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Management of coastal navigation channels based on vessel underkeel clearance in transit

By

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Management of coastal navigation channels based on vessel underkeel clearance in transit

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The United States Army Corps of Engineers (USACE) spends approximately $2 billion annually to investigate, construct, and maintain projects in its portfolio of coastal navigation infrastructure. Of that expenditure, approximately $1 billion is spent annually on maintenance dredging to increase the depth of maintained channels. The USACE prioritizes maintenance funding using a variety of metrics reflecting the amount of cargo moving through maintained projects but does not directly consider the reduction in the likelihood for the bottom of a vessel's hull to make contact with the bottom of the channel that results from maintenance dredging investments.

Net underkeel clearance, which remains between the channel bottom and the vessel's keel after considering several important factors that act to increase the necessary keel depth, is used as an indicator of potential reduction of navigation safety. This dissertation presents a model formulated to estimate net underkeel clearance using archival Automatic Identification System (AIS) data and applies it to the federal navigation project in Charleston, South Carolina. Observations from 2011 including

3,961 vessel transits are used to determine the probability that a vessel will have less than 0 feet of net underkeel clearance as it transits from origin to destination. The probability that a vessel had net underkeel clearance greater than or equal to 0 feet was 0.993.

A Monte-Carlo approach is employed to prioritize reach maintenance improvement order. A value heuristic is used to rank 7,500 dredging alternatives. 159 options were identified that meet an arbitrarily selected minimum reliability of 0.985. Cost reductions associated with options that met the minimum reliability requirement ranged from 7.7% to 42.6% on an annualized basis. Fort Sumter Range, Hog Island Reach, and Wando Lower Reach are identified as the most important reaches to maintain.

The underkeel clearance reliability model developed in this work provides a more accurate representation of the waterway users' ability to safely transit dredged channels with respect to available depth that is currently available to USACE waterway managers. The transit reliability metric developed provides an accurate representation of the benefit obtained from channel dredging investments, and directly relates the benefit to dredging cost.

DEDICATION

To my wife, Jessica, for her love, strength, and inspiration.

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I am indebted to the members of my committee for their support and guidance without which this work would be far inferior to its present state. I am grateful to the individuals that have seen promise in me and supported my professional development, and for those inspirational giants who have sparked in me a drive to endure the difficulties of academic pursuit, though my achievements pale in comparison. This journey would not have been possible but for the funding available through the GI Bill, an enduring gift to this country's veterans. Finally, to the men and women who sacrifice all so that others may live freely, thank you.

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CHAPTER I

INTRODUCTION AND PROBLEM BACKGROUND

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Introduction

The United States Army Corps of Engineers (USACE) programmatically maintains a portfolio of coastal navigation infrastructure (channels, disposal areas, locks, dams etc.) that includes over 12,000 miles of navigation channels at nearly 1,000 ports (NRC, 2013). Efficient design, operation, and maintenance of this navigation infrastructure are vital to the nation's economy and security.

In managing this portfolio, the USACE spends approximately $2 billion annually to investigate, construct, and maintain projects (NRC, 2011, USACE, 2012). Of that expenditure, approximately $1 billion is spent annually on maintenance dredging to remove sediment that reduces the depth of maintained channels. Recently, the full-depth availability of maintained channels has been reported as approximately 35% (GAO, 2008, Frittelli, 2011; USACE, 2014).

Execution of capital and maintenance dredging operations undertaken as part of the USACE navigation mission is hampered by constraints to available funding (GAO, 2008; Frittelli, 2011; NRC, 2013). Construction and major maintenance of inland navigation projects is funded through a fuel tax imposed on diesel fuel used to ship goods

(26 U.S. Code § 4042) and balances are held in the Inland Waterway Trust Fund (26 U.S. Code § 9506). Tax revenue balances of the Inland Waterways Trust Fund have been substantially reduced by over-budget construction projects (NRC, 2013). Inland waterway maintenance is also partially funded through general appropriations from the Congress (Frittelli, 2011, NRC, 2013).

Construction of coastal projects is funded through local cost sharing and congressional appropriation (USACE, 2012; NRC, 2013). Maintenance for coastal navigation projects, the focus area of this study, is primarily funded through Harbor Maintenance Tax (HMT) revenue, collected and placed in the Harbor Maintenance Trust Fund (HMTF) (GAO, 2008; Frittelli, 2011; 19CFR 24.24, 26 U.S. Code § 9505). The HMT is an ad valorem tax of 0.125% on the value of certain imported and coastwise cargo, established under Public Law 99-662. Outlays from the HMTF are approximately 50% of annual revenues levied on the value of imports (approximately 95% of revenue) and coastwise trade (approximately 5% of revenue (GAO, 2008; Frittelli, 2011)). Further funding is available through congressional appropriation. The Water Resources Reform and Development Act passed in 2014 (WRRDA 14, P.L. 113-121) gradually raises the target expenditure rate of the HMTF to 100% by 2025, but the deferred maintenance backlog of active projects far exceeds the balance of the HMTF (NRC, 2011).

Constraints on maintenance and construction funds exist despite shipping industry trends toward increasing vessel sizes to capture economies of scale while moving ever larger amounts of cargo (Waters et al., 2002; USACE, 2012, OECD, 2015). Harbors have subsequently deepened to accommodate this trend toward larger vessels. Capital dredging to previously un-dredged depths in many cases creates a future demand for additional maintenance dredging as deepened channels increase in sediment trapping efficiency (ASCE, 2005, USACE, 2006), although shoaling is a highly localized phenomenon dependent on site-specific conditions (NRC, 1983; Lund, 1990; Headland, et al., 2000; USACE, 2006). Thus, industry shipping trends impose additional demands on a constrained system, further compounding the problem of dredging requirements exceeding scarce dredging funds.

Concurrent with resource constraints and increasing dredging requirements, dredging costs have increased for a variety of reasons including inefficient funding appropriation by congress (NRC, 2011), increasing fuel and steel costs (GAO, 2012), and environmental restrictions (Dickerson et al., 1998; GAO, 2014). Performance of dredging work, at least in the case of work performed by hopper dredges, has shifted from USACE owned dredges in the 1970s to contracted industry dredges as encouraged by legislation passed in 1978 and 1993 (GAO, 2003). Initially enacted to spur cost savings and improve the competitive dredging environment, limited evidence of cost savings or increased industry competition has been documented subsequent passage of restrictive legislation. Landside costs have also increased, adding to the costs of upland management of material (GAO, 2012).

Absent sufficient funds to maintain its entire portfolio, USACE must prioritize investigations, construction, and maintenance of navigation projects (NRC, 2011; GAO, 2012; Rosati et al. 2013). USACE prioritizes expenditure of annual Operations and Maintenance (O&M) funding for navigation projects based on a variety of metrics generally reflecting the amount of cargo moving through each federal project. Those deep-draft coastal projects in the “high use” category each move more than 10 million tons of cargo per year (GAO, 2012; USACE, 2014). “Moderate use” commercial ports carry between 1 and 10 million tons of cargo per year. “Low use” harbors that have less than 1 million tons are prioritized based on other binary characteristics, such as whether the harbor is a “critical harbor of refuge”, a “subsistence harbor”, or home to a US Coast Guard (USCG) search and rescue station. Some quantitative criteria, such as tons of commercial fishery landings, and cargo value are also considered (USACE, 2014). Requests for funding are normally made two years prior to the year in which they will be used.

Within the hierarchy of USACE operations, oversight of maintenance and construction activity is the responsibility of a cadre of waterway managers charged with executing the navigation mission. The data that supports funding requests is regularly generated at the waterway manager level, and results in a prioritized slate of maintenance activities (USACE, 2014).

Data generation is hampered by several factors. One example is that cargo tonnage estimates are normally derived from data published by the USACE Waterborne Commerce Statistics Center (WCSC), though the data is generally only available to waterway managers two years after it is collected. Recent efforts within the USACE Research and Development program have increased ease of access to this data, through the Channel Portfolio Tool (CPT, Mitchell, 2012). There is sustained focus on bringing more transparent and objective criteria to O&M funding decisions. However, the fact remains that a two year lag in data availability combined with a two year lead in funding requests results in a four year information gap in the decision making process.

Dredging managers choose which reaches to dredge, and the depth to which they are dredged. The knowledge uncertainty fed in part by the 4-year information gap mentioned previously helps create an incentive structure for port and waterway managers that frequently leads to excessive funding requests every year. Mayer and Waters (2002) point out that it is within existing USACE regulations allow navigation managers to select dredging depth less than authorized depth when existing user demand can be met with a shallower channel.

Design & Construction vs. Maintenance

The design of navigation channels has been well studied in the last century, with a substantial number of navigation projects being constructed in the US and worldwide. The breadth of literature indicates design paradigms that can be classified as deterministic or probabilistic (Zwamborn, 2000, PIANC, 2014). Deterministic approaches used fixed, additive allowances to account for uncertainties in underkeel clearance contributors. Probabilistic approaches consider the mean and variance of empirical measurements of factors contributing to underkeel clearance, and select depth based on the probability of occurrence of threshold values. Both produce conservative results, which is desirable, except when overly conservative designs result in excess construction or maintenance costs, or when construction and maintenance funding sources become constrained (Briggs et al., 2003).

In recent decades, as computational power has increased, virtual simulations of proposed channel designs have come into contemporary practice (Webster, 1992, ASCE, 2005, USACE, 2006). Sophisticated implementations of these models incorporate full scale virtual representation of design vessels, harbor scenes along the transit route, and numerically simulated hydraulic forces acting on vessels in the proposed channel. Design has shifted toward an operator’s ability to safely maneuver simulated vessels through the virtual model of the channel, highlighting the importance of judgment and experience of professional pilots who navigate large vessels from the open ocean safely to port. The cost and time required to design channels using such a sophisticated approach are substantial, and generally beyond the resource and mission scope of those charged with maintaining channels post construction.

Given the commercial and strategic importance of the task of maintaining navigation projects, and the costs and constraints associated with doing so, many attempts to improve the ability of navigation system managers to reduce operational costs and improve management strategies are documented in the literature. As maintenance funds have remained constrained in the presence of increasing dredging costs, optimization of maintenance investment has emerged as a focus area. Recent works have incorporated the use of linear programming (Mayer and Waters, 2002), nonlinear and mixed integer programming optimization models (Ratick and Garriga, 1996; Mitchell et al., 2013; Khodakarami et al., 2014), genetic algorithms (Mitchell et al., 2014), and other sophisticated techniques (Lund, 1990; Lansey and Menon, 1993) to select the portfolio of navigation investments at the port level that results in the greatest throughput of cargo for a given funding level. These tools are valuable for strategic decision-making regarding allocation of O&M funds. However, USACE waterway managers lack requisite tools to efficiently estimate reach-level dredging requirements.

The landscape of USACE navigation maintenance operations is such that there are four fundamental strategies available in terms of infrastructure condition improvement:

1. the scope of maintenance must decrease
2. the cost of maintenance must decrease
3. the supply of maintenance funds must increase
4. the efficiency of capital application must improve

Work in the late 20th and early 21st century recognized the need to broaden the approach to sediment management beyond simply removing sediment from navigation channels (Martin, 2002, Shelly et al., 2016). This is fundamentally a capital efficiency strategy as it reduces mobilization and sediment management costs. Treating sediment as a resource instead of as a waste byproduct has resulted in cost savings where opportunities exist to use dredged material to achieve a desirable outcome, such as beach nourishment (Martin, 2002). The recent WRRDA 14 addresses capital supply constraints by mandating increased expenditures from the HMTF, and maintenance scope constraints by mandating deauthorization of unmaintained projects. It is estimated that deferred maintenance funding requirements will continue to eclipse available maintenance, even with full HMTF expenditure, for the foreseeable future (GAO, 2008; NRC, 2011). Some work has been focused on the functionality of vessels in spite of sediment, such as work on the nautical depth concept, which is fundamentally a scope reduction strategy (McAnally et al., 2015).

Two important areas that appear to have garnered limited additional study are vessel-centric scope reduction where fluid mud is not a concern, and reach-level capital application efficiency based on the network structure of navigation systems. It is possible that unnecessary routine maintenance is ongoing within the maintained USACE project portfolio, given the size of the portfolio and the lack of tools available to inform maintenance dredging depth requirements and prioritize selection of individual reaches. This is detrimental to unmaintained projects within the portfolio that fall just below performance-based funding thresholds. Further, metrics that capture network importance of individual links within the navigation can be improved. O&M funding decisions are instead directed toward multi-segment work packages or project sub-components assumed to support a greater project in a meaningful way.

Research Motivation

This study is primarily motivated by the confluence of several factors including the importance of supporting navigability of USACE waterway projects, rising production costs for dredging and sediment management, and the persistent constraints associated with available maintenance funding. The emergence of large-scale datasets such as condition information stored in e-HYDRO, channel shoaling information generated through Channel Shoaling Analysis Tool (CSAT, Dunkin and Mitchell, 2015), and operational vessel data captured by AIS (USACE, 2012; Mitchell and Scully, 2014; Shelmerdine, 2015) provides impetus for investigation into targeted user-based waterway performance metrics.

By leveraging traditional approaches with emerging technology, it is possible to develop a highly granular reliability-based model that estimates the channel depth requirements for individual waterway users compared to the depth available in reaches of coastal waterways. The unprecedented coverage and availability of AIS data in particular may close gaps that exist within traditional data sources and better inform management decisions on a broad scale. Developing such a model will be valuable to tactical level managers charged with maintaining waterways within the navigation portfolio. Recognizing that each waterway reach, and subsequently each navigation project exists within the larger context of the entire navigation portfolio network, USACE waterway managers will benefit from development of a transit reliability model that accounts for reach connectivity in addition to depth availability of a waterway project to aid in prioritizing which elements of the model are most necessary for ensuring maximum system reliability.

Dissertation Outline

This dissertation presents the development of a reliability-based tactical-level management model that can be used to recommend a maintenance dredging depth or to prioritize project reach maintenance to support safe navigation. Several important factors must be determined to achieve this goal. First, factors that serve to change the draft of vessels in transit, such as water surface changes due to tide fluctuations and the lowering of a ship’s keel due to squat, must be estimated. Second, factors that normally affect vessels in transit must be accounted for and incorporated into the model. Third, depth limitations due to shoaling effects must be estimated. Finally, a decision variable must be identified and treated such that model variables are optimized.

Chapter 2 presents a method for estimating vessel underkeel clearance from several data sources available to USACE navigation managers after review of existing design and operation models of underkeel clearance. Relevant input data and their sources are discussed as they pertain to model formulation. A procedure for delineating individual vessel transits from AIS data is outlined for its relevance to interpolating water surface elevation from the tidal record.

In Chapter 3, the developed navigation channel reliability model is validated through application in Charleston Harbor. AIS data is validated using vessel transit data collected by harbor pilots that navigate ships through the harbor. Bathymetric elevation data generated by the USACE during channel maintenance operations, and water level data collected and verified by NOAA are used as input to the model.

Measures of reliability for maintained reaches and vessel transits are explored in Chapter 4. Routes are proposed as an aggregation of maintained reaches transited when vessels move throughout a harbor. Vessel transit reliability is proposed as a measure of maintenance dredging efficacy that accounts for both available depth at the time of vessel transit and the interconnectivity of transited reaches. The sensitivity of reaches, routes, and transits to changes in available depth is explored, and relationships between reliability and depth loss are developed.

Transit reliability is applied to decision maintenance strategies in Chapter 5. A minimum reliability target is imposed to identify maintenance budget reductions can be achieved while ensuring minimal reliability using a Monte-Carlo optimization technique. Finally, transit reliability is applied to shoaling considerations to explore the impacts of shoaling on transit reliability losses and mitigation costs.

Chapter 6 summarizes the contributions of this dissertation to the practice of navigation channel maintenance. Areas for application of the developed management model as well as areas of future work are discussed.

CHAPTER II

UNDERKEEL CLEARANCE RELIABILITY MODEL

Underkeel Clearance

In general, the design of navigation channel depth is based on the probability that a design ship will transit a navigation channel without contact between the ship's keel and the channel bottom. Guidance is available from a variety of sources for selecting economic depths for channel construction. PIANC (2014) and USACE (2006, 2008) together provide comprehensive treatment of relevant studies and design methods used internationally and in the U.S. There has been a trend in contemporary practice toward a more probabilistic design approach (PIANC, 2014, Briggs et. al, 2013). Moreover, design methods are applied using forecasts of future ship conditions at a point before channels are constructed, which adds design uncertainty.

A definition sketch of relevant contributors to required depth below keel can be found in the USACE (2006), reproduced here as Figure 1. The major contributing factors that make up the gross underkeel clearance between a ship's keel and the nominal channel depth are freshwater effects, ship response to waves, underway squat, and a deterministic safety clearance value. Gross underkeel clearance is defined relative to a deterministic authorized channel level (USACE, 2002, USACE, 2006, PIANC, 2014), and a reference datum. This ensures that gross underkeel clearance will be a minimum at average lower low tides, if accumulated sediment does not encroach above the authorized channel level. The advance maintenance allowance provides a reservoir for the accumulation of sediment, reducing the frequency of dredging, while the dredging tolerance ensures that the uncertain surface resuling from sediment removal operations will be lower than the authorized channel level. Time-varying effects of tidal water surface elevation and shoaling are neglected in this definition. Less obvious but no less relevant is the fact that the design ship loaded draft is intended to be the maximum draft among the entire population of vessels that are anticipated to use the waterway. Many vessels using the waterway may have drafts less than the design ship loaded draft (Mayer et al., 2002).

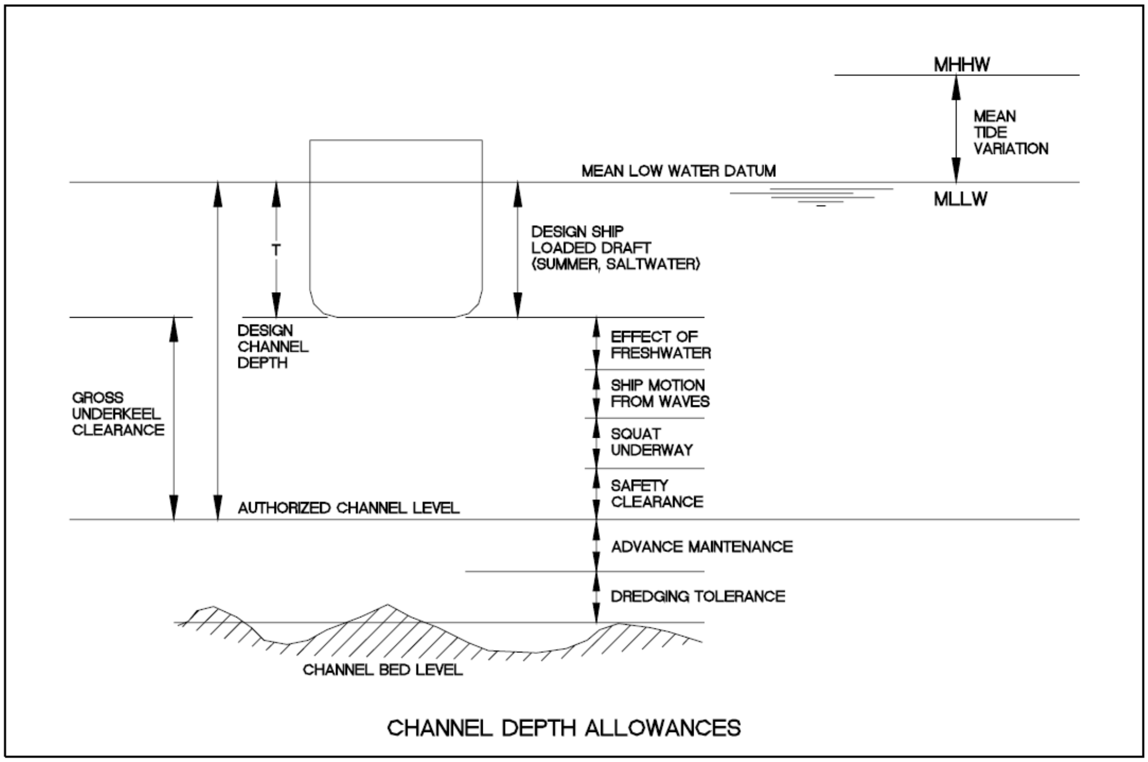


Figure 1 Definition sketch of navigation channel depth allowances.

(USACE, 2006)

Existing Underkeel Clearance Models

The problem of underkeel clearance estimation has been studied by many authors for its importance in contributing to safe transit of vessels through navigation channels as they move between ports and the sea (Kimon, 1982; Silver and Dalzell, 1998; Atkinson & O'Brien, 2008; Briggs et al., 2003; Briggs et al., 2004; Briggs et al. 2013; Briggs et al., 2015; others). Previous investigations of underkeel clearance can be broadly characterized as either operational underkeel clearance (Silver and Dalzell, 1998; Atkinson & O'Brien, 2008), or underkeel clearance for channel design (Kimon, 1982; Briggs et al., 2003; Briggs et al., 2004; Briggs et al. 2013; Briggs et al., 2015). The contextual approach of each application is different, but the goal of each is to reduce the likelihood of vessels touching bottom in artificial navigation channels.

Operational underkeel clearance is principally concerned with the near real time application by vessels in transit. Silver and Dalzell (1998) developed the Environmental Monitoring and Operational Guidance System (EMOGS) to help U.S. Navy vessel operators in transit to make risk based assessments of the likelihood of keel strike while entering a particular location under ambient conditions.

EMOGS was a land-based system that communicated with deployed U.S. Navy ships to improve the probability of safe transit from open-ocean through navigation channels and into protected harbors. The EMOGS considered near real-time conditions and relied on a database of vessel response functions particular to the specific vessel on which it was used. Equation 1 shows the model formulation:

$$C_{eff} = (E_{ch} + E_{at} + E_{mt}) - \left(T_j + S_j + A_j\right) \tag{1}$$

where:

C_{eff} = underkeel clearance (UKC)

E_{ch} = estimated channel depth at MLLW

E_{at} = water level change due to tides

E_{mt} = water level change due to wind or barometric pressure

T_j = static vessel draft at a vessel control point, *j*

S_j = squat at a vessel control point, *j*

A_j = motion allowance at a vessel control point, *j*

The water surface elevation was determined from separate components: predictions of tidal fluctuations, and near-time meteorological calculations accounting for fluctuations resulting from wind and barometric pressure. Channel bottom elevation variables relied on either the last available CCR made by the USACE, or the authorized dimension of the navigation channel. Squat was estimated from the vessel's speed, estimated water depth, and hull-form information particular to the vessel. The vessel motion allowance was estimated using near-time wave spectral measurements that were transmitted from a prepositioned monitoring station to the vessel on approach.

The authors go on to identify the minimum clearance between a vessel's keel and the channel bottom during a transit as C_M, and the probability density of the minimum clearance by $f_{CM}(C_M)$. The value of C_M is determined as shown in Equation 2:

$$C_M = D_{ch} + D_{at} + D_{mt} - T - S + Z \tag{2}$$

where:

D_{ch} = local channel depth

D_{at} = astronomical tide

D_{mt} = meteorological tide

$T =$ local ship draft

$S =$ local ship squat

$Z =$ local maximum downward motion of the ship

The value of Z in Equation 2 received rigorous statistical treatment. The other values on the right hand side of the equation were summed to the value C_C, called the calm water clearance. Two assumptions allowed variables in Equations 1 and 2 to be treated as random. The first assumption is that transits were viewed as in the context of a hypothetical long series of transits with statistically equivalent conditions. The second is that the location of the minimum distance between vessel keel and channel bottom cannot be predicted, thus the point of minimum underkeel clearance evaluation is random. Using this notation the authors define the risk of keel strike mathematically as shown in Equation 3:

$$Risk = \int_{-\infty}^{0} f_{CM}(C_M)dC_M \tag{3}$$

Probabilistic channel design was initially explored to reduce the cost of channel construction based on deterministic design methods (Kimon, 1982). Such statistical methods aim to select the most cost effective channel depth that provides a design vessel with both a specified underkeel clearance and a design reliability. Silver and Dalzell (1998) described a probabilistic design implementation of the EMOGS model at the US Navy bases at Mayport and San Diego that resulted in considerable dredging cost savings. These deployments used ship transit speeds of 6, 10 and 14 knots (instead of a ship's actual speed), and standard wave spectra (instead of field measurements) to determine the resulting under-keel clearance that represented the "optimum dredge depth" for a design aircraft carrier to safely enter the ports.

Briggs et al. (2013) modified the formulation of the operational EMOGS model for use in design scenarios based on the work by Silver and Dalzell (1998). The resulting Channel Analysis and Design Tool (CADET) determines an elevation below which a vessel would have a specified probability of exceedance. The model's omission of "ephemeral" water level fluctuations is defended by the authors on the basis that design is undertaken for vessel at any time in any direction, thus obviating the need to consider these fluctuations. This choice appears to be a concession made to limit model complexity given the fact that tidal water level fluctuations in particular directly and predictably affect UKC, and indirectly affect squat.

EMOGS and CADET require a specified failure criteria (1 exceedance per 1000 transits in the case of Navy vessels using EMOGS vs. 1 exceedance per 100 transits in the case of CADET) to identify optimal depth or acceptable transit conditions. Thus, both operational and design scenarios are reliability based.

These models are invaluable for determining the risk of keel strike under a wide variety of environmental conditions, but they are not without limitations. The first limitation is that they take as input the particulars of a single vessel. Squat and vessel wave response motions are well defined and validated using numerical and physical models, but the library of tested vessels represents a small fraction of the larger global vessel population.

In the operational case, model results are applicable to a single transit. In design applications, only the largest vessel anticipated to call on the port of interest is modeled, regardless of the frequency with which it calls. Further development is necessary to implement an underkeel clearance model capable of meeting the needs of waterway managers in selecting routine maintenance depths.

Underkeel Clearance Reliability Model Development

The literature suggests that contemporary navigation keel-strike risk models for vessel operation are data intensive, incorporating complex hull models and near-real time environmental data, to minimize the risk of keel strike during a particular transit (Silver and Dalzell, 1998; Atkinson & O'Brien, 2008). These models are very narrow, applying to a single vessel on a single transit, but the methodology can be applied to different vessels. Recent channel depth selection design models have branched from operational models by replacing real-time environmental data with statistical environmental models and applying the operational methods in a Monte-Carlo type approach (Briggs et al., 2013). These design models are motivated by and improve upon overly conservative designs resulting from earlier deterministic approaches.

A model to assist in selecting a defensible maintenance depth based on environmental factors and traffic composition requires several capabilities that are lacking in presently available models. Primarily, the model must consider a random distribution of vessels (both number and dimensions), calling at random water levels and bathymetric elevations. Considering only the design vessel may be a poor gage of channel reliability, especially if many smaller vessels have made successful transits.

Dynamic vessel parameters of a diverse traffic population must be accounted for, but due to the complexity of vessel hull forms and the unavailability of detailed hull models, it is impractical for this study to calibrate vessel motion models across the entire fleet of vessels calling at large ports. This study assumes all vessels call randomly.

Generally little is known about these vessels beyond nominal dimensions and type classifications, limiting the applicability of a traditional operational model. Mixed vessel population scenarios are not widely studied within the navigation channel maintenance literature.

The physical parameters (i.e. draft, water surface, and bathymetric elevation) of a hindcast underkeel clearance model are no different from those encountered by previous researchers. The proposed hindcast model has the advantages of a record of channel condition elevation measurements, historical vessel transit information derived from AIS, and measured water surface elevation that captures tidal and atmospheric fluctuations. However, vessel squat and vessel wave response must be based on assumed engineering properties and are prohibitive to model extensively.

Unlike an operational model, where the risk incurred relates to the consequence of an actual keel strike, a design model involves the consequence associated with inadequate depth available for future vessel transits. Rosati et al. (2013) discuss three primary alternatives shippers may consider when facing depth restrictions in navigation channels: divert traffic to alternative locations, lighter in transit, or light-load at origin. In this regard, a maintenance model will have risk implications similar to a design model. It is possible that these consequences are already being incurred where authorized channel depths cannot be fully maintained.

Silver and Dalzell (1998) identify six primary parameters that affect underkeel clearance of vessels at coastal locations. EMOGS accounts individually for tidal water level fluctuations, atmospheric water level fluctuations, bathymetric elevation, trimmed sailing draft, vessel squat, and vessel motions in response to waves. Each of these parameters is relevant to the proposed model.

Figure 2 shows the relationship of parameters contributing to underkeel clearance tracked by the proposed model. The parameter T_{ijt} is the draft of vessel *i* at location *j* and time *t*. The parameter h_{jt} is the available depth, calculated as the sum of the water surface elevation, E_{jt}, and the controlling depth, Z_{jt}, at time *t*, associated with the transit of vessel *i* at location *j*. E_{jt} accounts for both tidal and atmospheric water surface fluctuations that Silver and Dalzell (1998) considered separately, and that Briggs et al. (2013) consider after determination of required depth.

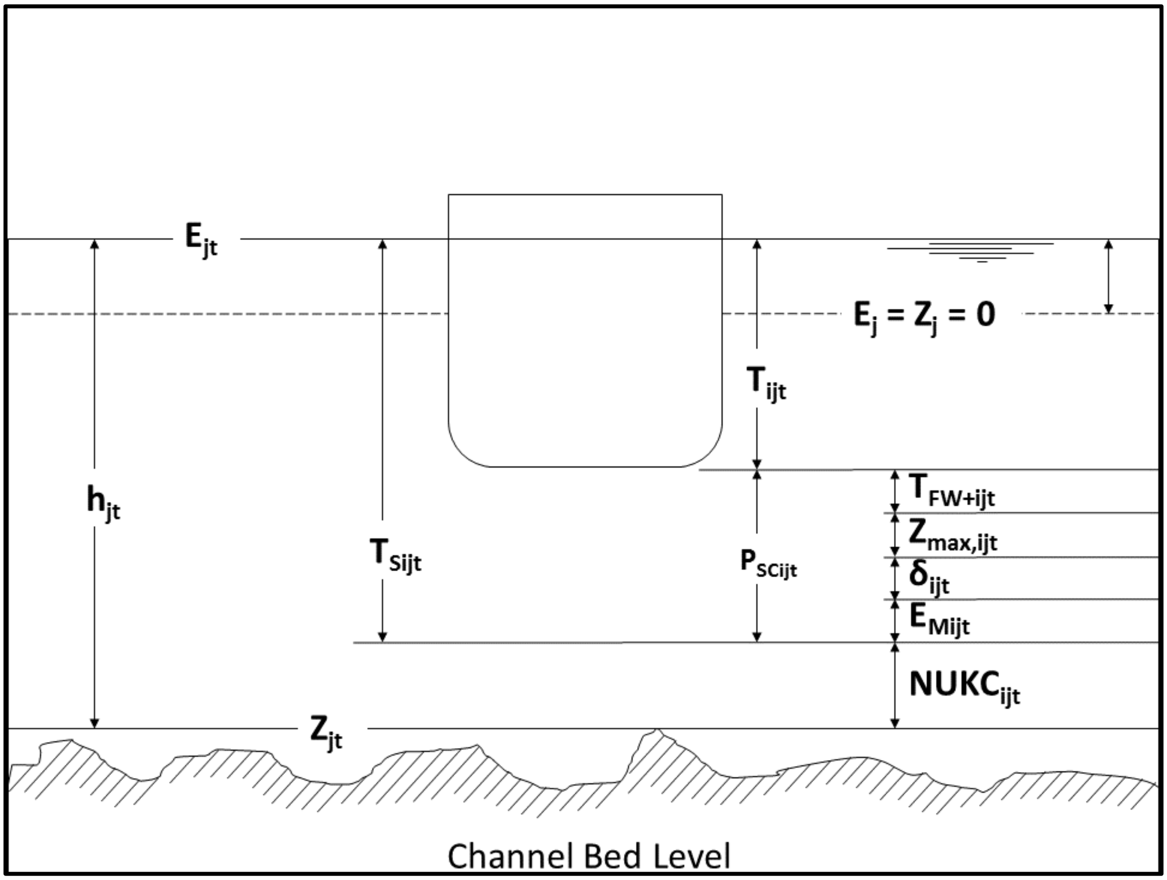


Figure 2 Underkeel Clearance Reliability Model parameter definitions.

Both E_{jt} and Z_{jt} are relative to the mean lower low water (MLLW) datum in this implementation. Z_{jt} will normally be positive unless the channel bottom at location *j* and time *t* is exposed at low tide. This differs from the implementations by Silver and Dalzell, and Brigs et al., who chose instead to model underkeel clearance between the vessel keel and the nominal bed level. That choice reflected the absence of timely bathymetric elevation information that does not exist in a hindcast scenario. E_{jt} will normally be positive unless the water surface elevation at location *j* and time *t* is below the MLLW datum. The effective draft, T_{Sijt}, of vessel *i* at location *j* and time *t* is the sum of its draft in transit, T_{ijt}, and the parameter P_{SCijt}. The parameter P_{SCijt} accounts for squat, fresh water, and wave response motion parameters that appear in EMOGS and CADET and handles them similarly. In practice, these parameters are accounted for by pilots navigating the vessel through the harbor. Additionally, the uncertainty factor E_{Mijt} accounts for various measurement uncertainties inherent in the model. The net underkeel clearance, NUKC_{ijt} results from the difference between the effective draft, and the controlling depth.

The net underkeel clearance can be calculated as shown in Equations 4 through 7 from the record of vessel movement information:

$$NUKC_{ijt} = h_{jt} - T_{Sijt} \tag{4}$$

where:

$$h_{jt} = Z_{jt} + E_{jt} \tag{5}$$

$$T_{Sijt} = T_{ijt} + P_{SCijt} \tag{6}$$

$$P_{SCijt} = T_{FW+ijt} + \delta_{ijt} + Z_{max,ijt} + E_{Mijt} \tag{7}$$

Vessel Sailing Draft, T_{ijt}

The preferred draft of a seagoing vessel that results in optimal performance is referred to as the design draft. It is possible but rare that vessels sail above design draft owing to stability and regulatory concerns. Vessels generally sail at drafts less than their design draft due primarily to insufficient cargo weight or restrictive channel depths (Waters et al., 2002). Vessel design draft is recorded by AIS technology for transiting vessels; users are cautioned to verify the quality of this data.

Channel Controlling Depth, Z_{jt}

Silver and Dalzell (1998) recognize that bathymetric data is normally either unavailable in real time or sufficiently old to be considered unreliable in an operational model, and formulate EMOGS to calculate the risk of vessel keel exceedance of the authorize channel depth vice the channel bottom. The hindcast model applied to a regularly maintained harbor benefits from a useful time series of bathymetric elevation data but must calculate the maximum depth of the vessel's effective keel. In the case of USACE maintained channels, this time series comes from the record of minimum channel depths compiled from CCRs and surveys performed in support of maintenance dredging. In the case of channel condition surveys, channel controlling depths are reported to the National Atmospheric and Oceanic Administration (NOAA) for reproduction on navigation charts used by mariners in transit, thus informing navigation decisions.

Water Surface Elevation, E_{jt}

Indexing a time series of recorded water surface elevation with the time of vessel transit can be used to determine the value of E_{jt}. For each location of interest, a separate time reference will be required to determine changes in water surface elevation between navigation channel reaches. Changes in water surface elevation between reaches as a vessel transits within a harbor are fundamentally time dependent and will vary based on a variety of factors, including transit speed, distance between reaches of concern, and the tide range (USACE, 2006).

Hydrostatic Effect, T_{FW+ijt}

The model is specified using salt water draft of vessels in transit. When transiting in fresh water, vessels will increase in draft from 2-3% owing to fresh water's relatively lower density. PIANC equation 2-C (2014) provides a relationship for determining the freshwater draft that is modified as shown in Equation 8 to calculate the draft increase:

$$T_{FW+ijt} = \left(0.25\,\frac{C_b}{C_{WP}}\right) T_{ijt} \approx 0.02\ to\ 0.025\ T_{ijt} \qquad (8)$$

where T_{FW+ijt} is the additional freshwater draft and C_{WP} is the ship's water plane area coefficient. The approximate relationship of saltwater draft is applicable only for conventional displacement ships, but most commercial vessels of interest to navigation channel maintenance fall into this category (Waters et al., 2002).

Vessel Squat, δ_{ijt}

The increasing availability of high quality data makes it possible to calculate transit-specific gross and net underkeel clearance by applying empirical squat relationships. The required variables are a vessel's speed through the water, its block coefficient, C_b, its submerged cross sectional area, and the cross sectional area of the transited channel. These can be readily estimated from data available to the study.

Briggs et al. (2004) compared three empirical squat equations by Barrass, Huuska, and Romisch in Charleston Harbor to global positioning system (GPS) based measurements of squat for 12 vessels transiting in Charleston Harbor. Of these formulations, Barrass and Huuska were found to over predict squat, which makes them good candidates for incorporation into an underkeel clearance reliability model. Barrass squat over-prediction averaged 23% for observed transits, while Huuska over-prediction averaged 34%. The empirical Barrass equation is selected for incorporation as it provides a reasonable tradeoff between conservatism and computational efficiency.

Barrass (2012) provides a conservative approximation, shown in Equation 9, of maximum vessel squat, δ_{max}, in meters. It is a function of a vessel's dimensionless block coefficient, C_B, its speed relative to the water, V_k, in knots, and the dimensionless blockage factor, S, for open or confined channels:

$$\delta_{max} = \frac{C_b S^{0.81} V_k^{2.08}}{20} \tag{9}$$

Values of C_b may be known, or approximated from vessel dimensions using references such as PIANC (2014). Values of V_k may be calculated from known vessel speed over ground by adding (or subtracting) a known current velocity to that speed. If current velocity is unknown, V_k can be conservatively estimated by adding the maximum observed current in a reach to the vessel's speed over ground, as this configuration will result in the greatest maximum squat value.

The value of S is calculated as the cross section of the ship's wetted volume divided by the cross section of the navigation channel. Channel cross section was measured as the authorized channel width times the distance from the interpreted water surface elevation to the interpolated controlling depth. In all locations of the test location the actual channel cross sectional area is significantly larger than the calculated area, making the approach conservative. The ship's wetted cross sectional area was taken as the product of draft and beam recorded in AIS.

Wave Response Motion, $Z_{max,ijt}$

Wave response motions result when waves incident to a vessel result in heave, pitch, and roll motions. For a given pitch or roll angle, a ship with larger beam and length dimensions will generally have larger vertical motions. PIANC (2014) presents a discussion of several wave estimation methods. USACE (2006) discusses the relationship of wave length to ship length. Generally, increasing wave height and decreasing ship length and beam tend to increase response motions. Wave periods of less than 10 seconds generally have limited effect on underkeel clearance of commercial ships. Wave response motions are considered in the design of navigation channels, and PIANC (2014) provides several internationally recognized methods to account for vessel wave response motions. As such, it is not necessary to reconsider underkeel clearance for waves – the project specific design value can be used deterministically for $Z_{max,ijt}$.

Uncertainty Parameter, E_{Mijt}

Each of the probabilistic model parameters will have an associated uncertainty. If each element contributing to the determination of underkeel clearance is assumed independent, and the uncertainty of each element is assumed to be normally distributed, then the joint probability of these parameters can be described by their combined standard deviation, calculated according to PIANC (2014), shown in Equation 10:

$$\sigma_c = \sqrt{\sigma_s^2 + \sigma_b^2 + \sigma_w^2 + \cdots} \tag{10}$$

where:

σ_c = combined standard deviation

σ_s = standard deviation of the motions of the design ship

σ_b = standard deviation of channel bed irregularities

σ_w = standard deviation of water levels

Treatment of probabilistic parameters in this manner results in a smaller standard deviation than the deterministic approach of direct addition of these uncertainty values (PIANC, 2014). However, the intent of the proposed underkeel clearance reliability mode is to ensure a conservative distance below a vessel in transit. To ensure that uncertainty is accounted for and that the model remains conservative, an uncertainty parameter is included that collects the uncertainty values using direct addition. The value of the uncertainty parameter should be chosen to adequately capture combined uncertainties shown in Equation 11:

$$E_{Mijt} = \varepsilon_T + \varepsilon_{FW} + \varepsilon_\delta + \varepsilon_{Zmax} + \varepsilon_{E1} + \varepsilon_{E2} + \varepsilon_{E3} + \varepsilon_Z \tag{11}$$

where ε_T is the uncertainty in ship draft, ε_{FW} is the uncertainty in freshwater draft increase, ε_δ is the uncertainty in maximum squat, and ε_{Zmax} is the uncertainty in maximum wave response motion. Water surface elevation has three uncertainty components: measurement uncertainty, ε_{E1}, time lag uncertainty, ε_{E2}, and height offset uncertainty, ε_{E1}. The bathymetric measurement uncertainty is ε_Z.

Underkeel Clearance Reliability

The proposed model applied to any navigation reach results in a distribution of net underkeel clearance values for all considered vessels. The probability of the failure condition, net underkeel clearance less than 0, and the reliability can be calculated from the distribution. Let f_{NUKCj} be the probability distribution function of *NUKC* at location *j*, then the reliability of the navigation channel at location *j* is the probability that net underkeel clearance is greater than or equal to 0, defined mathematically in Equation 12 as:

$$Reliability_j = \int_0^{\infty} f_{NUKCj}\left(NUKC_j\right) dNUKC_j \tag{12}$$

The probability of unacceptable performance of the channel can be defined mathematically as $1 - Reliability_j$. The management decision variable of channel depth in each reach can be selected as that depth that results in a net underkeel clearance with a specified failure probability, after accounting for channel shoaling effects and dredging return intervals.

Underkeel Clearance Reliability Model Benefits

The CADET formulation results in two distinct design outcomes relevant to the waterway manager which are among the alternative use cases identified by Hochstein et al., (1983) who recognize the importance of the extent to which available depth is used. One alternative errs on the side of reliability conservatism at the expense of cost. If the design vessel has adequate under-keel clearance at the design datum for a selected optimal depth, it and all smaller vessels can reliably transit the channel at any time and tidal fluctuations above the datum result in additional underkeel clearance. Work by authors including Lund (1990), Lansey and Menon (1993), Ratick et al. (1992, 1995), Ratick and Garriga (1996), and Mayer and Waters (2002) neglect water surface elevation and define reliability in terms of the probability that a specified minimum depth is available irrespective of water surface fluctuations or the presence of vessels. The result is excess expense to provide unnecessary design conservatism.

The second alternative errs on the side of cost conservatism at the expense of reliability for the design vessel. If the design vessel has inadequate underkeel clearance at the design datum for a selected optimal depth, then the design depth results in a period during the tidal cycle when the design vessel cannot reliably transit the channel. Briggs et al. (2015) employed post-processing of tidal distribution and calculation of accessible channel days based on when required additional tidal elevation will be available. However, this approach does not consider the frequency of design vessel transit. Further it considers smaller vessels only implicitly, and does not explicitly provide a measure of navigation channel reliability.

The proposed underkeel clearance reliability model opts to employ the cost conservative alternative. Unlike the CADET implementation, the proposed model explicitly considers the call frequency of all observed vessels regardless of draft and explicitly provides a direct measure of navigation channel reliability. The primary benefit of the underkeel clearance reliability model is that it can be used by waterway managers to measure the efficacy of reach improvement decisions directly.

The net underkeel clearance reliability model provides a secondary benefit in the form of reduced conservatism when compared to CADET or EMOGS. Both models omit some portion of the available channel depth when computing the probability of inadequate underkeel clearance. EMOGS uses the nominal channel depth to calculate squat. This has the effect of over-estimating squat when the controlling depth is below the authorized channel level as greater available flow area for a given ship geometry reduces the velocity of flow below the vessel’s keel. In addition to using the nominal channel depth, CADET neglects water surface fluctuations when calculating squat. The result is again an over-prediction of squat as the additional flow area reduces velocity of flow below the vessel’s keel.

Squat is computed in the net underkeel clearance reliability model using the Barrass squat equation, which is moderately more conservative than the Beck-Newman-Tuck squat equation (PIANC, 2014) employed by CADET. However, squat is calculated here using the controlling depth in the reach instead of the nominal depth, and the additional depth provided by water surface fluctuations.

CHAPTER III

MODEL APPLICATION

Test Location

The net underkeel clearance reliability model was tested at Charleston Harbor, South Carolina. The Charleston Harbor deep draft navigation project has an authorized depth of 45 feet below MLLW in the inner harbor and 47 feet below MLLW in the entrance channel to account for vessel wave response motions (USACE, 1996). The port handled 1.6 million twenty-foot equivalent units (TEUs) of containerized traffic in 2013, and 0.7 million tons of breakbulk cargo in 2013. Charleston was the 10th largest container port in the U.S. in 2013 (USACE, 2015).

The South Carolina State Ports Authority (SCSPA) is the project sponsor required under the Water Resources Development Act (1986) that shares costs with USACE for deepening and maintaining the project. Ship sizes, cargo tonnage, and containerized volume have increased steadily since 2009. USACE (2015) recently recommended increasing the depth of the navigation channel to accommodate containerships ranging from 8,000 TEU to 12,000. Figure 3 shows an image taken onboard an 8,200 TEU ship calling in Charleston Harbor in 2016. Ships of this size are among the largest calling presently in the harbor, but the feasibility study projected ships with capacity up to 12,000 TEU will begin calling in the near future. Capital dredging to the new project depth of 52 feet below MLLW in the inner harbor and 54 feet below MLLW in the entrance channel is not yet scheduled.

Figure 3 View from an 8,200 TEU container ship entering Charleston Harbor. Photo Credit: B. Scully.

The SCSPA operates five terminals in Charleston Harbor. The Wando Welch Container Terminal is the most active terminal operated by the port, and is located on the Wando River. The North Charleston Container Terminal is located at the northern extent of the federal project on the Cooper River. Break bulk and project cargo is handled by SCSPA at the Veterans Terminal on the Cooper River, and at the Columbus Street Terminal on Lower Town Creek. In addition to project cargo, the Columbus Street

Terminal also handles vehicular roll-on-roll off cargo. Union Pier Terminal is primarily used for commercial cruise traffic. A sixth terminal is being constructed on the Cooper River that will handle container traffic once completed. Figure 4, reproduced from USACE (2015) shows the location of SCSPA operated terminals. The federal navigation project supports additional traffic that calls at terminals owned by other interests in addition to SCSPA traffic.

Figure 4 SCSPA terminals served by the Charleston Harbor federal navigation project.

(USACE, 2015)

Data Sources

Three primary data sources were used in this analysis. AIS data was obtained via historical data requests from the USCG Navigation Data Center (USCG, 2016). Water level information was obtained from the National Oceanographic and Atmospheric Administration (NOAA) via the Coastal Oceanographic Observation System (CO-OPS) applications program interface and used to determine the water surface elevation at the time of vessel transit (NOAA, 2013). Hydrographic surveys, dredging records, and proprietary piloted vessel records were obtained from the USACE Charleston District internal records.

Automatic Identification System (AIS)

Vessel traffic information is available through the Automatic Identification System (AIS). This technology has emerged in the last 15 years to cover waterways globally for real-time improvement of waterway safety (Calder and Schwehr, 2009; USACE, 2012; Shelmerdine, 2015). AIS messages are broadcast by vessels in transit and include information about a ship's identity, physical parameters (e.g. length, beam, draft), and course, speed, and other behavior metrics (ITU, 2014). AIS data is collected by USACE on the inland rivers, and USCG in coastal harbors (Gonin and Johnson, 2014). Archival AIS data provides a record of behaviors for entire vessel populations, with nearly 100% coverage for coastal ports maintained by USACE.

When data generated by AIS transceivers broadcasting from vessels in transit are aggregated and archived, the archive serves as a remote sensing technology for those vessels (Calder and Schwehr, 2009, USACE, 2012; Mitchell and Scully, 2014, Shelmerdine, 2015). AIS data parameters are specified by the International

Telecommunication Union (ITU, 2014). This study is primarily concerned with dynamic timestamp and position (latitude and longitude) information from full-resolution AIS position reports, as well as static information contained in AIS message type 5 broadcasts. AIS data is used to determine the time of vessel transit through studied locations of the maintained navigation channel. Archival AIS data is available commercially, by request from the United States Coast Guard (USCG), or may be collected using recording AIS receivers.

Message 5 of the AIS broadcast system contains static information describing each broadcasting vessel (ITU, 2014). Static identifying information reported includes a vessel’s name, call sign, Maritime Mobile Service Identifier (MMSI), and International Maritime Organization (IMO) number. Descriptive information components include length, beam, design draft, and vessel type. The USCG is required to collect and archive AIS transmissions, and publishes AIS encoding requirements for vessels operating in U.S. waters (USCG, 2012). Since vessels usually transit below design draft, the draft value contained in AIS message 5 can be used as a conservative estimate of T_{Sijt}.

The human entered components of AIS data must be carefully considered (Harati-Mokhtari, et. al, 2007, Calder and Schwehr, 2009). Common errors found in AIS static data include missing or misspelled names, MMSI numbers, and ship and cargo type codes. Draft and beam values may also be incorrect resulting from recording errors, such as recording in feet instead of meters. All of these components are used in this study. Preprocessing steps including field standard error checking, evidence based manual data correction of pilot records, name string regularization, fuzzy string matching between AIS and pilot data records, and manual correction of AIS records closely matching pilot records, are taken to validate AIS data against vessel information recorded by the pilots at the test location to ensure adequate data quality.

Water Surface Records

The NOAA manages a network of coastal observing stations that track water surface elevation, many of which reside near USACE-managed navigation channels. Measurements are taken at 6 minute intervals and have a measurement accuracy of +/- 0.07 feet (0.02m) (NOAA2, 2013). Elevations can be referenced to a variety of datums. The NOAA predicts tides and currents at many more locations than it collects water surface elevation data. Harmonic stations have both predicted and verified water surface elevations; subordinate stations have only a record of predicted water surface elevations. When reaches of concern are distant from water surface recording stations, corrections must be made to account for hydraulic losses that result in timing and elevation of tidal phenomena. The NOAA provides predicted and verified water levels and prediction offsets for time and height differences for subordinate stations that allow for estimation of shifts of the tidal pattern at unmeasured locations on its pubic website. Water levels are measured at high frequency and are thus assumed to include atmospheric water level fluctuations owing to low pressure or wind setup (NOAA2, 2013).

This study uses water surface measurements from NOAA station 8665530 in Charleston, SC. Each location of interest, shown in Figure 5, varies in distance from the observing station that generated the water surface elevation record. Tidewater Reach is closest to station 8665530 at 0.1 miles. Ordnance Reach is furthest from station 8665530 to the north at 8.8 miles. Fort Sumter Range is furthest to the south at 10.4 miles. Water surface elevations may vary at each location as a function of its distance to the observation station, and channel bathymetry.

NOAA provides time and height offsets for subordinate stations near reaches of interest that allow for estimation of shifts of the tidal pattern at unmeasured locations. The northernmost subordinate station is 8664688 at 8.9 miles from the harmonic station. The southernmost subordinate station is 8665728 at 3.5 miles. Errors for tide height and time lag are +/- 5% of the observed height, and +/-0.03 feet, respectively. Time lag error is calculated as the diurnal tide range divided by tidal period, which is multiplied by the time lag factor. To ensure that the estimate of underkeel clearance was conservative at each location, time and elevation correction factors were subtracted from the estimated water surface elevation. The correction factors for each of the 13 reaches that are normally dredged are shown in Table 1. Authorized channel depths are also listed in Table 1.

Table 1 Reach distance to NOAA Tide Gage 8665530 with time lag and tide height correction factors, and authorized channel depths.

Reach	Distance to Tide Gage (mi.)	Time Lag Correction (ft.)	Elevation Correction (ft.)	Authorized Depth (ft. rel. to MLLW)
Daniel Island Bend	4.3	0.417	0	45
Daniel Island Reach	3.5	0.417	0	45
Drum Island Reach	2.3	0.03	0.04	45
Fort Sumter Range	10.4	0.03	0.04	47
Hog Island Reach	0.9	0.03	0.04	45
Myers Bend	2.5	0.03	0.04	45
Navy Yard Reach	5.8	0.417	0	45
Ordnance Reach	8.5	0.348	0	45
Port Terminal Reach	8.3	0.348	0	45
Shipyard River	3.3	0.567	0	45
Tidewater Reach	0.1	0	0	40
Town Creek Lower Reach	0.7	0	0	45
Wando Lower Reach	2.7	0.317	0.05	45

Hydrographic Surveys

Derivative products using hydrographic survey information are produced by the USACE in the course of normal maintenance operation. Channel Condition Reports (CCR) are routinely used by USACE Districts to report the controlling or shoalest depth of a navigation channel, obtained from channel condition surveys, to the NOAA for charting purposes. Before-dredging (BD) and after-dredging (AD) surveys are routinely used by USACE Districts as the basis for payment of dredging work performed by dredging contractors. Measurement accuracy of these surveys is recommended as repeatable to 0.3 feet and has a standard deviation of +/- 0.8 feet at 95% confidence by the USACE (USACE, 2013).

Time series of bathymetric elevation were compiled from CCRs and dredge contract drawings issued by the Charleston District. Bathymetric information on dredge contract drawings are normally available to harbor pilots, but are not reported on CCRs. Nonetheless, it can be assumed that pilots are aware of the location and severity of channel shoals if they have been surveyed. It was observed that most shoals in Charleston Harbor form from an outside edge of the navigation channel and progress toward the other side as sediment accumulates.

Data Processing

The following paragraphs describe data processing necessary to prepare data for analysis using the net underkeel clearance reliability model.

AIS Spatial Filtering

A spatial filtering boundary is required for each channel of interest in the study. Boundaries were created using a reference line in the vicinity of each dredged reach of interest, perpendicular to the normal traffic flow. Lines were buffered by 1000 feet to ensure that sufficient records of vessel traffic would be retained within the filter. The boundaries used to filter AIS data for the model application are shown in Figure 5.

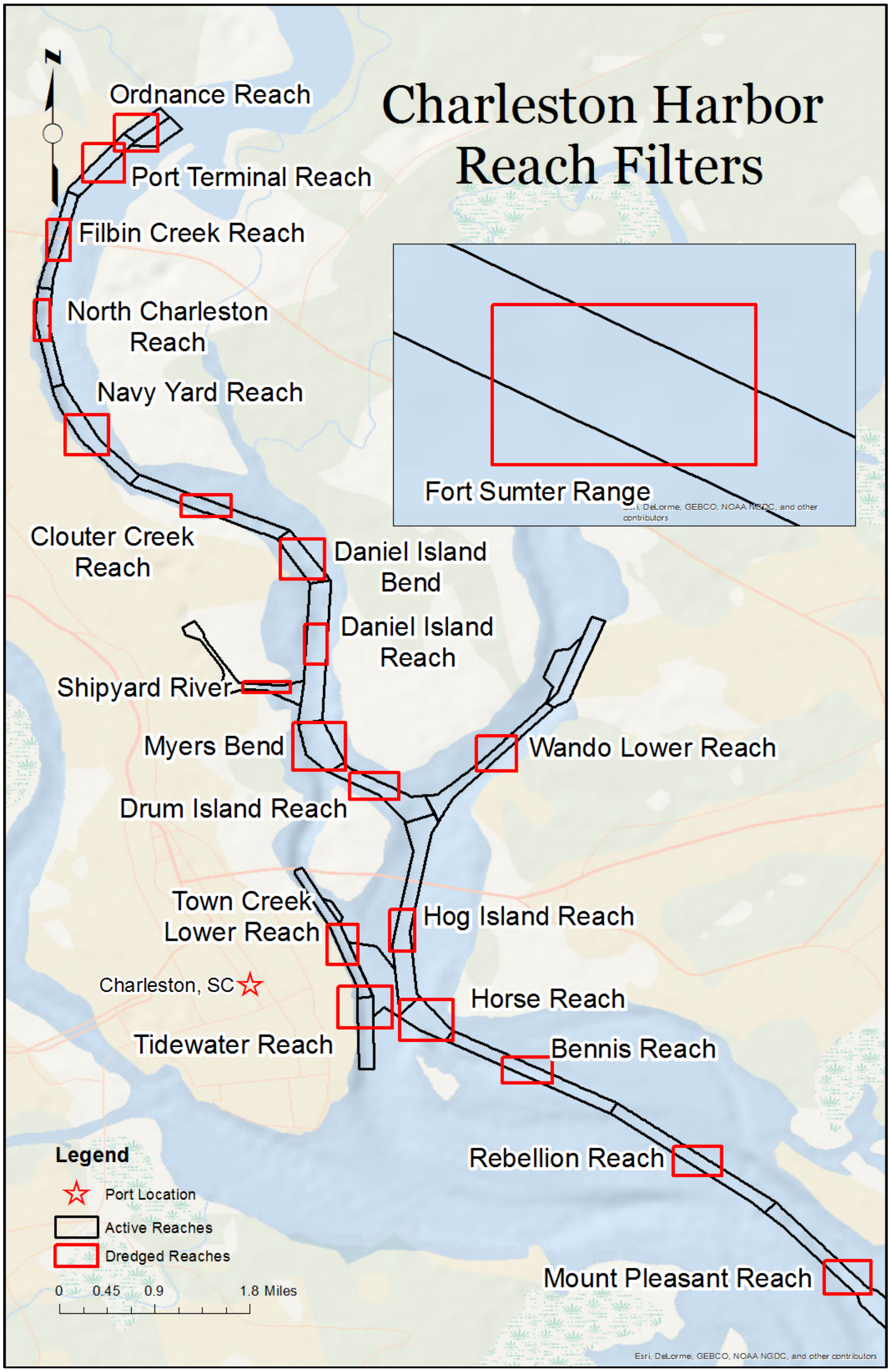


Figure 5 Model test location reach filters.

Vessel Transit Determination and Reference Time Calculation

Mitchell and Scully (2014) have demonstrated a method for determining water surface elevation at the time of vessel transit using AIS data. The method of determining unique transits and the time of vessel arrival in that study assumed a port-wide area of interest, and the method for determining time of vessel transit required the definition of observation points within the larger area. At the reach level, observation areas will be much smaller but more numerous. As a result, the method for determining vessel transits and reference arrival times can be simplified. The estimation of tidal elevation during transit using a reference transit time can otherwise be employed directly.

Silver and Dalzell reason that the point of interest for determination of underkeel clearance is that point of the transit with the greatest extreme value of ship motion, which is essentially random, and as such, a transit calculation point can be chosen anywhere along the route. The present formulation has essentially embedded the extreme motion value into the TP coefficient. Thus underkeel clearance can reasonably be investigated at any location along the navigation channel. If each designated reach is considered independently, then under keel clearance can be estimated at any point on each reach. For each reach of interest, an area of interest must be defined to spatially filtering the vessel position data set.

Consideration in definition of the reach area of interest must be given to the resolution of vessel position data. If a vessel position is recorded at a regular time interval, then the position spacing will be a function of the vessel’s speed. A minimum of one time indexed position report is required in each reach to estimate the water surface elevation, unless the water surface elevation is recorded simultaneously with the vessel position.

Filtered vessel position records were grouped by unique MMSI and ordered chronologically within respective spatial boundaries. Gaps of at least 10 minutes in each position report time series were identified, with each group of position reports between the gaps termed a trip. The 10 minute gap duration was chosen as deep draft commercial vessels transiting into the harbor take significantly longer to return to each reference location on subsequent outbound transits. The reference time of each trip was calculated as the average of the minimum and maximum position report time stamp of each trip. A process to determine individual reach-level trips and a minimum of one reference time for each vessel from a record of time indexed vessel position data is shown in Figure 6.

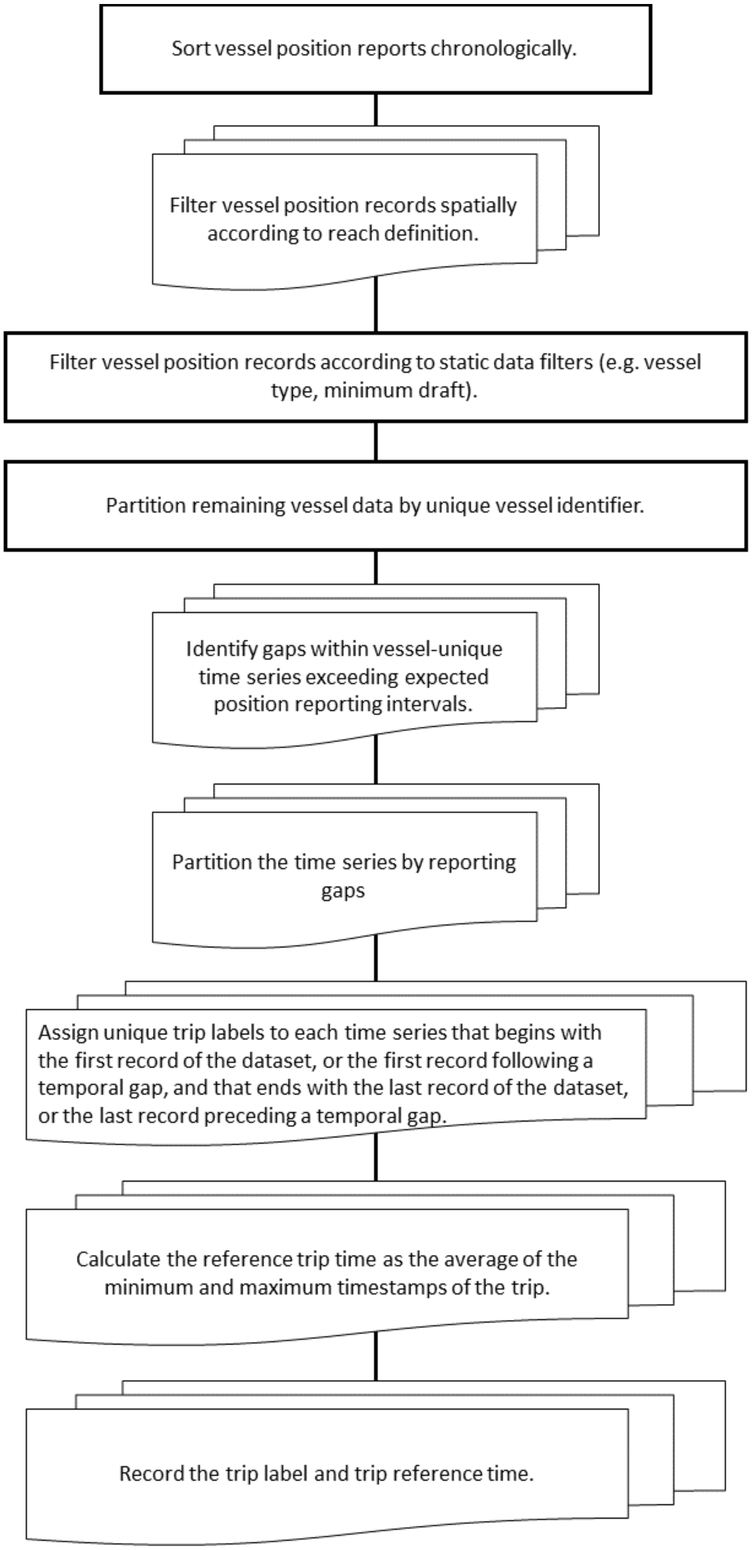


Figure 6 AIS transit definition and reference time assignment.

Layered shapes represent multiple applications.

Piloted Vessel Record Validation

AIS static records were validated against pilot records for 2011 to ensure high quality of the AIS data. Both sets were pre-processed and compared to determine agreement between the datasets, and to improve data quality by identifying and correcting obvious errors. Pre-processing steps included field standard error checking, evidence based manual data correction of pilot records, name string regularization, fuzzy string matching between AIS and pilot data records, and manual correction of AIS records closely matching pilot records. The most common observed discrepancies between both datasets were alternate and misspelled names.

The AIS data standard specifies reporting each vessel’s design draft in the static information contained in message 5 broadcasts. However, sailing draft is necessary to estimate hydrodynamic effects that determine underkeel clearance. AIS-derived transit records were updated to reflect the sailing draft data contained in the piloted record dataset.

Analysis of Validated Data

In all, 3,961 transits by 700 uniquely validated vessels from six classes (Container, Roll-Onn/Roll-Off, Tanker, Dry Cargo, Passenger, and Bulker) were observed in the AIS dataset. Table 2 shows transits in Charleston Harbor during 2011 by vessel type.

Table 2 Observed vessel transits by vessel type.

Vessel Type	Percent of Population
Container	64
Roll On – Roll Off (RO-RO)	15
Tanker	9
Passenger/Ferry	5
Dry Cargo	4
Bulker	3

Figure 7 shows the distribution of sailing drafts recorded by the harbor pilots. The sailing draft distribution was fit-tested with gamma, normal, lognormal, Weibull, and Rayleigh distributions. The data was best fit by a beta distribution, as determined by maximum likelihood estimation. The mean sailing draft was found to be 32.2 feet, with variance of 32.6 feet2. The distribution fit parameters were α = 57,011,650.9286, β = 26.8680001372, Location = -62,839,032.5981, Scale = 62,839,094.3983. The design vessel draft of 45 feet was found to be exceeded by 28 transits. Thus, the probability of design exceedance in 2011 was 0.69%.

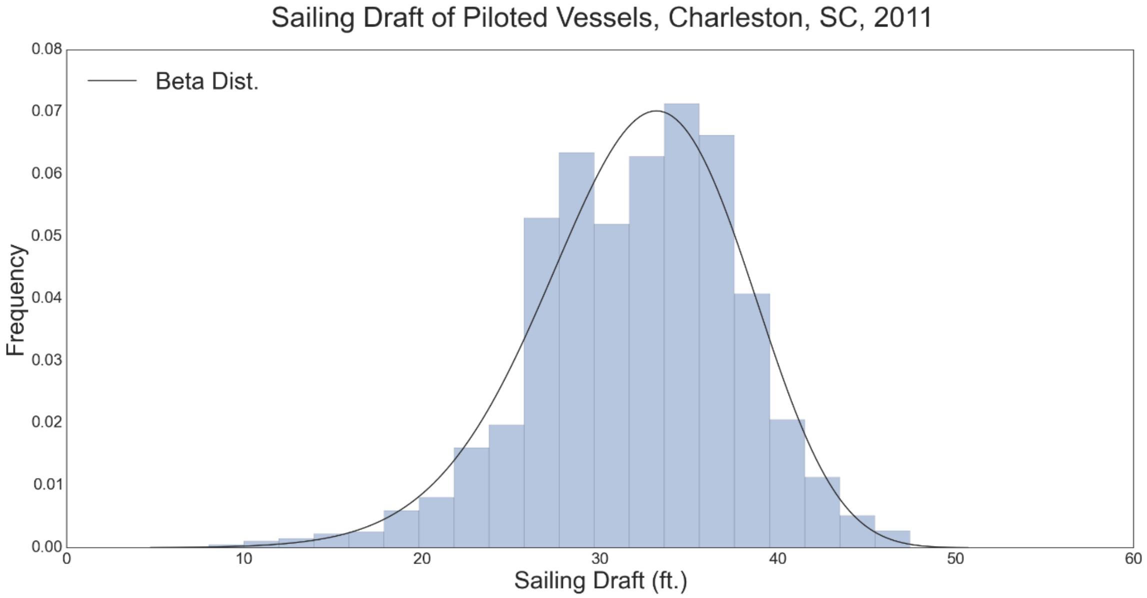


Figure 7 Sailing draft distribution for transiting vessels.

Four additional vessels had sailing draft equaling the project design vessel draft of 45 feet. Thus, the occurrence of vessels that meet or exceed the project design vessel limit is 0.79%. Less than 1% of total vessel traffic that called at Charleston Harbor in 2011 takes full advantage of navigation channels maintained of authorized channel depths based on the design vessel.

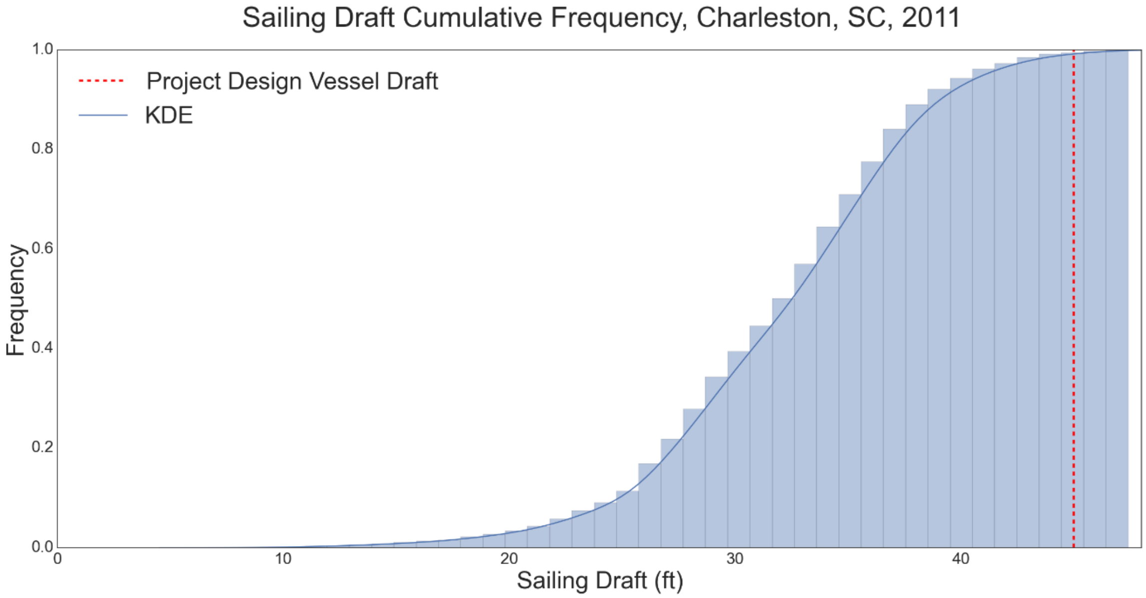


Figure 8 Cumulative distribution of vessel sailing draft.

Vessel sailing draft vs. design draft increment is shown in Figure 9. The greatest observed sailing draft and design draft was 47.4 feet and 50.5 feet, respectively. It was observed that all vessels transiting with sailing drafts greater than 45 feet had nominal design drafts of 49 feet. Of all piloted transits, 2.2% recorded sailing draft greater than design draft, which generally agrees with the findings of Waters et al. (2002). Using vessel design draft, which is broadcast by vessel AIS systems (USCG, 2012; ITU, 2014) as the basis for underkeel clearance estimation will produce a conservative result for most vessels.

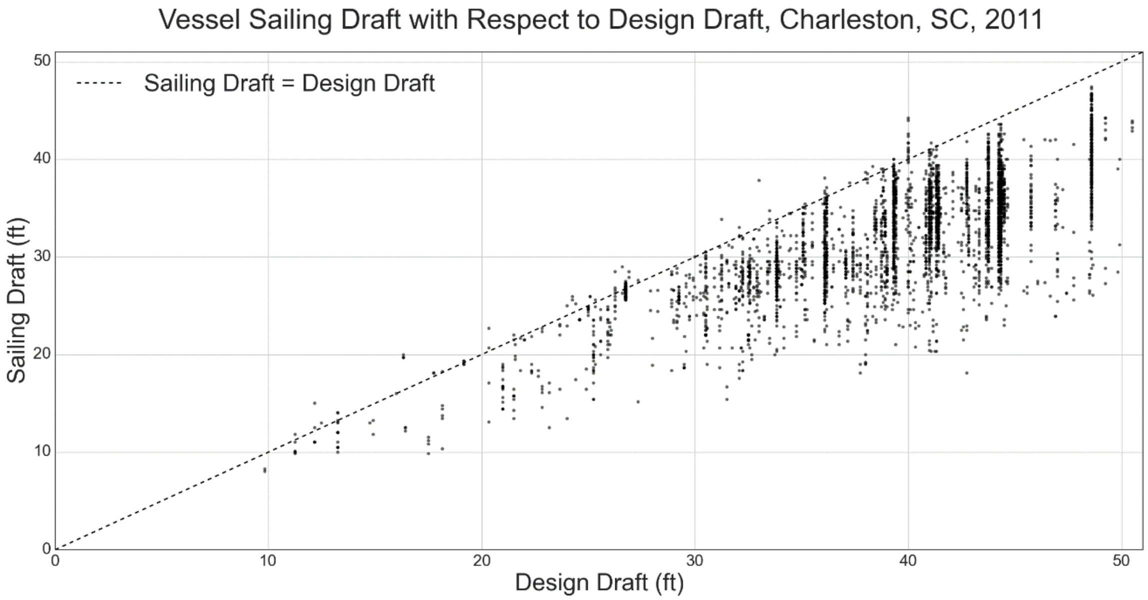


Figure 9 Vessel sailing draft with respect to vessel design draft.

Model Results

The following paragraphs describe the results obtained through application of the net underkeel clearance reliability model using validated AIS data in combination with bathymetric and water surface elevation data.

Sailing Draft Distributions

Figure 10 shows the relative frequency distribution of observed trips in each reach. Trips are extracted from the AIS dataset and have been updated with sailing draft information recorded by the pilots. All sailing draft distributions were fit-tested with gamma, normal, lognormal, Weibull, and Rayleigh distributions. A beta distribution was found to best fit all reaches, as determined by maximum likelihood estimation. Reaches where vessels sailing with drafts greater than the channel design vessel draft of 45 feet are listed in Table 3. The number of trips with drafts exceeding project design draft, and the design exceedance probability are provided. Table 4 lists the beta distribution parameters of each reach.

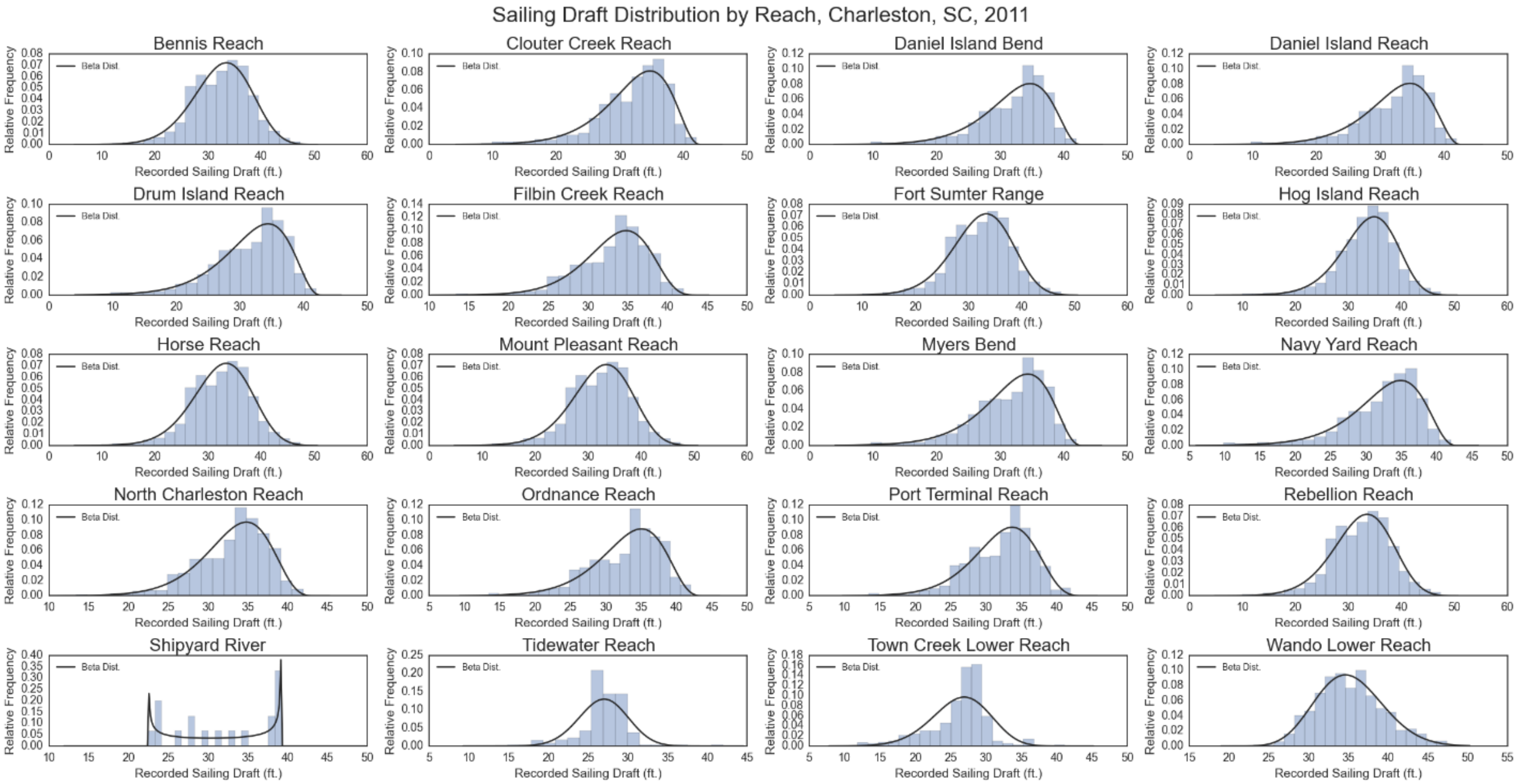


Figure 10 Distribution of transit sailing draft (ft.) with beta distribution fit.

Table 3 Model results: trips exceeding design sailing draft conditions, total trips, probability of sailing draft exceeding design draft, and description of reach dredge status.

Reach	Trips Exceeding Design Draft	Trips	Exceedance Probability	Dredged Reach
Bennis Reach	27	3902	0.692%	No
Fort Sumter Range	26	3926	0.662%	Yes
Hog Island Reach	27	3262	0.828%	Yes
Horse Reach	27	3906	0.691%	No
Mount Pleasant Reach	27	3936	0.686%	No
Rebellion Reach	27	3909	0.691%	No
Wando Lower Reach	27	1756	1.538%	Yes

Table 4 Beta distribution fit parameters, observed sailing draft.

Reach	μ (ft)	σ^2 (ft^2)	α	β	Location	Scale
Bennis Reach	32.4	31.4	2840.523867	26.75791631	-3058.744773	3120.290963
Clouter Creek Reach	31.9	30.6	3120578.994	3.908734945	-8724296.788	8724339.648
Daniel Island Bend	31.9	31.0	1828343.479	3.861647258	-5182359.49	5182402.329
Daniel Island Reach	31.9	30.5	2721981.072	3.955854421	-7561781.214	7561824.115
Drum Island Reach	31.6	32.5	392.7053135	3.866106725	-1114.161123	1157.002749
Filbin Creek Reach	33.2	18.3	661.742843	6.713257198	-1065.043429	1109.342577
Fort Sumter Range	32.3	32.0	1713939.022	26.80096204	-1873729.292	1873790.92
Hog Island Reach	33.5	27.9	1954457.717	15.81819778	-2594725.013	2594779.555
Horse Reach	32.4	31.3	3935.807021	29.25233926	-4051.339171	4114.112602
Mount Pleasant Reach	32.3	32.3	29313854.85	25.6286562	-32933771.01	32933832.12
Myers Bend	31.5	32.4	29755.71708	4.050688273	-84086.00342	84128.99764
Navy Yard Reach	32.4	26.9	222304564.2	4.188923237	-563015892.6	563015935.6
North Charleston Reach	33.0	19.4	2626.717857	6.056397757	-4676.349921	4720.256878
Ordnance Reach	32.9	24.2	1077.976168	5.071781663	-2329.4317	2373.405437
Port Terminal Reach	32.0	21.7	2534446734	7.839841392	-4215081506	4215081551
Rebellion Reach	32.4	31.9	4080.594927	24.07060959	-4681.555395	4741.756579
Shipyard River*	31.6	36.7	0.48834267	0.414617863	22.48268063	16.76731937
Tidewater Reach	26.9	9.5	2830.927434	290.8347277	-510.4144629	592.4768421
Town Creek Lower Reach	26.3	17.2	4253573.611	44.98790073	-2628031.215	2628085.321
Wando Lower Reach	35.3	17.8	14.81486395	40.12754393	16.0822864	71.09030791

Available Depth Distribution

Figure 11 shows the frequency distribution of modeled depth available at the reference time of each trip for all reaches.

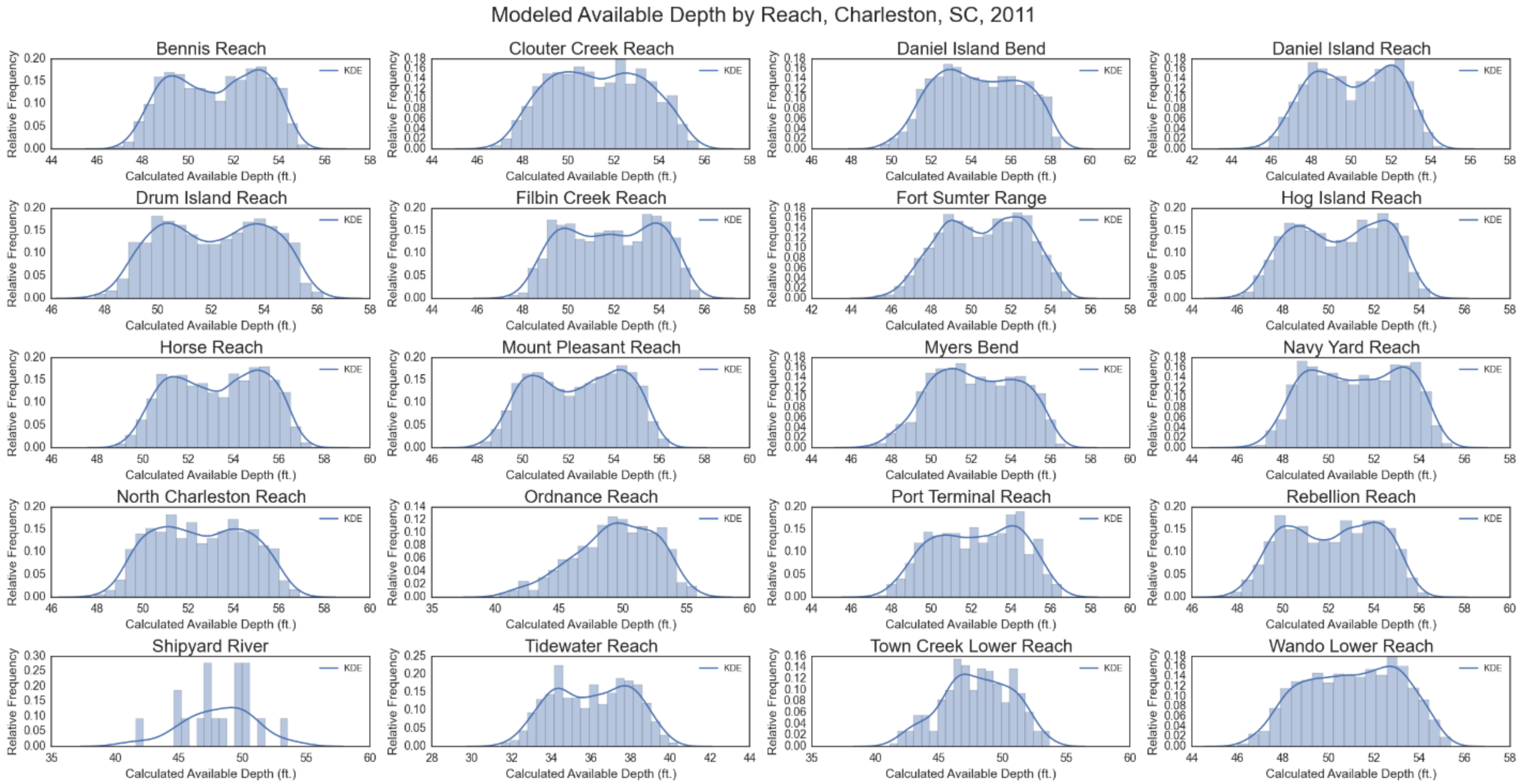


Figure 11   Distribution of modeled depth available at reference transit time.

Keel Modifier Results

The keel modifier is comprised of freshwater effects, squat, wave response motions, and additional safety clearance to account for error. Variation in salinity is insignificant in Charleston Harbor. Additional freshwater draft and associated error were both deterministically assigned a value of 0 feet. The Charleston Harbor navigation project was designed to have an additional 2 feet of dredged depth to account for wave response motion in the entrance channel. This value is applied deterministically with no associated error. The wave response motion allowance elsewhere is 0 feet as designed. The highest average squat was calculated in the entrance channel. This is also the reach with the greatest average vessel speed. The mean speed over ground and squat in the entrance channel were 14.4 knots and 1.7 feet, respectively. To conservatively estimate vessel speed through the water, a value of 3 knots was added to vessel speed over ground to account for vessel current (USACE, 2015).

The keel modifier value in the entrance channel had mean of 4.4 feet and standard deviation of 0.6 feet. According to interviews with Charleston Harbor Pilots, the minimum safety margin analogous to PSCijt provided for vessels in the entrance channel is 15% of sailing draft. For the maximum observed sailing draft of 47.4 feet, the minimum depth needed to transit the entrance channel is 54.5 feet. However, the estimated available depth at the time of this transit was 53.4 feet, and PSCijt was 5.2 feet, or 10.9% of sailing draft. On average, PSCijt was 13.9% of vessel sailing draft in the entrance channel, slightly less conservative than the pilots required minimum safety margin.

Table 5 shows the mean, standard deviation, minimum, and maximum safety margin, calculated as PSC / TS for each trip in a reach for the entrance channel (Fort Sumter Range) and non-entrance channel reaches.

Table 5 Modeled safety margins in the entrance channel and non-entrance channel reaches.

	Entrance Channel	Non-entrance reaches
Minimum safety margin*	15% of sailing draft	7% of sailing draft
Mean	13.9%	5.6%
Standard Deviation	2.0%	1.6%
Minimum (> 0)	9.0%	1.8%
Maximum	34.7%	15.0%

* Determined through personal communication.

Effective Draft Distribution

Table 6 lists the beta distribution parameters of each reach shown in Figure 13. Figure 12 shows the frequency distribution of modeled effective draft, TS, for trips in all reaches. All modeled effective draft distributions were fit-tested with gamma, normal, lognormal, Weibull, and Rayleigh distributions. A beta distribution was found to best fit all reaches, as determined by maximum likelihood estimation.

Table 6 Beta distribution fit parameters of modeled effective draft, P_{SC}.

Reach	μ (ft)	σ^2 (ft^2)	α	β	Location	Scale
Bennis Reach	34.4	33.9	48719.71057	27.80604897	-53838.04879	53903.1967
Clouter Creek Reach	33.8	32.0	1255632.684	3.868245815	-3610098.283	3610143.183
Daniel Island Bend	33.6	32.3	395696213	3.884394787	-1140882930	1140882975
Daniel Island Reach	33.6	33.1	2954355.162	3.763755339	-8763882.561	8763927.346
Drum Island Reach	32.9	32.8	283327.495	4.188782362	-793297.3817	793342.013
Filbin Creek Reach	34.9	18.7	256372227.8	7.026511348	-418314633.3	418314679.6
Fort Sumter Range	36.7	36.5	8269.415476	28.20037958	-9403.265274	9472.198166
Hog Island Reach	35.2	28.7	77794.06605	19.27304497	-94844.89511	94903.59396
Horse Reach	34.1	33.4	1398.782904	28.98010984	-1483.572937	1549.071675
Mount Pleasant Reach	34.6	35.9	273071.3974	24.93940569	-327687.1487	327751.6603
Myers Bend	32.9	32.7	521234.0886	4.327760535	-1432053.648	1432098.469
Navy Yard Reach	34.1	27.3	634253050.3	4.377216264	-1584310015	1584310060
North Charleston Reach	34.9	19.7	3898042.955	6.444761195	-6823467.139	6823513.314
Ordnance Reach	34.0	24.0	759207.783	5.274670671	-1619985.688	1620030.898
Port Terminal Reach	33.4	20.2	118969752.9	10.9454384	-161451778.8	161451827.1
Rebellion Reach	34.8	35.6	2886.636455	22.69562747	-3597.968938	3661.320546
Shipyard River	33.2	35.6	0.445375901	0.392949078	24.60123059	16.22240275
Tidewater Reach	28.0	10.2	156137.0929	431.1082351	-24057.9341	24152.39347
Town Creek Lower Reach	27.1	17.1	5881299.5	46.47453717	-3572426.621	3572481.905
Wando Lower Reach	37.3	19.1	20.34837571	92.98205489	15.43541368	121.9096337

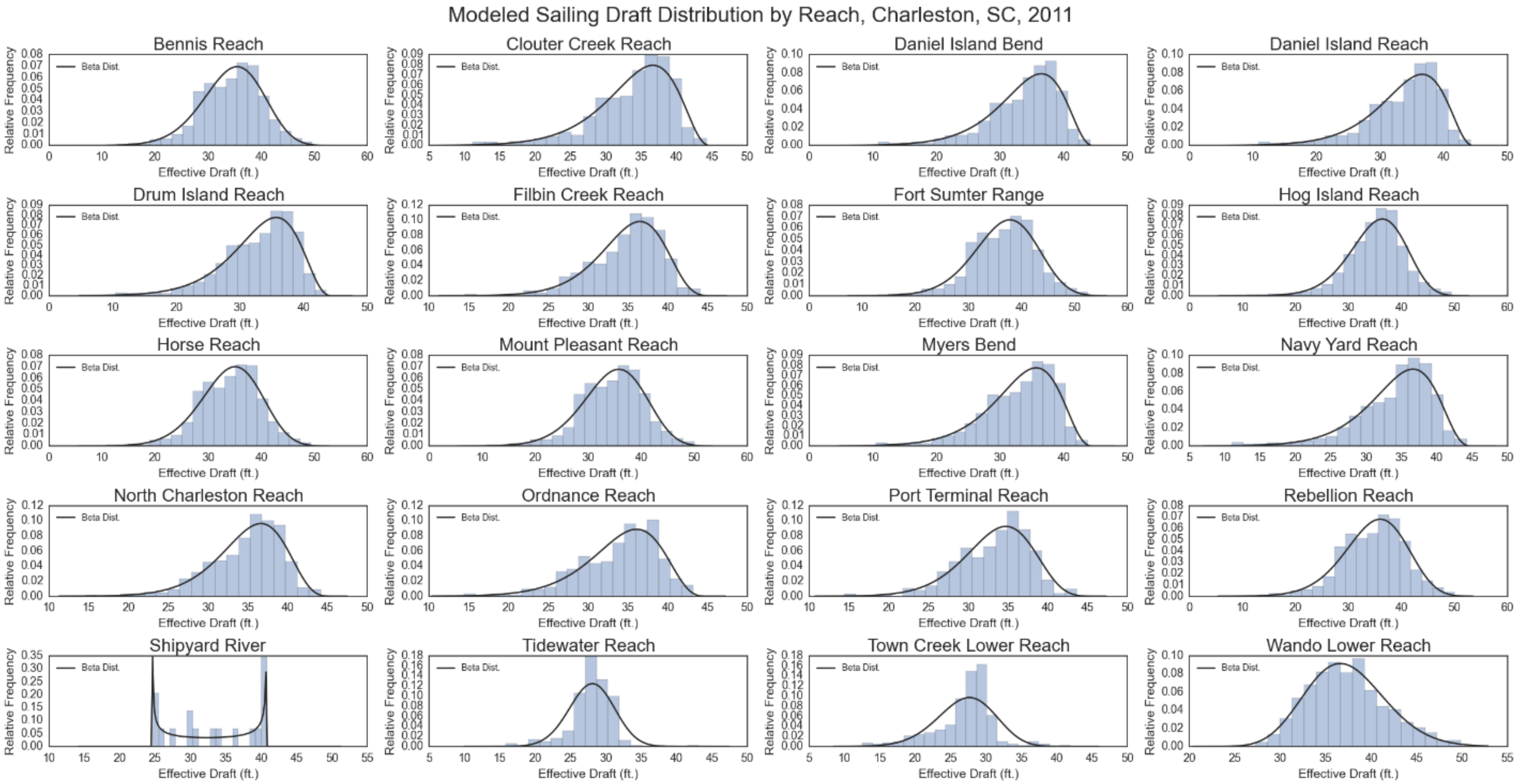


Figure 12 Modeled effective transit draft.

Net Underkeel Clearance Distribution

Figure 13 shows the frequency distribution of modeled net underkeel clearance, NUKC, for trips in all reaches. All modeled net underkeel clearance distributions were fit-tested with gamma, normal, lognormal, Weibull, and Rayleigh distributions. A beta distribution was found to best fit all reaches, as determined by maximum likelihood estimation.

Table 7 shows model results for dredged reaches. Results include, estimated reliability, number of observed trips, number of unique users, and minimum NUKC. Table 8 lists the beta distribution parameters of each reach.

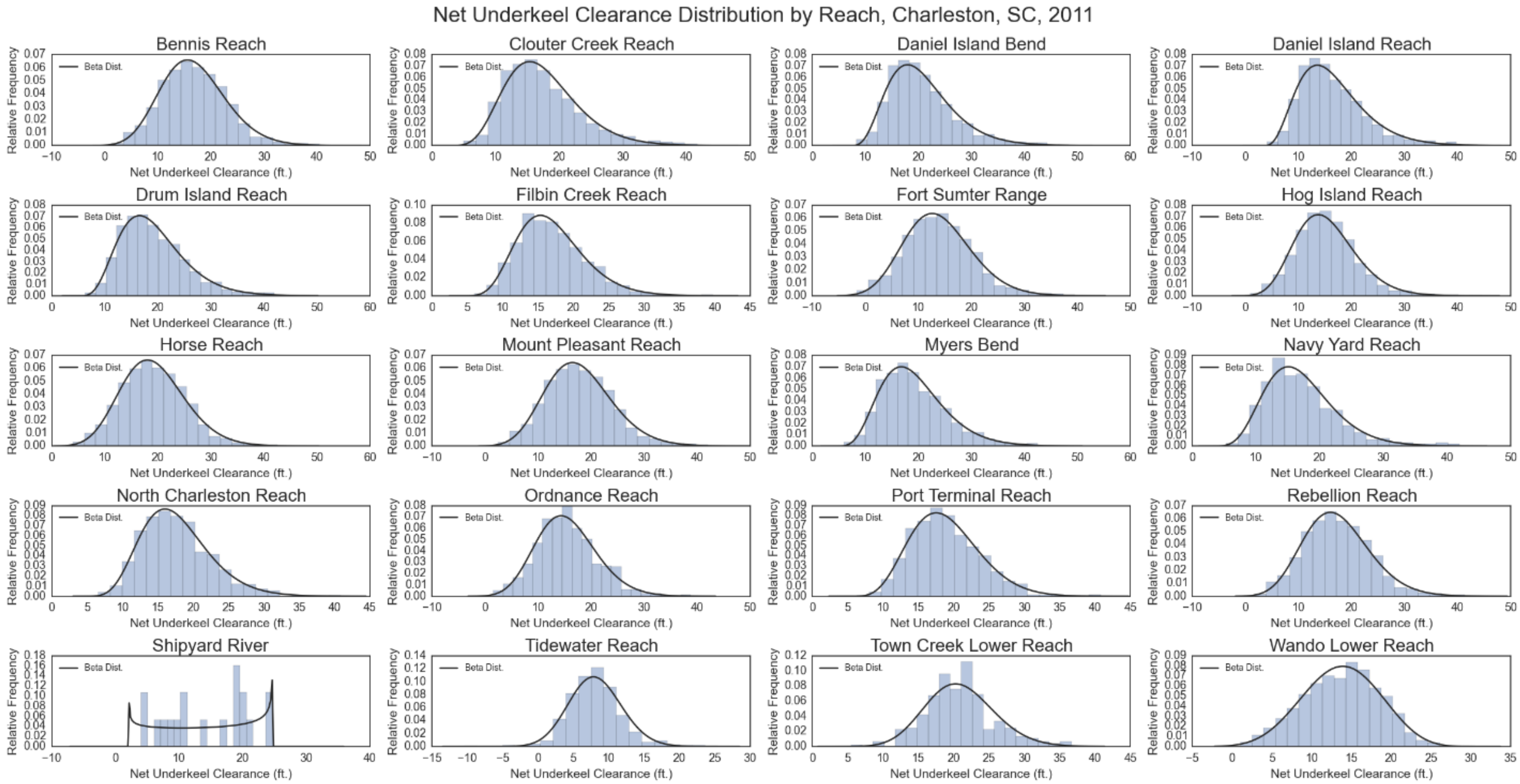


Figure 13 Distribution of net underkeel clearance (ft).

Table 7 Model results: reliability, trips, unique users, and minimum net underkeel clearance in dredged reaches.

Reach	Reliability	Trips	Unique Users	Minimum NUKC (ft)
Daniel Island Bend	1.000	1,297	245	8.3
Daniel Island Reach	1.000	1,297	245	4.1
Drum Island Reach	1.000	1,503	337	6.3
Fort Sumter Range	0.994	3,926	699	-1.6
Hog Island Reach	1.000	3,262	551	0.9
Myers Bend	1.000	1,503	337	6.0
Navy Yard Reach	1.000	1,219	214	5.3
Ordnance Reach	1.000	620	173	1.6
Port Terminal Reach	1.000	687	176	6.3
Shipyard River	1.000	18	12	4.0
Tidewater Reach	0.987	620	174	-10.4
Town Creek Lower Reach	1.000	287	131	5.5
Wando Lower Reach	1.000	1,756	215	1.1

Table 8 Beta distribution fit parameters of modeled net underkeel clearance, NUKC.

Reach	μ (ft)	σ^2 (ft^2)	α	β	Location	Scale
Bennis Reach	16.9	37.8	0.409071667	0.251009177	23.90340721	23514450.55
Clouter Creek Reach	17.5	32.7	0.733014715	0.805965859	7.444484064	65949259606
Daniel Island Bend	20.8	37.7	0.902293394	1.221199141	4.913188913	7919447.587
Daniel Island Reach	16.5	39.0	0.946200383	1.336401723	4.403352016	1115.195124
Drum Island Reach	19.2	37.8	0.869336744	1.133604343	5.292567775	468733.1093
Filbin Creek Reach	17.0	22.5	0.696303945	0.727258727	8.250156594	137409390.1
Fort Sumter Range	13.9	40.8	0.394331675	0.233246142	25.7238704	99145959.92
Hog Island Reach	15.3	33.1	0.542228482	0.441013006	13.60447528	1405046.654
Horse Reach	19.3	37.3	0.394943141	0.233969352	25.64404499	8053465.813
Mount Pleasant Reach	17.9	39.9	0.433729795	0.282178048	21.26188851	1476734.953
Myers Bend	19.3	37.7	0.809714391	0.977196897	5.986494854	1106.724766
Navy Yard Reach	17.1	28.9	0.727164402	0.793151915	7.564748022	36596109.85
North Charleston Reach	17.7	23.6	0.688274373	0.71058174	8.443753546	9891753.148
Ordnance Reach	15.5	32.6	0.388600297	0.226512932	26.48745265	2644772.448
Port Terminal Reach	18.9	23.7	0.506657795	0.212123407	6.613663657	27.3091461
Rebellion Reach	17.4	39.4	0.425034837	0.2709804	22.1413263	4127990.348
Shipyard River	14.3	49.7	-0.142137058	-1.295065746	0.835978496	0.713923557
Tidewater Reach	8.1	13.8	0.15409729	0.035617287	168.4258373	3602613.576
Town Creek Lower Reach	20.9	23.5	0.273039753	0.11101708	52.51714663	7499.466001
Wando Lower Reach	13.7	23.1	-0.05941049	-0.290390676	9.233679574	8.07608477

Contributions

Development and testing of an underkeel-clearance reliability model provides the following benefits:

1. The model provides a direct estimate of net underkeel clearance, the primary benefit provided to waterway users from maintenance dredging.

2. The model includes a factor of safety, in the form of the keel modifier, similar to that provided by harbor pilots.

3. The relative frequency distributions of sailing draft and effective draft can be used as the load factor of the waterway. The cumulative frequency of estimated available depth can be used as the resistance factor.

4. The model provides the number of trips and the number of users transiting each reach, further informing waterway managers.

CHAPTER IV

NAVIGATION TRANSIT RELIABILITY

Existing Practice

Rosati et al. (2013) detail the present challenges faced by the USACE navigation program with specific focus on the coastal portion of the navigation project portfolio. The authors present evidence of cumulative dredge volumes removed from channels over time that suggest a linear relationship of sediment deposition over short periods, and show that rates of sedimentation can increase as a function of increasing channel depth. The authors also highlight that CPT provides USACE waterway managers access to Waterborne Commerce Data (WCD) which allows commodity throughput to be compared to shoaling information.

Dunkin and Mitchell (2015) introduce reach-level maintenance decision support tools that address the current practice of managing individual navigation channels as separate maintenance work items. These tools are based off of the CSAT and CPT. The CSAT takes advantage of the centralized collection and storage of hydrographic surveys performed by the USACE and performs shoaling analysis from historical hydrographic surveys using a hindcasting algorithm to generate reach-specific sediment deposition rate projections.

The CPT (Mitchell, 2012) uses nearest-neighbor matching of docks reporting data inputs used to develop the WCD aggregate product to a spatial model of USACE maintained waterway reaches. Shortest path algorithms are used to route commodity flows through the network. Cumulative tonnage, value, vessel draft, commodity, and traffic type statistics result for each reach.

Dunkin and Mitchell present a value heuristic that compares CSAT derived shoal removal costs and CPT derived commodity throughput and demonstrate its use in prioritizing reaches for dredging. While this is acceptable for sediment removal operations, and somewhat necessary because of the nature of dredging contract methods, the connected nature of maintained reaches must be considered to ensure optimal system functionality.

Navigation channel maintenance cost optimization studies are common in the literature, and it is apparent that researchers have sought to reduce design and operation costs since the early 1980s (Hochstein et al., 1983). Studies can be classified as project selection or schedule optimization. The former chooses the basket of projects to maintain that results in the best improvement of the objective function. The latter selects the return interval of dredging projects that best improves the objective function.

Navigation channel maintenance practice has been moving toward incorporating network connectivity considerations into the maintenance investment framework. Optimizing commodity throughput of connected projects in a knapsack formulation has recently been explored by in studies by Mitchell et al. (2013), Khodakarami et al. (2014), and Mitchell et al. (2015).

Mitchell et al. (2013) propose a systems-based approach to considering maintenance investment for navigation projects. The authors formulate a mixed integer problem to select a basket of navigation maintenance projects to maximize commodity throughput value under a constrained budget. The problem selects whether or not to dredge projects and benefits accrue only between connected projects when both projects as well as any maintained channels in between are dredged. An important contribution of this work is demonstration of the ability to maximize navigation system throughput, instead of treating navigation projects independently.

Khodakarami et al. (2014) expand on the previous study by investigating a knapsack problem where several interconnected port areas must be dredged under a constrained budget. The authors formulate a mixed linear integer project selection program to maximize the throughput value of flows within the multimodal system. The program is capable of evaluating multiple dredging depths relative to an assumed datum and deterministic shoaling rates. Commodity flows are equally weighted and assumed to fill available capacity within maintained reaches. In addition to solving the original problem on a simplified waterway network using a branch and bound approach, the authors also consider several heuristic methods for solving the maximization problem at lower computational complexity.

Mitchell et al. (2015) formulate a mixed integer problem to select a basket of projects to dredge within an interconnected network. The model includes the ability to select across a 14-ft range of alternative dredge depths for each project and considers probabilistic shoaling rates, variable mobilization costs, and the historical distribution of commodity throughput at each depth for each project. The authors use a genetic algorithm to solve the maximization problem over a 20-year time horizon. This work explores the possibility that making early non-optimal project or depth selections may result in long-term optimality. This unintuitive result is a valuable contribution to the body of maintenance dredging knowledge.

These authors generally seek to select the slate of projects and their respective dredging depths that maximize the tonnage or value of cargo moved over a connected port network under varying cost constraints. Benefits accrue only when projects share a similar depth as vessels transiting from deeper to shallower projects must incur additional cost to lighter or light load cargo to safely transit the shallower project. These investigations consider aggregate commodity draft and tonnage or value distributions relative to a low water datum between connected ports.

Proposed Alternative Practice

The proposed underkeel clearance reliability model takes a different approach than authors seeking to optimize harbor dredging (e.g. Dunkin and Mitchell (2015); Mitchell, et al., (2013); Khodakarami et al., (2014); Mitchell et al., (2015)) by considering a direct measure of the user benefit resulting from maintenance dredging instead of proxy measures such as tonnage or value of cargo, after accounting for the variation in water level and channel bathymetry at the time and place a vessel transited. This chapter demonstrates the use of this model in considering the reliability of reaches connected along a vessel transit route within a single harbor, aiding navigation managers in selecting appropriate reach depths based on transit reliability.

Reach Reliability-Depth Relationship

Coastal ports receive vessels arriving from the open ocean that often retrace their paths when returning to sea. If a harbor has m regularly maintained reaches, θj, the set of reaches may be considered as vertices in a graph H. Figure 14 shows the dredged reaches in Charleston Harbor. The harbor's reach vertex set can be described as $V(H) = \{\theta_j, \theta_{j+1}, \dots \theta_m\}$.

Within the port, vessels may make one or more stops at different mooring or berthing locations. If each initiation of motion is considered a vessel route origin, and each termination of motion is considered a destination, then a transit, Θ_i, taken by vessel i within a port may be defined as the set of reaches traversed by each vessel from origin to destination and expressed as:

$$\Theta_i=[\theta_{ij}, \theta_{ij+1} \dots \theta_{ir}] \tag{13}$$

A vessel's transited route within a port may be considered as a group of elements (the reaches) operating in series. If the regularly maintained reaches are considered, the reliability of the route taken by each vessel may be modeled after Dhillon (2011) using reach reliability, R_θ, as described in Chapter 2:

$$R_{\Theta_i} = R_{\theta_{1j}} R_{\theta j_{i+1}} \cdots R_{\theta_{ir}} = \prod_{j=1}^{r} R_{\theta_{ij}} \tag{14}$$

The average reliability of routes taken by all vessels can be expressed as:

$$\bar{R}_\Theta = \frac{R_{\Theta_i} + R_{\Theta_{i+1}} \cdots + R_{\Theta_n}}{n} = \frac{\sum_{i=1}^{n} R_{\Theta_i}}{n} \tag{15}$$

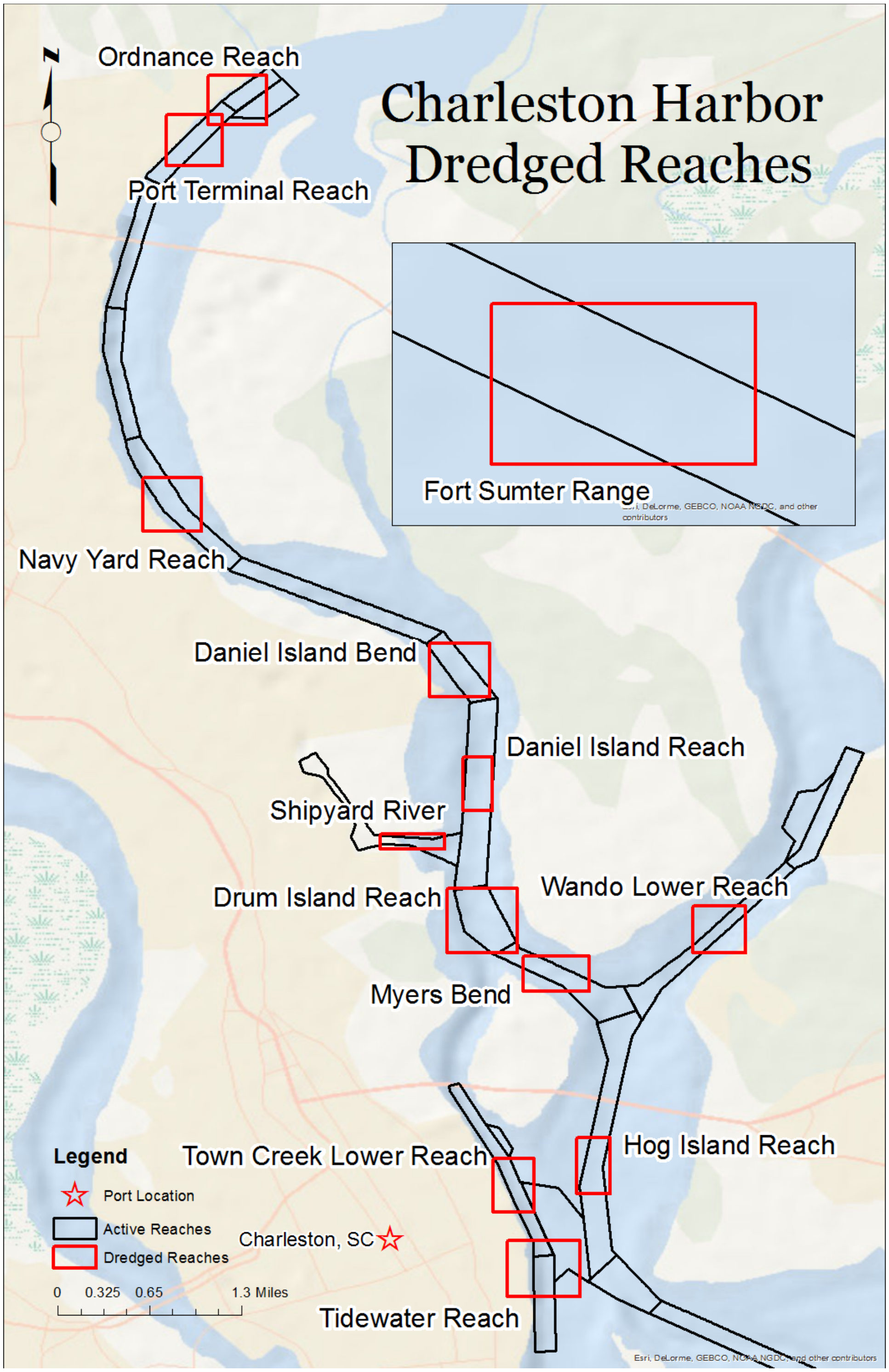


Figure 14 Charleston Harbor dredged reaches.

Reductions in available channel depth will reduce the probability that vessels will transit with a net underkeel clearance greater than 0. The reliability of each route will depend on both the number and the reliability of reaches within the route. It is therefore necessary to investigate the relationship of reach reliability as a function of channel depth reduction within each of the harbor’s dredged reaches.

To assess the change in reliability of each reach with respect to reductions of available depth, available depth at the time of observed vessel transits was reduced in 1 foot increments from 1 to 10 feet. This essentially represents a vertical translation of the time-series of reach controlling depths. At each reduction increment, underkeel clearance reliability model parameters were recomputed for each transit. Figure 15 shows the resulting reliability reduction for each reach with reliability below 0.90 over the range of depth reductions from 0 to 10 feet. Daniel Island Bend, Drum Island Reach, Myers Bend, Navy Yard Reach, Port Terminal Reach and Town Creek Reach demonstrated reliability greater than 0.90 with depth reductions up to 10 feet. Table 9 lists the corresponding reliability of each reach.

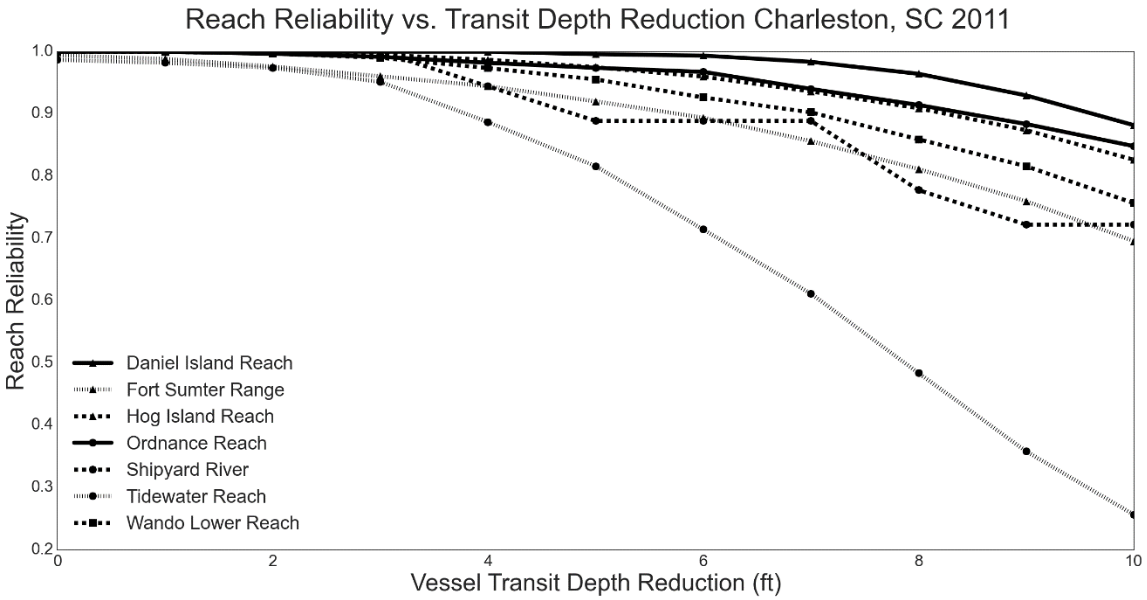


Figure 15 Reach reliability with respect to reductions in available channel depth.

Table 9 Initial and reduced reach reliability resulting from reduction in available depth at time of transit.

Reach, θ	Reach Reliability with Available Depth Reduction (ft)										
	0	1	2	3	4	5	6	7	8	9	10
Daniel Island Bend	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.997	0.990
Daniel Island Reach	1.000	1.000	1.000	1.000	1.000	0.996	0.994	0.984	0.965	0.930	0.882
Drum Island Reach	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.998	0.995	0.987	0.975
Fort Sumter Range	0.994	0.989	0.976	0.961	0.945	0.920	0.894	0.856	0.812	0.760	0.696
Hog Island Reach	1.000	1.000	0.999	0.995	0.987	0.975	0.960	0.936	0.909	0.874	0.826
Myers Bend	1.000	1.000	1.000	1.000	1.000	1.000	0.999	0.998	0.993	0.985	0.973
Navy Yard Reach	1.000	1.000	1.000	1.000	1.000	1.000	0.998	0.996	0.987	0.966	0.935
Ordnance Reach	1.000	1.000	0.997	0.992	0.982	0.974	0.968	0.940	0.915	0.884	0.848
Port Terminal Reach	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.999	0.999	0.996	0.991
Shipyard River	1.000	1.000	1.000	1.000	0.944	0.889	0.889	0.889	0.778	0.722	0.722
Tidewater Reach	0.987	0.982	0.974	0.952	0.887	0.816	0.715	0.611	0.484	0.358	0.256
Town Creek Lower Reach	1.000	1.000	1.000	1.000	1.000	1.000	0.997	0.997	0.997	0.993	0.990
Wando Lower Reach	1.000	1.000	0.997	0.990	0.974	0.956	0.927	0.903	0.859	0.816	0.757

A second order polynomial regression was performed on each reach reliability reduction series. The parameters of the regression in the form y = ax2 + bx +c are listed in Table 10 with the coefficient of determination, R2. The resulting equations provide navigation managers a method to predict the reliability loss in each reach for a depth reduction alternative, subject to the requirement that future vessel transit patterns and channel shoaling patterns behave within the bounds of the previously developed distributions.

Table 10 Reach reliability loss equation regression coefficients.

Reach, θ	a	b	c	R^2
Daniel Island Bend	-0.0001968	0.00140022	0.9986952	0.727940788
Daniel Island Reach	-0.00228877	0.01365658	0.9891142	0.940958661
Drum Island Reach	-0.00049939	0.00325193	0.997227	0.888945154
Fort Sumter Range	-0.00302995	0.00155905	0.9893796	0.998134499
Hog Island Reach	-0.00248893	0.00866944	0.9948828	0.99602752
Myers Bend	-0.00055522	0.00353202	0.9970548	0.91212764
Navy Yard Reach	-0.0012984	0.00836025	0.9929037	0.892050236
Ordnance Reach	-0.00206031	0.0061749	0.9957816	0.993641142
Port Terminal Reach	-0.00017135	0.00109153	0.9990839	0.888085988
Shipyard River	-0.0027195	-0.0041181	1.0097125	0.950970525
Tidewater Reach	-0.00782766	0.00123844	0.9971013	0.996248847
Town Creek Lower Reach	-0.0001665	0.00074641	0.9995614	0.943315018

A reach reliability definition provides an initial starting point to manage reliability of vessel movement through the harbor, but reliability determination requires calculation of reliability in reaches sequentially as they are encountered by each vessel. The active and dredged reaches shown in *Figure 14* can be used to define an adjacency matrix, $A^{(l)}=[\Theta_{jk}]$, of dredged reaches by assuming that transiting vessels are constrained to the active reaches. Each entry $\Theta_{jk}^{(l)}$, in row j and column k of the adjacency matrix $A^{(l)}$ represents the number of unique θ_j - θ_k walks (transits) of length l in H (Chartrand, and Zhang, 2012).

Table 11 associates each dredged reach to its index in j. The l=1 adjacency matrix is shown in Figure 16. Two practical limitations are inherent in this formulation. First, the compounding nature of a series definition of reliability means that longer transits will be penalized for passing through reaches where reliability is less than 1. Consider routes taken by two vessels, A and B, which include 2 and 5 reaches, respectively. If each reach has equal reliability of 0.95, the resulting route reliability will be $R_{\Theta_A} = 0.90$, and $R_{\Theta_B} = 0.77$. Second, the only restriction on a graph walk, and the only restriction on a vessel transit, is that the walk touches adjacent vertices in the graph (Chartrand and Zhang, 2012). Computing the transit matrix for an *l*-length walk can be performed by raising the matrix to the l^{th} power, but the unbounded nature of the route definition problem can be constrained to reduce computational complexity.

Table 11 Index, degree, and neighbors of Charleston Harbor maintained reaches.

Reach, θ	j	Degree j	Neighbors (j)
Daniel Island Bend	1	2	2, 7
Daniel Island Reach	2	3	1, 6, 10
Drum Island Reach	3	3	5, 6, 13
Fort Sumter Range	4	3	5, 11, 12
Hog Island Reach	5	5	3, 4, 11, 12, 13
Myers Bend	6	3	2, 3, 10
Navy Yard Reach	7	2	1, 9
Ordnance Reach	8	1	9
Port Terminal Reach	9	2	7, 8
Shipyard River	10	2	2, 6
Tidewater Reach	11	3	4, 5, 12
Town Creek Lower Reach	12	3	4, 5, 11
Wando Lower Reach	13	2	3, 5

$$A^1 = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Figure 16 Adjacency matrix of Charleston Harbor dredged reaches.

Route Reliability-Depth Relationship

Within a harbor, the set of regularly maintained reaches can be assumed to be fixed. With this assumption, pre-determined routes that cover the maximum extent of routes transited by individual vessels may be considered, instead of the routes taken by individual vessels. Routes are paths in the graph H. Unlike a walk, paths require that nodes be both adjacent and unrepeated. The benefit of this approach is that the set of considered routes will be much smaller than the set of possible walks (transits). The set of maintained routes may be expressed as H=[Θ_x, Θ_{x+1} … Θ_y]. Each route is comprised of its component reaches and expressed as Θ_x=[θ_j, θ_{j+1} … θ_r].

A relative score for comparing alternatives can be computed as the average reliability of all *y* routes in the harbor:

$$\bar{R}_{H_\Theta} = \frac{R_{\Theta_x} + R_{\Theta_{x+1}} \cdots + R_{\Theta_y}}{y} = \frac{\sum_{x=1}^{y} R_{\Theta_x}}{y} \tag{16}$$

The maintained harbor routes are proposed to be selected based on geographical constraints. Hydraulic flow paths or paths that connect port terminals to deep water are obvious choices. The proposed reach grouping for Charleston Harbor, including initial reliability, R_{Θ_x}, is shown in Table 12. The proposed routes correspond to direction-independent combinations covering each terminal end of the Charleston Harbor navigation project. The average reliability of the harbor routes, $\bar{R}_{\mathrm{H}_\Theta}$, is 0.994. Nominally, a harbor with 4000 transits per year and average reliability of 0.994 would incur 24 transits with net underkeel clearance less than 0 feet.

Table 12 Proposed maintenance routes, Charleston Harbor, SC.

Route, Θ_x	x	Reach Sequence (θj)	l	R_{Θ_x}
Fort Sumter Range – Ordnance Reach	1	4, 5, 3, 6, 2, 1, 7, 9, 8	9	0.994
Town Creek Lower Reach – Ordnance Reach	2	8, 9, 7, 1, 2, 6, 3, 5, 12	9	1.000
Tidewater Reach – Ordnance Reach	3	8, 9, 7, 1, 2, 6, 3, 5, 11	9	0.987
Wando Lower Reach – Ordnance Reach	4	8, 9, 7, 1, 2, 6, 3, 13	8	1.000
Shipyard River – Ordnance Reach	5	8, 9, 7, 1, 2, 10	6	1.000
Fort Sumter Range – Shipyard River	6	4, 5, 3, 6, 10	5	0.994
Town Creek Lower Reach – Shipyard River	7	10, 6, 3, 5, 12	5	1.000
Tidewater Reach – Shipyard River	8	10, 6, 3, 5, 11	5	0.987
Wando Lower Reach – Shipyard River	9	10, 6, 3, 13	5	1.000
Fort Sumter Range – Wando Lower Reach	10	4, 5, 13	3	0.994
Town Creek Lower Reach – Wando Lower Reach	11	12, 3, 13	3	1.000
Tidewater Reach – Wando Lower Reach	12	11, 3, 13	3	0.987
Fort Sumter Range – Town Creek Lower Reach	13	4, 12	2	0.994
Tidewater Reach – Town Creek Lower Reach	14	11,12	2	0.987
Tidewater Reach – Fort Sumter Range	15	4, 11	2	0.982

With functions relating reliability to reduction of available depth developed for individual reaches, it is further beneficial to determine the resulting reliability behavior for routes containing each reach. Route reliability was analyzed according to Equation 14 to establish a depth loss function for each route. The average reliability measure, $\bar{R}_{\mathrm{H}_\Theta}$, was also computed using Equation 16 with respect to reductions of available depth. Table 13 shows the route and harbor reliability measure at each depth reduction increment from 0 to 10 feet. Table 13 also shows the corresponding route reliability reduction resulting from reductions in channel depth.

Table 13 Initial and reduced route reliability resulting from reduction in available depth at time of transit.

Route, Θ_x	Route Reliability with Available Depth Reduction (ft)										
	0	1	2	3	4	5	6	7	8	9	10
R_{Θ_1}	0.994	0.988	0.972	0.948	0.916	0.871	0.823	0.735	0.634	0.509	0.375
R_{Θ_2}	1.000	1.000	0.996	0.987	0.970	0.946	0.917	0.855	0.779	0.665	0.533
R_{Θ_3}	0.987	0.982	0.970	0.940	0.860	0.772	0.658	0.524	0.378	0.240	0.138
R_{Θ_4}	1.000	1.000	0.994	0.982	0.957	0.927	0.888	0.827	0.739	0.625	0.493
R_{Θ_5}	1.000	1.000	0.997	0.992	0.928	0.863	0.853	0.818	0.676	0.569	0.496
R_{Θ_6}	0.994	0.988	0.975	0.956	0.881	0.798	0.763	0.710	0.567	0.466	0.394
R_{Θ_7}	1.000	1.000	0.999	0.995	0.932	0.867	0.850	0.826	0.697	0.609	0.560
R_{Θ_8}	0.987	0.982	0.973	0.947	0.827	0.707	0.609	0.507	0.338	0.220	0.145
R_{Θ_9}	1.000	1.000	0.997	0.990	0.920	0.849	0.823	0.799	0.661	0.573	0.519
$R_{\Theta_{10}}$	0.994	0.988	0.972	0.947	0.908	0.858	0.795	0.724	0.634	0.542	0.435
$R_{\Theta_{11}}$	1.000	1.000	0.997	0.990	0.974	0.956	0.923	0.898	0.852	0.800	0.730
$R_{\Theta_{12}}$	0.987	0.982	0.971	0.942	0.864	0.780	0.662	0.551	0.414	0.289	0.189
$R_{\Theta_{13}}$	0.994	0.989	0.976	0.961	0.945	0.920	0.891	0.853	0.809	0.755	0.688
$R_{\Theta_{14}}$	0.987	0.982	0.974	0.952	0.887	0.816	0.712	0.609	0.482	0.356	0.254
$R_{\Theta_{15}}$	0.982	0.971	0.951	0.914	0.838	0.751	0.639	0.523	0.393	0.272	0.178
$\bar{R}_{\mathrm{H}_\Theta}$	0.994	0.990	0.981	0.963	0.907	0.845	0.787	0.717	0.604	0.499	0.409

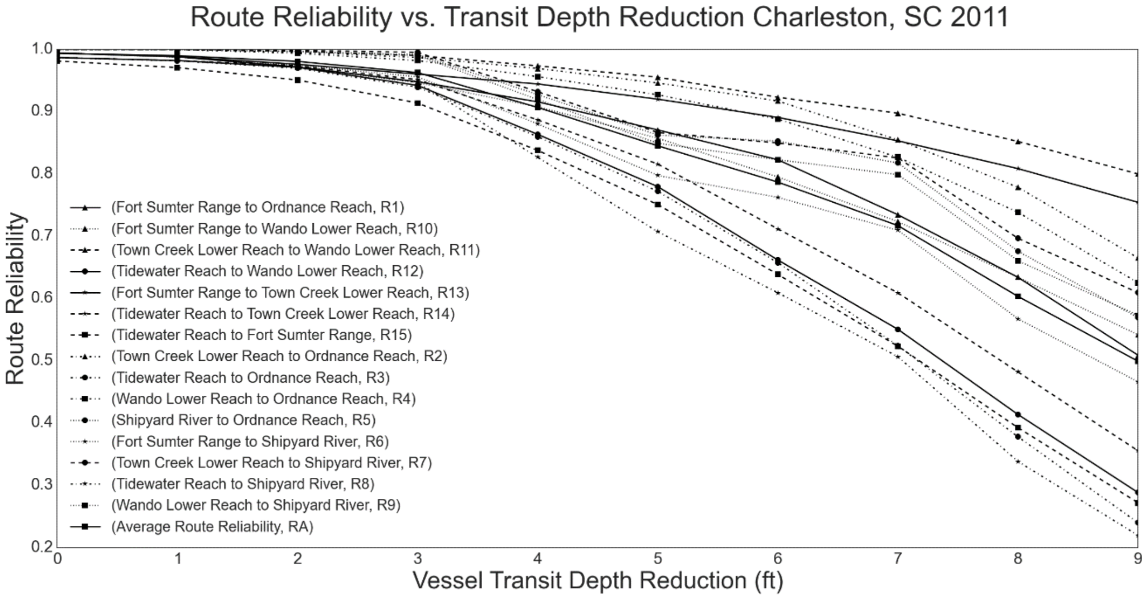


Figure 17 Route reliability with respect to reductions in available channel depth.

A second order polynomial regression was performed on each route reliability reduction series. The parameters of the regression in the form $y = ax^2 + bx + c$ are listed in Table 14 with the coefficient of determination, R^2. The resulting equations provide navigation managers a method to predict the reliability loss in each route for a uniform reduction in depth of all subtended reaches, subject to the requirement that future vessel transit patterns and channel shoaling patterns behave within the bounds of the previously developed distributions.

Table 14 Route reliability loss equation regression coefficients.

Route, Θ_x	a	b	c	R^2
R_{Θ_1}	-0.007629656	0.016755346	0.980124517	0.997295
R_{Θ_2}	-0.007332459	0.031130821	0.978036572	0.988186
R_{Θ_3}	-0.008516938	-0.005934046	1.004964983	0.994103
R_{Θ_4}	-0.007361624	0.026548539	0.98242796	0.993345
R_{Θ_5}	-0.006207137	0.010906663	0.998257258	0.98477
R_{Θ_6}	-0.005538571	-0.007553871	1.003669152	0.991628
R_{Θ_7}	-0.004977991	0.003542534	1.005201195	0.982479
R_{Θ_8}	-0.006808789	-0.025192502	1.022739977	0.987452
R_{Θ_9}	-0.005077236	-0.000163072	1.008628588	0.984044
$R_{\Theta_{10}}$	-0.005725588	0.001301356	0.993696848	0.999946
$R_{\Theta_{11}}$	-0.003553925	0.009928172	0.994820702	0.997131
$R_{\Theta_{12}}$	-0.007697726	-0.008676089	1.006554679	0.993969
$R_{\Theta_{13}}$	-0.003137272	0.001949499	0.989229699	0.998218
$R_{\Theta_{14}}$	-0.007848996	0.001131913	0.997337045	0.996158
$R_{\Theta_{15}}$	-0.006892576	-0.017138912	1.000789909	0.994519
$\bar{R}_{\mathrm{H}_\Theta}$	-0.006287099	0.00256909	0.997765272	0.997951

Route organization includes both network connectivity and reach reliability based on net underkeel clearance. The complexity of computing reliability has been reduced by providing an upper limit to the length of reach sequences, but reliability is still subject to the compounding series reliability problem. In addition, the focus of reliability has been shifted to the reaches, instead of remaining on reach users.

Transit Reliability-Depth Relationship

Vessel transits can be assumed independent, and modeled as a Poisson process if transits are labeled ‘failure’ when net underkeel clearance for a trip through any reach is less than 0, and labeled ‘success’ otherwise (Briggs, et al., 2003; Quy, 2007). The transit-reliability rate of the harbor in a maintained state can then be calculated as the probability that a transit through the harbor is not classified as failure. The probability mass function of a Poisson random variable where the mean and variance of the failure rate is denoted as μ and the number of failures is denoted as *x* can be written as (Briggs, et al., 2003):

$$f(x,t) = \frac{e^{-\mu}\mu^{x}}{x!} \tag{17}$$

The resulting reliability is calculated as $R(x,t)$ = 1- $f(x,t)$. By evaluating multiple states representing maintenance decision alternatives, a reliability-state relationship can be developed to inform the impact of making a decision.

Of 3,961 transits observed in Charleston in 2011, 29 were modeled to have a net underkeel clearance value less than 0. The probability of failure and the transit reliability are 0.007 and 0.993, respectively. If it is assumed that the set of dredging maintenance decisions preceding the vessel transits observed in 2011 resulted in the observed failure and reliability rates, then what-if analysis can be performed by manipulating the slate of underlying decisions to inform managers of the impacts to transit reliability resulting from reductions in dredging depth.

Figure 18shows the relationship of transit reliability to a universal reduction of depth available at time of transit in Charleston’s dredged reaches. For each dredged reach, the depth available at the time of vessel transit through the reach was reduced in 1-foot increments, and the underkeel clearance reliability parameters recalculated. The probability of failure for each vessel transit and the harbor-wide transit reliability was then recalculated for the reduced depth increment. The regression equation y = -0.0042 x^2 + 0.001 x + 0.9899 was found to fit the data with $R^2 = 0.998$.

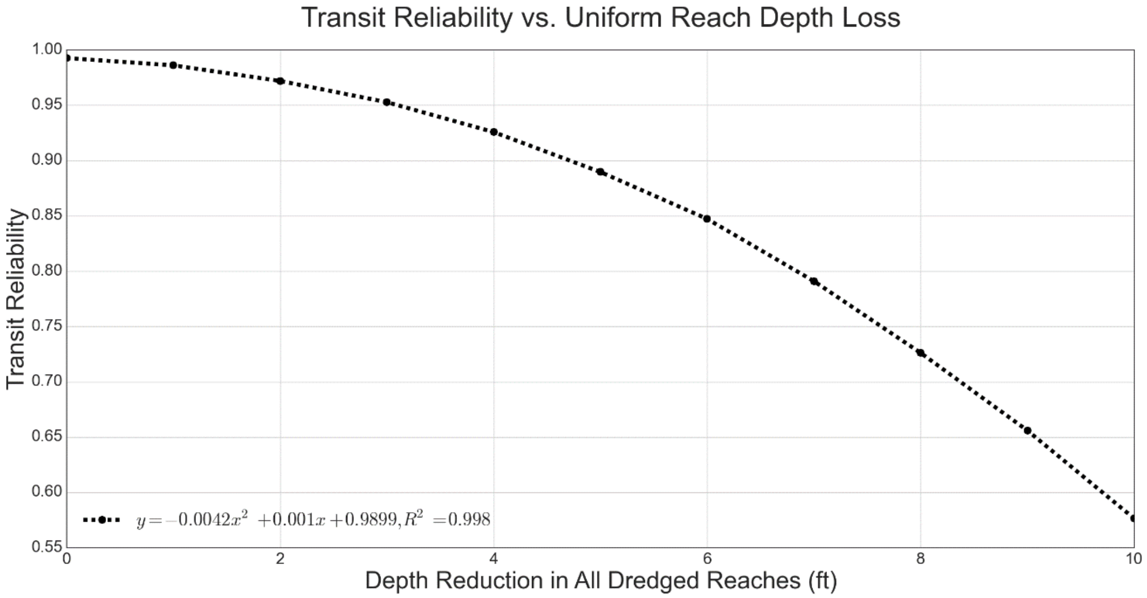


Figure 18 Transit reliability with respect to uniform reductions in available channel depth.

Universal reduction in dredging depth throughout all reaches is not necessarily a viable management strategy. However, this relationship demonstrates that reducing available depth across the dredged reach portfolio increases the probability of vessel transits with net underkeel clearance less than 0, provided vessel arrival distributions are within the bounds of those developed in Chapter 3.

By defining a vessel’s transit as failure or success, the transit reliability model has eliminated the compounding series reliability problem. The need to compensate for routes of differing lengths by averaging their reliability values, and the need to pre-define routes in order to constrain the number of computations required that resulted from an unlimited reach-walk length was also eliminated using this formulation. Harbor-wide transit reliability is now defined in terms of a waterway user's ability to transit from origin to destination while maintaining sufficient underkeel clearance.

Contributions

The following contributions result from development of transit, reach, and route reliability measures as they relate to reductions in channel depth:

1. A measure of harbor-wide transit reliability is proposed as a management metric to assist navigation managers in selecting dredging depths in maintained reaches. A relationship between reliability and reduction in available transit depth across the maintained reach portfolio indicating a loss in overall transit reliability with reductions in available channel depth in each reach.

2. Reach reliability and route reliability metrics are also developed to inform waterway managers of the impacts to vessel underkeel clearance reliability when reach depth is reduced. Functions are developed for each reach that relate reach reliability to reductions in available channel depth. This may be used as a tool by waterway managers to assess the impact of selected reach dredging depth on the probability that vessels transiting the reach will experience reduced underkeel clearance.

3. Modeling a set of reaches along a spatially oriented path as elements operating in series enables navigation maintenance mangers to assess the network reliability of routes connecting geographic locations within a harbor.

4. Functions relating reliability of harbor routes to uniform depth reductions for component reaches establish a relationship of reduced route reliability with reduced channel depth along the route.

CHAPTER V

RATIONALIZING DREDGING BUDGETS WITH TRANSIT RELIABILITY

Improving on Current Maintenance Practice

The navigation channel transit reliability model formulated in Chapter 5 can be used to inform managerial harbor maintenance decisions. The set of reaches to dredge, and the dredging depth are the primary decision variables available to the waterway manager in practice. This chapter considers the dredging depth in each reach in the context of an underkeel clearance reliability target. Channel reliability cases identified in the literature are generally defined in terms of the probability that sediment exceeds a certain elevation, or the probability that vessel drafts exceed a threshold value (Lund (1990); Lansey and Menon (1993); Ratick et al. (1992, 1995); Ratick and Garriga (1996); and Mayer and Waters (2002); USACE, 2014). Thus, the use of an underkeel clearance reliability target for maintenance appears to be a novel application similar to navigation channel depth design practice.

The practices employed to maintain the Charleston Harbor navigation project are outlined in USACE (2015). The report summarizes the project dredging volume history, dredging expense history, and vessel traffic growth trends driving increased channel depth. Maintenance dredging contracts since the harbor was deepened to its present depth in 2004 until 2015 were reviewed to determine the dredging costs and typical controlling depth improvement shown in Table 15. With the exception of Fort Sumter Range, these costs exclude mobilization of the dredge. For the purpose of this evaluation, it is assumed that dredges will be contracted according to normal maintenance practices – thus, mobilization costs will be incurred independently from unit depth dredging costs. These costs are stipulated as the reach-specific maintenance costs to be used in this chapter.

Table 15 Annualized reach maintenance costs and typical depth improvement.

Reach	Estimated Annual Maintenance Cost, C_A (x $1,000)	Estimated Annual Maintenance Unit Depth Cost, C_I (x $1,000/ft)	Annualized Controlling Depth Improvement, D_{max} (ft)
Daniel Island Bend	120	14	9
Daniel Island Reach	839	122	7
Drum Island Reach	240	32	8
Fort Sumter Range*	2,074	754	3
Hog Island Reach	432	76	6
Myers Bend	54	8	7
Navy Yard Reach	92	19	5
Ordnance Reach†	1,061	104	11
Port Terminal Reach	77	16	4
Shipyard River	831	101	9
Tidewater Reach	196	60	4
Town Creek Lower Reach‡	666	56	12
Wando Lower Reach§	751	108	7

* Fort Sumter Range is dredged independently and solely incurs mobilization and overhead costs. These costs are incorporated into the annualized maintenance cost.

† Ordnance reach maintenance costs include the costs for Ordnance Reach Turning Basin.

‡ Town Creek Lower Reach maintenance costs include the costs for Upper and Lower Town Creek Reach, and Columbus Street Turning Basin.

§ Wando Lower Reach maintenance costs include the costs for Middle Wando Reach, Upper Wando Reach and Wando Reach Turning Basin.

Cost-Per-User Analysis

A cursory analysis of dredging costs can be made by comparing the total number of transits, observed from analysis of AIS data, and the number of unique users observed in each reach as listed in Table 7. The estimated annualized maintenance cost per trip and the estimated annualized maintenance cost per unique user observed in each reach are shown in Table 16. The bubble plot in Figure 19 shows reach maintenance costs vs. total trips in each reach. Bubbles are scaled with the annualized reach maintenance cost per trip. Fort Sumter Range stands out as having relatively high dredging costs and trip counts. However, dredging costs in Shipyard River dwarf all other reaches when costs are considered on a per-user basis. Town Creek Lower Reach is also relatively costly to maintain per user, while Myers Bend and Navy Yard Reach are relatively inexpensive.

Table 16 Reach maintenance costs per transit and unique user.

Reach	Estimated Annual Dredging Cost per Trip ($/trip-ft)	Estimated Annual Dredging Cost per Unique User ($/user-ft)
Daniel Island Bend	93	490
Daniel Island Reach	647	3,425
Drum Island Reach	160	713
Fort Sumter Range	528	2,967
Hog Island Reach	133	785
Myers Bend	36	160
Navy Yard Reach	75	428
Ordnance Reach	1,711	6,130
Port Terminal Reach	90	350
Shipyard River	46,158	69,237
Tidewater Reach	316	1,125
Town Creek Lower Reach	2,319	5,080
Wando Lower Reach	428	3,492

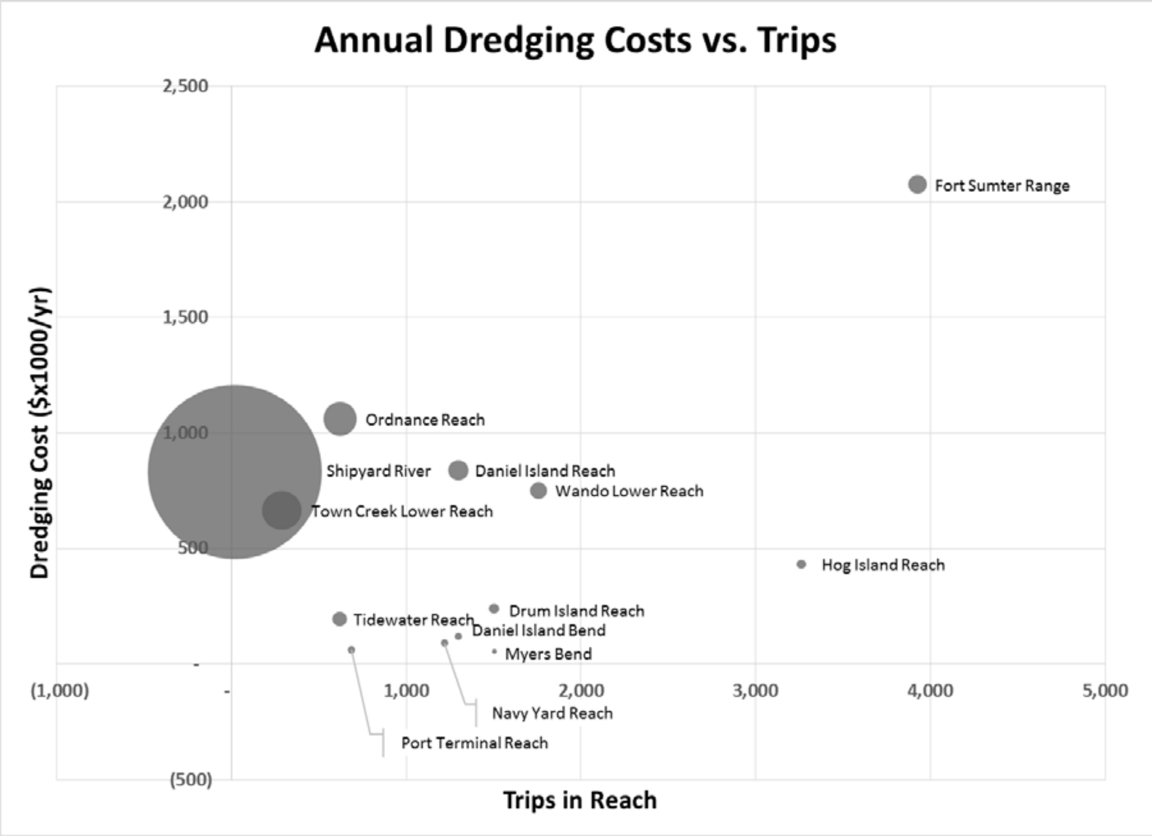


Figure 19 Reach dredging costs per user.

Reliability Impacts of Reduced Dredging

Figure 19 is informative in light of typical reach inclusion and depth selection schemes. It is generally recognized in the literature that inclusion of marginal dredging volumes increases the total volume over which equipment mobilization costs may be amortized. When mobilization costs are relatively high, it is practical to increase advance maintenance dredging depth (or volume of material) which tends to increase the time between dredging events and lower the mobilization cost per yard (Mayer and Waters, 2004; Mitchell, et al., 2015).

Figure 20 shows the impact on total dredging cost and transit reliability when the depth in Shipyard River is reduced up to the typical depth improvement per contract. In considering only this reach, the potential annualized cost reduction available amounts to 12% of total annual dredging cost, and the potential impact on transit reliability is a reduction of 0.2%.

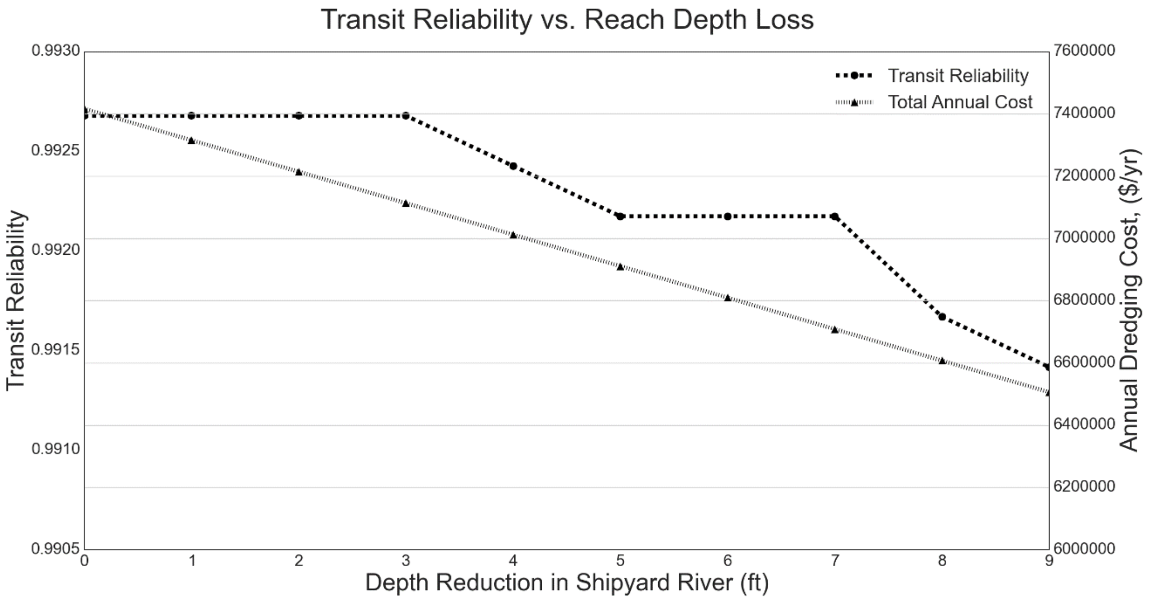


Figure 20 Effect of reducing available depth in Shipyard River on total dredging cost and transit reliability.

When considering only one of the dredged reaches, the resulting cost decreases according to the depth improvement cost function for the reach, which is assumed linear in this example. However, it is unlikely in most cases that only a single reach can be considered for cost minimization and reliability maximization problems. The relationship of reliability to depth reduction was shown in Chapter 5 to follow a second order polynomial regression when considering uniform depth reductions.

The depth selection optimization problem for the full slate of candidate reaches will generally take one of two forms. Either the manager will be interested in selecting the most reliable alternative given a budget ceiling, or determining the minimum cost to obtain a minimum acceptable reliability.

Monte-Carlo Optimization of Dredging Alternatives

A Monte-Carlo approach consisting of 7,500 iterations was employed to explore the relationship between reliability and cost for the 13 dredged reaches in Charleston Harbor. For each reach, a slate of reductions to normal dredging practices, D_{Rj} was selected randomly without replacement. The reach-wise dredging treatment ranged from full dredging according to the D_{max} values listed in Table 15 (D_{Rj}=0) to no dredging ($D_{Rj} = D_{maxj}$). Using these values, the net underkeel clearance reliability model parameters were recalculated for each reach, followed by the transit reliability. The total cost of the slate, C_S, was modeled as the sum of the annualized reach maintenance costs, C_A, minus the savings from reduced dredging depth. The dredging depth reduction savings is calculated as the sum of the selected depth reduction increment multiplied by the respective unit depth improvement cost, C_I:

$$C_S = \sum_{j=1}^{m} \left(C_{A_j} - C_{I_j} D_{R_j} \right) \tag{18}$$

Figure 21 shows the resulting total dredging cost with respect to the transit reliability for each slate. The univariate regression equation y = 3E+07 x^2 – 6E+08 x + 3E+08 was fit to the data with an R^2 value of 0.496. This fit suggests a variety of potential depth reduction configurations that will meet either cost or minimum reliability requirement; a more rigorous optimization scheme is required to find the best cost given a reliability target, or to maximize reliability given a cost constraint.

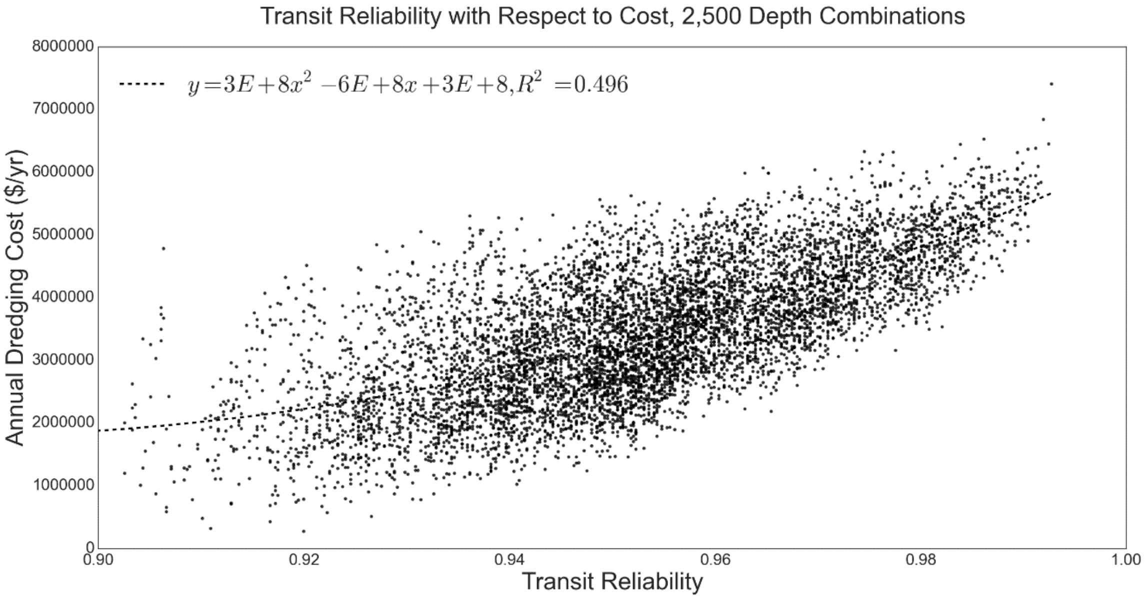


Figure 21 Dredging costs vs. transit reliability, 1,000 iterations.

A decision heuristic was calculated as the ratio of the reduced depth slate cost of option *x* to the total annualized cost for reach maintenance to guide selection of a desirable depth reduction slate when a minimum reliability must be obtained. The objective function shown in equation 19 was maximized subject to the constraint shown in equation 20 such that the transit reliability for each considered slate was greater than a specified minimum reliability.

$$\min Z_x = \frac{\sum_j \left(c_{A_j} - c_{I_j} D_{R_j}\right)}{c} \text{ s.t} \tag{19}$$

$$R_x - R_{min} \geq 0 \tag{20}$$

where:

C is the total annualized reach dredging cost

C_{Aj} is the annualized dredging cost for reach j

C_{Ij} is the annualized incremental depth improvement cost of reach j

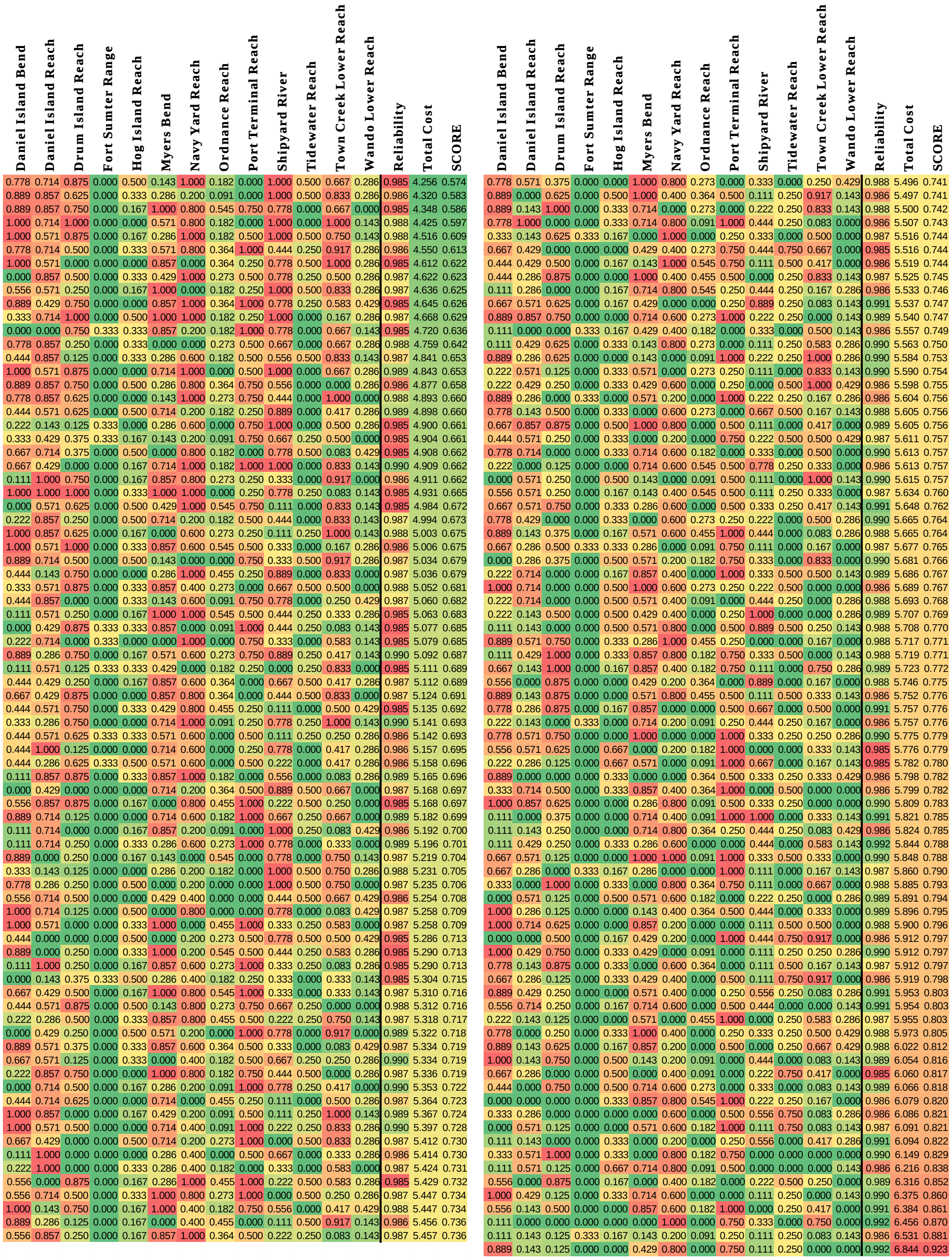
D_{Rj} is the depth reduction in reach j

R_{min} is the minimum target reliability

R_x is the reliability score of the depth reduction slate if $R_x - R_{min}$ is positive, and an arbitrarily large number otherwise

Z_x is the value heuristic for slate x calculated in equation 25 if $R_x - R_{min}$ is greater than 0 and 1 otherwise.

Figure 22 shows the heat map of the solution space for 159 feasible reduction slates (of 7,500 considered slates) that support a minimum reliability of 0.985. Decreasing scores are shown from upper left to lower right in Figure 22. The SCORE column follows a color gradient from lowest score (green, greatest reduction in overall cost, 42.6%) to highest score (red, least reduction in overall cost, 7.7%). The Total Cost column follows a color gradient from least cost (green, \$4.3M) to greatest cost (red, \$6.8M) of feasible alternatives. The Reliability column follows a color gradient from highest reliability (green, 0.992) to least reliability (red, 0.985). Named reaches are colored based on the considered depth reduction, normalized by the maximum possible annualized reduction listed in Table 15. Full-dredging alternatives are represented by green (0% reduction in dredging) and no-dredging alternatives are shaded red (100% reduction in dredging). The savings resulting from maintenance depth reductions ranged from 7.7% to 42.6%.



Daniel Island Bend	Daniel Island Reach	Drum Island Reach	Fort Sumter Range	Hog Island Reach	Myers Bend	Navy Yard Reach	Ordnance Reach	Port Terminal Reach	Shipyard River	Tidewater Reach	Town Creek Lower Reach	Wando Lower Reach	Reliability	Total Cost	SCORE
0.778	0.714	0.875	0.000	0.500	0.143	1.000	0.182	0.000	1.000	0.500	0.667	0.286	0.985	4.256	0.574
0.889	0.857	0.625	0.000	0.333	0.286	0.200	0.091	0.000	1.000	0.500	0.833	0.286	0.986	4.320	0.583
0.889	0.857	0.750	0.000	0.167	1.000	0.800	0.545	0.750	0.778	0.000	0.667	0.000	0.985	4.348	0.586
1.000	0.714	1.000	0.000	0.000	0.571	0.800	0.182	0.000	1.000	0.000	1.000	0.143	0.988	4.425	0.597
1.000	0.571	0.875	0.000	0.167	0.286	1.000	0.182	0.500	1.000	0.500	0.750	0.143	0.988	4.516	0.609
0.778	0.714	0.500	0.000	0.333	0.571	0.800	0.364	1.000	0.444	0.250	0.917	0.286	0.986	4.550	0.613
1.000	0.571	0.000	0.000	0.000	0.857	0.000	0.364	0.250	0.778	0.500	1.000	0.286	0.985	4.612	0.622
0.000	0.857	0.500	0.000	0.333	0.429	1.000	0.273	0.500	0.778	0.250	0.500	0.286	0.987	4.622	0.623
0.556	0.571	0.250	0.000	0.167	1.000	0.000	0.182	0.250	1.000	0.500	0.833	0.286	0.987	4.636	0.625
0.889	0.429	0.750	0.000	0.000	0.857	1.000	0.364	1.000	0.778	0.250	0.583	0.429	0.985	4.645	0.626
0.333	0.714	1.000	0.000	0.500	1.000	1.000	0.182	0.250	1.000	0.000	0.167	0.286	0.987	4.668	0.629
0.000	0.000	0.750	0.333	0.333	0.857	0.200	0.182	1.000	0.778	0.000	0.667	0.143	0.985	4.720	0.636
0.778	0.857	0.250	0.000	0.333	0.000	0.000	0.273	0.500	0.667	0.000	0.667	0.286	0.988	4.759	0.642
0.444	0.857	0.125	0.000	0.333	0.286	0.600	0.182	0.500	0.556	0.500	0.833	0.143	0.987	4.841	0.653
1.000	0.571	0.875	0.000	0.000	0.714	1.000	0.000	0.500	1.000	0.000	0.667	0.286	0.989	4.843	0.653
0.889	0.857	0.750	0.000	0.500	0.286	0.800	0.364	0.750	0.556	0.000	0.000	0.286	0.986	4.877	0.658
0.778	0.857	0.625	0.000	0.000	0.143	1.000	0.273	0.750	0.444	0.000	1.000	0.000	0.988	4.893	0.660
0.444	0.571	0.625	0.000	0.500	0.714	0.200	0.182	0.250	0.889	0.000	0.417	0.286	0.989	4.898	0.660
0.222	0.143	0.125	0.333	0.000	0.286	0.600	0.000	0.750	1.000	0.000	0.500	0.286	0.985	4.900	0.661
0.333	0.429	0.375	0.333	0.167	0.143	0.200	0.091	0.750	0.667	0.250	0.500	0.000	0.985	4.904	0.661
0.667	0.714	0.375	0.000	0.500	0.000	0.800	0.182	0.000	0.778	0.500	0.083	0.429	0.985	4.908	0.662
0.667	0.429	0.000	0.000	0.167	0.714	1.000	0.182	1.000	1.000	0.000	0.833	0.143	0.990	4.909	0.662
0.111	1.000	0.750	0.000	0.167	0.857	0.800	0.273	0.250	0.333	0.000	0.917	0.000	0.986	4.911	0.662
1.000	1.000	1.000	0.000	0.333	1.000	1.000	0.000	0.250	0.778	0.250	0.083	0.143	0.985	4.931	0.665
0.000	0.571	0.625	0.000	0.500	0.429	1.000	0.545	0.750	0.111	0.000	0.833	0.143	0.985	4.984	0.672
0.222	0.857	0.250	0.000	0.500	0.714	0.200	0.182	0.500	0.444	0.000	0.833	0.143	0.987	4.994	0.673
1.000	0.857	0.625	0.000	0.167	0.000	0.600	0.273	0.250	0.111	0.250	1.000	0.143	0.988	5.003	0.675
1.000	0.571	1.000	0.000	0.333	0.857	0.600	0.545	0.500	0.333	0.000	0.167	0.286	0.986	5.006	0.675
0.889	0.714	0.500	0.000	0.500	0.143	0.000	0.000	0.750	0.333	0.500	0.917	0.286	0.987	5.034	0.679
0.444	0.143	0.750	0.000	0.000	0.286	1.000	0.455	0.250	0.889	0.000	0.833	0.000	0.987	5.036	0.679
0.333	0.571	0.875	0.000	0.333	0.857	0.400	0.273	0.000	0.667	0.500	0.500	0.000	0.988	5.052	0.681
0.444	0.857	0.000	0.000	0.333	0.143	0.600	0.091	0.750	0.778	0.000	0.250	0.429	0.987	5.060	0.682
0.111	0.571	0.250	0.000	0.167	1.000	1.000	0.545	0.500	0.444	0.250	0.333	0.286	0.985	5.063	0.683
0.000	0.429	0.875	0.333	0.333	0.857	0.000	0.091	1.000	0.444	0.250	0.083	0.143	0.985	5.077	0.685
0.222	0.714	0.000	0.333	0.000	0.000	1.000	0.000	0.750	0.333	0.000	0.583	0.143	0.985	5.079	0.685
0.889	0.286	0.750	0.000	0.167	0.571	0.600	0.273	0.750	0.889	0.250	0.417	0.143	0.990	5.092	0.687
0.111	0.571	0.125	0.333	0.333	0.429	0.000	0.182	0.250	0.000	0.250	0.833	0.000	0.985	5.111	0.689
0.444	0.429	0.250	0.000	0.167	0.857	0.600	0.364	0.000	0.667	0.500	0.417	0.286	0.987	5.112	0.689
0.667	0.429	0.875	0.000	0.000	0.857	0.800	0.364	0.000	0.444	0.500	0.833	0.000	0.987	5.124	0.691
0.444	0.571	0.750	0.000	0.333	0.429	0.800	0.455	0.250	0.111	0.000	0.500	0.429	0.985	5.135	0.692
0.333	0.286	0.750	0.000	0.000	0.714	1.000	0.091	0.250	0.778	0.250	1.000	0.143	0.990	5.141	0.693
0.444	0.571	0.625	0.333	0.333	0.571	0.600	0.000	0.500	0.111	0.250	0.250	0.286	0.986	5.142	0.693
0.444	1.000	0.125	0.000	0.000	0.714	0.600	0.000	0.250	0.778	0.000	0.417	0.286	0.986	5.157	0.695
0.444	0.286	0.625	0.333	0.500	0.571	0.600	0.000	0.500	0.222	0.000	0.417	0.286	0.986	5.158	0.696
0.111	0.857	0.875	0.000	0.333	0.857	1.000	0.182	0.000	0.556	0.000	0.083	0.286	0.989	5.165	0.696
0.000	0.429	0.000	0.000	0.000	0.714	0.200	0.364	0.500	0.889	0.500	0.667	0.000	0.987	5.168	0.697
0.556	0.857	0.875	0.000	0.167	0.000	0.800	0.455	1.000	0.222	0.500	0.250	0.000	0.985	5.168	0.697
0.889	0.714	0.125	0.000	0.000	0.714	0.600	0.182	1.000	0.667	0.250	0.667	0.000	0.989	5.182	0.699
0.111	0.714	0.000	0.000	0.167	0.857	0.200	0.091	0.000	1.000	0.250	0.083	0.429	0.986	5.192	0.700
0.111	0.714	0.250	0.000	0.333	0.286	0.600	0.273	1.000	0.778	0.000	0.333	0.000	0.989	5.196	0.701
0.889	0.000	0.250	0.000	0.167	0.143	0.000	0.545	0.000	0.778	0.000	0.750	0.143	0.987	5.219	0.704
0.333	0.143	0.125	0.000	0.000	0.286	0.200	0.182	0.000	1.000	0.500	0.750	0.286	0.988	5.231	0.705
0.778	0.286	0.250	0.000	0.500	0.000	0.200	0.000	0.000	1.000	0.500	0.750	0.000	0.987	5.235	0.706
0.556	0.714	0.500	0.000	0.000	0.429	0.400	0.000	0.000	0.444	0.500	0.667	0.429	0.986	5.254	0.708
1.000	0.714	0.125	0.000	0.500	0.000	0.800	0.000	0.000	0.778	0.000	0.083	0.429	0.987	5.258	0.709
1.000	0.571	0.000	0.000	0.333	1.000	0.000	0.455	1.000	0.333	0.250	0.583	0.000	0.987	5.258	0.709
0.444	0.000	0.000	0.000	0.500	0.000	0.200	0.273	0.500	0.778	0.500	0.500	0.429	0.985	5.286	0.713
0.889	0.000	0.250	0.000	0.333	1.000	0.200	0.545	0.500	0.444	0.250	0.583	0.286	0.985	5.290	0.713
0.111	1.000	0.250	0.000	0.167	0.857	0.600	0.273	1.000	0.333	0.250	0.083	0.286	0.985	5.290	0.713
0.000	0.143	0.375	0.333	0.500	0.286	0.400	0.182	0.250	0.333	0.000	0.333	0.143	0.985	5.304	0.715
0.667	0.429	0.500	0.000	0.167	1.000	0.800	0.545	1.000	0.333	0.000	0.333	0.143	0.987	5.310	0.716
0.444	0.571	0.875	0.000	0.500	0.143	0.800	0.273	0.750	0.667	0.250	0.000	0.000	0.988	5.312	0.716
0.222	0.286	0.500	0.000	0.333	0.857	0.800	0.455	0.500	0.222	0.250	0.750	0.143	0.987	5.318	0.717
0.000	0.429	0.250	0.000	0.500	0.571	0.200	0.000	1.000	0.778	0.000	0.917	0.000	0.989	5.322	0.718
0.889	0.571	0.375	0.000	0.333	0.857	0.600	0.364	0.500	0.333	0.000	0.083	0.429	0.987	5.334	0.719
0.667	0.571	0.125	0.000	0.333	0.000	0.400	0.182	0.500	0.667	0.250	0.250	0.286	0.990	5.334	0.719
0.222	0.857	0.750	0.000	0.000	1.000	0.800	0.182	0.750	0.444	0.500	0.000	0.286	0.987	5.336	0.719
0.000	0.714	0.500	0.000	0.167	0.286	0.200	0.091	1.000	0.778	0.250	0.417	0.000	0.990	5.353	0.722
0.444	0.714	0.625	0.000	0.000	0.714	0.000	0.455	0.250	0.111	0.000	0.500	0.286	0.987	5.364	0.723
1.000	0.857	0.000	0.000	0.167	0.429	0.200	0.091	0.500	0.111	0.250	1.000	0.143	0.989	5.367	0.724
1.000	0.571	0.500	0.000	0.000	0.714	0.400	0.091	1.000	0.222	0.250	0.833	0.286	0.990	5.397	0.728
0.667	0.429	0.000	0.000	0.500	0.714	0.200	0.273	1.000	0.000	0.500	0.833	0.286	0.987	5.412	0.730
0.111	1.000	0.000	0.000	0.000	0.286	0.400	0.000	0.500	0.667	0.000	0.333	0.286	0.986	5.414	0.730
0.222	1.000	0.000	0.000	0.333	0.286	0.400	0.182	0.000	0.333	0.000	0.583	0.000	0.987	5.424	0.731
0.556	0.000	0.875	0.000	0.167	0.286	1.000	0.455	1.000	0.222	0.500	0.583	0.286	0.985	5.429	0.732
0.556	0.714	0.500	0.000	0.333	1.000	0.800	0.273	1.000	0.000	0.500	0.250	0.286	0.987	5.447	0.734
1.000	0.143	0.750	0.000	0.167	1.000	0.400	0.182	0.750	0.556	0.000	0.417	0.429	0.988	5.447	0.734
0.889	0.286	0.125	0.000	0.167	0.000	0.400	0.455	0.000	0.111	0.500	0.917	0.143	0.986	5.456	0.736
0.556	0.857	0.250	0.000	0.167	0.857	1.000	0.364	0.500	0.222	0.250	0.083	0.143	0.987	5.457	0.736

Daniel Island Bend	Daniel Island Reach	Drum Island Reach	Fort Sumter Range	Hog Island Reach	Myers Bend	Navy Yard Reach	Ordnance Reach	Port Terminal Reach	Shipyard River	Tidewater Reach	Town Creek Lower Reach	Wando Lower Reach	Reliability	Total Cost	SCORE
0.778	0.571	0.375	0.000	0.000	1.000	0.800	0.273	0.000	0.333	0.000	0.250	0.429	0.988	5.496	0.741
0.889	0.000	0.625	0.000	0.500	1.000	0.400	0.364	0.500	0.111	0.250	0.917	0.143	0.986	5.497	0.741
0.889	0.143	1.000	0.000	0.333	0.714	0.000	0.273	0.000	0.222	0.250	0.833	0.143	0.988	5.500	0.742
0.778	1.000	0.000	0.000	0.333	0.714	0.800	0.091	1.000	0.444	0.250	0.083	0.000	0.986	5.507	0.743
0.333	0.143	0.625	0.333	0.167	0.000	1.000	0.000	0.250	0.333	0.000	0.500	0.000	0.987	5.516	0.744
0.667	0.429	0.000	0.000	0.000	0.429	0.400	0.273	0.750	0.444	0.750	0.667	0.000	0.985	5.516	0.744
0.444	0.429	0.500	0.000	0.167	0.143	1.000	0.545	0.750	0.111	0.500	0.417	0.000	0.986	5.519	0.744
0.444	0.286	0.875	0.000	0.000	1.000	0.400	0.455	0.500	0.000	0.250	0.833	0.143	0.987	5.525	0.745
0.111	0.286	0.000	0.000	0.167	0.714	0.800	0.545	0.250	0.444	0.250	0.167	0.286	0.986	5.533	0.746
0.667	0.571	0.625	0.000	0.167	0.429	0.000	0.000	0.250	0.889	0.250	0.083	0.143	0.991	5.537	0.747
0.889	0.857	0.750	0.000	0.000	0.714	0.600	0.273	1.000	0.222	0.250	0.000	0.143	0.989	5.540	0.747
0.111	0.000	0.000	0.333	0.167	0.429	0.400	0.182	0.000	0.333	0.000	0.500	0.143	0.986	5.557	0.749
0.111	0.429	0.625	0.000	0.333	0.143	0.800	0.273	0.000	0.111	0.250	0.583	0.286	0.990	5.563	0.750
0.889	0.286	0.625	0.000	0.000	0.143	0.000	0.091	1.000	0.222	0.250	1.000	0.286	0.990	5.584	0.753
0.222	0.571	0.125	0.000	0.333	0.571	0.000	0.273	0.250	0.111	0.000	0.833	0.143	0.990	5.590	0.754
0.222	0.429	0.250	0.000	0.333	0.429	0.600	0.000	0.250	0.000	0.500	1.000	0.429	0.986	5.598	0.755
0.889	0.286	0.000	0.333	0.000	0.571	0.200	0.000	1.000	0.222	0.250	0.167	0.286	0.986	5.604	0.756
0.778	0.143	0.500	0.000	0.333	0.000	0.600	0.273	0.000	0.667	0.500	0.167	0.143	0.988	5.605	0.756
0.667	0.857	0.875	0.000	0.500	1.000	0.800	0.000	0.500	0.111	0.000	0.417	0.000	0.989	5.605	0.756
0.444	0.571	0.250	0.000	0.333	0.000	0.200	0.000	0.750	0.222	0.500	0.500	0.429	0.987	5.611	0.757
0.778	0.714	0.000	0.000	0.333	0.714	0.600	0.182	0.000	0.333	0.000	0.500	0.000	0.990	5.613	0.757
0.222	0.000	0.125	0.000	0.000	0.714	0.600	0.545	0.500	0.778	0.250	0.333	0.000	0.986	5.613	0.757
0.000	0.571	0.250	0.000	0.500	0.143	0.000	0.091	0.500	0.111	0.000	1.000	0.143	0.990	5.615	0.757
0.556	0.571	0.250	0.000	0.167	0.143	0.400	0.545	0.500	0.111	0.250	0.333	0.000	0.987	5.634	0.760
0.667	0.571	0.750	0.000	0.333	0.286	0.600	0.000	0.500	0.333	0.250	0.417	0.143	0.991	5.648	0.762
0.778	0.429	0.000	0.000	0.333	0.000	0.600	0.273	0.250	0.222	0.000	0.500	0.286	0.990	5.665	0.764
0.889	0.143	0.375	0.000	0.167	0.571	0.600	0.455	1.000	0.444	0.000	0.083	0.286	0.988	5.665	0.764
0.667	0.286	0.500	0.333	0.333	0.286	0.000	0.091	0.750	0.111	0.000	0.167	0.000	0.987	5.677	0.765
0.000	0.286	0.375	0.000	0.500	0.571	0.200	0.182	0.750	0.333	0.000	0.833	0.000	0.990	5.681	0.766
0.222	0.714	0.000	0.000	0.167	0.857	0.400	0.000	1.000	0.333	0.500	0.500	0.143	0.989	5.686	0.767
1.000	0.714	0.000	0.000	0.500	1.000	0.600	0.273	0.250	0.222	0.500	0.000	0.000	0.986	5.689	0.767
0.222	0.714	0.000	0.000	0.500	0.571	0.400	0.091	0.000	0.444	0.250	0.000	0.286	0.988	5.693	0.768
0.222	0.143	0.500	0.000	0.500	0.429	0.400	0.000	0.250	1.000	0.000	0.000	0.286	0.989	5.707	0.769
0.111	0.143	0.000	0.000	0.500	0.571	0.800	0.000	0.500	0.889	0.500	0.250	0.143	0.988	5.708	0.770
0.889	0.571	0.750	0.000	0.333	0.286	1.000	0.455	0.250	0.000	0.000	0.167	0.000	0.988	5.717	0.771
0.111	0.429	1.000	0.000	0.333	0.857	0.800	0.182	0.750	0.333	0.500	0.000	0.143	0.988	5.719	0.771
0.667	0.143	1.000	0.000	0.167	0.857	0.400	0.182	0.750	0.111	0.000	0.750	0.286	0.989	5.723	0.772
0.556	0.000	0.875	0.000	0.000	0.429	0.200	0.364	0.000	0.889	0.000	0.167	0.000	0.988	5.746	0.775
0.889	0.143	0.875	0.000	0.000	0.571	0.800	0.455	0.500	0.111	0.500	0.333	0.143	0.986	5.752	0.776
0.778	0.286	0.875	0.000	0.167	0.857	0.000	0.000	0.500	0.667	0.000	0.500	0.000	0.991	5.757	0.776
0.222	0.143	0.000	0.333	0.000	0.714	0.200	0.091	0.250	0.444	0.250	0.167	0.000	0.986	5.757	0.776
0.778	0.571	0.750	0.000	0.000	1.000	0.000	0.000	1.000	0.333	0.250	0.250	0.286	0.990	5.775	0.779
0.556	0.571	0.625	0.000	0.667	0.000	0.200	0.182	1.000	0.000	0.000	0.333	0.143	0.985	5.776	0.779
0.222	0.286	0.125	0.000	0.667	0.571	0.000	0.091	1.000	0.667	0.000	0.167	0.143	0.985	5.782	0.780
0.889	0.000	0.000	0.000	0.333	0.000	0.000	0.364	0.500	0.333	0.250	0.333	0.429	0.986	5.798	0.782
0.333	0.714	0.500	0.000	0.333	0.857	0.400	0.364	1.000	0.000	0.500	0.000	0.000	0.986	5.799	0.782
1.000	0.857	0.625	0.000	0.000	0.286	0.800	0.091	0.500	0.333	0.250	0.000	0.000	0.990	5.809	0.783
0.111	0.000	0.375	0.000	0.000	0.714	0.400	0.091	1.000	1.000	0.000	0.333	0.143	0.991	5.821	0.785
0.111	0.143	0.250	0.000	0.000	0.714	0.800	0.364	0.250	0.444	0.250	0.083	0.429	0.986	5.824	0.785
0.111	0.429	0.250	0.000	0.333	0.286	0.600	0.000	0.000	0.444	0.000	0.583	0.143	0.992	5.844	0.788
0.667	0.571	0.125	0.000	0.000	1.000	1.000	0.091	1.000	0.333	0.500	0.333	0.000	0.990	5.848	0.788
0.667	0.286	0.000	0.333	0.167	0.286	0.000	0.000	1.000	0.111	0.000	0.167	0.143	0.987	5.860	0.790
0.333	0.000	1.000	0.000	0.333	0.000	0.800	0.364	0.750	0.111	0.000	0.667	0.000	0.988	5.885	0.793
0.000	0.571	0.125	0.000	0.500	0.571	0.600	0.182	0.000	0.222	0.250	0.000	0.286	0.989	5.891	0.794
1.000	0.286	0.125	0.000	0.000	0.143	0.400	0.364	0.500	0.444	0.000	0.333	0.000	0.989	5.896	0.795
1.000	0.714	0.625	0.000	0.000	0.857	0.200	0.000	0.000	0.111	0.500	0.500	0.000	0.988	5.900	0.796
0.000	0.000	0.500	0.000	0.167	0.429	0.200	0.000	1.000	0.444	0.750	0.917	0.000	0.986	5.912	0.797
1.000	0.429	0.750	0.000	0.333	0.429	0.000	0.091	0.000	0.111	0.250	0.250	0.286	0.990	5.912	0.797
0.778	0.143	0.875	0.000	0.333	0.000	0.600	0.364	0.000	0.111	0.500	0.167	0.143	0.987	5.912	0.797
0.667	0.286	0.125	0.000	0.333	0.429	0.400	0.000	0.500	0.111	0.750	0.917	0.000	0.986	5.919	0.798
0.889	0.429	0.250	0.000	0.000	0.571	0.400	0.000	0.250	0.556	0.250	0.083	0.286	0.991	5.953	0.803
0.556	0.714	0.250	0.000	0.167	0.714	0.600	0.000	0.500	0.444	0.000	0.000	0.143	0.991	5.954	0.803
0.222	0.143	0.125	0.000	0.000	0.571	0.000	0.455	1.000	0.000	0.250	0.583	0.286	0.987	5.955	0.803
0.778	0.000	0.250	0.000	0.333	1.000	0.400	0.000	0.250	0.333	0.250	0.500	0.429	0.988	5.973	0.805
0.889	0.143	0.625	0.000	0.167	0.857	0.200	0.000	0.500	0.000	0.250	0.667	0.429	0.988	6.022	0.812
1.000	0.143	0.750	0.000	0.500	0.143	0.200	0.091	0.000	0.444	0.000	0.083	0.143	0.989	6.054	0.816
0.667	0.286	0.000	0.000	0.500	0.000	0.400	0.091	0.000	0.222	0.750	0.417	0.000	0.985	6.060	0.817
0.444	0.000	0.750	0.000	0.500	0.714	0.600	0.273	0.000	0.333	0.000	0.083	0.143	0.989	6.066	0.818
0.000	0.000	0.000	0.000	0.333	0.857	0.800	0.545	1.000	0.222	0.250	0.167	0.000	0.986	6.079	0.820
0.333	0.286	0.000	0.000	0.000	0.000	0.600	0.000	0.500	0.556	0.750	0.083	0.286	0.986	6.086	0.821
0.000	0.571	0.125	0.000	0.000	0.571	0.600	0.182	1.000	0.111	0.750	0.083	0.143	0.987	6.091	0.821
0.111	0.143	0.000	0.000	0.333	0.000	0.200	0.000	0.250	0.556	0.000	0.417	0.286	0.991	6.094	0.822
0.333	0.571	1.000	0.000	0.333	0.000	0.800	0.182	0.750	0.000	0.000	0.000	0.000	0.990	6.149	0.829
0.111	0.571	0.125	0.000	0.667	0.714	0.800	0.091	0.500	0.000	0.000	0.000	0.143	0.986	6.216	0.838
0.556	0.000	0.875	0.000	0.167	0.000	0.400	0.182	0.000	0.222	0.500	0.250	0.000	0.989	6.316	0.852
1.000	0.429	0.125	0.000	0.333	0.714	0.600	0.000	0.000	0.111	0.250	0.000	0.143	0.990	6.375	0.860
0.556	0.143	0.500	0.000	0.000	0.857	0.600	0.182	1.000	0.000	0.250	0.417	0.000	0.991	6.384	0.861
0.111	0.000	0.000	0.000	0.000	0.000	1.000	0.000	0.750	0.333	0.000	0.750	0.000	0.992	6.456	0.870
0.111	0.143	0.125	0.333	0.167	0.143	0.200	0.091	0.250	0.111	0.250	0.083	0.143	0.986	6.531	0.881
0.889	0.143	0.125	0.000	0.000	0.429	0.800	0.000	0.750	0.111	0.250	0.000	0.000	0.992	6.844	0.923

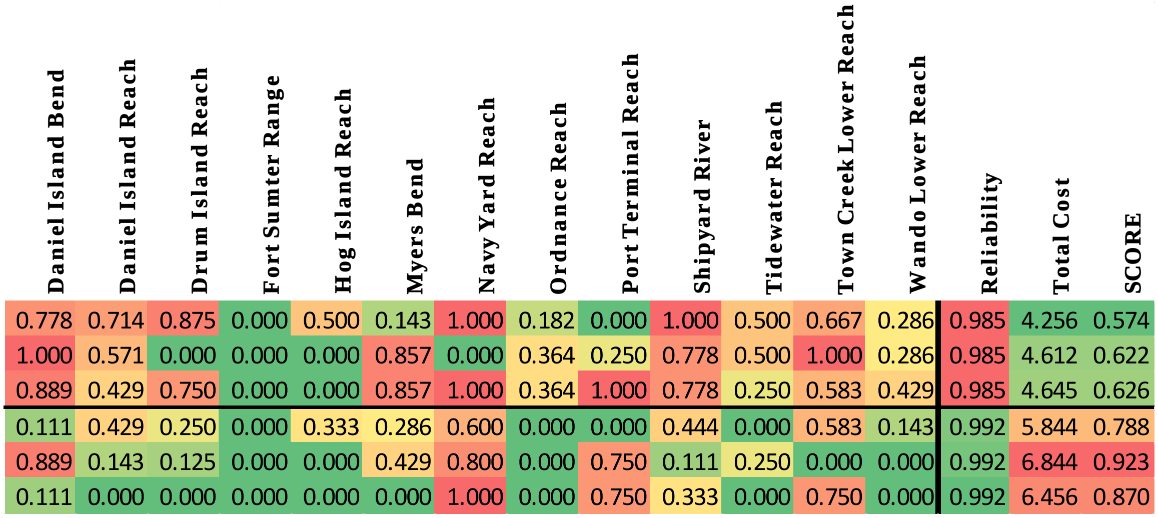
Figure 22 Scored feasible Monte-Carlo dredging reduction options.

Discussion of Monte-Carlo Results

The feasible Monte-Carlo alternatives inform the management of the Charleston Harbor project. The heat map visualization of reductions to regular maintenance practices shown in Figure 22 identifies clear trends within the feasible range. Perhaps the most obvious trend is the strong green band in Fort Sumter Range signifying a high frequency of full dredging in that reach across all feasible alternatives. A subtler trend is the lack of red cells within the Wando Lower Reach, Tidewater Reach, and Hog Island Reach columns. This indicates that these reaches are subject to moderately reduced dredging to achieve lowered maintenance costs. Conversely, Port Terminal Reach, Navy Yard Reach, and Daniel Island bend appear visually to have more frequent reductions of more than 50% of routine depth improvement. Further analysis of feasible dredging options with respect to cost and reliability is necessary to determine dredge prioritization insights.

Figure 23 shows the feasible alternatives with the highest (top 3) and lowest (bottom 3) transit reliability. The three minimally acceptable alternatives had reliability equal to 0.985, with costs ranging from $4.3M to $4.6M. The most reliable alternatives had reliability equal to 0.992, with costs ranging from $5.8M to $6.8M. Across both the high and low reliability alternatives, Fort Sumter Range again stands out as being fully maintained, indicating its relative importance to the reliability of the harbor. Hog Island Reach and Wando Lower Reach also have relatively full maintenance in the 0.985 reliability region.

Navy Yard Reach averages dredging of 50% or less in the high and low reliability ranges, indicating that it is a likely candidate for reduced dredging. However, one slate of reductions at 0.985 reliability has full dredging in this reach. Thus, it may not be possible to directly predict the dredging practice to employ in each reach with respect to reliability and a weight of evidence approach may be necessary to prioritize reach maintenance.

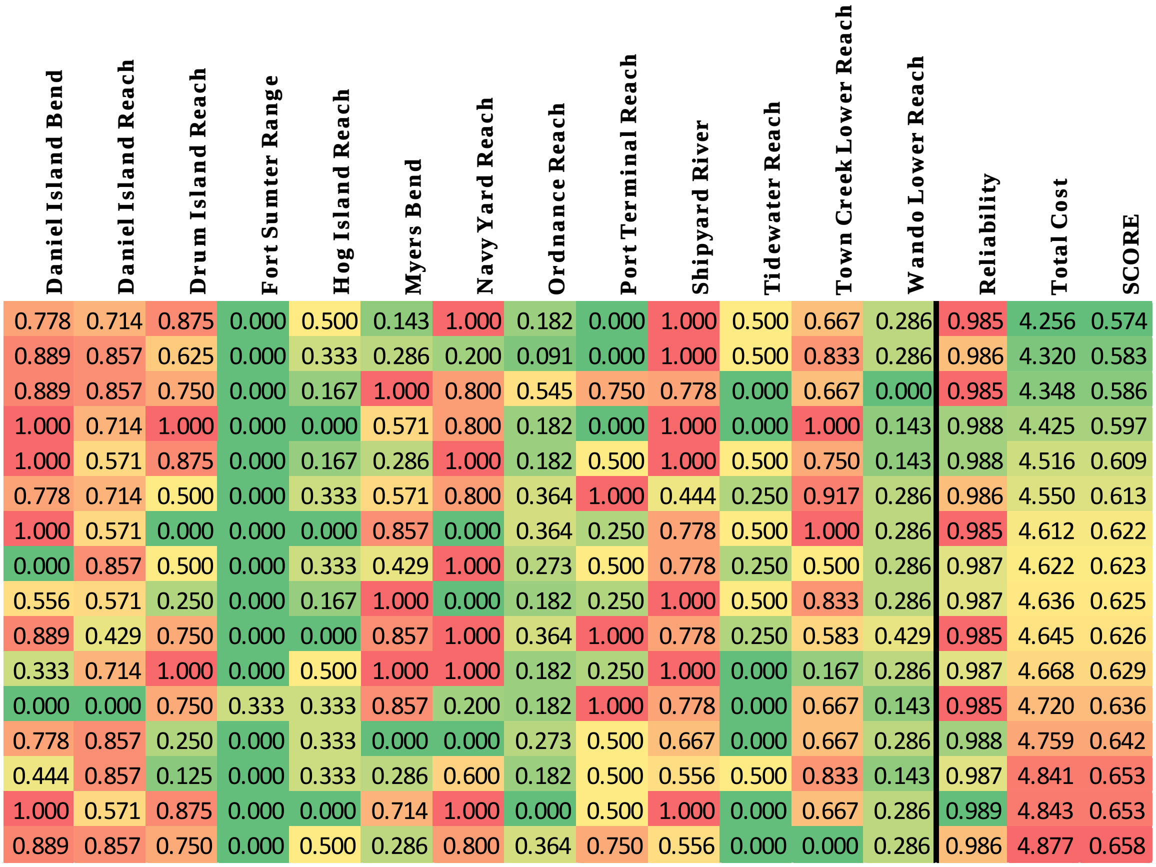


Daniel Island Bend	Daniel Island Reach	Drum Island Reach	Fort Sumter Range	Hog Island Reach	Myers Bend	Navy Yard Reach	Ordnance Reach	Port Terminal Reach	Shipyard River	Tidewater Reach	Town Creek Lower Reach	Wando Lower Reach	Reliability	Total Cost	SCORE
0.778	0.714	0.875	0.000	0.500	0.143	1.000	0.182	0.000	1.000	0.500	0.667	0.286	0.985	4.256	0.574
1.000	0.571	0.000	0.000	0.000	0.857	0.000	0.364	0.250	0.778	0.500	1.000	0.286	0.985	4.612	0.622
0.889	0.429	0.750	0.000	0.000	0.857	1.000	0.364	1.000	0.778	0.250	0.583	0.429	0.985	4.645	0.626
0.111	0.429	0.250	0.000	0.333	0.286	0.600	0.000	0.000	0.444	0.000	0.583	0.143	0.992	5.844	0.788
0.889	0.143	0.125	0.000	0.000	0.429	0.800	0.000	0.750	0.111	0.250	0.000	0.000	0.992	6.844	0.923
0.111	0.000	0.000	0.000	0.000	0.000	1.000	0.000	0.750	0.333	0.000	0.750	0.000	0.992	6.456	0.870

Figure 23 Feasible alternatives with the highest (top 3) and lowest (bottom 3) reliability.

Figure 24 shows the 10% of feasible alternatives with least cost. Within this range, individual reaches are demonstrated to have similar recommended dredging practices at different cost increments. This is especially true in the reaches where dredging is maintained (Fort Sumter Range, Hog Island Reach, Wando Lower Reach). In other reaches where dredging is more drastically reduced, dredging options are similar but less consistent, including occasional selections of limited reductions to dredging (Daniel Island Bend, Daniel Island Reach, Shipyard River). This figure indicates the need for further exploration of dredging options at each target reliability. This figure also indicates overlap with Figure 23 with regard to reaches that are fully or mostly dredged

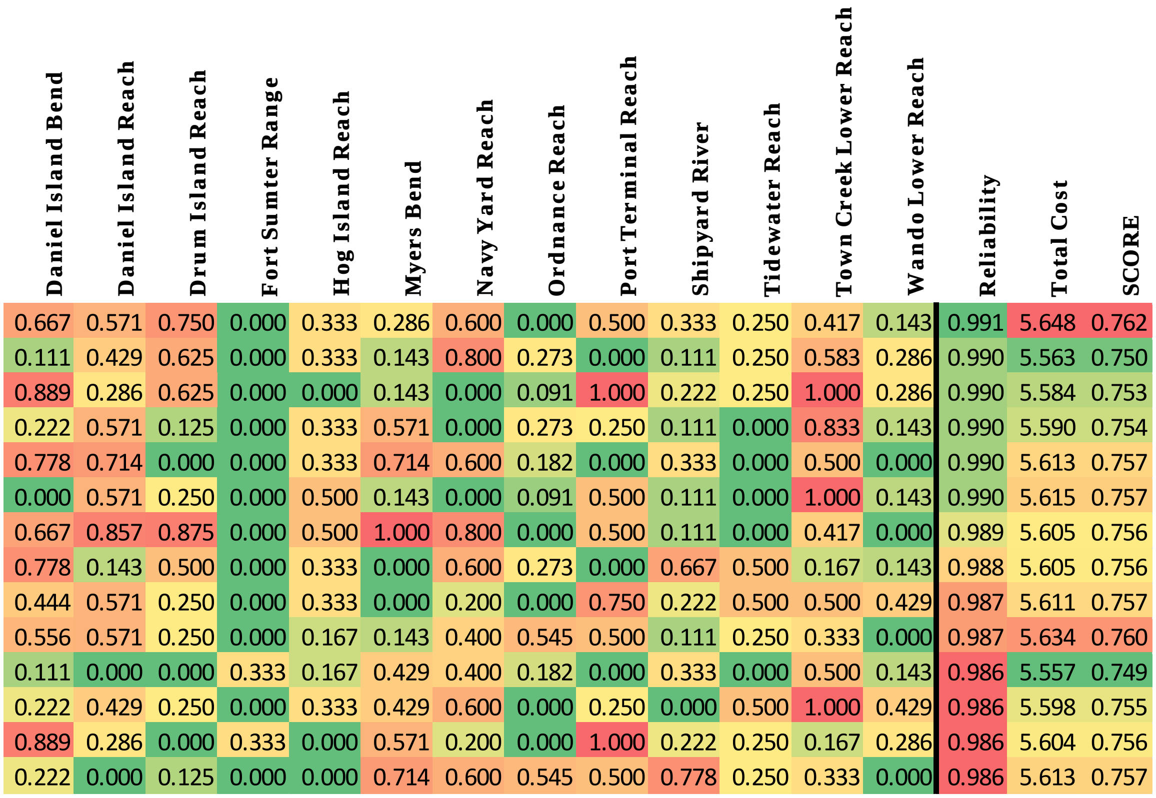
(Fort Sumter Range, Wando Lower Reach) and those reaches in which dredging is substantially reduced (Daniel Island Bend, Shipyard River).



Daniel Island Bend	Daniel Island Reach	Drum Island Reach	Fort Sumter Range	Hog Island Reach	Myers Bend	Navy Yard Reach	Ordnance Reach	Port Terminal Reach	Shipyard River	Tidewater Reach	Town Creek Lower Reach	Wando Lower Reach	Reliability	Total Cost	SCORE
0.778	0.714	0.875	0.000	0.500	0.143	1.000	0.182	0.000	1.000	0.500	0.667	0.286	0.985	4.256	0.574
0.889	0.857	0.625	0.000	0.333	0.286	0.200	0.091	0.000	1.000	0.500	0.833	0.286	0.986	4.320	0.583
0.889	0.857	0.750	0.000	0.167	1.000	0.800	0.545	0.750	0.778	0.000	0.667	0.000	0.985	4.348	0.586
1.000	0.714	1.000	0.000	0.000	0.571	0.800	0.182	0.000	1.000	0.000	1.000	0.143	0.988	4.425	0.597
1.000	0.571	0.875	0.000	0.167	0.286	1.000	0.182	0.500	1.000	0.500	0.750	0.143	0.988	4.516	0.609
0.778	0.714	0.500	0.000	0.333	0.571	0.800	0.364	1.000	0.444	0.250	0.917	0.286	0.986	4.550	0.613
1.000	0.571	0.000	0.000	0.000	0.857	0.000	0.364	0.250	0.778	0.500	1.000	0.286	0.985	4.612	0.622
0.000	0.857	0.500	0.000	0.333	0.429	1.000	0.273	0.500	0.778	0.250	0.500	0.286	0.987	4.622	0.623
0.556	0.571	0.250	0.000	0.167	1.000	0.000	0.182	0.250	1.000	0.500	0.833	0.286	0.987	4.636	0.625
0.889	0.429	0.750	0.000	0.000	0.857	1.000	0.364	1.000	0.778	0.250	0.583	0.429	0.985	4.645	0.626
0.333	0.714	1.000	0.000	0.500	1.000	1.000	0.182	0.250	1.000	0.000	0.167	0.286	0.987	4.668	0.629
0.000	0.000	0.750	0.333	0.333	0.857	0.200	0.182	1.000	0.778	0.000	0.667	0.143	0.985	4.720	0.636
0.778	0.857	0.250	0.000	0.333	0.000	0.000	0.273	0.500	0.667	0.000	0.667	0.286	0.988	4.759	0.642
0.444	0.857	0.125	0.000	0.333	0.286	0.600	0.182	0.500	0.556	0.500	0.833	0.143	0.987	4.841	0.653
1.000	0.571	0.875	0.000	0.000	0.714	1.000	0.000	0.500	1.000	0.000	0.667	0.286	0.989	4.843	0.653
0.889	0.857	0.750	0.000	0.500	0.286	0.800	0.364	0.750	0.556	0.000	0.000	0.286	0.986	4.877	0.658

Figure 24 Feasible alternatives with the lowest (bottom 10%) cost.

The costs for feasible alternatives averaged $5.6M. Figure 25 shows 14 feasible alternatives with costs approximately equal to the average cost of feasible alternatives. This range of costs shows a wider range of resulting reliability (0.986 to 0.991) than the least expensive 10% of feasible options, but similar patterns are evident with respect to which reaches are recommended for full or reduced dredging.



Daniel Island Bend	Daniel Island Reach	Drum Island Reach	Fort Sumter Range	Hog Island Reach	Myers Bend	Navy Yard Reach	Ordnance Reach	Port Terminal Reach	Shipyard River	Tidewater Reach	Town Creek Lower Reach	Wando Lower Reach	Reliability	Total Cost	SCORE
0.667	0.571	0.750	0.000	0.333	0.286	0.600	0.000	0.500	0.333	0.250	0.417	0.143	0.991	5.648	0.762
0.111	0.429	0.625	0.000	0.333	0.143	0.800	0.273	0.000	0.111	0.250	0.583	0.286	0.990	5.563	0.750
0.889	0.286	0.625	0.000	0.000	0.143	0.000	0.091	1.000	0.222	0.250	1.000	0.286	0.990	5.584	0.753
0.222	0.571	0.125	0.000	0.333	0.571	0.000	0.273	0.250	0.111	0.000	0.833	0.143	0.990	5.590	0.754
0.778	0.714	0.000	0.000	0.333	0.714	0.600	0.182	0.000	0.333	0.000	0.500	0.000	0.990	5.613	0.757
0.000	0.571	0.250	0.000	0.500	0.143	0.000	0.091	0.500	0.111	0.000	1.000	0.143	0.990	5.615	0.757
0.667	0.857	0.875	0.000	0.500	1.000	0.800	0.000	0.500	0.111	0.000	0.417	0.000	0.989	5.605	0.756
0.778	0.143	0.500	0.000	0.333	0.000	0.600	0.273	0.000	0.667	0.500	0.167	0.143	0.988	5.605	0.756
0.444	0.571	0.250	0.000	0.333	0.000	0.200	0.000	0.750	0.222	0.500	0.500	0.429	0.987	5.611	0.757
0.556	0.571	0.250	0.000	0.167	0.143	0.400	0.545	0.500	0.111	0.250	0.333	0.000	0.987	5.634	0.760
0.111	0.000	0.000	0.333	0.167	0.429	0.400	0.182	0.000	0.333	0.000	0.500	0.143	0.986	5.557	0.749
0.222	0.429	0.250	0.000	0.333	0.429	0.600	0.000	0.250	0.000	0.500	1.000	0.429	0.986	5.598	0.755
0.889	0.286	0.000	0.333	0.000	0.571	0.200	0.000	1.000	0.222	0.250	0.167	0.286	0.986	5.604	0.756
0.222	0.000	0.125	0.000	0.000	0.714	0.600	0.545	0.500	0.778	0.250	0.333	0.000	0.986	5.613	0.757

Figure 25 Feasible alternatives with cost approximately $5.6M.

In general, some reaches are frequently selected for full or near-full dredging (Fort Sumter Range, Wando Lower Reach), and others are recurrently selected for substantial reductions in dredging within the feasible range. Understanding the extent to which this happens will be useful for prioritizing reaches that get dredged. The distribution of dredging depth reductions among feasible options are shown in Figure 26 for each reach. Fort Sumter Range, Wando Lower Reach, Hog Island Reach and Ordnance reach all have median reductions to routine dredging practice below 20%. For Fort Sumter Range and Wando Lower Reach, 100% of considered options recommended reductions less than 33% and 50%, respectively. Daniel Island Bend, Myers Bend and

Navy Yard Reach all had median feasible reductions above 50%, indicating that reductions in these reaches are less impactful to overall reliability.

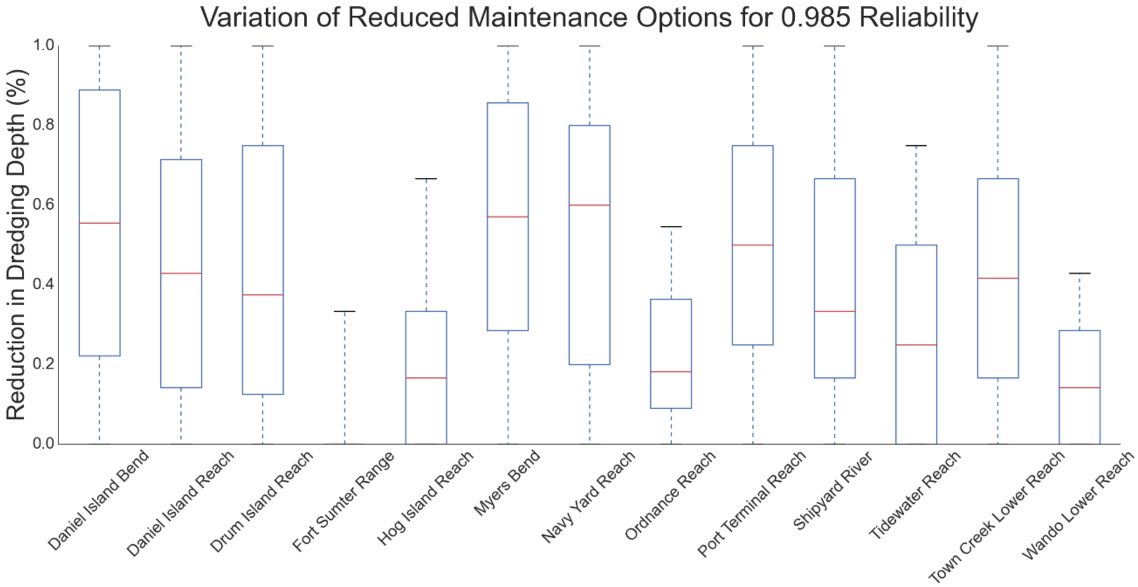


Figure 26 Reach-wise distribution of maintenance dredging depth reductions for feasible alternatives.

The frequency distributions of reaches that have reduced dredging can be used to prioritize reach maintenance. It is assumed that reaches which better tolerate reduced dredging occur more frequently in the feasible range with greater dredging reductions than those that do not. In fact, several reaches are present in the feasible range with multiple instances where they are not dredged. The frequency of non-dredging is used as an indicator of deferred maintenance tolerance, lowering maintenance priority.

A proposed reach maintenance priority ranking is based on the number of occurrences of full depth reductions in the set of feasible options divided by the fraction of total transits appearing in the reach was used as the prioritization score. Reaches with lower prioritization scores received higher priority for full-depth maintenance. Tied prioritization scores were broken using the number of unique users appearing in the reach. This approach values reaches with greater impact on reliability and greater support to the number and diversity of reach users. The number of full depth reductions, fraction of transits, and prioritization scores for each reach are shown in Table 17.

Table 17 Monte-Carlo reach maintenance prioritization ranking.

	Divide	by	Results in	
Reach	Full Depth Reduction Count	Fraction of Total Transits in Reach	Prioritization Score	Maintenance Priority
Daniel Island Bend	19	0.327	58.0	9
Daniel Island Reach	7	0.327	21.4	6
Drum Island Reach	9	0.379	23.7	7
Fort Sumter Range	0	0.991	0.0	1
Hog Island Reach	0	0.824	0.0	2
Myers Bend	19	0.379	50.1	8
Navy Yard Reach	22	0.308	71.5	10
Ordnance Reach	0	0.157	0.0	5
Port Terminal Reach	35	0.173	201.8	12
Shipyard River	14	0.005	3080.8	13
Tidewater Reach	0	0.157	0.0	4
Town Creek Lower Reach	9	0.072	124.2	11
Wando Lower Reach	0	0.443	0.0	3

According to this approach, Fort Sumter Range and Hog Island Reach stand out as being the two most important reaches to maintain across dredging slates. This is not surprising when considered with respect to major terminals within the harbor. Table 18 lists the major terminals maintained by the South Carolina State Ports Authority (USACE, 2015) and the percent of piloted transits moving between each port and the entrance channel (Fort Sumter Range) based on pilot records. Fort Sumter Range must be transited between the ocean and any of the four terminals, meaning that at least 81% of traffic must move through this reach. Similarly, Hog Island Reach lies between Wando Welch Container Terminal or North Charleston Container Terminal and the ocean, thus at least 53% of piloted traffic must pass through it. Wando Lower Reach receives 43% of vessel traffic. Thus prioritizing these reaches supports both the greatest number of vessel transits.

Table 18 Sponsor terminal traffic distribution.

Terminal	Percent of Traffic
Wando Container Terminal	43%
North Charleston Container Terminal	21%
Columbus Street RO/RO Terminal	11%
Union Pier Passenger Terminal	6%

High prioritization of Fort Sumter Range and Hog Island Reach also makes sense when vessel speed, which is important when predicting vessel squat, is considered. Vessels with increased squat effectively reduce net underkeel clearance, which increases the likelihood of keel strike. Fort Sumter Range and Hog Island Reach had the highest mean vessel speed of dredged reaches at 14.5 knots and 9.3 knots, respectively.

Tidewater Reach and Ordnance Reach also receive high priority (4th and 5th priority, respectively), although other reaches support more traffic, due to having 0 instances of recommended elimination of dredging. The divergence from gross traffic fraction in reach priority can be explained by the draft to available depth ratio, T/h, which is an important parameter for navigation channel design (PIANC, 2014).

The draft to available depth ratio is a function of the channel depth, the sailing draft of vessels transiting the reach, variations in the water surface elevation, and the shoaling rate. The 95th percentile draft to available depth ratio is shown in Table 19 as is the number of vessels with greater T/h values. At the 95th percentile, Tidewater Reach, Ordnance Reach and Shipyard River have T/h values comparable to Fort Sumter Range, Hog Island Reach and Wando Lower Reach. Shipyard River has the second highest *T/h* value of all dredged reaches, but only 1 vessel exceeds that value in the reach. Thus, a relatively low number of vessels will be impacted when shoaling or water level reduces available depth. Conversely, 31 vessels exceed the 95th percentile *T/h* value in Tidewater Reach and Ordnance Reach. The remaining reaches have relatively lower shoaling rates and 95th percentile *T/h* values. In fact, by the time *T/h* values in the reaches prioritized 6th or higher reach *T/h* values comparable to Tidewater Reach and Ordnance Reach 95th percentile values (0.82), less than half as many vessels exceed that ratio.

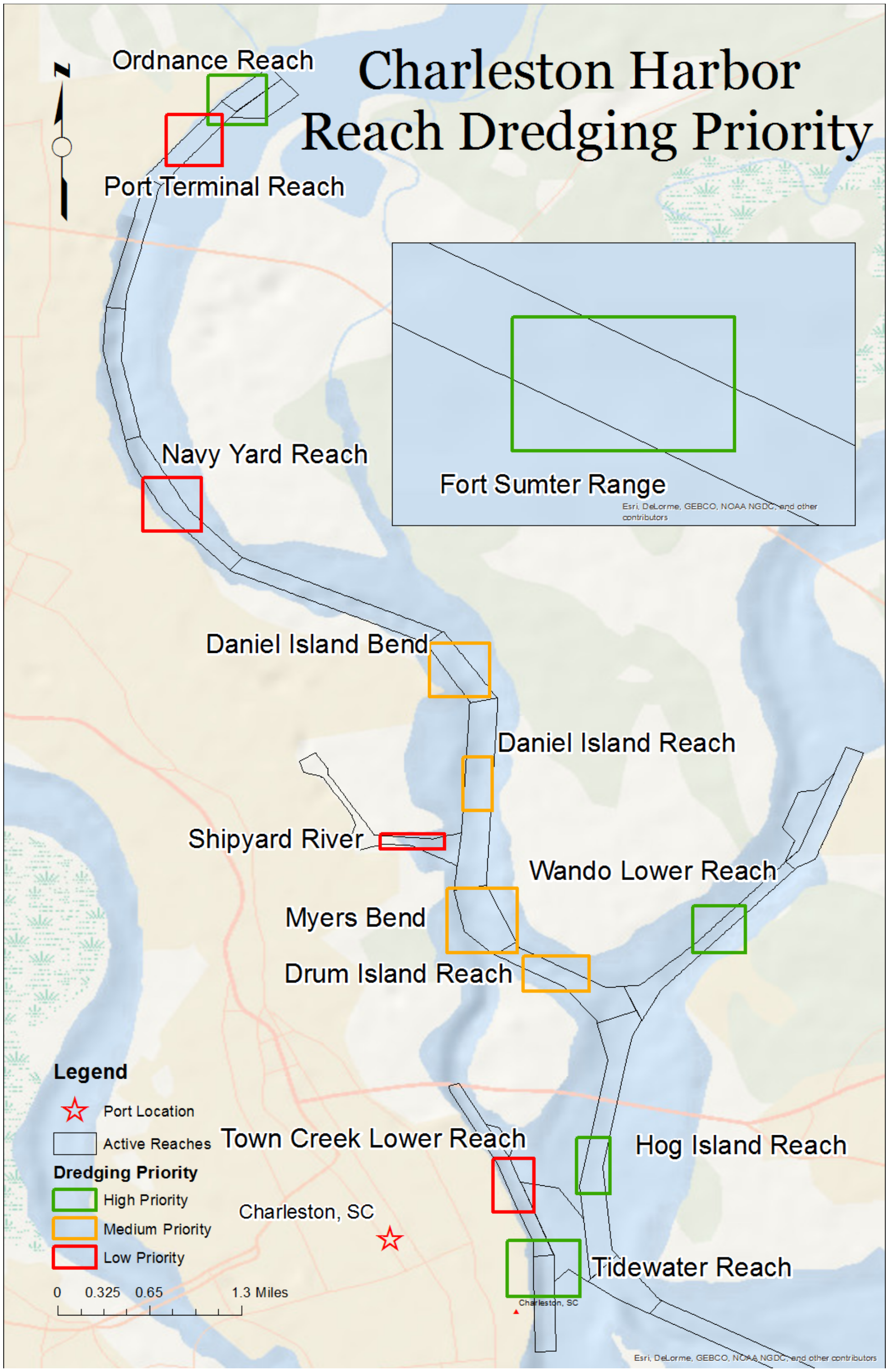
Table 19 95th percentile sailing draft to available depth ratio for dredged reaches.

Reach	95th percentile T	95th percentile T/h	No. of Vessels Exceeding 95th percentile	99th percentile T/h	No. of Vessels Exceeding 99th percentile
Daniel Island Bend	38.7	0.724	65	0.763	13
Daniel Island Reach	38.7	0.785	65	0.818	13
Drum Island Reach	38.7	0.754	75	0.795	15
Fort Sumter Range	41.0	0.819	196	0.877	39
Hog Island Reach	41.3	0.831	163	0.886	33
Myers Bend	38.7	0.753	75	0.800	15
Navy Yard Reach	38.7	0.770	61	0.784	12
Ordnance Reach	39.3	0.826	31	0.901	6
Port Terminal Reach	38.1	0.741	34	0.782	7
Shipyard River	39.1	0.859	1	0.870	0
Tidewater Reach	30.2	0.871	31	0.972	6
Town Creek Lower Reach	30.8	0.676	14	0.769	3
Wando Lower Reach	43.0	0.845	88	0.888	18

Vessels ranked 6th or higher show relatively lower impact to channel reliability with respect to available channel depth. Shipyard River, which was shown previously to have minimal impact on reliability but also to provide substantial cost savings ranked 13thth in maintenance priority.

The reach maintenance prioritization scores are mapped in Figure 27. It can be observed from this figure that the four highest priority reaches, (Fort Sumter Range, Hog

Island Reach, Wando Lower Reach and Tidewater Reach are closest to the ocean, lying between the upper reaches which have lower maintenance priority.



Esri, DeLorme, GEBCO, NOAA NGDC, and other contributors

Figure 27 Prioritized dredged reaches.

Summarizing the Monte Carlo analysis, the proposed reach prioritization scheme ranked reaches 1st through 3rd that individually supported over 40% of vessel transits. These reaches had high vessel speeds and relatively high sailing draft to available depth ratios. Reaches ranked 4th and 5th had relatively high draft to available depth ratios at the 95th percentile, but moderate to low vessel speed and moderate to low vessel counts. Reaches prioritized 6th to 12th had moderate vessel counts and vessel speeds, but relatively low draft to available depth to draft ratios at the 95th percentile. Finally, the lowest priority reach had the highest draft to available depth ratio, but an order of magnitude fewer vessels than the next highest prioritized reach.

Shoaling Impacts on Transit Reliability

The transit reliability measure hindcasts vessel net underkeel clearance to determine system reliability. Channel shoaling that has occurred is incorporated in the time series of bathymetric elevation. However, by applying an expected depth loss resulting from future shoaling, the transit reliability measure may be used to gain insight into transit reliability degradation.

Consider the shoaling rates in Charleston Harbor as calculated by CSAT, shown in Table 20. The enterprise bathymetric data management system performs statistical analysis of historical bathymetric surveys to determine the annual projection of minimum, average, and maximum depth lost per reach. These depth loss rates can be converted into integer depth loss options for the transit reliability model by rounding up to the next whole foot increment and replacing negative values with 0.

Table 20 Projected annual shoaling rates.

	Projected Shoaling Rate (ft/yr)		
Reach	Maximum	Average	Minimum
Daniel Island Bend	1	0.3	-0.3
Daniel Island Reach	1.7	0.9	0.2
Drum Island Reach	2.4	0.9	-0.5
Fort Sumter Range	1.3	0.4	-0.8
Hog Island Reach	1.4	0.8	0.1
Myers Bend	2.05	0.9	-0.15
Navy Yard Reach	1.1	0.5	-0.1
Ordnance Reach	3.8	1.7	-1
Port Terminal Reach	1.7	0.1	-1.8
Shipyard River	6.2	2.3	-0.6
Tidewater Reach	2.5	0.5	-1.8
Town Creek Lower Reach	4	2.5	1.1
Wando Lower Reach	2.8	0.4	-1.7

The projected depth loss arguments and calculated reliability values are shown in Table 21. The expected shoaling-related reliability degradation in the next year is 0.7% and 2.8% in the average and maximum cases, respectively. The minimum shoaling scenario had a negligible impact on reliability. The cost to mitigate reliability reductions arising from the expected shoaling scenario, CM, are also shown in Table 21 and can be calculated as:

$$C_M = \sum_{j=1}^{m} C_{I_j} D_{R_j} \tag{21}$$

Table 21 Transit reliability impacts due to channel shoaling.

	Shoaling Scenario Depth Reduction (ft)		
Reach	Max.	Avg.	Min.
Daniel Island Bend	1	1	0
Daniel Island Reach	2	1	1
Drum Island Reach	3	1	0
Fort Sumter Range	2	1	0
Hog Island Reach	2	1	1
Myers Bend	3	1	0
Navy Yard Reach	2	1	0
Ordnance Reach	4	2	0
Port Terminal Reach	2	1	0
Shipyard River	7	3	0
Tidewater Reach	3	1	0
Town Creek Lower Reach	4	3	2
Wando Lower Reach	3	1	0
Reliability	0.965	0.986	0.993
Cost to Mitigate	$3.96 M	$1.89 M	$0.31 M

The results in Table 21 highlight the discrepancy between the way channel controlling depth is recorded and communicated to navigation channel users, and the way that channel depth is calculated for budgetary purposes. Channel controlling depth, described in Chapter 3, is the shoalest depth in each reach. This is meaningful for the navigator in that it represents the minimum available depth in each reach. This depth is higher by definition than the average depth in the reach. Consequently, the controlling depth improvement rate, shown in Table 13, represents the change in controlling depth resulting from shoal removal. It is higher than the maximum shoaling rate shown in Table 15, which is the maximum observed change in depth at each measured location of the regularized grid used by CSAT, averaged over the reach.

This nuance merits discussion because the reach controlling depth does not necessarily inhibit navigation within a channel, as discussed in Chapter 3. However, USACE currently describes channel availability as the proportion of time that the channel controlling depth is below the channel authorized depth. The result is that navigation channel availability is generally under-reported. By considering the available depth at the time of vessel transit, and by determining the probability that the net underkeel clearance is less than 0, the reliability of navigation is more accurately represented.

Contributions

The following contributions result from development of a relationship between vessel transit reliability and annual dredging depth costs resulting from dredging depth reduction alternatives:

1. In the case of Shipyard River, the annual dredging cost per transit was shown to be disproportionately higher than all other reaches in the harbor. Forgoing maintenance dredging for a year in this location represents a potential savings of 11% of the harbor-wide annualized dredging budget while reducing transit reliability by 0.2%.

2. A second order polynomial regression equation was developed to estimate the annualized dredging maintenance cost necessary to support a specified transit reliability level. However, the relationship fit the data poorly, and inadequately described transit reliability-cost relationship. This indicated the need for more sophisticated optimization techniques to identify optimal dredging alternatives.

3. A Monte-Carlo analysis of alternatives was used to identify favorable alternatives based on a value heuristic. This approach revealed Fort Sumter Range, Hog Island Reach, and Wando Lower River as priority maintenance reaches. High priority reaches included many vessels with relatively high draft to available depth ratios moving at relatively high speeds. Moderate priority vessels had relatively high draft to depth ratios, moderate vessel counts and speeds. Low priority reaches had relatively fewer vessels impacted by moderate to high draft to available depth ratios.

4. The transit reliability model was applied to minimum, average, and maximum shoaling rate scenarios projected by the CSAT to estimate the annualized cost to mitigate the reach specific shoaling behavior in each scenario. The costs were estimated to range from \$0.31M to \$3.96M. The reduction in reliability resulting from one year of shoaling ranged from 0 to 2.8%.

CHAPTER VI

CONTRIBUTIONS AND FUTURE INVESTIGATION

Contributions

The management of waterways by USACE and others rely on a variety of metrics that describe performance of waterway projects. The risk of keel strike is a key indicator of safe vessel transit used in both design and operation cases. However, waterway managers have lacked a method to capture this risk for USACE projects. The need to prioritize maintenance work under continued budgetary constraints, trade globalization, and increasing demands placed on the system arising from trends in vessel size growth provides an impetus to seek alternative measures for prioritizing maintenance. Emergent technologies, including increases in computational power, enterprise spatial databases containing project performance measures, and ubiquitous AIS coverage, present an opportunity to improve on existing maintenance practices.

This dissertation developed a measure of navigation channel reliability that considered navigation channel users, and defined reliability in terms of the probability that vessels transited successfully, instead of channel depth availability terms. Further, this dissertation provided a means to address the interconnectivity of navigation channels when prioritizing channel maintenance.

The fundamental contributions of this work span several areas including concept modeling; mathematical modeling; data fusion, analysis, and interpretation; and practical managerial application. Specifically, the major contributions of this dissertation to each area include:

- Concept modeling: The need for a measurement of vessel underkeel clearance given the time dependent nature of water surface and bathymetric elevations, and the challenges inherent in the heterogeneous nature of waterway traffic were identified. Previous studies of the underkeel clearance problem have been relatively narrow, considering individual ships instead of entire traffic populations. Applications of previous underkeel clearance investigations have been limited to probabilistic channel design (Briggs et al., 2003; Briggs et al., 2004; Briggs et al., 2013; Briggs et al., 2015), or near-real time vessel operations (Silver and Dalzell, 1998). Mid-term maintenance investigations of the problem are scarce, at least in part owing to difficulties related to data availability in the design and near-real time applications. A solution was presented that addressed data availability problems by leveraging emerging technologies.

- Mathematical modeling: The time-varying elements critical to determining vessel underkeel clearance were formulated into a one dimensional model. The model is grounded in well-studied predecessor models (Silver and Dalzell, 1998; Briggs et al., 2004), but formulated to benefit from data available from regular USACE business functions and or open-source alternatives. The reach and reach-in-series reliability models resulted in predictive relationships for estimating impacts to navigation channel reliability resulting from reductions in available channel depth. The transit reliability model inherently considers interconnectivity of dredged reaches as the probability of successful vessel transits are determined.

- Data fusion, analysis, and interpretation: The work presented in this dissertation leveraged data available from a variety of different sources and integrated them such that a highly granular solution to a long-standing problem was developed. Channel condition information came from the USACE enterprise database systems e-HYDRO, CSAT, and their paper-based predecessors. Vessel information came from USCG, and water surface elevation from NOAA, via electronic web services requests. AIS data was validated using operational pilot logs and natural language processing techniques. The use of AIS data is particularly novel, as the system is designed for real-time applications only. The application of this data demonstrates the inherent value of archival vessel information as a remote sensing technology.

- Practical managerial application: This work focused on solving a real-world problem faced by navigation channel maintenance managers across the United States and perhaps globally – selecting the set of reaches in a waterway network to dredge and the depth of dredging. The solution to this problem represents an opportunity to reevaluate and more advantageously allocate a substantial sum of maintenance funding arising from reductions in investments that do not objectively improve navigation channel reliability.

In summary, this work addressed the depth dimension of the vessel transit problem that is likely to continue to challenge waterway managers as ship sizes increase and waterway maintenance funds remain constrained (Mayer, et al. 2008).

Future Investigation

A model that relates time-varying parameters to hindcast underkeel clearance of vessels in transit was presented in Chapter 2. The nature of the model inputs, specifically vessel data obtained through AIS, and water surface data is such that a near real-time implementation of this model is within reach.

Model validation was presented in Chapter 3 using a rigorous approach to ensure that the quality of AIS data was sufficient to implement the model. The net underkeel clearance reliability model can be simplified based on two observations from the present research. First, significant effort was spent to update vessel sailing draft to calculate vessel squat according to the Barrass (2012) equation. This step is not strictly necessary as design draft recorded in AIS typically exceeds sailing draft. Implementing the model using design draft will make the modeled net underkeel clearance more conservative. Second, the modeled keel modifier values were on average less conservative than the analog measure used by the harbor pilots. Replacing the parameter with a simple design-draft scaling coefficient will reduce model complexity. The resulting impact on modeled net underkeel clearance must be further studied.

Calder and Schwehr (2009) showed the application of AIS to analysis of problems associated with risk inherent in marine charting. Shelmerdine (2015) discussed the use of AIS in planning policy. Mayer et al. (2008) made the case for considering the relationship of channel width to vessel performance, which is historically neglected. The present use of AIS data to investigate waterway maintenance issues adds to the foundation demonstrated by Mitchell and Scully (2014) for further exploration into the use of the technology to address vessel data collection needs for other maritime engineering problems. AIS data is a candidate remote sensing technology that enables investigating the concerns of Mayer et al (2008).

Transit, reach, and route reliability methods were developed and applied to Charleston Harbor in Chapter 4. Future comparative analysis of these methods is warranted at other major navigation projects to determine the range of reliability measures across the USACE project portfolio with the objective being to determine the feasibility of general implementation of transit reliability metrics as a suitable replacement for current depth and tonnage measures.

In Chapter 5, historical maintenance practices in Charleston Harbor were assessed in the context of the developed transit reliability measures. Cursory cost analysis revealed candidates for reduction in routine maintenance depth improvement. Gross relationships were developed between maintenance cost and transit reliability using a brute force technique. The transit reliability measurement developed in Chapter 4 was applied to shoaling scenarios using shoaling rates developed from the CSAT to estimate the shoaling impact on reliability, and the cost to mitigate that impact. The work presented here would benefit from reformulation as a robust cost optimization model using the transit reliability measure as the cost parameter. Incorporation of probabilistic shoaling projections and use of more sophisticated techniques to explore the solution space of recommended dredging depths would further improve the work.

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26 U.S. Code § 9505 – “Harbor Maintenance Trust Fund”

26 U.S. Code § 9506 – “Inland Waterways Trust Fund”

19 C.F.R. 24.24 – “Harbor maintenance fee”

33 U.S. Code § 622 – “Contracts, etc., with private industry for implementation of projects for improvements and dredging; reduction of federally owned fleet”

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