005	Marcus Hook	5	White Catfish	1
			Spottail Shiner	1
02/15/2005	Marcus Hook	6		0
02/16/2005	Marcus Hook	7	Channel Catfish	2
02/16/2005	Marcus Hook	8	White Sucker	2
			Channel Catfish	1
02/16/2005	Marcus Hook	9	Spottail Shiner	1
			Channel Catfish	1
03/04/2005	Marcus Hook	10		0
03/04/2005	Marcus Hook	11	White Perch	1
			Eastern Silvery Minnow	1
03/04/2005	Marcus Hook	12	White Perch	2
			Eastern Silvery Minnow	1
03/06/2005	Tinicum	13		0
03/06/2005	Tinicum	14	Spottail Shiner	2
03/06/2005	Tinicum	15		0
03/17/2005	Marcus Hook	16		0
03/17/2005	Marcus Hook	17		0
03/17/2005	Marcus Hook	18	White Perch	1
03/18/2005	Marcus Hook	19		0
03/18/2005	Marcus Hook	20	Channel Catfish	1
03/18/2005	Marcus Hook	21	Channel Catfish	1

Table 3-3. Summary of video survey track analysis for USACE channel deepening between the downriver project area (Marcus Hook, Chester, Eddystone, and Tinicum Navigational Ranges) relative to upriver surveys near Trenton, NJ

Species	Down River – Project Area (39.0 survey miles)		Upriver – Trenton Area (7.9 survey miles)	
	Count	Count/100 meters	Count	Count/100 meters
Raw Count	411	0.655	322	2.526
Unidentified Fish	28	0.045	5	0.039
Unidentified Sturgeon	3	0.005	0	0.000
Shortnose Sturgeon (total)	0	0.000	61	0.479
Shortnose Sturgeon (inside runners)			30	0.235
Short nose sturgeon (outside runners)			31	0.243
White Perch	294	0.468	0	0.000
Channel Catfish	2	0.003	10	0.078
White Catfish	8	0.013	97	0.761
Catfish spp.	15	0.024	7	0.055
Unidentified Shiner	58	0.092	0	0.000
Temperate Bass spp.	0	0.000	1	0.008
White Sucker	0	0.000	3	0.024
American Eel	3	0.005	0	0.000
Tessellated Darter	0	0.000	77	0.604

A. White Catfish

B. White Perch

C. Channel Catfish

Figure 3-1. Examples of fish images taken by the Video Ray Explorer mounted to a towed bottom sled

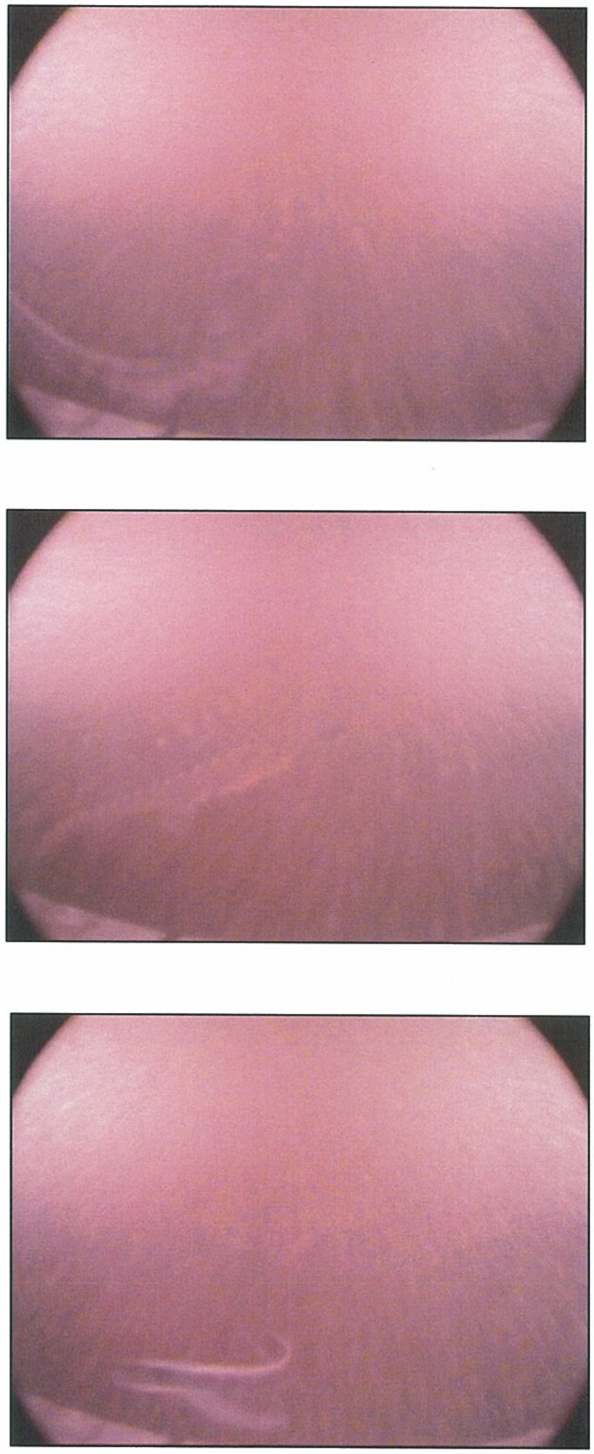

Figure 3-2. Images of the three unidentified sturgeon observed in bottom video recordings in the Marcus Hook project area.

Figure 3-3. Juvenile Atlantic Sturgeon collected in a gillnet set in the Marcus Hook anchorage

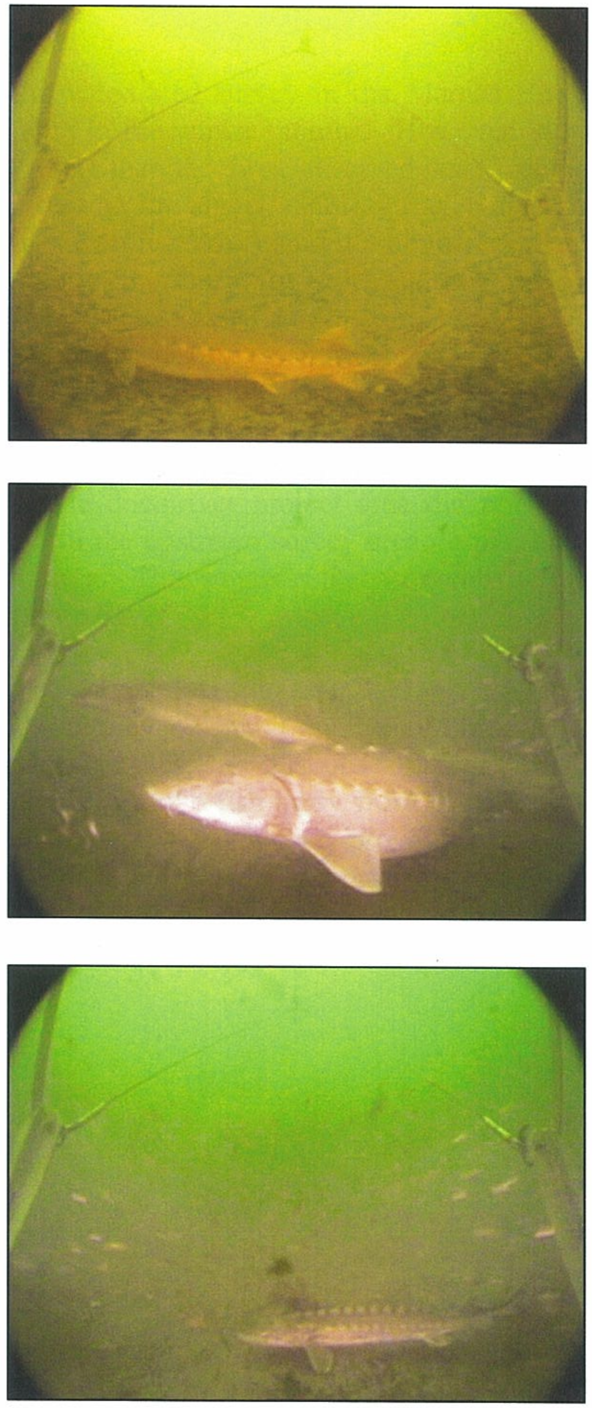

Figure 3-4. Images of the Shortnose Sturgeon observed in bottom video recordings in the upriver survey area near Trenton, NJ

5.0 PROTECTION OF STURGEON FROM BLASTING IMPACTS BLASTING EFFECTS

The high positive and negative pressures that result from underwater blasting may kill or injure fish. Typical blast-induced injuries in fish include swimbladder rupture, kidney damage, gill damage, and hemorrhaging in the coelomic and pericardial cavities (Yelverton et al. 1975; Teleki and Chamberlain 1978; Wiley et al. 1981). A detailed review of the literature on the effects of underwater explosions on fish is presented in Keevin and Hempen (1997)

Blast pressures may be reduced by limiting charge weight and using timing delays between the detonation of charges (Keevin 1998). Placing the charges in holes drilled into the rock and stemming the borehole with sand or rock also significantly reduce the blast energy propagated into the water. Hubbs and Rechnitzer (1952) reported that peak shock wave pressure in the sea near the bottom diminished inversely as the 2.6 power of the depth of the buried charge.

Blast pressures decrease with distance from the explosion. Burton (1994) conducted experiments to estimate the effects of blasting to remove bedrock for construction of a natural gas pipeline in the Delaware River, near Easton, Pennsylvania. In these experiments, juvenile smallmouth bass (*Micropterus dolomieui)*, caged at a range of distances from the blast, were exposed to charges of 248 lbs and 2,110 lbs detonated in the riverbed. These tests indicated a maximum kill radius of 39.4 ft, and no fish mortality occurred at the 78.7 ft location.

Moser (1999) investigated the effects of blasting on shortnose sturgeon in Wilmington Harbor, North Carolina. Hatchery-reared sturgeon were placed in cages 35, 70, 140, 280, 560 ft upstream and downstream of the blast site and at a control location 0.5 mile away. Each test blast consisted of the detonation of 32-33 charges (3 rows of 10-11 blast holes per row, with each hole and row 10 ft apart), each weighing between 52.9 and 61.7 lbs. Each bore hole was stemmed with angular rock, and the delay between detonations was approximately 25 msec. Seven test blasts were conducted, three with an air curtain in place and four without the air curtain. Survival of the caged fish was determined visually immediately after the blast and after a 24-hr holding period. Immediate survival rates at the 140 ft location and beyond were not significantly different. Immediate and 24-hour survival rates were similar and the use of the air curtain did not significantly affect survival.

Necropsies, performed primarily on shortnose sturgeon held 35 ft from the blast, showed relatively little swimbladder damage, but frequent distention of the intestines with gas bubbles and hemorrhage of the body wall lining. Some fish that exhibited no external signs of stress or discomfort had extensive internal damage (Moser 1999).

5.1 BEHAVIORAL EXCLUSION OF STURGEON FROM THE BLASTING AREA

Sturgeon could be protected from the effects of underwater blasting if they can be induced to move a safe distance from, and remain out of the blasting area. A literature review regarding the use of sensory stimuli to control and modify fish behavior was conducted as a first step in determining the feasibility of using a behavioral stimulus to exclude sturgeon from a blasting area. The vast majority of the research on this topic has been targeted at excluding fish from the intakes of steam electric, hydroelectric, and water diversion facilities, but is nonetheless applicable to excluding fish from an underwater blasting area. Sound has been most frequently investigated as a behavioral modifier, but relevant studies have also been performed with strobe lights and air bubble curtains (Carlson 1994; Popper and Carlson 1998).

5.2 REPELLING CHARGES

Small explosive "repelling" or "scare" charges have often been detonated immediately prior to an underwater blast in an attempt to frighten fish away from the blast area, although there has been little work to objectively assess their effectiveness. Keevin et al. (1997a) reported that repelling charges were generally ineffective in moving radio-tagged largemouth bass (*Micropterus salmoides*), channel catfish (*Ictalurus punctatus*), and flathead catfish (*Pylodictis olivaris*) out of the computed kill zones for typical underwater blasts.

Yelverton et al. (2000) concluded that scare charges were effective in moving acoustically tagged shortnose sturgeon in the Cooper River, South Carolina, a safe distance from an underwater blast site. However, the results of Yelverton's study appear to be confounded by herding of the test fish by the chase boat and imprecision in determining fish location using manual tracking methods.

The detonation of repelling charges has resulted in fish mortality in some cases (Keevin, 1998). Moreover, several recent studies indicate that very high intensity sound, such as that produced by repelling charges, may cause hearing loss and other sublethal effects in fish (McCauley et al. 2003; Smith et al. 2004a, b; Hastings and Popper 2005).

5.3 AIR GUNS

Several field studies suggest that the discharge of air guns, used to perform underwater seismic surveys, may affect the behavior and distribution of some species of fish. Air guns produce a short, sharp sound, with highest energy in the frequency range of approximately 20-100 Hz and significant energy over 100-1,000 Hz. Peak sound levels are typically in the range of 200-255 dB re: 1 μPa (Engas et al. 1996; McCauley et al. 2003). Engas et al. (1996) concluded, based on hydroacoustic surveys and fishing with trawls and longlines, that seismic shooting with air guns had a significant effect on the distribution, local abundance, and catch rates of cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) in the Barents Sea.

Slotte et al. (2004), also using hydroacoustics, reported that the abundance of pelagic fish was higher outside of a seismic shooting area in the Norwegian Sea, and concluded that the seismic survey was the likely causal factor.

Skalski et al. (1992) reported a 52 percent decrease in the catch of rockfish (*Sebestes* spp.) after exposure to a single air gun discharge at 186-191 dB re: 1 μPa (mean peak level).

Wardle et al. (2001) studied the effects of repeated discharges of an air gun array on fishes inhabiting a rocky reef off the coast of Scotland, using underwater video and acoustic tags. The air guns produced peak sound pressure levels of 210 dB re: 1 μPa at 52.5 ft from the source and 195 dB re: 1 μPa at 357.6 ft. Wardle et al. (2001) reported no changes in fish distribution or overall swimming patterns, but did observe an involuntary startle reaction to the air gun discharge in fish that were in visual range of the air gun.

5.4 FISHPULSERS AND PNEUMATIC POPPERS

Several studies evaluated the effectiveness of "fishpulsers" and pneumatic poppers, which produce sound of frequencies and amplitude similar to those produced by seismic air guns, as fish avoidance devices. Field studies at the Lennox Generating Station on Lake Ontario, Canada, showed that the fishpulser effectively controlled the movement of alewife (*Alosa pseudoharengus*). However, demersal coolwater (yellow perch *Perca flavescens*) and warmwater species (pumpkinseed, *Lepomis gibbosus;* black crappie, *Pomoxis nigromaculatus;* and rock bass *Ambloplites rupestris*) exhibited little response to the device (Patrick et al., 1988a).

Patrick et al. (1988b) studied the response of adult alewife to a pneumatic popper, singly and in combination with a strobe and bubble curtain, at the Pickering Nuclear Generating Station, on Lake Ontario. They reported that the popper was effective in excluding alewife, while the strobe had no effect and the air bubble curtain, used alone or in combination with the strobe resulted in inconsistent responses. Use of the three devices in combination did not surpass the effectiveness of the popper alone.

A similar study, with a pneumatic popper, strobe, and bubble curtain, was conducted at the Roseton Generating Station on the Hudson River (Matousek et al. 1988). Generally low and variable effectiveness was reported for the pneumatic popper. The strobe-air curtain combination had the highest effectiveness of the devices tested (61.8 percent for all species combined).

These studies suggest that fishpulsers and pneumatic poppers could be used to modify the behavior of alewife and, perhaps, other alosids, but are generally ineffective with other fish species. Concern has been raised that the high amplitude sound emitted by these devices may damage the hearing of both target and non-target species (Popper and Carlson 1998).

5.5 HIGH-FREQUENCY SOUND

Nestler et al. (1992) reported that sounds from 110-140 kHz at sound levels exceeding 180 db re: 1 μPa elicited statistically significant avoidance responses in caged blueback herring (*Alosa aestivalis*). A field evaluation at the Richard B. Russell Dam on the Savannah River found that sound of these frequencies and intensity was effective in excluding blueback herring from the intake of the dam at night, but not during the day.

Dunning et al. (1992) reported that pulsed broadband sound from 117-133 kHz at 163 dB re: 1 μPa caused an avoidance response in caged alewives. Ross et al. (1993, 1995) conducted a full-scale field study of a similar system at the James A FitzPatrick Nuclear Power Plant on Lake Ontario. They reported that pulsed sound at 122-128 kHz at 190 dB re: 1 μPa resulted in up to a 96 percent decrease in the density of alewife near the power plant intake and up to an 87 percent reduction in impingement of alewife on the intake screens. The system was effective during the day and at night, and had a range exceeding 262.5 ft.

The fish avoidance system tested by Dunning et al. (1992) and Ross et al. (1993, 1995) has been commercialized by Sonalysts, Inc. (Waterford, CT) as the FishStartle® Acoustic Fish Deterrent System. This system has been operationally deployed at several power plants and has been used to exclude fish from underwater blasting areas in Boston Harbor and Buffalo Harbor. However, the FishStartle® system has thus far been proven effective only with blueback herring, alewife, and American shad (*Alosa sapidissima*). Mr. Robert Janda (pers. comm.), of Sonalysts, stated that there has been no testing of the FishStartle® system with sturgeon, but suspected that it would not be effective due to the high frequencies used.

It has been hypothesized that alosids and other clupeiform fish, such as Pacific herring, have evolved special sensory mechanisms to detect high-frequency sound as a way to avoid predation by echolocating cetaceans (Mann et al. 1997, 1998, 2001; Wilson and Dill 2002). Other groups of fish do not appear to be sensitive to high-frequency sound (Popper and Carlson 1998).

5.6 LOW-FREQUENCY SOUND

Loeffelman et al. (1991) experimented with a low-frequency acoustic signal customized to the target fishes' hearing range as a fish deterrent. They reported that projection of a customized signal diverted 72 percent of upstream migrating steelhead trout (*Oncorhynchus mykiss*) from the entrance of the fish ladder at the Berrien Springs Hydroelectric Project, on the St. Joseph River, Michigan, despite strong environmental stimulus to enter the ladder. Working at the Buchanan Hydroelectric project, also on the St. Joseph River, Loeffelman et al. (1991) demonstrated that sound signals can be customized to the hearing of outmigrating steelhead trout and Chinook salmon (*Oncorhynchus tshawytscha*). Field tests showed that an average of 94 percent of the steelhead trout and 81 percent of the Chinook salmon were diverted from the hydro plant's headrace canal. In these studies, Loeffelman et al. (1991) used frequencies of 120, 240, 360, and 720 Hz, projected from underwater speakers that had sound pressure ratings of 160-180 dB re: 1 μPa at 100 Hz.

Goetz et al. (2001) reported that sound produced by a commercially available, low-frequency transducer (300-400 Hz; maximum sound levels of approximately 170-180 dB re: 1 μPa at 1 m) was ineffective in guiding yearling sockeye salmon (*Oncorhynchus nerka*), coho salmon (*Oncorhynchus kisutch*), and subyearling summer/fall Chinook salmon away from a lock and channel at the outlet of the Lake Washington Ship Canal, in Seattle, Washington.

Welton et al. (2002) reported on a novel concept, marketed by Fish Guidance Systems Ltd. (Southampton, UK), in which sound is injected into a vertical air bubble sheet to create a "wall of sound" designed to deflect fish. This system, know as the Bio-Acoustic Fish Fence (BAFF), pneumatically generates sound between 50 and 600 Hz. The sound is injected into the air bubble/water medium, where it is reflected at the air/water interface encapsulating the sound within the bubble sheet. Welton et al. (2002) reported that the BAFF system diverted significant numbers of Atlantic salmon smolts (*Salmo salar*) into a channel on the River Frome, UK. Deflections efficiencies were substantially higher at night (72.9-73.8 percent) than during the day (20.3-43.8 percent).

Another acoustic deterrent system marketed by Fish Guidance Systems Ltd. was tested in a multi-species environment at the Doel nuclear power plant on the Scheldt Estuary in Belgium (Maes et al., 2004). The system consisted of 20 large sound projectors, producing sounds within a range of 20-600 Hz, with a nominal sound pressure of 174 dB re: 1 μPa, installed near the offshore intake of the power plant. The effectiveness of the system varied with species, ranging from no effect to highly efficient deflection. Impingement on the plant's intake screens decreased most for herring (*Clupea harengus*) (94.7 percent reduction) and sprat (*Sprattus sprattus*) (87.9 percent). Dab (*Limanda limanda*), pipefishes, sticklebacks, and mullets, however, showed little or no response to the system. In general, fish with swimbladders and auxiliary anatomical structures that improve the sensitivity to sound responded better than fish that do not have these structures (Maes et al., 2004).

5.7 INFRASOUND

Knudson et al. (1992, 1994) studied the avoidance responses of downstream migrating Atlantic salmon smolts to high intensity, low-frequency sounds between 10 and 150 Hz. They found that the smolts responded best to frequencies of 5-10 Hz, which is within the infrasound range (<20 Hz). Subsequent studies, summarized in Sand et al. (2001), showed that Atlantic cod, (*Gadus morhua*), plaice (*Pleuronectes platessa*), and European freshwater perch (*Perca fluviatilis*) detect and respond to infrasound. Sand et al. (2000) reported that intense infrasound was effective in diverting downstream migrating European silver eels (*Anguilla anguilla*) at a fish trap on the River Imsa, Norway.

Ploskey and Johnson (2001), however, reported that 10-35 Hz sounds, produced by a particle motion generator, failed to elicit avoidance responses from hatchery yearling coho and subyearling coho and Chinook salmon. Sand et al. (2001) commented that the use of hatchery instead of wild fish and differences in the way the infrasound was generated may account for Ploskey and Johnson's (2001) results.

Amaral et al. (2001) reported that wild yearling chinook salmon and smallmouth bass did not demonstrate an avoidance response to sounds between 10 and 50 Hz, produced by a particle motion generator. Northern pikeminnow (*Ptychocheilus oregonensis*), however, evidenced moderate to strong avoidance of all frequencies tested except 20 Hz.

5.8 STROBE LIGHTS

A number of studies have investigated the effectiveness of strobe lights as a fish deterrent, often in combination with sound or other behavioral stimuli. As with sound, the results have varied considerably with species, test location, and environmental conditions. Laboratory studies conducted by the Electric Power Research Institute (EPRI), reviewed by Taft el al. (2001), have shown that some salmonids, including Chinook, coho, and Atlantic salmon, avoid strobe illumination. Bluegill (*Lepomis macrochirus*), adult channel catfish, juvenile walleye (*Sander vitreus*), and hybrid striped/white bass (*Morone saxatilis* x *M. chrysops*) also showed an avoidance response to strobes in the laboratory, whereas juvenile channel catfish and largemouth bass (*Micropterus salmoides*) did not consistently respond.

Juvenile American shad demonstrated a strong avoidance response to strobe light in a multi-year field study at the York Haven Hydroelectric project on the Susquehanna River in Pennsylvania (Taft et al. 2001). Adult American shad, however, did not respond to strobe illumination during daylight (when most of the shad movement occurred) in tests at the Hadley Falls Hydroelectric station on the Connecticut River, Massachusetts. The minimal difference between strobe and background illumination during daylight may have been responsible for the lack of response to the strobes (Taft et al. 2001).

Patrick et al. (2001) reported that both juvenile and adult American eel (*Anguilla rostrata*) strongly avoided strobe lights in laboratory and field studies at the Saunders generating station on the St. Lawrence River, Ontario, Canada. The juvenile eels responded immediately to the strobe, whereas the adults responded only after several minutes of exposure.

Maiolie et al. (2001) reported that free-ranging kokanee (*Oncorhynchus nerka*) showed a strong avoidance response to strobe light in tests conducted in clear water lakes in Idaho. Kokanee moved an average of 98.4-446.2 ft away from the strobes in waters with Secchi transparencies of 9.2-57.4 ft, and responded to flashes that were less than 0.00016 lux above background illumination.

Ploskey and Johnson (2001) showed that juvenile coho and Chinook salmon responded strongly to strobe lights in net-pen tests and a field evaluation at a lock and channel at the outlet of the Lake Washington Ship Canal. Extending on this work, Johnson et al. (2005) reported that strobe lights reduced entrainment of juvenile salmonids into a lock-filling culvert at this facility by 75 percent.

5.9 AIR BUBBLE CURTAINS

The effectiveness of air bubble curtains in modifying fish behavior has been studied by several investigators, typically in combination with other behavioral stimuli. Patrick et al. (1985) reported that air bubbles elicited an avoidance response in laboratory experiments with gizzard shad (*Dorosoma cepedianum*), alewife, and rainbow smelt (*Osmerus mordax*), and that avoidance was enhanced when combined with strobes.

Matousek et al. (1988) reported that, of the behavioral devices tested, a strobe-air curtain combination was most effective (61.8 percent for all species combined) in reducing entrainment at the Roseton Generating Station on the Hudson River.

Popper and Carlson (1998) speculated that the sound associated with the bubbles may be the actual stimulus responsible for the observed avoidance responses. As discussed above, Fish Guidance Systems Ltd. has developed a fish deterrent that combines a bubble curtain and pneumatically generated sound, which was demonstrated to be effective in guiding Atlantic salmon smolts (Welton et al. 2002).

Aside from a possible fish deterrent capability, an air bubble curtain may significantly reduce the pressures associated with underwater explosions. Keevin et al. (1997b) reported that peak pressures, impulse, and energy flux density from underwater blasts were reduced 81-99 percent when a bubble curtain was in operation. The mortality of bluegill caged at various distances from the blast was also significantly reduced with the bubble curtain. Moser (1999), however, reported that an air curtain did not significantly affect survival of caged shortnose sturgeon exposed to an underwater blast.

5.10 PERSONAL COMMUNICATIONS WITH FISH BIOACOUSTICS EXPERTS

Dr. Arthur Popper, of the University of Maryland, and Dr. David Lambert, of Fish Guidance Systems Ltd. (pers. comm.), experts in fish bioacoustics, were contacted to obtain their opinions regarding the feasibility of using sound to move sturgeon from an underwater blasting area.

Dr. Popper stated that, despite extensive research, there has been relatively little success in modifying the behavior of fish using sound. Dr. Popper believes that not generating sound within the frequency and intensity ranges that the target fish species can hear is a major factor in the failure of these studies. He stated that basic research on the hearing characteristics of the target fish must be performed before a potentially effective acoustic deterrent system can be designed. Dr. Popper stated that we know little about sturgeon bioacoustics. Dr. Popper's laboratory has recently initiated research on hearing in "primitive" fish, including shortnose sturgeon and lake sturgeon (Meyer and Popper 2002: Meyer et al. 2003).

Dr. Popper commented that to move fish out of, and exclude them from, a blasting area, a field of sound that is perceived as a negative stimulus and, therefore, avoided must be created. Simply creating a startle response is not likely to move the fish a sufficient distance to protect it from the blast. He stated that the detonation of repelling charges may create a startle reaction in the fish, but may not cause the fish to move a sufficient distance. Dr. Popper is also concerned about the sublethal, long term effects of scare charges on fish.

Dr. Popper believes that it may be feasible to develop an acoustic deterrent for sturgeon, but emphasized that basic research on their hearing characteristics must first be conducted. Dr. Popper commented that an air bubble curtain may be effective in attenuating blast pressures, if an intact bubble curtain can be maintained during the blast.

Dr. David Lambert stated that his firm recently conducted audiogram tests on lake sturgeon (*Acipenser fulvescens*) for the Minnesota Department of Natural Resources, and found that the species showed low response to acoustic stimulus. As a result of this low responsiveness, Dr. Lambert believes that acoustic deterrence of sturgeon may not be feasible.

5.11 SUMMARY AND CONCLUSIONS

- A review of the literature regarding the use of sound and other stimuli to modify the behavior of fish was conducted, as a first step in determining the feasibility of using a behavioral stimulus to exclude sturgeon from a blasting area.

- There has been substantial research on the use of sound and other stimuli to modify the behavior of fish. The vast majority of this research has been targeted at excluding fish from the intakes of power generation and water diversion facilities, but is nonetheless applicable to excluding fish from an underwater blasting area. Sound has been used successfully to control the behavior of some species of fish, such as clupeids and some salmonids, but results with other species have oftentimes been ambiguous. Use of sound outside of the frequency and intensity ranges that the target fish species can hear is likely a factor in the failure of some studies. There have been no laboratory or field studies on the use of generated sound to modify the behavior of sturgeon.

- Two experts in fish bioacoustics offered differing opinions regarding the feasibility of acoustic deterrence of sturgeon. Dr. Arthur Popper, of the University Maryland, believes that acoustic deterrence may be feasible, but commented that basic research on hearing in sturgeon would first have to be performed. Dr. David Lambert, of Fish Guidance Systems Ltd., believes that acoustic deterrence of sturgeon may not be feasible, based on a recent study indicating low response of lake sturgeon to an acoustic stimulus.

- Repelling or scare charges have frequently been used in an attempt to frighten fish away from an underwater blasting area, although there has been general disagreement and little objective assessment of scare charge effectiveness. There is concern regarding potential sublethal effects of scare charges on target and non-target species.

- Yelverton et al. (2000) concluded that scare charges were effective in moving acoustically tagged shortnose sturgeon in the Cooper River, South Carolina, a safe distance from an underwater blast site. The results of Yelverton's study, however, appear to be confounded by herding of the test fish by the chase boat and imprecision in determining fish location using manual tracking methods.

- Strobe lights have been demonstrated to be an effective deterrent for a number of species of fish, including several salmonids and juvenile American shad. There has been no work regarding the response of sturgeon to strobe light. In some studies, the avoidance response to the strobes appeared to be related to the relative intensity of the strobe light vs. background illumination. Turbidity may limit the utility of strobe lights as a fish deterrent in the Delaware River.

- Air bubble curtains have been show to be an effective deterrent for some species of fish, particularly when combined with sound. There have been no studies regarding the response of sturgeon to air bubble curtains.

- Air bubble curtains have been shown to be effective in reducing blast pressures and associated fish mortality, if an intact bubble curtain can be maintained in the water column. Gunderboom, Inc. (Sanford, FL) is marketing an underwater sound attenuation system that confines an air bubble wall within a physical barrier of water-permeable polypropylene/polyester fabric. Water depth, tidal currents, and the physical size of the Delaware River blasting area may, however, make such a system infeasible.

5.12 RECOMMENDATIONS

- At present, there is no "out-of-the box" behavioral deterrent system for excluding sturgeon from an underwater blasting area. However, generated sound of specific frequencies/intensities and strobe illumination have been demonstrated to effectively deter some species of fish. No research on acoustic deterrence has been performed with sturgeon. Further investigation on the hearing characteristics of sturgeon and the response of sturgeon to sound and strobe light may be warranted.

- The scare charge study performed by Yelverton et al. (2000) with shortnose sturgeon utilized imprecise manual tracking techniques and a chase boat that may have affected the behavior of the test fish. Repetition of Yelverton's work using currently available technology that allows precise, real-time tracking of acoustically-tagged fish in three dimensions using remote receivers would allow more definitive assessment of the effects of scare charges on sturgeon movement. However, obtaining a modification of ERC's Endangered Species Study Permit, issued by NOAA Fisheries, to perform such a study may be difficult. Use of sterile hatchery-reared shortnose sturgeon may be a desirable alternative to the use of wild fish. Assessment of the sublethal effects of scare charges on hatchery-reared shortnose sturgeon should also be performed.

- The feasibility of using an air bubble curtain in the Delaware River should be investigated further. Bubble curtains have been shown to be effective in attenuating underwater blast pressures and may also function as a fish deterrent.

- Investigations by Environmental Research and Consulting, Inc. (ERC 2003; Nealson and Brundage 2003) demonstrated that shortnose sturgeon can be effectively imaged using a split-beam scientific echosounder. Target strength, range from the bottom, and echo envelope width were identified as metrics that may be useful in differentiating sturgeon from other fish species. Consideration should be given to incorporating pre-blasting hydroacoustic and video sled surveys for sturgeon in the blasting plan for the Delaware River channel deepening work.

- Limit the blast pressure wave by limiting charge weight and using timing delays between the detonation of charges, placing the charges in holes drilled into the rock and stemming the borehole with sand or rock.

- Investigate the feasibility of using bubble curtains to reduce the pressures associated with underwater explosions.

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