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Dredging Innovations Group

Utilizing Stream Flows to Forecast Dredging Requirements

Elissa M. Yeates, Ahmad A. Tavakoly, Kenneth N. Mitchell,
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Elissa M. Yeates, Ahmad A. Tavakoly, Kenneth N. Mitchell, and Gregory W. Dreaper

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

Shahab Afshari

Climate System Research Center Laboratory
Department of Geosciences
University of Massachusetts
Amherst, Massachusetts 01003

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Abstract

In recent years, the United States Army Corps of Engineers (USACE) has spent an average of approximately a billion dollars annually for navigation channel maintenance dredging. To execute these funds effectively, USACE districts must determine which navigation channels are most in need of maintenance dredging each year. Traditionally, dredging volume estimates for Operations and Maintenance budget development are based on experiential knowledge and historic averages, with the effects of upstream, precipitation-driven streamflows considered via general-rule approximations. This study uses the Streamflow Prediction Tool, a hydrologic routing model driven by global weather forecast ensembles, and dredging records from the USACE Galveston District to explore relationships between precipitation-driven inland channel flow and subsequent dredged volumes in the downstream coastal channel reaches. Spatially based regression relationships are established between cumulative inland flows and dredged volumes. Results in the test cases of the Houston Ship Channel and the Sabine-Neches Waterway in Texas indicate useful correlations between the computed streamflow volumes and recorded dredged volumes. These relationships are stronger for channel reaches farther inland, upstream of the coastal processes that are not included in the precipitation-driven hydrologic model.

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Preface

Funding for this study was provided by the US Army Corps of Engineers (USACE) Navigation Business Line, Dredging Innovations Group under Funding Account No. 476553, “Watershed Informed Shoal Forecasting.” The technical monitor was Dr. Kenneth N. Mitchell. The Program Manager for Dredging Operations Technical Support was Dr. Burton Suedel. Mr. Michael E. Ott was Chief of the Headquarters, USACE Navigation Branch and the Navigation Business Line Manager.

The work was performed by the Hydrologic Systems, River Engineering, and Coastal Engineering branches of the Flood & Storm Protection and Navigation Divisions, US Army Engineer Research and Development Center, Coastal and Hydraulic Laboratory (ERDC-CHL). At the time of publication, Dr. Hwai-Ping Cheng was Chief, Hydrologic Systems Branch; Dr. Cary A. Talbot was Chief, Flood and Storm Protection Division; and Mr. Charles E. Wiggins, CHL, was the Technical Director for Navigation. The Deputy Director of ERDC-CHL was Mr. Jeffrey R. Eckstein, and the Director was Dr. Ty V. Wamsley.

COL Teresa A. Schlosser was the Commander of ERDC, and the Director was Dr. David W. Pittman.

Executive Summary

The US Army Corps of Engineers (USACE) navigation mission requires periodic dredging of channels nationwide to maintain sufficient navigable depths for safe, reliable, and cost-effective shipping. Presently, USACE dredging managers lack tools to account explicitly for the impact of inland, precipitation-driven streamflow on near-term channel dredging requirements. Researchers at the US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, have developed the Streamflow Prediction Tool (SPT), which uses global atmospheric and land-surface modeling products and a watershed-scale hydrologic routing scheme to produce estimated stream flow projections. This report documents the analytical steps used to estimate predictive relationships between modeled stream flows from the SPT and subsequent channel dredging requirements for the historical period of 1980–2014 for two federal navigation projects along the Texas coast. This analysis seeks to leverage existing dredging datasets and tools maintained by the USACE towards insights useful in the channel maintenance process.

Eight different single and multivariate, linear and nonlinear regression models were tested on the dredging event and streamflow datasets by stream reach in the Sabine-Neches Waterway and the Houston Ship Channel. Among the models tested, model performance is highest for a linear model that uses cumulative in-channel base flow volumes and high flow volumes between localized dredging events as predictors of subsequent dredged volumes. R-squared values indicate that this model captures 66%–94% of the variance in the dredged amounts in upstream reaches. This simple linear model can easily be applied to any reach for which historical, date-stamped dredging volumes are available.

For the river systems examined, inland riverine flow appears highly correlated with subsequent dredging loads at reaches inland of bays and coastlines. Dredging loads in stream reaches where coastal processes impact flow are not well-predicted by these models. Recognizing those limitations, precipitation-driven flow volumes can provide additional information about channel maintenance needs without the deployment of data-intensive, high-fidelity sedimentation models. As streamflow forecasting improves to give longer lead times on flow variability, techniques such as this can inform dredging managers of expected channel maintenance requirements over the upcoming seasons.

1 Introduction

1.1 Background

The US Army Corps of Engineers (USACE) navigation mission is to provide safe, reliable, efficient, and environmentally sustainable waterborne transportation systems (channels, harbors, and waterways) for movement of commerce, national security needs, and recreation. Dredging to navigable depths and the placement and management of dredged materials are crucial in meeting this mission. Periodic dredging of harbors and rivers nationwide is required for safe transit of ships, barges, ferries, and other vessels. In fiscal years 2009 through 2018, USACE spent an average of $984 million annually on contracts for maintenance channel dredging in the contiguous United States, resulting in a total of 1.96 billion cy[*] of material dredged (Dredging Information System 2018).

Currently, the standard in most USACE districts is for dredging managers and engineers to utilize their institutional knowledge gained from years of experience to estimate dredging patterns from year to year. USACE districts budget for channel dredging contract needs up to 2 years in advance. Providing these managers and engineers with additional information on stream conditions and projected sediment loads will improve the efficiency with which dredging contracts are designed and scheduled. Other current USACE efforts to improve dredging decision support include the Corps Shoaling Analysis Tool (CSAT) (Dunkin et al. 2018). CSAT processes historical channel survey data to produce channel-specific volumetric rates of change, which are then extrapolated to project near-term (i.e., 1-3 years) sediment loads. As CSAT is entirely empirical, it does not explicitly account for the inter-annual effects of coastal processes or runoff from inland hydrologic systems on channel sediment loads.

The Streamflow Prediction Tool (SPT) was developed by US Army Engineer Research and Development Center (ERDC) and university partners to generate historic streamflows and projected future streamflows for tens to

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[*] 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.

hundreds of thousands of reaches within watersheds that may not have available gage data (Snow et al. 2016). By incorporating a large spatial extent and the converging flow volumes of streams and tributary systems, the SPT accounts for unique watershed responses to precipitation in estimating stream flows. SPT output includes reconstructed 3-hourly flow rates for each stream reach in a given watershed from 1980 to the present day, and continually updated 2-week forecasted flow rates. The tool estimates flows for every channel in a dense hydrologic network, including locations for which gauge data are unavailable. SPT was originally developed to inform in-theatre military logistics and deployment questions but is applied here to benefit the USACE Civil Works mission area, including the estimation of future dredging needs and more efficient allocations of limited dredging resources.

This technical report expands on the findings presented in Yeates et al. (2019). That conference paper described results of this analysis for the Sabine-Neches study area using the first four of the eight models presented in this paper. Those limited results were presented at the Federal Interagency Sedimentation and Hydrology meeting in June 2019.

1.2 Objective

The objective of this study was to estimate predictive relationships between precipitation-driven inland streamflow and subsequent channel dredging requirements near the base of the respective watershed. This analysis leverages existing dredging datasets and tools maintained by the USACE for insights useful in the channel maintenance process. The relationship between flow rate outputs from the SPT (Snow et al. 2016) and historic dredged volume records for two large deep-draft Navigation projects along the Texas coast were investigated. Uncovering correlative relationships between precipitation-driven inland streamflows and subsequent channel dredging requirements will provide USACE dredging managers with additional information to develop plans and specifications for maintenance dredging contracts, out-year budget requests, and sequencing of nearby channel maintenance activities. This is similar to methods applied by Dahl et al. (2017) in assessing the potential impact of climate-varying future precipitation on dredging load requirements.

1.3 Approach

In Section 2, Watershed scale hydrologic modeling, an overview of the SPT is presented. The approach employed in the SPT to watershed-scale inland hydrology enables the generation of decades of historical simulated stream flows for thousands of stream reaches in the study area.

Section 3, Methodology, gives an overview of the study area of interest and explains the data sources and processing used in the study. Data were processed to spatially connect dredging histories to reconstructed streamflows in the corresponding watershed. Then the historic dredged volumes were analyzed as a function of cumulative flow volumes to characterize the relationship between precipitation-driven flow and subsequent dredging volumes in each reach.

In Section 4, Results, the Sabine-Neches and Houston Ship Channel navigation project results are discussed. Visualizations are provided of the data analyzed and findings for the regression relationships for cumulative flow volumes and dredged volumes in each of the test reaches.

Section 5 presents conclusions and the path for future work in this effort.

2 Watershed Scale Hydrologic Modeling

To explore the impact of recent inland watershed-scale hydrologic processes on the subsequent near-term dredging load requirements of coastal waterways, hindcast streamflow simulation results from the SPT were used. This section details the hydrologic routing model components used in this analysis.

2.1 Routing Application for Parallel computatIon of Discharge (RAPID) hydrologic routing model

The RAPID model is an open-source model for routing precipitation runoff overland into river networks. RAPID uses *blue lines* on the map for river reaches and a grid network for river networks with an automated parameter estimation procedure (http://rapid-hub.org/index.html). Hydrologic routing is done via a matrix-based version of the Muskingum flow-routing method, which computes flow rates in river networks containing many thousands of reaches (David et al. 2011b).

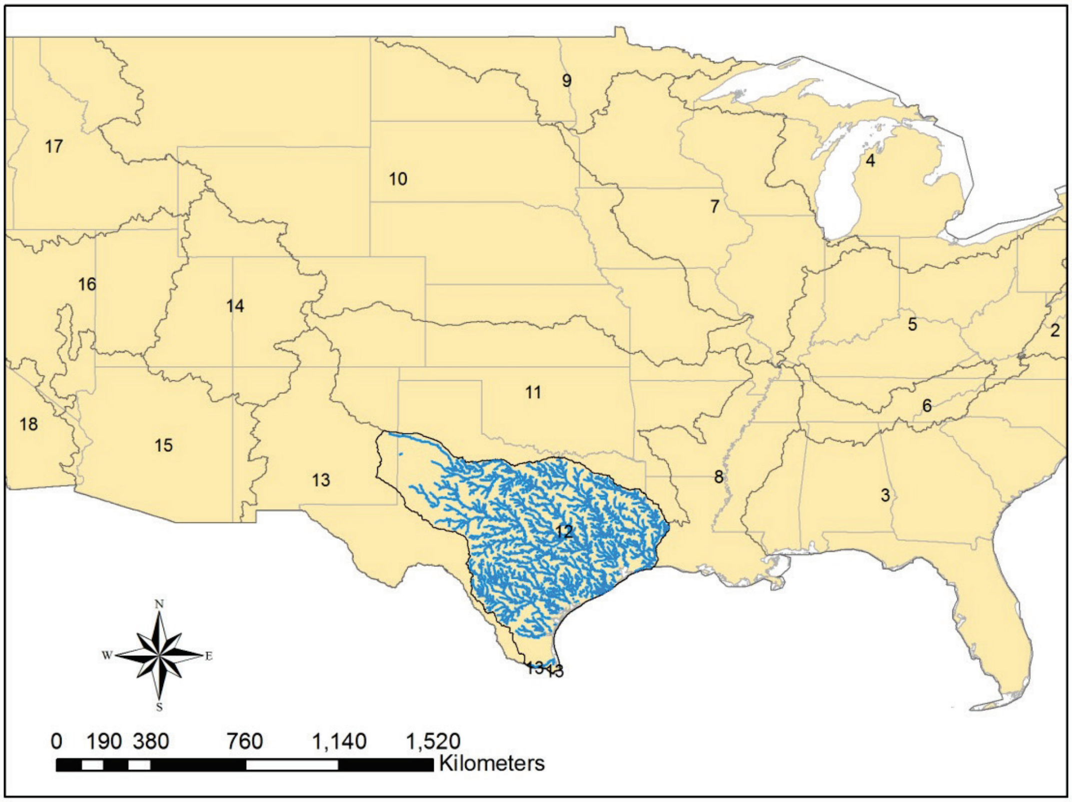
Inputs to RAPID are the gridded surface runoff time series, obtained from user-selected input atmospheric and land surface models and the calibrated Muskingum parameters for each river reach, which describe storage and flow behavior (David et al. 2011b). RAPID also requires catchment IDs to link individual river reaches to catchment areas. The specific input file types and preprocessing routines are described on http://rapid-hub.org/documents.html (David 2020). The output file of a RAPID run is a time series of flow rates (a synthetic hydrograph) for all river reaches in the examined river network. In the continental United States, the National Hydrography Dataset Plus (NHDPlus) dataset can be used to determine the location of a river reach as a blue line and to derive the Muskingum K and X parameters for RAPID input file preparation (Tavakoly et al. 2016a).

The performance of the RAPID model and application of the NHDPlus network for hydrologic routing have been described by: David et al. 2011a,b, 2013; Follum et al. 2016; Tavakoly et al. 2016a,b. David et al. (2013) found the hindcast RAPID model outflows to perform similarly to observed gage data in the Texas Gulf Hydrologic Region, which is the domain to which the RAPID model output in this study is applied.

2.2 NHDPlus stream network

The NHDPlus, version 2, is a major geospatial dataset used in this study. This dataset is a horizontal integration of the medium-resolution National Hydrography Dataset (NHD), the National Elevation Dataset, and the National Watershed Boundary Dataset (McKay et al. 2012; USGS USDA NRCS 2013). NHDPlus provides locations of perennial streams (i.e., blue lines) and the catchments that surround them. The attribute table of the NHDPlus flowline feature shows that the Texas Gulf Coast Region has a total of 68,901 river reaches with an average length of 3 km and an average catchment area of 6.8 km². Figure 1 shows the NHDPlus river network for the entire Texas Gulf Coast Region. The flow lines depicted are those with a Strahler stream order of three or higher (Pierson et al. 2008). The Strahler order is a methodology for ranking stream size; upmost headwater streams have an order of *one* (Pierson et al. 2008). The Hydrologic Unit Code of 12 refers to the Texas Gulf Coast Region in the NHDPlus Dataset.

Figure 1. The NHDPlus representation of the Texas Gulf Coast Region.



2.3 Streamflow Prediction Tool (SPT)

The SPT is a continuously updated instance of RAPID models run for watersheds near globally and an interface for accessing RAPID model results by watershed and stream reach. Hindcast 3-hourly flow rates from 1980 through 2014 and 2-week streamflow forecasts are available via the USACE Model Interface Portal (UMIP) at https://umip.erdc.dren.mil/apps/streamflow-prediction-tool/ (UMIP access requires a government common access card login).

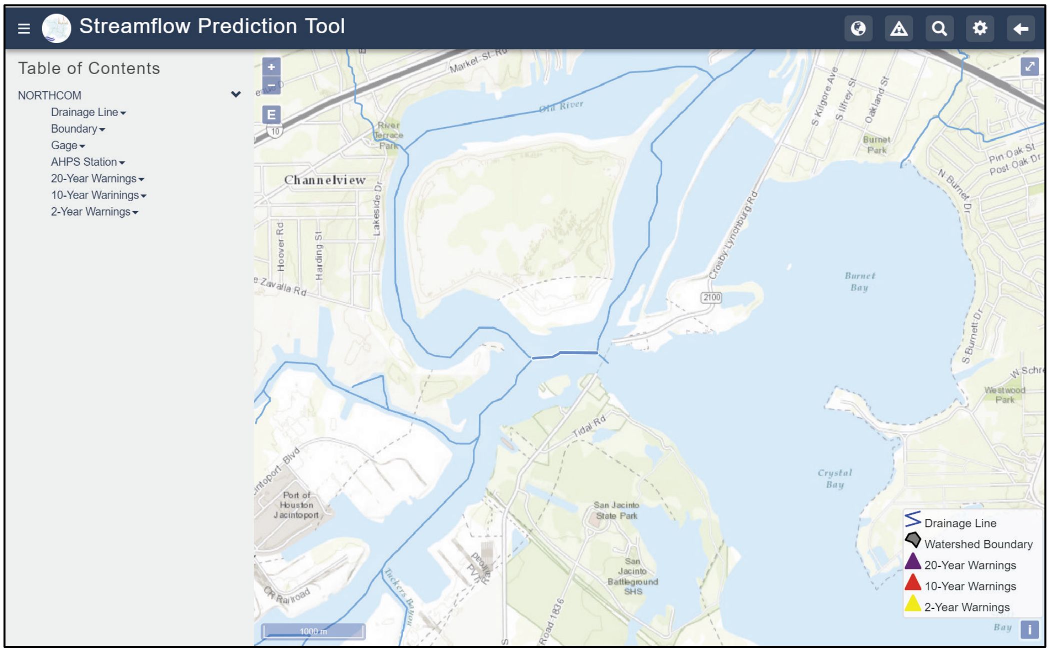
At the time of this analysis, the RAPID model results produced for the SPT were driven by atmospheric and land surface runoff data from the European Centre for Medium Range Weather Forecasts (ECMWF) (Balsamo et al. 2009). The ECMWF Reanalysis-Interim (ERA-I) runoff data needed to run RAPID are retrieved from the Meteorological Archive and Retrieval System, and covers the 1980–2014 time period at a 3-hourly time step (Berrisford et al. 2011). These simulated runoff volume estimates are one product of a complex coupled atmospheric-ocean-wave model, detailed in Balsamo et al. (2009) and Berrisford et al. (2011).

This hydrologic modeling framework takes advantage of over 30 years of the ERA-I runoff estimates available globally to reconstruct stream flows at ungauged locations. The atmospheric and land surface modeling inputs use energy and mass balancing to produce estimated gridded global surface water runoff. This runoff is routed into streamflow using the RAPID hydrological model. The benefit of this framework is the ability to calculate streamflow anywhere in a river network without a dependency on nearby available rainfall or streamflow gauges. Hence, the calculated streamflow can be obtained for any location of interest in any watershed.

To date, SPT development has been primarily funded by the ERDC military engineering program to support Warfighter Support via Reachback and Outside Contiguous United States operational demands. The US Army, ERDC, and university partners have developed the method for hindcasting and forecasting streamflow by routing globally available runoff estimates over continental-scale stream networks.

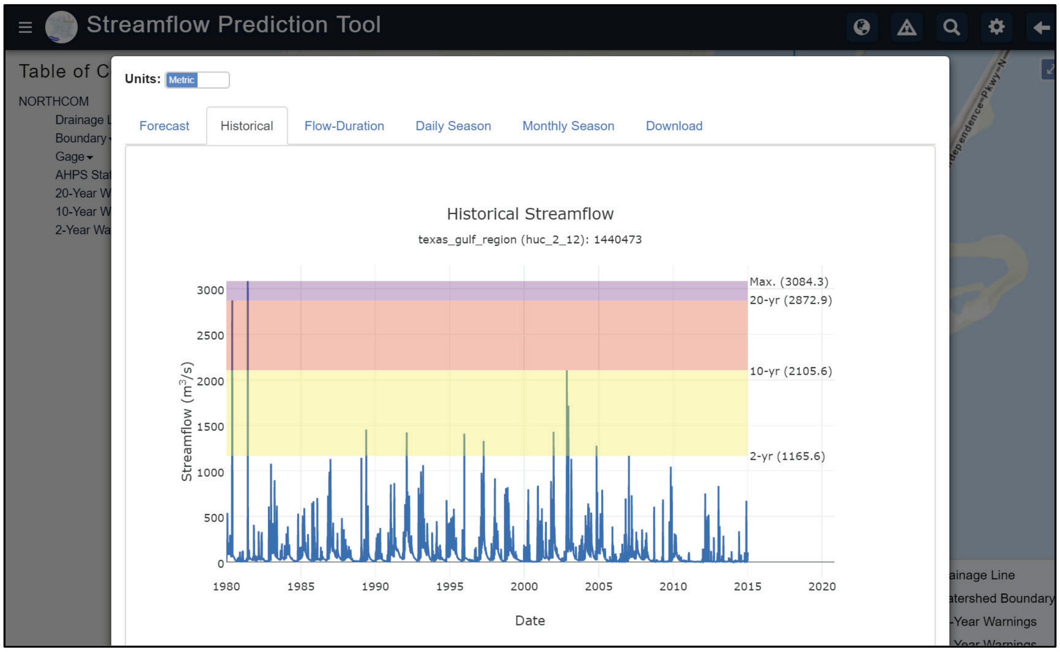
The RAPID streamflow results are stored in an open source data management portal, the Comprehensive Knowledge Archive Network (CKAN). Users download model results for a stream reach through a Tethys Platform web-based application connected to CKAN. Users can select and view results for specific stream reaches by NHD Common ID (COMID), a river reach identifier) as shown in Figure 2.

Figure 2. Selecting a stream reach through the SPT Tethys portal.



Users can then display and download the historic calculated streamflow time series for that reach, as shown in Figure 3.

Figure 3. Viewing historical flow time series in the SPT Tethys portal.



3 Methodology

For this analysis, historic dredging records from the USACE Dredging Information System and reconstructed stream flows from the SPT to connect them spatially by stream reach were processed. Dredged volumes at each reach were analyzed as a function of the cumulative flow volumes in the same reach to evaluate relationships between precipitation-driven flow and subsequent dredging requirements. The study area, data processing, and analytical methodology are detailed in this section.

3.1 Study area of interest

For initial investigation of the link between cumulative streamflow and dredging volumes, two study areas in Texas Gulf Coast Regions were selected: the Sabine-Neches Waterway and the Houston Ship Channel. These test sites represent a range of Texas coastal riverine systems and have available dredging records and calculated stream flow time series. Within these study areas, specific channels were chosen for analysis. Maps of the selected channels are presented in the Results section.

Fourteen river-reach COMIDs within the study area for analysis were selected: nine in the Sabine-Neches Waterway and five in the Houston Ship Channel. COMIDs were chosen to represent a variety of reach conditions in the regions of interest: those closer to inland riverine systems, closer to the outlet to bay areas, man-made channelized areas, and reaches before and after various stream confluences in each region. Furthermore, stream reaches with spatially matched robust historical dredging records were chosen.

It was determined that stream reaches with fewer than five dredging events in the study time period should be excluded from analysis, due to having too few data points to perform regression. This resulted in more eligible stream reaches in the Sabine-Neches Waterway than in the Houston Ship Channel system. Table 1 summarizes the stream reaches included in the analysis, including COMID, drainage area, and number of dredging events from 1980 through 2014.

Table 1. Summary of stream reaches analyzed.

Study Area	Stream ID	Drainage Area, km^2	Number of Dredging Events
Sabine-Neches Waterway	1112455	25,931	11
	1115825	26,058	9
	1477515	26,064	15
	1477595	26,220	15
	1477713	26,204	12
	1477589	26,215	16
	1477725	26,201	11
	1481563	27,705	23
	24719331	53,730	12
Houston Ship Channel	1440485	1,192	8
	1440511	2,012	8
	1440521	2,578	6
	1440525	1,205	9
	1440539	1,578	10

Consecutive stream reaches have drainage areas very similar in size because they are part of the same system, with the downstream reach having only the additional directly adjacent drainage area. The stream reaches in the Sabine-Neches Waterway have much larger drainage areas than those in the Houston Ship Channel. The stream reaches with the largest drainage areas are the outlets into the bay draining each of those basins. Maps of each river system are included in the Results subsections.

3.2 Data processing

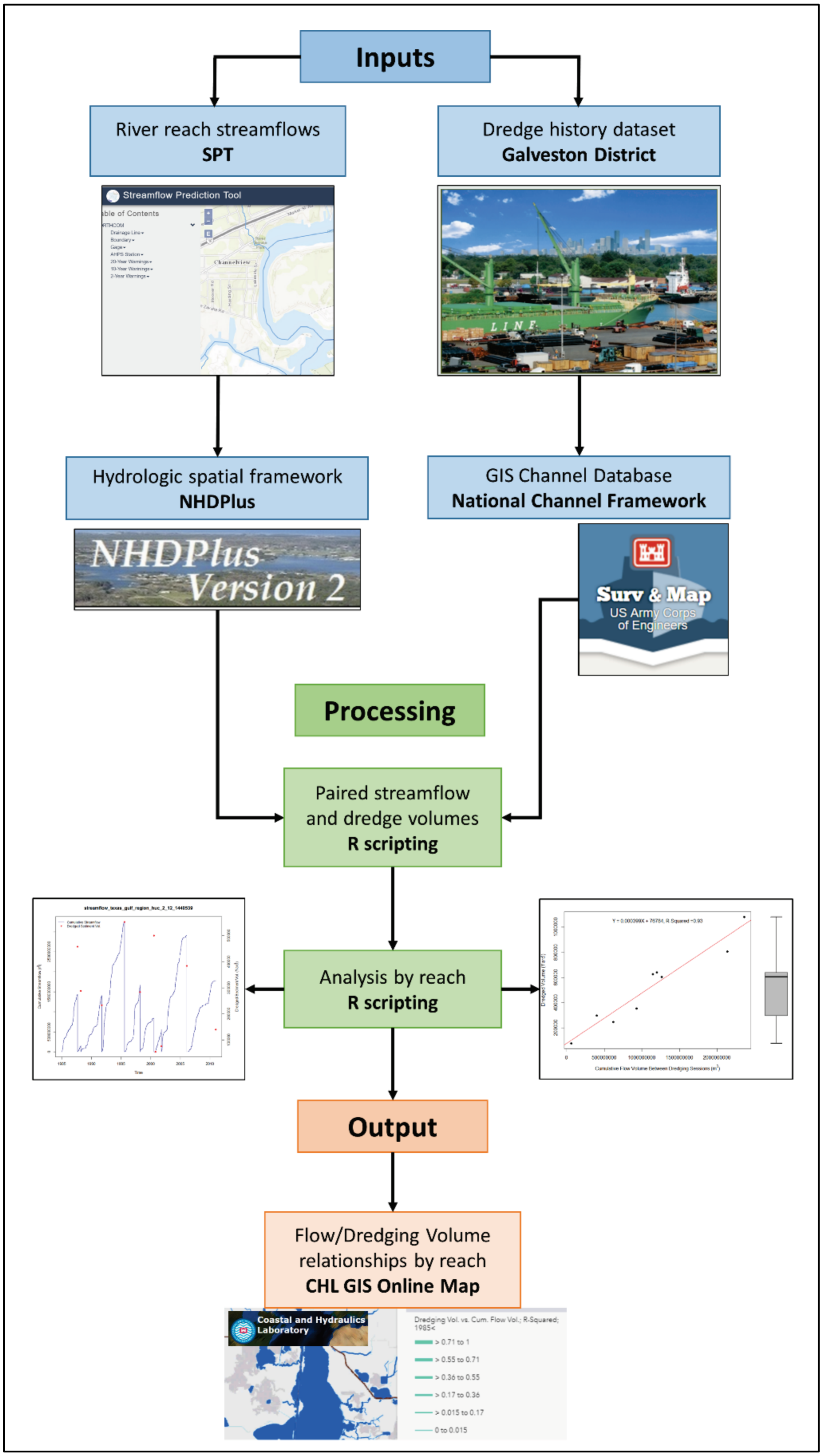
For this analysis, several existing USACE data sets and tools were used. The streamflow time series for selected reaches were downloaded from the SPT online portal interface. The historic dredging data records were provided by the USACE Galveston District, and dredging data were plotted spatially using the USACE National Channel Framework Geographic Information System database (USACE 2019). These inputs were processed via R scripting to match streamflow time series with dredged volume time series at the river reach level. Regression analyses of dredged volumes as a function of precipitation-driven streamflow in R were performed, and an online mapping tool to store the results spatially was created. Figure 4 illustrates this work flow.

To create spatial datasets of the dredging records used in this project, three main source datasets were used: the National Channel Framework (NCF) feature class, the National Hydrographic Dataset Plus Version 2 (NHDPlusV2) and the dredge histories dataset for the Galveston District, which includes all harbors in the study area.

The NCF (https://catalog.data.gov/dataset/national-channel-framework) is a set of enterprise Geographic Information System feature classes that provide geospatial locations of the congressionally authorized navigation channels maintained by the USACE. Details include reaches, channels, and quarters. The Galveston District dredge histories database includes channel reaches, river stations, dredged quantities in cubic yards, and project date end for each dredging event in the District in the last 40 years. This district dataset encompasses the two regions examined in this study, Sabine-Neches Waterway and the Houston Ship Channel.

To conduct this analysis, both the NHDPlusV2 stream reaches and the local dredge history records were connected spatially to the channel features in the NCF. Where there were several NHDPlusV2 reaches relating to a single NCF channel, the most downstream reach was associated with the feature. Associating each dredge history record with a channel feature allowed the relating of dredging events and amounts with historical streamflow at that location. These connections were all performed using ArcGIS software.

Figure 4. Data processing work flow.



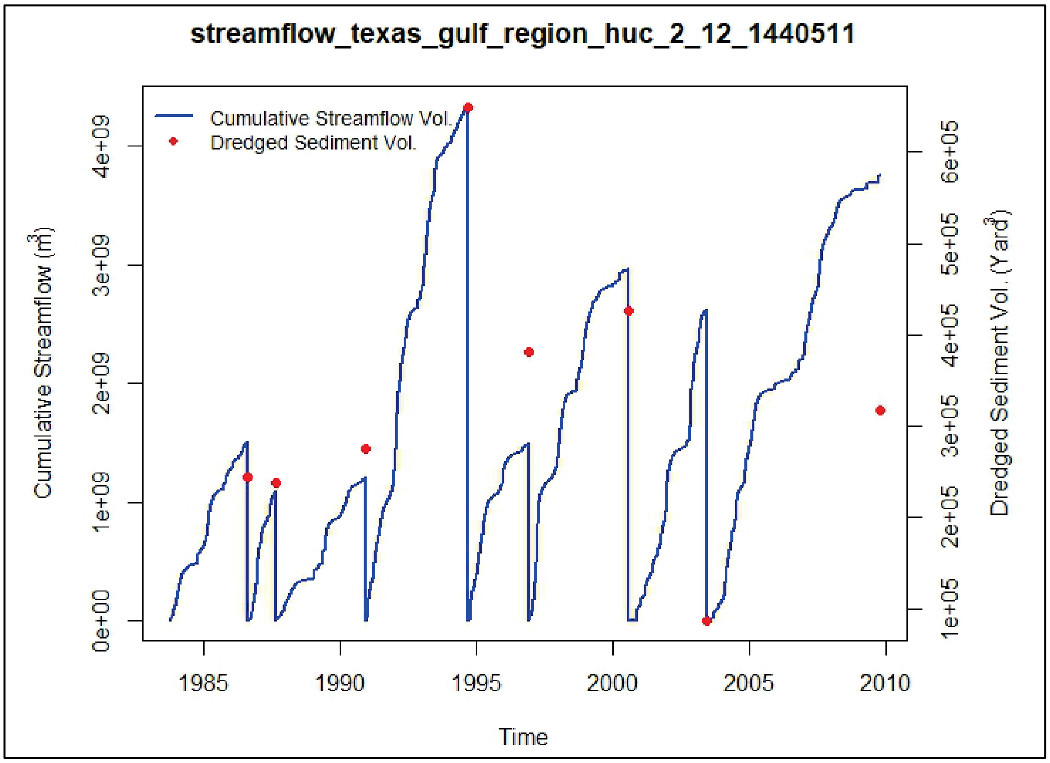
To correlate dredged amounts in each reach with the reconstructed streamflow produced by the SPT for that reach, a number of data manipulation measures were performed in an R script. Steps to relate dredged volumes and streamflows were performed as follows:

1. Link the streamflow reach COMIDs and dredging channel locations spatially.
2. Export the reconstructed streamflow time series for each stream reach of interest from the Streamflow Prediction Tool. The 3-hourly streamflow time series from 1980 to 2014 were retrieved in comma-separated values format.
3. Import streamflow data and dredging record data into R and reformat the date and time-stamp fields to be the same for both files.
4. Link streamflow data and all dredging data for that particular river reach by the common COMID.
5. Connect dredging project data to the streamflow time series by the date listed in the dredge project history as "Work Complete." Dredging records with work completion dates before 1981 were discarded to ensure sufficient overlap with the SPT time series output.
6. Aggregate dredging records with multiple project volumes reported for the same reach location and same day into a single project volume.
7. Perform a return period analysis on the flow time history for each reach to determine the magnitude of the 1.5-year flow at that reach. The 1.5-year return period interval was chosen as a proxy for bankfull discharge (Copeland et al. 2005).
8. Code all streamflow values in the time history for each reach as being either less than or greater than the 1.5-year flow value.
9. Partition streamflow data into time history sets separated by the dredging event dates for each reach. This enabled the calculation of cumulative stream flow between each dredging event.
10. Convert streamflow rates into volumes by multiplying each streamflow rate in the SPT output by the 3-hour time-step for which it was estimated.
11. Sum up streamflow volumes within the hydrograph sets partitioned by dredging events, producing a cumulative flow volume preceding each dredged volume.
12. Analyze these data by producing regression models relating dredged volume as the dependent variable and cumulative streamflow volume as the driving variable. Regression models used included linear and

exponential models, and are further described in the Results section of this technical report.

The cumulative streamflow volumes between dredging events were plotted as a time series, with the subsequent dredged volumes in cubic yards plotted on a secondary axis (an example is shown in Figure 5; the streamflow cumulative volume time series is in blue lines and the dredging event volumes are shown as red dots). This provides an intuitive way to relate cumulative flow volumes to corresponding subsequent dredged sediment volumes. It also represents both flow and dredged volumes as time series, allowing for visualization of changes in the dredging practices in each stream reach over time. Volume units are different following convention for stream flow and for dredged material.

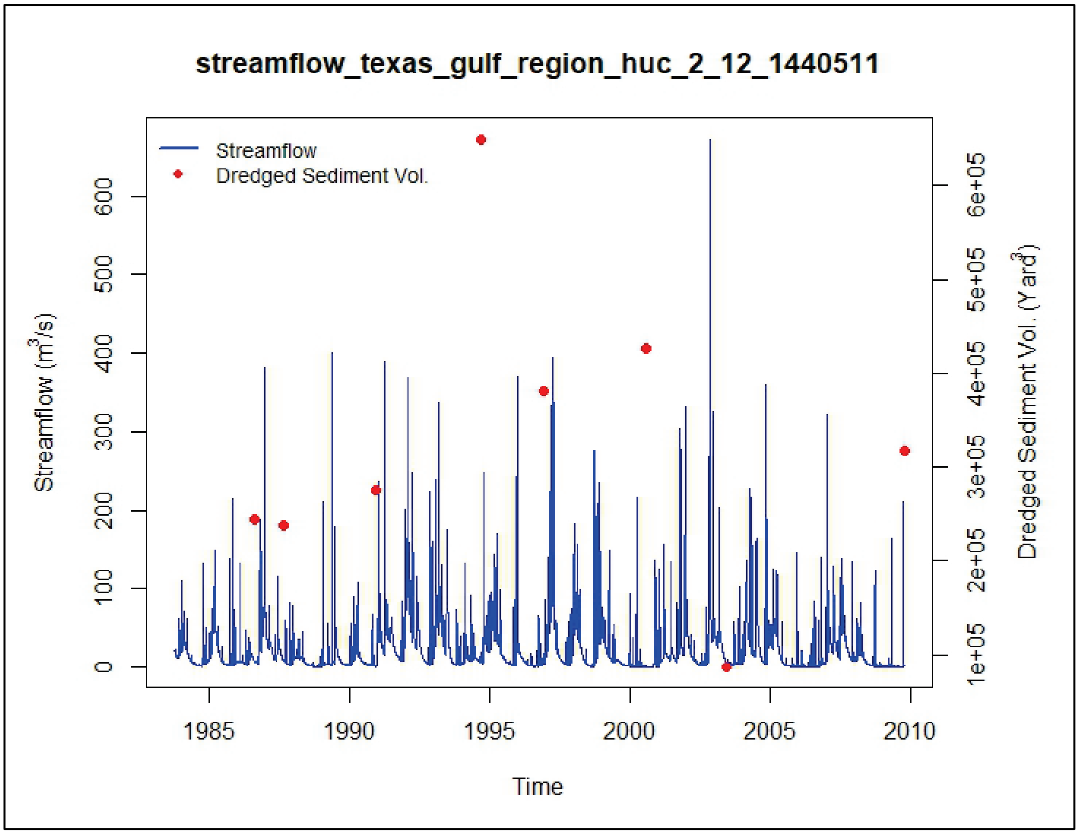
Figure 5. Time series output of cumulative streamflow and dredged volumes at reach 1440511 in the Houston Ship Channel.



Additionally, hydrographs of the stream flow rate over the entire time period of interest for each reach were produced. This provided the ability to view the seasonality of the flow for that reach and to see any dramatic spikes in precipitation rates. Volumes associated with dredging events at that reach were also graphed in these figures. An example is shown in

Figure 6, and the hydrographs for each analyzed reach are available in Appendix A.

Figure 6. Hydrograph output of the SPT flow rates for stream reach 1440511 in the Houston Ship Channel.



3.3 Models applied for analysis

To conduct the analysis, single and multivariate, linear and nonlinear regressions were performed on the dredging event and streamflow datasets by reach. Table 2 details all variables used in the regression models. Note that flow volumes are in cubic meters and sediment volumes are in cubic yards, following convention.

Table 2. Description of variables used in regression models.

Variable	Description
Vol_d	Total dredged volume from one dredging event (cubic yards)
Q_{tot}	Total cumulative flow since the prior dredging event (cubic meters)
Q_{base}	Cumulative in-channel flow (flow rate less than the 1.5-year flow rate for that stream) since the prior dredging event (cubic meters)
Q_i	Cumulative high flow (flow rate greater than the 1.5-year flow rate for that stream) since the prior dredging event (cubic meters)
Q_{tot-1}	Total cumulative flow between the two prior dredging events (cubic meters)
Q_{base-1}	Cumulative in-channel flow (flow rate less than the 1.5-year flow rate for that stream) between the two prior dredging events (cubic meters)
Q_{i-1}	Cumulative high flow (flow rate greater than the 1.5-year flow rate for that stream) between the two prior dredging events (cubic meters)
k	Regression intercept (cubic yards)
a, b, c, d	Regression coefficients

Eight different models were tested with the dredging data for the Houston Ship Channel and Sabine-Neches cases. These are described in Table 3 below. The simplest is a single-variate model to predict the next dredged volume as a linear function of the total cumulative flow in the reach since the last time the channel was dredged (Model 1). Model 2 is a multi-variate function which disaggregates that cumulative flow since the last dredging into in-channel flow and high flow. Models 3 and 4 mirror the variables tested in 1 and 2 but are nonlinear. Models 5–8 mirror the first four but incorporate the cumulative flow before the prior dredging event in an attempt to capture hysteresis in the sediment transport system.

Table 3. Equations of tested multi-level models.

Model	Equation
Linear models using the cumulative flow since the prior dredging event:	
1	$Vol_d = k + aQ_{tot}$
2	$Vol_d = k + aQ_{base} + bQ_i$
Exponential models using the cumulative since the prior dredging event:	
3	$Vol_d = k({Q_{tot}}^{a})$
4	$Vol_d = k({Q_{base}}^{a})({Q_i}^{b})$
Linear models using the cumulative flow since the prior dredging event and the cumulative flow before the prior dredging event:	
5	$Vol_d = k + aQ_{tot} + bQ_{tot-1}$
6	$Vol_d = k + aQ_{base} + bQ_i + cQ_{base-1} + dQ_{i-1}$
Exponential models using the cumulative flow since the prior dredging event and the cumulative flow before the prior dredging event:	
7	$Vol_d = k({Q_{tot}}^{a})({Q_{tot-1}}^{b})$
8	$Vol_d = k({Q_{base}}^{a})({Q_i}^{b})({Q_{base-1}}^{c})({Q_{i-1}}^{d})$

Matched pairs of cumulative streamflow volume and subsequent dredged material volume were plotted and fitted with linear lines of best fit (Model 1), including the regression equations and R squared values. A 5% confidence interval was selected to evaluate model significance. The plotted results for all analyzed reaches are presented in the Results section of this report.

4 Results

4.1 Analysis overview

Coefficients of determination (R-squared) values for many of the reaches across some of the tested models were sufficiently high to indicate that the incorporation of precipitation-driven inland hydrology into forecasts of future dredging load requirements can prove useful. The regression models performed best in channelized reaches upstream of coastal outlets, and found little to no relationships in reaches connected to coasts and bays where coastal sedimentation processes likely dominate over sediment delivered by the upstream watershed. These results strengthen the case for limiting application of these watershed hydrology based regression models to upper portions of coastal navigation channels where influences from coastal processes can be expected to be minimal. Results by model type and study area are presented in this section.

4.2 Single-variate linear model results

In the reaches with the best performance, Model 1 captured up to 63% of the variance in dredging amounts in the Sabine-Neches Waterway and up to 93% of the variance in dredging amounts in the Houston Ship Channel using total cumulative flow since the prior dredging event as the predictive variable. For reaches closer to the bays or coasts, this fell to 0% in Sabine-Neches and 11% in the Houston Ship Channel, with low confidence in the estimate.

Table 4 shows goodness of fit results (R-squared and p-value) for the single-variable linear regression model comparing dredged volumes to cumulative streamflow prior to each dredged event for nine stream reaches in the Sabine-Neches Waterway and five stream reaches in the Houston Ship Channel. R-squared is a measure of how close the observed data values are to the fitted regression line of the model; an R-squared value of 1.0 indicates a perfect fit of data to the model. An R-squared value close to 0.0 indicates that the variables used in the regression model do not explain the variance in the data. The p-value is the probability of the observed data occurring if the proposed regression model is not valid. A low p-value (for example, less than 0.05) indicates high confidence in the validity of the proposed model.

Table 4. Summary of single variable linear regression Model 1 fit.

Study Area	Stream ID	R-squared Value	P-value
Sabine-Neches	1112455	0.38	0.03
	1115825	0.30	0.10
	1477515	0.04	0.50
	1477595	0.16	0.10
	1477713	0.48	0.04
	1477589	0.16	0.10
	1477725	0.63	0.01
	1481563	0.20	0.02
	24719331	0.00	0.89
Houston Ship Channel	1440485	0.12	0.36
	1440511	0.32	0.15
	1440521	0.11	0.52
	1440525	0.93	0.00
	1440539	0.33	0.08

4.2.1 Single variate linear model results – Sabine-Neches Waterway

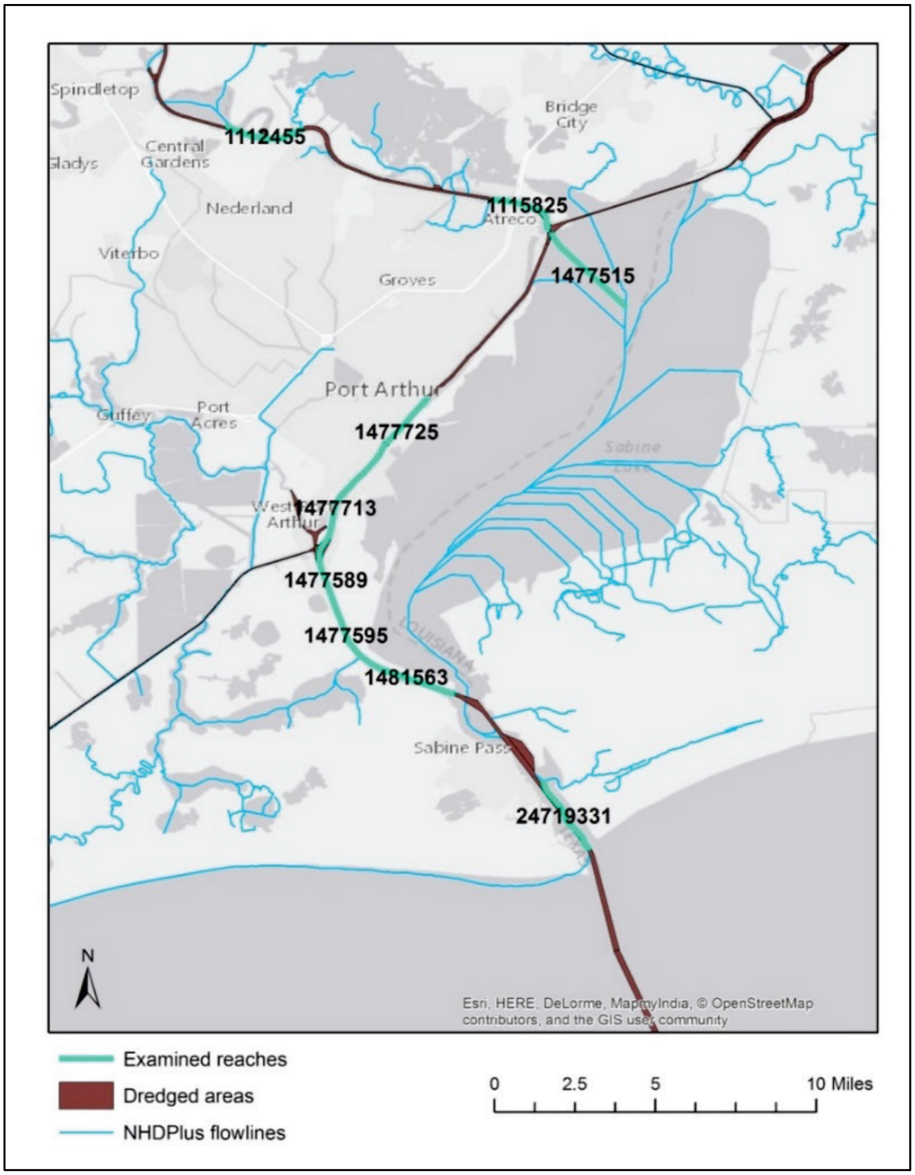
For the Sabine-Neches study area, reaches upstream, along the canal, and close to the outlet (Figure 7) were selected. Stream reaches are highlighted in light blue with the corresponding COMID displayed along the stream reach. Streams were filtered for analysis to include only those with more than five dredging event records from 1980 to 2014.

Linear relationships were found in inland, upstream stream reaches, such as the most upstream COMID 1112455 (R-squared of 0.38 with a p-value of 0.03), and in channelized reaches, such as COMID 1477725 (R-squared of 0.63 with a p-value of 0.01). No linear relationships were found in stream reaches that directly connected to bay and coastal outlets, including 1477515 (R-squared of 0.04 with a p-value of 0.50) and 247719331 (R-squared of 0.00 with a p-value of 0.89). COMID 1477515 is actually in Sabine Lake — the NHDPlus Streamlines dataset automatically represents lake bodies as series of streamlines. Although dredging occurs in this location, the dredged volumes are not well correlated with the associated streamline cumulative flow. This demonstrates the failure of the

SPT to accurately represent flows in areas like lakes, and the pitfall of using this association in an area like Sabine Lake.

Unsurprisingly, streamflow and dredged volumes were not correlated at the coastal outlet, at COMID 24719331. Sedimentation here is predominantly governed by coastal effects, not by upstream streamflow. It is not recommended to use this approach to predict dredging needs at coastal outlets.

Figure 7. Examined COMIDs and dredged channel areas in the Sabine-Neches Waterway.



Time series of the cumulative flow volumes and subsequent dredged amounts and the linear regression model results are reported on the following pages for each reach. Shown are the results for the nine analyzed COMIDs, from the most upstream (Figure 8) through the middle of the channel (Figure 9) to the most downstream near the coastal outlet (Figure 10). Note that the dredged amounts used for COMIDs 1477589 and 1477595 are the same as the location indicators in the dredging records were not specific enough to delineate between these reaches.

Regression coefficients, intercepts, and variable p-values are presented by reach in Appendix B.

Figure 8. Model 1 results for COMIDs 1112455, 1115825, and 1477515 in the Sabine-Neches Waterway.

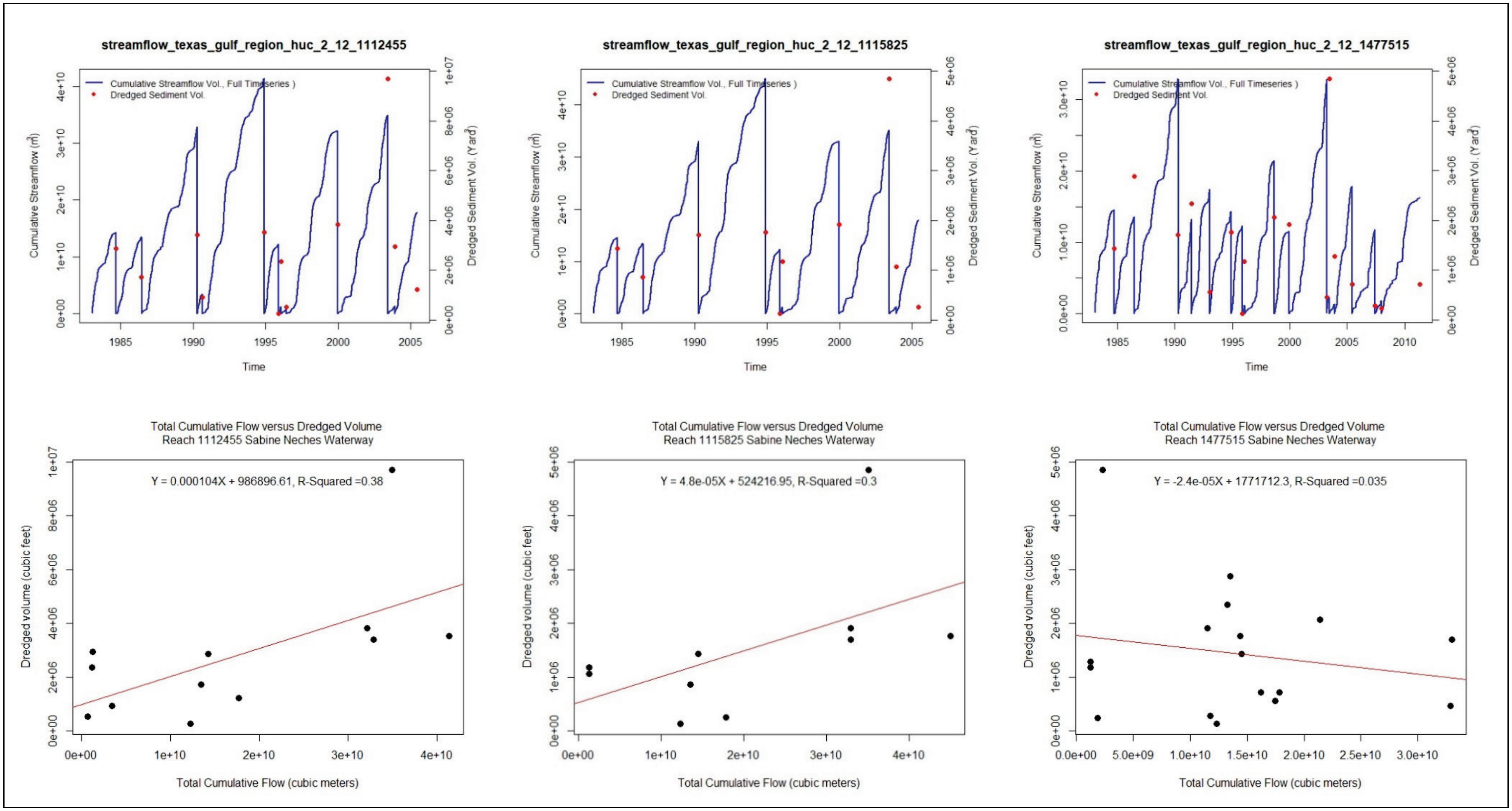


Figure 9. Results for COMIDs 1477725, 1477713, and 1477589 in the Sabine-Neches Waterway.

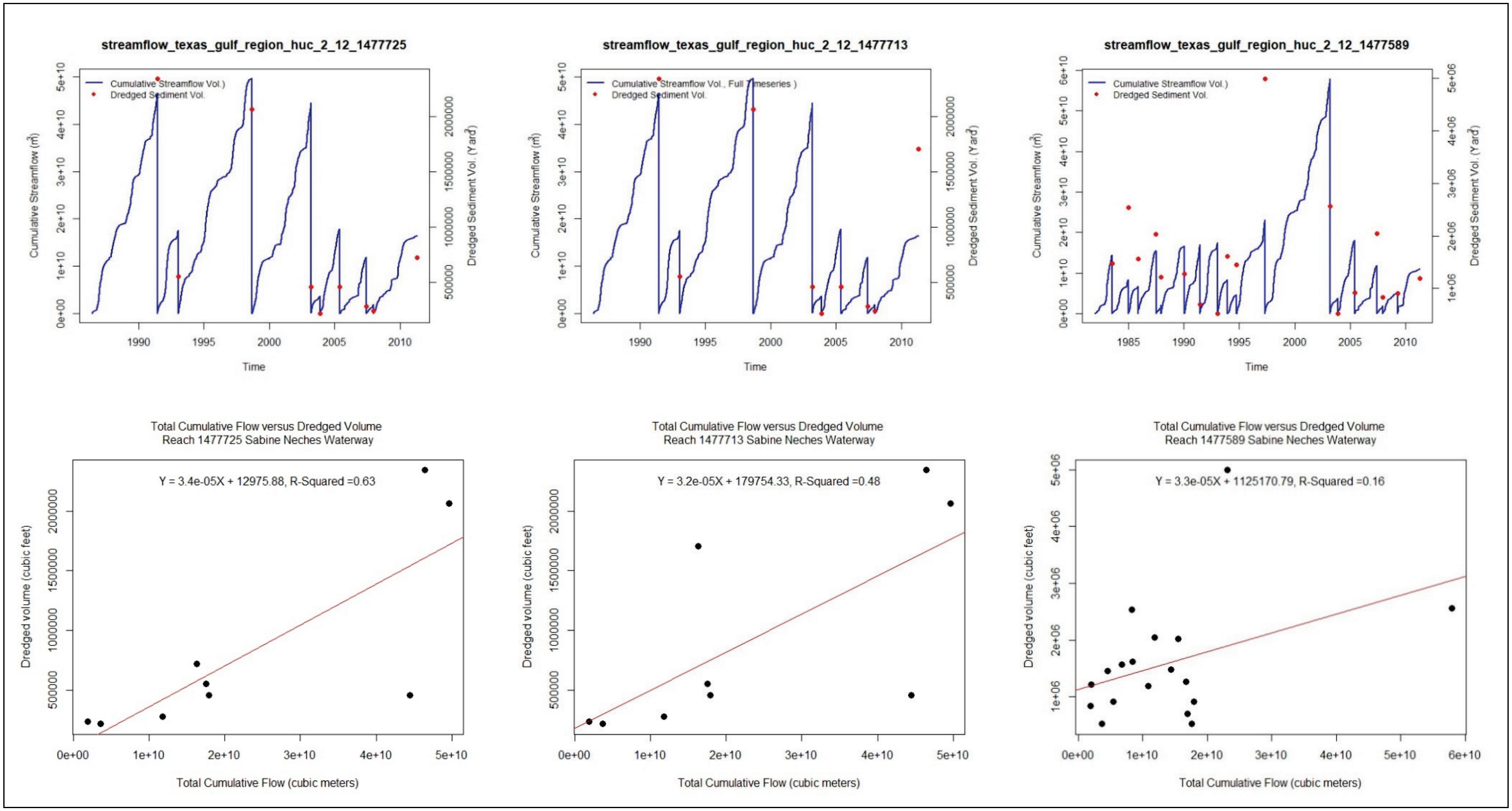
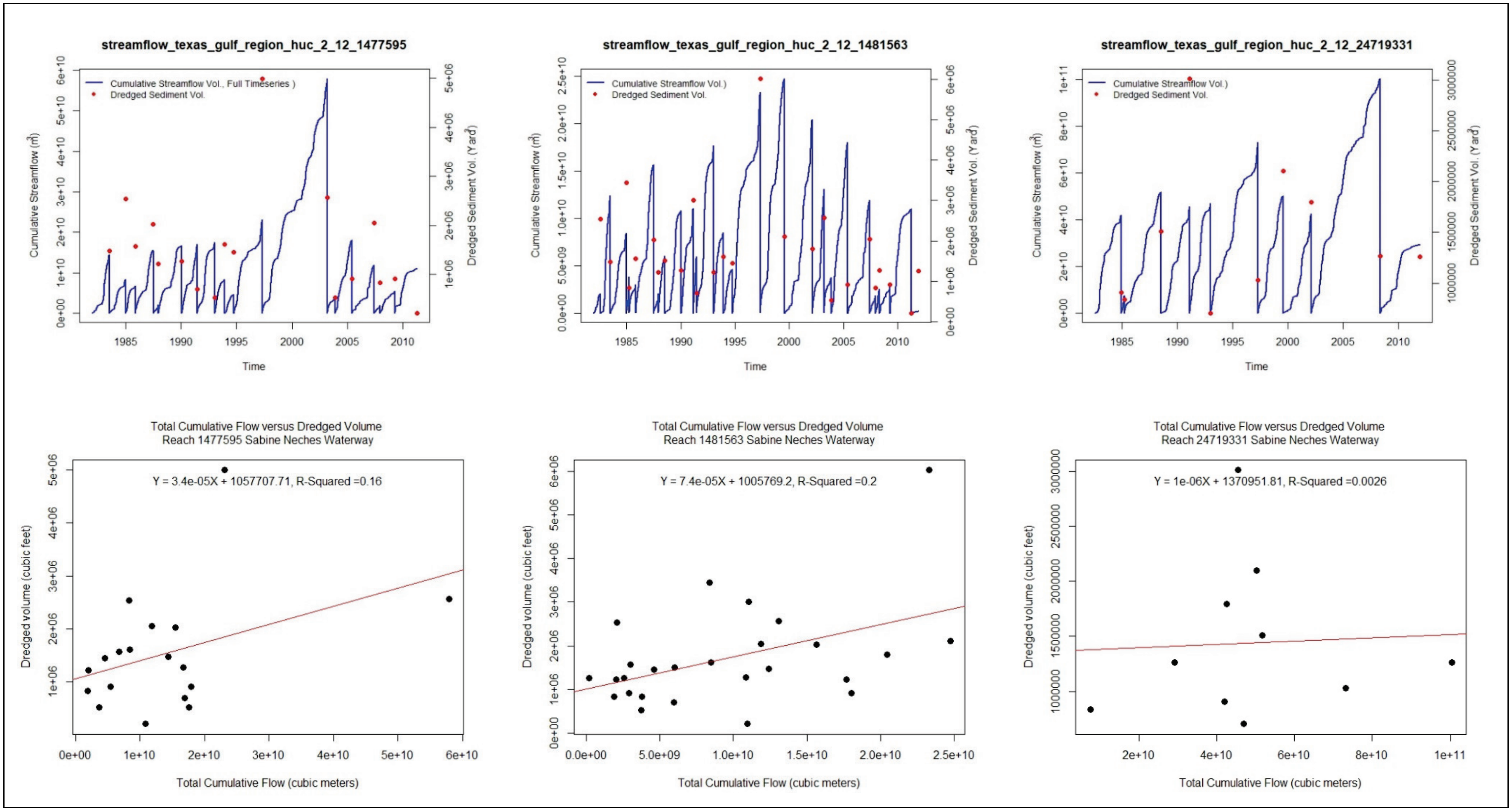


Figure 10. Results for COMIDs 1477595, 1481563, and 24719331 in the Sabine-Neches Waterway.



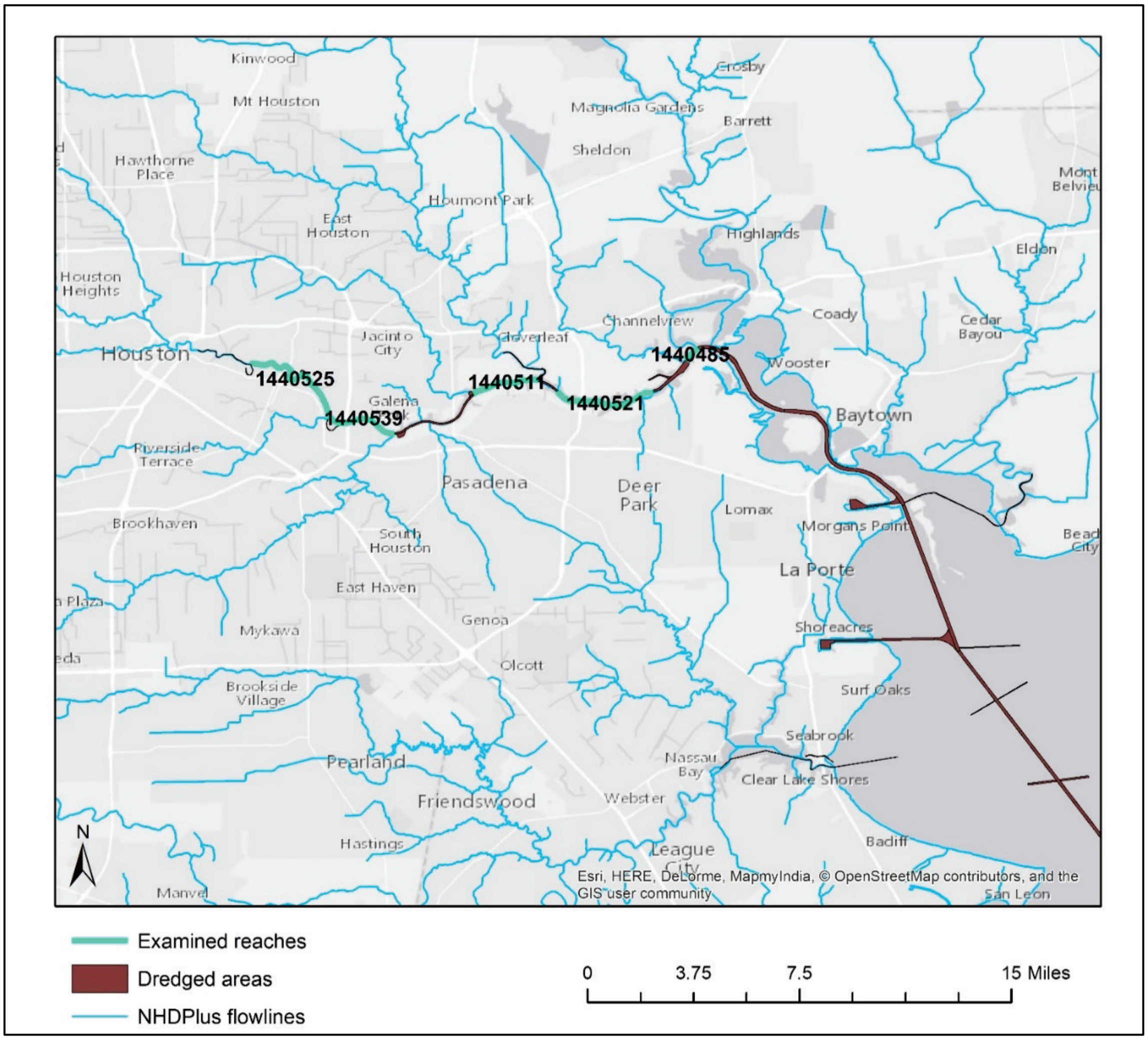
4.2.2 Single variate linear model results — Houston Ship Channel

Five stream reaches along the Houston Ship Channel were selected for analysis because they spatially matched dredging project areas and had at least five dredging records available for the period of analysis (shown in the map in Figure 11). These stream reaches ranged from well upstream of the bay system (COMID 1440525) to the outlet from the ship channel to the bay (COMID 1440485). In the upstream reaches, cumulative flow volume was a more skilled predictor of dredged volumes than in the downstream reaches.

The linear relationship between cumulative flow volume and dredged sediment volume was found to be strongest in the most upstream reach, COMID 1440525, with an R-squared of 0.93 and a p-value of 0.00 indicating an almost perfect correlation and very high confidence in the model. The correlation had a strong positive trend between precipitation-driven flow and dredged volumes. This is the most upstream reach in the system for which dredging records were available.

The correlation for this single-variate linear model was weaker for the remaining reaches, with the next two downstream reaches (COMIDs 1440539 1440511) demonstrating R-squared values of 0.33 and 0.32 and p-values outside the selected 5% confidence level (0.08 and 0.15) and the two farthest downstream reaches, COMIDs 1440521 and 0440485 demonstrating R-squared values of 0.11 and 0.12. This mirrors the trend found for the Sabine-Neches system in which the dredging load requirements in the upstream reaches can be more accurately predicted using precipitation-driven riverine hydrology. This indicates that other factors than precipitation-driven sediment transport affected dredging volumes here.

Figure 11. Examined COMIDs and dredged channel areas in the Houston Ship Channel.



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Individual reach results are reported on the following pages. The cumulative streamflow and dredged volume time series and the linear regression model results for the five analyzed COMIDs are shown, from the most upstream (Figure 12) to the most downstream near the coastal outlet (Figure 13). Regression coefficients, intercepts, and variable p-values are presented by reach in Appendix B.

Figure 12. Results for COMIDs 1440525, 1440539, and 1440511 in the Houston Ship Channel.

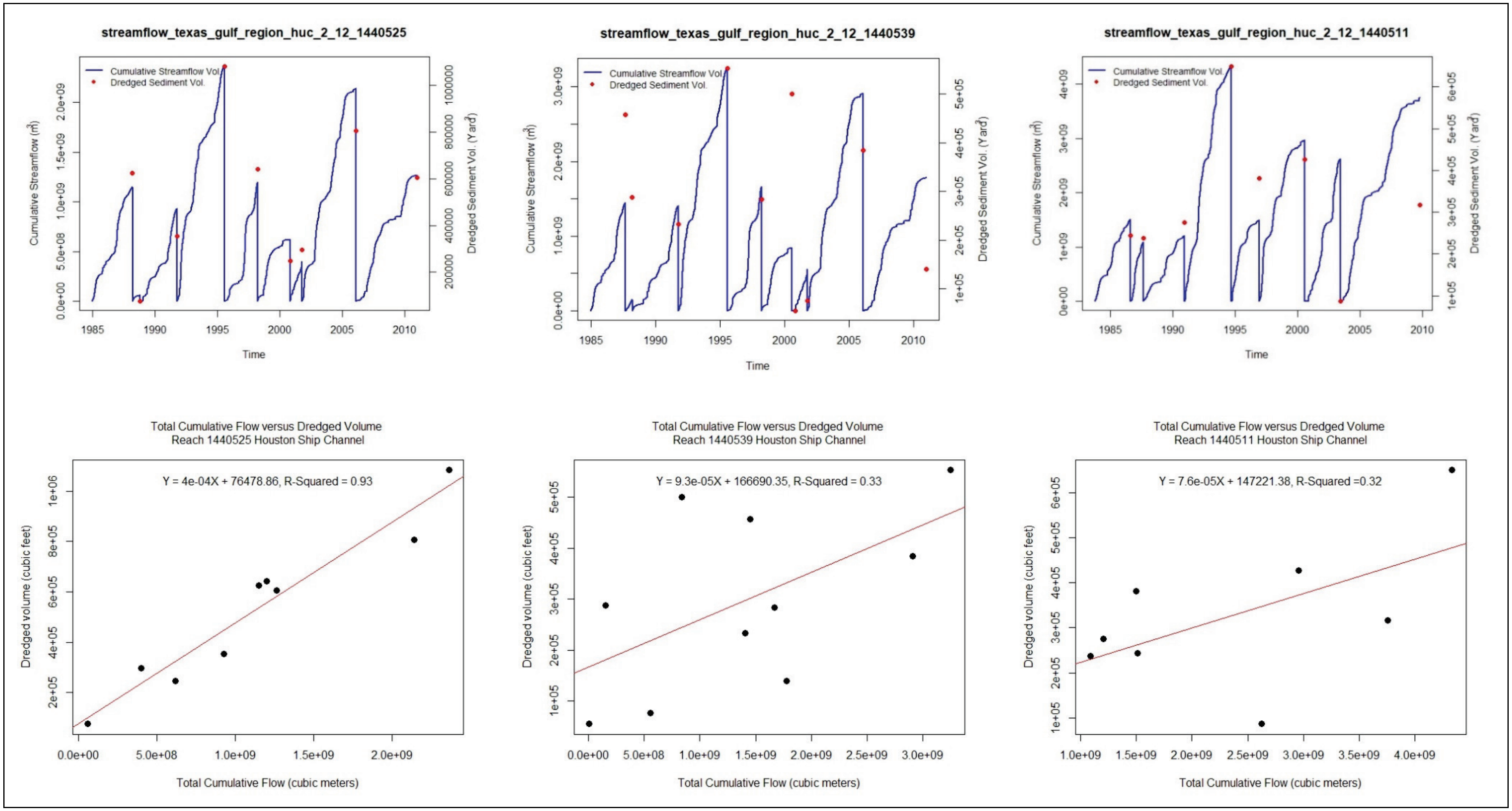
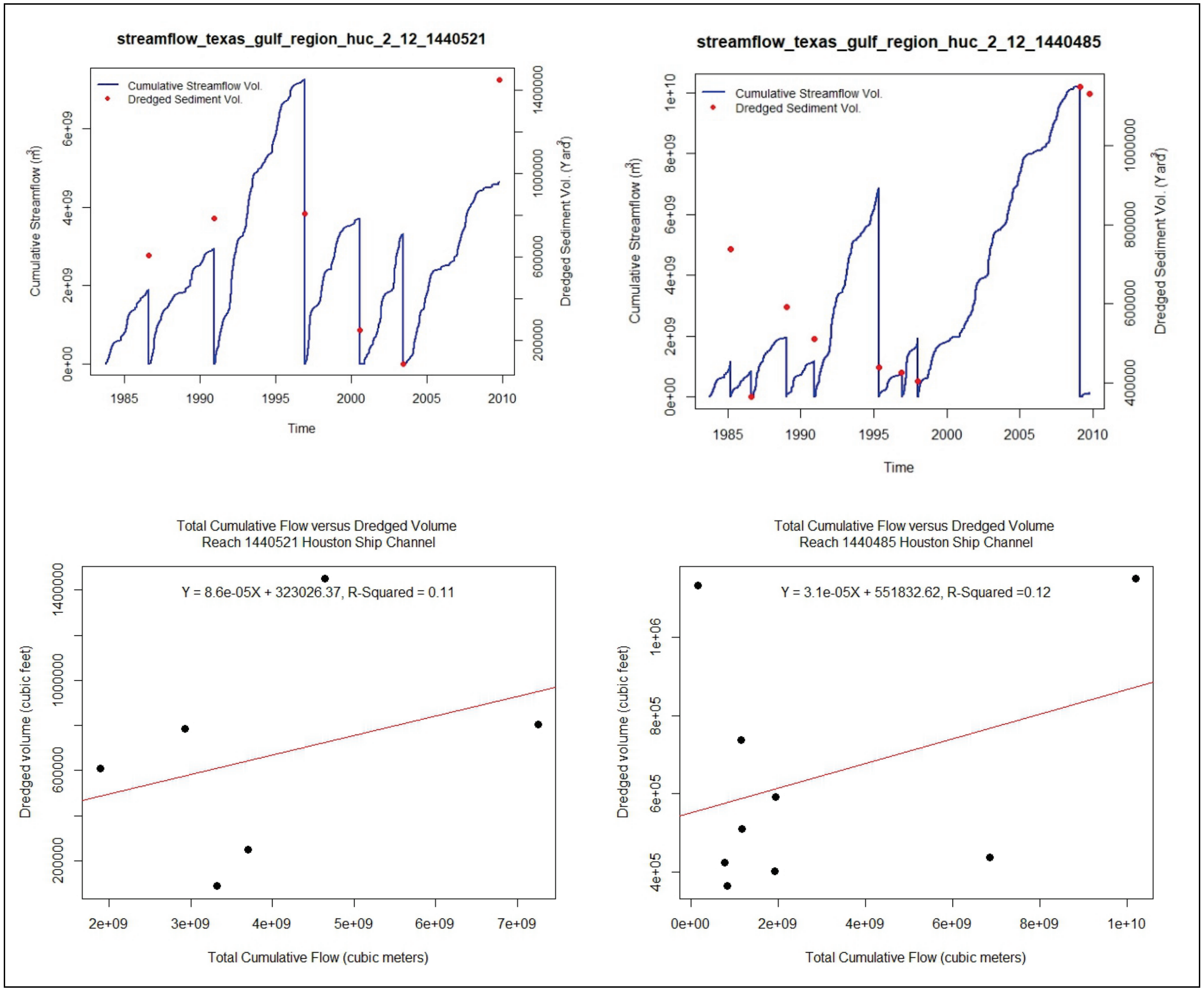


Figure 13. Results for COMIDs 1440521 and 1440485 in the Houston Ship Channel.



4.3 Nonlinear and multivariate model analyses

Seven additional models were applied to the dredging and streamflow datasets for reaches in Sabine-Neches Waterway and the Houston Ship Channel systems, as outlined in Table 3 in the Methodology section. Several of these models disaggregated the cumulative flow into in-channel flows (below the 1.5-year flow rate) and high flows (above the 1.5-year flow rate) (Models 2, 4, 6, and 8); applied non-linear frameworks (Models 3, 4, 7, and 8); and incorporated prior event flow volumes to account for system lag (Models 5, 6, 7, and 8).

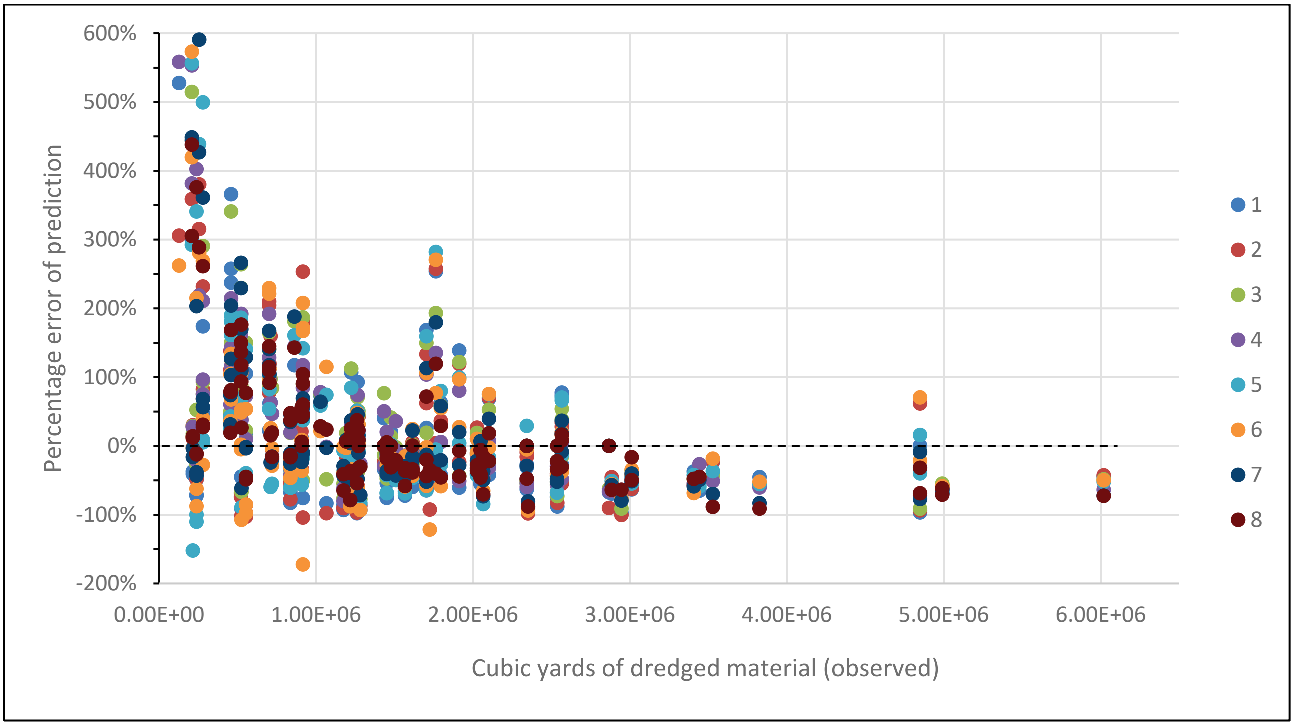
Model performance varied widely across model, harbor system, and river-reach COMID. For most of the tests, the percentage error in the predicted volumes was within one order of magnitude of the actual dredged volume from the record. Figure 14 and Figure 16 show the percentage error of prediction by dredging event for each reach and model for the Sabine-Neches and Houston Ship Channel systems, respectively. Errors were predominantly positive — the models tended to over predict dredging loads at lower volumes and under predict loads at higher volumes. The modeled and observed dredged volumes for each event are shown in Figure 15 for the Sabine-Neches and Figure 17 for the Houston Ship Channel.

The model with the highest R-squared values and highest number of reaches for which the model demonstrated significance was Model 2. This model is a simple linear regression equation that predicts dredged sediment volumes as a function of cumulative in-channel flow volumes and high flow volumes since the prior dredging event. It is interesting that in most reaches to which Model 2 was applied, the in-channel flow volume had a positive coefficient and the high flow volume had a negative coefficient, indicating that periods of high flow reduce sediment shoaling. This is possibly due to high flows scouring or flushing sediment from the channel, reducing the need for subsequent dredging. Regression coefficients, intercepts, variable p-values, and model performance metrics for each model are presented by reach in Appendix B.

4.3.1 Nonlinear and multivariate model results — Sabine-Neches Waterway

Figure 14 shows the percentage error of prediction for the eight tested models for 129 dredging events in the Sabine-Neches harbor system during the study period of record. Half of the model estimates were within a 40% error band of the actual magnitude of sediment dredged, and 26% of the estimates were within 20% of the magnitude. Model estimates were more accurate for events with higher volumes of dredged sediment, with error magnitude dropping significantly for dredging events above 3 million cy of sediment.

Figure 14. Percentage error of predictions by model, Sabine-Neches Waterway.



Among the eight models tested, model performance was highest for Model 2 and Model 8, which both captured 32% of the events within a 20% error band of the sediment magnitudes. Model 2 is a model of linear fit using cumulative in-channel flow and high flow input variables, and Model 8 is a nonlinear model of fit using in-channel and high flows and flows before the prior dredging event (equations presented in Table 3). For most of these reaches, there were a low number of dredging events in the history, so Model 8 is likely overfit.

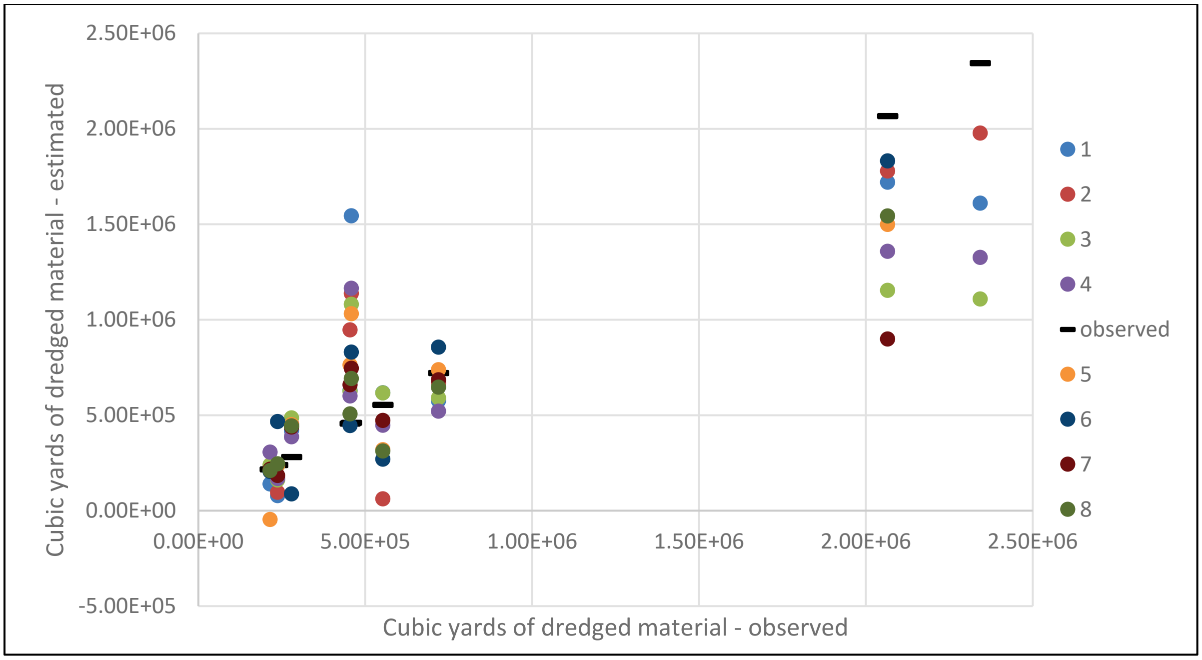
Table 5 summarizes model results by COMID for the Sabine-Neches system with best model performance. Across these, the models with higher R-squared values, indicating stronger model fit, and p-values below the significance threshold of 0.05 (shown in bold), were Models 1, 2, 3, and 4. Models 5–8, which incorporate the cumulative flows prior to the last dredging event as a predictive variable for the next dredged volume, had higher p-values indicating low confidence in the model. This may be due to model overfit. Among the first four models, Model 2 performed the strongest across these four reaches, with R-squared values indicating that the model captured 66%–77% of the variance in the dredged amounts and p-values indicating high confidence. Model 2 is a linear regression model that uses cumulative in-channel flows (defined here as below the 1.5-year flow) and high flows (above the 1.5-year flow) as separate input variables.

Table 5. R-squared and p-value by model for selected reaches, Sabine-Neches Waterway.

COMID Model	1477725		1477713		1115825		1112455	
	R^2	*p-val*	*R^2*	*p-val*	*R^2*	*p-val*	*R^2*	*p-val*
1	0.63	**0.01**	0.48	**0.04**	0.30	0.10	0.38	**0.03**
2	0.77	**0.01**	0.66	**0.04**	0.72	**0.01**	0.68	**0.01**
3	0.62	**0.01**	0.54	**0.02**	0.04	0.56	0.18	0.17
4	0.68	**0.03**	0.57	0.08	0.07	0.76	0.18	0.41
5	0.65	0.07	0.58	0.12	0.33	0.30	0.48	0.08
6	0.85	0.13	0.79	0.22	0.87	**0.05**	0.72	0.07
7	0.64	0.08	0.65	0.07	0.06	0.83	0.18	0.46
8	0.78	0.22	0.74	0.27	0.36	0.71	0.17	0.86

Figure 15 below shows the estimated versus observed volumes of dredged material for each dredging event and model for one reach in the Sabine-Neches system. This reach, COMID 1477725, had the highest model performance across the nine reaches examined in the Sabine-Neches. This figure shows the spread of estimate accuracy by model across the seven dredging events in the 1980–2014 study period.

Figure 15. Estimated versus observed volumes of dredged material for Reach 1477725 in the Sabine-Neches Waterway.



4.3.2 Nonlinear and multivariate model results — Houston Ship Channel

Figure 16 shows the percentage error of prediction for the eight tested models for 42 dredging events in the Houston Ship Channel harbor system during the study period of record. The figure presents that 74% of the model estimates were within a 40% error band of the actual magnitude of sediment dredged and 49% of the total estimates were within 20% of the observed dredged material magnitude. Model estimates were more accurate for events with higher volumes of dredged sediment, with error magnitude dropping significantly for dredging events above 200,000 cy of sediment. For larger dredged volumes, models tended to under predict the dredged volume.

Figure 16. Percentage error of predictions by model, Houston Ship Channel.

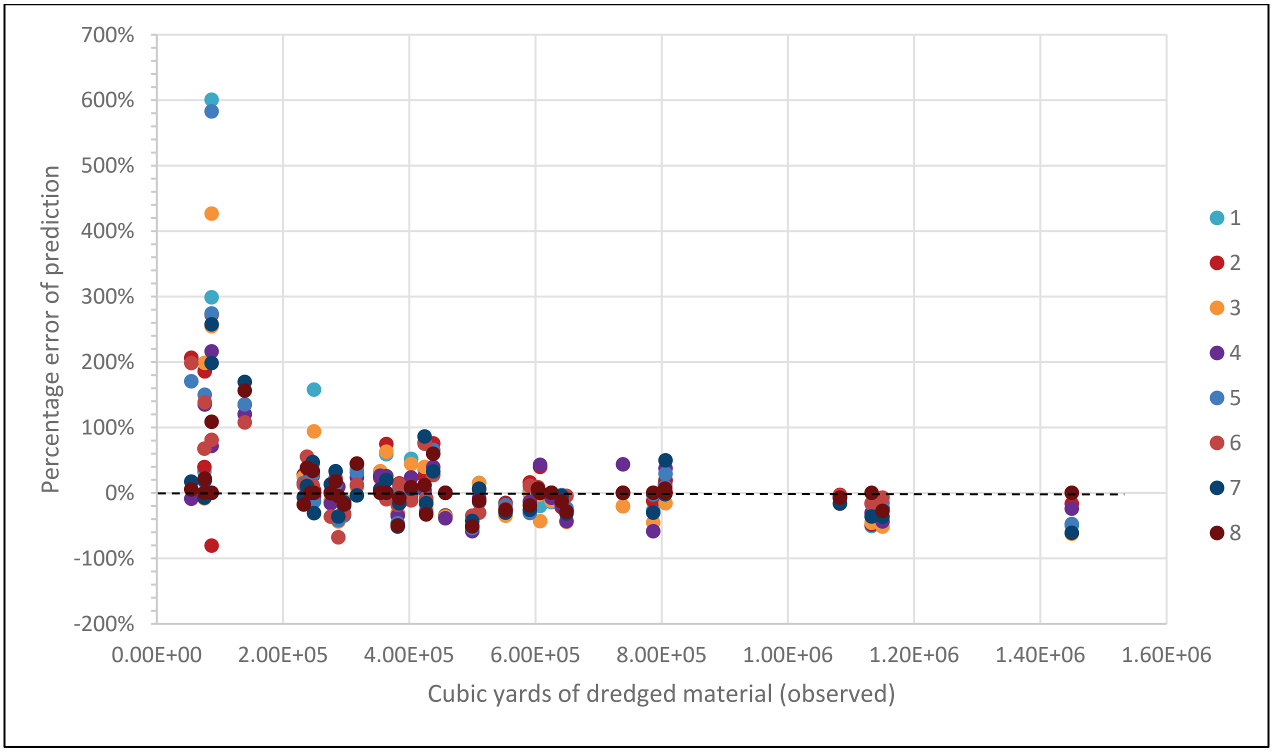


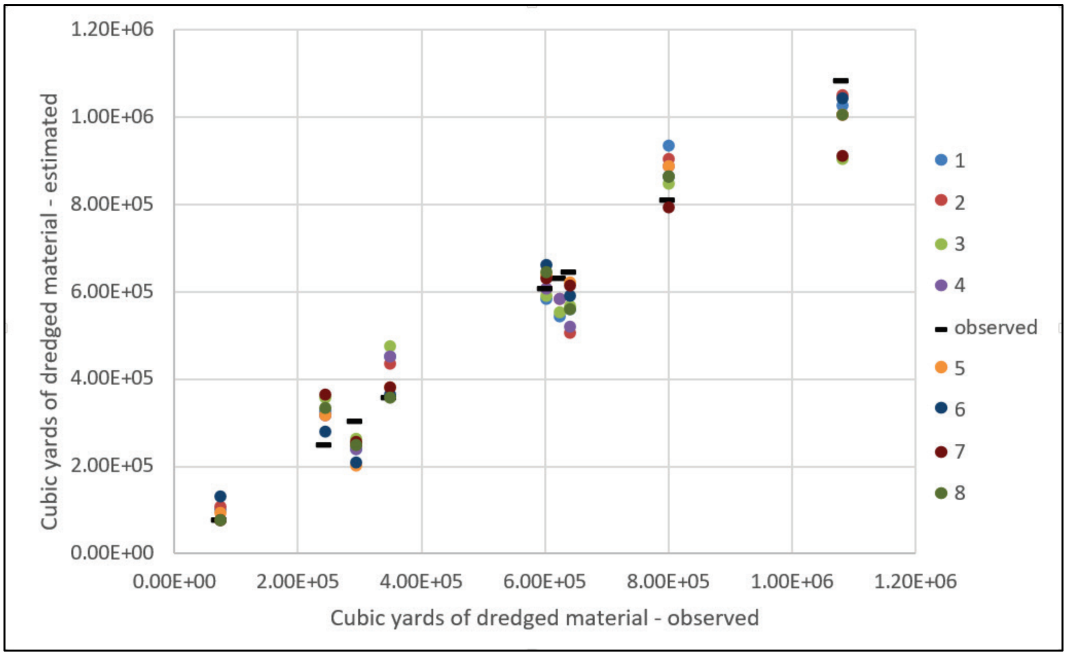
Table 6 shows the R-squared and p-values by model for three of the reaches for which inland precipitation-driven flow demonstrated some skill in predicting dredged sediment loads. Two of these reaches, the most upstream in the system, had high model performance for all eight tested models. This indicates that precipitation-driven flow generally was tightly correlated with dredging load requirements in these reaches. The third reach had much worse performance across most of the models, with the exception of Model 2 (a linear regression using in-channel flow and high flow cumulative volumes as the predictive variables). Model 2 had an R-squared value of 0.87 and a p-value within the 5% significance threshold for this reach.

Table 6. R-squared and p-value by model for selected reaches, Houston Ship Channel.

COMID Model	1440525		1440539		1440521	
	R^2	*p-val*	R^2	*p-val*	R^2	*p-val*
1	0.93	**0.00**	0.33	0.08	0.11	0.52
2	0.94	**0.00**	0.33	0.25	0.87	**0.05**
3	0.94	**0.00**	0.47	**0.03**	0.05	0.67
4	0.96	**0.00**	0.56	0.06	0.73	0.14
5	0.96	**0.00**	0.36	0.26	0.32	0.68
6	0.97	**0.01**	0.66	0.60	NA	NA
7	0.96	**0.00**	0.44	**0.04**	0.42	0.58
8	0.97	**0.01**	0.70	0.22	NA	NA

Figure 17 below shows the estimated versus observed volumes of dredged material for each dredging event and model for one reach in the Houston Ship Channel system. This reach, COMID 1440525, had the highest model performance across the five reaches examined in the Houston Ship Channel. This figure shows the spread of estimate accuracy by model across the nine dredging events in the 1980–2014 study period. For this reach, each model showed a tight correlation between precipitation-driven stream flow and subsequent dredging requirements.

Figure 17. Estimated versus observed volumes of dredged material for Reach 1440525 in the Houston Ship Channel.



5 Conclusion and Future Work

In this study, USACE hindcasted streamflow values with historical dredging records were connected for two federal navigation projects regions in Texas to investigate a causal relationship between inland hydrology and maintenance dredging needs. Results suggest that there is a correlation between higher precipitation-driven streamflows and greater volumes of dredged sediment in these managed channels. The relationship was stronger in river reaches farther upstream from the coastal outlet; near bays, lakes, and the coast there was not a strong correlation between streamflow and dredged loads. The coastal effects in these reaches either dominate sedimentation or are enough of a driver to conceal whatever correlation may exist for inland hydrology.

5.1 Study limitations

The dredging history datasets used made no distinction between maintenance channel dredging and special channel widening or deepening projects, which would not be well-correlated with inland precipitation. Additionally, channel maintenance dredging volumes are tied at least in part to budget availability, which is not captured in these models. Another limitation is the low number of dredging events for any one reach in a system over the 34-year period of reconstituted streamflows. This resulted in model overfit for the regression models with more than two input variables. Since the dredging record datasets are small, it was not possible to reserve data for testing outside of the regression process. This could be addressed in future studies by aggregating like reaches together or applying analysis to regions with more robust dredging records.

5.2 Conclusion from analysis

This approach demonstrates enough skill to be considered as potentially useful in estimating downstream dredging requirements. For the river systems examined, inland riverine flow seems highly correlated with subsequent dredging loads at reaches inland of bays and coasts. Recognizing those limitations, flow volumes can provide additional information about channel maintenance needs without deploying data-intensive, high-fidelity sedimentation models. The best-performing model, Model 2, used as input variables the streamflow volumes disaggregated into those above and below the 1.5-year flow by reach. This is a simple linear model that could easily be applied to any reach for which reconstituted flow data are available.

As streamflow forecasting improves to give longer lead times on flow variability, techniques like this can alert channel managers to the need for upcoming maintenance. The development of regional model equations and additional model validation would improve the approach.

5.3 Future work

This analysis could be extended to different hydrologic regions within the United States, particularly those dominated by inland flows. Accurate spatial information for dredging records is critical for this type of analysis, and it may be challenging to obtain long-term detailed dredge histories for some locations.

There is potential to incorporate reach-level shoaling rates as calculated in the USACE CSAT tool. Connecting the work done for the SPT and CSAT could leverage USACE capabilities to improve the information available to dredging managers and to optimize dredging activities.

Future work includes production of sub-seasonal scale streamflow forecasts in the SPT, which could provide USACE project managers and Operations personnel with a sense of the magnitude and timing of streamflow peaks several months in advance. This capability could enhance the usefulness of the results presented here for estimating near-term dredging requirements based on recent and ongoing inland flow events.

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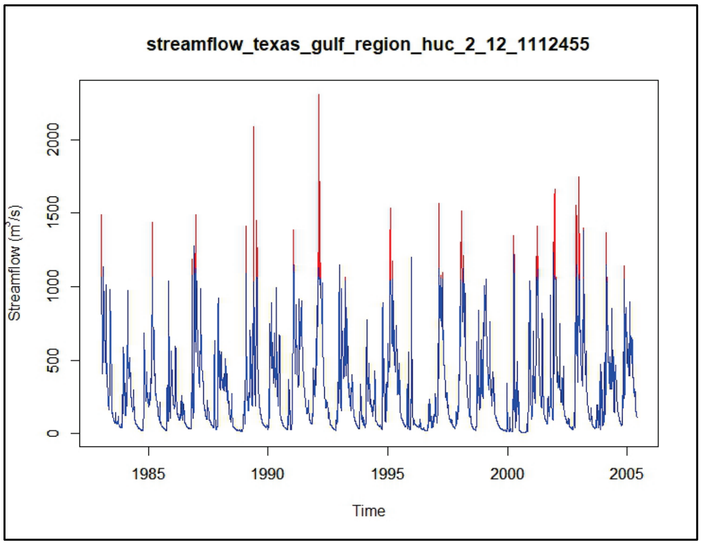
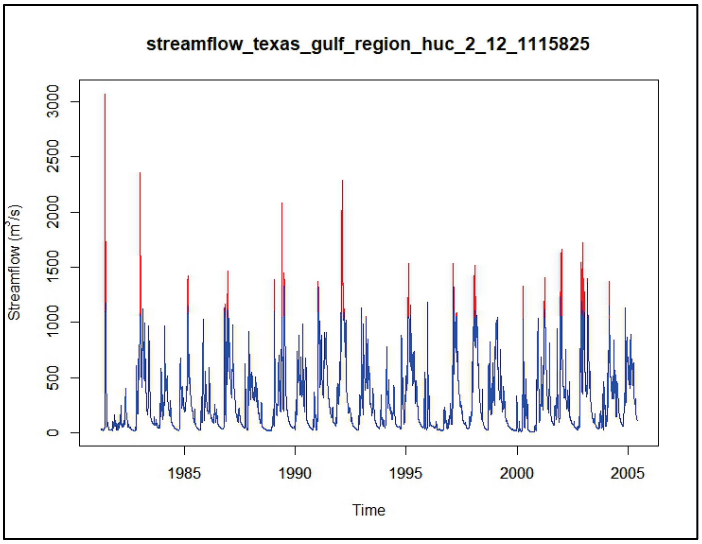
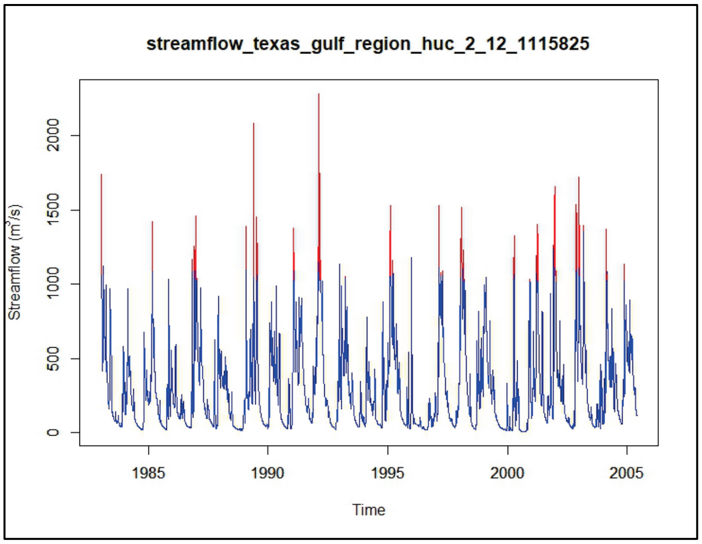
Appendix A: Hydrographs for Analyzed Streams

Hydrographs for the included reaches were produced in the course of this analysis. These hydrographs are disaggregated into the base, in-channel flow (below the 1.5-year flow in this study, shown in blue), and higher flows (above 1.5-year flow, shown in red). Hydrographs run from 1980 to the year of the last dredging event in the record used for each stream reach. In the following figures, the hydrographs are presented by harbor system.

Sabine-Neches Waterway



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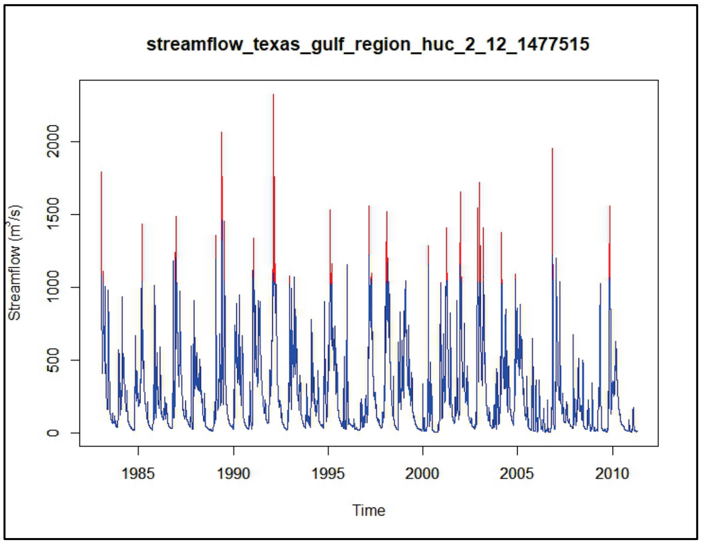
500
1000
1500
2000
1985
1990
1995
2000
2005
Time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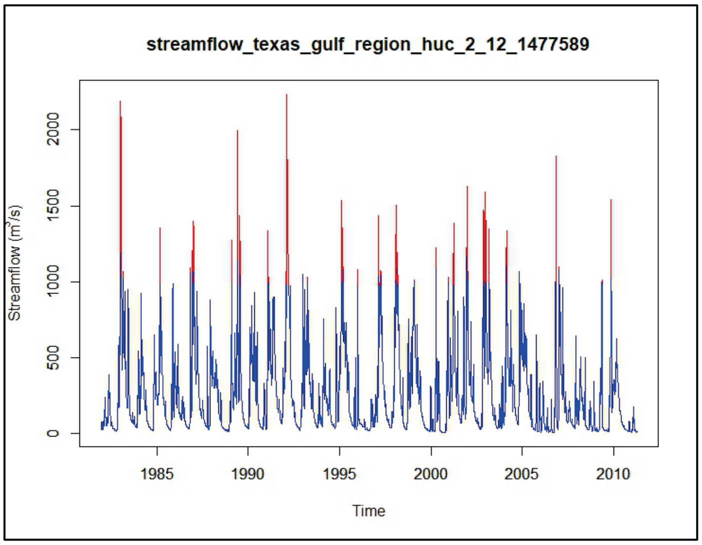
Time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Streamflow (m^3/s)
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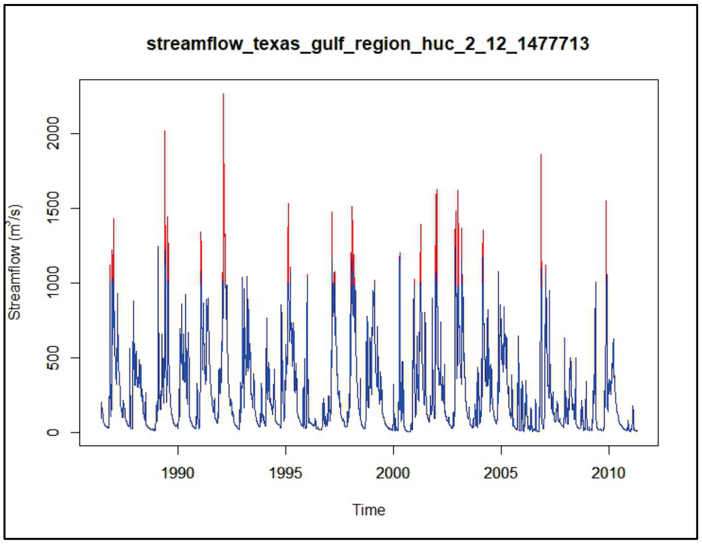
Time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Streamflow (m^3/s)
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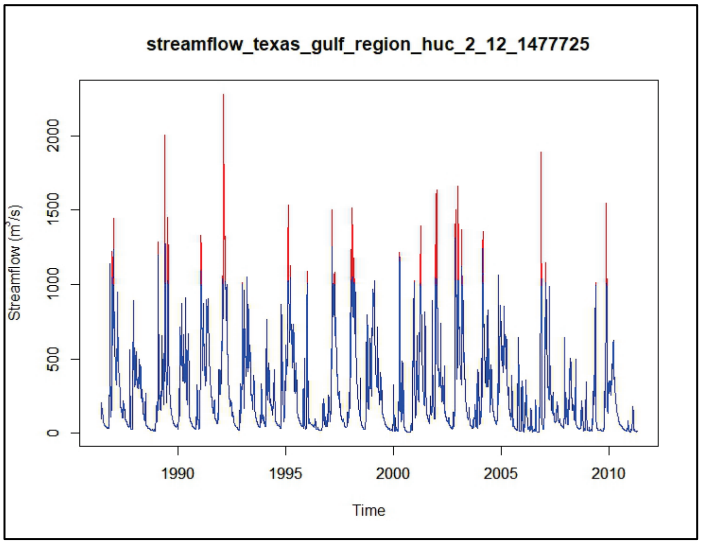
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Streamflow (m^3/s)
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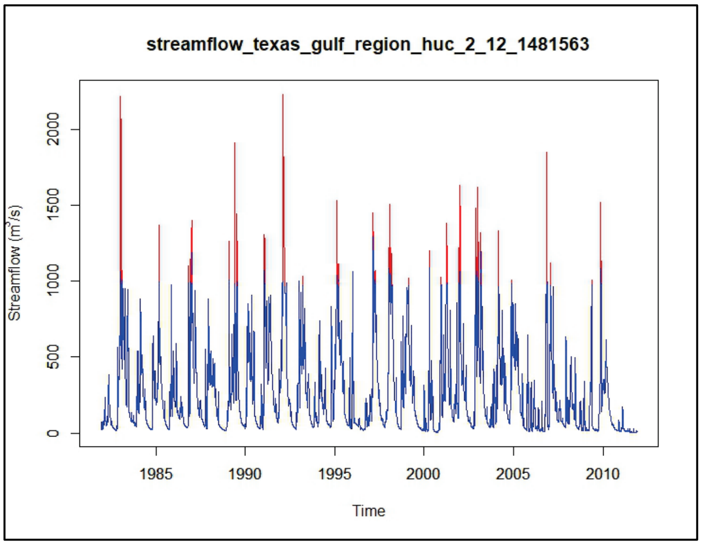
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Streamflow (m^3/s)
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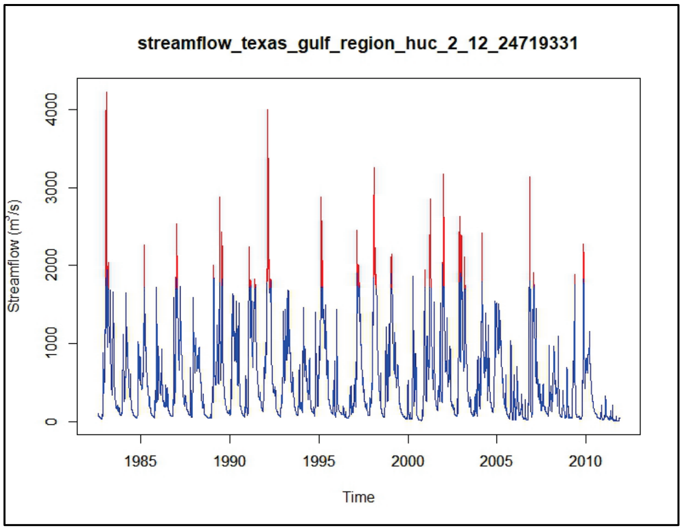
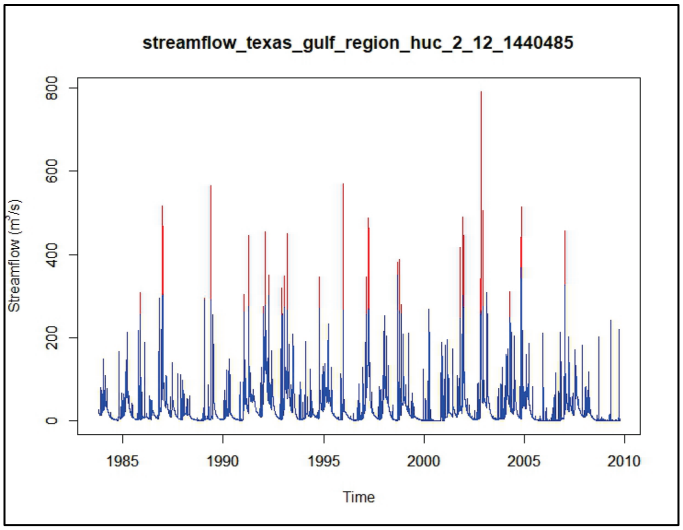
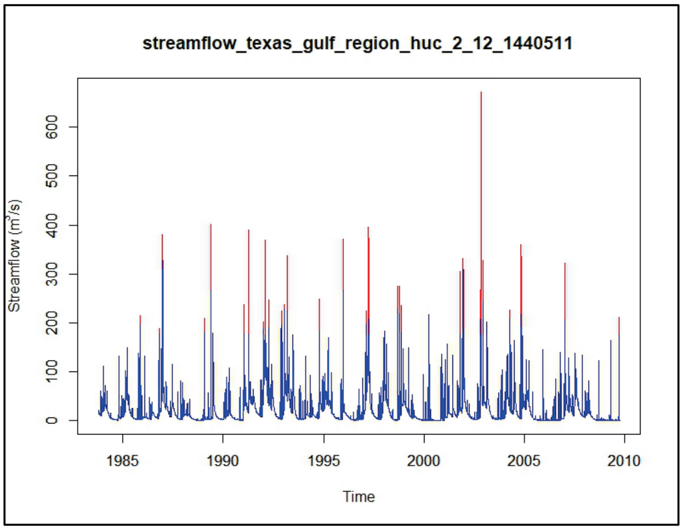
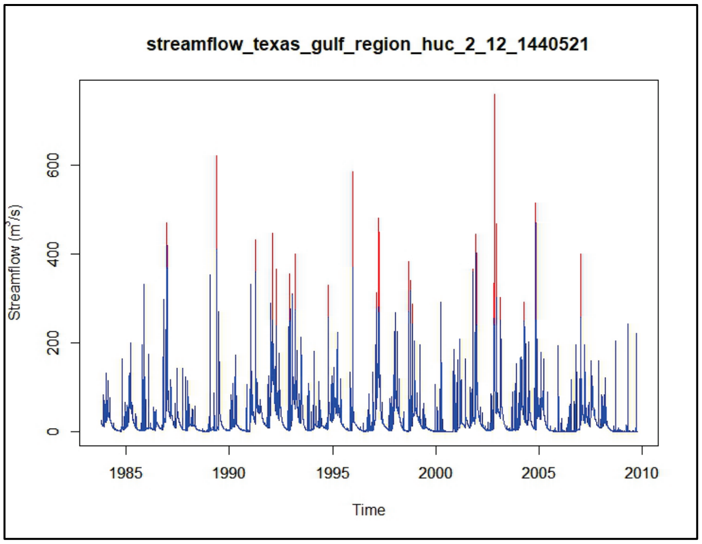
500
1000
1500
2000
1985
1990
1995
2000
2005
2010
Time

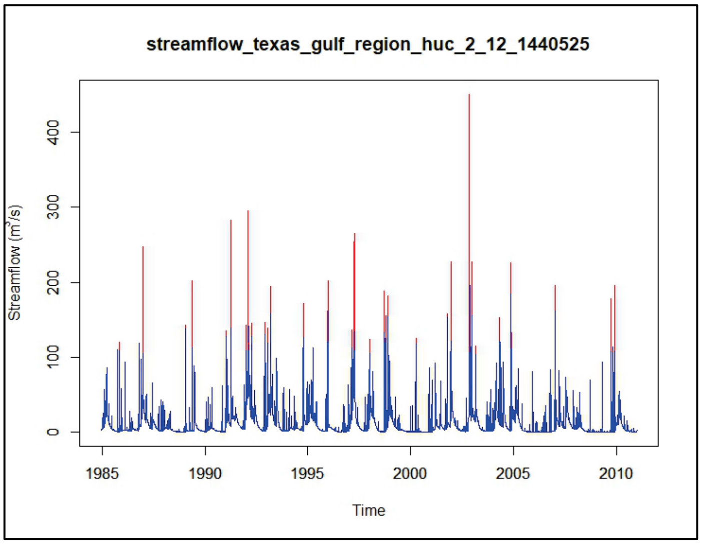


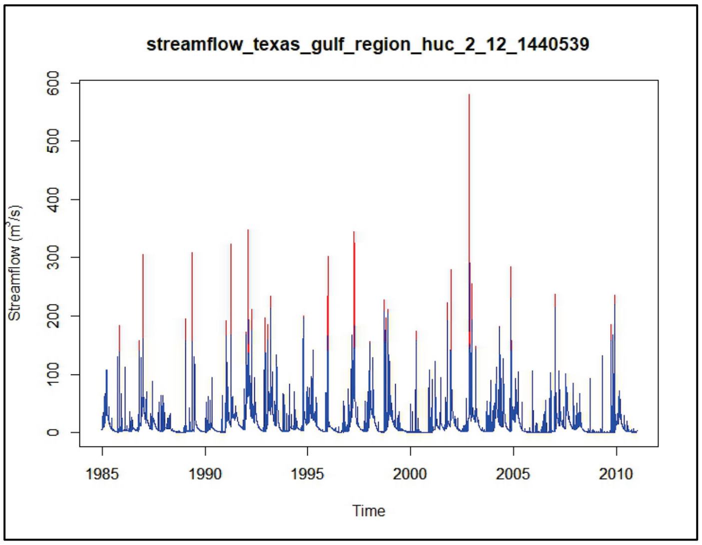
Houston Ship Channel






streamflow_texas_gulf_region_huc_2_12_1440521
Streamflow (m³/s)
0
200
400
600
1985
1990
1995
2000
2005
2010
Time


streamflow_texas_gulf_region_huc_2_12_1440525
Streamflow (m³/s)
0
100
200
300
400
1985
1990
1995
2000
2005
2010
Time


streamflow_texas_gulf_region_huc_2_12_1440539
Streamflow (m³/s)
0
100
200
300
400
500
600
1985
1990
1995
2000
2005
2010
Time

Appendix B: Regression Model Results

The following tables in this appendix present the regression analysis results for all 8 models and 14 stream reaches described in this report. Intercepts, coefficient values, p-values for individual variables, and the R-squared and p-values for each model and reach are tabled.

Model 1. Linear, using cumulative total flow since prior dredging event

$$Vol_d = k + aQ_{tot}$$

	Sabine-Neches Waterway								
COMID	**1481563**	**1112455**	**1115825**	**1477515**	**1477589**	**1477595**	**1477713**	**1477725**	**24719331**
k	1.01E+06	9.87E+05	5.24E+05	1.77E+06	1.13E+06	1.06E+06	1.80E+05	1.30E+04	1.37E+06
a	7.40E-05	1.04E-04	4.79E-05	-2.37E-05	3.32E-05	3.42E-05	3.19E-05	3.44E-05	1.45E-06
p-value, *k*	8.43E-03	3.17E-01	4.45E-01	4.63E-03	5.15E-03	1.02E-02	6.40E-01	9.66E-01	3.67E-02
p-value, *a*	2.06E-02	3.33E-02	1.03E-01	4.70E-01	9.84E-02	1.04E-01	3.90E-02	1.09E-02	8.89E-01
adjusted R-squared	1.71E-01	3.16E-01	2.10E-01	-2.89E-02	1.09E-01	1.04E-01	4.04E-01	5.74E-01	-1.22E-01
multiple R-squared	2.04E-01	3.78E-01	2.98E-01	3.54E-02	1.61E-01	1.57E-01	4.78E-01	6.27E-01	2.58E-03
p-value, model	2.06E-02	3.33E-02	1.03E-01	4.70E-01	9.84E-02	1.04E-01	3.90E-02	1.09E-02	8.89E-01
	Houston Ship Channel								
COMID	**1440485**	**1440511**	**1440521**	**1440525**	**1440539**				
k	5.52E+05	1.47E+05	3.23E+05	7.65E+04	1.67E+05				
a	3.14E-05	7.61E-05	8.63E-05	4.00E-04	9.29E-05				
p-value, *k*	4.70E-03	2.61E-01	5.74E-01	2.06E-01	7.60E-02				
p-value, *a*	3.56E-01	1.42E-01	5.21E-01	2.65E-05	8.43E-02				
adjusted R-squared	-3.21E-03	2.09E-01	-1.13E-01	9.21E-01	2.43E-01				
multiple R-squared	1.22E-01	3.22E-01	1.10E-01	9.30E-01	3.27E-01				
p-value, model	3.56E-01	1.42E-01	5.21E-01	2.65E-05	8.43E-02				

Model 2. Linear, using cumulative base and high flows since prior dredging event

$$Vol_d = k + aQ_{base} + bQ_i$$

	Sabine-Neches Waterway								
COMID	**1481563**	**1112455**	**1115825**	**1477515**	**1477589**	**1477595**	**1477713**	**1477725**	**24719331**
k	8.98E+05	1.68E+06	9.67E+05	1.56E+06	8.32E+05	7.01E+05	1.14E+05	-2.86E+04	1.30E+06
a	1.11E-04	-8.30E-05	-6.10E-05	2.42E-05	9.19E-05	1.05E-04	7.23E-05	6.62E-05	-1.54E-06
b	-5.40E-05	1.10E-03	5.99E-04	-2.33E-04	-1.49E-04	-1.81E-04	-1.69E-04	-1.33E-04	2.02E-05
p-value, *k*	2.75E-02	5.18E-02	7.33E-02	1.37E-02	8.65E-02	1.63E-01	7.34E-01	9.13E-01	7.12E-02
p-value, *a*	6.73E-02	2.79E-01	1.49E-01	6.42E-01	1.55E-01	1.30E-01	2.66E-02	1.25E-02	9.15E-01
p-value, *b*	7.58E-01	1.10E-02	9.51E-03	2.11E-01	4.26E-01	3.58E-01	1.79E-01	1.84E-01	7.31E-01
adjusted R-squared	1.55E-01	6.07E-01	6.43E-01	-3.76E-05	1.10E-01	1.20E-01	5.52E-01	6.90E-01	-2.62E-01
multiple R-squared	2.23E-01	6.78E-01	7.22E-01	1.25E-01	2.14E-01	2.23E-01	6.64E-01	7.67E-01	1.86E-02
p-value, model	5.51E-02	6.07E-03	1.13E-02	3.93E-01	1.64E-01	1.50E-01	3.80E-02	1.26E-02	9.36E-01
	Houston Ship Channel								
COMID	**1440485**	**1440511**	**1440521**	**1440525**	**1440539**				
k	5.61E+05	1.45E+05	3.64E+05	7.69E+04	1.67E+05				
a	1.51E-04	9.03E-05	2.84E-04	4.85E-04	8.55E-05				
b	-9.09E-04	-1.32E-05	-1.53E-03	-9.07E-05	1.33E-04				
p-value, *k*	6.35E-03	3.15E-01	2.23E-01	2.13E-01	9.92E-02				
p-value, *a*	2.93E-01	2.79E-01	3.04E-02	2.60E-03	5.50E-01				
p-value, *b*	3.98E-01	9.72E-01	3.11E-02	8.65E-01	8.53E-01				
adjusted R-squared	-1.97E-02	6.32E-02	7.75E-01	9.20E-01	1.35E-01				
multiple R-squared	2.35E-01	3.31E-01	8.65E-01	9.40E-01	3.27E-01				
p-value, model	4.47E-01	3.66E-01	4.95E-02	2.19E-04	2.50E-01				

Model 3. Exponential, using cumulative total flow since prior dredging event

$$Vol_d = k({Q_{tot}}^a)$$

	Sabine-Neches Waterway								
COMID	**1481563**	**1112455**	**1115825**	**1477515**	**1477589**	**1477595**	**1477713**	**1477725**	**24719331**
k	1.07E+01	7.98E+00	9.98E+00	1.49E+01	8.30E+00	8.57E+00	-9.59E-01	-9.05E-01	9.87E+00
a	1.52E-01	2.83E-01	1.66E-01	-4.60E-02	2.52E-01	2.36E-01	6.10E-01	6.04E-01	1.72E-01
p-value, *k*	5.72E-04	9.86E-02	1.59E-01	1.45E-02	3.28E-02	8.14E-02	8.53E-01	8.33E-01	1.07E-01
p-value, *a*	2.18E-01	1.69E-01	5.63E-01	8.47E-01	1.22E-01	2.56E-01	2.40E-02	1.12E-02	4.62E-01
adjusted R-squared	2.35E-02	9.83E-02	-7.59E-02	-6.39E-02	8.96E-02	2.24E-02	4.75E-01	5.71E-01	-4.67E-02
multiple R-squared	6.26E-02	1.80E-01	4.36E-02	2.57E-03	1.43E-01	8.00E-02	5.41E-01	6.25E-01	6.96E-02
p-value, model	2.18E-01	1.69E-01	5.63E-01	8.47E-01	1.22E-01	2.56E-01	2.40E-02	1.12E-02	4.62E-01
	Houston Ship Channel								
COMID	**1440485**	**1440511**	**1440521**	**1440525**	**1440539**				
k	1.38E+01	5.90E+00	1.98E+00	-1.30E+00	7.10E+00				
a	-2.38E-02	3.11E-01	5.04E-01	6.95E-01	2.60E-01				
p-value, *k*	1.74E-03	5.45E-01	9.38E-01	3.71E-01	7.71E-03				
p-value, *a*	8.63E-01	4.97E-01	6.69E-01	1.53E-05	2.98E-02				
adjusted R-squared	-1.38E-01	-7.31E-02	-1.87E-01	9.32E-01	3.98E-01				
multiple R-squared	4.56E-03	8.02E-02	5.05E-02	9.41E-01	4.65E-01				
p-value, model	8.63E-01	4.97E-01	6.69E-01	1.53E-05	2.98E-02				

Model 4. Exponential, using cumulative base and high flows since prior dredging event

$$Vol_d = k(Q_{base}{}^{a})(Q_i{}^{b})$$

	Sabine-Neches Waterway								
COMID	**1481563**	**1112455**	**1115825**	**1477515**	**1477589**	**1477595**	**1477713**	**1477725**	**24719331**
k	1.02E+01	8.13E+00	7.40E+00	1.16E+01	4.98E+00	1.27E+00	-4.65E+00	-7.72E+00	9.99E+00
a	1.77E-01	2.78E-01	2.78E-01	9.48E-02	3.96E-01	5.51E-01	7.70E-01	8.95E-01	1.38E-01
b	-1.57E-04	2.41E-04	-2.81E-03	-1.44E-03	-8.25E-04	-2.17E-03	-1.22E-03	-2.76E-03	3.30E-02
p-value, *k*	2.35E-02	2.88E-01	4.32E-01	2.07E-01	4.36E-01	8.75E-01	6.85E-01	4.08E-01	1.26E-01
p-value, *a*	3.43E-01	3.94E-01	4.91E-01	8.07E-01	1.60E-01	1.28E-01	1.48E-01	5.09E-02	6.90E-01
p-value, *b*	9.14E-01	9.52E-01	6.58E-01	7.22E-01	6.42E-01	3.42E-01	7.93E-01	4.66E-01	9.14E-01
adjusted R-squared	-1.89E-02	-3.34E-03	-1.95E-01	-1.32E-01	6.80E-02	4.28E-02	4.25E-01	5.70E-01	-1.99E-01
multiple R-squared	6.26E-02	1.79E-01	7.02E-02	9.42E-03	1.78E-01	1.55E-01	5.68E-01	6.77E-01	6.77E-02
p-value, model	4.75E-01	4.11E-01	7.75E-01	9.36E-01	2.31E-01	2.82E-01	8.04E-02	3.36E-02	7.82E-01
	Houston Ship Channel								
COMID	**1440485**	**1440511**	**1440521**	**1440525**	**1440539**				
k	1.01E+01	3.92E+00	-2.23E+01	-3.76E+00	2.79E+00				
a	1.47E-01	5.01E-01	2.32E+00	8.21E-01	4.68E-01				
b	-3.18E-03	-1.07E-01	-7.92E-01	-1.35E-03	-4.55E-03				
p-value, *k*	1.07E-02	7.20E-01	2.66E-01	1.96E-01	4.99E-01				
p-value, *a*	8.92E-11	4.55E-01	7.95E-02	6.40E-04	4.28E-02				
p-value, *b*	3.01E-01	7.58E-01	8.48E-02	4.41E-01	2.54E-01				
adjusted R-squared	2.71E-01	-2.23E-01	5.52E-01	9.41E-01	4.35E-01				
multiple R-squared	4.53E-01	1.26E-01	7.31E-01	9.56E-01	5.60E-01				
p-value, model	1.64E-01	7.14E-01	1.39E-01	8.46E-05	5.64E-02				

Model 5. Linear, using cumulative flow since the prior dredging event, and the cumulative flow before the prior dredging event

$$Vol_d = k + aQ_{tot} + bQ_{tot-1}$$

	Sabine-Neches Waterway								
COMID	**1481563**	**1112455**	**1115825**	**1477515**	**1477589**	**1477595**	**1477713**	**1477725**	**24719331**
k	8.65E+05	-2.38E+05	1.67E+05	6.36E+05	1.39E+06	1.28E+06	6.27E+05	3.05E+05	1.24E+06
a	8.29E-05	1.19E-04	4.92E-05	-9.71E-06	3.33E-05	3.42E-05	2.75E-05	2.77E-05	1.53E-06
b	-1.02E-08	5.42E-05	1.46E-05	6.83E-05	-1.89E-05	-1.60E-05	-1.83E-05	-1.02E-05	3.62E-06
p-value, *k*	6.21E-02	8.69E-01	8.74E-01	3.75E-01	8.21E-03	1.82E-02	1.59E-01	3.42E-01	2.49E-01
p-value, *a*	1.54E-02	2.95E-02	1.49E-01	7.48E-01	1.12E-01	1.22E-01	7.25E-02	3.06E-02	8.99E-01
p-value, *b*	1.00E+00	2.64E-01	6.38E-01	3.86E-02	3.51E-01	4.55E-01	1.52E-01	2.74E-01	7.72E-01
adjusted R-squared	1.81E-01	3.44E-01	1.05E-01	2.09E-01	1.02E-01	7.55E-02	4.08E-01	5.14E-01	-3.12E-01
multiple R-squared	2.49E-01	4.75E-01	3.29E-01	3.15E-01	2.14E-01	1.91E-01	5.77E-01	6.53E-01	1.57E-02
p-value, model	4.29E-02	7.59E-02	3.03E-01	8.59E-02	1.85E-01	2.27E-01	1.16E-01	7.11E-02	9.54E-01
	Houston Ship Channel								
COMID	**1440485**	**1440511**	**1440521**	**1440525**	**1440539**				
k	2.28E+05	7.21E+05	-3.17E+03	1.40E+05	2.28E+05				
a	7.05E-05	9.11E-05	4.02E-04	9.07E-05	7.05E-05				
b	-2.98E-05	-1.16E-04	5.94E-05	9.32E-06	-2.98E-05				
p-value, *k*	3.48E-01	5.81E-01	9.63E-01	2.37E-01	3.48E-01				
p-value, *a*	2.79E-01	6.69E-01	1.01E-04	1.24E-01	2.79E-01				
p-value, *b*	6.49E-01	5.35E-01	1.61E-01	8.61E-01	6.49E-01				
adjusted R-squared	2.52E-03	-3.66E-01	9.46E-01	1.49E-01	2.52E-03				
multiple R-squared	3.35E-01	3.17E-01	9.62E-01	3.61E-01	3.35E-01				
p-value, model	4.42E-01	6.83E-01	2.88E-04	2.60E-01	4.42E-01				

Model 6. Linear, using base and high flows since the prior dredging event, and the base and high flows before the prior dredging event

$$Vol_d = k + aQ_{base} + bQ_i + cQ_{base-1} + dQ_{i-1}$$

	Sabine-Neches Waterway								
COMID	**1481563**	**1112455**	**1115825**	**1477515**	**1477589**	**1477595**	**1477713**	**1477725**	**24719331**
k	8.02E+05	1.59E+06	1.64E+06	4.70E+05	1.13E+06	8.68E+05	1.58E+06	9.05E+05	1.34E+06
a	1.22E-04	-8.89E-05	-9.77E-05	4.10E-05	7.92E-05	9.89E-05	-6.29E-05	-2.91E-05	1.39E-06
b	-3.97E-05	1.18E-03	8.45E-04	-9.38E-05	-1.09E-04	-1.63E-04	4.04E-04	2.57E-04	3.83E-05
c	-2.70E-05	-3.92E-05	-5.86E-05	-7.96E-06	-2.01E-05	-1.02E-05	-1.01E-04	-6.60E-05	1.50E-05
d	1.01E-04	1.99E-04	9.03E-05	4.19E-04	-5.62E-07	-1.29E-05	2.43E-04	1.97E-04	-8.47E-05
p-value, *k*	1.32E-01	3.24E-01	7.99E-02	4.51E-01	2.01E-01	3.55E-01	1.27E-01	1.53E-01	2.49E-01
p-value, *a*	5.46E-02	4.55E-01	9.74E-02	3.36E-01	3.22E-01	2.58E-01	4.15E-01	5.39E-01	9.36E-01
p-value, *b*	8.30E-01	5.27E-02	1.28E-02	5.43E-01	6.54E-01	5.31E-01	2.53E-01	2.56E-01	5.89E-01
p-value, *c*	6.80E-01	6.85E-01	2.61E-01	8.52E-01	8.01E-01	9.07E-01	1.43E-01	1.24E-01	4.07E-01
p-value, *d*	5.82E-01	6.96E-01	6.98E-01	2.40E-02	9.98E-01	9.58E-01	2.11E-01	1.52E-01	2.81E-01
adjusted R-squared	1.39E-01	5.33E-01	7.42E-01	4.20E-01	-5.26E-03	-1.35E-02	5.01E-01	6.56E-01	-3.67E-01
multiple R-squared	2.83E-01	7.20E-01	8.71E-01	5.75E-01	2.46E-01	2.40E-01	7.86E-01	8.53E-01	3.16E-01
p-value, model	1.38E-01	6.93E-02	4.55E-02	3.78E-02	4.55E-01	4.71E-01	2.16E-01	1.29E-01	7.63E-01

Model 6. Linear, using base and high flows since the prior dredging event, and the base and high flows before the prior dredging event

$$Vol_d = k + aQ_{base} + bQ_i + cQ_{base-1} + dQ_{i-1}$$

	Houston Ship Channel				
COMID	**1440485**	**1440511**	**1440521**	**1440525**	**1440539**
k	8.45E+05	-8.53E+04	7.11E+05	-5.38E+03	1.49E+05
a	2.21E-04	1.82E-04	2.59E-04	5.04E-04	-1.23E-06
b	-2.44E-03	-1.21E-04	-1.92E-03	-1.68E-04	6.16E-04
c	-4.96E-04	2.27E-04	-4.39E-05	1.21E-04	-1.04E-04
d	4.00E-03	-1.13E-03	3.14E-04	-2.45E-04	5.74E-04
p-value, *k*	2.00E-01	7.60E-01	NA	9.46E-01	2.93E-01
p-value, *a*	2.29E-01	1.57E-01	NA	2.55E-02	9.95E-01
p-value, *b*	2.94E-01	7.66E-01	NA	8.11E-01	5.38E-01
p-value, *c*	3.70E-01	2.52E-01	NA	3.59E-01	6.19E-01
p-value, *d*	3.12E-01	1.86E-01	NA	6.96E-01	5.79E-01
adjusted R-squared	4.11E-01	3.27E-01	NA	9.30E-01	-1.29E-01
multiple R-squared	7.47E-01	7.76E-01	NA	9.70E-01	6.57E-01
p-value, model	2.69E-01	3.99E-01	NA	1.27E-02	5.96E-01

Model 7. Exponential, using cumulative flow since the prior dredging event, and the cumulative flow before the prior dredging event

$$Vol_d = k({Q_{tot}}^{a})({Q_{tot-1}}^{b})$$

Sabine-Neches Waterway

COMID	**1481563**	**1112455**	**1115825**	**1477515**	**1477589**	**1477595**	**1477713**	**1477725**	**24719331**
k	6.32E+00	7.40E+00	6.90E+00	1.29E+01	1.05E+01	8.85E+00	8.03E+00	4.38E+00	8.50E+00
a	1.80E-01	2.80E-01	1.86E-01	-4.82E-02	2.40E-01	2.32E-01	5.24E-01	5.00E-01	1.79E-01
b	1.64E-01	2.73E-02	1.11E-01	8.54E-02	-8.38E-02	-7.69E-03	-3.02E-01	-1.27E-01	5.13E-02
p-value, *k*	1.73E-01	3.43E-01	5.72E-01	1.52E-01	8.99E-02	2.60E-01	2.60E-01	4.64E-01	3.85E-01
p-value, *a*	1.50E-01	2.28E-01	5.82E-01	8.51E-01	1.71E-01	3.05E-01	4.68E-02	3.53E-02	4.95E-01
p-value, *b*	3.12E-01	9.02E-01	7.41E-01	7.40E-01	6.20E-01	9.72E-01	1.65E-01	4.70E-01	8.44E-01
adjusted R-squared	5.36E-02	-3.06E-02	-2.51E-01	-1.39E-01	3.65E-02	-5.48E-02	5.14E-01	4.90E-01	-2.23E-01
multiple R-squared	1.32E-01	1.76E-01	6.14E-02	1.24E-02	1.57E-01	7.71E-02	6.53E-01	6.36E-01	8.30E-02
p-value, model	2.10E-01	4.62E-01	8.27E-01	9.22E-01	3.03E-01	5.70E-01	7.11E-02	7.99E-02	7.71E-01

Houston Ship Channel

COMID	**1440485**	**1440511**	**1440521**	**1440525**	**1440539**
k	3.08E+00	1.50E+01	6.23E+00	-3.08E+00	4.05E+00
a	1.37E-01	3.10E-01	1.40E+00	6.98E-01	2.44E-01
b	3.40E-01	-4.24E-01	-1.11E+00	8.41E-02	1.65E-01
p-value, *k*	7.02E-01	3.93E-01	9.05E-01	1.89E-01	1.54E-01
p-value, *a*	4.46E-01	5.73E-01	4.96E-01	1.38E-04	3.25E-02
p-value, *b*	1.96E-01	4.80E-01	4.69E-01	2.65E-01	1.12E-01
adjusted R-squared	3.36E-02	-2.12E-01	-1.62E-01	9.39E-01	5.43E-01
multiple R-squared	3.10E-01	1.92E-01	4.19E-01	9.56E-01	4.36E-01
p-value, model	3.96E-01	6.52E-01	5.81E-01	4.01E-04	4.03E-02

Model 8. Exponential, using base and high flows since the prior dredging event, and the base and high flows before the prior dredging event

$$Vol_d = k(Q_{base}{}^{a})(Q_i{}^{b})(Q_{base-1}{}^{c})(Q_{i-1}{}^{d})$$

	Sabine-Neches Waterway								
COMID	**1481563**	**1112455**	**1115825**	**1477515**	**1477589**	**1477595**	**1477713**	**1477725**	**24719331**
k	1.15E+01	7.26E+00	1.28E+01	1.18E+01	8.33E+00	7.99E+00	1.17E+01	8.28E+00	9.04E+00
a	1.98E-01	2.61E-01	3.05E-01	9.46E-02	3.82E-01	5.18E-01	7.50E-01	7.57E-01	1.27E-01
b	5.82E-04	1.67E-04	-3.15E-03	-1.71E-03	-8.07E-04	-1.75E-03	-1.48E-03	-1.71E-03	1.10E-01
c	-7.06E-02	5.31E-02	-2.58E-01	-7.51E-03	-1.31E-01	-2.55E-01	-6.79E-01	-5.43E-01	4.11E-01
d	1.77E-03	-4.75E-04	8.74E-03	8.83E-04	3.27E-04	2.02E-03	3.77E-03	4.26E-03	-4.58E-01
p-value, *k*	2.65E-01	5.31E-01	4.12E-01	4.32E-01	4.54E-01	5.64E-01	4.92E-01	5.35E-01	4.32E-01
p-value, *a*	2.94E-01	5.91E-01	5.07E-01	8.29E-01	2.29E-01	1.94E-01	2.30E-01	1.51E-01	7.82E-01
p-value, *b*	7.46E-01	9.74E-01	6.68E-01	7.12E-01	6.99E-01	5.05E-01	7.72E-01	6.75E-01	7.94E-01
p-value, *c*	8.50E-01	9.08E-01	5.80E-01	9.87E-01	6.78E-01	5.22E-01	2.33E-01	2.28E-01	3.31E-01
p-value, *d*	4.30E-01	9.44E-01	2.60E-01	8.51E-01	8.78E-01	4.54E-01	4.72E-01	3.26E-01	2.34E-01
adjusted R-squared	-1.05E-02	-3.77E-01	-2.84E-01	-3.40E-01	-7.41E-02	-6.77E-02	4.04E-01	4.88E-01	-2.06E-01
multiple R-squared	1.58E-01	1.74E-01	3.58E-01	1.75E-02	1.94E-01	1.99E-01	7.44E-01	7.81E-01	3.97E-01
p-value, model	4.62E-01	8.58E-01	7.07E-01	9.95E-01	5.92E-01	5.79E-01	2.73E-01	2.23E-01	6.52E-01

Model 6. Exponential, using base and high flows since the prior dredging event, and the base and high flows before the prior dredging event

$$Vol_d = k(Q_{base}{}^{a})(Q_i{}^{b})(Q_{base-1}{}^{c})(Q_{i-1}{}^{d})$$

	Houston Ship Channel				
COMID	**1440485**	**1440511**	**1440521**	**1440525**	**1440539**
k	3.99E+00	5.51E+00	-1.88E+01	-4.32E+00	2.61E+00
a	2.93E-01	1.02E+00	2.52E+00	7.98E-01	3.78E-01
b	-4.97E-03	-4.83E-01	-1.66E+00	-9.57E-04	-2.76E-03
c	1.43E-01	-4.93E-02	7.25E-01	5.00E-02	1.02E-01
d	3.72E-04	-2.24E-01	-3.13E-01	5.10E-04	9.13E-04
p-value, *k*	6.22E-01	8.73E-01	NA	3.98E-01	6.54E-01
p-value, *a*	1.96E-01	4.76E-01	NA	1.29E-02	1.52E-01
p-value, *b*	1.38E-01	6.15E-01	NA	6.56E-01	5.48E-01
p-value, *c*	5.73E-01	9.72E-01	NA	7.61E-01	6.53E-01
p-value, *d*	8.48E-01	7.60E-01	NA	8.08E-01	8.32E-01
adjusted R-squared	3.53E-01	-9.36E-01	NA	9.27E-01	3.87E-01
multiple R-squared	7.23E-01	3.55E-01	NA	9.69E-01	6.94E-01
p-value, model	3.04E-01	8.74E-01	NA	1.35E-02	2.24E-01

Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
cubic yards	0.764555	cubic meters
feet	0.3048	meters
kilometer	0.6214	miles
miles (US statute)	1,609.347	meters
square miles	2.589998 E+06	square meters

Acronyms and Abbreviations

CKAN	Comprehensive Knowledge Archive Network
COMID	Common ID
CSAT	Corps Shoaling Analysis Tool
ECMWF	European Centre for Medium Range Weather Forecasts
ERA-I	ECMWF Reanalysis-Interim
ERDC	US Army Engineer Research and Development Center
NCF	National Channel Framework
NHD	National Hydrography Dataset
NHDPlus	National Hydrography Dataset Plus
NHDPlusV2	National Hydrographic Dataset Plus Version 2
RAPID	Routing Application for Parallel computatIon of Discharge
SPT	Streamflow Prediction Tool
UMIP	USACE Model Interface Portal
USACE	US Army Corps of Engineers

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14. ABSTRACT

In recent years, the United States Army Corps of Engineers (USACE) has spent an average of approximately a billion dollars annually for navigation channel maintenance dredging. To execute these funds effectively, USACE districts must determine which navigation channels are most in need of maintenance dredging each year. Traditionally, dredging volume estimates for Operations and Maintenance budget development are based on experiential knowledge and historic averages, with the effects of upstream, precipitation-driven streamflows considered via general-rule approximations. This study uses the Streamflow Prediction Tool, a hydrologic routing model driven by global weather forecast ensembles, and dredging records from the USACE Galveston District to explore relationships between precipitation-driven inland channel flow and subsequent dredged volumes in the downstream coastal channel reaches. Spatially based regression relationships are established between cumulative inland flows and dredged volumes. Results in the test cases of the Houston Ship Channel and the Sabine-Neches Waterway in Texas indicate useful correlations between the computed streamflow volumes and recorded dredged volumes. These relationships are stronger for channel reaches farther inland, upstream of the coastal processes that are not included in the precipitation-driven hydrologic model.

15. SUBJECT TERMS
Dredging—Management, Dredging spoil, Hydrology, Precipitation (Meteorology), Runoff, Streamflow

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