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Regional Sediment Management Program

Sediment Provenance Studies of the Calcasieu Ship Channel, Louisiana

A Synopsis Report

David W. Perkey, Anthony M. Priestas, Jeff Corbino, Gary L. Brown, Michael Hartman, Danielle R. N. Tarpley, and Phu V. Luong

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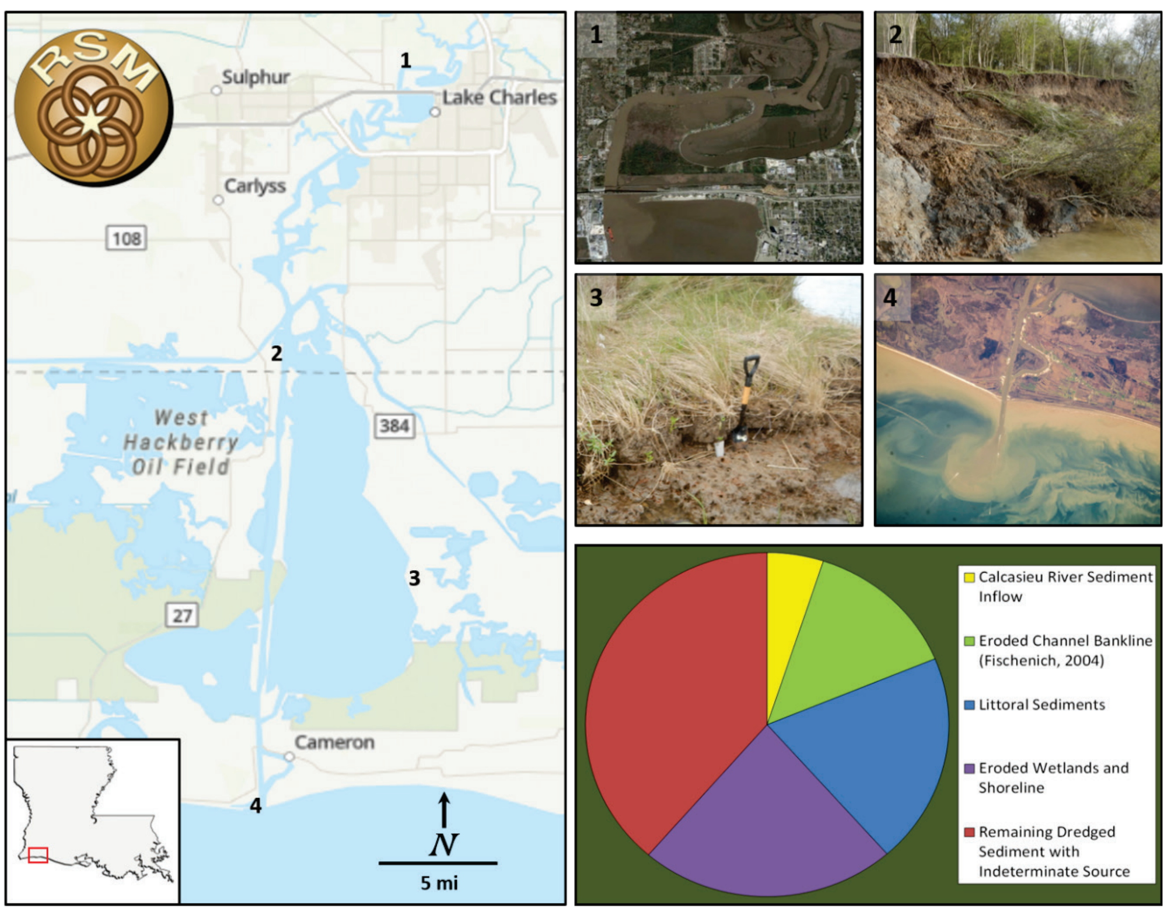

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Coastal and Hydraulics Laboratory
US Army Engineer Research and Development Center
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

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Abstract

To maintain the navigability of the Calcasieu Ship Channel (CSC), the US Army Corps of Engineers annually dredges millions of cubic yards of sediment from the inland channel. To assess sources of channel shoaling, a previous study examined river and bankline erosion as inputs. Results from that study accounted for approximately 20% of dredged volumes. Through the support of the Regional Sediment Management Program, a follow-up investigation reviewed prior sediment budgets, identified potential missing sediment sources, modeled potential sediment pathways, and utilized geochemical fingerprinting to discern primary shoaling sources to the channel. The missing sediment sources from the original budget include coastally derived sediment from the Gulf of Mexico and terrestrially derived sediment from Lake Calcasieu and surrounding wetlands. Results from geochemical fingerprinting of various potential sediment sources indicate the Calcasieu River and the Gulf of Mexico are primary contributors of sediment to the CSC, and sediments sourced from bankline erosion, Lake Calcasieu bed, and interior wetlands are secondary in nature. These results suggest that engineering solutions to control shoaling in the CSC should be focused on sources originating from the Gulf of Mexico and river headwaters as opposed to Lake Calcasieu, channel banklines, and surrounding wetlands.

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Preface

This study was conducted for the Regional Sediment Management (RSM) Program under Funding Account Code U4376577; AMSCO Code 008303. The technical monitor was Dr. Katherine E. Brutsché.

The work was performed by the Field Data Collection and Analysis Branch and the Coastal Engineering Branch of the Navigation Division, the River Engineering and Estuarine Branch of the Flood and Storm Protection Division, US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory (ERDC-CHL). At the time of publication of this report, Mr. William Butler was chief, Field Data Collection and Analysis Branch; Ms. Lauren Dunkin was chief, Coastal Engineering Branch; Mr. David P. May was chief, River and Estuarine Engineering Branch; Ms. Ashley Frey was chief, Navigation Division; Dr. Cary A. Talbot was chief, Flood and Storm Protection Division*;* and Mr. Charles E. Wiggins was the technical director for Navigation. The deputy director of ERDC-CHL was Mr. Keith W. Flowers, and the director was Dr. Ty V. Wamsley.

The commander of ERDC was COL Teresa A. Schlosser, and the director was Dr. David W. Pittman.

1 Introduction

1.1 Background

The Calcasieu Ship Channel (CSC) is a deep-draft federal channel located in southwest Louisiana that connects the city of Lake Charles to the Gulf of Mexico (Figure 1). To maintain the inland stretch (River Mile [RM] 5-34) of the navigation channel, the US Army Corps of Engineers annually dredges an estimated 4 to 5 million yd^3[1,2] of sediment. Maintenance dredging alternates between the lower channel (RM 5-17) and upper channel (RM 17-34) each year, with the Devil's Elbow industrial offshoot dredged annually, at costs that range from $3.00 to $5.00 per cubic yard of dredged material. In recent years, research has been conducted through the Regional Sediment Program (RSM) Program to evaluate previous sediment budgets for the CSC system and identify possible source(s) of shoaling through numerical modeling and geochemical fingerprinting techniques.

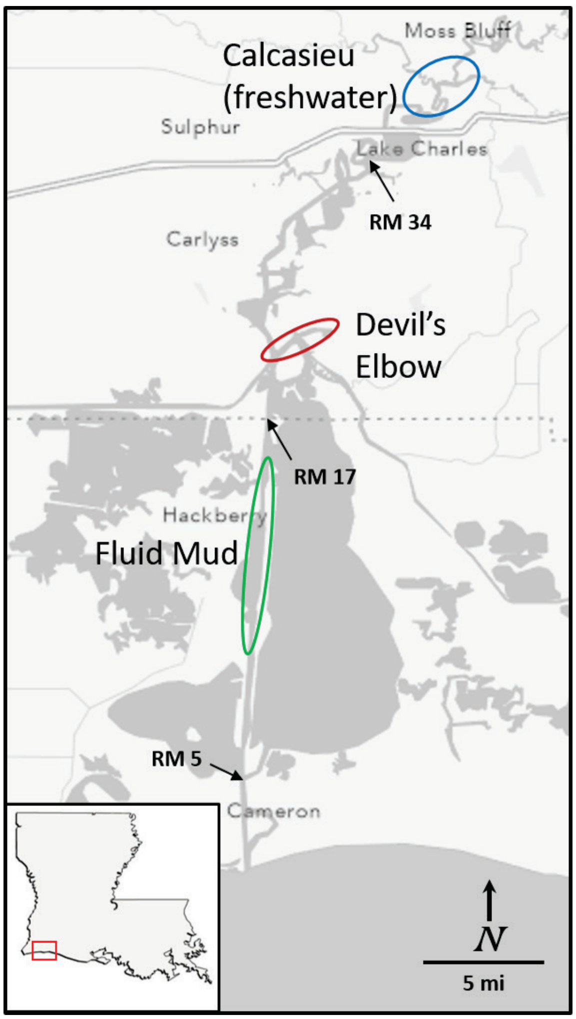
Average shoaling rates determined with the Corps Shoaling Analysis Tool (CSAT) (Dunkin et al. 2018) from 2016 to 2020 show areas of accretion on the order of 5 to 10 ft/yr in both the upper and lower portions of the channel (Figure 2). The highest rates of shoaling were observed in areas where straightened sections of the CSC intersect with the natal river channel, at the entrance to Devil's Elbow, and in a segment of the lower channel reach where the saltwater wedge is commonly observed. In 2003, the New Orleans District (MVN) sponsored a study conducted by the US Army Engineer Research and Development Center (ERDC) designed to evaluate the possible contribution of bankline erosion on shoaling rates adjacent to confined disposal facilities (CDFs). Those results suggested that contributions from CDF bankline erosion along with the sediment inflow from the Calcasieu River could account for approximately 20% of

[1] For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 248-52, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

[2] For a full list of the unit conversions used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 345-7, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

the annual volume of sediment dredged from the inland CSC[1]. Starting in 2018 and continuing through 2021, MVN and the RSM Program supported further investigations to identify the sources of the remaining 80% of dredged volume and potentially mitigate for channel sediment deposition. This report offers a summary of these efforts and highlights the value they provided to MVN in terms of understanding and managing the sediments within the CSC system.

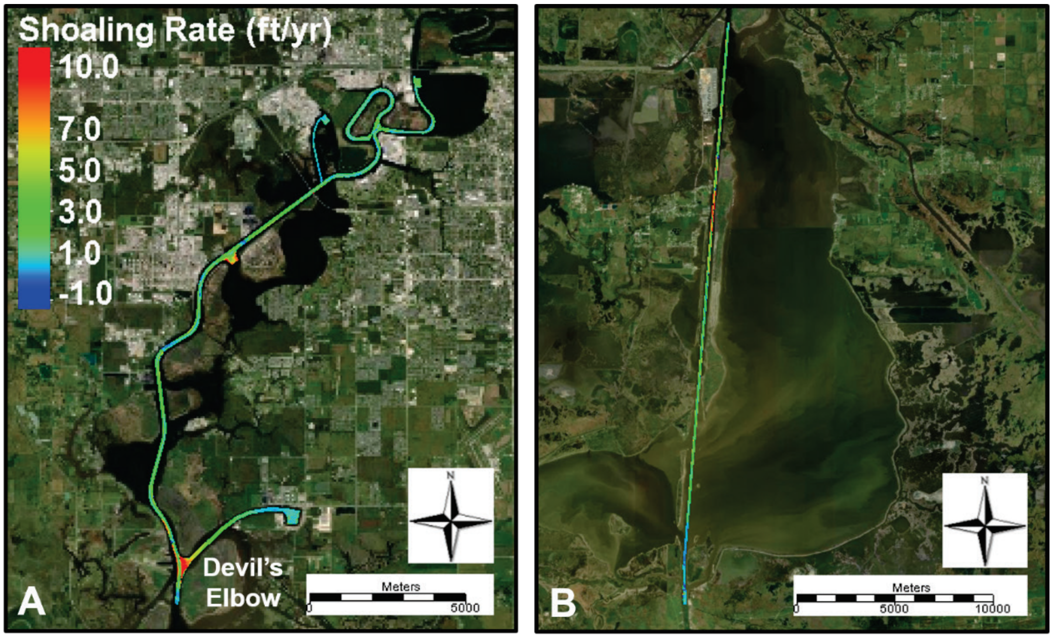
Figure 1. Map of the Calcasieu Basin. River Mile locations that divide the upper and lower inland portions of the CSC are indicated on the map. Colored ovals define the following Fiscal Year (FY)20 sampling areas: (green) fluid mud; (red) Devil's Elbow; (blue) upstream of salinity barrier.



[1] Fischenich, Craig G. Unpublished. *Calcasieu River and Ship Channel Erosion and Sediment Impact Assessment (Phase 1)*. DRAFT report prepared for the US Army Corps of Engineers, New Orleans District.

NOTE: From this point forward, the document will be referred to as "Fischenich."

Figure 2. CSAT-based average shoaling rates within the CSC in feet/year from 2016 to 2020 for (A) the upper inland channel and (B) the lower inland channel.



1.2 Objective

The objective of this study was to evaluate existing sediment budgets for the CSC system and attempt to identify additional sediment sources to account for shoaling (or dredging) volumes within the channel. Additionally, this work sought to estimate the quantity of sediment associated with each proposed sediment source so that potential mitigation strategies for channel shoaling could be developed and evaluated.

1.3 Approach

This study synthesized information from previous works and conducted additional data analyses on new field samples to investigate the potential sources of sediment to the CSC. The general approach is outlined as follows:

1. Revisited the original sediment budget in the Fischenich report and reviewed other available literature to identify additional potential sources.
2. Employed a numerical model to investigate the potential transport pathways for these sources and approximate their relative contributions to the sediment budget.

3. Used geochemical fingerprinting techniques to evaluate if unique signatures from proposed sediment sources could be identified, then applied to estimate their relative contribution to channel shoaling.

1.4 Report contents

A summarization of the results of these efforts is provided in the following sections of this document. Please note that full descriptions of methods and details regarding data analysis of the project are largely presented in other RSM publications, which are cited in this report. The goal of this report is to summarize the combined results of the research and highlight their importance to better understand the sediment budget of the CSC region. The reader is encouraged to refer to the associated reports for more detail descriptions.

2 Previous Sediment Budget Research

2.1 Review of prior sediment budget

At the onset of this research effort, the sediment budget developed by Fischenich was revisited to examine the sediment sources included within the budget and the methods utilized. The Fischenich study focused on two potential sediment sources to channel infilling: (1) bankline erosion along the CSC and (2) upstream sources from the Calcasieu River. Bankline erosion was assessed with methods utilizing aerial photography from 1972 and 1998 to account for bankline retreat. Sediment yield from the river was calculated using US Geological Survey (USGS) gage and suspended sediment data at nearby Kinder, LA, from 1978 through 1993. Results showed that the estimated yield from bankline erosion was 200,000 yd^3 per year, which was double the estimated yield from Calcasieu River suspended sediment loads (95,000 yd^3/yr, assuming a specific weight of 2.7 and 30% porosity). While the total annual yield of 300,000 yd^3 is substantially less than annual dredge volumes, adjusted volumes can be derived that consider differences in bulk density between compacted bankline sediments and channel sediments, or 15% of average dredge volumes.

As part of the 2019 RSM effort, a dry bulk density of 530 kg/m^3 obtained from previous measurements of channel sediments was used to convert the in situ density (1,855 kg/m^3) of bankline erosion volume reported by Fischenich to volumes representative of material deposited within the CSC[1]. Thus, the adjusted volume associated with bankline erosion for the sediment budget increased to nearly 700,000 yd^3/yr.

Brown and Luong revisited the suspended sediment load presented in Fischenich and integrated the rating curve with additional USGS discharge data spanning 1996 through 2016 to revise the annual sediment load. Again, using a dry bulk density of 33 lb/ft^3 (530 kg/m^3), the revised volume from river sourced sediment is approximately 260,000 yd^3/yr. Therefore, the revised sediment budget of Fischenich, as

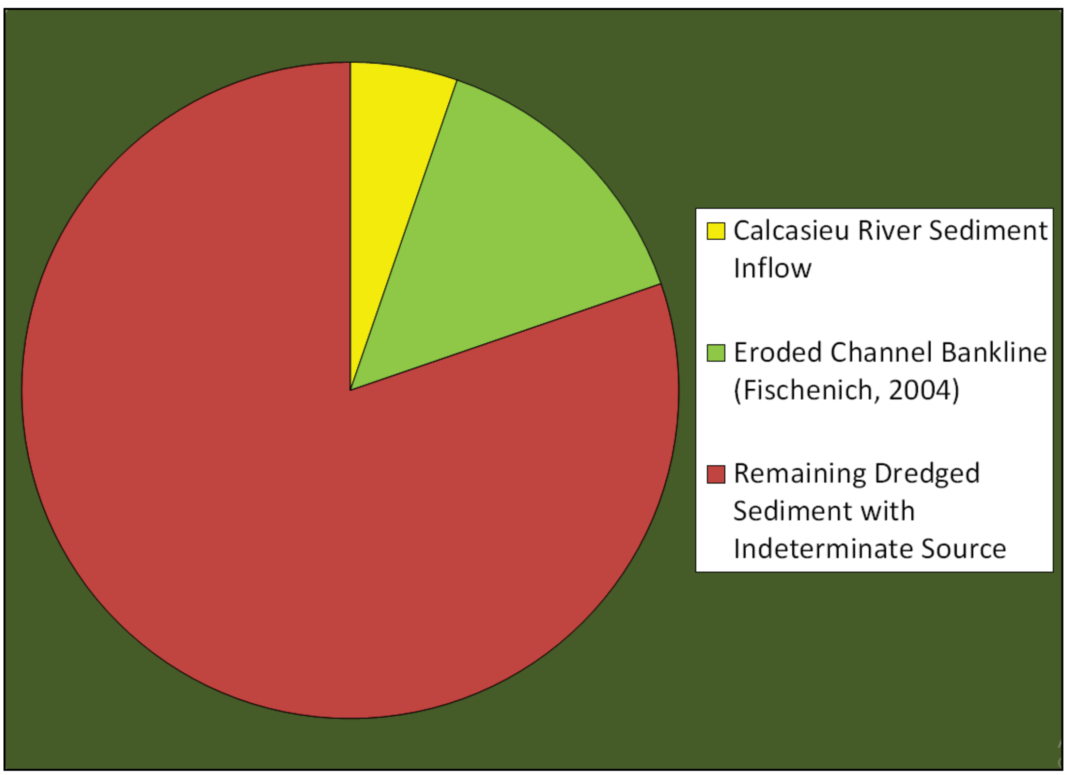
[1] Brown, G., and P. V. Luong. In Review. *Investigation of Sources of Sediment Associated with Deposition in the Calcasieu Ship Channel*. ERDC/CHL Technical Report. Vicksburg, MS: US Army Engineer Research and Development Center.

NOTE: From this point forward, the document will be referred to as “Brown and Luong.”

presented in Brown and Luong, constitutes 20% of the annual dredging volume (4.8M yd^3/yr) based on MVN dredging records.

The initial sediment budget presented in Brown and Luong indicated that approximately 20% of the annual dredge volume of the CSC could be attributed to contributions from bankline erosion and the discharge of the Calcasieu River (Figure 3). This budget assumed that all the sediment carried by the Calcasieu River eventually deposited in the channel and that there was no significant net deposition elsewhere in the system. Like the initial sediment budget presented by Fischenich, this updated budget did not account for 80% of annual dredging volumes and a review of other scientific literature was conducted to identify other potential sources.

Figure 3. The initial sediment budget.

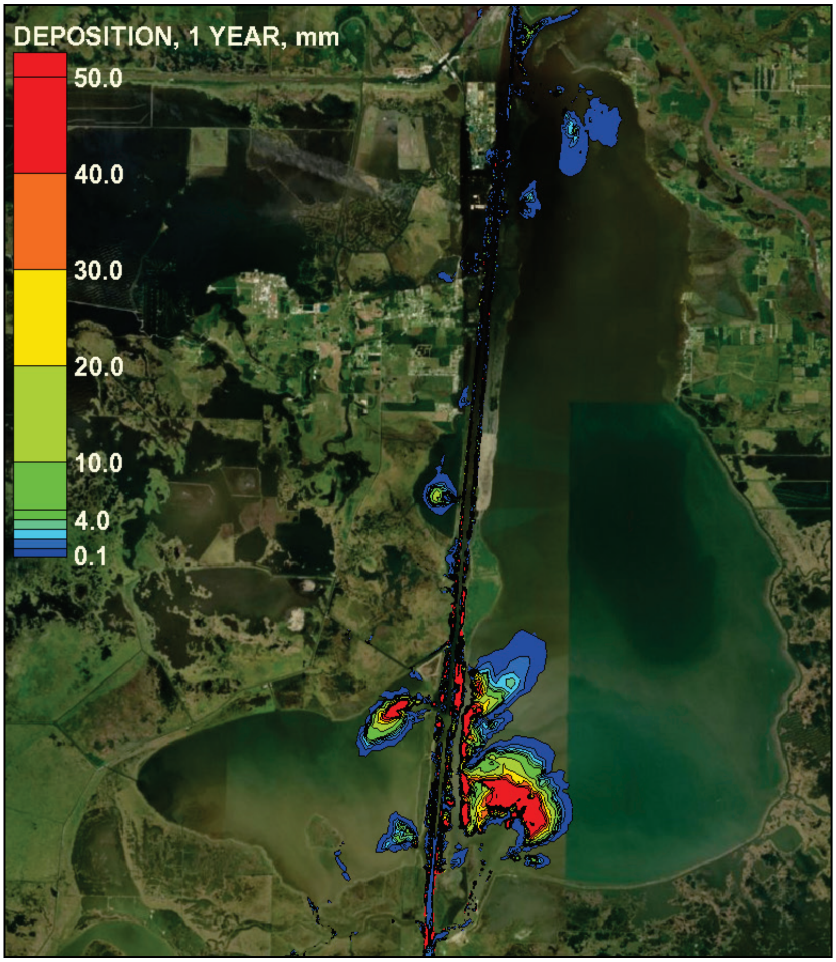


2.2 Identification of additional sediment sources

In reviewing previously published studies, Brown and Luong documented multiple potential sediment sources that might account for the missing 80% of dredged volume. These included Calcasieu Lake, the Gulf Intracoastal Waterway (GIWW), fluid mud from offshore bar channel areas, erosion of surrounding wetlands, and suspended sediment from the Gulf of Mexico. As part of the 2018 RSM effort, source volumes that could be attributed to erosion of the surrounding wetlands and the Gulf of Mexico were further explored.

Using published loss rates and dry bulk density values for the region's wetlands, a first order of magnitude estimate for eroded wetland sediment was made that ranged from 0.5M to 1.8M yd^3/yr. This equated to approximately 10% to 38% of the annual dredging volume of the inland CSC, per Brown and Luong. To investigate the mechanisms whereby coastal suspended sediments in the Gulf of Mexico could be delivered to the CSC, numerical model experiments were conducted with the Adaptive Hydraulics (AdH) Model with the SEDLIB sediment transport library (Tate et al. 2006; Brown 2012a,b). Due to limited hydrodynamic data for the CSC, the modeling efforts were qualitative in nature. Figure 4 presents the deposition patterns associated with coastally derived suspended sediments from Brown and Luong. The figure illustrates that model results predicted that offshore sediments were capable of being transported into the lower CSC and Calcasieu Lake region. Total masses of suspended sediment passing into the Calcasieu system from the Gulf were calculated. Using a dry bulk density of 530 kg/m^3, these suspended masses were converted to channel deposit volumes. Assuming an offshore suspended sediment concentration of 75 ppm, model results suggested that deposited sediment volumes sourced from the Gulf of Mexico could potentially be ~1M yd^3/yr, or ~21% of the annual dredging volume of the inland portion of the CSC, per Brown and Luong.

Figure 4. Spatial deposition patterns of coastally derived sediments after 1 yr of model simulation.



Utilizing these estimated volumes of sediment attributable to wetland erosion and suspended offshore sources, a revised sediment budget was generated (Table 1). While this budget could account for up to 79% of the annual dredged volume from the CSC, it was generated with gross estimates of the quantities associated with the various sources and therefore had significant uncertainty as reflected in Table 1.

Table 1. Estimated sediment source volumes.

Source Type	Volume (M yd^3/yr)	% CSC Dredging Volume
Calcasieu River	0.26	6
Bankline Erosion	0.7	14
Wetland Erosion	0.5–1.8	10–38
Gulf of Mexico	1	21
Total	2.5–3.8	51–79

In 2019, a study was published by the Water Institute of the Gulf (WIG) that presented a separate sediment budget for the Calcasieu system. It was based on field data obtained from December 2016 through January 2018 in conjunction with Delft3D numerical modeling simulations (WIG 2019). While the WIG study investigated many of the same sediment sources evaluated by Brown and Luong, the contributions of these sources to channel shoaling varied substantially. Most notably, the WIG budget estimated that the Calcasieu River accounted for almost 20% of the sediment dredged from the CSC and that Calcasieu Lake and its surrounding wetlands accounted for only 1% to 5% of dredged sediment. Additionally, their measurements and simulations of sediment fluxes through the CSC suggested the Calcasieu River and Gulf of Mexico might alternate as a sediment source or sink depending on specific storm conditions. Tropical storms *Cindy* (June 22, 2017) and *Harvey* (August 30, 2017) had both made landfall near Cameron, LA, during the study period. Despite these differences, the WIG investigation concluded that significant amounts of dredged sediment (52% to 73%) from the CSC could not be accounted for in their budget. While many of the differences between the two sediment budgets can be attributed to varying methodologies and data sources, further study was warranted to reduce uncertainties associated with the various sources identified in the sediment budgets.

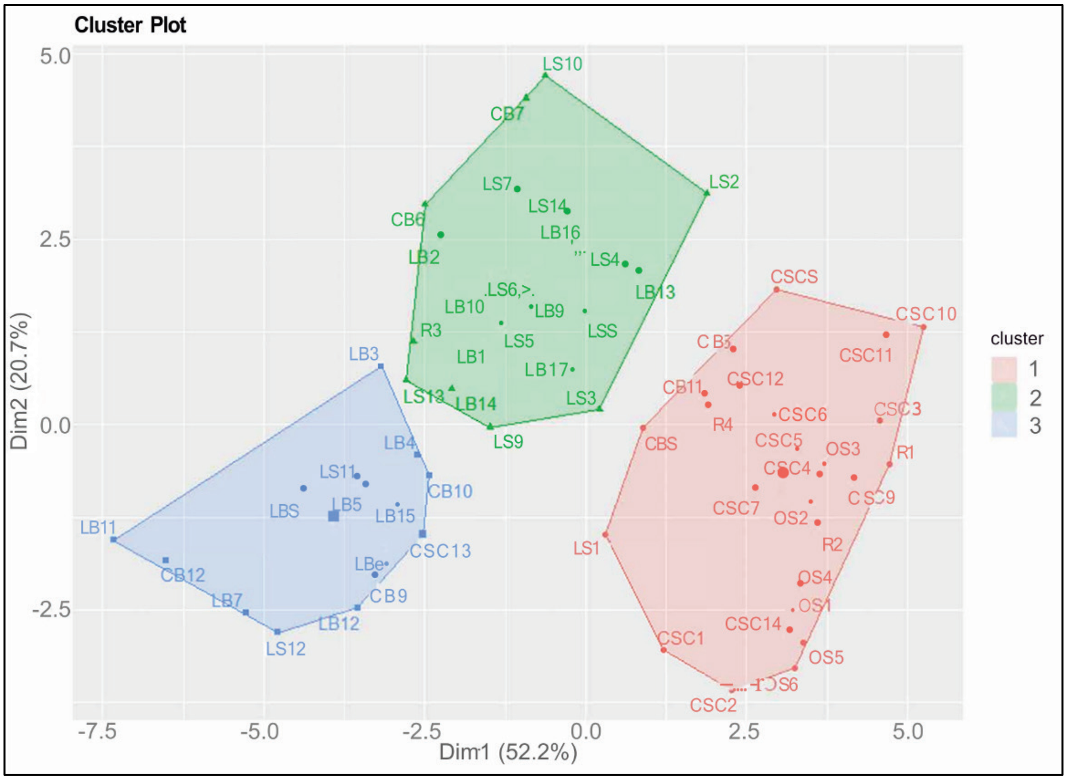
3 Evaluating Sediment Sources

3.1 Initial geochemical fingerprinting

Support from the RSM program was provided in FY19 to explore the use of geochemical fingerprinting as a method to evaluate the sediment budgets for the CSC system. Geochemical fingerprinting is a well-established method for distinguishing among sediment sources that relies on coupling the geochemical properties between the sediments transported into an area of interest and those of their suspected sources (Collins and Walling 2002; Collins et al. 2010; Papanicolaou et al. 2003; Gireeshkumar et al. 2013; Perkey et al. 2017). Perkey et al. (2020) describes in detail how these techniques were applied to the CSC system. Sediment samples from six geomorphological classifications were collected in the spring of 2019. Five of the classifications represented probable sources of infilling identified from the existing sediment budgets: (1) Calcasieu River sediments, (2) the banklines of the CSC, (3) the wetland shorelines of Calcasieu Lake (4) bottom sediment of Calcasieu Lake, and (5) offshore sediment delivered through tidal exchange. The sixth classification was designed to be representative of dredged material for the system and was collected from the bottom of the CSC.

A variety of laboratory tests were performed to evaluate the physical and chemical make-up of the samples that included grain size characterization, organic content, elemental composition, and stable isotope ratios for carbon and nitrogen. Principal component and K-Means cluster multivariate statistical analyses of the resulting data was used to evaluate similarities between the six classifications of sediment. The cluster analysis presented in Perkey et al. (2020) revealed that the six geomorphological classifications of sediment could best be described in three distinct groupings (Figure 5). The number of groupings was evaluated based on the total within sum of squares method (elbow method) and the gap statistic method (described further in the appendix).

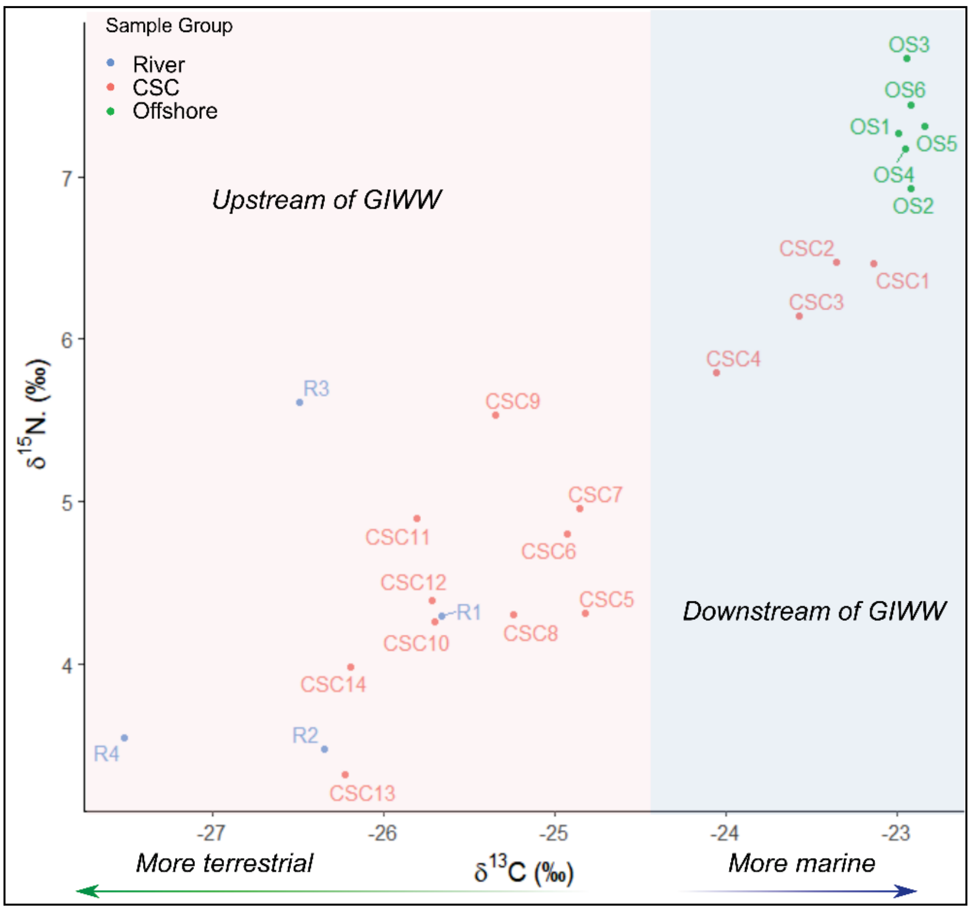
Figure 5. Result of the K-Means cluster analysis from Perkey et al. (2020). Cluster 1 (primarily offshore (OS), river (R), and channel sediments (CSC)) is distinct from the other two clusters (primarily lake bed (LB), lake shoreline (LS), and CSC bank sediments (CB)).



Group 1 showed the most homogeneity (indicating that its samples were the most similar to each other) and was predominantly composed of Calcasieu River, offshore bar channel, and CSC sediments. The strong similarity between these sediments suggested that the Calcasieu River and the offshore channel bar could be significant sources to channel shoaling. In contrast, Groups 2 and 3 had less homogeneity within their groupings and were largely composed of samples from the shoreline or bottom of Calcasieu Lake. This suggested that contributions of sediment from these sources to the CSC might be less significant. Samples from the banklines of the CSC were nearly equally distributed through all three groups and suggested substantial variability in bankline composition across the study region.

By further examining the stable isotope data of the samples in Group 1, Perkey et al. (2020) also documented an apparent inshore/offshore trend in source sediment within the CSC (Figure 6). Samples sourced from the Calcasieu River were more depleted in $\delta^{13}C$ (-27.5‰ to -25.7‰), indicative of terrestrial C3 plant-sourced organic material (Pilson 1998; Hoefs 2009). Conversely, samples from the offshore locations were less depleted, having a signature more typical of a marine phytoplankton, which has an average $\delta^{13}C$ value of approximately -22‰ (Faure 1986; Pilson 1998). Between these endmembers, samples collected from the CSC demonstrated a gradient in $\delta^{13}C$ values from marine to terrestrial that corresponded with upstream distance. The study also noted a relatively large shift (0.7‰) in $\delta^{13}C$ values that occurred in samples upstream of the GIWW. These isotope data suggested a mixing between terrestrial and marine sediment sources with a reduction in marine sourced carbon upstream of the GIWW. This reduction in offshore sediment upstream of the GIWW aligned with AdH model results from Brown and Luong.

Figure 6. Stable carbon and nitrogen isotope trends from Perkey et al. (2020). Plotted data are from Cluster 1 of Figure 5 and show an upstream strengthening in terrestrial isotopic signature.



Based on these initial geochemical fingerprinting results, the Perkey et al. (2020) report supported the concept that marine sediment from the Gulf of Mexico was a potentially significant source of shoaling material to the CSC, as suggested in both the WIG (2019) and Brown and Luong sediment budgets. Further, the geochemical distinction between Calcasieu Lake sediments (bottom and shoreline) and CSC sediments was consistent with the WIG sediment budget that indicated Calcasieu Lake was a relatively minor contributor of sediment to the channel.

3.2 Geochemical fingerprinting of high shoaling areas

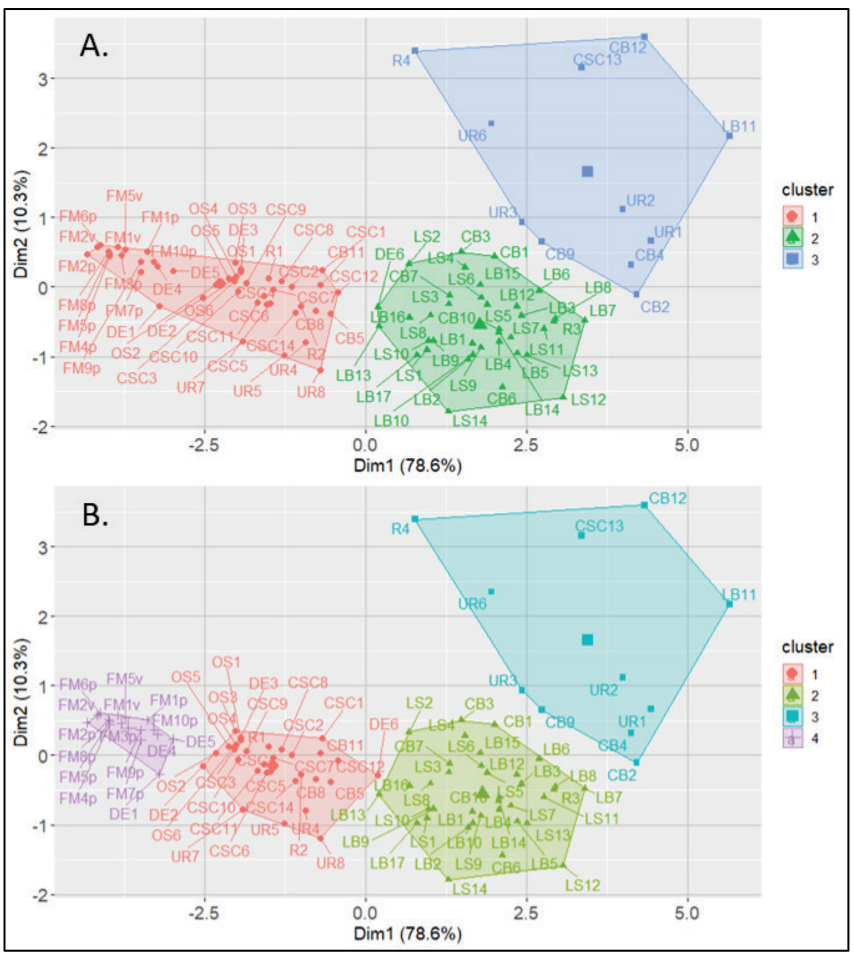
While the FY19 geochemical data provided insight to some of the potential sources in the CSC sediment budget, a few concerns remained unaddressed. One primary concern was the lack of samples from above the salinity barrier on the Calcasieu River, which prevented a true *terrestrial* geochemical endmember from being determined. Additional underrepresented sources included CSC fluid mud and areas within the CSC with high shoaling rates, which may be geochemically distinct from the rest of the CSC. Therefore, an additional sediment sampling campaign was conducted in FY20 to examine these potential sources that were not investigated in FY19.

The geochemical results and findings of this FY20 effort are summarized in this section. Unlike the data that have been summarized and presented in the prior sections of this report, the FY20 data have not been previously published. While field sampling, laboratory and statistical analysis methods used for geochemical fingerprinting generally followed those presented in Perkey et al. (2020), though a more detailed description of the FY20 work is presented in the appendix.

The FY20 sediment samples were collected from three regions of the Calcasieu River (Figure 1). Bathymetric surveys performed by MVN in association with maintenance dredging in the lower CSC revealed that layers of fluid mud on the order of 2 to 6 ft thick were forming in the channel from RM 10 to RM 17. Bottom sediment samples were collected from this stretch of the channel to characterize the fluid mud. MVN also identified the Devil's Elbow spur of the Calcasieu River as a high shoaling area, as indicated in the 2016–2020 CSAT data (Figure 2), and they requested bottom sediments be collected from this region for geochemical analysis. Last, to obtain freshwater river sediments uninfluenced by tidal signatures, a series of samples were collected above the Calcasieu River tidal gate (Figure 1).

The multi-variate statistical analysis performed on the combined data suggested that variability within the sediment samples was best described by either three or four groupings. Figure 7a presents the three-grouping cluster analysis. As with the previous geochemical fingerprinting model, most of the CSC, offshore channel bar, and river samples from FY19 clustered together in Group 1 along with the fluid mud and Devil's Elbow samples from FY20. Additionally, the muddy samples from upstream of the salinity barrier were also found in Group 1. Group 2 was predominantly composed of the shoreline and bottom sediment samples collected from Calcasieu Lake in FY19, and Group 3 was characterized by sediment samples in the data set with the highest sand content. Samples from the banklines of the channel and upstream of the salinity barrier dominated this last group. This clustering showed strong similarities between the sediment samples collected from within the Calcasieu River system, regardless of upstream/downstream location or time of collection and found the Calcasieu Lake sediments to be distinct from CSC material.

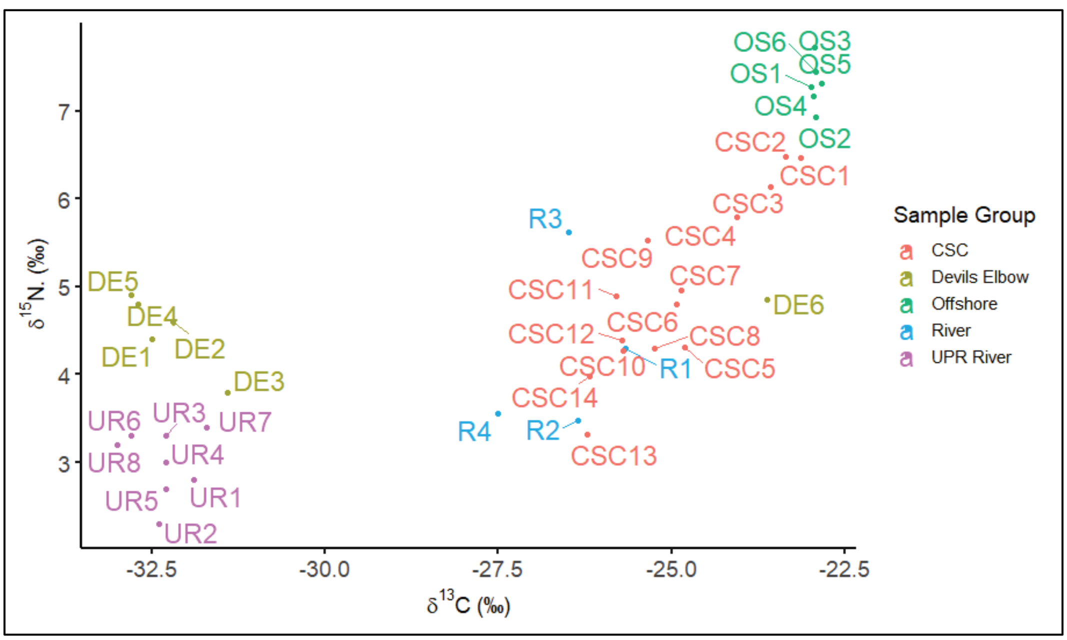
Figure 7. Result of the K-Means cluster analysis on the combined FY19 and FY20 datasets. (A) a three-cluster model; (B) a four-cluster model. Clusters 2 and 3 are virtually identical in both models. Cluster 4 is composed of FY20 fluid mud (FM) and Devil's Elbow (DE) samples from cluster 1.



When a four-cluster model was applied to the data (Figure 7b), groups 2 and 3 remained largely unchanged, and the fluid mud and Devil's Elbow samples from FY20 were separated from group 1 to form group 4. This suggested that while the fluid mud and Devil's Elbow samples were more similar to the other CSC and river samples than the bankline or Calcasieu Lake sediments, there was a potential distinction between these sediment classifications that were originally clustered in group 1.

To explore this further, stable isotope data of the FY20 samples were examined. Unlike the FY19 data that showed an increased terrestrial carbon signature with distance upstream, all the sediment samples collected in 2020 showed a very strong terrestrial $\delta^{13}C$ signature (-31.4‰ to -33.9‰) (Figure 8). The samples collected from Devil's Elbow and the fluid mud samples were collected from a region of the CSC that is consistently exposed to tidal waters from the Gulf of Mexico. The absence of any significant marine signature associated with the sediments from these areas implies either (1) a large pulse of terrestrially derived sediment was recently deposited in the lower stretches of the CSC or (2) daily tidal exchange is not the primary delivery and mixing mechanism of offshore sediment into the CSC and that an event resulting in significant inflow of marine sediment had not recently occurred.

Figure 8. Trend of isotopic signatures including FY20 fluid mud and Devil's Elbow samples.



Periodic influxes of large amounts of sediment to the CSC system was documented in the WIG (2019) report and associated with either tropical storm surge or high rainfall events. In the former case, while the 2020 hydrograph of the Calcasieu River did not indicate elevated discharge levels that might suggest a recent flood deposit prior to July, sediment movement in this section of the river may be influenced by other factors such as salinity gate operation. In the latter case, the introduction of marine sediments as dense slurries associated with storm and tidal events was observed by the WIG, where total suspended solids (TSS) concentrations up to 2,500 ppm were measured at the river's East Fork. The contribution of such event-scale introductions was not incorporated into modeled estimates of offshore sediment supply. While a full explanation for why the 2020 sediments had a strong terrestrial $\delta^{13}C$ signal cannot be provided, the differences between the 2020 and 2019 data highlight the temporal variability in geochemical signatures of sediments in the system and in turn the sources of those sediments to the CSC.

These results further support the observation that muddy sediment samples from within the Calcasieu River or the offshore channel bar are most similar in texture and elemental composition to the sediments found within the inland CSC, regardless of location within the channel, while material from the banklines of the CSC and Calcasieu Lake have a different geochemical signature. In turn, this strongly suggests that sediment derived from bankline erosion and Calcasieu Lake is secondary in importance to shoaling volume of the CSC in comparison to sediments delivered by the Calcasieu River and the Gulf of Mexico. Additionally, the fluid mud sampled in FY20 did not have a unique geochemical fingerprint that distinguished it from other material within the CSC, nor did it have a marine carbon signature indicating that it was transported from offshore. Similarly, no unique geochemical characterization could be made for the sediments within the high shoaling area of Devil's Elbow, indicating that a unique, localized sediment source does not appear to be the reason for elevated shoaling in the area. The Devil's Elbow reach is situated at the confluence of the Calcasieu River, Calcasieu Lake, and the IWW. Therefore, the shoaled material in this reach may consist of a mixture of sources caused by the interplay between sediment pulse events and temporal and spatial variations of the salinity wedge.

4 Conclusions

Using varied approaches to assess sediment processes and sources to the CSC over the course of this investigation, the following key conclusions were reached.

- The primary sources of sediment to the CSC appear to be the Calcasieu River and the Gulf of Mexico. While a quantifiable number for these sources could not be determined, geochemical fingerprinting and independent studies both indicated that local edge erosion or resuspension from Calcasieu Lake do not appear to be dominant sources of sediment to the system.
- The uncertainties in the sediment budgets presented in this work remain large, as geochemical data could not provide quantifiable amounts for potential sources. Additionally, it is important to point out that the river and offshore sources terms account for only suspended sediment measurements and do not consider fluid mud, density current, or bedload transport. Further, they also assume 100% deposition within the CSC, which likely overestimates their contribution to shoaling.
- The *missing* dredged volume is very likely not from an *unidentified* source but lost in the uncertainties in the volume estimates of the existing budgets. Additionally, the lack of hydrodynamic data makes it difficult to account for sediment transport pathways accurately, which includes fluid mud movement, bedload transport during salinity gate operations, and vessel traffic impacts to resuspension and circulation in the system. These certainly contribute to missing volumes. However, this information does not discredit the Calcasieu River and Gulf of Mexico as the primary source terms.
- No indication in any of the project's results suggests that an engineering solution can be offered that would clearly reduce substantial shoaling that is coming from a unique source within the system. In summary, there are no easy engineering solutions to reduce shoaling. However, the project results constrain the dominant sediment sources to the Gulf of Mexico and Calcasieu River and demonstrate that the shoaling material is not coming from a singular source that can easily be *turned off*.

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Appendix: 2020 Geochemical Fingerprinting

A.1 Sample collection

Sediment sample collection occurred between June 24 and June 30, 2020. To obtain fluid mud material, a series of 10 suspended sediment samples were collected with a VanDorn sampler during bathymetric surveys conducted by MVN from June 24–25, 2020. Locations for sample collection were determined based on results of dual frequency fathometer surveys and DensiTune casts to identify layers of fluid mud within the lower sections of the CSC (Table A-1). The VanDorn sampler was lowered to depths that corresponded to the surface of fluid mud to collect sediment. Approximately 1–2 L of sample were collected from each station and placed in sterile Whirl-Pak bags. All sampling equipment contacting the sediment was rinsed with site water prior to subsequent sampling at each location. Samples were stored in coolers at the Calcasieu Lock until pickup by ERDC personnel on June 30, 2020.

Table A-1. Coordinates of FY20 sample locations.

Sample Name	Sample Type	Latitude (° N)	Longitude (° W)
FM-1	VanDorn, Ponar	29.92091	93.3404
FM-2	VanDorn, Ponar	29.9373	93.3389
FM-3	VanDorn, Ponar	29.94551	93.3382
FM-4	VanDorn, Ponar	29.95886	93.3369
FM-5	VanDorn, Ponar	29.96202	93.3367
FM-6	VanDorn, Ponar	29.9717	93.3358
FM-7	VanDorn, Ponar	29.9867	93.3344
FM-8	VanDorn, Ponar	30.00038	93.3332
FM-9	VanDorn, Ponar	30.0278	93.3307
FM-10	VanDorn, Ponar	30.04274	93.3293
DE-1	Ponar	30.10664	93.2874
DE-2	Ponar	30.10861	93.2978
DE-3	Ponar	30.1042	93.3089
DE-4	Ponar	30.09863	93.3164
DE-5	Ponar	30.09317	93.323
FW-1	Bottom Drag	30.25386	93.2156

Table A-1. Continued.

Sample Name	Sample Type	Latitude (° N)	Longitude (° W)
FW-2	Bottom Drag	30.25214	93.2157
FW-3	Bottom Drag	30.25473	93.2114
FW-4	Bottom Drag	30.26078	93.2081
FW-5	Bottom Drag	30.26788	93.2119
FW-6	Bottom Drag	30.26633	93.2
FW-7	Bottom Drag	30.27101	93.1845
FW-8	Bottom Drag	30.28236	93.1923

On June 30, 2020, the field team returned to the locations with fluid mud and collected bottom sediments with a Petite Ponar. The Ponar sampler was also used to collect five bottom samples from the Devil's Elbow portion of the channel (DE, Table A-1). Additionally, eight bottom sediment samples were collected with a 6 in. diameter drag from portions of the Calcasieu River upstream of the salinity gate on June 30 (FW, Table A-1). All sediment samples were transferred to sterile Whirl-Pak bags and placed in coolers. Following collection, all sampling equipment was rinsed with site water prior to subsequent sampling at other locations. On July 1, 2020, all collected samples were transported to the ERDC where they were stored in a 4°C refrigerator until laboratory processing.

A.2 Sample processing

All sediment samples were processed at the ERDC Coastal and Hydraulics Laboratory. Initial examination of the VanDorn collected fluid mud samples indicated only three of the suspended sediment samples had sufficient mass (>50 g) for full geochemical fingerprinting analyses. Therefore, the remaining seven VanDorn samples were not included in the study. In preparation for fingerprinting analysis, all samples were first wet screened through 4 mm sieve to remove large organic matter and other debris. Samples were thoroughly mixed and subsampled for grain size distribution and geochemical analyses.

A.2.1 Grain size analysis

Grain size distributions were obtained using a Malvern Mastersizer 2000 laser diffraction particle. Specimens of 1–2 g were treated with a 40 g/L solution of sodium metaphosphate to disperse cohesive particles. Additionally, samples were passed through a 1 mm sieve over the instrument's reservoir to remove any residual macro organics, then sonicated for 60 sec prior to measurement.

A.2.2 Loss on Ignition (LOI) analyses

The total volatile organic content of the sediment samples was determined by LOI as described in ASTM (2014) method C. Following recommendations reported by Schumacher (2002) and Salehi et al. (2011), the combustion temperature was reduced from the ASTM guidance of 440°C to 360°C.

A.2.3 Geochemical analyses

Subsamples of sediment for geochemical analyses were placed in ceramic bowls and dried in a 50 °C oven. After drying, approximately 50 g of sample were pulverized to powder and passed through a 0.25 mm sieve. Aliquots of the powder were then set aside for the following analyses: X-ray fluorescence (XRF), soil nutrients, and stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotopes.

A.2.3.1 X-ray fluorescence (XRF)

Elemental compositions were determined through XRF techniques using a Thermo Fisher XL3 Analyzer in "Soil Mode." Powdered samples were analyzed with all three of the instrument's excitation filters enabled for 60 sec at each filter setting.

A.2.3.2 Soil nutrients

Routine soil nutrient analyses were performed at the Louisiana State University (LSU) Agricultural Center soil laboratory. The elemental content of phosphorous, potassium, calcium, magnesium, sodium, sulfur, copper, and zinc (P, K, Ca, Mg, Na, S, Cu, Zn) was obtained through Inductively Coupled Plasma mass spectrometry techniques (Mehlich 1984).

A.2.3.3 Carbon and nitrogen stable isotopes

Sediment samples were shipped to the LSU Stable Isotope Ecology Laboratory for carbon and nitrogen analysis. Percent total nitrogen (N) and organic carbon (OC) content was measured with a Costech ECS4010 elemental analyzer. Out-flowing gas was analyzed for $\delta^{13}C$ and $\delta^{15}N$ with a Thermo-Fisher Delta Plus XP stable isotope ratio mass spectrometer. The delta values are the isotope ratios of $^{13}C/^{12}C$ and $^{15}N/^{14}N$ reported in ‰ relative to the standard Vienna Pee Dee Belemnite and atmospheric N_2 (AIR) for $\delta^{13}C$ and $\delta^{15}N$, respectively.

A.2.4 Data analysis

Data analysis was performed primarily using built-in functions within the R statistics software environment (R Core Team 2019). Principal Components Analysis (PCA) and K-Means Cluster Analysis were used for data reduction; these common techniques are used to reveal informative relationships and patterns in multivariate datasets that would otherwise be difficult to interpret or visualize. The basic procedure for preparing and analyzing the data are provided along with additional results in the sections below.

A.2.4.1 Selection of variables

Geochemical results from the FY20 samples were pooled together with the FY19 samples, and new PCA and K-means cluster analyses were performed to examine the relationships between samples from the entire data set. However, XRF results of the 2020 samples showed non-detectible levels of multiple elements that were originally present in the FY19 data. As a result, nine variables from the FY19 dataset could not be included: Te, Sn, Sb, Cs, C, N, Na, Mg, P. Additionally, the selection criterion for inclusion in the analyses was heuristically based on a Pearson correlation (r) threshold of ≥0.65 among three or more covariates. Consequently, only eight variables met the statistical threshold for inclusion across sediment samples from both the FY19 and FY20 datasets as presented in Table A-2.

Table A-2. Variables used in geochemical fingerprinting models. Blue text indicates FY20 variables, red text indicates FY19 variables, and shaded cells indicate variable used in both models.

% Fines (<63µm)	Zr	Rb	Th	Zn	Fe	Mn	D_{50}	Cr	Pb
LOI	V	Ti	Mg	Cs	Te	Sb	Sn	N	

A.2.4.2 Principal Components Analysis (PCA)

Data analysis was performed using the built-in function *prcomp* within the R (R Core Team 2019) statistics software environment, and the output was visualized using the *Factoextra* package (Kassambara and Mundt 2017). The function *prcomp* uses singular value decomposition to derive the percent variance explained in each principal component (PC). When performing the PCA calculations, the data are standardized (centered and scaled) such that the variables have a mean of zero and variance of one. Standardization is advisable for variables with widely varying ranges and different units of measure (Johnson and Wichern 2007).

A summary of the PCA results is given in Table A-3, which shows that nearly 90% of the total variance in the data can be explained using the first two PCs.

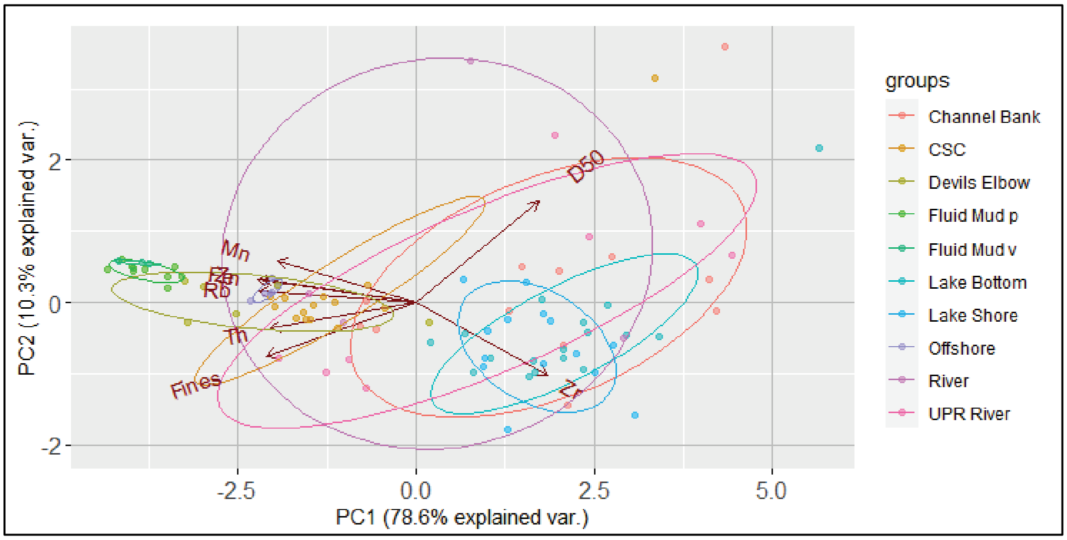
Table A-3. Eigen analysis of the correlation matrix.

	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8
Proportion of variance	0.79	0.10	0.04	0.03	0.02	0.01	0.01	0.00
Cumulative Proportion	0.79	0.89	0.93	0.96	0.98	0.99	1.00	1.00

Figure A-1 presents a biplot that graphically demonstrates the correlations between the original variables and the two primary PCs. Here, vectors of positively correlated variables point in the same direction whereas negatively correlated ones point in the opposite direction. Similarly, small angles between vectors indicate greater strength of correlation whereas orthogonal vectors would be non-correlative. Ellipses in the biplot represent the 68% confidence interval.

While many observations overlap, note that samples from locations Offshore, Devil's Elbow, Fluid Mud, and CSC are strongly separated from Lake Shore, Lake Bottom, Channel Bank. River and Upper River samples are more ambiguous. Nonetheless, the separation is driven primarily in differences grain size and the elements listed in Table A-2.

Figure A-1. Biplot of PCA scores (points) and loadings (vectors).



A.2.4.3 K-Means cluster analysis

To evaluate data clustering based on statistical similarity, a non-hierarchical K-Means procedure was also used on the standardized data set. Identifying the optimal number of clusters is user defined based on various algorithm used, which includes the within-cluster sum of squares (WSS) method, gap statistic method, and silhouette method contained within the *NBclust* package (Charrad et al. 2014). For the WSS method, each observation is assigned to the closest centroid generated by an iterative bootstrapping technique that minimizes the total WSS; the distance metric selected was Euclidean. The optimal number of partitions for the data using WSS techniques is generally identified using the *elbow* method, analogous to a scree plot. In this case, either three or four clusters could be selected as shown in Figure A-4. The more sophisticated gap statistic method determined four clusters as optimal, as shown in Figure A-5.

To evaluate the quality of the clustering resulting from randomized initial centroids positions, model runs were repeated with different seeding values, which did not significantly alter the clustering results.

Figure A-4. Optimal number of K-means clusters using the within-sum-of-squares elbow method.

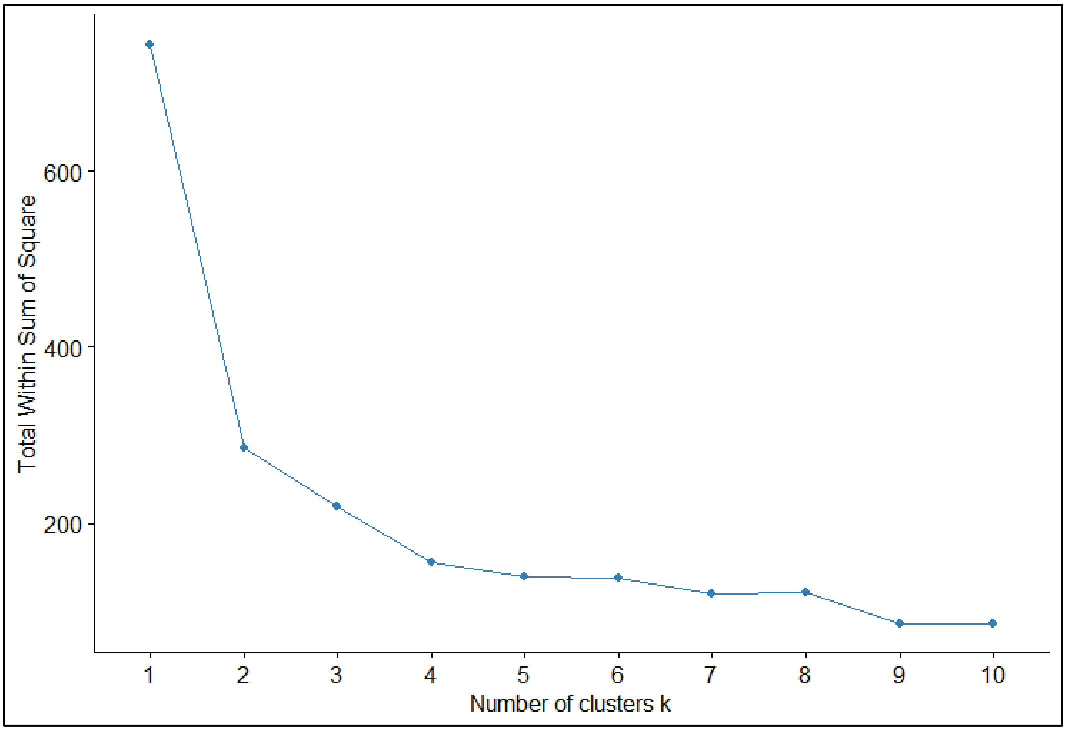
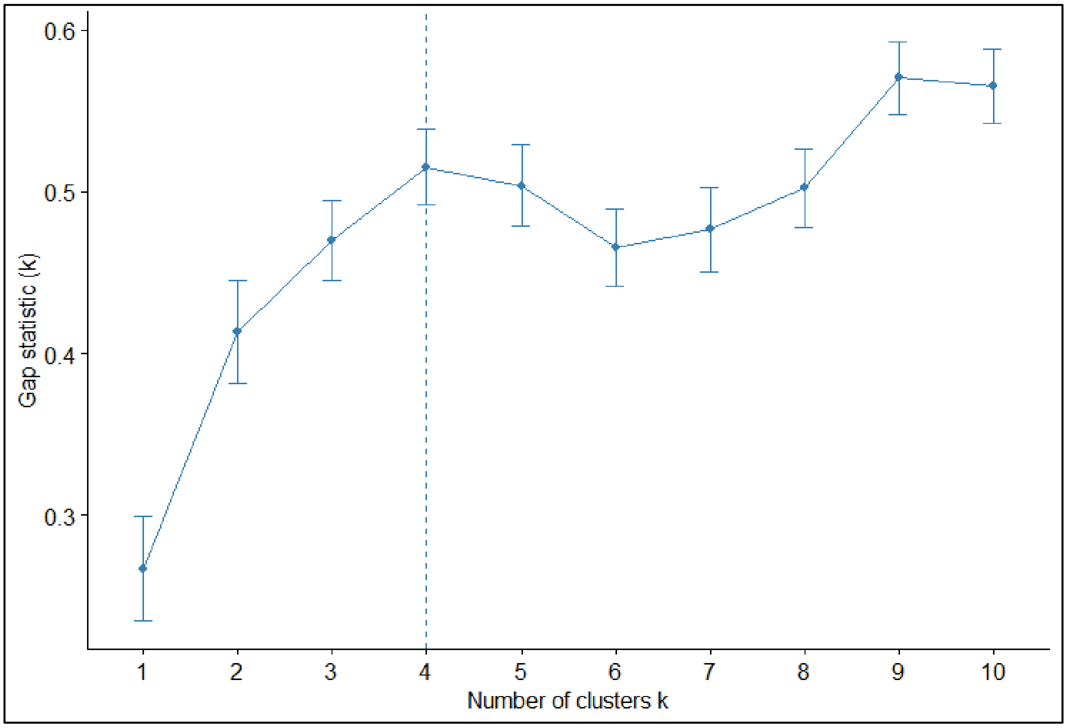


Figure A-5. Optimal number of K-means clusters using the gap statistic method.

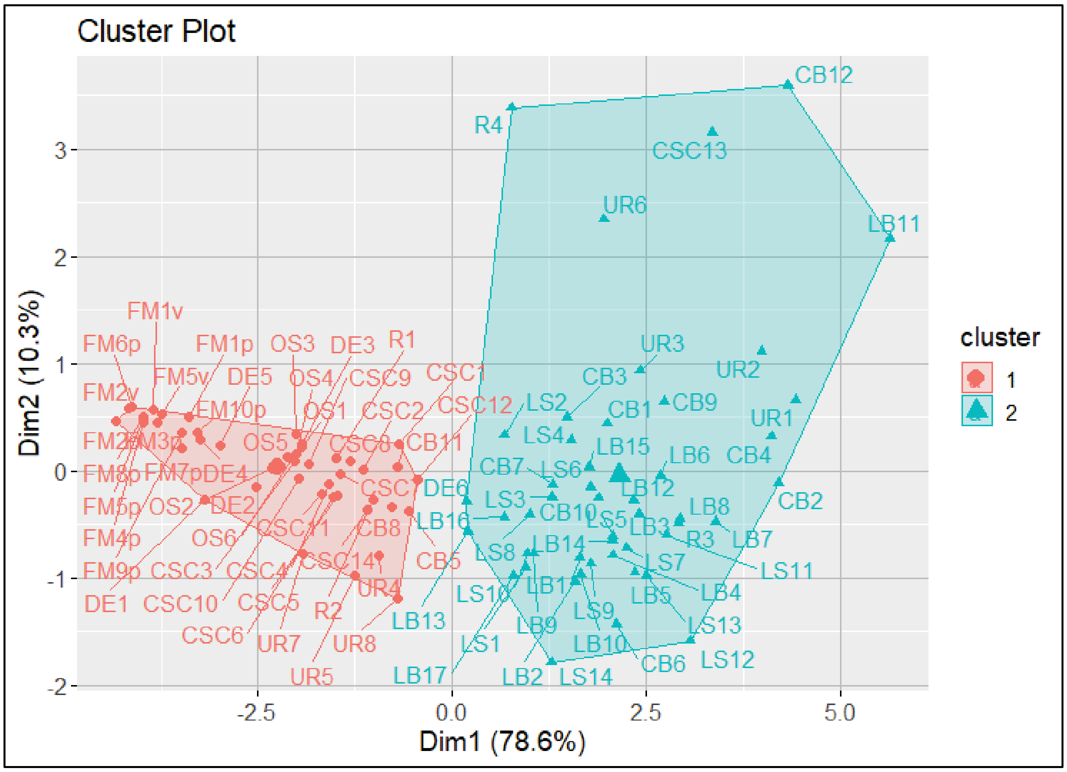


Measures of the total dispersion (from the sums of squares values) within and between clusters (WSS and between sum of squares [BTSS]) is provided in Table A-4. Smaller values of WSS indicate greater homogeneity, and therefore, tighter clustering. The ratio "Between SS/Total SS" provides a measure of the goodness of fit of the clusters; for four clusters, the variance explained is 79%. Thus, the observations within Cluster 4, which contain the fluid mud and Devil's Elbow samples, display the most homogeneity relative to the other clusters. Additionally, the Euclidean distance between cluster centroids provides a measure of their relative differences in the same way as the PCA scores in Figure A-3. Thus, the clusters appear to be meaningfully dissimilar to each other. Nonetheless, sample observations are broadly separated across PC1 space with the same interpretation as Figure A-3, though the partitioning of groups is more readily apparent as shown in Figure A-7.

Table A-4. K-Means cluster analysis sum of squares (SS).

Cluster	N Observations	Within SS
1	31	41.6
2	36	53.3
3	11	50.8
4	16	9.6
Between SS (BTSS)	**Total SS (TSS)**	**Variance Explained (BTSS/TSS)**
588.7	744.0	79%

Figure A-7. K-Means cluster plot with only two groups selected. Samples are generally partitioned across PC1 = 0, driven by differences in grain size and elemental composition.



Acronyms and Abbreviations

AdH	Adaptive Hydraulics
BTSS	Between sum of squares
CDF	Confined disposal facilities
CSAT	Corps Shoaling Analysis Tool
CSC	Calcasieu Ship Channel
ERDC	US Army Engineer Research and Development Center
FY	Fiscal Year
GIWW	Gulf Intracoastal Waterway
LOI	Loss on Ignition
LSU	Louisiana State University
MVN	New Orleans District
PC	Principal Component
PCA	Principal Components Analysis
RM	River Mile
RSM	Regional Sediment Program
SS	Sum of squares
TSS	Total suspended solids
USGS	US Geological Survey
WIG	Water Institute of the Gulf
WSS	Within-cluster sum of squares
XRF	X-ray fluorescence

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14. ABSTRACT
To maintain the navigability of the Calcasieu Ship Channel (CSC), the US Army Corps of Engineers annually dredges millions of cubic yards of sediment from the inland channel. To assess sources of channel shoaling, a previous study examined river and bankline erosion as inputs. Results from that study accounted for approximately 20% of dredged volumes. Through the support of the Regional Sediment Management Program, a follow-up investigation reviewed prior sediment budgets, identified potential missing sediment sources, modeled potential sediment pathways, and utilized geochemical fingerprinting to discern primary shoaling sources to the channel. The missing sediment sources from the original budget include coastally derived sediment from the Gulf of Mexico and terrestrially derived sediment from Lake Calcasieu and surrounding wetlands. Results from geochemical fingerprinting of various potential sediment sources indicate the Calcasieu River and the Gulf of Mexico are primary contributors of sediment to the CSC, and sediments sourced from bankline erosion, Lake Calcasieu bed, and interior wetlands are secondary in nature. These results suggest that engineering solutions to control shoaling in the CSC should be focused on sources originating from the Gulf of Mexico and river headwaters as opposed to Lake Calcasieu, channel banklines, and surrounding wetlands.

15. SUBJECT TERMS
Calcasieu River (La.), Channels (Hydraulic engineering), Dredging, Dredging spoil, Lake Charles (La.), Mexico, Gulf of, Sedimentation and deposition, Sediment transport

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