Vessel Draft and Velocity Updates for Tybee Island Vessel Wake Analysis

ERDC Dredging Operations Technical Support Program (DOTS)

U.S. ARMY CORPS OF ENGINEERS BUILDING STRONG®

Response Summary:

In response to safety concerns related to commercial vessel wakes along the Savannah Navigation Channel, a team from ERDC's Coastal and Hydraulics Laboratory collaborated with USACE Savannah District (SAS) and the City of Tybee, Georgia, to measure wake conditions at the jetty entrance during FY22 (see ERDC/CHL TR-22-21, https://hdl.handle.net/11681/46140). However, a major limitation of the original study was its use of static vessel draft from Automatic Identification System (AIS) records of vessel activity. Following the release of more accurate U.S. Customs foreign vessel entrances and clearances (FVEC) draft records for the study period, SAS requested updates to the data analysis through the DOTS program.

Figure 1. Sign alerting beachgoers to the vessel wake hazard at Tybee Island, GA.

Prior studies suggest that a vessel's drawdown should be a function of speed, length, beam, draft, and channel geometry, including the blockage ratio. Considering that reported draft varies substantially between the AIS and FVEC datasets, it was hypothesized that substituting the FVEC draft for the AIS draft in published predictive equations would yield a significant improvement in accuracy. When only modest improvements were achieved, the DOTS request subsequently explored alternative methods for increasing predictive accuracy. This led to the conclusion that vessel speed relative to the current could reasonably be determined using measurements from a USGS gauge 3.6 km upstream of the study area. The flow-corrected vessel speed was substituted for speed-over-ground in the predictive equations, leading to a visible improvement in the correlation between measured and predicted drawdown (Figure 2). The mean absolute predictive error was also reduced to 9 cm.

Period of Performance:

Data analysis for this DOTS response was performed in April 2024. The results were presented to SAS during a meeting in May 2024.

Benefits of the Response to the USACE Dredging/Navigation Program:

This DOTS response benefits the USACE navigation program by providing SAS with an improved method of predicting drawdown near Tybee Island. These results may support future efforts to address stakeholder concerns about vessel-generated hazards.

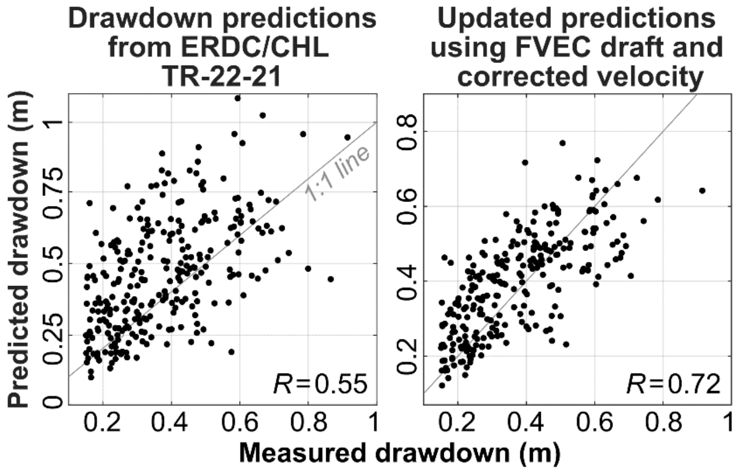

Figure 2. Performance of published drawdown relationship used in ERDC/CHL TR-22-21 (left) versus the improved performance achieved during the DOTS response (right). R denotes Pearson's correlation coefficient.

Deliverable:

The results of the updated analysis were delivered to SAS in an 11-page white paper, which included figures and tables that could be compared side-by-side with the original report. The cross-referenced draft database was also provided to the District in CSV format to facilitate future analyses.

Rachel Bain
Coastal and Hydraulics Laboratory • Rachel.L.Bain@usace.army.mil

DOTS ID: DOTS-24-R145

Unpublished report to Savannah District
May 2024

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by Rachel Bain and Richard Styles

PURPOSE: This paper describes updates to the vessel wake analysis detailed in ERDC/CHL TR-22-21 (Bain *et al.* 2022), with the goal of determining whether updated, more accurate data offers greater insight into the relationship between vessel characteristics and wake conditions near Tybee Island, GA. Whereas the original study used vessel draft information from the Automatic Identification System (AIS), the present analysis substitutes more accurate draft information from U.S. Customs foreign vessel entrances and clearances (FVEC) records. In addition, cross-sectionally averaged flow velocities from the USGS gauge at Fort Pulaski, GA, are used to update the AIS-reported speed-over-ground (SOG), yielding the vessels' speed relative to the water. The combination of these two updates leads to a visible improvement in forecasting ability. However, the mechanisms underlying drawdown oversteepening and bore formation near the beach remain poorly understood, and further study is recommended to determine the cause of this hazardous behavior.

INTRODUCTION: Commercial vessels transiting the Savannah Navigation Channel *en route* to the Port of Savannah, Georgia, often generate hazardous wake conditions on Tybee Island's North Beach. A particular concern for beachgoer safety is the tendency large vessels' primary wakes to cause a large-amplitude drawdown followed by a bore-like surge of water ("uprush") onto the beach. However, the relationship between vessel characteristics and hazardous wake conditions remains ambiguous, especially considering that some commercial vessels cause no measurable wake on the beach, and it is difficult to convince beachgoers to take safety precautions without understanding the likelihood of a given vessel generating a large wake event.

In response to ongoing safety concerns, a team from the USACE Engineer Research and Development Center, Coastal and Hydraulics Laboratory, collaborated with USACE Savannah District (SAS) and the City of Tybee to measure wake conditions at the jetty entrance from late August 2021 to early December 2021. The results of this study are detailed in ERDC/CHL TR-22-21 (Bain *et al*. 2022). For the original study, vessels were characterized using Automatic Identification Systems (AIS) records obtained via a data request to the U.S. Coast Guard. Although AIS data are a valuable source of information about vessel position and identity, inaccurate draft values are a known source of error in many AIS-based analyses (*e.g*., Bailey *et al.* 2008; Scully and McCartney 2017; Scully and Mitchell 2017; Zhou *et al*. 2020; Scully and Young 2021; Meyers *et al*. 2022). Unlike vessel coordinates and heading, which are dynamic values that update automatically within the AIS transponder, draft is a static field which is manually set by the vessel operator. Consequently, the draft reported by AIS is often the time-invariant design draft. Given that a commercial vessel's real-time draft may vary from the design draft by several meters, it was unclear whether the lack of correlation between vessel dimensions and wake height in ERDC/CHL TR-22-21 was a real phenomenon or an artifact of inaccurate draft records.

To compensate for known inaccuracies in AIS-derived vessel draft, recent studies substitute vessel draft from U.S. Customs foreign vessel entrances and clearances (FVEC) records (*e.g.*, Scully and Young 2021; Bain *et al.* 2023a, b; Young *et al.* 2024), which are compiled by the

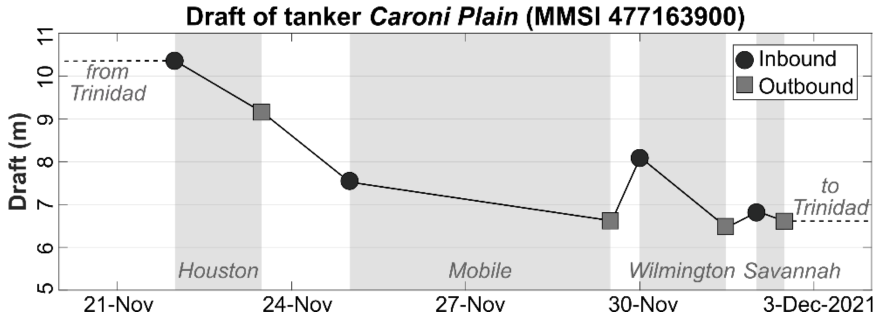


Figure 1. *Example draft time series constructed from U.S. Customs FVEC records. The vessel is in the labeled port during the gray shaded periods. Note that timestamps are only accurate to the day.*

USACE Institute for Water Resources (IWR). Historically, there has been a lag of one to two years between a port visit and the IWR data release, which means that the more accurate FVEC records were unavailable when ERDC/CHL TR-22-21 was published. FVEC data for the 2021 calendar year were subsequently released in July 2023. In response to a request for updated results from SAS, this paper reconsiders the relationship between vessel draft and wake conditions near Tybee Island using the FVEC draft dataset.

UPDATED METHODOLOGY: To update the vessel wake analysis, records of time-varying vessel draft for 2021 were downloaded from the IWR's Waterborne Commerce Statistics Center (WCSC 2023) and restructured into a vessel draft time series for each unique IMO (International Maritime Organization ship identification number) in the dataset. An example draft time series for the tanker *Caroni Plain* appears in Figure 1. Within the two-week period shown, the vessel's draft varies from 6.5 m to 10.4 m as it completes a circuit between Trinidad; Houston, TX; Mobile, AL; Wilmington, NC; and Savannah, GA.

Whereas U.S. Customs identifies vessels by IMO, vessel in the original AIS dataset were identified by MMSI (Maritime Mobile Services Identity ship identification number). A MMSI-to-IMO lookup table was therefore constructed using an archived vessel inventory database from the USACE AISAP tool (Kress *et al.* 2020; Kress and Mitchell 2023). For each MMSI-identified vessel transit from the original Tybee Island study, the corresponding IMO was determined from the lookup table. The FVEC draft record with a matching IMO, timestamp, travel direction (inbound or outbound), and Savannah's numeric port code was then identified and appended to the original AIS-derived vessel record.

The Tybee Island wake measurements and analytical methods remained unchanged between the 2021 study and this paper. For additional details, the reader is directed to ERDC/CHL TR-22-21 (Bain *et al.* 2022).

UPDATED RESULTS AND DISCUSSION: A comparison of the AIS drafts from the original study and the updated FVEC drafts appears in Figure 2. Out of the 1,511 commercial vessel transits represented in both datasets, 794 (53%) have an FVEC draft which is smaller than the broadcast AIS draft, while 716 transits (47%) have an FVEC draft which is larger than the broadcast AIS draft. The difference between FVEC and AIS draft follows an approximately Gaussian distribution with a standard deviation of 1.7 m. However, some outliers are also present in the dataset, including the container ship *Cosco Europe* with a reported FVEC draft of 21.0 m. Considering that the Savannah Navigation Channel has a maintained depth of 14.3 m MLLW and a mean tide range of 2.1 m, any reported drafts exceeding 16 m are almost certainly errors. A second notable outlier is the container ship *YM Warmth*, which has an AIS-reported draft of 14.0 m and a corresponding FVEC draft of 3.6 m. It should be noted that the two data

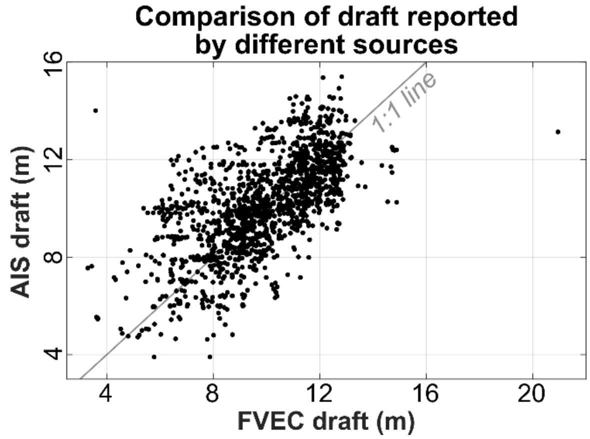


Figure 2. *Comparison of AIS vessel drafts used in ERDC/CHL TR-22-21 versus drafts from U.S. Customs FVEC records. Each point corresponds to one commercial vessel transit of the Savannah Navigation Channel between late August 2021 and early December 2021. AIS generally indicates the vessel's static design draft, whereas FVEC data provide a dynamic record of vessel loading.*

sources become more consistent if the real-time draft is 11.8 m (rather than 11.8 ft, as listed in the FVEC records), so this may represent a unit conversion issue. After removing these two outliers from the dataset, the distribution of the FVEC-AIS difference has a mean of -0.3 m and a standard deviation of 1.6 m.

A major focus of the original Tybee Island vessel wake analysis was evaluating which static and/or dynamic vessel characteristics were the best predictor of wake behavior in the study area. During this analysis, it was observed that vessels with an AIS-derived draft below 7 m almost never produced a drawdown exceeding 0.3 m or a secondary wake height exceeding 0.6 m at the North Range (Figure 23 of Bain *et al.* 2022). Similarly, virtually no relationship between AIS-derived draft and drawdown or secondary wake height was observed at the South Range (Figure 24 of Bain *et al.* 2022). Updated plots of these relationships using the FVEC draft data appear in Figure 3 of this paper. These results indicate that although vessels of any draft may produce a small drawdown, the probability of a large drawdown increases with draft (Figure 3a and Figure 3b). A similar pattern is observed for secondary wake heights at the North Range: although vessels with a large draft may produce a small wake, it is unlikely for vessels with a

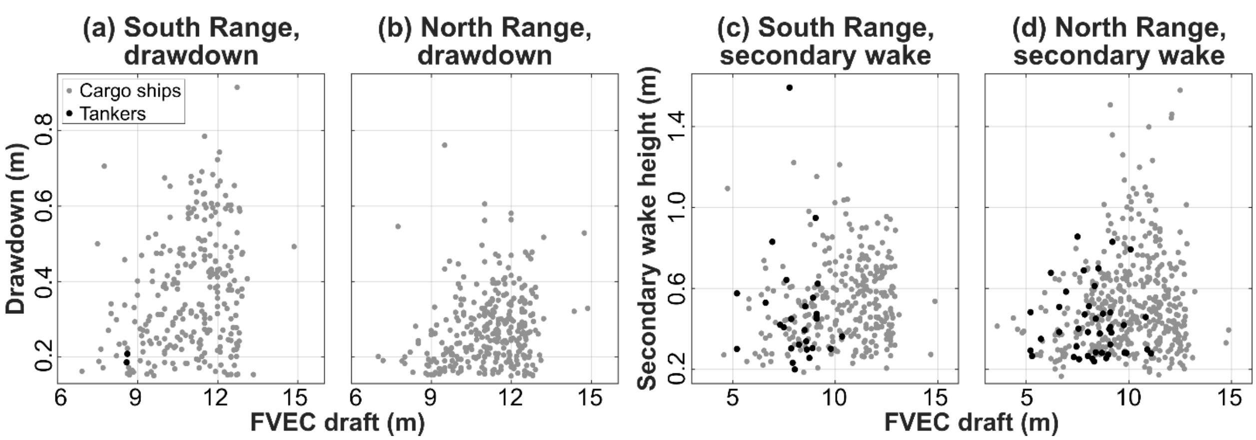


Figure 3. (a, b) *Relationship between draft and drawdown measured at both instrument locations.* ***(c, d)*** *Relationship between draft and maximum secondary wake height measured at both instrument locations. (Compare to Figures 23 and 24 in ERDC/CHL TR-22-21.)*

small draft to produce a large wake (Figure 3d). This relationship is weaker at the South Range, where the largest secondary wake in the dataset was generated by the tanker *Chem New York* drafting at a moderate 7.8 m (Figure 3c).

Even though Figure 3 shows some improvement relative to the results in ERDC/CHL TR-22-21, it does not provide adequate insight for *a priori* prediction of which vessels will generate the largest wakes near Tybee Island. One possible explanation for the lack of a strong correlation between wake height and FVEC draft is that wake height may be simultaneously controlled by multiple variables, including vessel length, beam, velocity, and channel blockage ratio (*i.e.*, the fraction of the channel cross section occupied by the vessel). Prior studies have attempted to derive multivariate functions for the drawdown magnitude H_D. For example, the Schijf (1949) equation is

$$H_D = \frac{v^2}{2g}\left[\left(\frac{A_c}{A_c - BD}\right) - 1\right] \quad , \tag{Eq. 1}$$

where v is the vessel velocity, g is gravitational acceleration, A_c is the channel cross-sectional area, B is vessel beam, and D is vessel draft. A subsequent evaluation of published drawdown equations (Almström and Larson 2020) determined the best-performing formula to be

$$H_D = 0.22\left(\frac{v^2}{2g}\right)\left(\frac{v}{\sqrt{gR_c}}\right)^{0.42}\left(\frac{B}{X}\right)^{0.85}\left(\frac{B}{W_c}\right)^{0.32}\left(\frac{D}{R_c}\right)^{1.46}\left(\frac{L}{D}\right)^{0.80} \quad , \tag{Eq. 2}$$

where L is vessel length, R_c is channel hydraulic radius, W_c is the channel top width, and X is the distance between the vessel and the wave gauge. Drawdown predictions from Equation 1 and Equation 2 were compared to the drawdown measurements in the original Tybee Island study, but overall performance was poor (Figure 25 of Bain *et al.* 2022).

Updated drawdown predictions based on the FVEC draft are shown in Figure 4, with a summary of the relative performance provided in Table 1. Substituting the FVEC draft for the AIS draft yields a slightly higher correlation between measured and predicted drawdown using the Schijf (1949) equation at the South Range, along with the Almströng and Larson (2020) equation at both the South and North Ranges. The mean absolute error and the bias magnitude are also slightly reduced when the FVEC draft is used in the Schijf (1949) equation at the North and South Ranges, along with the Almström and Larson (2020) equation at the North Range (Table 1). However, the overall impact of using the more accurate FVEC draft in Equation 1 and

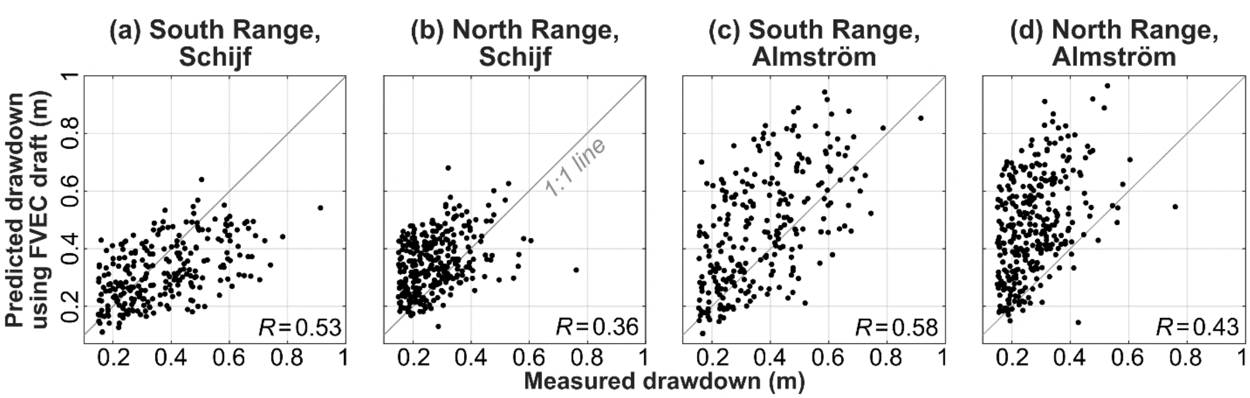


Figure 4. *Comparison of measured and predicted drawdown for all commercial vessel transits with a corresponding U.S. Customs FVEC record using* ***(a, b)*** *the Schijf (1949) equation, and* ***(c, d)*** *the best-performing equation from Almström and Larson (2020). Pearson's correlation coefficient R is shown for all plots. (Compare to Figure 25 in ERDC/CHL TR-22-21.)*

Table 1. *Performance of theoretical drawdown equations (i.e., Figure 4 of this paper; Figure 25 of Bain et al. 2022) for predicting measured drawdown using AIS-derived draft and FVEC draft values.*

Instrument location and equation	Pearson's correlation coefficient (R)		Mean absolute error[1] (MAE, meters)		Bias[2] (meters)	
	AIS	***FVEC***	***AIS***	***FVEC***	***AIS***	***FVEC***
South Range, Schijf	0.51	0.53	0.114	0.113	-0.056	-0.053
North Range, Schijf	0.36	0.36	0.106	0.104	+0.074	+0.070
South Range, Almström	0.55	0.58	0.146	0.148	+0.091	+0.097
North Range, Almström	0.42	0.43	0.219	0.216	+0.209	+0.208

[1] *Calculated as* $MAE = \frac{1}{N}\sum_{i=1}^{N}\left|\widehat{H}_{D,i} - H_{D,i}\right|$ *, where* $\widehat{H}_D$ *is the predicted drawdown and* H_D *is the measured drawdown.*

[2] *Calculated as* $bias = \frac{1}{N}\sum_{i=1}^{N}\left(\widehat{H}_{D,i} - H_{D,i}\right)$ *.*

Equation 2 is small, and many of the limitations identified in ERDC/CHL TR-22-21 remain unresolved. For example, the original report noted that a significant source of positive bias at the North Range was likely the distance between the instrument and the confined region within the jetties, where the channel cross-sectional area A_c, channel top width W_c, and channel hydraulic radius R_c are calculated. As no explicit guidance exists for how the theoretical drawdown equations should be adapted at locations where a confined channel transitions into an unconfined bay, it is unclear if further improvements in the vessel parameter accuracy will lead to significant improvements in predictive skill at the North Range.

Another limitation of ERDC/CHL TR-22-21 was using AIS-derived speed-over-ground (SOG) for the velocity v in Equations 1 and 2. Although SOG is convenient to use in these calculations because it is easily determined from the vessel's GPS, the velocity of the vessel relative to the velocity of the water is the more relevant variable from the perspective of wake dynamics. Data collection for the original Tybee study included a bed-mounted ADCP at the South Range, which was intended to provide the flow velocity measurements necessary for correcting the AIS-based SOG. Unfortunately, failure of the ADCP meant that SOG was the only velocity data collected for the original study. Bain *et al.* (2022) noted that a published velocity time series was available for the Fort Pulaski USGS gauge, which is approximately 3.6 km inland of the South Range. However, it was decided that these data should not be used due to (1) uncertainties surrounding the tidal phase lag between the USGS gauge and the South Range instrument, and (2) uncertainties related to flow acceleration as the unconfined entrance channel transitions to confined flow at the jetty entrance.

Reevaluating the channel geometry for the present analysis suggests that the decision to discard the USGS flow velocity data may have been unnecessarily conservative. There is minimal variation in channel width and depth between Fort Pulaski and the end of the jetties, and no channel bifurcations are present. Additionally, a shallow-water wave will propagate with a celerity of $\sqrt{g \cdot (14.3\ \mathrm{m})} =$ 11.8 m/s at MLLW, which implies that the phase lag between Fort Pulaski and the South Range should not exceed 5 minutes. Given these observations, this paper reconsiders whether published expressions for H_D may see improved performance if flow-adjusted vessel speed is substituted for SOG. This was achieved by either adding or subtracting the USGS-reported flow velocity from the vessel's SOG (depending on the direction of vessel travel relative to the tide) to obtain a corrected velocity v^*. In addition, considering that the fitted coefficient of 0.22 in Equation 2 was determined using data from a single geographic location (the Stockholm Archipelago; Almström and Larson 2020), the present analysis re-fit the coefficient for Tybee-specific observations, leading to the following drawdown equation:

$$H_D = K\left(\frac{[v^*]^2}{2g}\right)\left(\frac{v^*}{\sqrt{gR_c}}\right)^{0.42}\left(\frac{B}{X}\right)^{0.85}\left(\frac{B}{W_c}\right)^{0.32}\left(\frac{D}{R_c}\right)^{1.46}\left(\frac{L}{D}\right)^{0.80}, \quad \text{(Eq. 3)}$$

where K is an updated coefficient chosen to eliminate bias. Equation 3 was applied only to South Range data because the effects of flow expansion on the current should be less at this location compared to the North Range, which is farther east.

A comparison of measured drawdown to the predictions generated by Equation 3 appears in Figure 5, with the coefficients and associated performance metrics shown in Table 2. By using the corrected velocity v^* instead of SOG, the correlation between measured and predicted drawdown increases from $R = 0.58$ to $R = 0.72$ (compare Figure 4c to Figure 5a), and the MAE is reduced by 6 cm (compare Table 1 and Table 2). Considering that ERDC/CHL TR-22-21 observed that drawdown behavior may vary for inbound versus outbound vessels, Equation 3 was also applied to subsets of the data corresponding to a single travel direction (Figure 5b and 5c). This increased the correlation between measured and predicted drawdown to $R = 0.74$ but had minimal impact on the MAE.

From a safety perspective, it is desirable to predict which vessels and/or operating conditions are most likely to generate hazardous wake conditions on North Beach. Bain *et al.* (2022) noted a nearly one-to-one relationship between drawdown magnitude at the South Range and drawdown magnitude in the North Beach surf zone (see Figure 33 of ERDC/CHL TR-22-21). This suggests that if drawdown magnitude can be accurately predicted near the jetties, determining the drawdown magnitude on the beach should be straightforward. However, the poor performance of the theoretical drawdown equations in the original study raised questions about the feasibility of generating offshore drawdown predictions. The present paper achieved a marked improvement in drawdown prediction by (1) substituting the more accurate FVEC draft for the original AIS draft and (2) adjusting the vessel's SOG using the USGS-reported flow

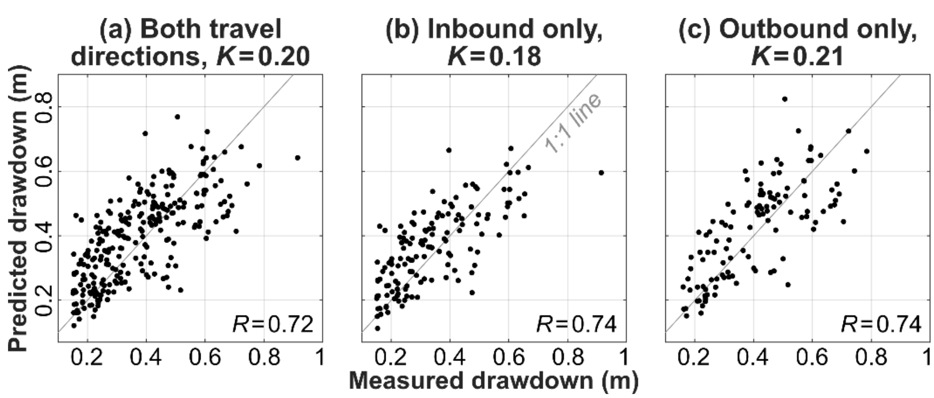


Figure 5. *Application of Equation 3 for predicting South Range drawdown magnitude. To improve the predictions relative to Figure 4, SOG has been adjusted by the USGS-reported flow velocity at Fort Pulaski to estimate the vessel's speed relative to the water. Performance is summarized in Table 2.*

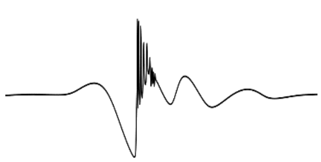
Table 2. *Performance of Equation 3 using corrected velocity and FVEC draft at the South Range, as pictured in Figure 5. Re-fitting the coefficient K largely eliminates the bias.*

Data	**Best-fit value of K for Eq. 3**	**R**	**MAE (meters)**
Both travel directions	0.20	0.72	0.089
Inbound vessels only	0.18	0.74	0.083
Outbound vessels only	0.21	0.74	0.089

velocity at Fort Pulaski to obtain the vessel's speed relative to the water. With these corrections, the correlation between measured and predicted drawdown was increased from $R = 0.55$ in the original study to $R = 0.72$ in the present paper (Figure 5), with a mean absolute error of only 9 cm. It should be noted that the one-to-one relationship between offshore and nearshore drawdown magnitude was based on only seven commercial vessel transits due to a lack of overlapping data (Bain *et al.* 2022), and additional measurements would be necessary to validate the strength of this relationship for a larger sample of vessels. Nevertheless, the improved predictive ability of Equation 3 introduces a possible forecasting opportunity that was unrecognized in the original study.

The more significant obstacle for creating a vessel wake warning system is predicting the behavior of the high-frequency wake components. In more than half of the nearshore observations collected for the original study, the drawdown's rising limb displayed significant deformation between the jetties and the North Beach surf zone (see Appendix A of ERDC/CHL TR-22-21; note that updated FVEC draft values for all figures in the appendix are provided in Table 4 of this document). In several instances, the rising limb oversteepened into a "shock" or bore-like feature, which included a rapid jump in water level accompanied by high-frequency oscillations. Bore generation was only observed for inbound vessels with an average FVEC draft of 10.0 m and an average v^* of 7.3 m/s (Table 3). A second type of unusual wave behavior on North Beach involved a "step-like" rise in water level, in which the rising limb of the drawdown returned partway to still-water level and then remained stationary for ~30 seconds before abruptly rising a second time. This behavior was only observed for outbound vessels with an average FVEC draft of 11.4 m and an average v^* of 7.4 m/s (Table 3). However, the ranges of FVEC draft and corrected velocity associated with both types of deformation overlap with the range of values observed for relatively undeformed primary waves, so an obvious predictive relationship is unavailable. Both types of nonlinear wake behavior have been observed in other navigation channels (*e.g.*, Maynord 2003; Maynord *et al.* 2006; Scarpa *et al.* 2019), and

Table 3. *Updated draft and speed ranges for vessel wakes measured on North Beach. The "corrected speed" is the speed of the vessel relative to the USGS-reported current at Fort Pulaski (rather than SOG, as in ERDC/CHL TR-22-21).*

~8 min water level time series (idealized)	Description and notes
	Relatively small-magnitude drawdown followed by slow, gentle swashing with no amplification of high-frequency trailing waves. • Inbound and outbound tankers, container ships, and bulk carriers. • FVEC draft: 6.8 m to 12.5 m (average 9.7 m) • Corrected speed: 5.5 m/s to 8.1 m/s (average 6.6 m/s)
	Larger-magnitude drawdown followed by a sudden, bore-like uprush with amplified high-frequency trailing waves. • Only observed for inbound container ships, inbound general cargo, and inbound vehicle carriers. • FVEC draft: 6.6 m to 12.8 m (average 10.0 m) • Corrected speed: 6.9 m/s to 7.9 m/s (average 7.3 m/s)
	Larger-magnitude drawdown followed by a step-like increase in water level on the rising limb. • Only observed for outbound container ships and outbound vehicle carriers. • FVEC draft: 9.0 m to 12.3 m (average 11.4 m) • Corrected speed: 6.7 m/s to 8.7 m/s (average 7.4 m/s)

theoretical solutions have been derived (*e.g.*, Soomere *et al.* 2011), but fully characterizing the controls on this behavior would require numerical modeling beyond the scope of the present analysis.

CONCLUSION AND RECOMMENDATIONS: Large wakes generated by commercial vessels increase the risk to beachgoers on Tybee Island's North Beach, but an earlier study (Bain *et al.* 2022, ERDC/CHL TR-22-21) was unable to definitively identify the vessel characteristics or operating conditions associated with hazardous wake events. This paper describes how additional data (*i.e.*, recently-released foreign vessel entrances and clearances records from U.S. Customs, along with USGS-reported cross-sectionally averaged flow velocities from Fort Pulaski) may be incorporated into the analysis. The updated analytical procedure yields improved predictions of drawdown magnitude using vessel dimensions, channel geometry, and relative speed, with the correlation between measured and predicted drawdown increasing to $R = 0.72$ (compared to $R = 0.55$ in the original study). Provided that a one-to-one relationship exists between offshore and nearshore drawdown magnitude, these updated calculations offer a promising opportunity to better predict the amplitude of vessel primary waves on the beach.

However, a significant limitation of both this and the earlier study is a poor understanding of nonlinear, high-frequency wake behavior in the nearshore. Drawdown of sufficient amplitude has been observed to oversteepen during the rising limb, leading to bore-like behavior with high-frequency oscillations that may cause the water level to rise by a meter or more in a matter of seconds. During a second type of deformation, the rising limb acquires a "step-like" appearance in which it remains stationary for ~30 seconds before rapidly jumping to still-water level. ERDC/CHL TR-22-21 noted that the first type of nonlinear behavior occurred for inbound vessels, where the second type of nonlinear behavior appeared to be associated with outbound vessels. However, these initial observations of wake behavior on the beach included only 22 vessels, and a clear correlation between vessel size, draft, or speed of travel cannot be established.

To address the knowledge gaps identified in ERDC/CHL TR-22-21 and the present study, the following recommendations are made:

- Several outliers are present in the FVEC draft dataset, including a vessel reported to be drafting 21.0 m. Considering that this this would be ~5 m below the bed of the channel even at MHHW, the FVEC dataset clearly is not free of errors. Future studies should consider methods of independently verifying vessel draft (*e.g.*, high-resolution cameras positioned to capture the vessel's draft marks near the study area). More accurate vessel draft records may lead to additional improvements in performance for Equation 3.
- Although the USGS gauge at Fort Pulaski is 3.6 km inland of the jetty entrance, a visible improvement in predictive accuracy was obtained when the vessel SOG was corrected by flow velocity to obtain the vessel's speed relative to the water. Future studies should emphasize obtaining current velocities near the study site. However, if installing an ADCP is infeasible, the Fort Pulaski dataset has been determined to be an acceptable substitute.
- Due to a lack of overlapping measurements, the one-to-one relationship between offshore and nearshore drawdown magnitude (Figure 33 of ERDC/CHL TR-22-21) was based on only 7 vessels. It is recommended that additional data be collected contemporaneously at both the South Range and in the surf zone to confirm that drawdown amplitudes do not change as the primary wave propagates into shallow water.

- The parameters associated with drawdown oversteepening and shock generation remain poorly understood, yet this is the most hazardous characteristic of Tybee Island's nearshore wake behavior. Additional studies are recommended to (1) generate a more robust dataset of field measurements capturing wake behavior on the beach and (2) undertake numerical modeling efforts to determine which vessel characteristics, operating conditions, or aspects of shoreface geometry control nonlinear wake behavior on North Beach.

ACKNOWLEDGMENTS: This analysis was funded through the Dredging Operations Technical Support (DOTS) Program in response to a request from USACE Savannah District. Data collection for the original Tybee Island vessel wake study was cost-shared by Savannah District and the City of Tybee, which was supported by a Georgia Department of Community Affairs grant. The authors are grateful to Dr. Marin Kress for providing the archived AISAP vessel inventory records.

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ADDITIONAL INFORMATION: This report was prepared by Dr. Rachel Bain, Research Physical Scientist at the US Army Corps of Engineers, Engineer Research and Development Center, Coastal & Hydraulics Laboratory. Questions about this report can be addressed to Rachel.L.Bain@usace.army.mil or Richard.Styles@usace.army.mil.

Table 4. *Updated vessel drafts corresponding to figure captions in ERDC/CHL TR-22-21.*

Figure # in TR-22-21	Vessel name; MMSI / IMO	Timestamp (UTC) and direction	AIS draft reported in TR-22-21	FVEC draft
A-1	*Caroni Plain* 477163900 / 9392327	2-Dec-2021 19:07 Inbound	6.6 m	6.8 m
A-2	*APL California* 248712000 / 9350044	3-Dec-2021 02:18 Outbound	12.0 m	11.1 m
A-4	*Nevzat Kalkavan* 271042759 / 9365867	3-Dec-2021 02:57 Inbound	9.1 m	10.3 m
A-5	*Vienna Express* 636093194 / 9450416	3-Dec-2021 10:12 Inbound	10.3 m	12.5 m
A-6	*CMA CGM Argentina* 215331000 / 9839909	3-Dec-2021 12:00 Outbound	12.3 m	12.3 m
A-7	*CS Jenna* 538007269 / 9748409	3-Dec-2021 16:37 Outbound	10.0 m	6.7 m
A-8	*Isabella* 241747000 / 9874820	3-Dec-2021 22:16 Outbound	11.5 m	11.0 m
A-9	*Grand Uranus* 538010400 / 9472206	3-Dec-2021 23:10 Outbound	9.8 m	9.0 m
A-10; 6a and 6b	*Tamerlane* 25775800 / 9218648	4-Dec-2021 00:01 Inbound	8.8 m	10.6 m
A-11; 6a and 6b	*BBC Edge* 305472000 / 9407598	4-Dec-2021 00:22 Inbound	4.8 m	6.0 m
6a and 6b	*Hansa Salzburg* 218826000 / 9516753	4-Dec-2021 00:26 Outbound	9.5 m	9.1 m
A-12	*Zim Luanda* 249830000 / 9403229	4-Dec-2021 03:39 Inbound	10.4 m	9.8 m
A-13	*MSC Tianjin* 636019332 / 9285471	4-Dec-2021 08:27 Outbound	11.0 m	11.0 m
A-14	*Cosco Africa* 370188000 / 9345439	4-Dec-2021 10:55 Inbound	11.4 m	12.7 m
A-15	*Drawno* 636017075 / 9727508	4-Dec-2021 16:09 Inbound	10.0 m	6.9 m
A-16	*Grande Senegal* 247285500 / 9377470	4-Dec-2021 17:03 Inbound	8.0 m	8.4 m
A-17	*APL Sentosa* 215560000 / 9632040	5-Dec-2021 00:37 Outbound	12.6 m	12.0 m
A-19	*CPO Bremen* 636020326 / 9450387	5-Dec-2021 02:36 Outbound	10.6 m	12.0 m
A-20	*Vienna Express* 636093194 / 9450416	5-Dec-2021 03:12 Outbound	10.3 m	12.3 m
A-22	*Maersk Kinloss* 338241000 / 9333022	5-Dec-2021 04:06 Inbound	13.7 m	11.6 m