Effects of Rostrum Injuries on Body Condition, Dam Passage, and Hydrodynamics of Paddlefish (*Polyodon spathula*) in the Alabama River

by

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Abstract

The rostrum of Paddlefish (*Polyodon spathula*) aids in finding zooplankton prey as well as provides lift and stability during swimming, but this structure can sometimes be damaged or even completely missing. Injury or loss of the rostrum may have non-lethal impacts on body condition and swimming ability, although little data exist concerning such effects. Here I quantify the extent and prevalence of Paddlefish rostrum damage across the Alabama River, as well as potential sublethal effects of such damage. Data collected across the Alabama River during 2017-2023 by both Auburn University and Alabama Division of Wildlife and Freshwater Fisheries personnel were combined to determine (1) the proportion of fish with damaged rostra across the four river sections separated by three lock-and dam structures, and how rostrum condition varied by length and sex, (2) the impact of damage on body condition and gonad development, (3) whether severity of rostrum damage was related to passage/non-passage over the crested spillway at Claiborne Lock and Dam, and (4) impacts of various types of rostrum damage on hydrodynamics around the rostrum. I found that the highest percentage of Paddlefish with rostrum damage was in the lower two sections of the Alabama River (lower Alabama River and Claiborne Lake), with lower values in the upper two sections (William “Bill” Dannelly Reservoir and Jones Bluff Reservoir). Female paddlefish had significantly better rostrum condition scores than males. Rostrum condition did not vary as a function of length. Males with rostrum damage had significantly lower body condition than those fish without damage, however there was no difference in females. Passage rate past Claiborne Lock and Dam did not differ between individuals with versus those without rostrum damage, and a calculated rostrum damage score did not differ significantly between fish that passed versus those that did not pass.

Differences in flow disruption around rostrum models showed an overall effect of rostrum damage type. However, there were no differences between rostrum damage types at low water velocity, and some differences were observed at higher water velocity. This project calls for additional investigation into how water forces interact with different types of rostrum damage to fully characterize the effects on hydrodynamics.

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Table of Contents

List of Tables

List of Figures

List of Abbreviations

2DKS	2 dimensional Kolmorgorv-Smirnov
ADCNR	Alabama Department of Conservation and Natural Resources
ANOVA	analysis of variance
AU	Auburn University
CLD	Claiborne Lock and Dam
CT	computed tomography
ERTL	eye-to-rostrum-tip length
FEFL	flat eye-to-fork length
GSI	gonadal somatic index
K	coefficient of condition
K_n	relative condition factor
MFLD	Miller’s Ferry Lock and Dam
RCS	rostrum condition score
RFHLD	R. F. Henry Lock and Dam
RKM	river kilometer
SRI	severity of rostrum injury
w	observed weight
W	expected weight

Introduction

Dams are structures that alter the hydrology of rivers, dramatically changing the habitat for the organisms in the river. They can have both positive and negative economic and ecological effects on river systems. Positive economic effects can include hydropower energy production, flood control, water supply, navigation, irrigation, recreation, and the resulting jobs (Jackson 2001; Altinbilek 2002; Poff and Hart 2002; Lambert 2010; Johnson and Martinez 2015; Singh and Singal 2017). Ecologically, dams can provide physical barriers that block or delay unwanted range expansion of invasive organisms (Cooper et al. 2021) and create habitat for lentic species.

However, negative effects of dams can include altered flow and habitat, sedimentation, and effects on fish migration cues (Ligon et al. 1995; Bednarek 2001; Petts and Gurnell 2005; Williams et al. 2012). Dams can also lead to direct physical injury or even death to fish (Keefer et al. 2013; Algera et al. 2020), with fatalities attributed to pressure changes, shear forces, and contact injuries related to dam operations (Keefer et al. 2013). Lock-and-dam facilities can be a source of fish injuries or death via hydropower turbine collisions, disorientation in turbulent water, and collisions with lock-and-dam structures (Pracheil et al. 2016).

Migratory species that often travel long distances in rivers may be particularly affected by the presence of dams. One such species is the Paddlefish *Polyodon spathula*, which is found in large rivers and accompanying lakes distributed throughout the Mississippi River drainage and several Gulf of Mexico tributaries (DeVries et al. 2009; Jennings and Zigler 2009). Paddlefish are large cartilaginous fish identified by smooth scaleless skin, heterocercal caudal fin, and a large rostrum extending from the head. The rostrum accounts for approximately one-half the body length of juvenile Paddlefish and one-quarter to one-third the body length of adults

(Kuhajda 2014). The rostrum has numerous sensory organs that are olfactory and electroreceptive that allow the fish to detect food organisms. This structure also generates high velocity vortices that increase feeding efficiency by directing food particles into the throat and across the gill rakers (Patel and Riveros 2013). In addition to feeding (Wilkens et al. 1997), the rostrum of Paddlefish also helps with stabilization while swimming (Allen and Riveros 2013). The rostrum generates lift and vortices to counteract the downward force and drag produced when Paddlefish are filter feeding (Allen and Riveros 2013; Patel and Riveros 2013).

Morphological characteristics, such as altered rostrum shape and position due to injury, could have differential effects on hydrodynamics and swimming performance as fish move through the water (Ohlberger et al. 2006; Allen and Riveros 2013; Patel and Riveros 2013). Although the rostrum of a Paddlefish assists via both prey location and swimming efficiency, individuals can survive with a damaged or even with a completely missing rostrum. Injuries have been attributed to various causes such as collisions with turbines and rock piles at the base of dams (Coker 1929), strikes from powerboats, impacts of snag fishing, or interactions during dam passage (Rosen and Hales 1980; Southall 1982), although to date a cause-and-effect relationship has not been determined. Published records indicate that Paddlefish were collected with damaged rostra as early as 1904 (Stockard 1907). Paddlefish were noted to have damaged rostra on the Mississippi River near the newly constructed Lock and Dam No. 19 in Keokuk, Iowa, built in 1913 (Coker 1929), where 36 of 53 (66%) of individuals in 1916 had broken rostra (Coker 1929), while none (out of 500) sampled on Pepin Lake, a reservoir of the Mississippi River located further upstream from Lock and Dam No. 19, had broken rostra during that same year. Despite the published occurrence of damaged rostra and the importance of the rostrum to individual Paddlefish, little is known about the occurrence, extent, or distribution of damage in other systems. Determining the general prevalence and effects of rostrum damage will help managers better understand and perhaps mitigate this injury.

My overall objective for this research is to quantify the prevalence of injuries throughout the Alabama River and evaluate the potential impacts of this damage on body condition and performance relative to dam passage. Specifically, the questions I am asking are:

- What is the proportion of Paddlefish with a damaged rostrum in the Alabama River, and how does this vary by location (along the river), length, and sex?
- How does Paddlefish rostrum damage relate to body condition and gonad development?
- How is Paddlefish rostrum injury related to dam passage rate at Claiborne Lock and Dam?
- How do flow dynamics differ for Paddlefish rostra with varying degrees of damage?

Methods

Study Area

The Alabama River is formed by the confluence of the Tallapoosa and Coosa Rivers, after which it flows downstream 512.6 km until merging with the Tombigbee River to form the Mobile River, which then ultimately flows into the Gulf of Mexico (Figure 1). The Alabama River is divided by three lock-and-dam structures: Robert F. Henry Lock and Dam (RFHLD) at river kilometer (RKM) 380.3 (measuring upstream from its confluence with the Tombigbee River), Miller's Ferry Lock and Dam (MFLD) at RKM 214, and furthest downstream Claiborne Lock and Dam (CLD) at RKM 116.6. Both RFHLD, completed in 1972, and MFLD, completed in 1969, were constructed for navigation, flood control, and hydropower. CLD was completed in 1969 and constructed for navigation and flood control.

My study area includes the section of the Alabama River from the tailrace below RFHLD downstream to the confluence with the Tombigbee River including both MFLD and CLD. The majority of the study is focused around CLD which has a crested spillway, six floodgates, and a navigational lock chamber. When the downstream gage height reaches 10.06 meters, the crested spillway becomes inundated, which potentially allows for upstream and downstream passage of migratory fishes (Mettee et al. 2004; Simcox et al. 2015; Laubach 2020; Hershey et al. 2022). Both MFLD and RFHLD differ from CLD in that they are substantially taller, have hydropower facilities, and do not have crested spillways.

Paddlefish Data Sources

To fully describe the extent and impact of rostrum damage on the behavior and body condition of Paddlefish from the Alabama River, this project combined data from Auburn University (AU) collections with data collected by Alabama Department of Conservation and Natural Resources (ADCNR) biologists. These two sources of data allowed for detailed analyses of movement patterns and passage past CLD, as well as damage prevalence across river sections and the impact of rostrum damage on body condition.

AU Paddlefish Collection, Surgery, and Tagging Methods

My (AU) collections of Paddlefish were via large mesh (150-200 mm square measure) multifilament gill nets below CLD during the winter and spring of both 2022 and 2023. Gill nets were set for no longer than 1 hr and tended constantly to minimize stress and injury to the fish. The following metrics were recorded for every Paddlefish: sex, flat eye-to-fork length (FEFL; nearest mm), eye-to-rostrum-tip length (ERTL), rostrum condition, and weight (nearest 0.01 kg). Only Paddlefish greater than 650 mm FEFL were tagged to ensure reproductive maturity and therefore higher likelihood to migrate (Hoxmeier and DeVries 1997). To quantify movement patterns and dam passage rate, Paddlefish were internally tagged with combined acoustic/radio transmitters (LOTEK Wireless Model CART MM-MC-16-50). All fish tagged exceeded the minimum weight necessary to ensure tag weight did not exceed 2% of body weight (Winter 1993; Cooke et al. 2012). In addition, a uniquely numbered anchor tag (Model FM-95W; Floy Tag) was inserted into the right ventral side of each fish for external identification in the event of recapture. Surgical implantation methods followed standard protocols (Harms and Lewbart 2000;

Cooke et al. 2012; Hershey et al. 2022; Thomas et al. 2024). All tags and surgery tools were soaked in 2% chlorhexidine gluconate solution for sterilization. During surgery, fish were placed on a V-shaped surgery board with water continuously pumped through their mouth and over their gills. A small incision (~3 cm) was made to insert the CART tags into the body cavity on the ventral side of the fish. A 14 gauge needle was inserted 2 cm anterior to the incision to guide the tag antenna outside of the fish's body. The incision was closed using simple interrupted sutures and cyanoacrylate glue was applied to assist with incision closure and healing. I tagged 42 Paddlefish from 1/24/2022-3/15/2022 and 58 from 12/05/2022-3/15/2023 for a total of 100 Paddlefish, which included various degrees of rostrum damage (see examples in Figure 2A-E). For each tagged fish, I recorded its CART tag identification numbers, anchor tag identification number, date of capture, capture location, and took a photograph of the fish. Tagged Paddlefish were held in a recovery tank until they regained equilibrium and could swim off on their own, then released at their capture location within 11 RKM downstream of CLD.

ADCNR Paddlefish Collection and Biological Measures

Paddlefish were collected throughout the Alabama River by Alabama Department of Conservation and Natural Resources (ADCNR) personnel as part of their population assessment for this stock. ADCNR used similar techniques to those described above to collect Paddlefish (i.e., large-mesh gillnets). Data for this study were from Paddlefish collected in 2017, 2018, and 2022, with most sampling occurring during winter and spring. ADCNR collections included 76 individuals collected from 2/28/2017-5/16/2017, 136 from 10/23/2017-6/26/2018, and 97 from 3/28/2022-5/19/2022, for a total of 309 Paddlefish. Metrics recorded for each individual at the time of sampling included sex, FEFL, weight, gonad weight, rostrum condition, date of capture, and capture location. All fish collected by ADCNR were euthanized to permit the measurement of gonad weight.

Quantifying Rostrum Condition

To determine how the extent of rostrum damage might be affecting Paddlefish in the Alabama River, it was necessary to develop a rostrum condition index. This index quantified rostrum condition using a scoring system based on a combination of the proportion of rostrum remaining and the severity of injury. To determine the expected ERTL for a fish with a damaged rostrum, I generated a linear regression of the natural log of ERTL of fish with an undamaged rostra versus the natural log of FEFL based on all collected fish with fully intact rostra to calculate the proportion of rostrum remaining for each fish. The proportion of rostrum remaining was defined as the measured ERTL that was present divided by the expected ERTL of an undamaged fish of that same FEFL. The proportion of rostrum remaining multiplied by 10, generated the ERTL Score of 0-10. For 8 individuals collected by AU and the 309 individuals collected by ADCNR without a measured ERTL, the proportion of rostrum remaining was visually estimated in the field and from photos.

The severity of rostrum injury was quantified based on observation and rating of three components: bleeding (score of 0-3.3, where 0 = actively bleeding and 3.3 = no active bleeding), cartilage protrusion (score of 0-3.3, where 0 = cartilage protruding from the wound and 3.3 = no cartilage protruding), and discoloration, which can indicate infection in the wound or stress from injury (score of 0-3.3, where 0 = discolored tissue or skin and 3.3 = no discoloration). These components were summed for the severity of rostrum injury (SRI) score which ranged from 0-10. The SRI and ERTL scores were summed for a final score of 0-20, which was the overall Rostrum Condition Score (RCS). A Paddlefish with a score of 0 was completely missing its rostrum, the base of the rostrum was in poor condition, evidence of a recent injury, open, actively bleeding, cartilage protruding, and there was discoloration of the affected wound region. At the other extreme, a Paddlefish with a score of 20 indicated that the rostrum was full in length and its rostrum was undamaged.

Stationary Acoustic Tracking

Stationary acoustic receivers (LOTEK Wireless Model WHS 3250L), anchored to the riverbank, were deployed throughout the study area (Figure 1). One stationary receiver was located at the furthest upstream location of the study area in the tailrace directly below RFHLD (RKM 380.3). Additional stationary receivers were located in the Alabama River at approximately every 5-15 RKM from RFHLD tailrace downstream to RKM 0, where the Alabama and Tombigbee rivers join to form the Mobile River, for a total of 42 stationary acoustic receivers. At MFLD, one acoustic receiver was located directly below the gates on the lock wall (RKM 214), and another was located in the lock chamber. For CLD at RKM 116.6 of the Alabama River, there were three acoustic receivers anchored in the tailrace (two directly below the gates of the dam on the lock wall, one directly below the crested spillway in the tailrace) plus one in the lock chamber. For all detections, stationary acoustic receivers recorded the date, time, and fish's unique identification number.

Stationary Radio Tracking

Two radio receiver stations were established at CLD, one downstream of the dam and one upstream of the dam, to record fish detections near CLD while minimizing variation associated with detection range and acoustic interference of the stationary acoustic receivers located close to CLD. Receiver stations were installed on the roofs of public picnic shelters. Each receiver station consisted of a Yagi antenna connected to a SRX 800 receiver. Each antenna was pointed perpendicular to the river channel and directed downward into the water column. The receiver detected any fish with a tag emitting the targeted frequency that passed through the detection zone and recorded the fish's unique identification. Two 12-volt 125 amp-hour rechargeable deep cycle batteries provided power and were changed monthly to allow the radio receiver to continuously scan for fish. The stationary radio receiver below CLD recorded the presence of tagged fish in the tailrace and the radio receiver above CLD recorded those in the forebay.

Hydrodynamics and Paddlefish Rostrum Flow Visualization

Paddlefish rostra with varying degrees of damage (range of RCS = 0-20) from 5 adult Paddlefish collected from the Alabama River by ADCNR were scanned using a computed tomography (CT) scan, which provided a complete 360° imagery of the rostra and internal anatomy. Images were combined, and a single digital rotational 3D image was produced for each of the 5 rostra. Using a 3D printer, the rostra models were printed in exact proportion to the original rostra. The 5 different rostra included: 1) a completely normal, undamaged Paddlefish rostrum with 100% of the rostrum remaining intact (RCS = 20, Figure 2F), 2) a damaged rostrum pushed dorsally upward at the breakage point of 55% of the original rostrum shape and healed in that position with 100% of the rostrum remaining intact (RCS = 15.5, Figure 2G), 3) a damaged rostrum pushed ventrally downward at the breakage point of 65% of the original rostrum shape and healed in that position with 100% of the rostrum remaining intact (RCS = 16.5, Figure 2H), 4) a damaged rostrum partially split anterior to posterior with one side of the split tip pushed ventrally downward and the other dorsally upward and healed in that position with 60% of the rostrum remaining intact (RCS = 9.33, Figure 2I), and 5) a damaged rostrum partially severed off and splintered with approximately 10% remaining intact (RCS = 1, Figure 2J). These 5 models are from Paddlefish in the Alabama River and reflect the diversity of rostrum conditions observed.

The 3D-printed Paddlefish models were individually placed in a 90 L Loligo Systems Brett-type swim tunnel to quantify flow dynamics among rostra with different proportions remaining intact and different types and degrees of injuries. Each of the 5 rostrum damage types was exposed to 2 different water speeds (0.25 and 0.50 m/s) for 5 min to ensure consistent flow dynamics were observed, for a total of 10 trials. Laminar flow before the rostrum was encountered was maintained using flow straighteners in the swim tunnel for consistency across experiments and to ensure any flow disruption or turbulence observed was due to the rostrum’s hydrodynamic qualities. The model was placed in the swim tunnel with water flow directed parallel to the rostrum to replicate the flow forces that a Paddlefish with different rostrum damage would encounter while swimming against the current or maintaining position in a flowing environment. Small (600-710 µm diameter), violet, neutrally buoyant (~1 g/cc) polyethylene microspheres (Cospheric LLC, Somis, California) were added to the water of the swim tunnel at a density of ~0.33 g/L to allow for flow visualization. Videos of the 10 trials were recorded, slowed down, and clipped (3.0 sec at 0.25 m/s, 1.5 sec at 0.5 m/s) for analysis. Flow disruption was quantified by measuring the linear distance traveled by 10 individual beads in the flow path and within 5 mm from the leading edge of each rostrum for the length of the clip. Linear distances were scaled and measured using ImageJ software (version 1.8; Schneider et al. 2012).

Data Analysis

To quantify variation in rostrum damage occurrence throughout the Alabama River, the proportion of Paddlefish with a damaged rostrum out of the total number of Paddlefish sampled was quantified in 4 distinct sections of the Alabama River (lower Alabama River, Claiborne Lake, William “Bill” Dannelly Reservoir, and Jones Bluff Reservoir) separated by the 3 lock and dam structures and compared across sections using a chi-square test. To determine how rostrum condition varied spatially across each of the 4 river sections, an ANOVA was used to compare RCS as a function of the river section. In addition, to determine how the severity of rostrum damage varied spatially among Paddlefish with rostrum damage across river sections, an ANOVA was used to compare RCS of those individuals with rostrum damage (RCS< 20) as a function of the river section. I used linear regression to quantify how RCS related to FEFL, body condition, and gonad proportion of weight. If the relationship violated the necessary assumptions of variance of the residuals for a regression to be valid, data were either natural log transformed or a non-parametric test, a 2-dimensional Kolmorgorv-Smirnov test (2DKS; Garvey et al. 1998) was used to determine if the relationship between variables could be distinguished from a random pattern. A Welch's t-test was used to determine if there was a difference in RCS as a function of sex. Statistical analyses were performed in Rstudio (version 1.4.1717) with an alpha level of 0.05 (Rstudio Team 2021).

Relative condition factor (K_n) is the ratio of the observed weight (w) of a fish at a given length compared to the expected weight (W) of a fish at the same length derived from the length-weight regression derived from all measurements of fish in the study (calculated as K_n=w/W; Le Cren 1951). To accurately compare K_n of fish with variation in rostrum damage, I first needed to account for the missing rostrum weight for damaged fish. To do so, I first generated a ln transformed FEFL-rostrum weight regression using only fish with fully intact rostra to find the expected intact rostrum weight of a fish as a function of length. Then, this full expected rostrum weight was multiplied by the proportion of rostrum missing for each individual to estimate the missing rostrum weight specific to that individual. The calculated missing rostrum weight for that fish was added to the total measured body weight of the fish at the time of its collection. Next, a ln-transformed length-weight regression was calculated separately by sex from Paddlefish in the Alabama River (sampled by both AU and ADCNR) to find the W of a fish of a given length. In this regression, the length was measured as FEFL, and the weight was measured as total body weight measured at the time of collection plus the missing rostrum weight. After K_n was calculated for each fish separately, it was compared as a function of RCS by sex using a linear regression.

Given that the gonad weight of a fish can be influenced by food consumption and swimming energetics, impairment of rostrum function could impact gonad weight. Gonadal somatic index (GSI), the ratio of gonad weight to total body weight, was calculated for each individual (again, while accounting for the missing rostrum weight for those with damaged rostra). Linear regressions were analyzed separately by sex to determine the relationship between RCS and GSI.

The stationary acoustic and radio receivers at both CLD and MFLD and radio receivers deployed above and below CLD allowed the determination of successful passages. The location and time detections of individuals from the distributed stationary acoustic and radio receivers were combined based on the CART tag identification numbers to create large-scale location/movement profiles of all tagged individuals throughout the study area. Passage rate was determined as the number of tagged Paddlefish identified as successfully having passed upstream of CLD or MFLD (dams considered separately) out of the total number of Paddlefish that were tagged, at large, and detected in the tailrace of the dam (downstream within ~500 meters of the structure) 24 hours or later after tagging. In order to determine if upstream passage of CLD was influenced by rostrum condition, a Fisher’s exact test was used to determine whether RCS of tagged fish detected below CLD differed between fish that passed upstream of CLD versus those not passing for 2022 and 2023 separately.

The mean linear distance that beads travelled for each of the 5 rostrum models at each water velocity was compared separately due to different lengths of the video clip between the two speeds. ANOVA and Tukey multiple comparison of means were used to determine whether there were differences in hydrodynamic properties among rostrum damage types. Greater linear distance travelled by a bead corresponded with less interference of the rostrum to disrupt its flow path.

Results

A greater proportion of Paddlefish from the lower Alabama River (n= 137/191, 71.7%) and Claiborne Lake (n= 37/52, 71.2%) had at least some level of damage to their rostrum (RCS < 20) versus those from Dannelly (n= 20/135, 14.8%) and Jones Bluff (n= 4/31, 12.9%) reservoirs (chi-square test; χ^2= 129.01, df= 3, p < 0.001; Figure 3). Paddlefish from the lower Alabama River (*n*= 191) and Claiborne Lake (*n*= 52) had significantly lower RCS than individuals from Dannelly (*n*= 135) and Jones Bluff (*n*= 31) when all fish were considered (ANOVA; $F_{3,405}$= 31.62, p< 0.001; Figure 4). However, among only Paddlefish that had rostrum damage, RCS did not differ across the 4 river sections: lower Alabama River (*n*= 129), Claiborne Lake (*n*= 37), Dannelly (*n*= 20), and Jones Bluff (*n*= 3) (ANOVA; $F_{3,185}$= 0.91, p= 0.44; Figure 5). Although, there were fewer Paddlefish without damaged rostra that were longer than 877 mm FEFL than would have been expected at random (2DKS; *n*= 409, D= 0.04, p= 0.05, inflection point= (877, 19.49); Figure 6). Female Paddlefish (*n*= 167) had significantly better rostrum condition scores than males (*n*= 198) (Welch's t-test; t = 2.42, df = 362.08, p= 0.02; Figure 7).

K_n of male Paddlefish (*n*= 198) increased significantly with RCS (linear regression; $F_{1,196}$= 4.37, p = 0.04, R^2 = 0.02; Figure 8). However, K_n and RCS were not related for females (*n*= 167) (linear regression; $F_{1,165}$= 0.17, p = 0.68, R^2 = -0.01; Figure 8). GSI did not differ with RCS for males (*n*= 158) (linear regression; $F_{1,156}$= 1.04, p= 0.31, R^2= 0.00) or females (*n*= 39) (linear regression; $F_{1,37}$= 1.44, p= 0.24, R^2= 0.01; Figure 9).

Mean RCS did not differ between tagged fish that were detected in the tailrace of CLD and passed upstream (*n*= 12) versus those that were detected in the tailrace and did not pass upstream (*n*= 17) in 2022 (Welch's t-test; t = 0.92, df = 22.98, p= 0.37), and did not differ for those that passed (*n*= 29) or did not pass (*n*= 38) in 2023 (Welch's t-test; t= 1.89, df = 65.94, p= 0.06; Figure 10). In both 2022 and 2023, Paddlefish that were tagged and at large, and detected in the CLD tailrace 24 hours or later after tagging had an upstream passage rate of 41.4-43.3% (Table 1), and there was no significant effect of a fish's rostrum being damaged (RCS < 20) versus not damaged (RCS= 20) on whether fish passed upstream of CLD in 2022 (Fisher's exact test, p= 1) or 2023 (Fisher's exact test, p= 0.34; Table 2).

Assessment of the flow disruption around the physical rostrum models showed that the linear distances beads travelled differed significantly as a function of rostrum type at water velocities of both 0.25 m/s (ANOVA; $F_{4,45}$= 2.875, p= 0.033) and 0.5 m/s (ANOVA; $F_{4,45}$= 5.125, p= 0.002). However, at 0.25 m/s there were no differences in pairwise comparisons between damage types. The angled up rostrum damage type had significantly shorter linear distances traveled compared to half remaining/split, normal/fully intact, and short/splintered at 0.5 m/s, however, the linear distances between the other rostrum damage types did not differ (Figure 11).

Discussion

The rostrum of Paddlefish has been well-documented to affect swimming and feeding efficiency (Wilkens and Hofmann 2007, Allen and Riveros 2013, Haines and Sanderson 2017). In my sampling as well as that of previous investigations, damage to the rostrum can be common in some populations of Paddlefish (Rosen and Hales 1980; Hoxmeier and DeVries 1997; Mestl and Sorensen 2009). Here I documented prevalence and distribution of rostrum damage, measured impact on passage over a dam with a crested spillway, determined correlates of damage related to individual fish, and explored some effects of damage on flow around the rostrum. I was able to document that Paddlefish rostrum damage occurred throughout the Alabama River, and the occurrence of damage varied spatially. However, rostrum damage did not appear to affect the ability of fish to pass the crested spillway at the lowermost lock-and-dam structure with mixed effects on the response variables I measured.

Spatial variation of rostrum damage across river sections in the Alabama River suggested that proximity to the lowermost lock-and-dam structure may be related to damage; fish with rostrum damage were observed in about 71% of fish in the two downstream river sections (directly above and below CLD) versus about 14% of fish from the two upstream sections. This difference suggests there is variation in factors contributing to damage across river sections or lock-and-dam structures. Given that there are proportionally fewer occurrences of fish with rostrum damage in the two upstream sections, it is possible that the infrastructure at MFLD and RFHLD may be less injurious to Paddlefish. Neither MFLD nor RFHLD has crested spillways, which could reduce Paddlefish collisions with barriers at these lock-and-dam structures compared to CLD which has a crested spillway. In addition, unlike CLD, MFLD and RFHLD both have hydropower facilities. While this could mean lower damage potential exists at the structures containing hydropower facilities, an alternative explanation could be that the reduced number of Paddlefish with rostrum damage results from high mortality rates due to hydropower operations with the result being that fish are not surviving hydropower related injuries and these fish are no longer available to be sampled. However, no dead Paddlefish were observed during my sampling efforts and there have not been any studies directly assessing any injury or mortality to Alabama River Paddlefish due to hydropower generation. Further investigation into direct sources of Paddlefish rostrum damage and mortality would be helpful to understand this complex issue and inform future management strategies. The damage observed could be due to Paddlefish swimming directly into dam structures as they move upstream. Other hazards could involve falling over spillways, gates, passage through hydroelectric turbines, turbulent water forces as they reside in and navigate dam tailrace environments, colliding with boats near lock-and-dam structures, or other interactions. We simply have no data to determine this at this time.

The prevalence of rostrum damage has been shown to vary dramatically in different river systems and spatially with changing habitats. In the Missouri River, 10% of Paddlefish collected within an 84 km stretch of the Missouri River downstream of Gavins Point Dam had lost most or all of their rostrum (Rosen and Hales 1980), similar to values found in my two upstream river sections. Incidence of rostrum damage observed in Paddlefish collected from the Missouri River below Gavins Point Dam did not differ based on whether Paddlefish were netted before or after the snagging season, indicating that snagging did not contribute to rostrum injuries in that system (Mestl and Sorensen 2009). And the proportion of individuals with rostrum damage can vary spatially by habitat type within a river system, For example, in a previous study 1% of fish collected in oxbow habitats, 9.3% in channel habitats, and 13.4% in backwater habitats had rostrum damage (Hoxmeier and DeVries 1997) and Paddlefish collected for this present study in the tailrace of CLD exceeded 70%. Although rostrum injuries have been observed in Paddlefish throughout much of their range, it is not often reported and can vary considerably in the proportion of fish affected across waterbodies, with limited information concerning the spatial variation of rostrum damage within bodies of water, making identification of important factors contributing to this damage difficult.

My study focused on the effects of non-lethal rostrum injuries, although, mortality associated with damage to a Paddlefish's rostrum could certainly be occurring as well. While it is difficult to directly quantify mortality due to injury, additional investigation could help to better understand potential sources of rostrum damage and resulting effects. Mortality rates due to infection and stress from rostrum injuries would be difficult to determine for wild free range fish, but nonetheless could still be important to recognize for future management; particularly in the Alabama River where fish appear to display particularly high rostrum injury rates. Lesions and open wounds on the rostrum can make Paddlefish susceptible to infectious pathogens (Durborow et al. 2015). Estimating Paddlefish mortality in the Alabama River due to rostrum damage would likely require a large-scale long-term tagging and biomonitoring study, likely also including a recapture study, which would be nearly impossible given the spatial scale of the study area, long-distance movements of Paddlefish, low recapture rates, and ultimately the difficulty in attributing specific causes of mortality to wild fish. Despite severe rostrum damage, Paddlefish do appear to be resilient and adaptable as demonstrated by the continued survival of individuals with damaged rostra. Paddlefish clearly can recover from such injuries, as evidenced by fish with injuries that appear to have occurred sufficiently in the past to have allowed them to fully heal. Tests with juvenile Paddlefish passing through turbines demonstrated that blade strikes can cause mortality and rostrum damage (Pflugrath et al. 2021). When juvenile Paddlefish were struck on the lateral surface of the head with a 52 mm turbine blade moving at 7.3 m/s, the rostrum was nearly amputated (Pfugrath et al. 2021). Rostrum injuries consistent with near amputation and breakage of the rostrum have been observed in adult Paddlefish throughout the Alabama River and other waterbodies. Further study is needed to determine if some of the damage observed in this study could be due to turbine blade strikes on adult Paddlefish.

One Paddlefish that was captured, tagged, and released below CLD on 12/05/2022, subsequently made a downstream movement out of the tailrace, only to return to CLD during the same migratory season, and was recaptured below CLD again on 3/15/2023. The rostrum injuries of this individual changed very little over the 3 month period from initial capture (Figure 12A) to recapture (Figure 12B), although the time between captures may have been too short to draw conclusions on healing time. The transmitter implantation surgery site did fully heal over this time period, demonstrating to some degree the healing ability of Paddlefish, even those with previous injuries, and ability to recover from the surgical process (Figure 12C). Similar observations concerning the healing capacity of Paddlefish have been noted in reference to previously healed wounds and scars commonly observed and attributed to snagging, boat propellers, lamprey, and other undefinable sources of damage from which they have recovered (Rosen and Hales 1980; Scarnecchia and Stewart 1997; Runstrom et al. 2001).

Rostrum condition did not vary linearly as a function of FEFL. However, the 2DKS analysis demonstrated that the relationship between RCS and length was not random. The analysis showed there were fewer Paddlefish with undamaged rostra that were longer than 877 mm FEFL than would have been expected at random. There are multiple potential explanations for this pattern including reduced growth or survival rate of Paddlefish with damage. Given the chance that a fish will sustain damage at any time in life and the cumulative probability of receiving damage increases with time, there is a greater likelihood that a Paddlefish will experience damage to the rostrum before reaching large size and presumably older age.

Alternatively, very large paddlefish with undamaged rostra may have lower catchability in large mesh gill nets. Further studies to address this are needed to determine the best explanation for this pattern. In a previous study, the frequency of rostrum damage did not significantly change with the length of fish for fish from 460 to 1020 mm FEFL (Rosen and Hales 1980). Male Paddlefish make upstream spawning movements earlier in the season and remain in spawning areas longer than females, which may contribute to higher risk of rostrum injury and males displaying lower RCS than females (Stancill et al. 2002, Schwinghamer et al. 2019).

Relative to my second question, male Paddlefish with lower rostrum condition scores had lower body condition (K_n), which could be due to decreased ability to find and consume prey with a damaged rostrum, which they use to find prey (via electrosensory reception with the ampullae of Lorenzini; Wilkens et al. 1997) and maintain position in the water column. In addition, reduced K_n in males could also be due to less hydrodynamically efficient swimming of fish with a damaged rostrum, causing them to spend more energy than their uninjured counterparts. Similarly, Rosen and Hales (1980) found Paddlefish with scars or rostrum damage had a lower coefficient of condition (K) than those without scar or rostrum damage. Reduced K values of scarred fish suggest that growth was influenced by trauma from these injuries (Rosen and Hales 1980). However, in this study females with lower rostrum condition scores did not exhibit reduced K_n, which may be due to the large variation in body weight across times of year and spawning condition at the time of capture (given that mature females rapidly gain weight with increased egg production near spawning times and lose weight quickly when eggs are released), which covers the time period when most Paddlefish were sampled for this project. In addition, for Paddlefish with more recent injuries, much of the weight gain and increased body condition likely occurred prior to the rostrum injury. Alternatively, a lack of relationship between rostrum damage and K_n in females could indicate that females were simply not affected by rostrum damage in the same way as males in a way that has not been fully understood.

Finally, GSI was not affected by rostrum condition, which suggests that egg production and development were not hindered due to rostrum damage. Relative to harvest, the lack of reduction in GSI due to rostrum damage should allow the output of roe by harvested females to not be diminished by rostrum damage.

Relative to my third question, upstream passage of Paddlefish at CLD was not significantly influenced by rostrum condition, suggesting that rostrum damage was not important in determining whether an individual would pass the lowermost lock-and-dam structure (with the crested spillway). In addition, no observed difference in passage success suggests that any effect of rostrum damage on swimming performance was not of a degree that affected upstream passage ability, although future work should evaluate this more precisely via modeling and laboratory swimming performance trials. Clearly, given there was no difference in upstream passage ability at CLD as a function of RCS, rostrum damage should not be a hindrance in population connectivity between Paddlefish in the lower Alabama River and Claiborne Lake sections. Other factors, such as gage height and year, may be better predictors of whether a Paddlefish successfully passes upstream of CLD rather than rostrum condition (Hershey et al. 2022). Similarly, mean dam head and 10th percentile water temperature were the most important variables determining successful upstream passage of Paddlefish in the Mississippi River (Zigler et al. 2004). However, the spring season and 25th percentile water temperature were most important for downstream passage of Paddlefish in the Mississippi River (Zigler et al. 2004).

Relative to my fourth question, there was an overall significant effect due to rostrum damage type, which became more apparent at the higher water flow velocity. Differences in rostrum hydrodynamics of Paddlefish can have further implications based on the function of the rostrum (i.e., hydrodynamic swimming and providing lift, directing food into the mouth, and decreasing drag while feeding; Patel and Riveros 2013). Given this, variation in rostrum damage types may influence a fish's feeding efficiency and should be evaluated more directly to determine potential differences. In the future, more detailed experiments measuring water flow forces and how those interact with different rostrum damage types will be required to fully characterize if there are any effects on hydrodynamics.

In conclusion, Paddlefish from the lower two sections of the Alabama River displayed significantly higher proportions of fish with rostrum damage than the two upstream sections, which may be influenced by differences in the design of the lock-and-dam structures that divide these sections of the river. Female Paddlefish had significantly better rostrum condition than males, suggesting males may be more susceptible to rostrum damage than females. Males with better rostrum condition had better body condition, however, there was no difference observed in females. GSI was not significantly affected by rostrum condition for males or females. There was no difference in the upstream passage rate of Paddlefish at CLD relative to their rostrum condition. There were minimal effects of rostrum damage type on flow disruption, but should be investigated further to fully quantify effects on the hydrodynamics of Paddlefish.

Tables

TABLE 1.—Number of individuals tagged and at large, detected in the CLD tailrace 24 hours or later after tagging, and passed upstream of CLD in 2022 and 2023.

	2022	**2023**
Tagged and at large	42	100
Detected in CLD tailrace	29	67
Passed upstream	12	29
Passage rate	41.4 %	43.3%

TABLE 2.—Number of tagged individuals that passed/ did not pass CLD in 2022 and 2023, and whether they had a damaged or undamaged rostrum.

	2022		**2023**	
	Damaged	Undamaged	Damaged	Undamaged
Passed	9	3	22	7
Not Passed	13	4	33	5

Figures

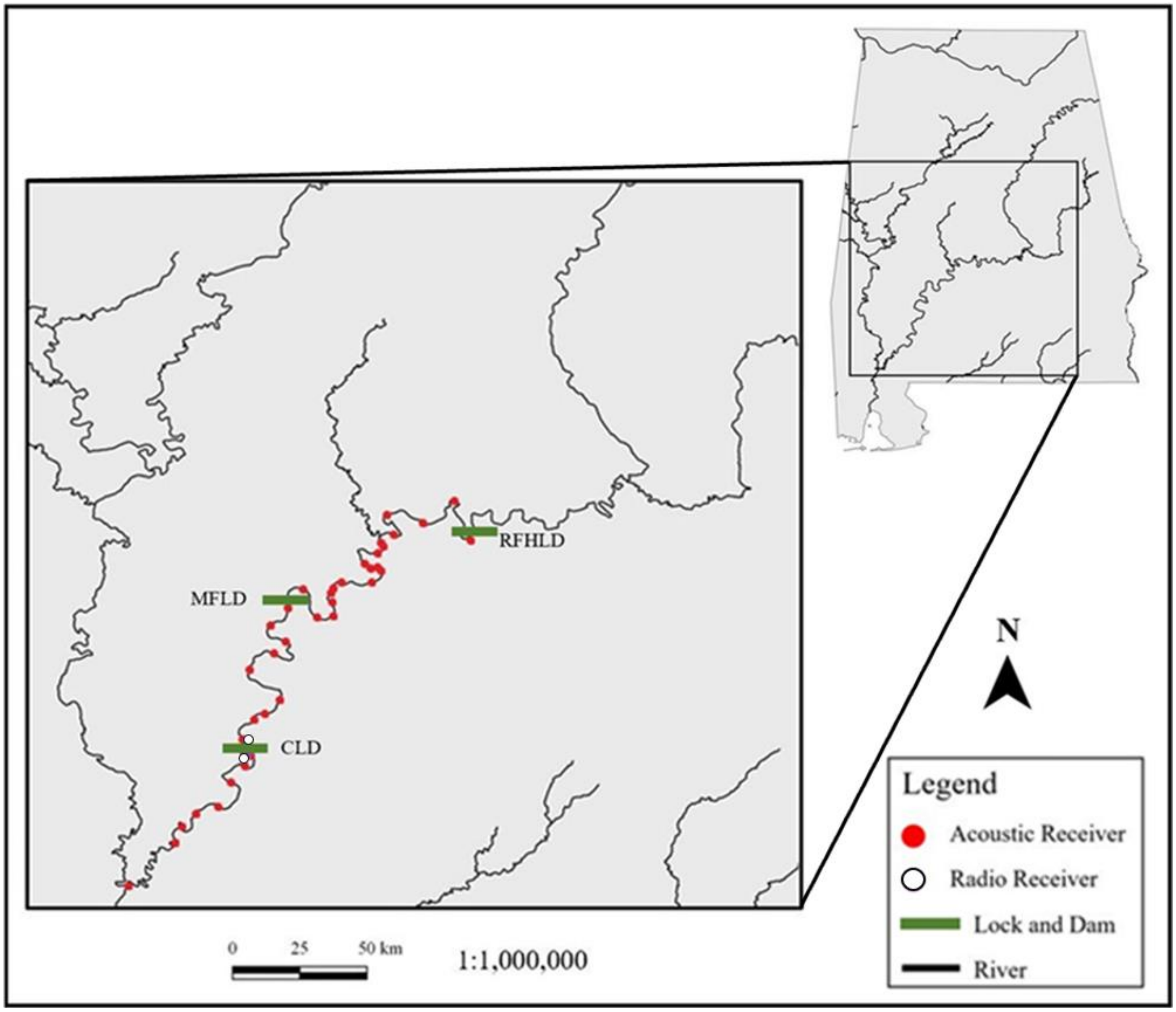

FIGURE 1.—Map of study area, including locations of acoustic receivers (red circles), radio receivers (white circles with black outline), and lock and dam structures (green bars) in the Alabama River. Abbreviations for dams are defined in the text.

(A)

(B)

(C)

(D)

(E)

(F)

(G)

(H)

(I)

(J)

FIGURE 2.—Photographs from various angles of 5 individual Paddlefish (panels A-E) sampled from the Alabama River demonstrating variation in rostrum damage, and photographs of the 5 Paddlefish rostra (panels F-J) used for 3D printing models and flow visualization.

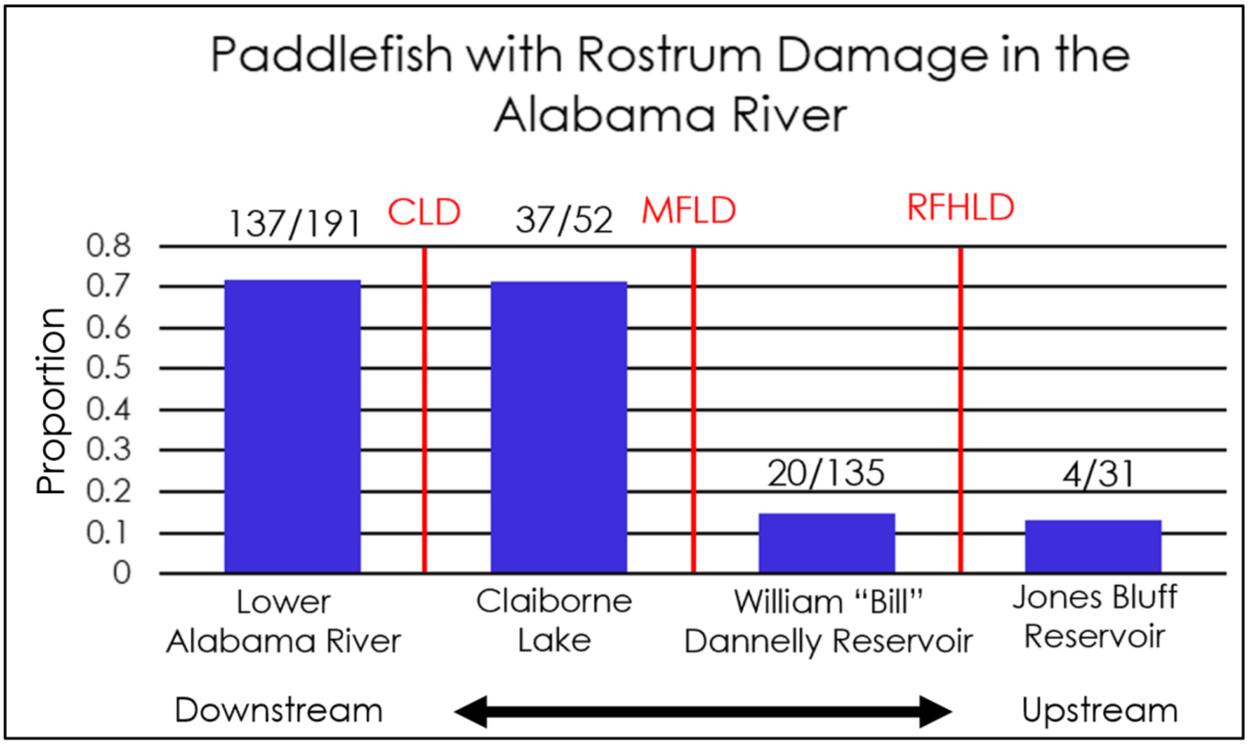

FIGURE 3.—The proportion of fish collected in each of the four Alabama River sections (Lower Alabama River, Claiborne Lake, William "Bill" Dannelly Reservoir, and Jones Bluff Reservoir) that had any kind of rostrum damage (i.e. RCS < 20).

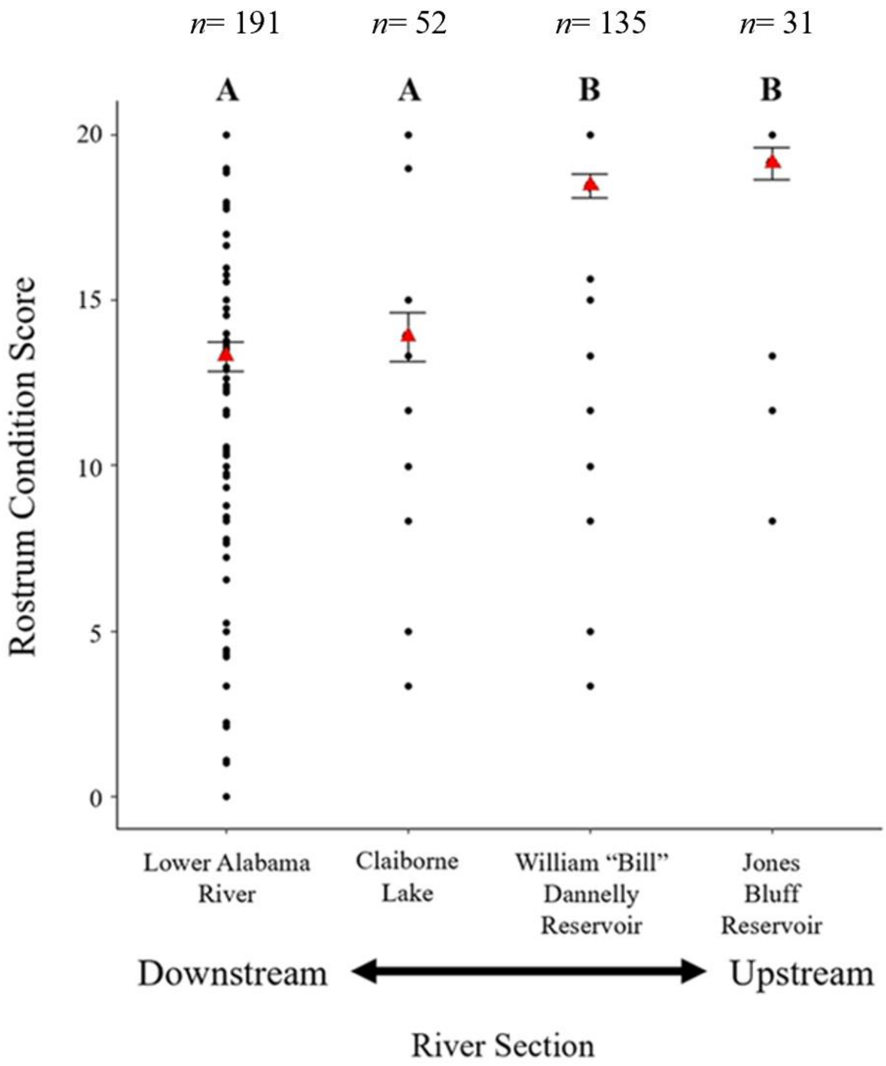

FIGURE 4.—Paddlefish rostrum condition scores as a function of river section divided by 3 lock-and-dam structures in the Alabama River. Black dots indicate individual fish data points, while larger red triangles represent the mean ± SE.

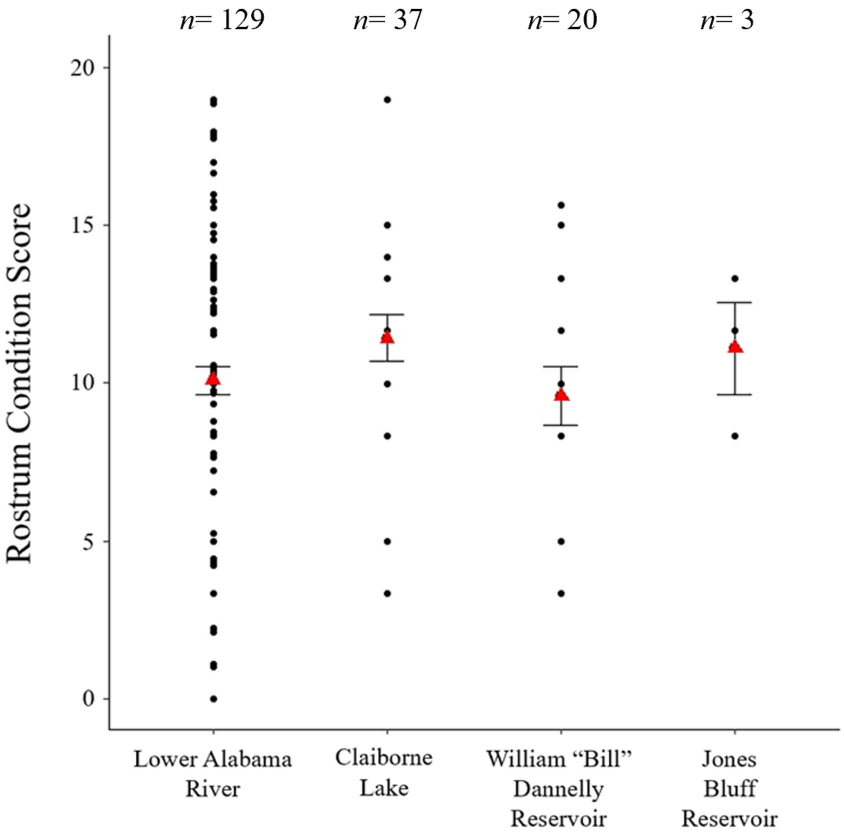

FIGURE 5.—Paddlefish rostrum condition scores of Paddlefish with any rostrum damage (RCS< 20) as a function of river section divided by 3 lock-and-dam structures in the Alabama River. Black dots indicate fish data points, while larger red triangles represent the mean ± SE.

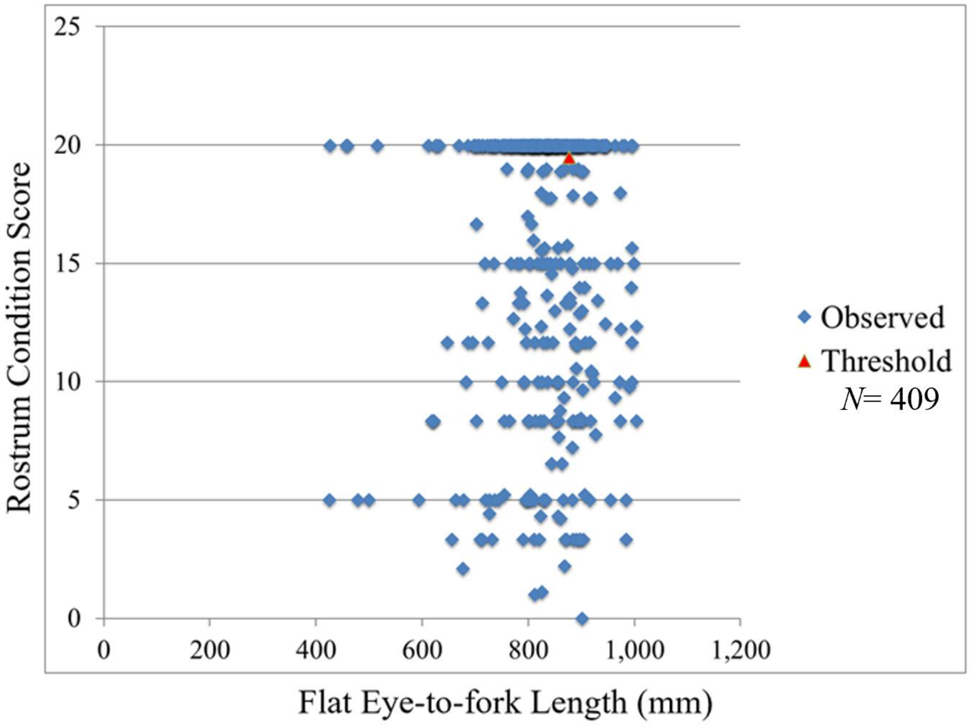

FIGURE 6.— RCS as a function of FEFL for male and female Paddlefish in the Alabama River. Blue diamonds represent each individual fish and the red triangle represents the inflection point above which there are fewer Paddlefish with undamaged rostra than would have been expected at random.

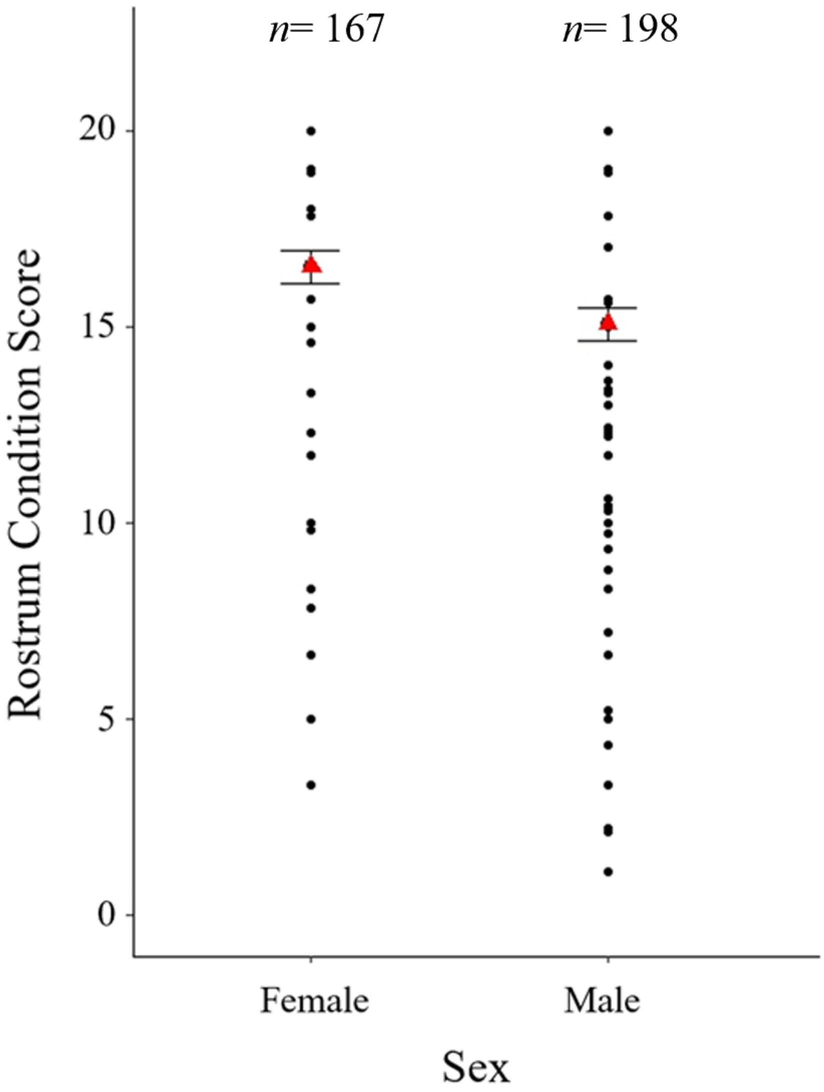

FIGURE 7.—Rostrum condition scores for female and male Paddlefish. Black dots indicate individual fish data points, while larger red triangles represent the mean ± SE for females and males.

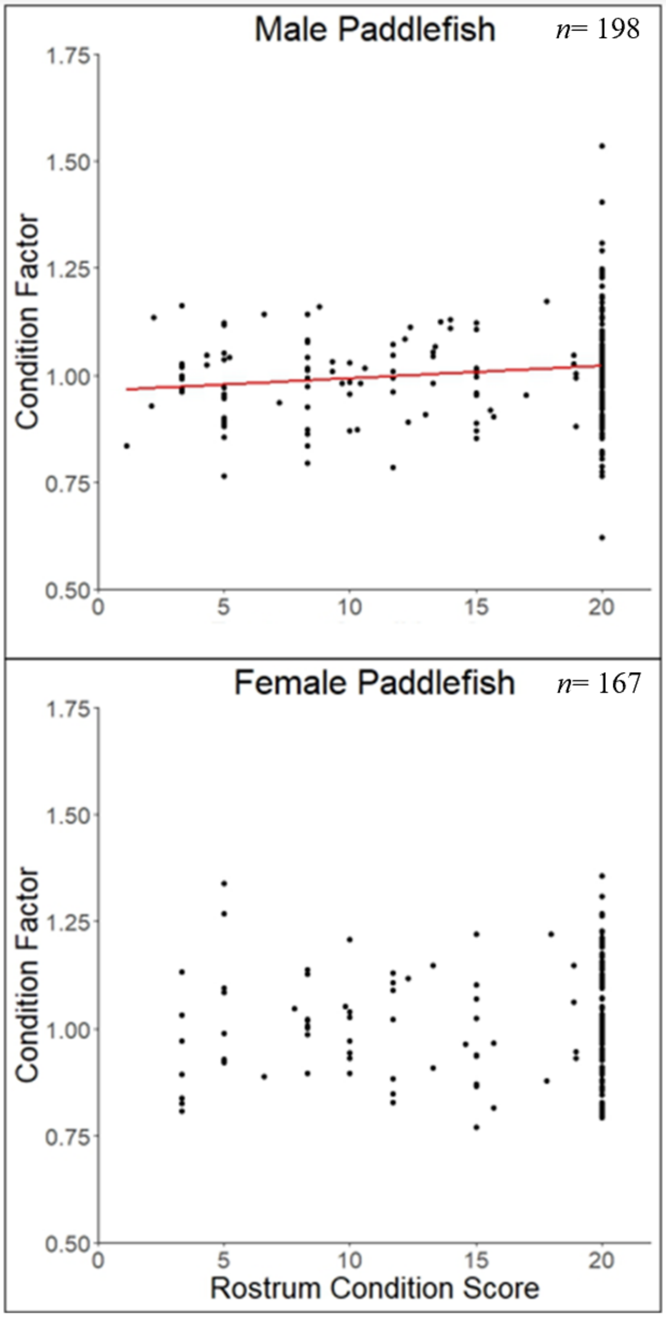

FIGURE 8.—K_n as a function of RCS for male and female Paddlefish in the Alabama River.

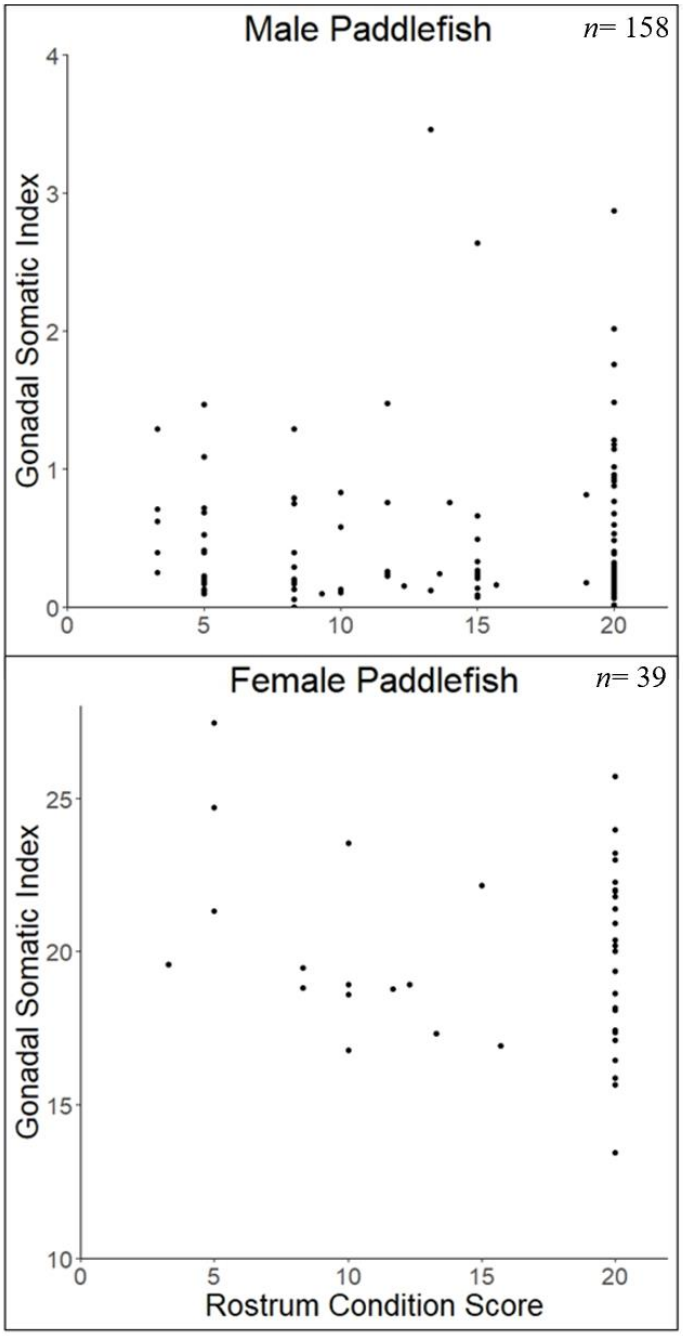

FIGURE 9.—Gonadal Somatic Index as a function of the Rostrum Condition Score for males and females with GSI >10 in the Alabama River.

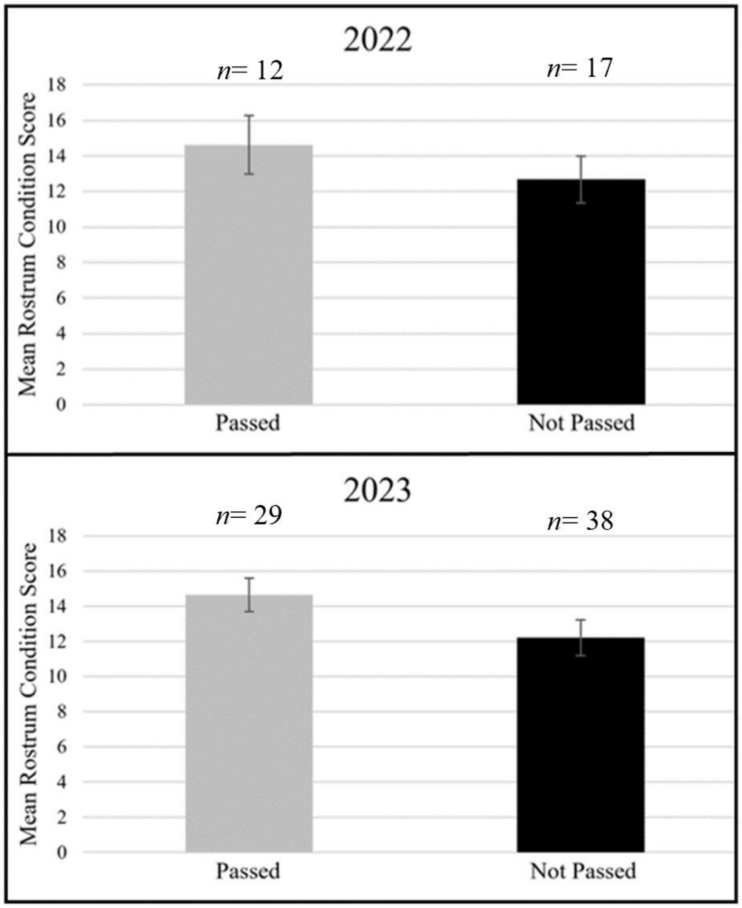

FIGURE 10.—Mean (± SE) RCS for Paddlefish that were detected in the CLD tailrace and passed or did not pass upstream of CLD in 2022 (top panel), and for Paddlefish that passed or did not pass upstream of CLD in 2023.

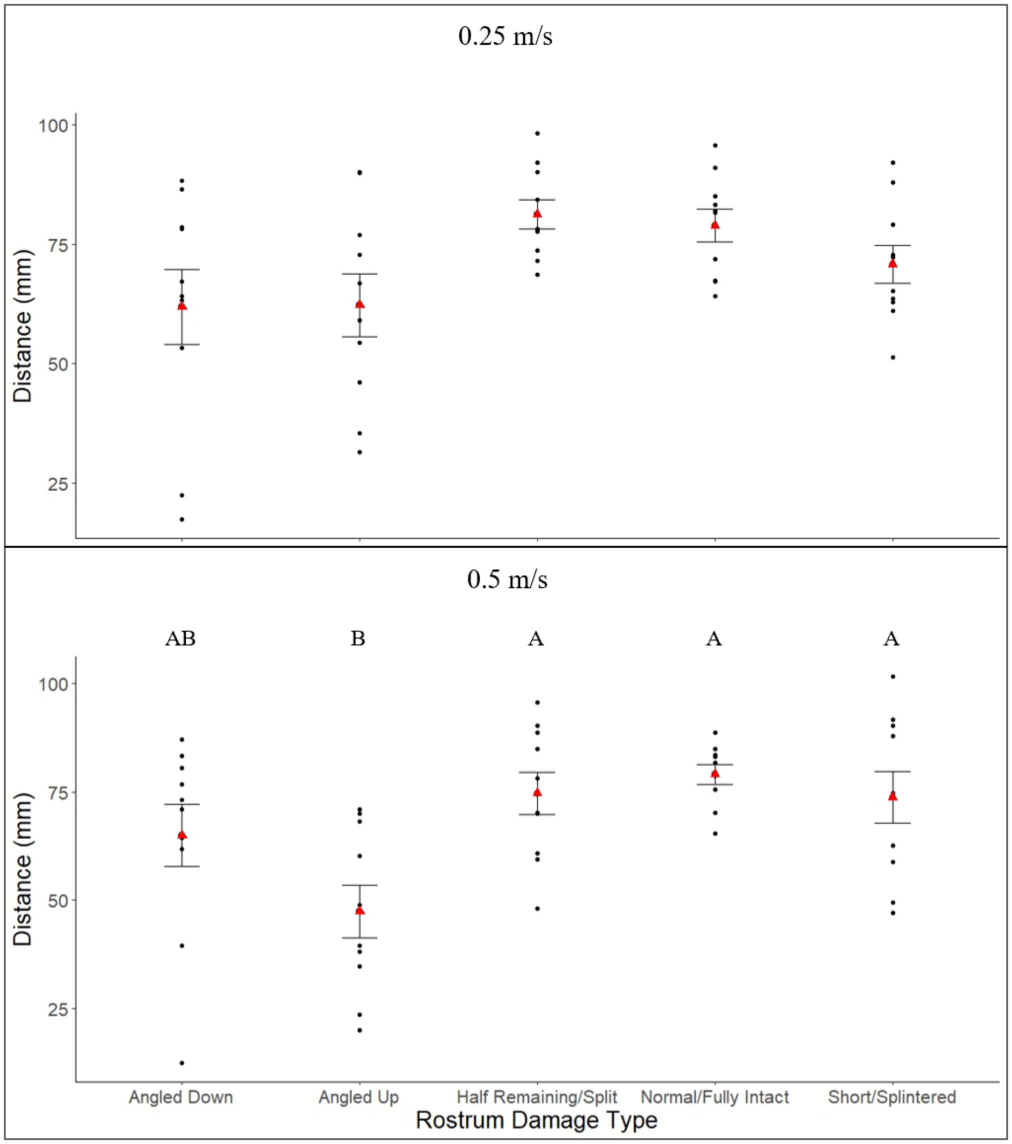

FIGURE 11.—Linear distance (mean ± SE) individual beads travelled as a function of rostrum damage type for two different water velocities. Individual circles represent the individual observations, and different letters indicate differences within a water velocity.

(A)

(B)

(C)

FIGURE 12.—Photographs of an individual Paddlefish upon its initial capture (panel A), its recapture (panel B), and the surgical incision healing at the time of recapture (panel C).

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