Methodology for Estimating Waterway Traffic Capacity at Shanghai Estuary of the Yangtze River

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The objective of this study is to propose a methodology for assessing waterway traffic capacity at the Shanghai estuary of Yangtze River. To achieve this objective, we firstly put forward the estimation method by utilizing the minimum collision distance taking the dynamic ship domain into consideration. Considering possible effects caused by unknown external factors, the waterway traffic capacity is then represented by a probability distribution. Finally, we quantify the equivalent units of ships with various ship sizes as well as the effects of longer ships on the waterway traffic capacity. Results show that a longer ship is equivalent to more small-sized ships during the daytime period than that at night. In addition, the deployment of longer ships could increase the waterway traffic capacity and such increment highly depends on the increased proportion of longer ships in waterway traffic.

KEYWORDS
1. AIS. 2. Estimation. 3. Uncertainty. 4. Ship domain.

1. INTRODUCTION. **W**aterway traffic capacity is defined as the capability of a waterway to allow ships passing through at a certain time period. When a waterway is crowded that ships cannot undertake any overtaking maneuvers, the corresponding traffic volume can be considered as the capacity of the waterway. For both waterway administration and carriers, there is a critical need to predict shipping traffic capacity when it is subject to a quick change, for example, traffic incensement or upsize of ship.

However, it is challenging to accurately predict the waterway capacity because the capacity might be affected by a number of influencing factors, such as, waterway physical conditions (e.g., the width of narrow points, waterway depth), ship characteristics (e.g., ship types, ship sizes, ship speed), traffic composition of different ship types and also environmental factors (e.g., weather, sea condition, visibility, tidal current). To date, many models have been proposed to predict waterway capacity (Fujii and Tanaka, 1971; Fan and Cao, 2000; Liu et al., 2016; Bellsolà Olba et al., 2017). Nevertheless, it should be pointed out that these models could only provide a single estimate of waterway capacity without considering the impact from those exogenous factors (e.g., ship composition, weather changes and so on), which could cause unpredictable fluctuations/variability on waterway capacity.

In previous studies, data deficiency can be one of the major reasons explaining why

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this issue hasn't be addressed. According to the International Convention for the Safety of Life at Sea (SOLAS) regulation V/19, AIS class A shall be installed on all ships of 300 gross tonnage and upwards engaged on international voyages and cargo ships of 500 gross tonnage and upwards not engaged on international voyages and passenger ships irrespective of size. Additionally, according to the regulation V/1 of this convention, the ship's flag administration shall determine whether requirement of regulation V/19 apply to the fishing ships. In Yangtze River, fishing ships of 100 gross tonnage and upwards are found to be equipped with AIS devices of Class B. With the huge number of AIS data, we can take most of the influencing factors into account and predict the waterway traffic capacity with a probability distribution.

In 2016, a project of channel dredging from Shanghai to Nanjing along the Yangtze River has been completed, since then ship with 50,000-ton dwt (deadweight ton) can sail to the Nanjing from Shanghai. With this in mind, the trend of longer ships is expected to be accelerated, which may lead to a big influence on the waterway traffic capacity administration of the Yangtze River.

This study aims to propose a methodology to estimate the waterway capacity. With actual data of estuary at the mouth of Yangtze River channel collected from AIS and other data resources, we can obtain the probability distribution of its capacity rather than a single estimate. We then further calculate its capacity variance under different confidence levels, so as to obtain a more practical and accurate forecasting result of the waterway traffic capacity. The methodology proposed in this study can be applied to many rivers and also canals in other regions.

2. LITERATURE REVIEW. Waterway traffic safety could be affected by waterway traffic capacity (e.g., Wu et al., 2018). Compared to the huge literature regarding traffic capacity estimation in land transportation system, the literature on waterway traffic capacity estimation is much less. Fujii and Tanaka (1971) firstly provided the theoretical maximum estimation value of waterway traffic. The maximum capacity indicates the maximum number of ships which pass through a waterway in a unit of time. In other literatures, there is no unanimous waterway traffic capacity definition, which depends on each research goal.

The theoretical maximum estimation value of waterway traffic strongly relates to the navigation safety of ships because ships should maintain Minimum Distance to Collision (MDTC) when they pass through certain waterway. Hereafter, the MDTC is the same as those in introduced in earlier studies (e.g., Montewka et al., 2010; Montewka et al., 2012). More specifically, if the distance between these two ships becomes less than MDTC, it means that a collision cannot be avoided by any maneuvers and both ships will collide (Montewka et al., 2012). Thus, we focus on the theoretical maximum estimation of waterway traffic capacity. Refer to the definition of highway capacity (Michiel et al., 1997), the maximum traffic volume is reached when the average intervals among all vehicles (ships) are minimized, that is, the distances among any pairs of ships are MDTC. In all studies on shipping capacity estimation, the ship domain is used as an effective parameter to determine the MDTC between two ships. The MDTC and ship domain have been discussed in many literatures, for example, Fujii and Tanaka (1971) proposed the idea of ship domain that would provide MDTC for each ship to ensure the safety of navigation. Fan and Cao (2000) provided models to calculate different ship domains for berthing areas, anchorage areas, fairways and their intersections as well as the entire sea space system. Liu et al. (2016) proposed a dynamic ship domain model considering different encounter scenarios of two ships. Kadarsa et al. (2017) studied the fairway traffic capacity in Indonesia, by deriving the MDTC among different ship types.

Szłapczyński and Szłapczyńska (2017) provided a critical review on the existing ship domains. In the literature, many ship domains with various shapes and scales have been proposed in previous studies, including ellipse domain, circle domain and polygon domain. It should be pointed out that ship domain size are related to ship length in the majority of previous studies while Hörteborn et al. (2018) found that the ship domain is not affected by the ship length. Fujii and Tanaka (1971) assumed the ship domain is an ellipse in their study of traffic capacity estimation in Japanese waters. They adopted the semi-major and semi-minor values to determine the domain's size. Later, researchers proposed a series of elliptical ship domains based on statistical models (e.g., Coldwell, 1983; Kijima and Furukawa 2001, 2003; Hansen et al., 2013). Goodwin (1975) proposed a circular ship domain model, which includes three different radius centered a ship. Some modified circular ship domains has been further provided by Davis et al. (1980), Zhao et al. (1993), and Zhu et al. (2001). Recently, researchers put forward the ship domain to be dynamic (e.g., Śmierzchalski and Michalewicz, 2000; Pietrzykowski, 2008). This leads to great difficulties for the estimation of waterway capacity, because many factors, such as ship characteristics (e.g., speed, route, type, length) and external factors (e.g., traffic mix proportion, weather), used in determining the dynamic domain are difficult to obtain in practice. Therefore, we found that previous waterway capacity related studies rarely provided an accurate estimate under a comprehensive consideration. In order to pursue a more accurate prediction of waterway traffic capacity, this study will build upon the previous literature by taking the dynamic ship domain into consideration in estimating the waterway traffic capacity. In addition, the ship traffic capacity should not be represented by a single number because of the uncertainty caused by unknown exogenous factors. Therefore, it is desired that the waterway traffic capacity should be represented by means of a probability distribution.

This study has two main contributions to previous literature. First, it proposes that the prediction result of the waterway traffic capacity is a probability distribution, assuming the influence of capacity is stochastic. Second, it provides a range of waterway traffic capacity at different confidence levels and also ascertains the influence on capacity from various factors, which can help the local authority to better perform the traffic control measures and make more appropriate development plan. The prediction method of this study is applicable to the prediction of the capacity distribution for many waterways globally.

3. METHODOLOGY

3.1 Research framework. As mentioned earlier, the waterway capacity is equal to the maximum number of ships sailing through a waterway section over a certain time period, e.g., from the time t to the time $t+T$ under a given shipping environment condition. The waterway capacity could vary with factors including the waterway width, ship type composition, the minimum separation required between successive ships and so on. In this study, we will take these factors into account for the estimation of waterway traffic capacity based on practical AIS data.

Figure 1 shows the flowchart of the proposed waterway traffic capacity prediction model. To predict the waterway traffic capacity, we firstly extract ship navigation data from AIS and the physical conditions of the waterway data. Here, ship navigation data contains the information including ship location, ship length, ship speed and time. The physical condition of the waterway mainly indicates the width of the waterway. We secondly predict the capacity of the waterway for each day based on the extracted data. The capacity of waterway traffic is treated as a probability distribution considering the effects of unknown influencing factors. Thirdly, we analyze the probability distribution of the capacity at different confidence levels so as to understand the range of the capacity under dynamic environment conditions.

3.2 Waterway traffic capacity observation during the given time interval

According to the waterway traffic capacity definition given by Fujii and Tanaka (1971), the waterway traffic volume reaches the capacity of the waterway under the situation that overtaking is nearly impossible and ships of the same group sail at almost the same speed. In other words, it will reach the waterway traffic capacity when all ships keep the minimum distance to collision (MDTC) one by one. We assume that two ships are sailing on the waterway link r simultaneously at the same average speed V_r. Considering the fact that the percentages of different ship types are independent, the proportion of ships with type i sailing after ships with type j can be calculated as $\omega_{ij} = \omega_i \cdot \omega_j$, where ω_i and ω_j are the percentages of ship type i and ship type j in the waterway traffic, respectively.

Let d_{ij} denote the MDTC between the two ships of the i^{th} and j^{th} types. The average MDTC along the waterway link r, denoted by d_a, could be thus calculated by

$$d_a = \sum_{i \in Z} \sum_{j \in Z} d_{ij} \omega_{ij} \tag{1}$$

It should be pointed out that the MDTC might be affected by various influencing factors such as ship type, time (daytime or night time) and ship speed (e.g., Krata et al., 2016). In this study, we assume the ship domain of ship i has an elliptical shape with its major axis x_i and minor axis y_i. Considering the possible effects of ship type, time and ship speed, the major axis x_i and minor axis y_i of the domain of ship i can be expressed by

$$x_i = (\alpha_1 + \beta_1 S_O + \gamma_1 S_{B-G} - \delta_1 D_{\text{Day}} - \varphi_1 V_S - \tau_1 V_M) L_i \pm L_i \tag{2}$$

$$\text{y}_i = (\alpha_2 + \beta_2 S_O + \gamma_2 S_{B-G} - \delta_2 D_{\text{Day}} - \varphi_2 V_S - \tau_2 V_M) L_i \pm 0.5 L_i \tag{3}$$

where α_{n}, β_n, γ_n, δ_n, φ_n, and τ_n ($n = 1, 2$) are the adjustment coefficients for influencing factors; S_O, S_{B-G}, D_{Day}, V_S and V_M are the influencing factors related to ship type, time and ship speed. Hereafter, V_S equals to 1 if the ship sails at a speed between 0 and 1 knot, 0 otherwise. V_M equals to 1 when the ship sails at a speed between 1 and 3 knots, 0 otherwise. More specifically, S_O represents whether the ship i is an oil/gas/chemical tanker or not. It equals to 1 when it belongs to an oil/chemical tanker, otherwise it is 0. S_{B-G} denotes whether the ship i is a bulk carrier or a general cargo ships. D_{Day} indicates the time of the day. In general, the ship domain is usually larger for the daytime period than the nighttime period. It should be pointed out that the above ship type grouping scheme for capturing the effects of ship type on ship domain size could be determined by the following procedure. Initially, we enumerate all possible ship type grouping schemes. For each grouping scheme, we then determine the adjustment factors for each ship group and calculate the model performance in terms of R^2 based on the questionnaire survey data. Finally, we choose the best grouping scheme with the largest R^2 from all feasible grouping schemes.

As pointed out in many previous studies (e.g., Montewka et al., 2010), the overlap of two ship domains is fully equivalent to the situation when the distance between two ships reaches the MDTC. This implies that the MDTC could be determined as an half of the sum of major axis of two ship domains. After taking into account the possible effects of ship type, time and ship speed, the average MDTC between the two ships shown by Eq.(1) can be further expressed by

$$d_a = \sum_{i \in Z} \sum_{j \in Z} \left[\frac{(\alpha_1 + \beta_1 S_O + \gamma_1 S_{B-G} - \delta_1 D_{\text{Day}} - \varphi_1 V_S - \tau_1 V_M)(L_i + L_j) \pm (L_i + L_j)}{2} \right] \omega_{ij} \tag{4}$$

Similarly, the average minimum width of two ships, denoted by b_a, can be estimated by

$$b_a = \sum_{i \in Z} \left[(\alpha_2 + \beta_2 S_O + \gamma_2 S_{B-G} - \delta_2 D_{\text{Day}} - \varphi_2 V_S - \tau_2 V_M) L_i \pm 0.5 L_i \right] \omega_i \tag{5}$$

Therefore, the waterway traffic capacity (denoted by C_r), namely the maximum number of ships that could pass through the given waterway from the time t to $t+T$, can be calculated by

$$C_r = \theta \cdot T \frac{V_r}{d_a} \cdot \frac{W_r}{b_a} \tag{6}$$

where θ is the close packing ratio (Fujii and Tanaka, 1971), V_r is the average speed of the ship sailing on the waterway link r and W_r is the average width of the waterway link r.

Considering possible hydrodynamic interactions, it is not allowed that more than two ships are always sailing in parallel in one waterway link in reality. Taking into account the constraint from the practical implication viewpoint, the waterway traffic capacity shown in Eq. (6) should be expressed by

$$C_r = \theta \cdot T \frac{V_r}{d_a} \cdot \max\left\{ N_{acc}, \frac{W_r}{b_a} \right\} \tag{7}$$

where N_{acc} is the maximum number of ships allowed to sail in parallel in the waterway link r (e.g., N_{acc} =2 for Shanghai estuary of the Yangtze River).

Note that the true average MDTC and minimum width of two ships do not exactly equal to d_a and b_a. This may be because both d_a and b_a have some randomness caused by many factors including ship type, ship size and etc. For simplicity, we assume that both d_a and b_a follow uniform distributions. Therefore, considering the randomness caused by ship type (Wu et al., 2017), the waterway traffic capacity should be estimated by

$$C_r = \int_{\underline{d_a}}^{\overline{d_a}} \int_{\underline{b_a}}^{\overline{b_a}} C_r \frac{1}{\overline{b_a} - \underline{b_a}} \frac{1}{\overline{d_a} - \underline{d_a}} d_{b_a} d_{d_a} = \frac{\theta T V_r W_r}{2L_a^2} \ln\frac{\overline{d_a}}{\underline{d_a}} \ln\frac{\overline{b_a}}{\underline{b_a}} \tag{8}$$

where $L_a = \sum_{i \in Z} L_i \omega_i = \sum_{i \in Z} \sum_{j \in Z} 0.5(L_i + L_j)\omega_{ij}$; $\overline{d_a}$ and $\underline{d_a}$ are the upper and lower bounds of the average MDTC, respectively; $\overline{b_a}$ and $\underline{b_a}$ are the upper and lower bounds of the average minimum width of the two ships.

3.3 Probability distribution of waterway traffic capacity

In reality, the variations in exogenous unknown factors like weather conditions could cause unpredictable fluctuations/variability on the waterway traffic capacity. In other words, the waterway traffic capacity may not be always the same at different times that are characterized by various weather conditions. Therefore, the waterway traffic capacity should be represented by means of a probability distribution rather than a single number.

In general, there are many distribution types available for describing the randomness of waterway traffic capacity caused by unknown weather conditions and waves. For simplicity, we take into account five commonly distribution types including lognormal distribution, uniform distribution, exponential distribution, normal distribution and Triangular distribution in this study. The probability density functions of these five distribution types are shown in Table 1.

A goodness-of-fit test should be conducted to select the best distribution type out of the five candidate distributions. In this study, the most widely-used K-S test is adopted to measure the goodness of fit for the waterway traffic capacity distribution. More specifically, we first measure the absolute difference between the cumulative percentage of the measured frequency and the cumulative percentage of the expected frequency in the K-S test. We then select the distribution type associated with the smallest K-S statistic.

4. DATA

4.1. Waterway layout of Yangtze River Estuary. The waterway at Shanghai estuary of the Yangtze River is the busiest segment along the whole Yangtze River. Figure 2 shows the navigation map of this waterway. The blue circles indicate the estuary of this waterway. It can be seen that it is the narrowest part at the mouth of Yangtze River. When huge shipping traffic passes through this estuary, the ship is most likely to be stranded at this location, thus affecting the navigation of the entire Yangtze River. Consequently, the accurate estimate of the waterway capacity within this area is very crucial to support the local authority to control ship traffic and improve the Waterway traffic safety.

A detailed shipping route chart is shown in Figure 2. The blue lines indicate two bottleneck points of this shipping channel. The width of the bottleneck at the northwest is 642.1 meters and the width of bottleneck at the southwest is 659.4 meters. According to the government regulations, the maximum sailing speed allowed in this area is 11 knots and no overtaking maneuvers are allowed in these water areas.

4.2. Ship characteristics. In this study, we collected the AIS data at Shanghai estuary of the Yangtze River in March and April of 2014. According to the collected AIS data, we can extract the information including ship length, ship type, ship speed, ship course, latitude and longitude positions. It should be pointed out that there may exist some errors in the AIS data. For example, the AIS data report that some ships have extremely large ship lengths, which is obviously inconsistent with the reality. Therefore, we adopted the procedure proposed by Qu et al. (2011) to clean the errors of the AIS data. A total of 8826 ships were collected, including almost all ship types, e.g., oil tanker, cargo ship, bulk carrier, passenger/RORO ship, container ship, chemical carrier, tug, fishing ship, fishing, small boats and others.

Figure 3 presents the length distribution among 8826 ships. It can be seen from Figure 3 that the majority of ships have lengths between 40 meters and 240 meters. It should be pointed out that the length of each ship type generally has considerable differences. As shown by Eqs. (2) and (3), the ship domain is significantly affected by the ship length. Therefore, there is a critical need to examine the ship classification in terms of ship length. In this study, the optimum number of ship groups in terms of ship length can be determined using the Centroid Clustering (CC) algorithm. In the CC algorithm, the objective function is to minimize the sum of the squared distances from the group means. The algorithm terminates when the number of iterations arrives at the preset maximum value. The optimum number of groups is found to be six: Group 1 (0, 40 meters], Group 2 (40 meters, 80 meters], Group 3 (80 meters, 160 meters], Group 4 (160 meters, 240 meters], Group 5 (240 meters, 320 meters] and Group 6 (320 meters, 369 meters]. Table 2 presents the descriptive statistics of the ship lengths in these six ship groups. It can be found that the majority of ships in Group 1 are the fishing and tug ships. Cargo ships and bulk carrier are the major ship types in Groups 1-3, as shown in Table 2.

4.3. Adjustment factors for ship domain. In order to investigate the effects of ship speed, ship type and time on the ship domain, we conducted a questionnaire survey on 80 ship captains and crew members. Each ship captain or crew member averagely has 6.14 years of navigation experience (standard deviation=3.75 years). With the collected 80 sets of questionnaire survey results, the parameters shown in Eqs. (2) and (3) can be determined using the least square error method, which are α_1=5.1504, α_2=2.2073, β_1=0.1854, β_2=0.1854, γ_1=0.4458, γ_2=0.1911, δ_1=0.4128, δ_2=0.1769, φ_1=0.4596, φ_2=0.1970, τ_1=0.2298 and τ_2=0.0985, respectively. The positive signs for β_1, β_2, γ_1 and γ_2 shows that the ship domain size for the oil/gas/chemical tanker and bulk carrier/general cargo ships is generally bigger than that for the tug, fishing ship, fishing, small boats. In addition, these results also show that a smaller ship domain is associated with the daytime period and smaller sailing speed.

5. RESULTS AND DISCUSSIONS

5.1 Capacity of waterway traffic composed of single ship type. In order to reflect the uncertainty associated with the waterway traffic capacity mentioned above, the waterway traffic capacity should be represented by means of probability distribution whose parameters can be determined based on the observed capacity data according to Eq. (8). For example, one scenario is assumed that the waterway traffic is only composed of cargo ships/bulk carriers with the lengths between 80 meters and 160 meters. The best-fitted capacity distribution for this scenario is the normal distribution: Norm (63.96, 4.04) because the corresponding K-S statistic is lower than those from other four distributions, as shown in Figure 4.

Let us analyze five scenarios that the waterway traffic is composed of only one ship type: (a) tanker; (b) cargo ship/bulk carrier; (c) passenger/ roll-on roll-off ship; (d) container ship; and (e) others. Figure 5 shows the capacity distributions for these five scenarios. As can be seen from the figure, for each ship type, the maximum number of ships (e.g, passenger/roll-on roll-off ship) allowed to sail through the Shanghai estuary of the Yangtze River decreases significantly with the ship size (from Group 1 to Group 6). In reality, the waterway traffic could not be composed of only ship type.

Therefore, we also create a more realistic scenario that the waterway traffic composed of various ship types. Figure 5(f) presents the capacity distribution for this more realistic scenario. Similar to Figures 5(a)-5(e), Figure 5(f) also shows that more small-sized ships (e.g., Group 1) are allowed to sail through the waterway. For example, there is a capacity of 638.43 ships per hour for the waterway traffic composed of various types of ships less than 40 meters, while it is reduced to 7.06 ships per hour for the waterway traffic composed of ships larger than 320 meters.

5.2 Ship equivalent unit (seu) from the capacity viewpoint. As mentioned above, due to the unique ship characteristics, the maximum number of ships sailed through the waterway varies with different ship sizes. Therefore, it is also of utmost importance to calculate how many benchmark ships are equal to one ship with a specific ship length in terms of waterway traffic capacity. For simplicity, the ships having lengths between 40 meters and 80 meters in Group 2 are considered as the benchmark ships in this study. Table 3 presents the ship equivalent units for different ship groups characterized by various ship lengths. It can be clearly seen from the table that the ship equivalent unit for the ship Group 6 is the largest, followed by the ship Group 5. Consistent with our expectation, it is also found that the ship equivalent unit could be affected by the time of the day, as shown in Table 3. This might be because the waterway traffic capacity could be affected by the time of the day. For example, one-way Analysis of Variance (ANOVA) test results show that the average maximum number of ships with lengths between 240 and 320 meters allowed to sail along the waterway is 33.2 ships per hour during the daytime period, which is statistically larger than that during the nighttime period (27.2 ships per hour) at a significance level of 0.05. Therefore, one longer ship in Group 5 (i.e., 240meters<length≤320meters) equals to 28.94 benchmark ships (e.g., the ship length ranging from 40 meters to 80 meters) during the daytime period. However, a longer ship in Group 5 is only equivalent to 25.90 benchmark ships at night. The smaller equivalent unit of a ship with longer ship length at night may be explained by the fact that the longer ship will sail along the waterway at a slower speed.

5.3 Effects of the high proportion of longer ships on the mean of waterway traffic capacity. In reality, the waterway traffic could not be composed of only one type of ships with the same ship size. The realistic waterway traffic is composed of various ship groups with different proportions. For the sake of presentation, the scenario with the observed ship compositions is considered as the benchmark scenario. Table 4 gives four scenarios for examining the effects of longer ships on waterway traffic capacity. Scenario A is considered as the benchmark scenario, where the ship compositions are calculated according to ship voyages extracted from the AIS data in March and April of 2014. For example, the total number voyages for ships in Group 1 (516,337) accounts for about 12.64% of the total voyages (4,086,149). For voyages under Groups 2-6, the proportions are 8.14%, 52.87%, 20.68%, 4.86% and 0.81%, respectively. As mentioned before, the average ship size has been increasing rapidly (Zheng and Yang, 2016). In order to reflect the fact of increasing proportion of longer ships in the Yangtze River, we further assume that the proportions of longer ships in Groups 5 and 6 increase by 5%, 10% and 15% in Scenarios B, C and D, respectively. In addition, the proportions of ships in other groups decrease proportionally for these three scenarios. The detailed ship compositions for these four scenarios are tabulated in Table 4.

Figure 6 presents the capacity distribution of waterway traffic in four scenarios associated with different proportions of longer ships. It can be clearly seen from Figure 6(a) that the use of longer ships could increase the waterway traffic capacity. More specifically, the mean capacity for Scenario D is 257.4 seu/hr (i.e., ship equivalent unit per hour), which is larger than that for Scenario A by 6.4% during the daytime period. Similarly, Scenario D also has 8.2% larger capacity during the nighttime period, as compared with Scenario A. In addition, Figure 6 also shows that the increment of waterway traffic capacity also increases with the proportion of longer ships. This provides adequate support for the argument that the deployment of larger ships will increase the capacity of busy waterway.

5.4 Effects of the high proportion of longer ships on the uncertainty of waterway traffic capacity. In order to measure the uncertainty of waterway traffic capacity caused by external stochastic factors such as unknown weather conditions, we can determine the confidence interval of waterway traffic capacity that is traditionally described as a range around the mean of the data (Weng and Yan, 2016). In general, the confidence interval (*CI*) can be calculated by

$$CI_\alpha = [U - w_\alpha, U + w_\alpha] \tag{9}$$

where U is the mean of waterway traffic capacity, w_α is the absolute difference between the mean and lower bound of waterway traffic capacity at the confidence level of α.

Using Eq. (9), the confidence interval of waterway traffic capacity can be easily determined. Figure 7 tabulates the CIs at various confidence levels for the four scenarios. It can be seen that the CI of waterway traffic capacity in Scenario A is [233.15 seu/hr, 250.69 seu/hr] at a confidence level of 95%, [236.78 seu/hr, 247.06 seu/hr] at a confidence level of 75%. This implies that the probability of waterway traffic capacity falling within a range from 233.15 seu/hr to 250.69 seu/hr is 0.95 in Scenario A. It can be found that confidence interval length increases with the proportion of longer ships at any specific confidence level. For example, the waterway traffic capacity in Scenario D has the widest confidence interval. Considering the fact that one longer ship is equivalent to a number of small-sized ships, it is apparently easier to guide the longer ship operations for maritime authorities. Actually, if the longer ships are not converted into the benchmark ships (i.e., small-sized ships), the difference between upper and lower bounds of waterway traffic capacity is the smallest for Scenario D (only 13.8 ships/hr) at a confidence level of 0.95. This suggests that the deployment of longer ships could provide a more stable waterway traffic capacity predict that is more helpful for maritime authorities to check the viability of waterway proposals in Master Planning of Yangtze River.

6. CONCLUSIONS. This study proposed an effective methodology to determine waterway traffic capacity at Shanghai estuary of the Yangtze River. Firstly, we put forward the calculation method based on the distribution of the MDTC to determine the observed waterway traffic capacity. Secondly, considering the possible effects caused by unknown factors like weather conditions, the waterway traffic capacity was further represented by a probability distribution rather than a single number in this study. Using the proposed methodology, we also examined the equivalent units of the ships with various ship sizes as well as the possible effects of longer ships on the waterway traffic capacity finally. The results show that a longer ship is equivalent to more small-sized ships during the daytime period than that at night. In addition, it was also found that the deployment of longer ships could increase the waterway traffic capacity at Shanghai estuary of the Yangtze River. Moreover, the increment of waterway traffic capacity depends on the increased proportion of longer ships in waterway traffic.

It is worth mentioning that the waterway traffic capacity is estimated based on the assumption that all ships should keep the MDTC and have no violations of their safety domain when it reaches the capacity. However, ships may have dynamic interactions and influences to each other in reality. In this situation, it is very difficult to determine whether the waterway traffic estimate is exactly close to the true value in reality. Therefore, future study will adopt traffic simulators to determine the effects of ship interaction on the waterway traffic capacity. Because of data limits, the effect of visibility on the waterway traffic capacity has not been taken into account though time of the day has partially captured the effect of this factor. We will examine the effect of visibility after collecting more data in the future.

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Table 1

Five common distribution types for waterway traffic capacity

Distribution type	Probability density function (PDF)
Lognorm (μ, σ)	$f(x;\mu,\sigma)=\dfrac{e^{-(1/2)((\ln x-\mu')/\sigma')^2}}{x\sqrt{2\pi}\sigma'}$ $\mu'=\ln(\mu^2/\sqrt{\sigma^2+\mu^2})\ \sigma'=\sqrt{\ln\left[1+(\sigma/\mu)^2\right]}$
Uniform (μ, λ)	$f(x;\mu,\lambda)=\sqrt{\lambda/2\pi x^3}\,e^{-\left[\frac{\lambda(x-\mu)^2}{2\mu^2 x}\right]}$
Expon (β, θ)	$f(x;\beta,\theta)=(1/\beta)e^{-(x-\theta)/\beta}$
Normal (μ, σ)	$f(x;\mu,\sigma)=(\frac{1}{\sqrt{2\pi}\sigma})e^{-\frac{1}{2}(\frac{(x-\mu)}{\sigma})^2}$
Triang (a, c,b)	$f(x;a,c,b)=\begin{cases}0 & \text{for } x<a \text{ or } b<x\\ \dfrac{2(x-a)}{(b-a)(c-a)} & \text{for } a\le x<c\\ \dfrac{2}{(b-a)} & \text{for } x=c\\ \dfrac{2(b-x)}{(b-a)(b-c)} & \text{for } c<x\le b\end{cases}$

Table 2

Ship groups characterized by different ship lengths

Group	Index	Length (m)	Total number	Percentage	Mean length(m)	Ship types
1	ρ_1	0-40	16397	3.18%	35.06	I
			12824	2.48%		II
			-	-		III
			-	-		IV
			487116	94.34%		V
2	ρ_2	40-80	91712	27.56%	62.6	I
			145726	43.79%		II
			8224	2.47%		III
			-	-		IV
			87111	26.18%		V
3	ρ_3	80-160	341880	15.83%	115.99	I
			1138680	52.71%		II
			3521	0.16%		III
			213987	9.90%		IV
			462297	21.40%		V
4	ρ_4	160-240	35343	4.18%	187.48	I
			595418	70.45%		II
			3577	0.43%		III
			181398	21.46%		IV
			29406	3.48%		V
5	ρ_5	240-320	999	0.51%	281.26	I
			66487	33.5%		II
			12340	6.22%		III
			105426	53.12%		IV
			13201	6.65%		V
6	ρ_6	320-369	3453	10.45%	338.57	I
			2659	8.05%		II
			-	-		III
			23462	71.01%		IV
			3465	10.49%		V

Note: I-Tanker, II-Cargo ship and Bulk Carrier, III-Passenger ships and Roll-on/Roll-off, IV-Container ship, V-Others (e.g., tug, fishing ships).

Table 3
Ship equivalent unit in terms of waterway traffic capacity

Group / Time	Group 2 (Benchmark) (40meters<length≤80meters)	Group 1 (length≤40 meters)	Group 3 (80meters<length≤160meters)	Group 4 (160meters<length≤240meters)	Group 5 (240meters<length≤320meters)	Group 6 (320meters<length≤369meters)
Day	1	0.37	4.27	9.73	28.94	42.38
Night	1	0.46	3.81	8.49	25.90	35.97

Table 4
Scenario design of ship traffic composition

Ship group	Scenario A*	Scenario B	Scenario C	Scenario D
Group 1	12.64%	11.30%	9.96%	8.62%
Group 2	8.14%	7.28%	6.41%	5.55%
Group 3	52.87%	47.26%	41.66%	36.06%
Group 4	20.68%	18.49%	16.30%	14.10%
Group 5	4.86%	9.86%	14.86%	19.86%
Group 6	0.81%	5.81%	10.81%	15.81%

* Scenario A is designed based on the observed AIS data in March and April, 2014.

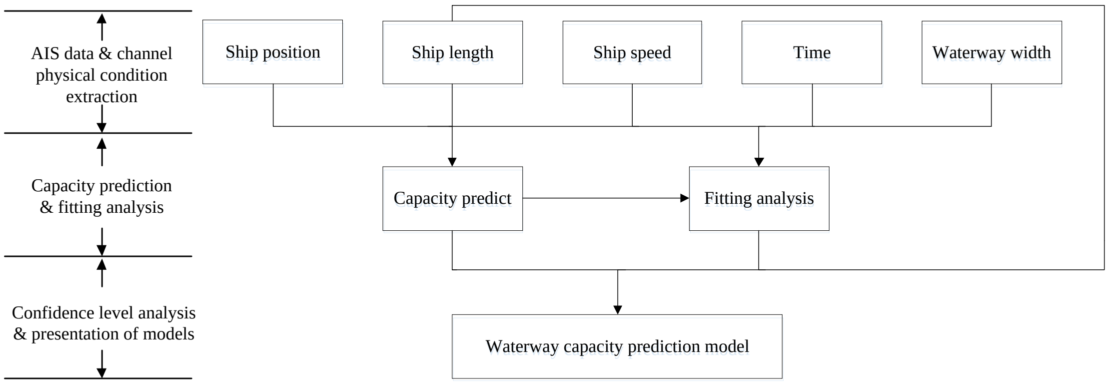

Figure 1 A flowchart for estimating waterway traffic capacity

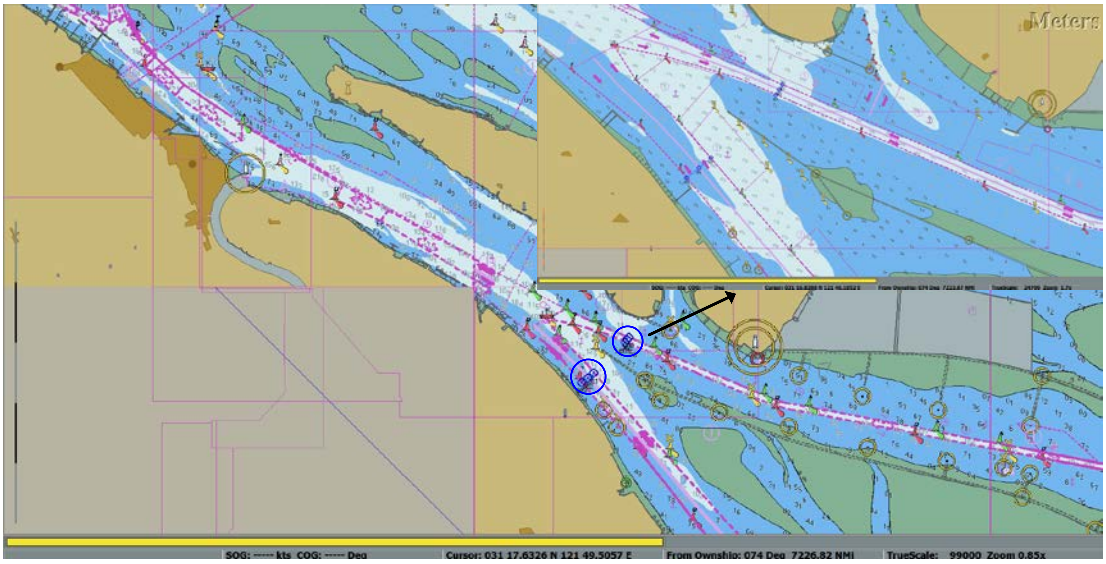

Figure 2 Waterway layout of Shanghai estuary of the Yangtze River.

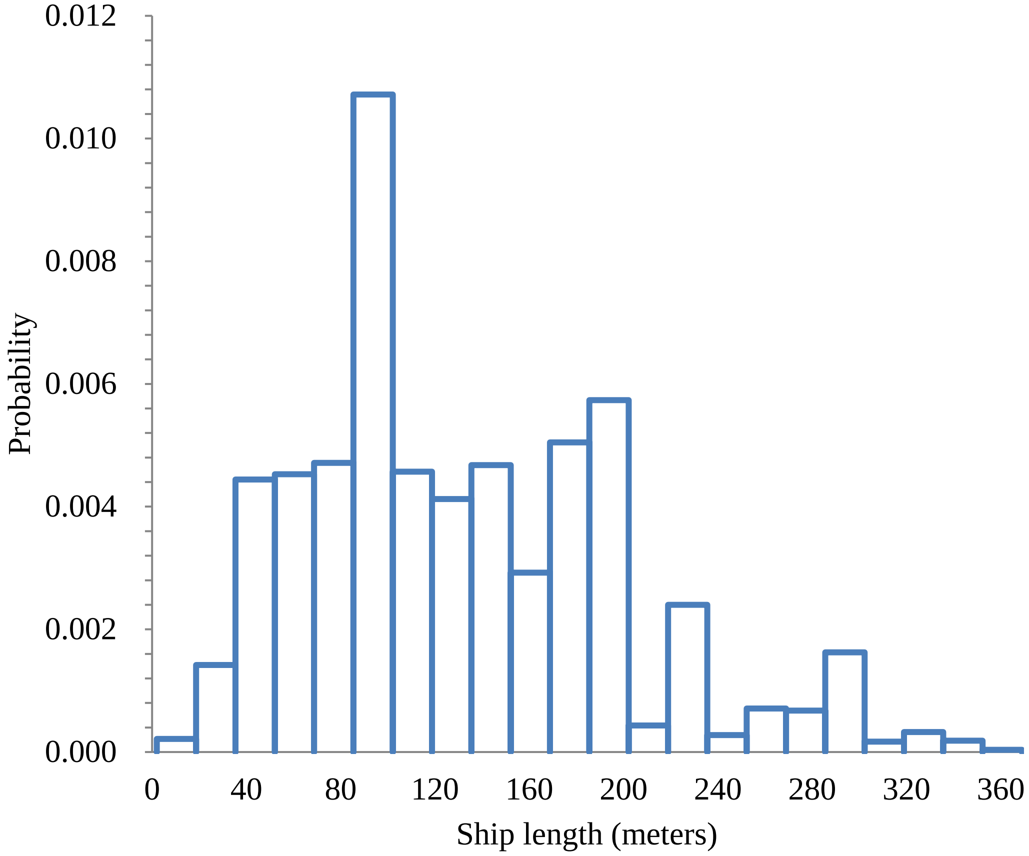

Figure 3 Distribution of ship lengths extracted from the AIS data

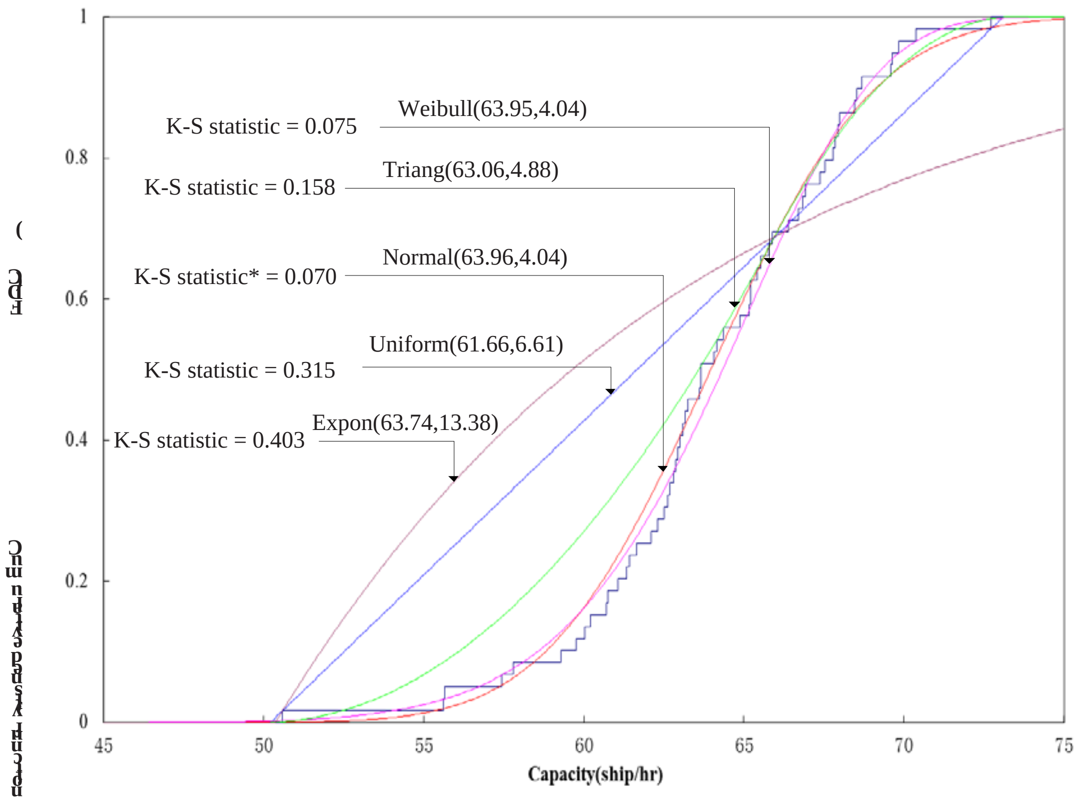

Figure 4 Cargo ship/bulk carrier capacity distribution in Group 3.

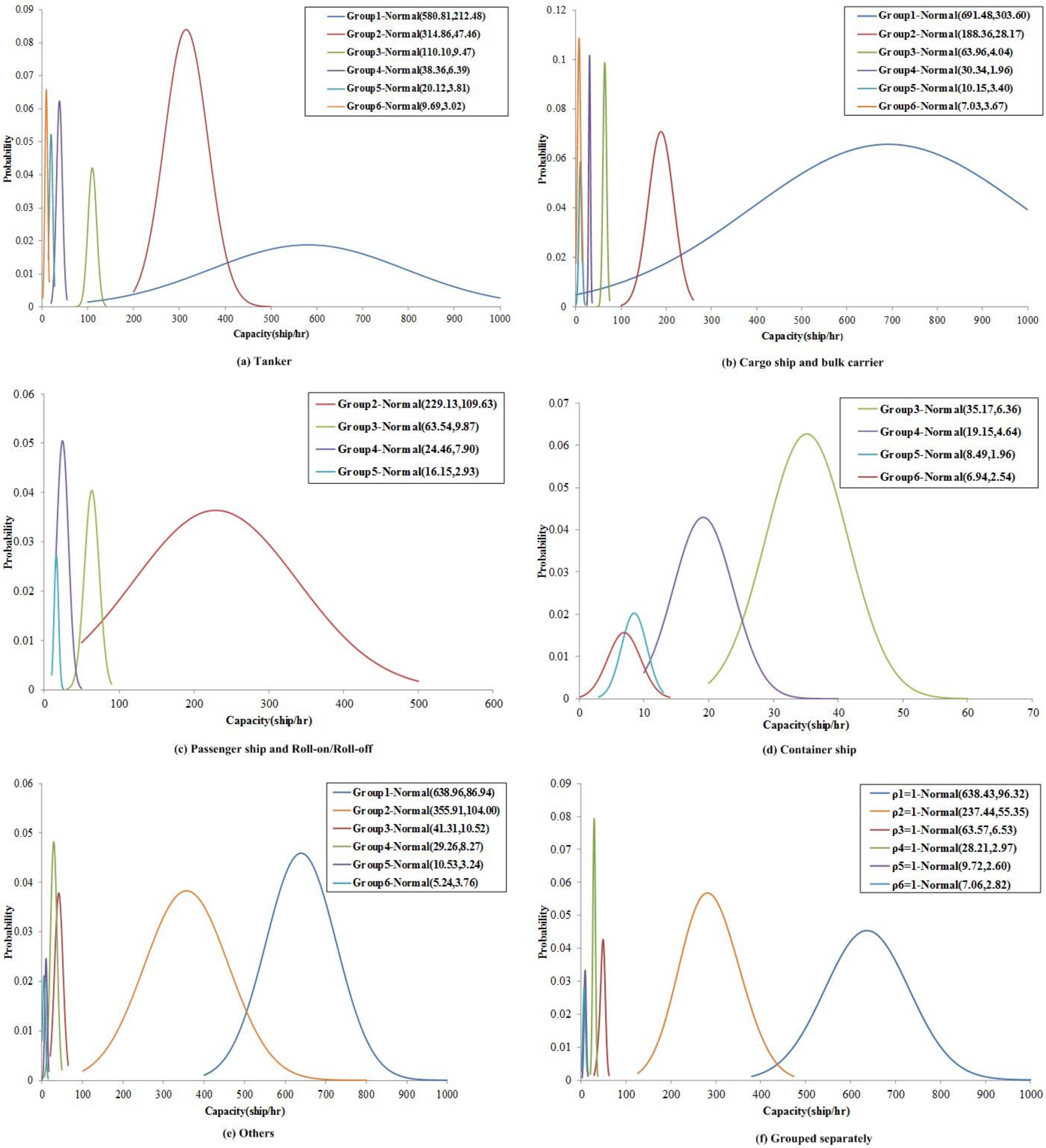

Figure 5 Capacity distribution for different ship types

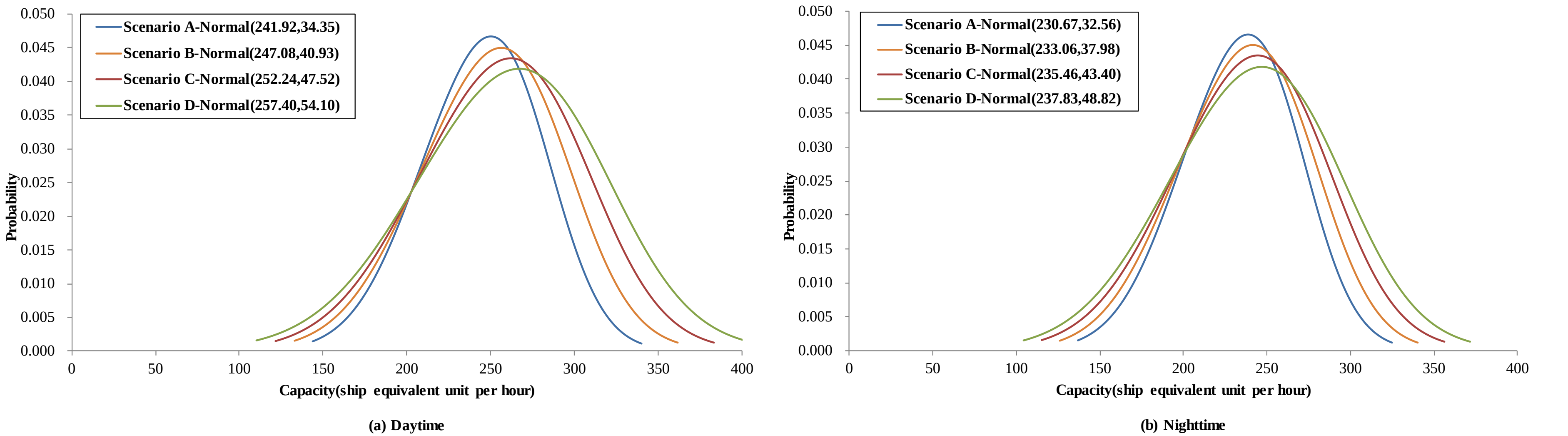

Figure 6 Distribution of waterway traffic capacity under four different scenarios

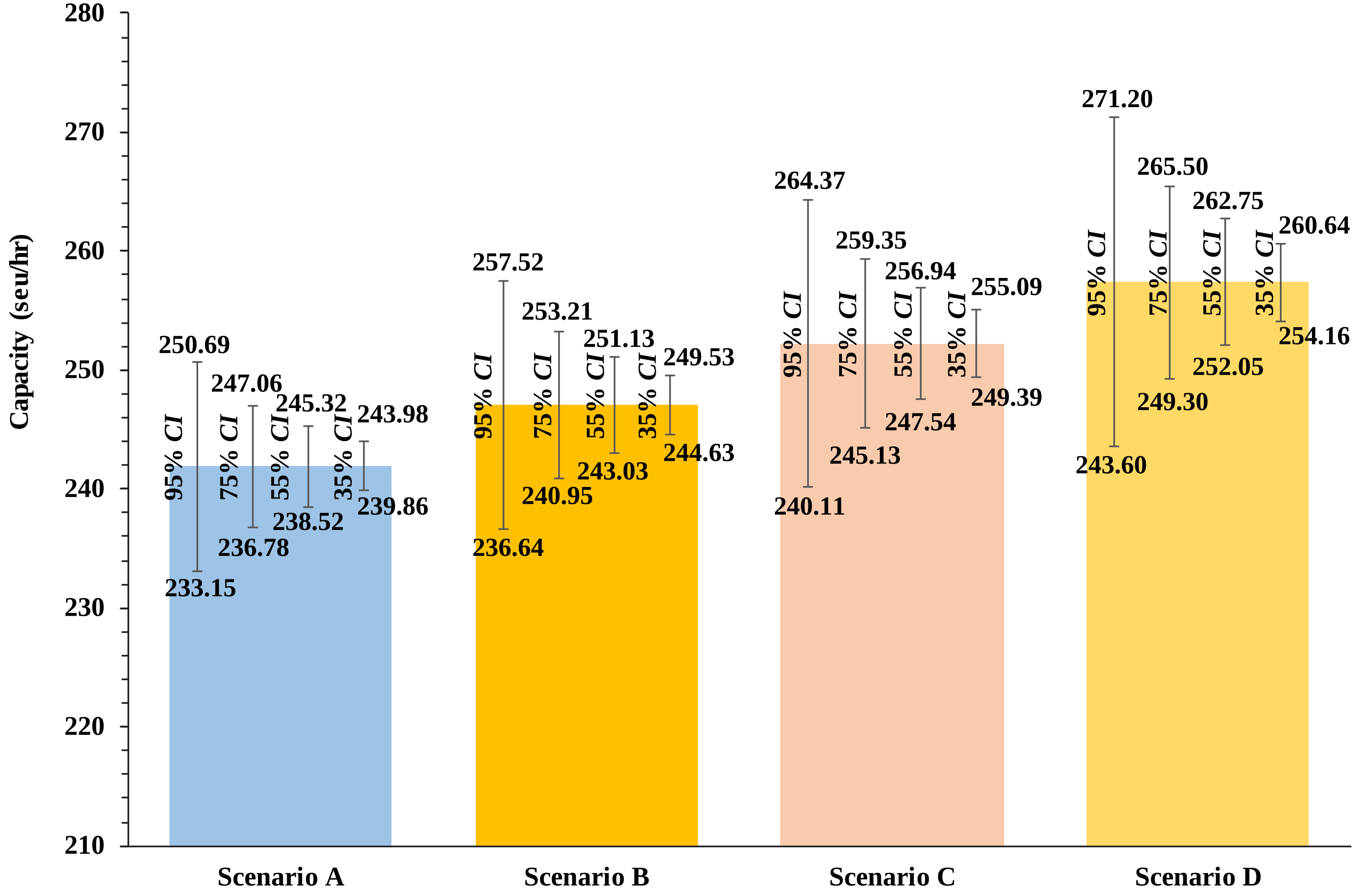

Figure 7 *CI*s at various confidence levels for the four scenarios