

## Article

# Integrating Island Spatial Information and Integer Optimization for Locating Maritime Search and Rescue Bases: A Case Study in the South China Sea

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**Abstract:** Maritime search and rescue (SAR) operations are critical for ensuring safety at sea. Islands have been considered as feasible solutions for the construction of new maritime SAR bases to improve the capacity of SAR operations in remote sea areas. This paper proposes a new framework, based on island spatial information, for determining the optimal locations for maritime SAR bases. The framework comprises four steps. First, candidate islands for the construction of maritime SAR bases are selected. Second, the potential rescue demand is estimated by employing ship location data and marine incident data. In the third step, the response time from candidate islands to any site at sea is calculated, with explicit consideration of the impact of sea conditions on the ship's speed. Fourth, the final island locations are proposed by solving the maximal covering location problem (MCLP). The proposed framework was applied to the South China Sea. The results showed that there would be a decrease of 1.09 h in terms of the mean access time for the South China Sea if the six selected island bases were constructed, whilst the primary coverage increased from 62.63% to 80.02% when using a 6-hour threshold. This new framework is expected to contribute to improvements in safety at sea and should be applicable to any sea area where the construction of island rescue bases is being considered.

**Keywords:** maritime search and rescue; island; base location selection; integer optimization; South China Sea

#### 1. Introduction

Maritime transportation is associated with various types of risk, and many accidents occur at sea in navigational areas, such as collisions, groundings, sinkings, and fires [1]. The consequences of accidents can be high in terms of the loss of life, injuries, property damage, and environmental degradation. Maritime search and rescue (SAR) is the most important step in the maritime accident response, with the aim of rescuing people in distress or danger at sea, assisting ships in difficult situations, accident prevention, and patient transportation [2–5]. In order to rescue people fallen overboard quickly,



response time is a key factor in maritime SAR, and shorter response times correspond to greater chances for survival [6]. For a quick responding SAR system, it is always a priority to optimize the efficiency of resource utilization, such as through finding the best locations for maritime SAR bases [7].

Maritime SAR bases have been established in many countries. However, most bases are located along coastal areas; consequently, rescue ships may not arrive at the accident site in remote sea areas within an effective rescue time [8]. In this context, islands are being considered as suitable base sites to improve the capacity of maritime SAR in remote sea areas [6]. For example, since 2010, the countries around the South China Sea, including China, Vietnam, Malaysia, and the Philippines, have built artificial islands and announced that these artificial islands are being constructed for the provisioning of international public services such as maritime SAR [9]. Generally, greater numbers of maritime SAR bases spread out in multiple locations would effectively shorten SAR response times. However, the available budget for such bases is limited, and thus, some kind of trade-off is inevitable [10]. Consequently, the optimal deployment of limited rescue bases over a large area is vital for maintaining cost-effective maritime SAR systems and efficient emergency responses.

Commonly, research on maritime SAR can be divided into the following two groups [11]: operational support [12–15] and strategic planning [16–18]. The former concerns methods where real-time SAR operations are supported by computational methods, e.g., to detect a missing object at sea in the minimum possible time [11]; the latter concerns strategic planning that aim to evaluate the overall performance of the SAR response system, e.g., to obtain maximal coverage of a sea area with the minimum required number of rescue units [18]. Furthermore, there are some research projects that have focused on optimal plans for siting maritime SAR resources and related decisions. For instance, Norrington et al. [19] used a Bayesian Network methodology to assess the reliability of SAR operations. Goerlandt et al. [20] proposed a simulation model for evaluating the performance of a SAR system. Ai et al. [21] developed an integrated model considering both the location-allocation of maritime emergency supply reserve bases and the configuration of salvage vessels. Pelot et al. [22] examined the optimal locations of rescue vessels in Atlantic Canada to ensure the maximum likelihood of saving lives and secondarily of mitigating property loss using available resources. More recently, Razi and Karatas [17] proposed the Incident Based-Boat Allocation Model (IB-BAM), a multi-objective model designed to allocate SAR boats depending upon a set of criteria. Similarly, Akbari et al. [23] applied a modular capacitated multi-objective model to optimize the location-allocation of maritime search and rescue vessels with regard to several criteria, including primary and backup coverage and mean access time. Akbari et al. [24] further developed an integer optimization model to determine the best possible type of equipment and the optimal locations of the Coast Guard vessels. In addition, Akbari et al. [7] presented two integer-linear optimization models with different objectives, namely, maximizing primary coverage and minimizing mean access time, to solve the maritime SAR location problem and applied the models to a case study in the Atlantic region of Canada. However, no study has investigated the optimal locations of islands for constructing maritime SAR bases, which could potentially lead to great improvements in the capacity of maritime SAR in remote sea areas.

In light of this, this paper propose a new framework for determining the best locations for maritime SAR bases based on island spatial information to improve the capacity of maritime SAR. Moreover, the potential demand for rescue activities is estimated by using ship location data and location data for marine casualties and incidents. The problem of finding the optimal locations of islands for maritime SAR bases is solved by the maximal covering location problem (MCLP) model. This new framework is then applied to the South China Sea, which contains over 250 small islands, atolls, cays, shoals, reefs, and sandbars. The findings of this study can help policy makers to understand and improve the capacity of maritime SAR in the South China Sea, and thus create better strategic plans for maritime SAR operations.

The remaining parts of this paper are organized as follows. In Section 2, the method used in this study is introduced, and this is followed by a case study and discussion of the study area and data sets

in Section 3. Sections 4 and 5 present the results and discussion, respectively. Section 6 summarizes the conclusions, describes the limitations of this study, and presents suggestions for future studies.

#### 2. Methodology

The methodological framework for selecting optimal locations for maritime SAR bases based on island spatial information is shown in Figure 1. In Step 1, candidate islands are selected for maritime SAR bases. Step 2 estimates the potential demand. In Step 3, the response time from candidate islands to any site at sea is calculated. The optimal locations for constructing maritime SAR bases are selected in Step 4.



Figure 1. Framework for selecting the location for a maritime search and rescue base.

#### 2.1. Selection of Candidate Islands for a Maritime SAR Base

In the location-allocation problem, potential sites can be categorized into two types: discrete or continuous [25]. A discrete problem confines potential facilities at a finite number of points in advance, whereas a continuous problem allows candidate locations to be anywhere in a continuous space [26,27]. The island rescue base siting problem can be considered as a discrete location problem. Generically, a finite number of islands can all be selected as candidate sites for constructing maritime SAR bases. Furthermore, some certain conditions can be used to select more suitable candidate locations [28]. For example, the overall building process should be faster, more reliable and more cost effective. In this study, the developed islands are selected as the potential location of the candidate bases from a cost–benefit perspective.

Remote sensing technique, with the advantage of large information capacity, huge observation scope, high accuracy, has become a primary tool for island monitoring and evaluation [29]. In this context, remote sensing image of the island is applied to identify the candidate islands by using visual interpretation. The island is selected as the potential location of the candidate bases if artificial facilities have been built in the island (e.g., port and house). By such an approach, in Step 1, the suitable types of islands that meet the predetermined conditions are selected for the potential construction of maritime SAR bases. Policymakers can adjust the number of potential sites in a discrete location problem according to their own preferences [30].

### 2.2. Estimation of the Potential Demand

A maritime SAR base is expected to provide coverage for a large area of rescue demand. Therefore, it is an important step to estimate the potential incident locations in the future that could represent the stochasticity of demand before location selection [28]. Generally, the number of ship accidents is

proportional to the ship density [31]. Clearly, with greater ship densities, there will be higher risks to safe navigation. In addition, although maritime accidents may occur at any site, some places have high levels of accident risk. The historical data are a strong predictor of future occurrences of incidents [7]. But this approach ignores potential demand for the areas that have not experienced any incidents in the recorded past. In this context, an index of combined historical accidents and distributions of ships was developed to estimate the potential rescue demand, and the index is expressed as follows:

$$w_{i} = \frac{D_{i}^{\text{incident}} * D_{i}^{\text{ship}}}{\sum D^{\text{incident}}}$$
(1)

where  $w_i$  represents the amount of demand at point i,  $D_i^{\text{incident}}$  represents the incident density at point i,  $D_i^{\text{ship}}$  represents the ship density at point i, and  $D^{\text{incident}}$  represents the incident density in the South China Sea.

The density and distribution of ships and incident points can be generated with a kernel density analysis [7].

#### 2.3. Calculation of the Response Time of the Rescue Vessel

In order to calculate the navigation time of the rescue vessel from SAR base to incidents' locations, the actual ship speed should be considered. It is the involuntary ship speed reduction due to oceanographic conditions [32]. Because of the added resistances induced by weather conditions, e.g., wind, waves, or ocean currents, the actual ship speed is usually lower than the nominal one [33]. In this study, the added resistances caused by waves and wind are considered because waves and wind are the main types of resistance phenomena encountered at sea [34]. To this end, the added resistance model developed by Mannarini et al. [35] is applied. Specifically, this model is a general one, independent of specific ship features [36]. The actual ship speed V<sub>a</sub> can be calculated by the following equation:

$$V_a = V(H, \Theta) = V_0 - f(\Theta) \cdot H^2$$
<sup>(2)</sup>

where  $V_a$  is the actual ship speed,  $V_0$  is the ship speed in calm water, and f is the coefficient; the values of coefficient f are reported in Table 1. Additionally, H is the significant wave height, and  $\Theta$  is the ship-wave relative direction as shown in Figure 2.

Θ	Configuration Name	f [kn/ft <sup>2</sup> ]
$0^{^\circ} \le \Theta \le 45^{^\circ}$	Following seas	0.0083
$45^{^\circ} < \Theta < 135^{^\circ}$	Beam seas	0.0165
$135^{^\circ} \le \Theta \le 180^{^\circ}$	Head seas	0.0248
Following sea (0deg – 45deg)	Sailing direction	Head sea (135deg – 180deg)

Table 1. Values of the coefficient f.

Beam sea (45deg – 135deg)

Figure 2. The ship-wave relative direction.

The response time for maritime SAR can be understood as the time that it takes to reach an incident site. Intuitively, a short response time would potentially improve the survival of victims in a maritime accident. In this context, the response time for maritime SAR is defined as the minimum travel time from all rescue bases to the incident site. It is a cumulative cost time, which is calculated for each cell by summing up the costs of moving from a cell center to another via least-cost route. The time required to cross a cell is calculated with the equation: T = L/V, where L is distance, V is actual ship speed and T is time. Distance is the cell resolution. As shown in Figure 3, when crossing a cell costs 0.65 or 0.92, the cost distance algorithm determines the minimum cost path by moving to the neighboring cell with the lowest value [11].

0.65	*	0.65	1.30
0.92	0.65	0.92	1.57
1.57	1.30	1.57	1.84
2.22	1.95	2.22	2.49
↓ 2.22=0.65+0.65+0.92			

**Figure 3.** The response time for maritime SAR. It is calculated for each cell by summing up the costs of moving from a cell center to another through least-cost route.

The calculation procedure consists of the following two steps: (a) calculation of the minimum travel time for each rescue base of a particular country to the incident site; (b) selection of the minimum value among the minimum travel times as the final response time for maritime SAR. The response time can be calculated with the following equations:

$$T_{B_k S_j} = Min \sum_{i=1}^{n} \frac{L_i}{V_i}$$
(3)

$$T_{rt} = Min\left(T_{R_k S_j}\right) \tag{4}$$

where  $T_{B_kS_j}$  is the minimum travel time from the rescue base  $B_k$  to the incident site  $S_j$ ,  $L_i$  is the distance crossing cell i,  $V_i$  is the actual ship speed crossing cell i, and  $T_{rt}$  is the response time for maritime SAR.

#### 2.4. Selection of the Optimal Location

In a location-allocation problem, the typical framework used in many studies is to develop a mathematical model that tries to maximize services with respect to resource constraints, or to minimize costs with respect to minimum service constraints [36,37]. Finding optimal base locations is a typical location-allocation problem. The optimal island sites for constructing maritime SAR bases are selected by solving the MCLP, which aims to achieve maximum coverage. The task of the MCLP is to locate a fixed number of facilities to provide as many services as possible within a pre-specified distance/time [38]. The MCLP has been widely used in many applications [39], including emergency facility siting [40,41], ground-based precipitation station siting [42], transportation infrastructure siting [43], etc. According to the MCLP suggested by Church and Revelle [44], the following model is proposed for selecting the final rescue bases with the goal of maximizing coverable demands within the predetermined travel time:

$$Max z = \sum_{i \in I} w_i y_i$$
(5)

s.t.

$$y_i - \sum_{j \in N_i} x_j \le 0 \ (i \in I) \tag{6}$$

$$\sum_{j \in J} x_j = P \tag{7}$$

$$N_i = \left\{ j \in J | t_{ij} \le T \right\} \ (i \in I; j \in J) \tag{8}$$

$$x_{j} = \begin{cases} 1, & \text{if site j is selected as a station} \\ 0, & \text{otherwise} \end{cases}$$
(9)

$$y_{i} = \begin{cases} 1, & \text{if the demand from point i is satisfied} \\ 0, & \text{otherwise} \end{cases}$$
(10)

where i is the index of demand points, I is the set of demand points, j is the index for potential rescue bases, J is the set of potential rescue bases,  $t_{ij}$  is the response time between location i and j, T is the maximum access time for acceptable coverage,  $N_i$  is the set of rescue stations j within time T from demand point I, P is the number of islands to be selected as rescue bases,  $x_j$  is a binary variable for base j, and  $y_i$  is a binary variable for every cell i.

The objective function (5) maximizes the demand with primary coverage. Constraint (6) implies that at least one maritime SAR base must be within T from i to meet the demands of site i. The maximum number of island rescue bases is limited by constraints (7). Constraint (8) means that the time between demand site i and supply site j that meets the demand site i is below the maximum access time T. Constraints (9) restricts  $x_j$  to become one only if island j is selected as a base. Constraints (10) restricts  $y_j$  to become one only if there is a base j that can reach cell i in time.

#### 3. An Illustrative Case Study

To demonstrate the usefulness and effectiveness of the proposed framework for solving the location selection of maritime SAR base site, this subsection presents a case study.

#### 3.1. Study Area

The South China Sea (SCS) is a large, semi-enclosed, tropical, marginal sea, and it extends from 23° N to 3° S and from 102° E to 121° E in the tropical and subtropical western Pacific Ocean, as shown in Figure 4. The SCS has an area of 3.3 million km<sup>2</sup> excluding the gulfs of Thailand and Tonkin, and it is bordered by the Chinese mainland and Taiwan to the north, the Philippines to the east, Vietnam to the west, and Brunei, Singapore, and Malaysia to the south [45]. It connects with the eastern part of the China Sea, the Indian Ocean, and the Pacific Ocean through the Taiwan Straits, the Straits of Malacca, and the Luzon Straits, respectively [46]. The average depth of the water is 1212 m, and the maximum depth is over 5000 m [47]. The SCS contains over 250 small islands, atolls, cays, shoals, reefs, and sandbars that can be divided into the following four regions: Dongsha Islands, Xisha Islands, Zhongsha Islands, and Nansha Islands [48].



Figure 4. Location of the South China Sea (SCS), and distribution of seaports around the SCS.

In the SCS, as one of the heaviest traveled areas of sea in the world, over half of the world's merchant fleet passes through its waters [45,49]. This area is known as a "dangerous area", which continues to pose various threats from factors such as shallow water, rocks, coral reefs, typhoons, pirates, and so on [6]. Therefore, ship accidents occur frequently in this region. In fact, shipping accident losses in the SCS from 2006 to 2015 were the largest compared with other regions around the world [50]. The coastal states are responsible for providing maritime SAR services in the SCS.

#### 3.2. Data and Preprocessing

The data used in this study are as following:

(1) Marine environment data. The ERA-Interim is the latest global atmosphere numerical reanalysis data set, and it was created by the European Centre for Medium-Range Weather Forecasts (ECMWF) [51]. In this paper, wave field data ( $0.125^{\circ} \times 0.125^{\circ}$ ) including significant wave height and wave direction data recorded from 2008 to 2017 were collected from the ECMWF ERA-Interim reanalysis materials.

(2) Ship location data. The Automatic Identification System (AIS) is an automatic reporting system widely installed on ships by reporting their kinematic and identity information continuously (e.g., ship's position, and course) [52].International voyaging ships with a gross tonnage (GT) of more than 300, passenger ships of all sizes, and inland ships with a GT of more than 100 are all required to be equipped with the AIS [53]. In this study, the information for ship locations on the SCS in 2016 was obtained from the AIS data, which, besides location data, also included the ship name, ship speed over ground, ship type, position, etc.

(3) Marine casualty and incident data. The data on marine casualties and incidents in the SCS from 1988 to 2017 were collected from the Global Integrated Shipping Information System (GISIS) of the International Maritime Organization.

(4) Seaport data. The coast guard, as a maritime security organization of a particular country, mainly is responsible for maritime SAR. Governments usually construct ports to serve as bases for the vessels involved in SAR activities. In this paper, 36 civil or military seaports were used as the bases for SAR vessels, and these belonged to China, the Philippines, Vietnam, Singapore, and Malaysia, as

shown in Figure 3. The data for seaports were collected from open data on government web pages (http://www.nh-rescue.cn/) and related studies [53–56].

(5) Island data. The small islands, atolls, reefs, and banks in the SCS (hereinafter referred to as islands) were digitized manually from TIANDITU (http://map.tianditu.gov.cn/). In addition, remote sensing images of the island (GF-2 and WorldView-2 images) were collected.

Figure 5 illustrates the overall process of our analysis. First, all non-spatial data (including ship location data, marine casualty and incident data, seaport data, and island data) were represented in vector format, and reprojected to the geographic coordinate system with the WGS-84 datum. Second, the annual average significant wave height and wave direction of all grid cells were obtained based on the wave field data, which were then used to calculate the response time of the rescue vessel. Third, the density and distribution of ships and incident points can be generated with a kernel density analysis before estimating the potential rescue demand. Finally, after selecting the candidate islands, the MCLP method was applied to select optimal SAR bases.



Figure 5. Flowchart diagram of location selection.

## 4. Results

#### 4.1. Candidate Islands for Maritime SAR Bases

The SCS contains over 250 small islands, atolls, cays, shoals, reefs, and sandbars, which can be considered as potential sites for maritime SAR bases. In particular, some islands or reefs have been developed into artificial islands by the countries around the SCS. These islands, such as Spratly Island and Subi reef, have a seaport and airport, which can already be used for maritime SAR services. In this study, remote sensing images of the island (GF-2 and WorldView-2 images) were collected. The developed islands in the SCS were selected as the candidate islands from a cost–benefit perspective. Consequently, 24 artificial islands obtained from remote sensing visual interpretations were used as candidate islands for maritime SAR bases, as shown in Figure 6.



Figure 6. The locations of candidate islands in the South China Sea.

## 4.2. Potential Demand

In this study, AIS data in 2016 and data on marine casualties and incidents from 1988 to 2017 were collected and analyzed. The density and distribution of the potential rescue demand in the SCS were generated by using the "Spatial Analyst Toolbox" option of ArcGIS. Figure 7 shows the potential incident density in the SCS in the future. The color shades represent the different density values of potential incidents (the deeper the color, the higher the density of potential incidents). The areas with higher incident density were located along two sailing route from the Singapore Strait to the Taiwan Strait and Luzon Strait. These sailing routes are among the busiest shipping lanes in the world [6], and they contain a large portion of the total traffic volume in the SCS. As mentioned by Wang et al. [45], the sailing routes of the SCS are frequently threatened by both natural and human factors such as extreme weather, piracy, and armed robbery, as well as various navigational hazards. These threats have resulted in some serious SCS maritime incidents including the loss of life and property, and environmental disasters [57].



Figure 7. The potential demand density in the South China Sea.

#### 4.3. Optimization Solutions

According to Shi et al. [6], the displacements of offshore patrol vessels are usually larger than those of inshore patrol boats (over 1000 tons). The top speed of these patrol vessels can reach 20–30 knots, and the range is over 3000 nautical miles. Therefore, in this study offshore patrol vessels were selected as the principal searchers and rescuers, and the top speed of a ship in calm water was set as 30 knots. In addition, the maximum access time in this study for an acceptable level of primary coverage was considered to be 6 h [7]. The MCLP model was solved by using commercial optimization software, Lingo (version 16.0).

The optimal solutions found for the different numbers of island bases (P) were compared to each other, and these results are summarized in Table 2. When the number of islands was set as 1, Yongxing Island was found to be an optimal rescue base. The main reason is that Yongxing Island is located along the sailing route from the Singapore Strait to Taiwan Strait, and thus, an island rescue base in this location could provide coverage for the higher demands. As the number of available island bases increased beyond 6, the rate of change of coverable demands was equal to 0, thus indicating that the primary coverage reaches the maximum capacity when the selected six islands are built as rescue bases. The addition of any other island bases will not lead to an increase in new coverage for the sea area.

Number (P)	Island Name	Rate of Change of Coverable Demands, $\frac{(Z_{i+1}-Z_i)}{Z_i}$ (%)
1	Yongxing Island	-
2	Yongxing Island; Swallow Reef	50.47
3	Yongxing Island; Spratly Island; Mischief Island	26.41
4	Yongxing Island; Spratly Island; Mischief Island; Southwest Cay	19.10
5	Yongxing Island; Spratly Island; Mischief Island; Southwest Cay; Swallow Reef	14.28
6	Yongxing Island; Spratly Island; Mischief Island; Southwest Cay; Swallow Reef; Fiery Cross Island	1.98
7–24	-	0

Table 2. The optimal solutions for the different number of island bases.

Among various factors relevant to emergency service station locations, access and service coverage are the most widely used criteria when measuring emergency service system performance [58,59]. In the proposed model, the former is defined by the minimum mean access time from all rescue bases to the incident site, and the latter is represented by the proportion of all calls that can be responded to within a predefined threshold of time that was set to 6 h in this study. As shown in Table 3, it can be observed that the mean access time declines with the increase of P. The results show the average access is improved when more island bases are sited. When P was set as 0, the existing inshore base covered an estimated 62.63% of the SCS, this illustrating the necessity for building other island bases. Consequently, there would be an estimated decrease of 1.09 h in the mean access time following the construction of six island rescue bases, whilst the primary coverage would increase from 62.63% to 80.02%.

Number of Islands	Primary Coverage (%) <sup>1</sup>	Mean Access Time (hour)
0	62.63	5.15
1	66.57	4.79
2	70.23	4.57
3	74.11	4.32
4	77.33	4.15
5	78.19	4.09
6	80.02	4.06

Table 3. Comparison of the maximum coverage solutions.

<sup>1</sup> Access within six hours.

Figure 8 shows the response time map with the maximal covering solution's arrangement where the number of islands (P) to be selected as rescue stations increased from 0 to 6. The model was solved by assuming no existing island bases, i.e., P = 0. It was obvious that the rescue bases were fairly evenly distributed spatially, with service coverage delineated by the isotime curve. However, the response time for remote sea areas needs to be increased, especially in the Zhongsha Islands sea area (more than 12 h). If a rescue base were to be built at Yongxing Island, the response time to the Zhongsha Islands sea area could be reduced (see P = 1). Furthermore, the Nansha Islands sea area would benefit the most, since most island bases would be built in this area. In addition, the model results indicated that approximately 20% of the area could not be accessed within 6 h, and these places were located in the northeast and southwest area of the SCS.



**Figure 8.** Response times with the maximum coverage solution arrangements. The purple triangles represent the inshore SAR bases, and the green pentagons represent potential island bases.

# 5. Discussion

Growth in ship traffic and construction of offshore installations have important effects on navigation safety [60,61]. It is significant that early planning takes place to ensure that safety at sea and navigation requirements are adequately addressed [62]. The establishment of an effective SAR system is an important way to mitigate the damage caused by marine incidents. Compared with traditional emergency systems, the complexity of maritime natural conditions brings about

a number challenges for the establishment of a maritime SAR system [21]. It is well known that increasing available resources can help to effectively shorten the response times, but the budget is always limited. Therefore, the location of emergency bases, the allocation of emergency supplies, and the configuration of salvage vessels are always major concerns. In particular, the capacity of SAR systems in remote sea areas needs to be improved [8]. Therefore, a new framework for determining the best locations for maritime SAR bases was presented on the basis of island rescue bases. The case study in the SCS demonstrates the practicability and feasibility of the model and the solution method. Generally, the coastal states should be prepared to respond when a ship requests assistance [5]. As previously mentioned, China, Malaysia, Vietnam, and the Philippines are coastal countries with extensive coastlines and large shipping fleets. These coastal countries have been under extreme pressure to provide safe and secure navigation through the SCS [49]. Therefore, many bases along the coast were built for SAR activities in this region. However, the different distributions of bases in a particular country result in different SAR capabilities. The results show that only the offshore area can be arrived at in a short response time with the current distribution of coastal ports built for SAR activities. After SAR bases were constructed on islands in the modeling research, the SAR system showed improvements to different degrees. However, there remained approximately 20% of the area that could not be accessed within 6 h, and these places were located in the northeast and southwest areas of the SCS. Hence, SAR capabilities need to further be improved in the region. One possible measure would be to improve ship performance, such as a SAR ship's speed.

In addition, there are possible delay times of operating of SAR vessels in jurisdictions of other coastal states. Therefore, effective communication and cooperation among the different partners and stakeholders is a vital factor for success in every SAR operation [63]. The response time in this study were obtained under a condition of cooperation among the states around the SCS (China, the Philippines, Vietnam, Malaysia, etc.). In this case, the possible delay times of operating of SAR vessels could be ignored. In fact, maritime security problems involving transboundary problems cannot be solved by any one country [49,64]. Therefore, some sort of cooperation mechanism has to be implemented. China launched the ASEAN-China Maritime Cooperation Fund with a budget of \$500 million in 2011, in which SAR cooperation was highlighted [65]. A series of joint search and rescue exercises have been held. However, SAR cooperation faces a series of problems. For example, countries compete against each other to achieve their own interests rather than obtaining the possibility of a "win-win" outcome achieved through cooperation. For some countries around the SCS, the proposed international coordination for maritime security is a lesser priority than other issues such as controlling ocean resources [49]. Therefore, more effort from coastal countries would be useful for improving the SAR system in the SCS.

Commonly, rescue vessels are the main force in maritime SAR. When ships have to send out SOS signals for rescue, some adjacent ships or SAR organizations which receive SOS will send patrol ships or rescue vessels to accident water area [6]. In fact, other equipment also provides important supports in such missions. For example, modern SAR aircraft and helicopter provide an enormous advantage due to their range, flexibility, state-of-the-art equipment and capacity in maritime SAR [66]. Unmanned aerial vehicle that does not require human pilot on board can also perform the search task of a SAR mission [67]. The deployment of different rescue equipment in the South China Sea can improve the flexibility of maritime SAR. However, these benefits come at a cost. High costs associated with the purchasing, maintaining and operating a SAR helicopter and limited flight times per sortie limit their application. In addition, adjacent ships in the accident water area may quickly take part in maritime SAR operations, but the participation of adjacent ship is random. Therefore, it is always a priority to find the best locations for maritime SAR bases equipped with rescue vessels.

Input data quality can influence the results of location selection in a number of ways. An available and valid data source can enhance maritime search and rescue processes [68]. The input data in this study can be divided into two categories after considering the nature of data sources. The first category is vector data including seaport location, island location, incident location and ship location.

The positional errors of some points such as island location could influence the accuracy of response time of the rescue vessel. Therefore, it is important to perform quality check to ensure uncertainties are minimized. The second category is raster data, including wave field data. In general, a higher resolution data can improve the quality of data and the model's accuracy. However, it is not feasible to improve data accuracy indefinitely, due to cost restraints, and the technical limitations of the data collection technology [69]. Therefore, wave data with a resolution of 0.125° was chosen for response time calculations, which is a suitable trade-off between computation time and accuracy. In addition, the coverage scope of the raster data should be intersecting with the vector data (e.g., seaport location, island location), otherwise the response time of this point cannot be calculated.

#### 6. Conclusions

Maritime search and rescue (SAR) services remain fundamental to the safety of humans, property, and the marine environment. Efficient SAR systems can greatly reduce the loss of lives and lessen economic damage. This paper has proposed a framework for optimally locating maritime SAR bases to improve the capacity of SAR efficiently. The novelty of this framework lies in the integration of spatial information and integer optimization for determining the optimal locations for maritime SAR bases in the marine environment. Specifically, the candidate islands were identified by visual interpretation methods. Moreover, the response time of the rescue vessel was calculated using cost distance that the wave height and direction are considered, which improves the accuracy of response time. Furthermore, an index of combined historical accidents and distributions of ships was developed to estimate the potential rescue demand, by which the stochasticity of demand is better reflected. Then, the maximal covering location problem (MCLP) method was applied to select optimal SAR bases. This methodology was applied to South China Sea, and the optimum locations for maritime SAR bases were identified successfully. The results show there would be a decrease of 1.09 h in the mean access time for the South China Sea following the construction of six island rescue bases, whilst the primary coverage would increase from 62.63% to 80.02% when using a 6-hour threshold. Policymakers can choose to apply the framework in accordance with their policy purposes.

In this research, there were several limitations encountered. First, the response time was obtained under a condition of cooperation among the states around the SCS (China, the Philippines, Vietnam, Malaysia, etc.), while joint search and rescue is still in its infancy. Therefore, future work should concentrate on investigating the performance of the rescue vessel under different conditions. Second, offshore installations, e.g., wind mill parks, oil rigs etc., may support maritime SAR; this too warrants a topic for further research and development. Third, all rescue bases were regarded as the same in this study. The differences in search and rescue equipment of island bases should be considered in future work. In summary, the proposed framework was found to be useful for determining the best locations for constructing SAR bases and further research is being planned to improve upon the model.

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