Use of a Gridded Runoff Flow Routing Model to Estimate Sedimentation and Dredging Burdens

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Abstract

The United States Army Corps of Engineers (USACE) mission includes the maintenance of about 25,000 miles of waterways critical to national commerce and security. Operations and Maintenance budgets for these waterways have to be planned in advance of two-year budget cycles, which challenges managers to estimate future sediment loads and channel dredging burdens. Inland hydrologic activity can drastically impact sedimentation in channels and harbors, often with a timing lag after major hydrologic events in the upstream watershed. The Coastal and Hydraulics Laboratory (CHL) at the United States Army Engineer Research and Development Center (ERDC) has developed the Streamflow Prediction Tool (SPT), which employs a watershed-scale gridded runoff routing flow model to forecast flows within a fine-scaled stream network using ensemble precipitation forecasts. Here, the 30-year hindcast flow records produced within the Streamflow Prediction Tool are applied to the watersheds feeding the Sabine and Port Arthur Harbor systems in Texas to evaluate whether watershed-level modeling of inland streamflow in response to precipitation can be appropriately used to improve estimations of future dredging burdens at maintained waterways. Several modeled relationships are explored between base flow volumes, peak flow volumes, and dredging event volumes from 1980 through 2014 for stream reaches in these navigation systems. Results indicate that for maintained channels some distance from the coast, inland hydrologic activity is correlated with subsequent dredged sediment loads. Established numerical relationships between flows and resulting dredging burdens could potentially enable managers of channel dredging to better estimate future needs by accounting for inland hydrologic activity.

Introduction

The purpose of this study is to leverage existing USACE models and datasets for potential insights useful in the channel management process for USACE Operations and Maintenance budget development. We investigated correlations between precipitation-driven, inland riverine flow rates calculated using the USACE-developed Streamflow Prediction Tool (SPT) (Snow et al. 2016) and historical dredged volume records from 1980 through 2014 for the Sabine and Port Arthur harbor channel system in Texas. Regression relationships between precipitation-driven riverine flows and subsequent channel dredging burdens could provide channel managers with additional tools to plan for likely future operations and maintenance needs, and lead to better optimization of channel dredging resources.

Methodology

For this analysis, we processed historic dredging records (reported in total cubic yards dredged per event) and reconstructed stream flow hydrographs (reported in three-hourly average flow in cubic feet per second) to connect these spatially by stream reach. Then dredged volumes were analyzed as a function of the cumulative flow volumes in the same reach using eight different regression models to evaluate relationships between precipitation-driven riverine flow and subsequent dredging at the channel reach level. This is similar to methods applied by Dahl, et al. (2018) in assessing the potential impact of climate-varying future precipitation on dredging burdens. In this section we detail the study area, datasets and models used, and data processing methodology for this analysis.

Study Area

The study the link between cumulative streamflow and dredging volumes, we selected three study areas in Texas Gulf Coast Regions (Figure 1): Sabine and Port Arthur Harbor (Sabine-Neches river system), the Houston, Galveston, and Texas City Harbor system (Houston Ship Channel), and Corpus Christi Harbor (Nueces River). We selected these test sites to represent a full range of Texas coastal riverine systems, and to take advantage of available historic dredging records. This report covers the results of the analysis in the Sabine and Port Arthur Harbor. Within this study area, specific channels were used in the analysis based on the availability of dredging records. Detailed maps of the selected channels in this system are presented in the Results section.

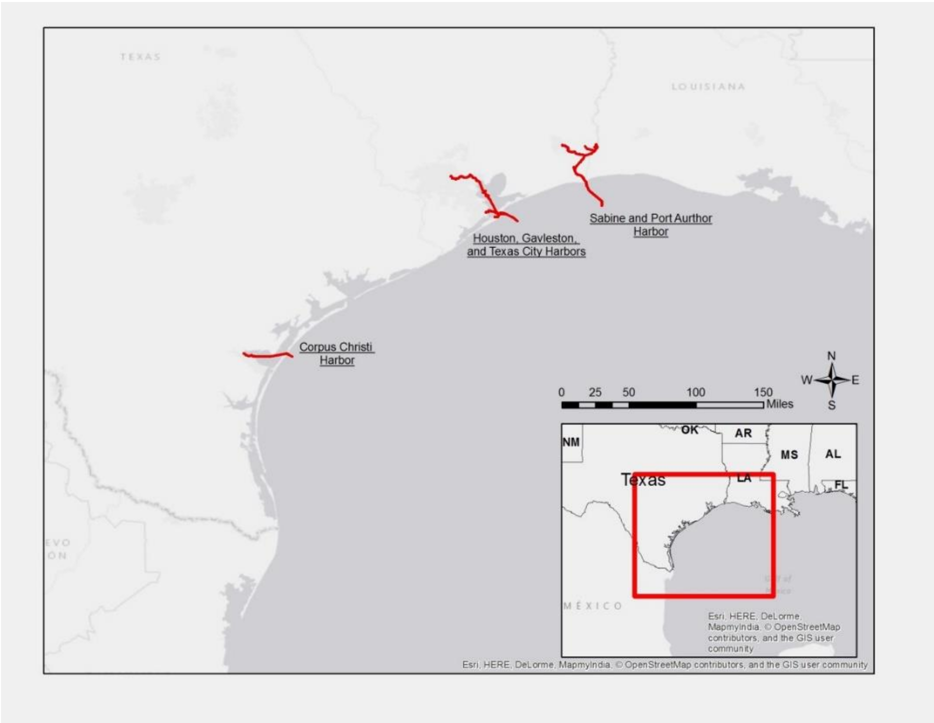

Figure 1. Study area of interest: three harbors in the Texas Gulf Hydrologic Region

Watershed-Scale Hydrologic Routing Model and Input Data

To simulate historical watershed-scale hydrology for this analysis, we used hindcast streamflow simulation results from the Streamflow Prediction Tool (SPT). The SPT was used to produce three-hourly flow rates from 1980 through 2014 for every stream reach in the Texas Gulf Region by routing historical atmospheric data from the European Centre for Medium Range Weather Forecasts (ECMWF, Balsamo et al., 2009) through the river routing model Routing Application for Parallel computatIon of Discharge (RAPID, David et al., 2011b). This framework takes advantage of over 30 years of runoff estimates available globally to reconstruct flows at ungauged locations. The benefit of this framework is to calculate streamflow anywhere in a river network without a dependency on rainfall or streamflow gages. Hence, the estimated historical and forecast streamflow can be obtained for the locations of dredging projects in any watershed of interest.

The RAPID model is an open source river network routing model. Notable features of RAPID include the use of the “blue lines” on the map and a grid network for river networks with an automated parameter estimation procedure (RAPID, David et al., 2011b). RAPID uses a matrix-based version of the Muskingum flow-routing method (Overton, 1966, and Gill, 1978) to compute the flows in river networks containing many thousands of reaches. Inputs to RAPID are runoff time series (in this case, ECMWF historical atmospheric data), K and X Muskingum parameter files (produced within the SPT), and catchment ID files. The output file of RAPID is a time series of flow rates for all river reaches in the river network.

The NHDPlus dataset, available for the continental United States, was used in this study to determine the locations of river reaches in the watershed as a “blue line” and to derive required parameter attributes for RAPID input file preparation. This dataset is a horizontal integration of the medium-resolution (1:100,000 scale) National Hydrography Dataset (NHD, McKay 2012), the National 3D Elevation Program dataset (NED, Sugarbaker 2015), and the National Watershed Boundary Dataset (WBD, U.S. Geological Survey, 2013).

The performance of the RAPID model and application of the NHD data for river routing were described in detail by several authors: David et al., 2011a, 2011b and 2013; Follum et al., 2016; Tavakoly et al., 2016 and 2017. David et al. (2013) found the RAPID model to perform similarly to observed gage data in the Texas Gulf Hydrologic Region, which is the domain to which we apply the RAPID model output in this study.

Data Processing Work Flow

A number of steps were taken to connect the stream flow time series data with the historical dredging datasets for analysis. The streamflow time series for reaches in the study area were downloaded from the SPT online portal interface (accessible at https://umip.erdc.dren.mil/apps/streamflow-prediction-tool/ with a Common Access Card authentication). The historic dredging data came from the USACE Galveston District records, and was plotted spatially using the USACE National Channel Framework GIS database. This enabled spatial matching of channel dredging records with the Common IDs (COMIDS) used to identify river reaches within the SPT results. The National Channel Framework (NCF) is a set of enterprise Geographic Information System (eGIS) feature classes providing geospatial locations of the congressionally authorized navigation channels maintained by USACE. Galveston District dredge history database includes channel reaches, stations, quantities, and project date end for each dredging event in the last forty years of dredging.

Two spatial relationships were needed for this analysis. First, we related the NHDPlusV2 to the channel reaches from the National Channel Framework. Typically, there were several stream links for each reach and we noted the most downstream link. Next, we linked the local dredge history records to that of the NCF. These relationships provide the ability to pull all dredging events and amounts and relate those events to the COMID stream flows. These connections were all performed spatially in ArcGIS software version 10.3 (ESRI, 2011). Several further data manipulations and assumptions were required to correlate dredged amounts in each reach with the reconstructed stream flows produced be the SPT:

1. Dredging events were coded as occurring on the date recorded as “Work Complete.” Dredging records with work completion dates before 1980 were discarded, to ensure sufficient overlap with the SPT time series output. Dredging records with multiple project volumes reported for the same reach location and same day were aggregated into a single project volume for that day.

2. Return period analyses were performed on the flow time history for each reach to determine the magnitude of the 1.5-year, or bankfull, flow, at that reach. All streamflow values in the time history for that reach were then coded as being either less than or greater than this bankfull flow value. This was done to enable analyses of base flows (considered here to be below bankfull, 1.5-year flow) and peak flows (considered here as flows above bankfull, 1.5-year flow), further discussed in the “Methodology for Analysis of Results” section below.

3. Streamflow data were partitioned into time history sets separated by the dredging events for each reach to enable the computation of cumulative flow between dredging events.

Methodology for Analysis of Results

We selected nine stream channel COMIDs in the Sabine and Port Arthur Harbor for analysis to represent a variety of reach conditions in the regions of interest: closer to inland riverine systems, closer to the outlet to bay areas, man-made channelized areas, and before and after various stream confluences in each region. Furthermore, stream reaches with spatially matched robust historical dredging records were chosen.

We then performed single and multivariate regression analyses of dredged volumes as a function of precipitation-driven streamflow at the matched stream reach and region level. As mentioned in the Data Processing Work Flow section above, stream flow rates were categorized as above or below the average 1.5-year stream flow rate by reach to approximately disaggregate base flows and peak flows. Flow rates were multiplied by the three-hour time step to approximate channel flow volumes for the time series. The flow volumes were summed for the time periods between dredging events to obtain cumulative flow volume in a channel between dredging events. Table *1* describes the variables used in analysis. Note that flow volumes are in cubic meters and dredged sediment volumes are in cubic yards, following convention.

Table 1. Description of regression model variables

Variable	Description (units)
Vol_d	Total dredged volume from one dredging event (cubic yards)
Q_{tot}	Total cumulative flow since the last dredging event (cubic meters)
Q_{base}	Cumulative base flow (flow rate less than the 1.5 year flow rate for that reach) since the last dredging event (cubic meters)
Q_i	Cumulative peak flow (flow rate less than the 1.5 year flow rate for that reach) since the last dredging event (cubic meters)
k	Regression intercept (cubic yards)
a, b, c, d	Regression coefficients

Four different models were tested with the dredging data for the Sabine Neches cases. These are described in Table 2 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 base flow and peak flow. Models 3 and 4 mirror the variables tested in 1 and 2 but are nonlinear.

Results by reach were visualized in two ways: First, the cumulative streamflow volume in cubic meters between dredging events was plotted as a time series, with the subsequent dredged volumes in cubic yards plotted on a secondary axis. 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. Second, the plot for Model 1 was presented with the observed dredging data to illustrate how skillfully the single-variate model describes the relationship between cumulative flow rates and dredged volumes. These plots are shown for selected reaches in the Results section.

Table 2. Equations for tested regression models

Model	Equation
Linear models using the total cumulative flows immediately prior to the dredging event:	
1	$Vol_d = k + aQ_{tot}$
2	$Vol_d = k + aQ_{base} + bQ_i$
Exponential models using the total cumulative flows immediately prior to the dredging event:	
3	$Vol_d = k(Q_{tot}{}^{a})$
4	$Vol_d = k(Q_{base}{}^{a})(Q_i{}^{b})$

Results

Coefficients of determination (R-squared) values for many of the tested models were sufficiently high to indicate that the incorporation of precipitation-driven inland hydrology into forecasts of future dredging burdens can improve these estimates. In general, the models performed best in channelized reaches upstream of coastal outlets, and worse in the reaches connected to coasts and bays where coastal sedimentation processes would likely dominate over sediment delivered by the upstream watershed. Results by model type are further presented below.

Single-Variate Linear Model Results

For this model, Model 1, up to 63% of the variance in dredging amounts in the Sabine-Neches system from the 1980-2014 period can be explained using the total cumulative flow since the last dredging event as the predictive variable. For reaches closer to the bays or coasts, this falls to 0%.

Table 3 shows goodness of fit results 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. Reported P-values are for confidence in the null hypothesis that dredging burdens are not correlated with the cumulative flow volumes between dredging events. For this model, Model 1, up to 63% of the variance in dredging amounts in the Sabine-Neches system in the 1980-2014 period can be explained with a simple linear model using the total cumulative flow since the last dredging event as the predictive variable. For reaches closer to the bays or coasts, this falls to 0% with low confidence in the estimate.

Table 3. Summary of single variable linear regression Model 1 fit

Stream ID	Drainage Area, square km	Number of dredging events since 1980	R-squared value	P-value
1112455	25,931	11	0.38	0.03
1115825	26,058	9	0.30	0.10
1477515	26,064	15	0.04	0.50
1477595	26,220	15	0.16	0.10
1477713	26,204	12	0.48	0.04
1477589	26,215	16	0.16	0.10
1477725	26,201	11	0.63	0.01
1481563	27,705	23	0.20	0.02
24719331	53,730	12	0.00	0.89

For the Sabine-Neches study area, we selected reaches upstream, along the canal, and close to the outlet (Figure 2). Stream reaches are highlighted in light blue in the figure, 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. This accounts for the gaps in the streams analyzed in the figure.

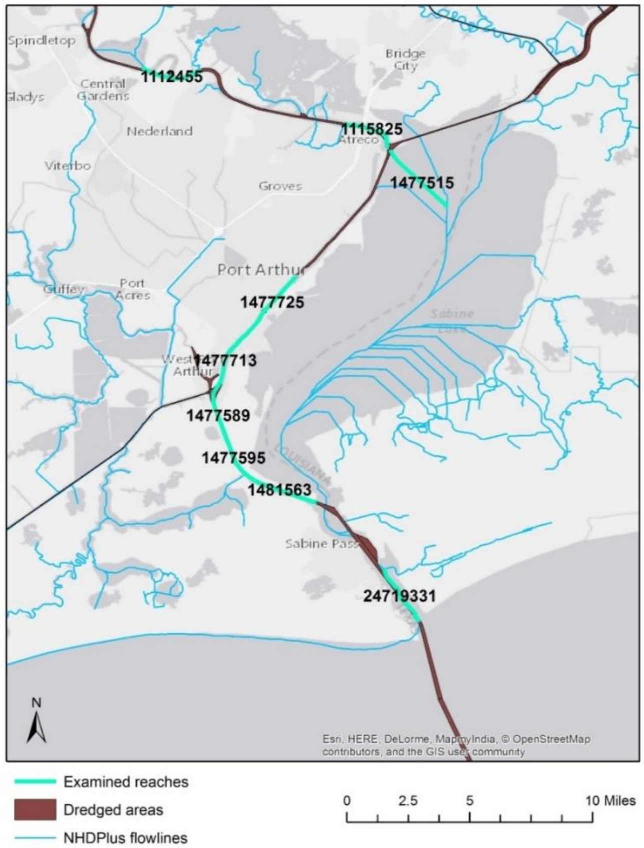

Figure 2. Examined COMIDs and dredged channel areas in the Sabine Neches Waterway

Stronger linear relationships were found in inland stream reaches, such as the most upstream COMID 1112455 (R-squared of 0.37 with a p-value of 0.03), and channelized reaches, such as COMID 1477725 (R-squared of 0.62 with a p-value of 0.01). R-squared values close to 0, indicating no correlation between streamflow and dredging burden, and high p-values indicating low confidence in the validity of the model 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 0.47) 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 the lake is dredged often, 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.

Visualizations of stream reach Model 1 results for the reaches in the Sabine Neches Waterway with the highest model skill are presented below in Figure 3. These streamflow and Figures were produced using Rstudio (Rstudio Team, 2015).

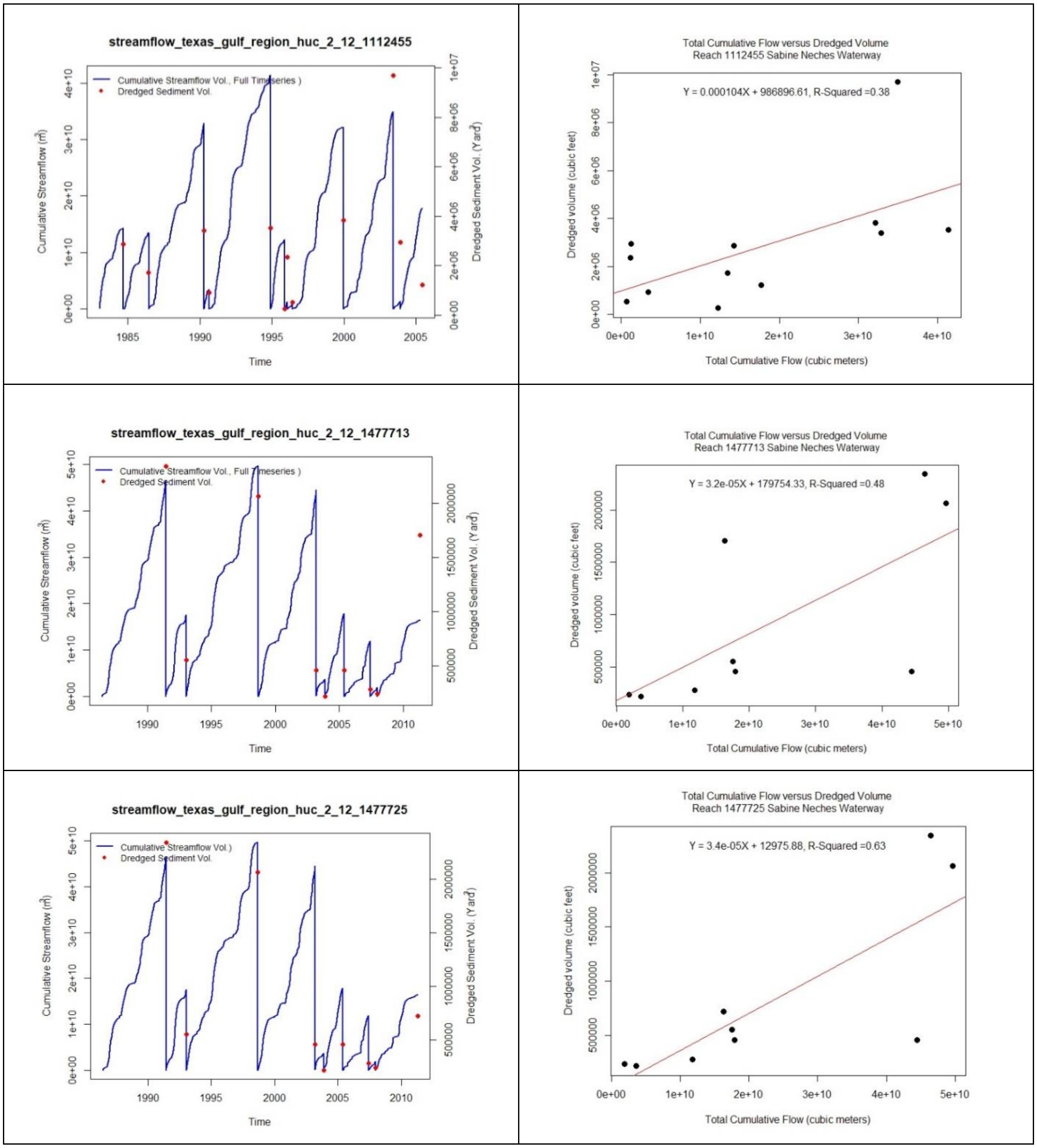

Figure 3. Visualization of selected stream reach results in the Sabine Neches Waterway

Nonlinear and Multivariate Model Analyses

Seven additional models were tested, as outlined in Table 2 in the Methodology section. These models disaggregated the cumulative flow into base flow (below the 1.5 year flow rate) and peak flow (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

COMID. Most of the time, the percentage error in the predicted volumes was within one order of magnitude. In the Sabine-Neches system, 50% of the model estimates were within 40% error of the actual magnitude of sediment dredged. Model estimates became more accurate as the dredged sediment volumes increased. Figure 4 shows the percentage error of prediction by event for each model for the reaches in the Sabine Neches system. Errors were predominantly positive – the models tended to over-predict dredging loads at lower volumes and under-predict loads at higher volumes.

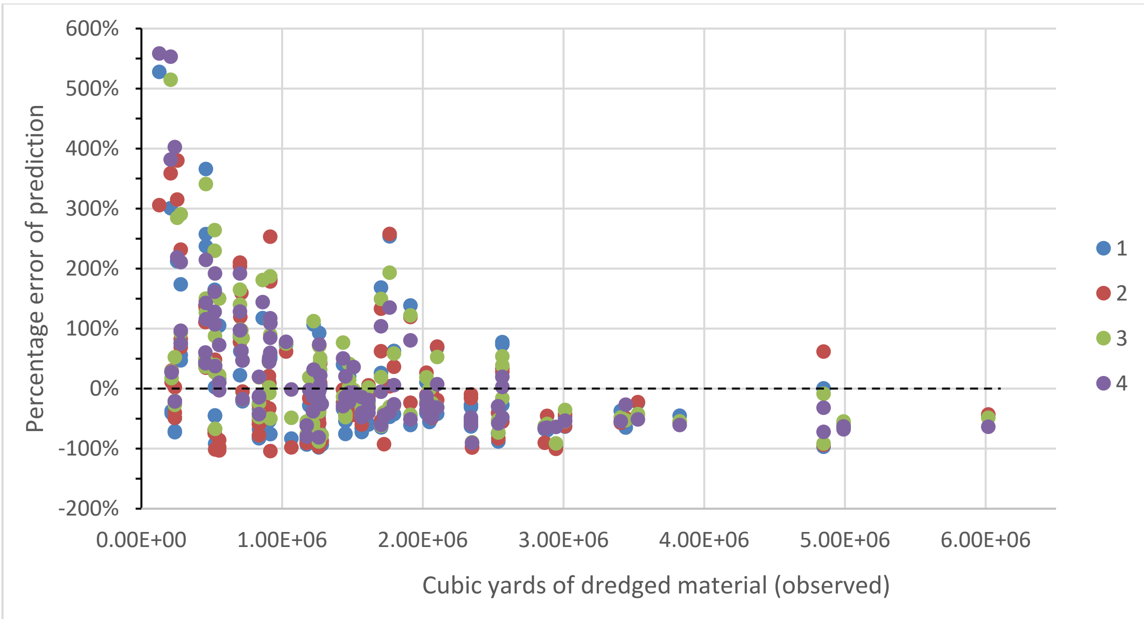

Figure 4. Percentage error of predictions by model, Sabine Neches

Table 4 shows the R-squared and p-values by model for two of the reaches for which inland precipitation-driven flow demonstrated the most skill in predicting dredged sediment loads. Generally, these models had the high associated levels of confidence. The models which disaggregated flow volumes into base flow and peak flow, 2 and 4, tended to outperform the models which treated all cumulative flow as a single variable, 1 and 3. Interestingly, for most reaches the coefficient of the peak flow term was negative, indicating that peak flows may reduce total sediment loads, and subsequent dredging burdens, and base flows may contribute more in terms of deposition.

Table 4. R-squared and p-value by model for best performing reaches

	Sabine-Neches			
COMID	**1477725**		**1477713**	
Model	R^2	*p-val*	R^2	*p-val*
1	0.63	**0.01**	0.48	**0.04**
2	0.77	**0.01**	0.66	**0.04**
3	0.62	**0.01**	0.54	**0.02**
4	0.68	**0.03**	0.57	0.08

Discussion

This approach demonstrates enough skill to be considered as potentially useful in estimating downstream dredging burdens. For the river system examined, inland riverine flow seems highly correlated with subsequent dredging loads at reaches inland of bays and coasts. 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 is strongly tied to budget availability, which is not captured in these models. Recognizing those limitations, it does seem that using flow volumes can provide additional information about channel maintenance needs without necessarily deploying data-intensive, high-fidelity sedimentation models.

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.

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