

A evaluation and selection model of dredger considering marine ecological environment and dredger performance

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Abstract. There will be total suspended solids in port dredging, which will affect aquatic organisms and water quality. Therefore, with the Green Port becoming the core concept of port development, it is necessary to consider the impact of dredging on marine ecological environment when selecting dredgers. In this paper, the calculation method of biomass loss caused by dredging is proposed, and the biomass loss is taken as the evaluation index to establish a dredger selection model considering marine ecological environment and dredger performance. The dredger selection model uses the fuzzy synthetic evaluation method based on norm grey relational grade to evaluate and select dredgers quantitatively, avoiding the influence of subjective factors on dredger selection. Finally, the feasibility of dredger selection model is verified by a practical dredging engineering and the results indicate that the dredger selection model can serve as a scientific basis for the construction of ecological port and the protection of marine environment.

1 Introduction

Dredging is necessary to maintain the water depth of harbour basin and channel and ensure the port navigation. However, dredging has a great impact on the marine ecological environment [1], producing a large number of total suspended solids (TSS) that are insoluble in water and can be suspended in sea water for a long time. TSS spread with currents, causing direct damage to aquatic organisms, such as fish and plankton [2,3]. Moreover, the production of TSS will lower water quality and affect the marine ecological environment [4].

With a boom of the ecological concept, some studies have been conducted investigating the impact of TSS generated by dredging on the marine ecological environment. The effects of TSS at different concentrations on aquatic organisms were studied by comparing the relationship between TSS concentration and biomass at different dredging stages [5]. The dredging intensity was managed with the aim of improving water quality and reducing the mortality of aquatic organism, but the dredger type and efficiency were not considered [6]. In addition, dredgers are selected from the perspective of economy and efficiency rather than ecology and environmental protection at present [7,8].

In this paper, a calculation model of biomass loss is established firstly to calculate the loss of various aquatic organisms caused by dredgers of different types and dredging efficiency. Then, the biomass loss obtained in the first step is used as an evaluation index to establish a dredger selection model combining the impact of TSS generated by dredging on marine ecological environment

and dredger performance. Considering that the selection of dredger is subjective to some extent, the fuzzy synthetic evaluation method based on norm grey relational grade is applied to dredger selection model to make a scientific and comprehensive evaluation and selection of dredger.

2 Methods

2.1. Relationship between dredger performance and biomass loss

According to *Specifications for Environmental Impact Assessment of Port Engineering (JTS105-1-2011)*, the amount of TSS generated by dredging can be calculated from the following formula.

$$Q = \frac{R}{R_0} \times W_0 \times T \quad (1)$$

where $Q(t/h)$ is the amount of TSS generated by dredging and $W_0(t/m^3)$ is TSS generation coefficient. R and R_0 are respectively cumulative percentage of TSS size in W_0 and TSS critical size under the velocity of dredging location. $T(m^3/h)$ is dredging efficiency. Note that R , R_0 and W_0 are related to actual dredging situation such as dredger type and seabed sediment, and these parameters could be determined better through actual measurement. So formula could be written as follow.

$$Q = g(D, T, S) \quad (2)$$

where D is the type of dredger and S is the median size of seabed sediment.

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It is assumed that there is a source of silt with fixed location and constant concentration when dredging in a limited area. Therefore, there is a linear relationship between the amount of TSS generated by dredging and the concentration increment of TSS in the location of silt source, as shown below.

$$\Delta S_{\max} = f(Q) = \alpha Q + \beta \quad (3)$$

Combined with formula (1) and (3), the relationship between actual dredging situation and the increment of TSS concentration in the location of silt source is as follows:

$$\Delta S_{\max} = f[g(D, T, S)] = h(D, T, S) \quad (4)$$

Based on the relationship equation between the concentration of TSS and the mortality of plankton established by Li et al. [9], combining with the formula (4), the mortality of plankton in the location of silt source is calculated as follows:

$$n_{S_{\max}} = \frac{1}{1 + e^{r(LC_{50} - S_0 - h(D, T, S))}} \times 100\% \quad (5)$$

where $n_{S_{\max}}$ is the plankton mortality in the location of silt source and r is the parameter of increasing plankton mortality caused by TSS. LC_{50} and S_0 are the median lethal concentration of TSS for plankton and background value of TSS concentration respectively.

The *Sea Water Quality Standard (GB 3097-1997)* indicates that the concentration increment of TSS in sea water of class I water quality is not more than 10mg/L, which is suitable for marine fishery areas and nature reserves. In this study, the area where the concentration increment of TSS exceeds 10mg/L is divided into n areas according to the gradient of 10mg/L. Assuming that the average concentration increment of TSS corresponding to each gradient is ΔS_i (mg/L) and the diffusion area is A_i (m^2), the following equation is available.

$$\begin{aligned} \Delta S_i &= 10i + 5 \quad (i = 1, 2, \dots, n-1), \\ \Delta S_n &= \frac{10n + h(D, T, S)}{2} \end{aligned} \quad (6)$$

The mortality n_{S_i} and predicted loss L_{S_i} of plankton in any concentration increment gradient area A_i are shown in formula (7) and formula (8), respectively.

$$n_{S_i} = \frac{1}{1 + e^{r(LC_{50} - S_0 - \Delta S_i)}} \times 100\% \quad (7)$$

$$L_{S_i} = n_{S_i} A_i \bar{h}_i C_s \quad (8)$$

where \bar{h} is the average water depth in area A_i and C_s is the average biomass of plankton before dredging.

Before dredging, TSS will be generated in the dredging area due to hydrodynamic conditions such as wave and current, which will cause damage to plankton. The amount of biological loss is called background loss. Therefore, the loss of plankton L_S caused by dredging is

equal to the predicted loss of plankton minus the background loss, which can be expressed as formula (9).

The relationship between TSS concentration and fish mortality is also derived from the relationship equation constructed by Li et al. [9], and the method of calculating the loss of fish biomass caused by dredging is the same as that of plankton. Therefore, the loss of fish biomass caused by dredging can be calculated by formula (10).

In dredging, benthos will die because of excavation, burying and covering. Therefore, the loss of benthos caused by dredging can be calculated by multiplying the average biomass of benthos before dredging by the area of dredging, which has nothing to do with type and efficiency of dredger.

$$\begin{aligned} L_S &= \sum_{i=1}^n L_{S_i} - \sum_{i=1}^n \frac{A_i \bar{h}_i C_s}{1 + e^{r(LC_{50} - S_0)}} \\ &= \sum_{i=1}^n n_{S_i} A_i \bar{h}_i C_s - \sum_{i=1}^n \frac{A_i \bar{h}_i C_s}{1 + e^{r(LC_{50} - S_0)}} \\ &= \sum_{i=1}^n \frac{A_i \bar{h}_i C_s}{1 + e^{r(LC_{50} - S_0 - \Delta S_i)}} - \sum_{i=1}^n \frac{A_i \bar{h}_i C_s}{1 + e^{r(LC_{50} - S_0)}} \\ &= \sum_{i=1}^{n-1} \frac{A_i \bar{h}_i C_s}{1 + e^{r(LC_{50} - S_0 - 10i - 5)}} + \frac{A_n \bar{h}_n C_s}{1 + e^{r(LC_{50} - S_0 - \frac{10n + h(D, T, S)}{2})}} \\ &\quad - \sum_{i=1}^n \frac{A_i \bar{h}_i C_s}{1 + e^{r(LC_{50} - S_0)}} \left(n = \left\lceil \frac{h(D, T, S)}{10} \right\rceil \right) \end{aligned} \quad (9)$$

definitions of the variables and parameters are the same as described above.

$$\begin{aligned} L_F &= \sum_{i=1}^n L_{F_i} - \sum_{i=1}^n n_{F_0} A_i \bar{h}_i (1 - v_F) C_F \\ &= \sum_{i=1}^n n_{F_i} A_i \bar{h}_i (1 - v_F) C_F - \sum_{i=1}^n n_{F_0} A_i \bar{h}_i (1 - v_F) C_F \\ &= \sum_{i=1}^{n-1} n_{F_i} A_i \bar{h}_i (1 - v_F) C_F + n_{F_{\max}} A_n \bar{h}_n (1 - v_F) C_F \\ &\quad - \sum_{i=1}^n n_{F_0} A_i \bar{h}_i (1 - v_F) C_F \left(n = \left\lceil \frac{h(D, T, S)}{10} \right\rceil \right) \end{aligned} \quad (10)$$

where L_F is the loss of fish and L_{F_i} is the predicted loss of fish in any concentration increment gradient area. Similar to C_s in formula (9), C_F represents the average biomass of fish before dredging. Note that v_F denote the avoidance ratio because of the ability to swim of fish.

2.2. Fuzzy synthetic evaluation of dredger selection based on norm grey relational grade

Considering that the selection of dredger is subjective to some extent, a dredger selection model is established by the fuzzy synthetic evaluation method based on norm grey relational grade. This model is composed of three steps. Firstly, an evaluation index system of dredger selection is built up which take account marine ecological environment and dredger performance. Then, determining the index weights using norm grey relational grade analysis. Finally, evaluating and select

suitable dredger based on fuzzy synthetic evaluation method.

2.2.1 Building up the evaluation index system

In establishment of index system, marine ecological environment and dredger performance are chosen as first-grade indexes and they are quantitative and qualitative indicators respectively. By referring to *Specification for Environmental Impact Assessment of Port Engineering (JTST105-1-2011)* and considering the availability and representativeness of data, the first-grade index of marine ecological environment includes of the increment of TSS concentration, areas exceeding class I and class II and meeting class III water quality standards, areas exceeding class III and meeting class IV water quality standards, areas exceeding class IV water quality standards, plankton loss and fishery resources loss. According to the characteristics of dredger, the first-grade index of dredger performance is also divided into six second-grade indexes, namely excavation surface flatness, anti-wind and anti-wave performance, impact on ship navigation, impact by long-distance mud dumping, independent operation ability and the universality of seabed sediment that can be excavated.

Table 1. The evaluation index system of dredger selection.

	First-grade index	Second-grade index
The evaluation of dredger selection A	The marine ecological environment (A_1)	the increment of TSS concentration (A_{11})
		areas exceeding class I and class II and meeting class III water quality standards (A_{12})
		areas exceeding class III and meeting class IV water quality standards (A_{13})
		areas exceeding class IV water quality standards (A_{14})
		plankton loss (A_{15})
		fishery resources loss (A_{16})
	The dredger performance (A_2)	excavation surface flatness (A_{21})
		anti-wind and anti-wave performance (A_{22})
		impact on ship navigation (A_{23})
		impact by long-distance mud dumping (A_{24})
		independent operation ability (A_{25})
		the universality of seabed sediment that can be excavated (A_{26})

2.2.2 Determining the index weights

Combining the traditional grey theory with the norm concept to determine the index weights in this paper. The index weights determined by norm grey relational grade can analyse the degree of interaction influence among indexes under the condition of incomplete information and avoid the influence of subjective factors on weight determination, which is very suitable for determining the weight of evaluation index of dredger. The specific steps determining the index weight of norm grey relational grade could be seen in [10].

Qualitative indexes are graded by questionnaire adopting fuzzy mathematics theory and weighted average is taken as the index value of qualitative indexes in this paper.

2.2.3 Fuzzy synthetic evaluation

The purpose of the fuzzy synthetic evaluation is to determine the optimal evaluation result from the evaluation grade set, with qualitative and quantitative indexes being comprehensively considered. The specific steps of fuzzy synthetic evaluation can refer to [11,12].

In this paper, the evaluation grade set could be divided into five level, namely higher, high, middle, low, and lower, with 90, 80, 70, 60, 50 respectively assigned to each level of evaluation. It can also be described as $V=\{V_1, V_2, V_3, V_4, V_5\}=\{90, 80, 70, 60, 50\}$. The evaluation grades of qualitative and quantitative indexes are shown in Table 2 and Table 3 respectively. For quantitative indexes, A_{11} is classified according to the increment of TSS concentration, and other indexes are classified according to the relative value obtained from the comparison among different dredgers.

Table 2. The evaluation grade for qualitative index.

Evaluation index	Mechanical dredger			Hydraulic dredger	
	bucket dredger	clamshell dredger	scoop dredger	cutter suction dredger	trailing suction dredger
A_{21}	high	lower	lower	high	lower
A_{22}	higher	higher	higher	lower	high
A_{23}	lower	lower	lower	low	high
A_{24}	lower	lower	lower	higher	high
A_{25}	low	low	low	higher	high
A_{26}	higher	high	higher	low	low

Table 3. The evaluation grade for quantitative index.

Evaluation index	Evaluation grade				
	higher	high	middle	low	lower
$A_{11}(\text{mg/L})$	10	50	100	150	200
A_{12}	0.2	0.6	1.0	1.4	1.8
A_{13}	0.2	0.6	1.0	1.4	1.8
A_{14}	0.2	0.6	1.0	1.4	1.8

A_{15}	0.2	0.6	1.0	1.4	1.8
A_{16}	0.2	0.6	1.0	1.4	1.8

Qualitative evaluation could be transformed into quantitative evaluation by the theory of membership degree in fuzzy synthetic evaluation. In this paper, lower semi-trapezoid distribution function is chosen to determine the membership degree of quantitative degree and the membership degree r_{ij} of qualitative index is determined by questionnaire, that is, the number of participants who choose grade j of the i th index divided by the total number of participants in the questionnaire.

3 Empirical research

3.1 Study area

A harbour basin in northern China needs 0.4 million m^3 of excavation and the dredging area is 300m long and 350m wide. The seabed sediment is mainly composed of muddy silty clay and silty sand with a median size of 0.005-0.007mm. The background value of the concentration of TSS in the water is $S_0 = 10mg/L$, and the average biomass of phytoplankton, zooplankton and fish before dredging is $24mg/m^3$, $138mg/m^3$ and $12mg/m^3$ respectively.

The parameters of calculating biomass loss are as follows: $r = 0.065$, LC_{50} for phytoplankton and zooplankton are $100mg/L$ and $60mg/L$, avoidance ratio v_F of fish is 0.9 and the average water depth \bar{h} is 9m.

In view of the seabed sediment conditions, bucket dredger, cutter suction dredger and trailing suction dredger can be selected for dredging. The dredging efficiency range of the three dredgers is 100-1000 m^3/h with gradient of 100, 500-5000 m^3/h with gradient of 500 and 1000-7000 m^3/h with gradient of 500.

3.2 Diffusion of TSS and its impact on biomass

By referring to the practical cases, the values of R , R_0 and W_0 in formula (1) can be determined, and then the amount of TSS generated by dredging corresponding to different dredging efficiency can be obtained and used as a source of silt with fixed location and constant concentration.

The diffusion range and concentration of TSS can be obtained by hydrodynamic software, such as the sediment transport module of MIKE 21. The biomass loss caused by various types and efficiency of dredgers, based on the above values and the method in Section 2.1, can be finally obtained, and shown in Fig. 1, Fig. 2 and Fig. 3.

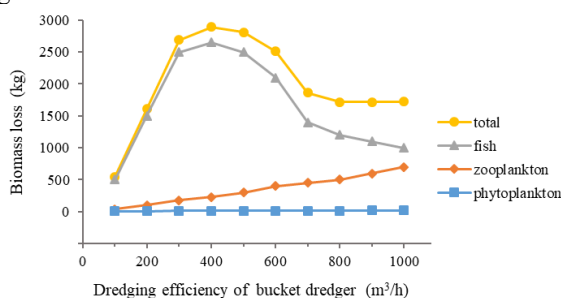


Fig. 1. Biomass loss caused by bucket dredger.

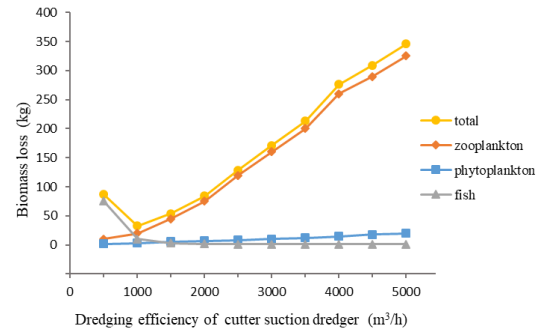


Fig. 2. Biomass loss caused by cutter suction dredger.

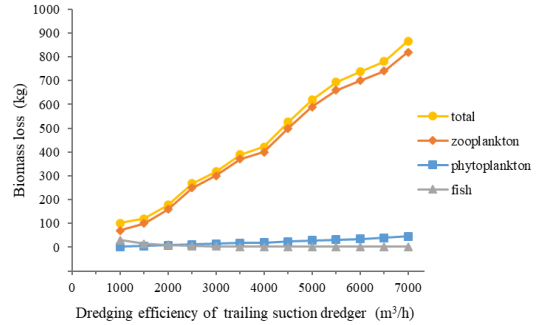


Fig. 3. Biomass loss caused by trailing suction dredger.

3.3 Evaluation and selection of dredger

The following six are selected as alternative dredgers: bucket dredgers with dredging efficiency of 300 m^3/h ($B1$) and 800 m^3/h ($B2$), cutter suction dredgers with dredging efficiency of 1500 m^3/h ($C1$) and 4000 m^3/h ($C2$), and trailing suction dredgers with dredging efficiency of 2000 m^3/h ($T1$) and 6000 m^3/h ($T2$).

3.3.1 Index weights

According to the index weight determination method mentioned above, after all the evaluation indexes are normalized, the norm grey relational grades of each index relative to the other 11 indexes are calculated based on the normalized sequence, and the mass grey relational degree and the index weights are further obtained. Table 4 presents the weights of first-grade indexes and second-grade indexes.

It can be seen from Table 4 that the weights of A_{11} , A_{12} , A_{13} , A_{14} and A_{15} in the second-grade indexes are higher than 0.09 and the weights of other indexes, and the weight of first-grade index A_1 is higher than A_2 . therefore, more attention should be paid to the impact on the marine environment when selecting dredgers.

Table 4. The mass grey relational degree and weight of evaluation index.

First-grade index	Weight	Second-grade index	Mass grey relational degree	Weight
A_1	0.539	A_{11}	0.576	0.093
		A_{12}	0.571	0.093
		A_{13}	0.586	0.095

		A_{14}	0.568	0.092
		A_{15}	0.598	0.097
		A_{16}	0.424	0.069
		A_{21}	0.518	0.084
		A_{22}	0.396	0.064
		A_{23}	0.547	0.089
A_2	0.461	A_{24}	0.491	0.080
		A_{25}	0.406	0.066
		A_{26}	0.483	0.078

3.3.2 Results of fuzzy synthetic evaluation

The fuzzy synthetic evaluation method based on norm grey relational grade is applied to evaluate six dredgers from perspectives of the impact on the marine ecological environment and dredger performance. The evaluation results are provided in Table 5 and the priority of six alternative dredgers is as follows:

$$C1 > T1 > C2 > B1 > T2 > B2$$

As shown in Table 5, for each type of dredger, the higher the dredging efficiency, the better the dredging performance, but the greater the impact on the marine environment.

Table 5. The evaluation score of six alternative dredger.

The alternative dredgers	Evaluation score		
	The impact on the marine ecological environment	Dredger performance	Overall
$B1$	79.28	70.94	75.43
$B2$	51.16	71.01	60.31
$C1$	87.95	71.71	80.46
$C2$	79.48	71.79	75.93
$T1$	83.29	76.21	80.03
$T2$	55.10	76.29	64.87

The evaluation results of dredger are only applicable to the current engineering background. For the specific engineering situation, the dredger selection model established in this paper can be used to comprehensively select the appropriate dredger.

4 Conclusion

In this paper, on the basis of making clear that TSS generated by dredging is the main pollutant, the calculation method of biomass loss caused by dredging is put forward, and the biomass loss is taken as the evaluation index to establish a dredger selection model combining the impact of TSS generated by dredging on marine ecological environment and dredger performance. Finally, the dredger selection model is applied and

analysed combined with the practical dredging engineering. Some main conclusions can be drawn, as follows.

(1) The dredger selection model applies the biomass loss caused by dredging to the selection of dredger, which provides a scientific basis for the construction of ecological port and the protection of marine environment.

(2) Considering that the selection of dredger is subjective to some extent, the fuzzy synthetic evaluation method based on norm grey relational grade is applied to dredger selection, which effectively avoids the influence of human factors on the calculation results.

(3) Based on the practical dredging engineering, this paper analyses the impact of different dredging efficiency of three types of dredgers on biomass loss, but the impact of dredgers on marine organisms is related to factors such as seabed sediment and current, so the evaluation results of dredger selection are different due to different engineering situation.

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