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QUANTITATIVE APPROACH TO NAVIGATION CHANNELS ASSET MANAGEMENT

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ABSTRACT

The U.S. Army Corps of Engineers maintains hundreds of deep-draft coastal ports and waterways as part of its navigation mission, and this infrastructure portfolio is vital for sustaining maritime commerce, multimodal freight supply chains, and national security. Within an asset management framework, these dredged channels are evaluated in terms of the value they bring to the overall navigation portfolio of projects as well as the costs of regular maintenance dredging required to keep the channels at sufficient depths to enable cost-effective marine transportation. To keep the evaluations objective, consistent, and transparent, this work seeks a quantitative approach that compares the cargo tonnage utilizing the deepest, shoal-vulnerable channel depths to the dredging costs required to maintain those corresponding depths. The Corps' detailed Waterborne Commerce figures are used to obtain the annual tonnage totals using each 0.3-m (1-ft) increment of maintained channel depth. Recent development efforts have focused on predicting required dredging quantities in out years using historical hydrographic survey data to inform future shoaling rates. The Corps Shoaling Analysis Tool (CSAT) calculates channel-shoaling volumes using historical channel surveys and uses the shoaling rates to predict future dredging volumes. The CSAT leverages ongoing efforts by the USACE to standardize the manner in which hydrographic surveys are uploaded and processed through its eHydro program. The CSAT estimates future localized shoaling rates through a hindcasting algorithm and historic shoal volumes and is designed to incorporate new hydrographic surveys as they become available. The forecasted shoaling volumes from CSAT are combined with the detailed Waterborne Commerce annualized tonnage figures within the Channel Portfolio Tool (CPT), enabling a straightforward, quantitative comparison of cargo supported by dredging to any specified target depth to the requisite dredging costs. Via this approach, dredging work packages from across the Corps' Navigation portfolio of projects can be objectively compared for cost-effectiveness.

Keywords: navigation channel, shoaling, tonnage, dredging.

INTRODUCTION

The U.S. Army Corps of Engineers maintains hundreds of deep-draft coastal ports and waterways as part of its navigation mission, and this infrastructure portfolio is vital for sustaining maritime commerce, multimodal freight supply chains, and national security. Within an asset management framework, these dredged channels are evaluated in terms of the value they bring to the overall navigation portfolio of projects as well as the costs of regular maintenance dredging required to keep the channels at sufficient depths to enable cost-effective marine transportation.

Leveraging USACE specific datasets and other agency resources provides the unique opportunity to evaluate navigation channels in an objective and standardized approach. Spatial and economic datasets are the primary inputs needed to objectively quantify the benefits of maintaining navigation channels to specified depths. The USACE mission to maintain navigation channels requires spatial delineation of the channel framework and regular hydrographic surveys. The outside channel limits and the channel quarters are delineated in the USACE National Channel Framework (Libeau, 2007). In addition, the USACE regularly collects hydrographic surveys at navigation channels at various time intervals to provide updates on channel conditions. The USACE has developed a costume suite of tools aimed at standardizing and efficiently processing coastal channel hydrographic surveys to be served out at the enterprise level. The enterprise Hydrosurvey Processing (eHydro) tool provides a user interface to process hydrosurveys using automated Geographic Information System (GIS) routines (ESRI, 2015). The current condition of the navigation channel is quantified using the eHydro process and a series of condition reports and plots are generated. Defining navigation channel boundaries and knowing the channels current condition answers two of the

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three fundamental asset management requirements. Predicting the future performance of the navigation channel is the third asset management requirement.

Recent development efforts have focused on predicting required dredging quantities in out years using historical hydrographic survey data to inform future shoaling rates. The Corps Shoaling Analysis Tool (CSAT) calculates channel-shoaling volumes using historical channel surveys and uses the shoaling rates to predict future dredging volumes. The CSAT leverages ongoing efforts by the USACE to standardize the manner in which hydrographic surveys are uploaded and processed through its eHydro program. The CSAT estimates future localized shoaling rates through a hindcasting algorithm and historic shoal volumes and is designed to incorporate new hydrographic surveys as they become available. The forecasted shoaling volumes from CSAT are quantified at varying depth intervals and are projected at different time steps.

The USACE Channel Portfolio Tool (CPT) incorporates detailed Waterborne Commerce annualized tonnage figures to provide usage statistics at varying depths (Mitchell and Walker, 2009). Incorporating the shoaling volumes from CSAT within CPT enables a straightforward, quantitative comparison of historic cargo totals supported by any specified dredge-to depth to the requisite dredging costs. Via this approach, dredging work packages from across the Corps' Navigation portfolio of projects can be objectively compared for cost-effectiveness. Several pilot channels from USACE coastal districts were used to demonstrate this quantitative approach to asset management of navigation channels.

PILOT NAVIGATION CHANNELS

To keep the evaluations objective, consistent, and transparent, the pilot effort focused on providing a quantitative approach that compares the cargo tonnage utilizing the deepest, shoal-vulnerable channel depths to the dredging costs required to maintain those corresponding depths. Navigation channels from six USACE coastal districts were selected to demonstrate the quantitative approach. A list of the coastal navigation channels is provided in Table 1.

Table 1. Pilot navigation channels and the associated coastal district where the channels are located.

Pilot Coastal Navigation Channels	District	MSC
Charleston Harbor	Charleston District (SAC)	South Atlantic Division (SAD)
Calcasieu	New Orleans District (MVN)	Mississippi Valley Division (MVD)
Rouge River	Chicago District (LRC)	Great Lakes and Ohio River Division (LRD)
Houston Ship Channel	Galveston District (SWG)	Southwestern Division (SWG)
Texas City	Galveston District (SWG)	Southwestern Division (SWG)
Galveston	Galveston District (SWG)	Southwestern Division (SWG)
Columbia River	Portland District (NWP)	Northwestern Division (NWD)
Cook Inlet	Alaska District (POA)	Pacific Ocean Division (POD)

The pilot navigation channels were chosen based on recommendations by the USACE Division representatives as a result of the completeness of the NCF at the respective district and the availability of hydrographic survey data. The NCF provides detailed information about the boundaries of the navigation channel and is divided into reaches that are designated at the district level and may represent known historical shoal areas, typical dredging areas, hydrographic survey areas, or changes in operational use. An example of the NCF for the Galveston Ship Channel is shown in Figure 1.

The location of the selected pilot navigation channels is also important to show the regional context for the quantitative asset management approach. The navigation channels selected represent several Major Subordinate Command (MSC) areas.

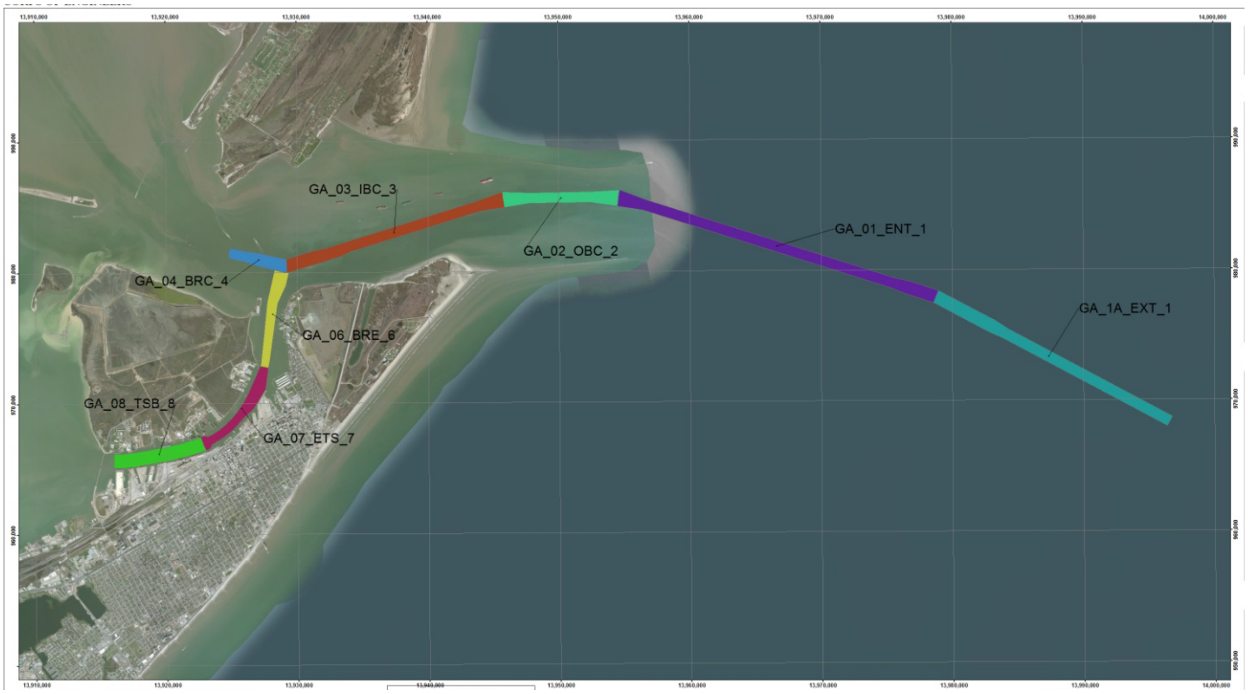

Figure 1. Galveston Ship Channel NCF with reaches identified.

HYDROGRAPHIC SURVEY DATA

The USACE districts conduct routine hydrographic surveys of navigation channels in order to acquire information about the current condition of the channels relative to design widths and depths. The eHydro tool provides a standard process for uploading hydrographic surveys and generates several reports and maps detailing the condition of the channel. The standard format of the hydrographic survey data processed through eHydro is also provided to NOAA in accordance with 33 CFR 209.325 which requires the USACE to provide Navigation data for charting purposes.

The eHydro tool is able to process X, Y, Z spatial datasets and then generates standardized output in a geodatabase format. Standard output files in the geodatabase include a survey job table with the survey metadata, processed survey data, and survey planning quantities for the current survey. The USACE’s top 59 tonnage navigation channels are in the process of fully implementing eHydro. Leveraging the eHydro efforts offers the opportunity for additional analysis with the hydrographic datasets.

SHOALING ANALYSIS

The foundation of the CSAT relies on incorporating historical hydrographic survey data. For the pilot effort, three to five years worth of historical hydrographic survey data at each participating navigation channel was processed through eHydro. Once the data were processed into a consistent format through eHydro, the hydrographic surveys are then generated into a uniform grid system on a per reach basis using costume scripts (Figure 2).

An attribute table is created that provides information about the date and the reach designation of the hydrographic surveys. In addition, a column is included in the table to allow the end user with options to include or remove surveys from the analysis. Table 2 is an example of the attribute table.

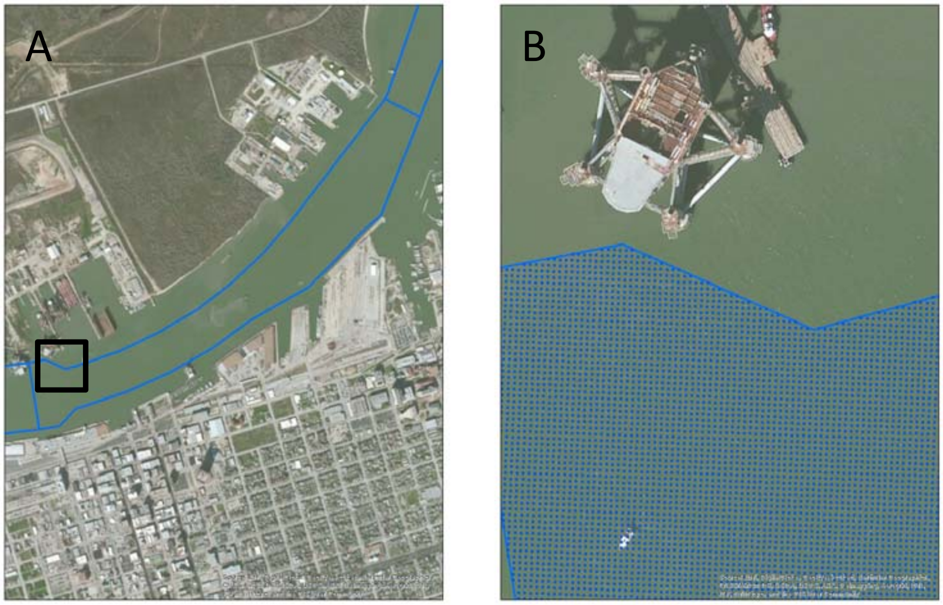

Figure 2. Galveston Ship Channel reach (A) and zoom showing 3.3 x 3.3 m (10ft x 10ft) cell size of uniform grid (B).

Table 2. CSAT attribute table of hydrographic survey data.

Survey Date	Survey Type	Survey ID	Reach Name	Reach_ID	Use
20110823	conditional	GA_01_ENT_20110823_EX2P	001 Entrance Channel	GA_01_ENT_1	1
20120304	conditional	GA_01_ENT_20120304_EX1	001 Entrance Channel	GA_01_ENT_1	1
20130301	conditional	GA_01_ENT_20130301_EX3	001 Entrance Channel	GA_01_ENT_1	1
20130628	conditional	GA_01_ENT_20130628_BD	001 Entrance Channel	GA_01_ENT_1	1

The shoaling analysis portion of CSAT is written in the Matlab software (Mathworks, 2015) in order to take advantage of the efficient matrix processing. The shoaling analysis is based on a hindcasting algorithm that uses historical hydrographic surveys to predict future shoaling.

The CSAT analyzes the hydrographic survey data and outputs the average, maximum, minimum shoaling rates per reach. In addition, the shoaling rates for each individual point location are output with the corresponding X and Y coordinates to provide a spatial representation of the shoaling rates for the channel.

Hydrographic survey pairs are designated between dredging events. The hydrographic survey sets are differenced to generate an elevation change and the time between the surveys is used to determine the rate of change (Figure 3). In addition, volumes are calculated for each survey pair separated by a dredge event. Volume change rates based on all available hydrographic survey data are calculated by summing change at each grid point within the region.

The predicted volume is calculated by adding the average annual shoaling rate at the various time intervals to the last hydrographic survey elevation. This method results in annual average, maximum, and minimum shoaling rates in the different regions. The following general process for CSAT was applied:

1. Calculate the difference between every survey set not separated by a dredging event to create many different estimates of shoaling as a function of time, flagging data that does not meet specific thresholds or where data does not exist to be excluded in later calculations.
2. Calculate average, maximum, and minimum shoaling rates at each point on the 3.3 m x 3.3 m (10ft x 10ft) grid.
3. Calculate volume of shoaling between every survey set.
4. Generate a spatial file of the shoaling rate for the entire navigation channel.
5. Use the CPT designated economic reaches to split the spatial shoaling rate file.
6. Calculate the predicted volume for each economic reach.

The spatial representation of the shoaling rate for the Galveston Ship Channel is shown in Figure 4. Areas with higher shoaling rates are shown in the warm colors while lower shoaling rates are associated with cool colors. Higher shoaling rates are seen in the entrance channel seaward of the jetties in addition to the outer boundaries of the navigation channel in the area between Galveston and Pelican Island.

Table 3 presents the average calculated shoaling rates for each area shown in Figure 1. The link number is a unique identifier for the Waterborne Commerce economic reaches that are used within CPT. Rates are calculated based on all available hydrographic survey data. Volume change rates based on all available data are calculated by summing change at each grid point per reach. Shoaling seaward of the jetties in the entrance channel results in the higher shoaling volumes for the entrance channel reach (Link Number 1643).

Table 3. Calculated average shoaling rate per reach.

Reach_ID	Link Number	Average Rate (ft/yr)	Average Volume (CY/yr)
CESWG_GA_1A_EXT_1	2029	0.928	591,457
CESWG_GA_01_ENT_1	1643	1.312	1,032,427
CESWG_GA_02_OBC_2	1644	1.724	501,174
CESWG_GA_03_IBC_3	1645	1.194	658,476
CESWG_GA_04_BRC_4	2008	0.015	2,326
CESWG_GA_06_BRE_6	1646	1.807	404,388
CESWG_GA_07_ETS_7	1647	1.447	330,810
CESWG_GA_08_TSB_8	1648	2.129	587,413

The shoaling rates are used to predict future volumes required for dredging at various depth intervals. The last hydrographic survey is used to determine the volume of material needing to be removed at the various depth intervals in order to maintain the navigation channel. The shoaling rate provides the forecasting capability to determine volume at the various depths and time intervals. The volume tables are calculated per reach. Table 4 provides an example of the volume table. The forecasted shoaling volumes from CSAT are combined with the Waterborne Commerce annualized tonnage figures within the Channel Portfolio Tool (CPT), enabling a straightforward, quantitative comparison of cargo supported by dredging to any specified target depth to the requisite dredging costs.

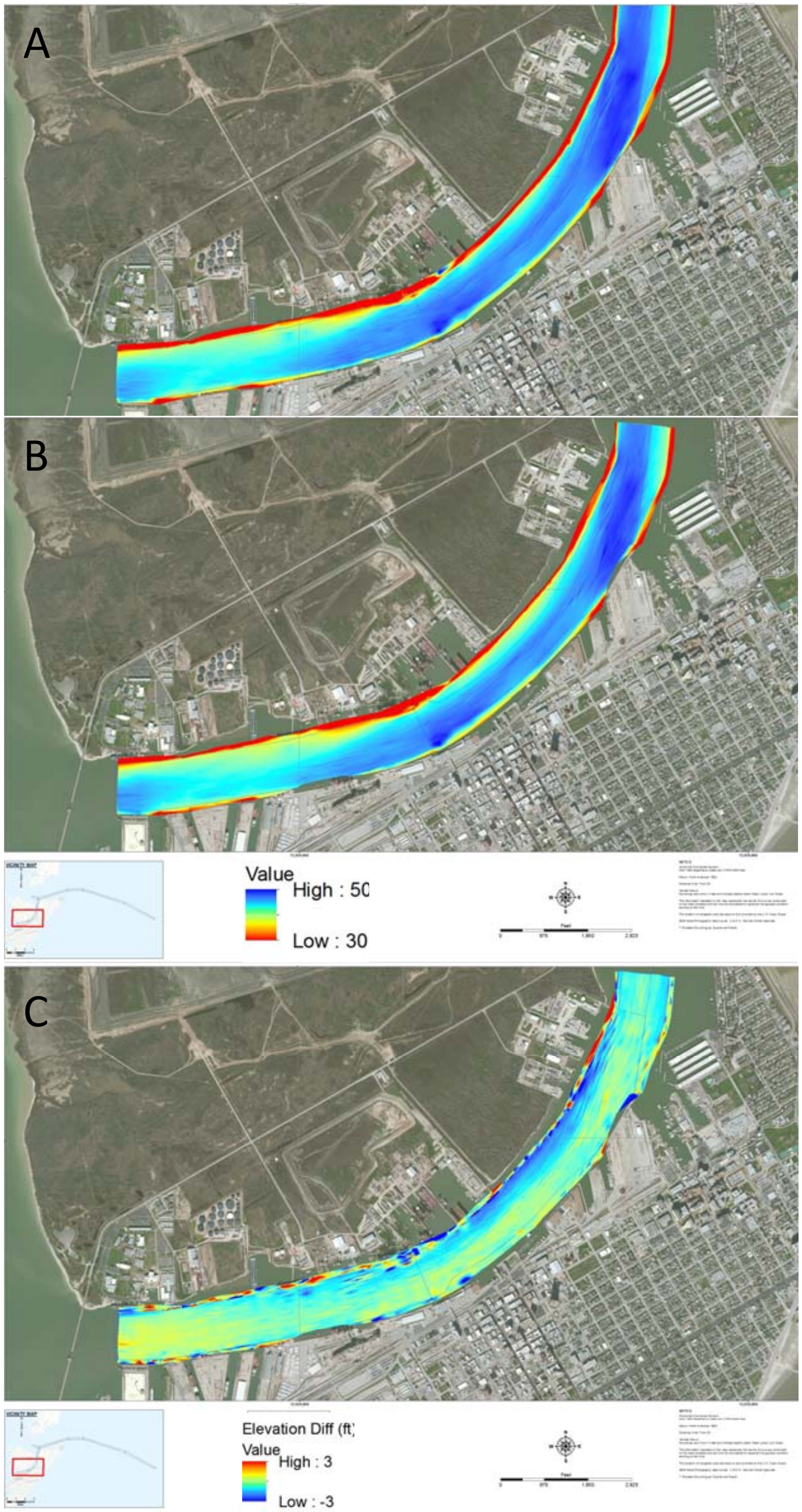

Figure 3. Example of hydrographic survey sets from (A) 20121024 and (B) 20130226 and (C) elevation difference of B-A.

Figure 4. Galveston Ship Channel shoaling rates.

Table 4. Volumes at various depths and time intervals for 007 Exxon Oil Dock to Todd Shipyards (Mile 1.5 To Mile 3.0) - (GA_07_ETS_7).

Dredge Cut (ft)	Now (CY)	6 months (CY)	12 months (CY)	18 months (CY)	24 months (CY)	30 months (CY)	36 months (CY)
-45	195,320	271,020	373,070	492,200	624,890	771,020	931,220
-44	125,140	173,140	238,620	331,710	444,910	572,680	713,450
-43	76,249	109,860	153,260	210,570	293,080	399,730	522,310
-42	43,628	65,655	95,990	135,350	186,480	258,070	356,920
-41	24,409	37,093	56,313	83,402	119,100	165,270	227,370
-40	14,958	21,022	31,470	48,147	72,041	104,370	146,170
-39	10,060	13,343	18,250	26,832	41,017	61,922	91,020
-38	7,083	9,092	11,945	16,084	23,035	34,823	53,059
-37	5,194	6,480	8,241	10,728	14,312	19,888	29,576
-36	3,865	4,787	5,944	7,496	9,673	12,784	17,358
-35	2,806	3,555	4,412	5,465	6,843	8,751	11,457

CPT BACKGROUND

The Channel Portfolio Tool (CPT) is a web-based decision-support package that shows the extent to which Corps-maintained navigation channel depths are utilized by commercial shipping. CPT uses the confidential, dock-level tonnage database maintained by the Corps' Waterborne Commerce Statistics Center (WCSC) to provide an objective, consistent basis by which channels may be quickly compared to others for prioritization of limited Operation & Maintenance (O&M) funding. This capability provides Corps navigation managers and project engineers with improved justification for annual O&M dredging budget requests. Since its inception in 2008, CPT has evolved from a proof-of-concept tool covering only a few deep-draft ports into a mature, robust analysis package covering the entire navigation portfolio of projects, both inland and coastal. Though not available to the general public, CPT is available to federal employees at: https://www.cpt.usace.army.mil/.

The USACE actively maintains navigation channels in over 360 individual projects nationwide, while the total number of authorized federal projects exceeds 1,400. In recent years the Corps has averaged more than $700 million annually in O&M dredging expenditures in support of the navigation mission. In order to make the current budgeting process more transparent and objective, project managers and District operations personnel need to be able to defend their budget requests in quantifiable terms and dredge their navigation projects so as to optimize local and regional economic benefits. Likewise, at the Division and USACE-HQ levels, limited dredging funds must be allocated across regions according to a rational, consistent methodology using readily-available performance metrics.

To help address these needs, CPT provides decision makers with relevant data concerning commercial shipping activity that is directly supported by Corps dredging activities. CPT conducts nearest-neighbor matching of WCSC's Master Docks database with a spatial network representing Corps-maintained channels and waterways. Entries in the tonnage database are routed from origin to destination docks through this network using well-established shortest-path algorithms. The cumulative statistics for tons, $-value, vessel draft, commodity types and traffic types are then compiled for each individual link (i.e. channel segment) in the network. The web-based CPT interface provides a straightforward means of querying and filtering the resulting data to suit user specifications, such as tonnage totals transiting at depths most vulnerable to shoaling.

CPT output includes vessel draft profile charts showing the cumulative annual commercial tonnage transiting selected navigation projects at each 0.3-m (1-ft) increment of maintained channel depth. Present channel conditions and historical shoaling rates are compared to the draft profile to determine the amount of cargo that is directly impacted by channel shoaling conditions. CPT also contains a "Rollup" feature that is essential for evaluating dredging work packages that cover more than a single reach or channel. These rollup summaries are not simply additive totals for all navigation projects in a specified spatial domain; rather, by taking advantage of the movement-level resolution in the detailed Waterborne Commerce records, these consolidated statements of commerce avoid double-counting of tonnage that transits more than one channel in the defined system. Figure 5 is an example of this high-level summary depth utilization charts from CPT for the Southwestern Gulf of Mexico region. The rollup of the various ports along the Texas and Louisiana coasts shows the overwhelming amounts of crude petroleum imports in the deeper draft ranges. There is a significant drop-off in tonnage magnitude at 12.2-m(40-ft), though significant levels of cargo move all the way out to 13.7-m (45-ft). One can also see the contribution of the Gulf Intracoastal Waterway (GIWW), with significant levels of petro-chemical products moving via shallow-draft barges.

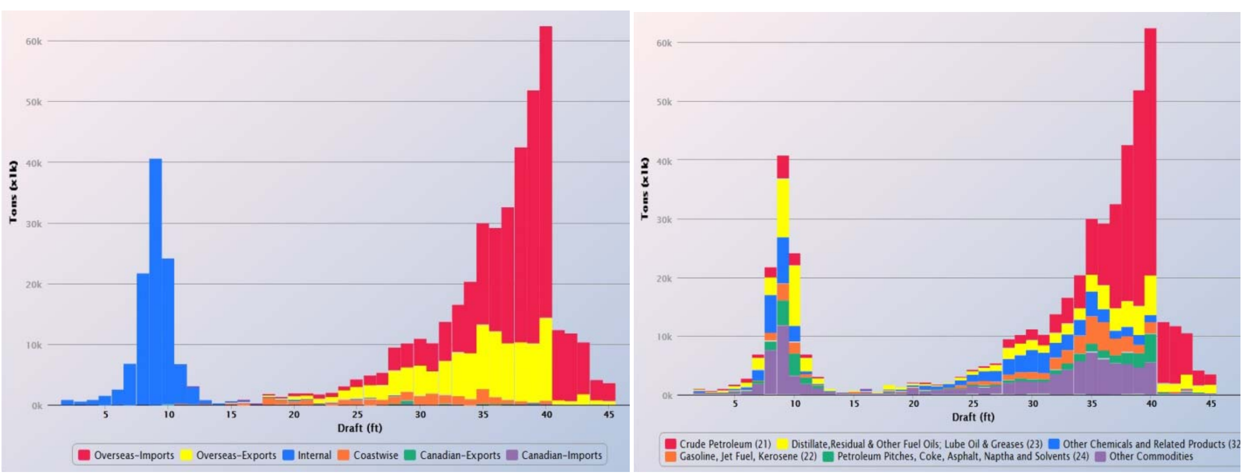

Figure 5. Draft-utilization charts for the Louisiana and Texas coasts (does not include Lower Mississippi River) showing traffic type (left) and top-5 commodity (right) breakdowns, FY09-FY13.

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The central concept underlying CPT is that the USACE portfolio of maintained navigation channels and waterways is an interconnected transportation system. That is, waterborne traffic utilizing any one portion of the system likely also transits other portions during the course of its journey. Likewise, the impacts to waterborne commerce from the physical condition (i.e. channel controlling depth) of any given navigation channel are not isolated within just that channel; they are realized system wide, in all other portions of the waterway network through which transiting tonnage also travels (Mitchell, et al., 2013).

The systems-based approach to navigation channel portfolio management adopted by CPT represents a promising path forward for the Corps. In a time of constrained budgets and an uncertain fiscal outlook for civil works O&M, the Corps must use limited resources optimally so as to maximize national benefits while also providing objective, consistent justification for annual maintenance dredging investments. CPT provides a straightforward, accessible decision-support package for achieving these objectives.

GALVESTON HARBOR AND CHANNEL COMMERCE SUMMARY

The Galveston Harbor and Channel navigation project is a critical national freight corridor, carrying over 200M tons of cargo annually and serving as the single largest entrance channel by far for petroleum products in the country. Galveston Harbor branches off of the main Galveston Entrance Channel and carries over 11M tons annually. However, this total is modest compared to the total throughput of the main Entrance Channel, which serves as the deep-water gateway for the Texas City Channel, the Houston Ship Channel, the Bayport Ship Channel, and the Barbours Terminal project. Table 5 shows the maintained depths and annualized summary cargo totals for the sub-channels making up the Galveston Harbor and Channel navigation project. Refer to Figs. 1 or 4 for the corresponding reach identifiers (e.g. GA_1A_EXT_1) for each spatial extent of channel.

Table 5. Reaches and respective annualized tonnage for Galveston Harbor and Channel Project, FY09-FY13.

CPT Reach Name	Maintained Depth (ft)	Average Annual Tonnage (x1M)	Average Annual Tonnage (x1M), Deepest 10-ft
01a Extended Entrance Channel (GA_1A_EXT_1)	45	212.0	126.0
001 Entrance Channel (GA_01_ENT_1)	45	212.0	126.0
002 Outer Bar Channel (GA_02_OBC_2)	45	212.0	126.0
003 Inner Bar Channel (GA_03_IBC_3)	45	212.0	126.0
004 Bolivar Roads Channel (GA_04_BRC_4)	45	209.1	123.6
006 Bolivar Roads to Exxon Oil Dock (Mile 0.0 To Mile 1.5) - (GA_06_BRE_6)	40	11.8	5.6
007 Exxon Oil Dock to Todd Shipyards (Mile 1.5 To Mile 3.0) - (GA_07_ETS_7)	40	11.6	5.5
008 Todd Shipyards to Pier B (Mile 3.0 To Mile 4.2) - (GA_08_TSB_8)	40	10.4	5.0

Note that the outermost column shows just the annualized tonnage utilizing the 3.3 deepest meters (10 deepest feet) of the respective channel segments. CPT allows users to summarize just the cargo utilizing the deepest *n*-feet of channel depth, in order to place the focus on the cargo that is most directly dependent (or even possibly dependent) on year-to-year maintenance dredging. This is in an effort to provide improved prioritization approaches for O&M

channel dredging, since total annual tonnage by itself does not necessarily convey the degree to which cargo relies upon fully-maintained channel depths for cost-effective transport.

Per Table 5, the drastic variation in commercial utilization between reaches and across the range of depths for the Galveston Harbor and Channel project has implications for how limited dredging resources are allocated. Figures 6-7 reinforce this point by showing the average annual depth-utilization charts (as shown previously for the Southwestern Gulf of Mexico region in Figure 5) for the Galveston entrance channel and Galveston Harbor, respectively.

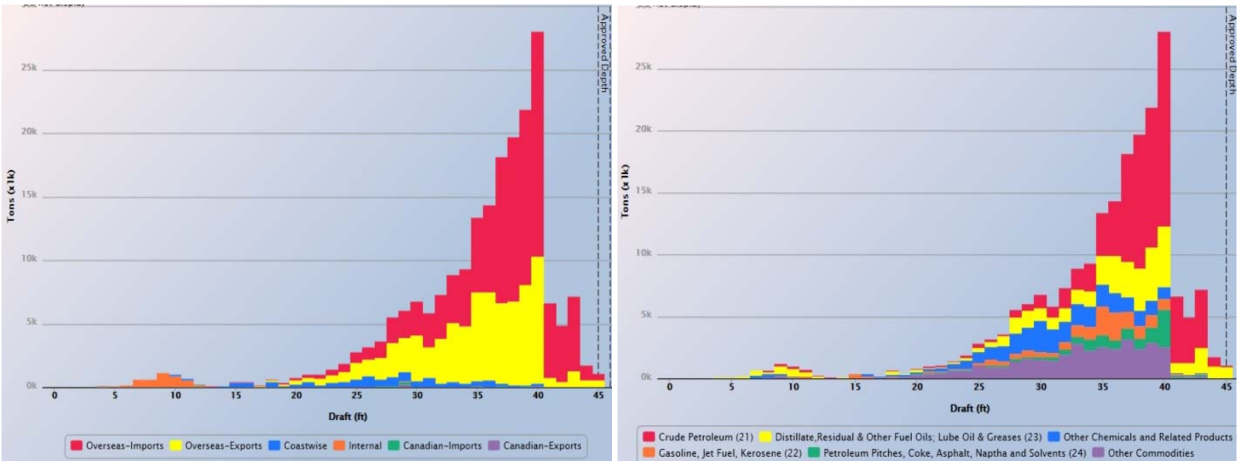

Figure 6. Draft-utilization charts for the 13.7-m (45-ft) Galveston entrance channel reaches showing traffic type (left) and top-5 commodity (right) breakdowns, FY09-FY13.

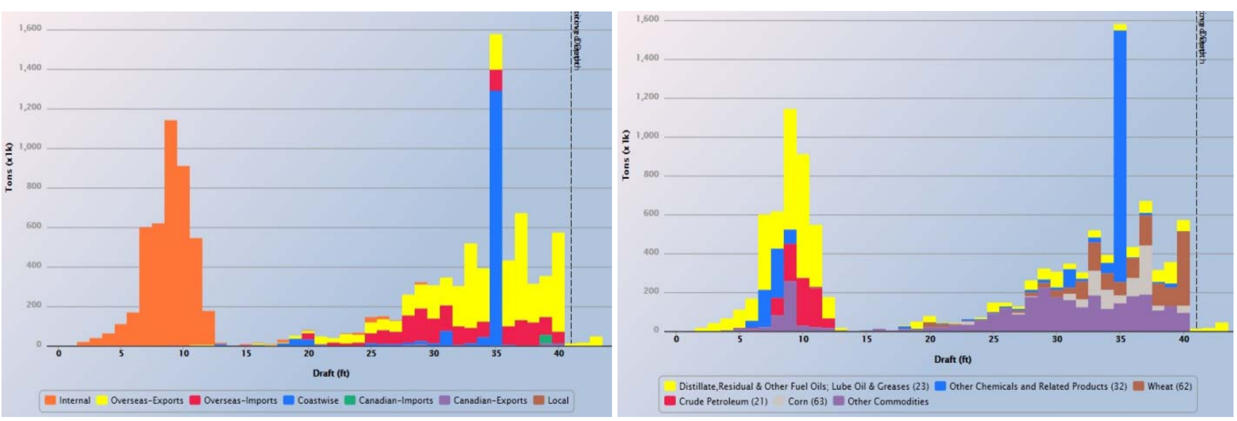

Figure 7. Draft-utilization charts for the 12.2-m (40-ft) Galveston Harbor reaches showing traffic type (left) and top-5 commodity (right) breakdowns, FY09-FY13.

At the 12.2-m (40-ft) increment of vessel draft, over 25M tons of cargo (mostly imported crude petroleum) move through the Galveston entrance channel annually, but there is a pronounced drop-off in tonnage at depths beyond this increment (Figure 6). Likewise, within Galveston Harbor, the draft increment with the largest total tonnage is 10.7-m (35-ft), with nearly 1.6M tons of cargo (mostly domestic shipments of chemicals and related products) moving annually (Figure 7). Note also that proportionally, roughly half the tonnage moving through Galveston Harbor is shallow-draft as a result of barge traffic from the GIWW (this is reinforced in the outermost column for the deepest 3.3-m (10-ft) in Table 5).

This background discussion of the Channel Portfolio Tool (CPT) serves as an introduction of two main points that are critical to the overall approach to navigation channel asset management presented in this work: 1) the rollup concept for summarizing cargo movements across multiple channel segments, and 2) the distribution of cargo across

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the range of maintained channel depths. When combined with the shoaling forecasts generated by CSAT, the information captured by these two concepts enables formulation of an objective basis by which to compare the relative cost-effectiveness of dredging work packages. The overall approach is presented in the following sections.

COMPARISON OF CARGO SUPPORTED TO DREDGING COSTS

The basic approach towards navigation channel asset management described in this paper involves comparing the depth-utilization information presented above via the CPT with the shoaling volume forecasts generated by the CSAT, as shown in Table 4. Figure 5 emphasizes that only a subset of the tonnage utilizing any channel or system of channels is directly affected by a single maintenance dredging decision. In order to focus on the cargo utilizing the deepest, most shoal-vulnerable depths, CPT allows users to specify a range of depths, *n*, that are to be tallied when evaluating benefits of any specified target dredge-to depth, D_T. A schematic of a depth-utilization channel profile is shown in Figure 8.

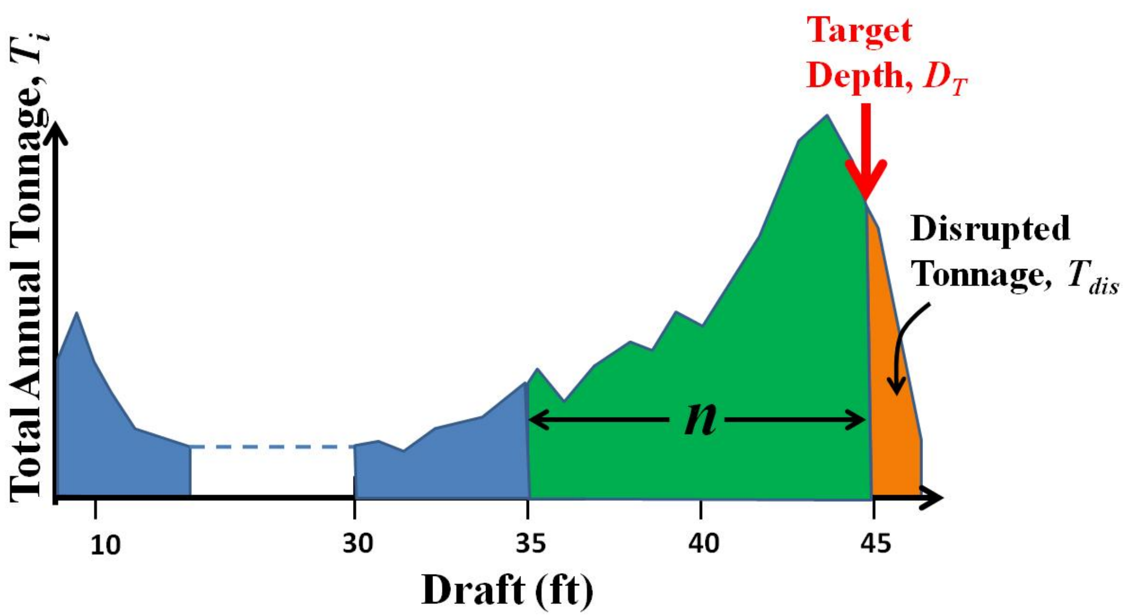

Figure 8. Schematic of depth-utilization profile showing various approaches to tallying supported waterborne cargo.

The area shaded in green represents the range of depths, *n*, that are to be summed when calculating benefits. Note that *n* can be adjusted as needed depending on the localized shoaling rates and other considerations that may convey the degree to which transiting tonnage depends on periodic maintenance dredging. If total annualized tonnage is to be considered, then *n* can be extend all the way back to the 0.3-m (1-ft) draft increment. The average annual tonnage that has historically transited at depths in excess of the specified target depth, D_T, is indicated by the orange portion of the profile chart and would presumably experience some disruption were the channel allowed to shoal in beyond D_T. This tonnage is therefore referred to as T_{dis}.

CSAT forecasts shoaling volumes for specified target depths as well as for specified future time increments as seen in Table 4. The tonnage data described above can be directly compared to the sediment volume forecasts for any specified target depth at future 6-month intervals in order to evaluate relative cost effectiveness. The resulting straightforward, proxy benefit-cost ratio (BCR) is described in Equation 1:

$$BCR_{D_T,k} = \frac{\left(1+\frac{k}{2}\right)\left[\left(\sum_{i=(D_T-n)}^{D_T} T_i\right)-T_{dis}\right]}{C_{MB}+C_{CY}V_{D_T,k}} \qquad (1)$$

Where

$BCRD_{T,k}$ = the proxy benefit-cost ratio for dredging to D_T at time interval k
D_T = the target depth for dredging (ft below mean lower low water, MLLW)
k = number of 6-month intervals into the future dredging will take place
n = number of feet shallower than D_T considered for summing annualized tonnage
T_i = annualized tonnage amount using draft increment i
T_{dis} = historic annualized tonnage transiting deeper than the specified target dredge-to depth
C_{MB} = typical mobilization-demobilization costs for dredging the project or reach
C_{CY} = historic dredging cost per cubic yard of material at the project or reach
$V_{DT,k}$ = volume of material predicted by CSAT that must be dredged to achieve specified target depth, D_T, after k 6-month increments
k = number of 6-month intervals into the future that dredging is to be conducted

Eq. 1 can be evaluated over a full range of target depths and future time intervals in order to find the most cost-effective balance for maintenance dredging in a particular channel. Figure 9 shows several such examples from Galveston, and also shows how the proxy BCR values change as a function of the localized mobilization-demobilization costs, C_{MB}, and the unit costs of dredging, C_{CY}.

	Years between Dredging Events						
Target Elev, ft (MLLW)	1	1.5	2	2.5	3	3.5	4
45	16.16	21.71	25.15	27.35	29.03	30.70	33.17
44	16.46	22.52	26.36	28.78	30.64	32.47	35.19
43	16.71	23.30	27.58	30.27	32.32	34.34	37.34
42	15.94	22.60	27.11	29.91	32.00	34.03	37.04
41	15.75	22.73	27.65	30.68	32.92	35.04	38.17
40	15.19	22.14	27.33	30.56	32.89	35.07	38.21
39	14.48	21.32	26.71	30.12	32.52	34.73	37.87
38	13.14	19.42	24.65	28.12	30.47	32.60	35.57
37	11.96	17.76	22.82	26.35	28.68	30.74	33.57
36	10.51	15.64	20.28	23.69	25.96	27.89	30.47
35	8.92	13.30	17.39	20.57	22.71	24.44	26.72
34	7.28	10.87	14.28	17.05	19.02	20.54	22.45
33	5.93	8.86	11.69	14.11	15.89	17.23	18.84
32	4.88	7.31	9.66	11.75	13.36	14.57	15.95
31	4.13	6.19	8.20	10.04	11.53	12.65	13.86
30	3.31	4.97	6.59	8.11	9.39	10.38	11.40
29	2.47	3.70	4.92	6.08	7.10	7.91	8.71
28	1.92	2.88	3.83	4.75	5.58	6.27	6.92

	Years between Dredging Events						
Target Elev, ft (MLLW)	1	1.5	2	2.5	3	3.5	4
45	13.95	16.09	16.05	15.60	15.31	15.35	16.15
44	14.81	17.62	17.71	17.14	16.76	16.77	17.68
43	15.72	19.42	19.68	18.96	18.45	18.43	19.47
42	15.22	19.58	20.24	19.49	18.91	18.82	19.85
41	15.29	20.56	21.75	20.94	20.22	20.05	21.12
40	14.86	20.52	22.38	21.69	20.90	20.68	21.75
39	14.27	20.27	22.86	22.35	21.48	21.19	22.26
38	13.01	18.70	21.74	21.68	20.84	20.51	21.52
37	11.89	17.30	20.80	21.22	20.40	20.02	20.98
36	10.48	15.35	18.87	19.74	19.14	18.75	19.61
35	8.91	13.14	16.54	17.79	17.42	17.03	17.77
34	7.28	10.78	13.74	15.14	15.10	14.79	15.40
33	5.93	8.82	11.39	12.88	13.12	12.87	13.36
32	4.88	7.29	9.47	10.93	11.37	11.26	11.67
31	4.13	6.18	8.09	9.53	10.14	10.14	10.50
30	3.31	4.96	6.53	7.79	8.46	8.59	8.92
29	2.47	3.70	4.89	5.91	6.56	6.78	7.05
28	1.92	2.88	3.82	4.65	5.25	5.52	5.78

	Years between Dredging Events						
Target Elev, ft (MLLW)	1	1.5	2	2.5	3	3.5	4
45	9.44	8.44	7.09	6.23	5.77	5.58	5.77
44	10.95	10.00	8.24	7.09	6.48	6.23	6.45
43	13.02	12.27	9.82	8.21	7.38	7.03	7.28
42	13.16	13.35	10.73	8.79	7.77	7.34	7.57
41	13.86	15.40	12.45	9.91	8.60	8.02	8.24
40	13.80	16.34	13.69	10.76	9.19	8.49	8.68
39	13.59	17.31	15.19	11.74	9.82	8.96	9.11
38	12.56	16.54	15.39	12.04	9.90	8.93	9.03
37	11.66	15.89	15.88	12.61	10.14	9.02	9.07
36	10.35	14.39	15.18	12.46	9.97	8.74	8.73
35	8.88	12.58	14.11	12.07	9.59	8.26	8.18
34	7.26	10.45	12.13	10.88	8.78	7.47	7.33
33	5.93	8.66	10.43	9.88	8.14	6.83	6.62
32	4.88	7.21	8.86	8.80	7.47	6.27	6.02
31	4.13	6.16	7.72	8.09	7.13	5.99	5.68
30	3.31	4.96	6.31	6.84	6.28	5.36	5.06
29	2.47	3.70	4.79	5.38	5.18	4.51	4.23
28	1.92	2.88	3.77	4.32	4.34	3.90	3.66

	Years between Dredging Events						
Target Elev, ft (MLLW)	1	1.5	2	2.5	3	3.5	4
45	11.58	11.58	10.41	9.49	8.95	8.77	9.12
44	12.87	13.29	11.86	10.67	9.98	9.72	10.12
43	14.44	15.54	13.76	12.15	11.23	10.88	11.33
42	14.26	16.32	14.67	12.81	11.71	11.27	11.71
41	14.64	17.98	16.48	14.18	12.81	12.21	12.65
40	14.38	18.49	17.59	15.11	13.52	12.80	13.22
39	13.97	18.89	18.79	16.11	14.23	13.37	13.75
38	12.81	17.71	18.48	16.15	14.14	13.18	13.51
37	11.79	16.67	18.36	16.42	14.23	13.15	13.42
36	10.42	14.92	17.09	15.79	13.73	12.58	12.78
35	8.90	12.89	15.40	14.79	12.91	11.70	11.83
34	7.27	10.63	13.00	12.96	11.54	10.42	10.47
33	5.93	8.75	10.96	11.40	10.39	9.33	9.30
32	4.88	7.26	9.20	9.90	9.29	8.40	8.32
31	4.13	6.17	7.93	8.86	8.59	7.82	7.70
30	3.31	4.96	6.43	7.35	7.37	6.83	6.72
29	2.47	3.70	4.85	5.67	5.89	5.58	5.49
28	1.92	2.88	3.80	4.50	4.82	4.68	4.63

Figure 9. Sensitivity of dredging work plans to unit costs, CCY, ($/CY) and mobilization-demobilization costs, CMB, ($M); CCY/CMB ratio value is, clockwise from top left, 0.5, 01.5, 3.0, and 5.0.

The units for the numbers shown in each cell are tons of cargo supported per dollar spent dredging, but the relative values are more important than the absolute figures. Figure 9 shows that as the mobilization-demobilization costs decrease relative to the costs of dredging (a function of both unit costs and volumes to be dredged), Eq. 1results in more frequent dredging events with a slightly shallower target depth. Stated differently, if it is relatively expensive to mobilize a dredge to the navigation project before any material has actually been dredged, then it makes sense to space these dredging events as far as possible and to conduct at least some advance maintenance dredging; that is, D_T is deeper than it would be otherwise. The charts in Figure 9 give Corps navigation project managers the tradeoff information that is important when weighing any one particular maintenance dredging decision against others. Depending on the shoaling rates forecast by CSAT and the depth-utilization information captured by CPT, dredging managers can see a range of possible alternatives and their relative cost-effectiveness, per the proxy BCR metric (Eq. 1).

DREDGING WORK PACKAGE ROLLUP FORMULATION

The previous sections of this paper have described a process for rigorously quantifying the dredging requirements for maintaining navigation channels to specified dimensions while also factoring in the relative benefits from dredging in terms of deep-drafting cargo throughput that is directly supported by the restored channel depths. By comparing these two quantities, the cost of dredging and the supported waterborne commerce, a proxy benefit-cost ratio (Eq. 1) provides a straightforward and scalable means by which maintenance dredging activity throughout the country can be objectively compared. The final step involves combining multiple channel segments or reaches into a single dredging work package that will be evaluated during the Corps annual budget development process. Smaller navigation projects are typically covered by single dredging work packages, while larger projects (Lower Columbia River, Houston Ship Channel, etc.) may require dozens of individual budget proposals to cover the entire spatial extent. Because shoaling is a highly localized phenomenon, dredging project managers typically determine which reaches to include within a proposed work package based on present conditions and time that has elapsed since the last dredging occurred. The tradeoff is between overall costs of the work package and the anticipated benefits to navigation, and dredging managers must weigh these considerations when deciding which reaches to include and to what extent they are to be maintained. The CSAT-CPT suite described here provides additional quantitative rigor to inform this decision making process.

Recall from Table 4 and Figure 6-7 the large differences that exist in the depth-utilization profile for the respective reaches comprising the Galveston Harbor and Channel navigation project. In addition to having much lower levels of overall tonnage than the main entrance channel, the three Galveston harbor reaches (Fig. 4) actually have relatively higher shoaling volumes and rates. This is true even when accounting for the shallower maintained depths in the harbor reaches. The result of this dynamic is that a work package crafted for just the entrance channel reaches will score relatively high using Eq. 1 while a work package for just the harbor reaches will score relatively low. Table 6 shows the relative BCR scores for three sample work package formulations, one each for the Galveston entrance channel and harbor, and a combined work package for the entire project.

Table 6. Summary of sample work package rollups and BCR scores for Galveston Harbor and Channel.

Work Package	Present BCR	6-month BCR	1 year BCR	1.5 year BCR	2 year BCR	2.5 year BCR	3 year BCR
Entrance only (45 ft)	58.0	61.2	58.7	55.4	52.4	49.9	47.7
Harbor only (41 ft)	2.3	2.6	2.6	2.7	2.7	2.9	3.0
Entire project (45 ft and 41 ft)	29.7	30.4	29.4	28.2	27.3	27.2	27.1

For the results in Table 6, a uniform dredging unit cost of \$3.00/CY was assumed along with an overall mobilization/demobilization cost of \$1M. Additional work packages could be formulated at varying target depths for the respective reaches comprising the project. The CPT interface allows Corps dredging managers to specify these target depths when deciding which reaches to include in a work package. It is important to note that the CPT "Rollup" feature (see previous discussion in CPT Background section and Figure 5) provides the numerator for Eq. 1 whenever more than one reach is being considered for a work package. By using this feature, double-counting of tonnage that transits multiple reaches under consideration is avoided. The dredging costs, in contrast, are additive and can simply be summed up across the respective reaches. Example results from reaches for the other pilot projects considered in this effort (Table 1) are shown in the chart in Figure 10. Note that some locations are shown more than once with different target depths specified. The absolute values reflect localized assumptions of unit costs and mobilization-demobilization costs, and should not be interpreted as necessarily reflective of the true dredging cost effectiveness at each location. Nonetheless, the wide variation in proxy BCR scores demonstrates how this approach could be used within the Corps existing budget development process to evaluate maintenance dredging decisions nationally.

		Time Until Dredging Takes Place (Years)						
	Optimal Target Depth (ft)	1	1.5	2	2.5	3	3.5	4
Calcasieu Outer	38	20.43943	22.99373	16.1911	11.49139	8.791689	7.167862	6.138435
Calcasieu Gap	40	35.03011	52.46583	68.87481	82.36058	90.64498	94.80497	94.14798
Columbia near MCR	41	35.77783	26.92696	11.9538	7.313952	5.418806	4.439269	3.880387
Texas City outer	40	39.39505	55.06927	62.90344	64.24062	62.38521	59.47904	56.6367
Texas City total	40	38.41477	46.30422	44.95194	41.97186	39.26637	37.47005	36.23801
Charleston Entrance	35	12.3408	18.51115	24.65794	30.19148	33.13396	32.6626	30.26347
Cook Inlet	30	2.296588	3.44487	4.593099	5.741193	6.888865	8.034747	9.174922
Galveston Entrance	40	185.0326	255.9148	280.0451	262.7408	230.1306	197.8446	170.9211
Galveston Entrance	45	77.2865	81.43576	78.16375	73.73789	69.79972	66.44992	63.59281
Galveston Harbor	35	2.881098	3.141968	3.078682	2.926068	2.788178	2.876293	2.961408
Galveston Harbor	37	2.719758	2.909423	2.875424	2.788714	2.723247	2.844596	2.969029
Charleston Entrance	40	11.60721	15.01959	16.36798	16.45441	15.96604	15.24692	14.45367
Charleston Wando	44	6.095054	9.142581	12.19011	15.23764	18.28516	21.33269	24.38022

Figure 10. Example work package BCR scores for the pilot projects considered in this effort.

CONCLUSIONS

The USACE maintains hundreds of deep-draft coastal ports and waterways as part of its navigation mission, and therefore must manage these assets in an objective and standardized approach in order to maximize national benefits while also providing consistent justification for annual maintenance dredging investments. This work discusses efforts by USACE Research and Development to leverage spatial and economic datasets needed to objectively quantify the benefits of maintaining navigation channels to specified depths.

CPT summarizes cargo movements across multiple channel segments via the rollup function in addition to showing the distribution of cargo across the range of maintained channel depths. Combining these two concepts with the shoaling forecasts generated by CSAT enables formulation of an objective basis to quantify comparison of cargo supported by dredging to any specified target depth to the requisite dredging costs. Incorporating the shoaling rates forecast by CSAT and the depth-utilization information captured by CPT, Corps dredging managers can see a range of possible alternatives for maintaining the navigation channels at specific depths and time increments and their relative cost-effectiveness, per the proxy BCR metric. Via this approach, dredging work packages from across the Corps' navigation portfolio of projects can be objectively compared for cost-effectiveness.

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