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Impacts of the Bonnet Carré Spillway on common bottlenose dolphins in the Mississippi Sound from 2010 to 2021

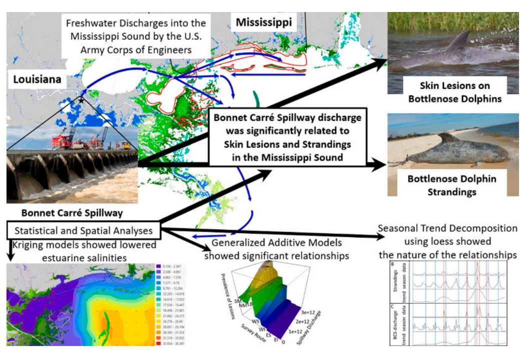
John W. Baker [*,1], Drew T. Suffoletta, Jessica N. Lewis, Kailey M. Pamperin, Rachel M. Giordano, Theresa Madrigal, Moby Solangi

Institute for Marine Mammal Studies, Gulfport, MS, USA

HIGHLIGHTS

- Prevalence of dolphins with skin lesions in the Mississippi Sound was significantly related to Bonnet Carré Spillway discharge.
- Bonnet Carré Spillway discharge was also significantly related to the frequency of stranded dolphins across the sound.
- STL models show that freshwater leakage of the Bonnet Carré Spillway likely increases the prevalence of lesions and strandings.
- Research is needed to understand the effects of the duration and degree of exposure to low salinity waters on dolphin health.

GRAPHICAL ABSTRACT



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ABSTRACT

In the last decade, the frequency of the use of the Bonnet Carré Spillway (BCS) to divert water from the Mississippi River by the United States Army Corps of Engineers (USACE) has dramatically increased. The BCS is designed to protect the city of New Orleans, Louisiana from levee breaches and devastating floods. In 2011 and 2019, during extreme flood events, the USACE diverted 6.4 trillion gallons and 10.07 trillion gallons of Mississippi River water into Lake Borgne and Biloxi Marsh, Louisiana, and the Mississippi Sound, Mississippi. The 2011 and 2019 diversions and lower-discharge diversions in other years have coincided with high freshwater discharges of coastal Mississippi streams, the appearance of common bottlenose dolphins (*Tursiops truncatus*, dolphins) with skin lesions, and large numbers of stranded dolphins. To determine what might be causing dolphin skin lesions and strandings, we investigated BCS and coastal stream discharges between 2010 and 2021 as possible drivers. Generalized additive, kriging, and seasonal-trend decomposition using loess models showed that the prevalence of skin lesions in the western Mississippi Sound and Biloxi Marsh was significantly related to BCS discharge and not to stream discharge. From 2010 to 2021, the frequency of stranded dolphins across the Mississippi Sound was significantly related to BCS discharges, while coastal stream discharges had localized effects. Between 2018 and 2019, the relationship between the frequency of dolphin strandings and BCS discharge was highly significant. In this model, the relationship between dolphin strandings and stream discharge was not

* Corresponding author.
E-mail address: johnwbakerphd@gmail.com (J.W. Baker).
[1] Current address: Geoengineering.global, Waynesville, North Carolina, USA.

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significant. This research provides evidence that freshwater diversions through the BCS likely increase the prevalence of skin lesions on live dolphins, strandings, and mortality in the Mississippi Sound.

1. Introduction

The Mississippi Sound is an elongated estuary in the Northern Gulf of Mexico bordered by the Mississippi, Alabama, and Louisiana coastlines to the north, east, and west, and the sound's barrier islands and the Gulf of Mexico to the south. The Mississippi Sound and adjacent estuaries, including Lake Borgne and Biloxi Marsh, support estuarine benthic communities, including sandy shoals, mud bottoms, saline and brackish marsh, oyster reefs, seagrass meadows, artificial reefs, and associated estuarine pelagic zones (Fig. 1). These estuaries and their abundant fish populations and complex food webs support the largest inshore common bottlenose dolphin (*Tursiops truncatus*) (dolphin) population in the Northern Gulf of Mexico (Mullin et al., 1990). Dolphins are long-lived apex predators that establish home ranges for most of their lives and remain in these areas even when the environment becomes degraded and unsafe, known as site fidelity (Wells et al., 2004; Titcomb et al., 2015; Takeshita et al., 2021). Due to these characteristics, they are also considered sentinel species (Wells et al., 2004; Van Dolah et al., 2015; Reif et al., 2015) that serve as indicators of estuarine and marine ecosystem health. Garrison et al. (2021) estimated that the Mississippi Sound and Biloxi Marsh support 1265 dolphins. Pitchford et al. (2016) estimated the dolphin population of the Mississippi Sound including Lake Borgne (2866 km^2) to be between 774 and 3210 individuals.

In estuaries, the health of dolphins can be adversely affected by exposure to low-salinity water due to natural and anthropogenic freshwater discharges. Below salinities of 10 ppt, dolphins can develop skin lesions (Sweeney and Ridgway, 1975; Wilson et al., 1999; Mullin et al., 2015; McClain et al., 2020; Deming et al., 2020). When exposed to freshwater, these lesions can develop within a week (McClain et al., 2020; Takeshita et al., 2021; Toms et al., 2021). Lesions can completely heal if the dolphin is exposed to higher-salinity waters (Deming et al., 2020; Fazioli and Mintzer, 2020). The severity of the lesions depends on the degree and length of exposure to low-salinity waters. Longer exposure times result in more severe lesions (Mullin et al., 2015; McClain et al., 2020; Booth and Thomas, 2021; Takeshita et al., 2021). Exposure to low-salinity water can also cause electrolyte abnormalities in the blood. McClain et al. (2020) detected changes in the serum electrolyte levels of dolphins within 1 to 13 days after exposure to low-salinity water. Within days to weeks, electrolyte imbalances can lead to multiple blood-related illnesses, cellular damage, and even mortality with severe and prolonged exposure (Mullin et al., 2015; Deming et al., 2020; Takeshita et al., 2021).

Freshwater inputs into the Mississippi Sound and Lake Borgne include the Pearl and Pascagoula Rivers, multiple small streams, and the Bonnet Carré Spillway (BCS). The coastal rivers and streams have a combined average daily discharge of ≈987 m^3s^{-1} from a drainage area of ≈59,647 km^2 (Christmas, 1973; Wu and Xu, 2007). The BCS is a water control structure located on the east bank of the Mississippi River ≈32 river miles upstream of New Orleans. The primary purpose of the BCS is to reduce the water level in the river and relieve pressure on the levees protecting New Orleans, Louisiana and other Lower Mississippi River communities. During high flood events caused by unusually high spring snow meltwater and/or rainfall, the BCS is used by the United States Army Corps of Engineers (USACE) to divert trillions of gallons of water from the Mississippi River into Lake Pontchartrain, where it then flows into Lake Borgne, Biloxi Marsh, and the western Mississippi Sound (Fig. 1).

Beginning in February 2019, the BCS discharged 10.07 trillion gallons over 121 days. The Pearl and the Pascagoula Rivers were also discharging unusually large amounts of water (see Supplementary Material 1). During these discharges, the monthly prevalence of skin lesions on dolphins on photo-identification (photo-id) routes surveyed by the

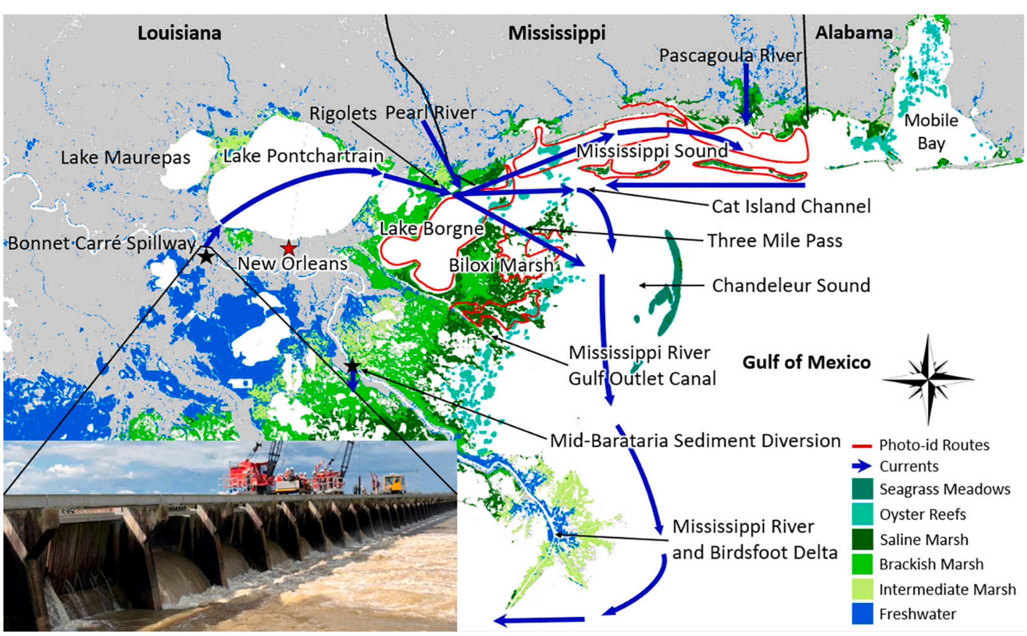

Fig. 1. Map of the study area showing the location of the Bonnet Carré Spillway (BCS, Photograph Credit: USACE) and the path the diverted water takes (see Currents) from Lake Pontchartrain, through the Rigolets deepwater pass, into Lake Borgne and the western Mississippi Sound, and through and around Biloxi Marsh and into the Chandeleur Sound by way of Three Mile Pass and Cat Island Channel. The map also shows the location of the Institute for Marine Mammal Studies' seven bottlenose dolphin photo-id survey routes (in red), Mid-Barataria Sediment Diversion, Mississippi River Gulf Outlet canal, Pearl and Pascagoula Rivers, west/east near mainland beach current, east/west near barrier island current, and estuarine communities. Notice in the photograph that river water is visibly leaking through the timbers of the first bay of the BCS.

Institute for Marine Mammal Studies (IMMS) appeared to increase. Lesions appeared more prevalent on a photo-id route in the western Mississippi Sound and two routes in Biloxi Marsh. In this period, many dolphins stranded along the Mississippi Coast with 47 dolphins stranding in May alone. An Unusual Mortality Event (UME) was declared by the National Oceanic and Atmospheric Administration (NOAA) from February 1 to November 30 for Florida, Alabama, Mississippi, and Louisiana (Fig. 2). Based on necropsy, histopathology, and diagnostic findings, NOAA determined that the cause of the UME was "exposure to low-salinity waters discharged from watersheds that drain into the Northern Gulf of Mexico" (NOAA Fisheries, 2022). NOAA also found that 47 % of the dead stranded dolphins in Mississippi that were fresh to moderately decomposed exhibited skin lesions consistent with exposure to low-salinity water (NOAA Fisheries, 2022).

To date, no research has been published on the potential drivers of the skin lesions on dolphins in the Mississippi Sound and Biloxi Marsh in 2019 or the unusually large number of strandings in the Mississippi Sound during that period. It is currently unknown if these events were related to coastal stream discharge from the Pearl and Pascagoula Rivers and/or from the openings of the BCS. If these events were related to the operation of the BCS, it would be important to understand the nature of the relationship and the extent to which the BCS has impacted dolphin health in the past. The need for this research is urgent, as the use of the BCS has increased dramatically since 2010, and some of these openings are discharging enormous volumes of water that could have severe implications for the conservation of dolphins in this area. In addition, this problem is global in nature as 50 % of all freshwater stream flow is managed through hydrologic modifications (Allan et al., 2021), and many large rivers around the world have been channelized and disconnected from their floodplains creating the potential for the release of large volumes of freshwater into estuaries. To develop an understanding of this problem, we investigated 1) the relationship between skin lesions on live dolphins and dolphin strandings, and BCS and coastal stream discharge, 2) the characteristics of these relationships, and 3) the areal extent to which stream and/or the BCS discharges impacted the dolphins in the Mississippi Sound, Lake Borgne, and Biloxi Marsh.

Fig. 2. Skin lesions on bottlenose dolphins during the 2019 Unusual Mortality Event declared by NOAA. Lesions were observed on numerous live dolphins on multiple IMMS' bottlenose dolphin photo-id survey routes including in A) South Marsh in March, B) South Marsh in July, C) West Sound in June, and also on stranded dolphins including D) this adult female dolphin that stranded in Pass Christian, Mississippi in March. Photographs courtesy of IMMS' Photo-id and Stranding Programs.

2. Materials and methods

2.1. Study area

For the analyses of skin lesions of live dolphins, the study area included the Mississippi Sound in Mississippi's territorial waters, Lake Borgne, Louisiana, and Biloxi Marsh, Louisiana. The study area of all stranded bottlenose dolphin analyses was restricted to Mississippi's territorial waters and beaches. The Mississippi Sound has a diurnal tide range of 0.46 m with an average depth at mean high water of 3.54 m. Water temperature ranges between 3.4 and 36.5 °C (Christmas, 1973). Salinity ranges from an average of 33 ppt near the barrier islands to 0 ppt in the western Pearl River and Lake Pontchartrain drainage areas (Christmas, 1973). The average rainfall is 149.6 cm yr^{-1}(Christmas, 1973). From east to west, the streams flowing into the Mississippi Sound and Lake Borgne include the Escatawpa River, Pascagoula River, Tchoutacabouffa River, Biloxi River, Bayou Bernard, Wolf River, Jourdan River, Pearl River, Bogue Chitto River, Tchefuncte River, Natalbany River, Tickfaw River, Amite River, and Blind River.

Currents in the vicinity of the barrier islands of the Mississippi Sound generally flow east to west (Morton, 2007) due to regular southeast winds (Fig. 1, Thompson and Leming, 1978). Water that piles up in the western sound flows south through the Chandeleur Sound (Hart, 1976) and around the Mississippi River delta (Walker, 1996). Based on hydrodynamic model simulations of BCS openings between 2012 and 2015, Linhoss et al. (2023) found that water in the western sound sometimes flows east, relatively close to the beach, along the coast of Mississippi (Fig. 1). Based on Modis satellite imagery from 2019, discharge from the BCS flows from Lake Pontchartrain into Lake Borgne via the Rigolets (a deep-water tidal pass). From here, BCS discharge flows into the Biloxi Marsh via the Three Mile Pass before entering the Chandeleur Sound (Fig. 1). In high discharge years, water from the BCS also flows south through the Cat Island Channel into the Chandeleur Sound and east relatively close to the beach along the Mississippi coast (Linhoss et al., 2023).

2.2. History of Mississippi River freshwater inputs into the Mississippi Sound

Historically, the Mississippi River was connected to the Mississippi Sound through Bayou Manchac which flows into the Amite River before entering Lake Maurepas (Camp, 1982). The Mississippi River has also flowed into the Mississippi Sound by way of Lake Pontchartrain through breaches in the levee or crevasses. Between 1850 and 1927, over 1000 crevasses formed in the levee on the lower Mississippi River (Davis et al., 1993). One crevasse that formed in 1874, near the present location of the BCS, allowed river water to flow into Lake Pontchartrain for ten years, decimating oysters and other fisheries in Lake Pontchartrain (Davis et al., 1993). Between 1937 and 2010, the BCS was opened nine times. In contrast, from 2010 to 2020, it was opened five times (see Supplement 1). The BCS discharges in 2011 and 2019 were associated with devastating impacts to commercial oyster fisheries and a severe algal bloom in 2019 (Armstrong et al., 2021; Gledhill et al., 2020). Excluding the BCS discharges, the Mississippi Sound has not received flow from the Mississippi River in over a century due to the enlarging of the levee along the bank of the Mississippi River.

2.3. Data collection

2.3.1. Bottlenose dolphin photo-identification

From 2010 to December 31, 2021, IMMS conducted monthly, weather permitting, dolphin photo-id surveys on seven survey routes. Data collection began on three survey routes in 2010 and four in 2011 (Supplement 1). The four survey routes in the Mississippi Sound included East Sound, West Sound, East Islands, and West Islands. The three routes in Louisiana included Lake Borgne, North Marsh, and South

Marsh (Table 1). Photo-id methodologies followed Wursig and Jefferson (1990), Rosel et al. (2011), and Urian et al. (2014). Photo-id survey crews consisted of a boat captain, two photographers, and at least one data recorder, who all contributed to spotting and observing dolphins and collecting survey data. Surveys were conducted on days with a Beaufort Sea State of 3 or less. Survey platforms included a 6.7 m NauticStar center console boat with a 200 hp. Yamaha outboard and a 6.4 m Frontier center console bay boat with a 150 hp. Yamaha outboard. When looking for dolphins on the monthly surveyed routes, the boats were driven at approximately 40 km hr^{-1} until a solitary dolphin or a pod (a sighting) was found. An individual group or pod was defined as all dolphins within 100 m of each other exhibiting similar behaviors (Quintana-Rizzo and Wells, 2001). Once observed, photographers collected high-quality photos of the left and right sides of the dorsal fins of all individuals in the pod, if possible. Sightings generally took <30 min but sometimes took up to 40 min for large pods spread out over a large area. Photographs were taken from 2010 to 2021 with the Canon EOS 30D, 50D, 60D, and 70D cameras and Canon 100–400 Mk 1 telephoto lens using sports mode, aperture-priority (Av) mode, and manual exposure settings. Beginning in October 2021, photos were taken with the Canon EOS R5 camera and the Canon RF 100–500 mm telephoto lens utilizing manual exposure settings. Other sighting/pod-specific data collected included pod GPS points, depth, water transparency, salinity, dissolved oxygen, water temperature, pH, weather and sea conditions, recordings of dolphin behaviors (following Shane (1990) and Miller et al. (2010)), and counts of adults, juveniles, and calves. Once the field surveys were completed, collected photos were sorted following the photo quality and distinctiveness methodology of Urian et al. (2014). The Darwin software system (Wilkin et al., 1998), from 2010 to 2021, and R package finFindR in 2021 (Thompson et al., 2022) were used to identify new and known distinctive individuals. Adobe Bridge was used to enhance and increase the contrast of all photos before processing in finFindR. All photo-id survey data was entered and managed in FinBase v.2 (Adams et al., 2006) and Esri's ArcGIS Pro 3.1.2.

2.3.2. Quantifying skin lesions on bottlenose dolphins using photos from IMMS' photo-identification program

To quantify the number of dolphins with skin lesions in the Mississippi Sound, Lake Borgne, and Biloxi Marsh from 2010 to 2021, we utilized IMMS' Bottlenose Dolphin Photo-id Program photos. IMMS' Research Department staff looked through 778,717 photos of 4595 dolphin pods taken between January 1, 2010, and December 31, 2021, to count the monthly number of individual dolphins with skin lesions on their bodies for each of IMMS' seven photo-id survey routes (Table 1 and Fig. 1). Skin lesions were identified utilizing examples from Duignan et al. (2020), Hart et al. (2012), Mullin et al. (2015), Ronje et al. (2018), Toms et al. (2020), and Townsend and Staggs (2020). IMMS' head veterinarian trained IMMS' Research Program staff to identify dolphin skin lesions. Two or more research staff confirmed the presence of lesions on each affected dolphin by examining the visible discoloration on the animal's epidermis.

Between 2010 and 2021, the quality of the photographs varied over time due to advances in the camera technologies and the different photography methodologies used. Photographs taken between June 1, 2018, and January 31, 2020, which were used in a separate statistical analysis (see Generalized Additive Models section below), were all taken with Canon 70Ds and Canon 100–400 Mk 1 telephoto lenses using the aperture-priority (Av) mode. Only photos with Overall Photographic Quality scores of 6–12 based on angle, clarity, contrast, and distance to target (Urian et al., 2014) were used in the analyses. Suspected skin lesions were not counted if there was uncertainty due to poor photo quality or difficulty distinguishing skin lesions from other skin features.

Both distinctive (dolphin individuals with relatively permanent identifiable marks that allow for identification over time) and nondistinctive dolphins were included in monthly lesion sums. All dolphins photographed between 2010 and 2021 were examined for the presence

Table 1
Bottlenose dolphin photo-id survey data summary for monthly surveys conducted between 2010 and 2021 on the Institute for Marine Mammal Studies seven survey routes. The length in kilometers and the date range of collected data are provided for each survey route. Basic statistics for surveys include total number of surveys, total sightings, total number of individuals, and average pod size. Also provided are the total number of distinct dolphins in IMMS' catalog for each route, the average number of dolphins seen with lesions per month, the average number of distinct dolphins seen per month, and the average number of distinct dolphins seen with lesions per month.

Photo-id survey route	Survey route length (km)	Date range of survey data	Total number of monthly surveys	Total sightings (pods)	Total number of individuals in pods	Average pod size	Total number of distinct dolphins identified 2010–2021	Average number of dolphins with lesions per month	Average number of distinct dolphins seen per month	Average number of distinct dolphins seen with lesions per month
Lake Borgne	144	8/10–12/21	84	409	2789	6.8	190	4.14	3.4	0.35
North Marsh	92	9/10–12/21	84	446	2435	5.5	153	2.85	3.61	0.33
South Marsh	93	9/12–12/21	85	480	2187	4.6	109	2.91	2.85	0.29
East Sound	125	3/10–12/21	120	942	5556	5.9	619	0.98	11	0.37
West Sound	140	10/10–12/21	109	901	5635	6.3	528	2.15	9.17	0.32
East Islands	78	10/10–12/21	107	797	7016	8.8	625	1.49	19.77	0.31
West Islands	67	9/12–11/21	93	620	5441	8.8	419	1.38	15.99	0.36

of skin lesions. Each image was digitally magnified and closely examined. When lesions were detected, IMMS research technicians used various identifiable features on the dolphin's bodies, including patterns on the trailing edge of dorsal fins, lesion patterns, scars, rake marks, parasites, discolorations, and other features, to distinguish all the pod-specific lesioned individuals from each other. This study only used these identifiable features to obtain counts of dolphins with lesions for the immediate sighting on that specific date and route. These features were not used to identify or track individual dolphins over time (e.g., month to month). For each pod surveyed, research technicians identified all distinguishable dolphins with lesions and calculated the monthly sum for each route (Supplementary Material 1). Dolphins with no detectable lesions in IMMS' photographs were not counted in the monthly sums. Dolphins photographed on only one side of their body during a sighting were counted and included in the monthly sum as long as they could be differentiated from other dolphins with lesions in the pod. Each dolphin with a lesion or multiple lesions was counted as one individual for that monthly sum, irrespective of the severity or degree of coverage of skin lesions over the dolphin's body.

2.3.3. Bottlenose dolphin stranding data

The NOAA Marine Mammal Health and Stranding Response Program database (received from NOAA on May 22, 2023) was used to acquire data on dolphin strandings in Mississippi. A subset of the database was used in the analyses. This subset (Supplementary Material 2) included only dolphins with an assigned "Age Class" of either adult, subadult, or yearling that stranded in Mississippi between January 1, 2010, and December 31, 2021. The number of stranded dolphins per month was calculated from this sample of 430 bottlenose dolphins and used in these analyses.

2.3.4. Water quality data

Monthly BCS discharge data from 2010 to 2021 was obtained from the USACE (USACE's New Orleans District Website, 2023a (Historic Operations of the Bonnet Carré Spillway)). Monthly stream discharge data was collected for all the streams flowing into Lake Borgne (by way of Lake Pontchartrain and Lake Maurepas) and the Mississippi Sound, which had United States Geological Survey (USGS) daily or monthly stream discharge data. Streams with discharge data included the Escatawpa River (USGS gage 02479560), Pascagoula River (USGS 02479000), Biloxi River (USGS 02481000), Wolf River (USGS 02481510), Pearl River (USGS 02489500), Bogue Chitto River (USGS 02492000), Tangipahoa River (USGS 07375500), Natalbany River (USGS 07376500), Tickfaw River (USGS 07376000), Amite River (USGS 07378500), and Tchefuncte River (USGS 07375000). Approximately 10.3 % (163/1584) of all measurements were missing in the above stream data. This missing data was estimated using the 12-year monthly average for each month per stream. Daily salinity data (304,367 data points) for Louisiana, Mississippi, and Alabama between Jan 1, 2010, and December 31, 2021, were collected from multiple federal, state, and other organizations, including IMMS, Mississippi Department of Marine Resources, Louisiana's Coastwide Reference Monitoring System, Louisiana Department of Environmental Quality, Louisiana Department of Wildlife and Fisheries, Lake Pontchartrain Basin Foundation, NOAA's National Data Buoy Center, USGS, Dauphin Island Sea Lab, and the University of Southern Mississippi.

2.4. Quantitative analyses

2.4.1. Kriging interpolation models of skin lesions and salinity

To investigate the relationship between lesions and salinity, we created two 2-dimensional continuous prediction surfaces or raster maps to visualize these variables using the data collected from January 1, 2010, to December 31, 2021. Ordinary kriging, a geostatistical interpolation method that uses spatial autocorrelation to estimate unknown or unmeasured values, was used to generate these continuous prediction surfaces (Asal, 2023; Kostopoulou, 2021). Ordinary kriging is based on Tobler's Law of Geography which states that near spatial data values are more similar to each other than distant values (Tobler, 1970). Ordinary kriging estimates unknown values by utilizing the spatial variogram of nearby data (Zhang et al., 2007; Kostopoulou, 2021). It has been used for many purposes including coastal planning (Kostopoulou, 2021), mapping groundwater salinity (Boudibi et al., 2019; Bodaghabadi, 2018; Fu et al., 2021), and creating digital terrain models (Asal et al., 2023). Ordinary kriging with optimized spherical variogram models, were used to create both output prediction surfaces in ArcGIS Pro 3.1.2 Spatial Analyst extension. Each surface represents the monthly average sum of skin lesions and salinity.

2.5. Generalized additive models

Statistical analyses were performed in the statistical programming language R (v.4.0.0; R Development Core Team, 2019). Generalized additive models (GAMs) using the R package mgcv (v.1.8.42; Wood, 2017) were used to investigate the relationship between skin lesions, dolphin strandings, and BCS and coastal stream discharges. Response variables modeled included monthly sums of the prevalence of photo-id-based lesions (for each route) and stranded dolphins. Each dolphin with lesions was treated as an independent response unit. Predictor variables included monthly sums of BCS daily discharge in m^3/s, coastal stream discharge in m^3/s, and pod size. The monthly sum of coastal stream discharge (stream discharge) used in the models was the sum of the discharges of all the streams flowing into Lake Borgne and the Mississippi Sound that had USGS stream gages (see above). The predictor variables of salinity and water temperature were monthly averages. Other predictor variables included month, time, and route. Statistical analyses focused on the long-term relationships using data from January 1, 2010, to December 31, 2021, and the period around the BCS opening in 2019 (June 1, 2018, to January 31, 2020).

The gam.check function in mgcv and appraise function in Gratia (v.0.8.1; Simpson and Singmann, 2018) were used to select the correct distribution, test model assumptions, and select k. The negative binomial distribution with a log link function was used for all models. Correlation between predictor variables was investigated using ggscatmat in GGally (v.2.1.2; Schloerke, 2018). Collinearity between predictor variables was assessed using the variance inflation factor (VIF) function (Wood, 2017). Selection between collinear predictor variables was made by selecting the predictor variable with the lowest Akaike information criteria value (AIC; Anderson and Burnham, 2004). Cyclic cubic regression splines (bs = "cc") were used to fit the variable month. A Gaussian process smooth (bs = "gp") with a Matérn covariance function was used to model long-term trends using the variable year (Wood, 2017). Thin plate regression splines with shrinkage (bs = "ts") were used to fit all other predictor variables. Restricted maximum likelihood (REML) with mgcv's automated double penalty approach (select = TRUE; Marra and Wood, 2011), which adds an extra penalty in the null space of all smooths in the model, was used to estimate the smoothing parameters of predictor variables. Concurvity was investigated using mgcv's concurvity function. All figures were produced using ggplot2 (v.3.3.6; Wickham, 2011), Gratia, and the vis.gam function in mgcv.

GAMs were fitted with IMMS' photo-id Research Program data, with an average of approximately 20 % of the monthly data missing depending on the route. Separate GAMs were used to model the number of dolphins with lesions and salinity as a function of month and year, the number of dolphins with lesions (with the route as a random effect), and the number of stranded dolphins as a function of BCS and stream discharge (Table 2).

2.6. Seasonal-trend decomposition using loess

Seasonal and long-term trends were modeled to investigate the relationship between skin lesions, strandings, and BCS and stream

Table 2

Generalized additive models (GAMs), effective degrees of freedom (edf), *p*-values, percent deviance explained (DE), and Akaike Information Criteria (AIC). Response variables include salinity, and the number of live dolphins with skin lesions and stranded bottlenose dolphins. Predictor variables include route, BCS discharge (BCS, BCS discharge), coastal stream discharge (stream, stream discharge), pod size, month, and year. Bold numbers indicate significant *p*-values. Month and year were fit with cyclic cubic regression splines (bs = "cc") and Gaussian process smooths (bs = "gp").

Generalized Additive Time Series Models 2010 to 2021		Month		Year		Model	
		edf	p-value	edf	p-value	DE	AIC
Lesions (photo-id) ~ Month (bs = "cc") + Year (bs = "gp")		3.20	**0.0007**	7.75	**2.0e-16**	9.57	3025
Salinity (photo-id) ~ Month (bs = "cc") + Year (bs = "gp")		5.79	**2.0e-16**	7.92	**2.0e-16**	27.4	4526
Generalized Additive Models 2010 to 2021	**By Route**	**BCS Discharge**		**Stream Discharge**		**Model**	
Lesions (ph.-id) ~ Route (re) + BCS by route + stream by route + pod size		edf	p-value	edf	p-value	DE	AIC
	South Marsh	0.88	**0.005**	0.46	0.164	32.2	2431
	North Marsh	1.45	**0.002**	0.0002	0.38	32.2	2431
	Lake Borgne	0.0002	0.64	0.0001	0.83	32.2	2431
	West Sound	1.17	**0.020**	1.19	0.20	32.2	2431
	West Islands	0.73	0.24	0.0003	0.54	32.2	2431
	East Sound	0.17	0.24	0.0002	0.72	32.2	2431
	East Islands	0.003	0.41	1.40	**0.020**	32.2	2431
Stranded dolphins ~ BCS discharge + stream discharge	–	1.75	**2.2e-05**	1.73	**0.0005**	24.2	617
Generalized Additive Models June 2018 to January 2020							
Lesions (ph.-id) ~ Route (re) + BCS by route + stream by route + pod size	South Marsh	0.861	**0.009**	1e-05	0.55	50.6	410
	North Marsh	1.27	**0.011**	1.08	0.09	50.6	410
	Lake Borgne	6e-06	0.51	0.081	**0.03**	50.6	410
	West Sound	1.36	**0.006**	2e-05	0.43	50.6	410
	West Islands	1e-05	0.69	2e-05	0.50	50.6	410
	East Sound	1.31	**0.019**	8e-06	0.95	50.6	410
	East Islands	1e-05	0.75	0.712	0.07	50.6	410
Stranded dolphins ~ BCS discharge + stream discharge	–	1.93	**2.7e-05**	1.08	0.077	69.7	96.8

discharge. Seasonal-trend decomposition using loess (STL) was carried out in the R package stats (v.4.2.0; Cleveland et al., 1990). STL is a robust non-parametric smoothing approach that fits a smooth or regression surface to data using locally weighted regression or loess (Cleveland et al., 1990). STL applies repeated loess fitting to data segments to decompose monthly time series into seasonal, trend, and residual components. To model lesions on dolphins utilizing STL (for the seasonal (season) trend and long-term trend (trend)), missing monthly data for each route was replaced with the monthly average (based on data from 2010 to 2021). This data set with estimated missing data was also used to look for autocorrelation in the monthly sum of lesions photo-id survey data.

3. Results

3.1. Summary of photo-id surveys

Between 2010 and 2021, IMMS' Photo-id Program conducted 682 monthly surveys on their seven routes (Table 1). A total of 4595 dolphin pods consisting of 31,059 individuals were photographed and surveyed. The average pod size for the different routes ranged from 4.6 to 8.8 dolphins, with the island routes having the largest average pod size. The Lake Borgne route had the largest average number of dolphins with lesions per month (4.14), followed by South Marsh (2.91), North Marsh (2.85), and the West Sound (2.15). The East Sound, West Islands, and East Islands routes have the lowest average number of dolphins with lesions per month. The dolphins on the western routes of Lake Borgne, North Marsh, and South Marsh had more lesions per month than the eastern routes of East Sound and East Islands (Fig. 3). The monthly average number of distinctive dolphins with lesions on the seven routes ranged from 0.29 to 0.37 (Table 1).

3.2. Relationship between skin lesions and salinity

Kriging models of lesions and salinity, and GAMs of lesions and salinity as a function of month and time show an inverse relationship between lesions and salinity (Fig. 3 and Table 2). When comparing the kriging models, areas with the lowest salinity (e.g., Lake Borgne, the western sound, and Biloxi Marsh) have the highest prevalence of lesions (a 12-year average), and areas with the highest salinity (e.g., the eastern

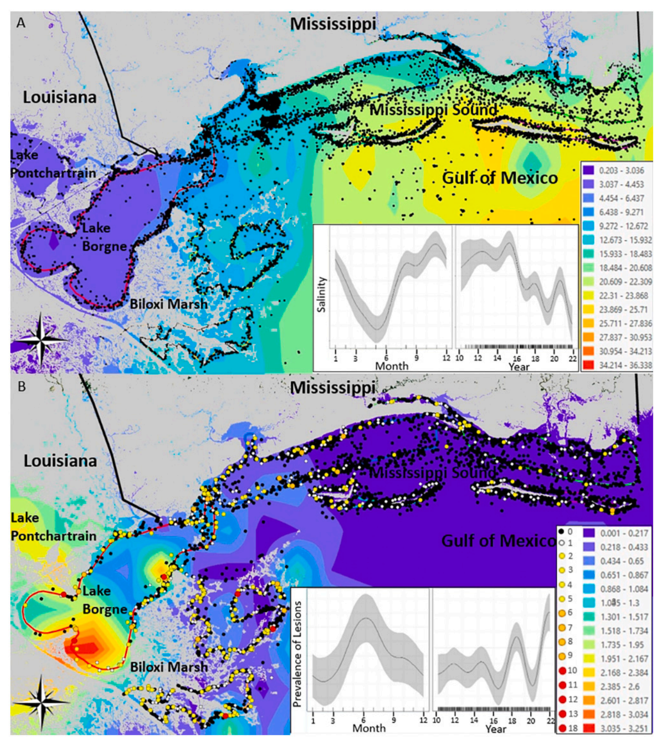

Fig. 3. ArcGIS Pro kriging models of the Mississippi Sound and Biloxi Marsh between January 1, 2010, and December 31, 2021. A) Average salinity (ppt) ranged from 0.203 to 36.338. The black points represent the locations where salinity data was collected. B) The average prevalence of skin lesions ranged from 0.001 to 3.251 dolphins per 0.08-sized grid cell. The points indicate the location and number of dolphins in each pod that had lesions which is represented by black (0), white (1), yellow (2–5), orange (6–9), and red (10–13 and 18). In each map there are seasonal and long-trend smooths of a generalized additive model of A) salinity as a function of month and year and B) the prevalence of lesions as a function of month and year. Shaded areas around the fitted smooths are 95 % confidence intervals.

sound and the waters around Mississippi's barrier islands) have the lowest prevalence of lesions. Smooths produced from GAMs of lesions and salinity also show an inverse relationship. Lesions were significantly related to month (p = 0.0007) and year (p = 2.0e-16). Salinity was significantly related to month (p = 2.0e-16) and year (p = 2.0e-16).

3.3. Relationship between skin lesions and BCS and coastal stream discharge

GAMs showed a significant association between skin lesions, and BCS and stream discharge (Fig. 4). The GAM fitting skin lesions as a function of route (random effect), BCS and stream discharge (by route), and pod size using data from 2010 to 2021 (Table 2) showed that lesions were significantly related to BCS discharge on the South Marsh (p = 0.005), North Marsh (p = 0.002), and West Sound (p = 0.020) routes. On these routes, the frequency of lesions increased as BCS discharge increased. At higher discharges, there was an inflection point, after which the strength of the relationship decreased (Fig. 4). Skin lesions were not significantly related to the BCS discharge on the Lake Borgne (p = 0.64), West Islands (p = 0.24), East Sound (p = 0.24), or East Islands (p = 0.41) routes. In this GAM, skin lesions were not significantly related to stream discharge for the South Marsh (p = 0.164), North Marsh (p = 0.38), Lake Borgne (p = 0.83), West Sound (p = 0.20), West Islands (p = 0.54), or East Sound (p = 0.72) routes. Lesions were significantly and positively related to the stream discharge for the East Islands (p = 0.020) route. Lesions were not significantly related to water temperature. Water temperature was, therefore, not included in the final GAMs. Both route and pod size have highly significant effects (p < 0.0001) in the models.

The 2018 to 2020 GAM analyses were used to investigate the impacts of the BCS opening of 2019 (Table 2). Kriging models showed that the salinity of the Mississippi Sound and surrounding estuaries had decreased significantly from March to June in 2019 (Fig. 5). GAMs showed that lesions were significantly related to the BCS discharge on the South Marsh (p = 0.009), North Marsh (p = 0.011), West Sound (p = 0.006), and East Sound (p = 0.019) routes. On the South Marsh, North Marsh, West Sound, and East Sound routes, as the BCS discharge increased, the presence of lesions also increased with an inflection point in this relationship at higher discharges (Fig. 4). Lesions were not significantly related to BCS discharge on the Lake Borgne (p = 0.51), West Islands (p = 0.69), or East Islands (p = 0.75) routes. Lesions were significantly and positively related to stream discharge for the Lake Borgne route (p = 0.03). Lesions were not significantly related to stream discharge for the South Marsh (p = 0.55), North Marsh (p = 0.09), West Sound (p = 0.43), West Islands (p = 0.50), East Sound (p = 0.95), or East Islands (p = 0.07) routes.

Visualization of data trendlines and long-term trendlines via STL models show that peaks in the occurrence of lesions are offset from peaks in salinity, BCS, and stream discharges (Fig. 6). The spike in the lesion data trend around the opening of the BCS in 2019, for instance, appears to have occurred slightly before the BCS was opened. This spike in lesions, however, does coincide with a spike in the data trend of stream discharge in 2019. A spike in the prevalence of lesions in late 2015 also precedes spikes in both BCS and stream discharge in early 2016. In 2021, a year with no reported BCS discharge, high-stream discharge correlated with an increase in the prevalence of lesions.

3.4. Relationship between stranded dolphins and BCS and stream discharge

The GAM using data from 2010 to 2021 showed highly significant and positive relationships between the monthly prevalence of stranded dolphins and BCS (p = 2.2e-05) and stream discharge (p = 0.0005). Smooths showed that the prevalence of stranded dolphins primarily increased as BCS and stream discharge increased with an inflection point at higher discharges (Fig. 7). The GAM using data from 2018 to 2020 also showed a highly significant and positive relationship between the prevalence of stranded dolphins and BCS discharge (p = 2.7e-05). The smooth showed that the prevalence of stranded dolphins increased as BCS discharge increased with an inflection point at higher discharges (Fig. 7). The prevalence of stranded dolphins was not significantly related to stream discharge (p = 0.077). Data trend lines and long-term trend lines in STL models show a correlation between the prevalence of strandings and BCS and stream discharges (Fig. 6). In 2016 and 2019, a spike in the data trend in dolphin strandings correlated with the BCS

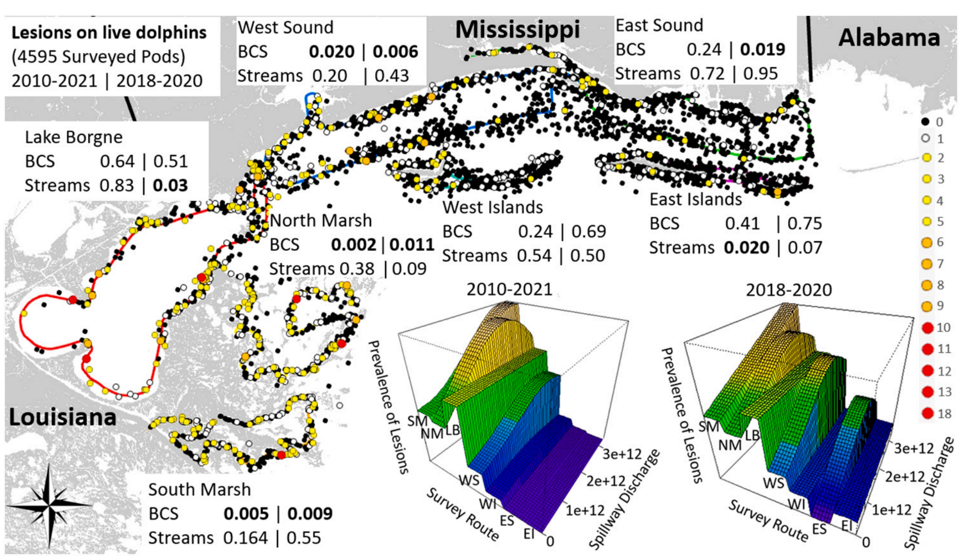

Fig. 4. Spatial representation of *P*-values for GAMs relating the average monthly prevalence of skin lesions of bottlenose dolphins to BCS and coastal stream discharges along IMMS' seven routes in the Mississippi Sound and Biloxi Marsh. One GAM modeled data between 2010 and 2021. The other GAM modeled data around the 2019 BCS discharge event from June 2018 to January 2020. Bold numbers indicate significant *p*-values. The background map shows the locations of the 4595 dolphin pods on IMMS' photo-id routes between 2010 and 2021. The colors of the points indicate the number of dolphins in each pod are had lesions which is represented by black (0), white (1), yellow (2–5), orange (6–9), and red (10–13 and 18). Also displayed are smooths of the GAMs. For both models, the routes of South Marsh (SM), North Marsh (NM), and West Sound (WS) were significant. East Sound was also significant for the 2018 to 2020 GAM. Lake Borgne (LB), West Islands (WI), and East Islands (EI) were nonsignificant in both models.

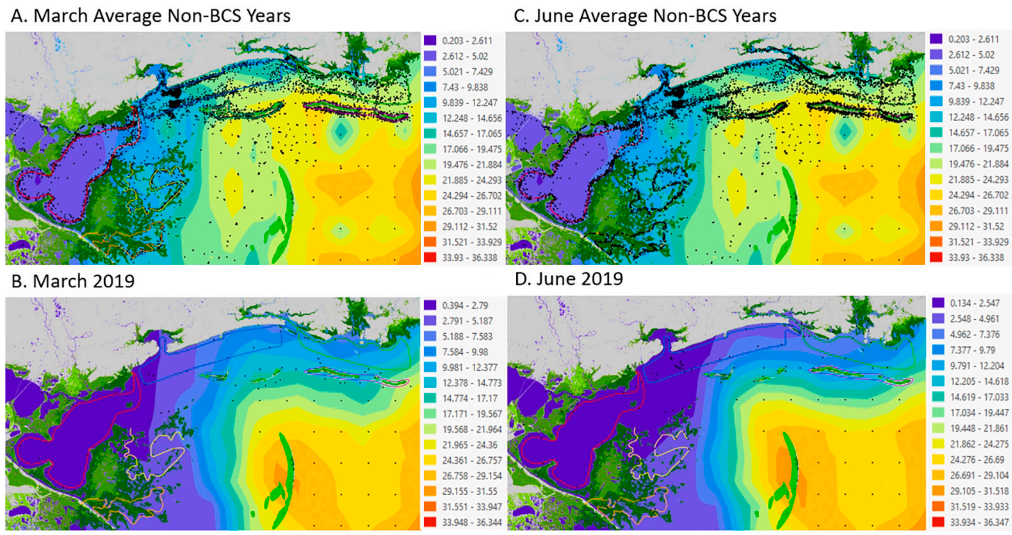

Fig. 5. ArcGIS Pro kriging salinity (ppt) models of the Mississippi Sound and Biloxi Marsh comparing the average salinity in non-BCS years (including 2010, 2012, 2013, 2014, 2015, 2017, and 2021) in March (A) and June (C) to the average salinity in March (B) and June (D) of 2019. Black points indicate the locations of salinity data used in this analysis.

openings and stream discharge.

4. Discussion

Since 2010, the USACE has used the Bonnet Carré Spillway five times to divert trillions of gallons of Mississippi River water into Lake Pontchartrain, Lake Borgne, the Mississippi Sound, and Biloxi Marsh. Coinciding with these diversions have been unusually high discharges from the Pearl and Pascagoula Rivers, sightings of dolphins with skin lesions, and dolphin strandings, including an Unusual Mortality Event declared by NOAA in 2019. To inform mitigation strategies for freshwater diversions and help conserve dolphins in Lake Borgne, the Mississippi Sound, and Biloxi Marsh, we implemented generalized additive, kriging, and seasonal trend decomposition using loess models to investigate the relationship between dolphin health, and BCS and coastal stream discharges. Objectives of this research were to determine if the prevalence of skin lesions on live dolphins and dolphin strandings in the Mississippi Sound area are significantly associated with BCS and/or coastal stream discharge, investigate the characteristics of these relationships, and determine what areas of the sound were likely affected by these discharges. We found that BCS and stream discharge were significantly related to the prevalence of lesions on dolphins and dolphin strandings. This is the first study that has modeled skin lesions on live dolphins and dolphin strandings over a decade with multiple large freshwater diversions and river discharges. It builds on several studies that have evaluated the effects of freshwater exposure on dolphin health using various approaches (e.g., physiological responses (Ewing et al., 2017; Deming et al., 2020; McClain et al., 2020); behavioral changes (Fazioli and Mintzer, 2020; Takeshita et al., 2021); mortality (Toms et al., 2021)). The significance of our results is far-reaching, as many channelized rivers worldwide can potentially impact coastal dolphin populations with large freshwater discharges, especially during high flood events.

Multiple GAMs found that the increase in the occurrence of lesions and stranded dolphins was significantly related to BCS and stream discharge. The effects of BCS and stream discharge varied spatially. Lesions on dolphins on the North Marsh, South Marsh, and West Sound routes were significantly associated with the BCS discharge but not to stream discharge for both the 2010–21 and 2018–20 GAMs. We expected lesions on these routes to be significantly related to BCS discharge because BCS water predominately flows through the area where these routes are located. Despite the Pearl River also discharging in this area, stream discharge did not influence the occurrence of lesions on these routes. The orders of magnitude difference between BCS discharge and stream discharge may explain this pattern. Between February and July 2019, the BCS discharged 10.07 trillion gallons of water, whereas the combined discharge of all the coastal streams in the area was only 154 billion gallons. Stream discharge increased the occurrence of lesions on the Lake Borgne (2010–21 GAM) and East Islands (2018–20 GAM) routes. This is expected as the Pearl River flows directly into Lake Borgne and discharge from the Pascagoula River generally flows between Horn and Petit Bois Islands in the middle of the East Islands route. These results indicate that BCS and stream discharges predominantly affect dolphins in areas close to where these discharges enter Lake Borgne or the Mississippi Sound, and in areas where these discharges mainly flow. These findings and the significant relationship between lesions and BCS discharge on the East Sound route (2018–20 GAM) provide evidence that the near-beach, eastward flowing current described by Linhois et al. (2023) transports enough freshwater from the BCS to the east side of the Mississippi Sound to cause an increase in lesions on dolphins. When considering that stream discharge increased the occurrence of strandings in the 2010–2021 GAM and ≈47 % of the stranded dolphins in Mississippi in 2019 had skin lesions, it is surprising that the prevalence of skin lesions was not significantly related to stream discharge on more survey routes than just Lake Borgne and East Islands. Because stream discharge increased the occurrence of strandings, we also expected stream discharge to increase the occurrence of skin lesions which often form on the bodies of dolphins before they strand. This discrepancy may be due to the difference in order of magnitude between BCS and stream discharge. In addition, both 2010–21 and 2018–20 GAMs showed that lesions were related to BCS discharge on the West Sound route. This route is the closest to the Mississippi beaches where most of the stranded dolphins were recovered between 2010 and 2021.

The skin lesions and strandings GAMs produced smooths (Figs. 4 and 7) that showed variation in the strength of the relationship as discharge increased. Most of these smooths, at least initially, showed a strong positive correlation between these dolphin population health indicators and BCS and stream discharge. Some of these smooths, however, show a positive relationship that increases up to an inflection point, after which there is a decrease in effect. We suspect that these decreases in effect in these smooths at larger BCS discharges may be evidence that most of the susceptible individuals in the population were likely affected by these freshwater discharges. The population essentially was running out of individuals that could develop lesions or strand during larger BCS and

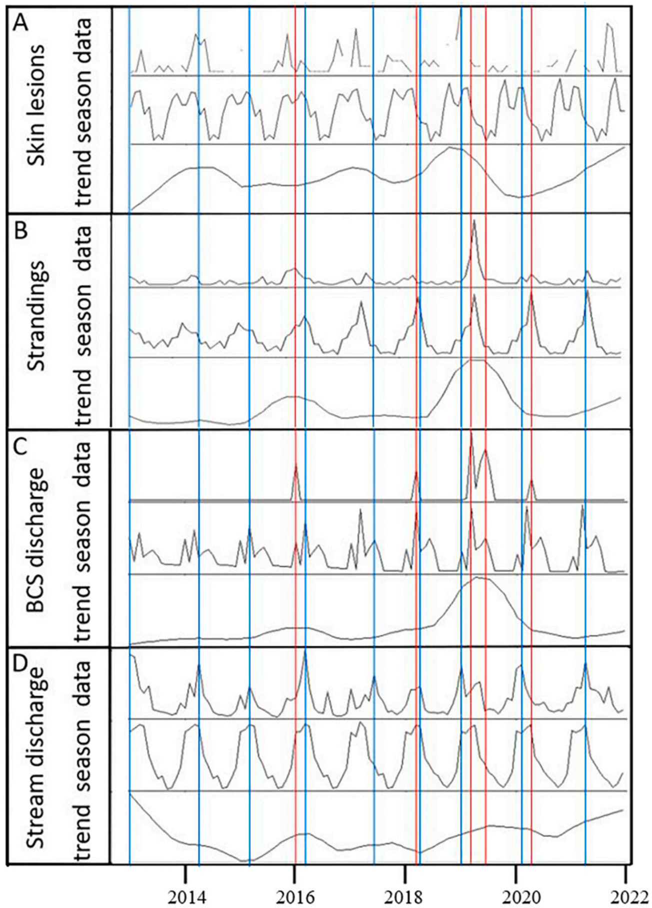

Fig. 6. Seasonal-trend decomposition using loess comparing the prevalence of skin lesions on bottlenose dolphins (A) and bottlenose dolphin strandings (B) to BCS discharges (C) and coastal stream discharges (D) in the Mississippi Sound and Biloxi Marsh from 2013 to December 31, 2021. From top to bottom, each figure shows the original time series data (data), seasonal trend (season), and multi-year trend (trend) in this data. The red lines (peaks in BCS discharge) and blue lines (peaks in stream discharge) are included to help visually compare peaks and troughs in lesion and stranding trends to BCS and stream discharge trends.

stream discharges.

The relationship between lesions and BCS discharge for the Lake Borgne route, which is the closest route to the BCS, was not statistically significant. This was surprising because Lake Borgne generally has the lowest salinities in the area and the highest average number of dolphins with skin lesions per month (Table 1). Lake Borgne is the first area that receives all the discharge (BCS and stream) from Lake Pontchartrain, through the Rigolets deep water tidal pass, and the Pearl River. The Lake Borgne area is predominately surrounded by salt marsh that restricts mixing with higher salinity Gulf waters compared to the other survey route areas. The West Islands route, for instance, is exposed to high-salinity Gulf waters, and, as expected, BCS or stream discharge had no significant influence on the occurrence of lesions in this area. In addition, out of all of IMMS' routes, the Lake Borgne route has the highest ratio of the average number of dolphins observed with skin lesions to the total number of dolphins counted per survey. Upon close inspection, we found that in 2019, very few pods were spotted in Lake Borgne during the BCS discharge between February and July. IMMS' Lake Borgne surveys sighted no dolphins in February, April, and May, only one pod consisting of five dolphins in March, two pods of 22 dolphins in June, and two pods of 10 dolphins in July. We believe the low number of sightings in the first half of 2019 resulted in a very low number of detected lesions, leading to a nonsignificant result. Although the low number of sightings could have been related to random probability, the Lake Borgne route consistently was the IMMS route with the sparsest number of dolphin sightings per kilometer from 2010 to 2021. The lack of sightings, however, could also have been directly related to the BCS discharge and likely large-scale impacts on the dolphin habitat and food resources leading to potential dispersal away from the area. During Hurricane Harvey, for instance, Fazioli and Mintzer (2020) found that dolphins in Galveston Bay, Texas, likely moved to areas with higher salinities during this severe rainfall and flood event. Pitchford et al. (2016) suggested that some dolphins in the Mississippi Sound likely move out of the area during the winter and spring when water temperatures and salinities are at their lowest annual values, potentially following the migration of prey species.

Visualization of STL model data trendlines comparing peaks in the prevalence of lesions and BCS discharge surprisingly showed that peaks in lesions around December 2015 and early 2019 occurred before openings of the BCS. In both years, data trendlines of stream discharge do not appear to explain the peaks in lesions either. In addition, based on the lack of statistical significance of the relationship between lesions and stream discharge for most routes, we believe that these peaks that occurred before the BCS opening may be due to freshwater leakage of the BCS into the study area before the BCS was opened.

Both stream gage data from the USACE's BCS gage (USACE RiverGages.com, 2023) (the BCS starts leaking when river height gets above ≈11.8 ft. on the BCS gage) and satellite imagery (Sentinelhub by Planet Labs, 2023) of plumes of Mississippi River water flowing into Lake Pontchartrain from the BCS on October 18 and October 28, 2018, confirm that the BCS started to leak sometime in October, approximately four to five months before the BCS was opened on February 27, 2019. Satellite imagery from January 11 and January 21, 2019, show the BCS leaking much more than previous satellite images taken between October and December 2018. Salinity kriging models comparing non-BCS year average monthly salinities in the Mississippi Sound in November and January of 2019 clearly show that the western Mississippi Sound salinity had decreased considerably by January 2019 (Fig. 8), well before the BCS was opened. Based on the kriging model, a large percentage of the western sound was below 5.8 ppt by January. Stream discharge, however, especially from the Pearl River, may have contributed to this. The USACE (USACE's New Orleans District Website, 2023b (Spillway Operation Information)) and Lane et al. (2001) have estimated BCS leakage to be as high as 11,150 cfs (April 3, 2020) and 8758 cfs, respectively. The USACE's estimate of 11,150 cfs is very close to the average monthly discharges from 2010 to 2021 of the Pearl River (including the discharge from the Bogue Chitto River) and the Pascagoula River (including the discharge from the Escatawpa River), which are 12,912 cfs and 11,954 cfs, respectively. This shows that the BCS leakage can be comparable to the discharge of the largest coastal streams in the Lake Borgne and Mississippi Sound area and may likely contribute to the development of lesions in dolphins, as the STL models show.

When looking at the numbers of strandings and the opening of the BCS in the STL models, there is evidence that dolphins can tolerate reasonably large pulses of freshwater for a few weeks without large stranding events. In 2018, for instance, 1.5 trillion gallons of water were released from the BCS over 22 days without a sizeable stranding event despite significant stream discharge around the same time. Strandings in 2018 (43 total) were lower than the non-BCS year average of 44.6 (an average including years from 2010 to 2021). The 1.05 trillion gallons of water discharged over 28 days in 2020 also did not produce a prominent stranding peak. Strandings for the year (51) were larger than the non-BCS year average. Toms et al. (2021) study of dolphin strandings in Pensacola Bay after a historic flood event also did not see a statistically significant stranding event despite prolonged, low-salinity water exposure of bottlenose dolphins in the bay. As a whole, this information is ecologically important because we know that dolphins likely evolved mechanisms to tolerate natural pulses of stream discharge in estuarine areas (McClain et al., 2020). It is unclear, however, how long dolphins

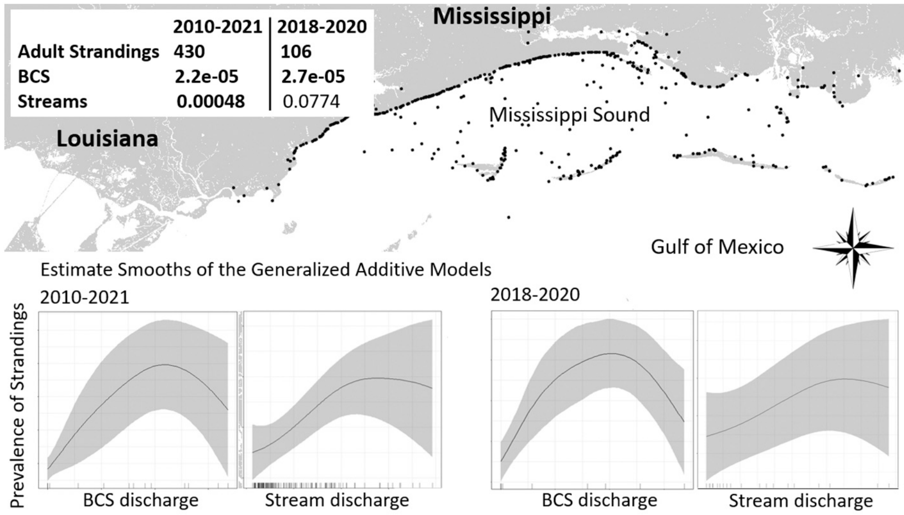

Fig. 7. P-values and smooths for fitted generalized additive models relating the prevalence of stranded adult bottlenose dolphins (430 dolphins between 1/2010 and 12/2021; 106 dolphins between 6/2018 to 1/2020) to BCS and stream discharges in the Mississippi Sound. Shaded areas around the fitted smooths are 95 % confidence intervals. Significant *p*-values are represented with bold numbers. The background map shows the locations of the 430 bottlenose dolphins that stranded along the Mississippi coast between 2010 and 2021.

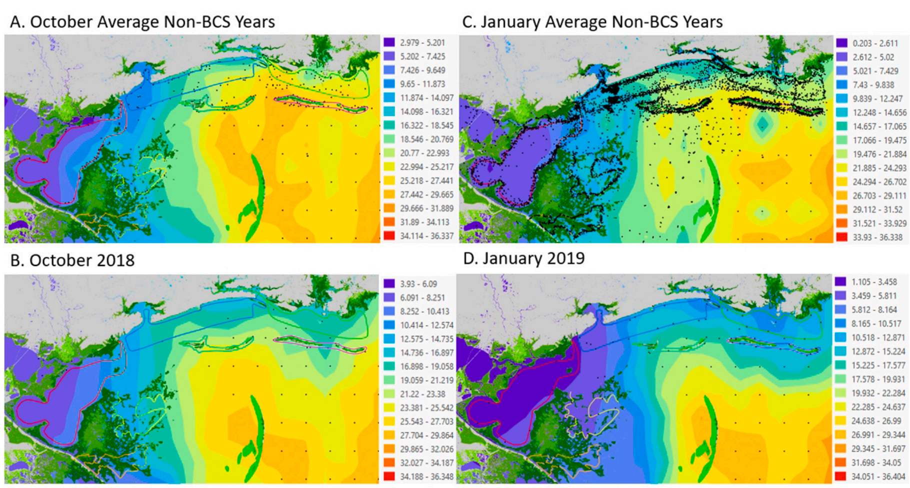

Fig. 8. Evidence of BCS leakage. ArcGIS Pro kriging salinity (ppt) models of the Mississippi Sound and Biloxi Marsh comparing the average salinity in non-BCS years (including 2010, 2012, 2013, 2014, 2015, 2017, and 2021) in October (A) and January (C) to the average salinity in October 2018 (B) and January 2019 (D). Black points indicate the locations of salinity data used in this analysis.

can tolerate exposure to low-salinity water as most studies evaluated responses of live stranded dolphins (Deming et al., 2020; Ewing et al., 2017) and only in rare cases are there data from experimental exposure to low salinity conditions (McClain et al., 2020). Understanding the tolerance of dolphins to freshwater pulses could be critically important in conserving populations exposed to freshwater diversions such as the BCS and Mid-Barataria Sediment Diversion (Thomas et al., 2022).

Our dataset quantifies monthly lesions per route based on the sum of individuals observed with lesions irrespective of dolphins having distinctive fins. We made this decision because most dolphins with skin lesions in each pod did not have distinctive fins or could not be identified (Table 1). Because we could not distinguish and track individual dolphins on a month-to-month basis, we could not add a predictor variable of “individual” as a random effect in the GAMs. Thus, it is likely that individual dolphins may have been included in the monthly sums in consecutive months. To investigate this, we analyzed the data using ACF and PACF plots (Zuur et al., 2010). We found negligible autocorrelation, indicating that the previous month’s sum of lesions is not predictive of the next month’s sum of lesions. Moreover, all models were not very “wiggly,” which likely indicates a lack of autocorrelation (Simpson, 2018) and that dolphins were not significantly resampled. It could also indicate that the presence of skin lesions is related to environmental conditions (e.g., salinity during monthly sampling) rather than the dolphin’s condition in the previous month. Indeed, STL models show that lesions’ prevalence is closely correlated to salinity. When the salinity is low, numerous dolphins have lesions, and the prevalence of lesions decreases when the salinity improves. In addition, dolphins can develop lesions within a week of exposure to low-salinity water, and Fazioli and Mintzer (2020) found that dolphins can heal up, and reduce the severity of skin lesions in 30 days (individual 85 in the study) when conditions improve. To reduce potential autocorrelation, we incorporated route as a random effect and modeled monthly sums (i.e., the sum of all the dolphins with lesions in every pod found along that route on that survey date) (Schank and Koehnle, 2009). Consistently, we found high significance in these modeled relationships with two different datasets (IMMS and NOAA), which reveal a strong relationship between low-salinity estuarine water and the frequency of lesions and strandings in the common bottlenose dolphin population of the Northern Gulf of

Mexico.

5. Future research directions

To further advance this critical research, multiple directions could help improve our understanding of the relationship between freshwater diversions, stream discharges, freshwater exposure, and dolphin health, and minimize the likely impact of freshwater diversions on dolphin populations. To improve this current study, future modeling efforts should incorporate estimates of BCS leakage, which might improve the models and help explain some patterns that don't seem to be completely accounted for. Moreover, GAMs could incorporate lags to investigate the time it takes dolphins to develop lesions and/or strand once exposed to low-salinity waters. Further investigations of the relationship between dolphin skin lesions and strandings and exposure to low-salinity waters could help determine the salinity levels and exposure times they can tolerate without adverse health impacts from spillway discharges or unusually high stream discharges (Booth and Thomas, 2021). In addition, it would be essential to determine what salinities and exposure times are needed to help dolphins fully recover from the effects of exposure to low-salinity water. This information could be incorporated into the operational protocols of spillways such as the BCS and the Mid-Barataria Sediment Diversion. Lastly, hydrodynamic models for high river stage flood management should be developed to investigate approaches to maximize flood risk protection and land building while conserving dolphin populations and their habitats and ecosystems (e.g., Wu and Meselhe, 2022). This effort is critical as Louisiana plans to build multiple diversions to divert sediment-laden Mississippi River water into coastal marshes and estuaries to build land and provide hurricane storm surge protection to the state (Coastal Protection and Restoration Authority of Louisiana, 2023). These hydrodynamic models should ideally simulate and quantify: 1) the effects of new modern diversions that are designed to not leak or leak less; 2) new diversions that protect New Orleans from flooding while diverting river water away from the Mississippi Sound; 3) scenarios where the Mississippi River channel is deeper due to increased dredging in the lower river; 4) scenarios where more floodplains along the Mississippi River have been reconnected to the river (e.g., the USACE is currently relocating broken levees away from the river and further into the floodplain, these reclaimed floodplain areas are called "setbacks"); 5) using the Mississippi River Gulf Outlet canal with an installed flood gate to raise salinities in Lake Borgne and Lake Pontchartrain during BCS discharge and leakage events. As new diversion projects such as the Mid-Barataria Sediment Diversion near completion, it is essential to utilize this information to effectively manage these diversions. This will help protect coastal human residents, sentinel species like dolphins, and the estuarine and marine resources they rely on.

6. Conclusion

This study's main objective was to investigate whether BCS and/or coastal stream discharges likely impact the health of dolphins in the Mississippi Sound and adjacent waters. Complementary modeling approaches (GAMs, kriging models, and STL) showed that the importance of each driver (BCS and/or stream discharge) varied spatially. The prevalence of skin lesions in the western Mississippi Sound and Biloxi Marsh was significantly related to BCS discharge and not to stream discharge. In addition, in 2019, the frequency of dolphin strandings across the Mississippi Sound was highly significantly related to BCS discharge and not to stream discharge. This research provides evidence that freshwater diversions through the BCS likely increase the prevalence of skin lesions on live dolphins, strandings, and mortality in the Mississippi Sound and Biloxi Marsh dolphin populations. Further research is needed to understand the effects of the duration and degree of exposure to low-salinity waters on the health of dolphins and its application to managing spillways and freshwater diversions.

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CRediT authorship contribution statement

John W. Baker: Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Drew T. Suffoletta:** Writing – review & editing, Investigation, Data curation. **Jessica N. Lewis:** Writing – review & editing, Investigation, Data curation. **Kailey M. Pamperin:** Writing – review & editing, Investigation, Data curation. **Rachel M. Giordano:** Writing – review & editing, Investigation, Data curation. **Theresa Madrigal:** Writing – review & editing, Investigation, Data curation. **Moby Solangi:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare no conflict of interest.

Data availability

The data presented in this research is available upon request from the Institute for Marine Mammal Studies and is provided in the supplementary materials.

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