Security risk assessment and visualization study of key nodes of sea lanes: case studies on the Tsugaru Strait and the Makassar Strait

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Abstract

Key nodes of sea lanes are important hubs for global trade and cargo transportation and play important roles in ensuring the safety of maritime transportation and maintaining the stability of the global supply chain. The safety guarantee of key nodes of sea lanes is facing more risks and higher requirements currently because the global shipping industry is gradually recovering. This paper focuses on key nodes of sea lanes, conducting regional security risk assessment and risk spatial scale visualization. A set of security risk assessment and visualization study methods for key nodes of sea lanes is constructed, which includes constructing a security risk assessment index system of key nodes of sea lanes with 25 indicators selected from three risk categories (hazard, vulnerability and exposure, and mitigation capacity) and using geospatial analysis to form the multi-criteria spatial mapping layers and then creating comprehensive risk layers to realize the risk visualization in the strait area by weighted overlaying based on the combined weights calculated by Analytic Hierarchy Process and Grey Relational Analysis. After taking the Tsugaru Strait and Makassar Strait as case studies, the results show that the comprehensive risk layers can effectively present the spatial distribution of security risks of key nodes of sea lanes, reflecting the spatial changes of risk levels (i.e., very low, low, medium, high and very high) and the methods can precisely identify and analyze crucial factors affecting the security risk of key nodes. These findings may strengthen the risk prevention and improve the safety of the navigation environment in the strait to ensure the safety and stability of maritime trade.

Keywords Key nodes of sea lanes · Security risk assessment · Geospatial analysis · Risk visualization · Risk spatial distribution

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1 Introduction

Cargo transportation by sea accounts for more than 80% of the global shipping of goods (Akyildiz and Mentes 2017) and the maritime transportation which is large-volume and high-efficiency has changed from an oversupply to a shortage due to some objective reasons such as the COVID-19 and supply chain blockages. As the global shipping industry is gradually recovering and the uncertainties and risks of the maritime environment are increasing, maritime transportation requires safer navigation conditions. Key nodes of sea lanes refer to specific sea areas in key geographical locations or with important navigation functions in sea lanes (Lv and Wang 2015), which have crucial effects on the safety of maritime transportation, such as straits and canals. Key nodes of sea lanes are hubs for economic exchanges and transportation and act important roles in ensuring the development of economic and energy, maintaining the stability of the global supply chain and stabilizing the safety of maritime traffic. Once they are blocked, intercepted or forced to change the navigation direction, they will lead to regional and even global logistics paralysis, economic stagnation and energy blockade. For example, the blockage of the Suez Canal in March 2021 had seriously affected the global supply chain (Lee and Wong 2021). Key nodes of sea lanes are facing severe traditional security threats (Bailey 2005.) and non-traditional security threats (Caballero-Anthony 2008; Soomro et al. 2009; Hong 2020), especially the increasingly serious threats of piracy and maritime terrorist activities. As these threats may cause key nodes to meet major impacts and hazards from social and natural aspects such as accidents or blockages, the importance of maintaining the safety of sea lanes and key nodes has become increasingly prominent. By comprehensively grasping basic conditions in the natural and humanity environment of key nodes of sea lanes, it is helpful to accurately understand the geographical location, navigation environment and surrounding situation of important key nodes. Thus, the study can efficiently evaluate the security risks of key nodes of sea lanes and explore the spatial distribution of security risks.

Most studies on the security risk of key nodes of sea lanes focus on the value and risk of energy transportation and marine navigation at key nodes and conducts qualitative analysis and quantitative calculation. These studies mainly take straits as the object, expound the transportation conditions and management measures of specific straits (Rusli 2012), evaluate the vessel traffic safety in certain straits (Qu et al. 2011; Gorcun and Burak 2015), analyze the factors of straits affecting the safety of oil transportation (Zhao and Ji 2011), analyze the vulnerability of key nodes of sea lanes (Li et al. 2018), and explore the threats of pirates and other factors to straits (Shepard and Pratson 2020), etc. The selection range of straits is mostly in the Strait of Malacca (Li 2006), the Strait of Hormuz (Shi and Li 2013b), and the Turkish Strait (Bolat and Jin 2013), among which the Strait of Malacca has been valued by most scholars, evaluating its navigable environment (Tian 2011), exploring the cooperation mechanism (Huang 2008), analyzing the situation and breakthrough plan of the “Malacca Dilemma” of China (Zhao 2007). Many scholars have practiced a variety of models and methods to achieve relevant study goals, such as analyzing various factors influencing the safety of straits by the regression model (Uluscu et al. 2009), evaluating the safety status of key nodes by the risk assessment model (Bolat and Jin 2013), the projection pursuit method (Lv and Wang 2015) and the Generalized Analytic Network Process (Liu 2020). The approaches, the TOPSIS-DEA model (Lv and Gao 2015), the two-stage DEA model (Gao and Lv 2017) and the undesired factor slack variable model (Gong and Lv 2017), have been proposed to evaluate the safety guarantee and emergency efficiency. Li (2017) has presented the risk coupling study of key nodes based on the mutation theory.
Jiang and Lv (2019) have conducted a PSO-BP neural network model used for achieving the security risk early warning of key nodes. And the dynamic risk assessment of natural environment has been realized based on Dynamic Bayesian Network (Qian et al. 2020). These models and methods have certain reference basis and practical value for ensuring the security risk of key nodes of sea lanes.

Most researches on key nodes of sea lanes are based on the identification of safety factors, the proposal of countermeasures, the safety of maritime transportation and the emergency efficiency, etc., combining with mathematical models to realize the risk quantification. However, there are few studies on the security risk of key nodes of sea lanes by means of space remote sensing and visualization technology from a geographical perspective. It is urgent to strengthen scientific research on key nodes of sea lanes with the help of relevant technical means (Shi and Li 2013a). And existing researches lack comprehensive analysis of the factors affecting the security risk of key nodes of sea lanes and the comprehensive assessment of the natural and humanity environment risk.

Geospatial analysis can play an important role in overall planning and situation analysis. It provides scientific methods and basis for the ecological carrying capacity evaluation (Meng et al. 2020), the early warning of natural disasters such as typhoons (Hoque et al. 2019), the accident risk hotspot analysis (Yu et al. 2020), and the spatial analysis of sea rescue risk (Liu et al. 2020). Meanwhile, geospatial analysis has combined closely with risk assessment to achieve the spatial multi-criteria assessment of tropical cyclone risk (Hoque et al. 2018; Mansour 2019), the regional risk assessment of major urban disasters (Zhao and Liu 2017), the sustainability risk assessment (Sajjad and Chan 2019) and the spatial multi-criteria evaluation of maritime transport risks in the South China Sea (Zhou et al. 2020). Geospatial analysis can find a wide variety of implementation, which can effectively realize quantitative risk assessment and risk visualization and assist resource allocation and decision-making, but it has not been widely used in marine risk assessment (Vander Hoorn and Knapp 2015).

Inspired by the above studies, this study takes the Tsugaru Strait and Makassar Strait as examples to conduct the regional risk assessment and the spatial scale visualization of security risk by combining with evaluation methods to integrate natural and humanity factors. And thematic maps can be created to fully display the risk status of key nodes with the help of geospatial analysis and mapping tools. Therefore, it is available and efficient to explore the basic situation of key nodes of sea lanes, identify and analyze crucial factors affecting security risks and parse the spatial distribution of security risks of key nodes of sea lanes.

2 Study area

Straits are important parts of key nodes of sea lanes and able to shorten the voyage between continents and control the entry and exit of vessels. Considering the geographical features and the routes of important strategic materials, this study selects the Tsugaru Strait and the Makassar Strait as the study area, the high-utilization key nodes of sea lanes. The major vessels transporting important strategic materials are LNG ships, LPG ships, bulk carriers, oil tankers and container ships. The Tsugaru Strait is the necessary node to cross the Pacific Ocean and travel to and from the Americas. The Makassar Strait is the important nodes to ship between the Pacific and Indian Oceans. The Tsugaru Strait lies between the Hokkaido Island and Honshu Island, whose center coordinates are 41°32.261 N, 140°39.600E.
The strait is regarded as an inter-island strait, which is an ice-free node connecting the Sea of Japan and the Pacific Ocean. The Makassar Strait is located between the Sulawesi Island and Kalimantan Island in the Indonesian archipelago, whose center coordinates are 0°57.495S, 118°27.729E. The strait is also an inter-island strait with sufficient water depths, which is long and narrow connecting the Sulawesi Sea to the north and the Java Sea and the Flores Sea to the south (Fig. 1).

3 Materials and methods

This paper focuses on the security risk of key nodes of sea lanes and explores the risk status and spatial distribution in study areas with the methods of safety risk assessment and visualization. Figure 2 shows the overall framework of security risk assessment and visualization research.

3.1 Security risk assessment

The sources, factors, objects and consequences of security risks of key nodes of sea lanes have been systematically analyzed with the literature and basic investigation.

According to the risk theory, the security risk assessment index system of key nodes of sea lanes has been constructed, integrating the natural and humanity environment information to comprehensively include the factors influencing the security risk. According to the literature and specific data distribution, the risk ranking levels of each indicator have been set according to the literature and specific data distribution.

3.1.1 The construction of index system and data sources

The risk factors of key nodes of sea lanes and their correlations have been identified after comprehensively analyzing the traditional security threats and non-traditional security

Fig. 1 Study area and objects
threats faced by key nodes of sea lanes and clearing the risk sources, factors, objects, consequences and existing researches (Table 1).

In risk theory, hazards are defined as dangerous processes or phenomena that may lead to losses of lives, property damage, environmental pollution and social destruction (UNISDR 2009), which are existing natural and man-made hazards. Vulnerability refers to the degree that is susceptible to the damaging effects of hazards (UNISDR 2009; Hoque et al., 2019) and is related to the exposure of risk elements and the degree to which the environment may be affected by hazards. Exposure is the state in which the subjects are present in hazard zones that may result in loss or damage. Mitigation capacity is defined as the ability of humans to use various measures to mitigate the impact of hazards (UNISDR 2009). Risk (R) is proportional to hazard (H), vulnerability and exposure (V&E), and inversely proportional to mitigation capacity (M), the risk calculation formula is as follows (Mansour 2019; Zhou et al. 2020):

$$ R = \frac{H \times V&E}{M} \quad (1) $$

According to the risk characteristics of hazard, vulnerability and exposure, and mitigation capacity, the first-level indicators in the system to screen risk factors are determined and the cross-integration of nature and humanities is realized, in order to build a complete security risk assessment index system, as shown in Table 2.

### Table 1  Security risk analysis of key nodes of sea lanes

| Risk sources       | Risk subjects        | Risk objects                                      | Risk consequences                                      |
|--------------------|----------------------|---------------------------------------------------|--------------------------------------------------------|
| Natural environment| Vessels at sea       | Sea lanes, personal, vessels, Infrastructure      | Waterway pollutions or blockades, lane congestions, marine accidents, damages to port facilities, damages to infrastructure, losses at sea, casualties |
| Humanity environment| Sea lanes, personal, vessels |                                           |                                                        |
The security risk assessment index system is a layered, multi-factor and fuzzy mechanism coupling system, which integrates multi-source, uncertain natural and humanity environmental information. Most of the natural and humanity environment data come from public datasets, such as the Cross-Calibrated Multi-Platform (CCMP), European Centre for Medium-Range Weather Forecasts (ECMWF) and Global Integrated Shipping Information System (GISIS) and a few need to be measured or consulted in books and literature. According to the specific indicators listed, the representative data of the indicators are selected to obtain the indicator values when the humanity environmental data cover a wide range. For example, the national stability is represented by the data of countries’ regime stability around the strait, which can be obtained from the UCDP/PRIO Armed Conflict Dataset.

According to the open source condition, numerical precision and time interval of each data set, appropriate data sources are selected to ensure the objective and accurate data obtained. The specific data access and time periods for each indicator are shown in Table 3.

### 3.1.2 Data standardization and ranking

#### (1) Data standardization

Data standardization is able to solve the problem which the indicators are difficult to compare in the same system due to their different physical meanings and numerical values. The SAVEE normalization equation (Chen 2011) is used to normalize the quantitative data to make the indicators comparable.

The values of positive factors were standardized to a scale from 0 to 1, and the values of negative factors were standardized to a scale from –1 to 0 using the SAVEE normalization equation. Positive factors mean that numerical increases of factors can add values of the risk of assessment objects, keeping a positive correlation; while the positive negative factor indicates that numerical increases of factors can reduce the risk of assessment objects and the more numerical increases are, the more values will be reduced. The specific equations for determining various factors are as follows:

| Target layer | System layer | Index layer |
|-------------|--------------|-------------|
| Security risk of key nodes of sea lanes | Hazard | Wind, wave, visibility, precipitation, water depth, width, tropical cyclones, temperature, piracy and maritime terrorism, infectious diseases |
| | Vulnerability and exposure | Distribution of obstructions to navigation, distribution of ports and terminals, national stability, political corruption, terrorism, major power intervention, military bases, competitiveness of neighboring countries, diplomatic relations, regional delimitation, strait jurisdiction countries, vessel traffic density |
| | Mitigation capacity | Institutional management strength, legal guarantee, emergency response capability |
| System layer     | Index layer                        | Data access                                                                 | Time periods     |
|------------------|------------------------------------|------------------------------------------------------------------------------|------------------|
| Hazard           | Wind                               | CCMP (https://data.remss.com/ccmp/)                                         | 2009–2018        |
|                  | Wave                               | ECMWF (https://www.ecmwf.int)                                               | 2011–2020        |
|                  | Visibility                         | ECMWF (https://www.ecmwf.int)                                               | 2011–2020        |
|                  | Precipitation                      | ECMWF (https://www.ecmwf.int)                                               | 2011–2020        |
|                  | Water depth                        | The General Bathymetric Chart of the Oceans (https://www.gebco.net/)         | 2020             |
|                  | Width                              | Hifleet Online (www.hifleet.com)                                            | 2020             |
|                  | Tropical cyclones                  | International Best Track Archive for Climate Stewardship                     | 2011–2020        |
|                  | Temperature                        | NOAA OI SST V2 High Resolution Dataset (https://psl.noaa.gov/data/gridded/data.noaa.oisst.v2.highres.html) | 2011–2020        |
|                  | Piracy and maritime terrorism      | GISIS (https://gisis.imo.org/Public/Default.aspx)                            | 2011–2020        |
|                  | Infectious diseases                | World Health Organization (https://covid19.who.int/), World Bank Open Data   | 2020             |
| Vulnerability and exposure | Distribution of obstructions to navigation | Hifleet Online (www.hifleet.com)                                      | 2020             |
|                  | Distribution of ports and terminals | http://ports.com/ . Hifleet Online (www.hifleet.com)                       | 2020             |
|                  | National stability                 | UCDP/PRIO Armed Conflict Dataset (https://ucdp.uu.se/downloads/)            | 2011–2020        |
|                  | Political corruption               | Trading Economics (https://tradingeconomics.com/)                         | 2011–2020        |
|                  | Terrorism                          | The Global Terrorism Database (https://gtd.terrorismdata.com/)              | 2010–2019        |
|                  | Major power intervention           | Fragile States Index (https://fragilestatesindex.org/data/)                | 2011–2020        |
|                  | Military bases                     | Military times, U.S. States Department, Global Security (https://www.globalsecurity.org/military/) | 2017             |
|                  | Competitiveness of neighboring countries | Report on National Competitiveness (World Economic Forum)   | 2010–2019        |
|                  | Diplomatic relations               | Report of Country-risk Rating of Overseas Investment from China (CROIC-JWEP) (2021) | 2013–2020        |
|                  | Regional delimitation              | OpenStreetMap (https://www.openhistoricalmap.org/), ArcGIS Buffer Analysis | 2020             |
|                  | Strait jurisdiction countries      | OpenStreetMap (https://www.openhistoricalmap.org/), ArcGIS Buffer Analysis | 2020             |
|                  | Vessel traffic density             | Hifleet Online (www.hifleet.com), MarineTraffic (https://www.marinetraffi c.com/) | 2020             |
| System layer       | Index layer                          | Data access                     | Time periods |
|--------------------|--------------------------------------|---------------------------------|--------------|
| Mitigation capacity| Institutional management strength     | Qualitative assessment          | 2020         |
|                    | Legal guarantee                       | International Country Risk Guide (https://epub.prsgroup.com/products/icrg/) | 2011–2020    |
|                    | Emergency response capability         | Qualitative assessment          | 2020         |
where $y$ represents the normalized value, $b$ represents the original data of the quantitative indicator, $X$ represents the threshold value set according to the actual situation of the indicator and $K$ represents the dispersion degree of the original data, the greater the dispersion degree is, the larger $K$ will be, whose value is classified in five levels, namely $K = \{1, 2, 3, 4, 5\}$.

(2) Data ranking

The numerical size of the indicators in the index system can reflect the risk of key nodes of sea lanes, and data ranking is the data processing of risk visualization to numerically reflect the risk distribution. By analyzing the relationship between the numerical data distribution, size and risk of each indicator, the spatiotemporal data risks of multi-source, multi-dimensional and uncertain natural and humanity indicators are ranked into five levels, which are “Very low” (Very low, vl), “Low” (Low, l), “Medium” (Medium, m), “High” (High, h) and “Very high” (Very high, vh). Based on the determined relationship, the specific numerical ranking of each indicator corresponding to the five risk levels is shown in Table 4 in detail.

The five risk levels are marked and assigned value, respectively, to facilitate the numerical calculation of risk and data visualization. The specific value assignments are shown in Table 5. The latitude and longitude of data remain the same during the value assignments. In the data processing using MATLAB, the point value of one indicator matching into the corresponding risk levels is marked as the corresponding value. And with the value accumulation in the time period, the point value label is accumulated to distinguish the data of the same indicator. The preprocessed point value is imported into ArcGIS for reclassification on isometric scales and ranked into the corresponding risk level to support to form the multi-criteria spatial mapping layers.

3.1.3 Evaluation methods

Analytic Hierarchy Process (AHP) analyzes the spatial multi-criteria layers through constructing a hierarchical structure with the quantification of the influence of factors per layer on the decision-making target to effectively obtain the weight and ranking of each criterion (Dewan 2013). AHP has been widely used in the risk assessment of natural disasters such as landslides (Castellanos Abella and Van Westen 2007), floods (Chen et al. 2015), earthquakes (Panahi et al. 2013) and tropical cyclones (Hoque et al. 2018). However, AHP allows for the subjective influence from the expert knowledge on determining the weights. Combining with an objective weighting method can make the weight result more scientific. Grey Relational Analysis (GRA), an objective weighting method, uses similarity and dissimilarity to measure the correlation between the reference sequences and comparison sequences, making global comparisons rather than local comparisons with mitigating the influence of subjective parameters (Kocak 2020). This method has been used in many study fields such as environmental...
Table 4  The specific numerical ranking of the indicators corresponding to the risk levels

| System layer                  | Index layer          | Very low | Low    | Medium | High    | Very high |
|-------------------------------|----------------------|----------|--------|--------|---------|-----------|
| Hazard                        | Wind (m/s)           | <5.4     | 5.4–8  | 8–10.8 | 10.8–13.8 | ≥ 13.8    |
|                               | Wave (m)             | <1.25    | 1.25–2.5 | 2.5–4 | 4–6     | ≥ 6       |
|                               | Visibility           | <0.2     | 0.2–0.4 | 0.4–0.6 | 0.6–0.8 | ≥ 0.8     |
|                               | Precipitation (mm/day)| 0–0.01  | 0.01–0.025 | 0.025–0.05 | 0.05–0.10 | ≥ 0.10    |
|                               | Water depth (m)      | <(-250) | (-250)–(-150) | (-150)–(-50) | (-50)–(-10) | ≥ (-10)    |
|                               | Width (nm)           | ≥ 60     | 48–60  | 36–48  | 24–36   | < 24      |
|                               | Tropical cyclones (number) | < 10 | 10–30  | 30–40  | 40–50   | ≥ 50      |
|                               | Temperature (℃)      | <29      | 29–31  | 31–33  | 33–35   | ≥ 35      |
|                               | Piracy and maritime terrorism (number) | < 2 | 2–3  | 3–4  | 4–5  | ≥ 5 |
|                               | Infectious diseases (%) | 0 | 0–2.5 | 2.5–5 | 5–7.5 | ≥ 10 |
| Vulnerability and exposure    | Distribution of obstructions to navigation (nm) | ≥ 5 | 4–5 | 3–4 | 2–3 | 0–2 |
|                               | Distribution of ports and terminals (nm) | ≥ 12 | 9–12 | 6–9 | 3–6 | 0–3 |
|                               | National stability (number) | < 1 | 1–10 | 10–20 | 20–30 | ≥ 30 |
|                               | Political corruption | 0–20 | 20–40 | 40–60 | 60–80 | 80–100 |
|                               | Terrorism (number)   | <200    | 200–400 | 400–600 | 600–800 | ≥ 800 |
|                               | Major power intervention | 0–2 | 2–4 | 4–6 | 6–8 | 8–10 |
|                               | Military bases (km)  | ≥ 3036  | 2277–3036 | 1518–2277 | 759–1518 | <759 |
|                               | Competitiveness of neighboring countries | 80–100 | 60–80 | 40–60 | 20–40 | 0–20 |
|                               | Diplomatic relations | ≥ 0.8 | 0.6–0.8 | 0.4–0.6 | 0.2–0.4 | < 0.2 |
|                               | Regional delimitation (nm) | ≥ 48 | 36–48 | 24–36 | 12–24 | 0–12 |
|                               | Strait jurisdiction countries (nm) | 0–12 | 12–24 | 24–36 | 36–48 | ≥ 48 |
|                               | Vessel traffic density (route/0.31km2/year) | < 5 | 5–26 | 26–42 | 42–271 | ≥ 271 |
| Mitigation capacity           | Institutional management strength | 8–10 | 6–8 | 4–6 | 2–4 | 0–2 |
|                               | Legal guarantee      | ≥ 0.8   | 0.6–0.8 | 0.4–0.6 | 0.2–0.4 | < 0.2 |
|                               | Emergency response capability | 8–10 | 6–8 | 4–6 | 2–4 | 0–2 |
pollution assessment (Li et al. 2015), water quality improvement (Deng 2019) and soil erosion (Pandey et al. 2022). The combination of AHP and GRA can effectively evaluate and optimize the complex uncertainty among the multi-criteria in a given system. Therefore, the weights of the security risk assessment system for key nodes of sea lanes are determined by the group methods of AHP and GRA.

(1) Description of the AHP

AHP is a decision analysis method that combines qualitative and quantitative methods to solve complex multi-objective problems (Lee et al. 2020). In this study, three hierarchical structure models are required based on the hazard, vulnerability and exposure, and mitigation capacity layer, respectively, to facilitate the risk mapping of multi-criteria layers. Then, a pairwise comparison matrix A is created with the criterion scores. The indicator weight $W_i$ can be calculated by normalizing eigenvectors corresponding to the largest eigenvalue $\lambda_{max}$ of A. Then, the consistency check comes behind, which is obtained by the following formula:

$$CI = \frac{\lambda_{max} - n}{n-1}; \quad \text{and} \quad CR = \frac{CI}{RI}$$  \hspace{1cm} (4)

where $n$ is the number of indicators in each hierarchical structure, CI is the consistency indicator, RI is the average random consistency indicator and CR is the consistency ratio. When CR $< 0.1$, A will pass the one-time test.

(2) Description of the GRA

GRA is a multi-factor statistical analysis method (Lin et al. 2019), which is based on the sample data of factors and uses the grey relation to describe the strength, size and order of the relationship between factors. More specifically, the reference sequence $X_0$ that reflects the characteristics of the system behavior and the comparison sequence $X_j$ that affects the system behavior need to be determined firstly. Then, the grey correlation coefficient $\xi(x_j)$ is calculated as:

$$\xi_{0j} = \frac{\Delta(min) + \rho \Delta(max)}{\Delta_0(k) + \rho \Delta(max)}$$  \hspace{1cm} (5)

where $\rho$ is the resolution coefficient, whose value is generally between 0 and 1, usually 0.5; $\Delta(min)$ is the second-level minimum difference; $\Delta(max)$ is the maximum difference between the two levels; and $\Delta_0(k)$ is the absolute difference between each point on the curve of $X_j$ and that on the curve of $X_0$.

After computing the gray relational grade $r_j$, the relation of the subsequences to the parent sequence is arranged in order of sizes to form an relational sequence, marked as $\{X\}$. The $r_j$ is computed as:

| Table 5 Value assignment for the risk levels |
|-------------------------------------------|
| Risk levels       | Very Low | Low | Medium | High | Very High |
| Value assignment  | 1        | 2   | 3      | 4    | 5         |

Table 5 Value assignment for the risk levels
where \( r_j \) is the gray relation between \( X_j \) and \( X_0 \), also namely the sequence relation, the average relation and the line relation. The closer the value of \( r_j \) is to 1, the higher the relation will be. \( N \) is the number of samples.

Finally, the weight vector \( w_j \) is given by:

\[
w_j = \frac{r_i}{\sum_{k=1}^{N} r_i}
\]  

(3) Combined weight

The combined weight was obtained by using Lagrange multiplier method to integrate the weight vector \( w_i \) from AHP and \( w_j \) from GRA:

\[
W = \frac{(w_{ik}w_{jk})^{1/2}}{\sum_{k=1}^{n}(w_{ik}w_{jk})^{1/2}}
\]  

(8)

Through the above methods and steps, the weight value of indicators in the security risk assessment of key nodes of sea lanes is finally obtained.

3.2 Security risk visualization research

By forming the multi-criteria spatial mapping in the assessment system, the visualization of risks can create a strait security risk map to further explore the spatial distribution of risks in the strait and support to understand the spatial correlation between risks and various indicators (Poggio and Vrscaj 2009; Wang et al. 2021).

3.2.1 Geospatial analysis

The geospatial analysis of data is conducted by using ArcGIS. After creating the vector surface layers of the boundary range of key nodes of sea lanes, the multi-criteria space mapping layers which are raster layers with a grid cell of 0.01°*0.01° are available by a group of spatial analysis methods, such as the Buffer, Kriging, Merge and Intersect. Finally, the layers are reclassified according to the ranking levels and present the spatial distribution of risk levels of the indicators in the study area.

The model for realizing the spatial distribution of the risk levels of an indicator is shown in Fig. 3.

3.2.2 Data visualization

The assessment results were visualized by creating thematic maps in ArcGIS with the traditional two-dimensional visualization technology.

Based on the combined weight results and the geospatial analysis results, the Weighted Sum of Overlay was carried out and the hazard, vulnerability and exposure, and mitigation
capacity layers were created. And then, the spatial risk value of the key nodes of sea lanes was calculated by using the risk calculation formula. In order to effectively present the relative risk status of the study area, the obtained spatial risk values were standardized and the standardized results were reclassified corresponding to the five risk levels, which are “Very low” (vl) “Low” (l), “Medium” (m), “High” (h) and “Very high” (vh). The value-at-risk normalization formula is as follows:

$$R_n = \frac{r - \min(r)}{\max(r) - \min(r)}$$  \hspace{1cm} (9)

where $R_n$ is the standardized value at risk, whose numerical result is controlled between $[0, 1]$; $r$ is the value at risk of each grid; $\max(r)$ is the maximum value at risk; and $\min(r)$ is the minimum value at risk.

The above methods can intuitively and effectively display the two-dimensional visualization results and create thematic maps of the security risks of key nodes of sea lanes, so as to reflect the spatial distribution of the security risks of key nodes of sea lanes and support to analyze the environmental conditions of important lanes in detail.

4 Result and discussion

4.1 Security risk assessment results

In the security risks of key nodes of sea lanes, the weight of each indicator in the assessment system was determined by the combined weights based on AHP and GRA. In the AHP assessment, the opinions and suggestions of experts were widely consulted and the relative importance of each indicator was reasonably determined. In the GRA assessment, the data processing was unified and standardized to ensure the objectivity and accuracy of the assessment.
In the assessment process, the hazard layer, the vulnerability and exposure layer, and the mitigation capacity layer were, respectively, assigned a weight value of 1. In the process of expert scoring and weighting, it was ensured that the weight sum of specific indicators of each layer was equal to 1, respectively. Using the Lagrange multiplier method to combine the subjective weights determined by the AHP and the objective weights determined by the GRA, the more reasonable combined weights were obtained. The weight results of the assessment indicators for the security risk assessment of the Tsugaru Strait and the Makassar Strait are as follows in Table 6.

4.2 Security risk visualization results

Using spatial analysis techniques such as the Create fishnet, Kriging, Buffer and Intersect in the ArcGIS, the GIS spatial analysis of specific indicators of each layer was completed and the raster layers of the spatial distribution of indicator risk levels were obtained. And then, the raster layers of each indicator and its corresponding combined weight were superimposed and analyzed by the Weighted Sum of Overlay and the hazard, vulnerability and exposure, and mitigation capacity layers were created in the ArcGIS. The spatial risk value of key nodes of sea lanes was obtained by using the Math tool based on the risk calculation formula. After standardizing and reclassifying the spatial risk value, the raster layers of risk spatial distribution of study areas were obtained and finally, the thematic maps of the risk distribution in study areas were drawn. The spatial distribution of results in the Tsugaru Strait and the Makassar Strait is shown as follows (Figs. 4, 5).

After standardizing and reclassifying, the risk visualization results of each object are shown below.

(1) The Tsugaru Strait

According to statistics, the proportions of “Very low” and “Low” areas in the Tsugaru Strait are approximately 9.22% and 30.07%. The “Medium” area covers 39.49% of the total Tsugaru Strait. Nearly 19.11% and 2.12% of the Tsugaru Strait are accounted in the “High” and “Very high” areas, respectively (Fig. 6).

(2) The Makassar Strait

According to statistics, the “Very low” and “Low” areas account for 20.31% and 56.81% in the Makassar Strait. The “Medium” area covers 20.70% of the total Makassar Strait. Approximately 2.06% and 0.11% of the Makassar Strait are lain in the “High” and “Very high” areas, respectively (Fig. 7).

4.3 Security risk analysis of key nodes of sea lanes

4.3.1 The security risk analysis of the Tsugaru Strait

The Tsugaru Strait is an important lane connecting the Sea of Japan and the Pacific Ocean and one of the important maritime gateways of the Japanese archipelago. The risk distribution map of the Tsugaru Strait shows the spatial variation of risks in the
| System layer                  | Index layer                             | Subjective weights | Objective weights | Combined weights |
|-------------------------------|-----------------------------------------|--------------------|-------------------|------------------|
| Hazard                        | Wind                                    | 0.1781             | 0.1122            | 0.1553           |
|                               | Wave                                    | 0.1207             | 0.1060            | 0.1243           |
|                               | Visibility                               | 0.0696             | 0.1194            | 0.1002           |
|                               | Precipitation                            | 0.0370             | 0.1387            | 0.0787           |
|                               | Water depth                              | 0.0681             | 0.1016            | 0.0914           |
|                               | Width                                    | 0.0316             | 0.0917            | 0.0592           |
|                               | Tropical cyclones                       | 0.0663             | 0.0736            | 0.0768           |
|                               | Temperature                              | 0.0247             | 0.1022            | 0.0552           |
|                               | Piracy and maritime terrorism           | 0.3376             | 0.0816            | 0.1824           |
|                               | Infectious diseases                     | 0.0663             | 0.0731            | 0.0765           |
| Total                         |                                         | 1                  | 1                 | 1                |
| Vulnerability and exposure    | Distribution of obstructions to navigation | 0.1433             | 0.0638            | 0.1020           |
|                               | Distribution of ports and terminals      | 0.0466             | 0.0842            | 0.0668           |
|                               | National stability                       | 0.0211             | 0.0615            | 0.0384           |
|                               | Political corruption                     | 0.0916             | 0.0842            | 0.0937           |
|                               | Terrorism                                | 0.0917             | 0.0583            | 0.0780           |
|                               | Major power intervention                 | 0.0486             | 0.0818            | 0.0673           |
|                               | Military bases                           | 0.0917             | 0.1137            | 0.1089           |
|                               | Competitiveness of neighboring countries | 0.0505             | 0.1095            | 0.0793           |
|                               | Diplomatic relations                     | 0.0505             | 0.0970            | 0.0746           |
|                               | Regional delimitation                    | 0.0505             | 0.0841            | 0.0695           |
|                               | Strait jurisdiction countries            | 0.0486             | 0.0841            | 0.0682           |
|                               | Vessel traffic density                   | 0.2653             | 0.0779            | 0.1533           |
| Total                         |                                         | 1                  | 1                 | 1                |
| Mitigation capacity           | Institutional management strength        | 0.2431             | 0.2955            | 0.2943           |
|                               | Legal guarantee                          | 0.0882             | 0.3929            | 0.2044           |
|                               | Emergency response capability            | 0.6687             | 0.3116            | 0.5013           |
| System layer | Index layer | Subjective weights | Objective weights | Combined weights |
|--------------|-------------|--------------------|-------------------|------------------|
| Total        |             | 1                  | 1                 | 1                |
The overall risk of the Tsugaru Strait is mainly based on the “Medium” risk level, accounting for 39.49% of the strait, which is basically dispersed throughout the strait. The areas of the “Low” risk level cover 30.07% of the strait, mainly distributed in the eastern and western fringes of the Tsugaru Strait. The “High” risk level areas also account for 19.11% of the strait, mainly distributed in the central area and the southwest of the Tsugaru Strait. However, the areas of “Very low” and “Very high” risk levels cover small proportions of the strait and the “Very high” areas are mainly distributed in the central and southwestern regions of the Tsugaru Strait. The following will analyze the specific performance of important indicators in the hazard, vulnerability and exposure, and mitigation capacity layers combining with the actual situation.

(1) Hazard layer analysis

In the hazard layer, the important factors affecting the risk distribution of the Tsugaru Strait are wind, wave, water depth and width. In the Overlay analysis, the larger the cumulative value of the areas with high speed winds, large waves, shallow water depth and limited width is, the higher the hazard value will be. Among them, the wind speed shows

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**Fig. 4** Spatial distribution of results in the Tsugaru Strait: **a** hazard layer; **b** vulnerability and exposure layer; **c** mitigation capacity layer; **d** risk results layer.
an increasing trend from northeast to southwest of the Tsugaru Strait in terms of spatial distribution; in terms of time distribution, the wind speed is relatively higher in January, February and December with an average wind speed exceeding 8.5 m/s and the highest wind speed in the year occurs in December; the wind speed is lower in March to November with an average wind speed of about 5.5 m/s and the lowest wind speed in the year occurs in July. The wave height in the Tsugaru Strait is relatively stable in the range of [0, 2.5] m, whose risk levels are classified into the “Very low” and “Low.” The water depth in the Tsugaru Strait is sufficient, as the water depth in the Tsugaru Strait is more than 50 m except for the coastal areas. The width of the Tsugaru Strait varies from place to place, but the narrowest point on the east side of the strait is 10.35 n mile.

(2) Vulnerability and exposure layers analysis
In the vulnerability and exposure layer, the important factors affecting the risk distribution of the Tsugaru Strait are the vessel traffic density, military bases and the distribution of ports and terminals. In the Overlay analysis, the larger the cumulative value of the areas with higher vessel traffic density, closer to the military bases, ports and terminals is, the higher the vulnerability and exposure value will be. Among them, the areas with high vessel traffic density in the strait are located in the center of the strait and along with the...
direction of the strait. The nearest US military base from the strait is the Misawa Air Force Base (about 40.7032°N, 141.3684°E), which is within a control range of 759 km. And the longest length of the military airport runway in this base is 3048 m, and the risk level of the military base in the strait is classified into “Very high.” Two ports are located in the strait, namely Hakodate Port in Hakodate Bay and Aomori Port in Aomori Bay. The closer vessels to the ports are, the higher the risk will be.

(3) Mitigation capacity layer analysis

In the mitigation capacity layer, Japan has set up the Japan Coast Guard equipped with more than 200 patrol boats and more than 70 maritime patrol aircraft to protect its own maritime rights and interests. According to the institutional staffing, facility deployment and management capabilities of Japan, the risk levels of the emergency response capability and institutional management strength in the Tsugaru Strait are classified into “Low” and “Low,” respectively. The legal guarantee in the Tsugaru Strait is ranked into the “Very low” risk level because of the relatively complete legal system of Japan.

4.3.2 The security risk analysis of the Makassar Strait

The Makassar Strait connects the western Pacific Ocean and the northeastern Indian Ocean, which is one of the eight major straits in the world with important military and economic significance. It has become the key node of important routes from the South China Sea, the Philippines to Australia. The risk distribution map of the Makassar Strait shows the spatial variation of risks in the Makassar Strait. The overall risk of the Makassar Strait is mainly based on the “Low” risk level, accounting for 56.81% of the region, which is mainly in the central and eastern areas of the strait. The risk level of “Medium” with a regional proportion of 20.70% is mainly distributed in the east and west coastal areas of the Makassar Strait. The areas classified into the “Very low” risk level also account for a large proportion of 20.31%, mainly in the central and northern areas of the Makassar Strait. But the areas of “High” and “Very high” risk levels account for small proportions of the strait and the “Very high” areas are mainly distributed in the western coastal area of the Makassar Strait. Combining with the actual situation, the specific performance of important indicators in the hazard, vulnerability and exposure, and mitigation capacity layers will be analyzed as follows.

(1) Hazard layer analysis

In the hazard layer, the important factors affecting the risk distribution in the Makassar Strait are the piracy and maritime terrorism, visibility and water depth. In the Overlay analysis, the hazard value will get higher with the increasing cumulative value of areas with the frequent piracy and maritime terrorism incidents, high cloud cover and shallow water depth. Among them, the piracy and maritime terrorism incidents have took place 90 times in the Makassar Strait from 2011 to 2020 according to the statistics of piracy incidents released by the IMO, indicating that the Makassar Strait is faced with serious non-traditional security threats and more security risks. The risk levels of the visibility
in the Makassar Strait are classified into “High” and “Very high.” Because the proportion of high cloud cover is relatively high throughout the year and the annual average high cloud cover accounts for 0.75 in the strait. It can be proofed by the statistics that the average proportion of high cloud cover from 2011 to 2020 is in the range of [0.6, 0.8]. The water depth in the Makassar Strait is sufficient, and the water depth in the central and eastern part of the strait is more than 250 m except for the area near the western coast.

(2) Vulnerability and exposure layers analysis

In the vulnerability and exposure layer, the important factors affecting the risk distribution of the Makassar Strait are the vessel traffic density, military bases and the distribution of obstructions to navigation. In the Overlay analysis, the larger the cumulative value of the areas with higher vessel traffic density, closer to the military bases, obstructions to navigation is, the higher the vulnerability and exposure value will be. Among them, the areas with high vessel traffic density in the strait cover the center of the strait and are along with the direction of the strait. The nearest US military base from the strait is the Lumbia Airport (about 8.4156°N, 124.6111°E), which is within 2 times the control range of 759 km, and the longest length of the military airport runway in this base is 2454 m. So the risk level of the military base in the strait is regarded as “high.” There are 16 ports on both coastal sides of the strait, and the closer distance to the port will bring more risks. Large shoals are located in the southwest of the strait and reefs and other obstructions scatter along with the west coastal of the strait, which will increase the navigation risk of vessels.

(3) Mitigation capacity layer analysis

In the mitigation capacity layer, Indonesia has established the Maritime Safety Bureau and the Maritime Safety Department to protect its own maritime rights and interests. Considering the institutional staffing, facility deployment and management capabilities of Indonesia, the emergency response capability and institutional management strength in the Makassar Strait are regarded as the “Medium” and “Medium” risk levels, respectively. And the legal guarantee in the Makassar Strait is classified into the “Medium” risk level.

4.4 Methodology review and analysis

Based on the existing researches and objective data, this paper has constructed a set of methods for the security risk assessment and visualization research of key nodes of sea lanes and performed the weighted overlay of spatial layers to visualize the spatial distribution of risks in the strait. Taking the two key nodes of the Tsugaru Strait and the Makassar Strait as case studies, the indicators of the assessment index system have been collected data and determined weights to conduct the security risk assessment and form multi-criteria spatial mapping layers to visualize risks. As important gateways to sea areas, the Tsugaru Strait and the Makassar Strait are different in the important factors affecting the risk distribution of the two straits due to the spatial heterogeneity, as well as in the water area and geographical location. But the results show that the set of methods is suitable for risk assessment and visualization study in different waters based on effectively synthesizing
and processing multi-source elements and realize risk assessment and visualization based on objective data and humanity information. Moreover, this study still has limitations:

1. The accuracy of natural data needs to be improved. The accuracy of most natural data is 0.25° * 0.25°. For straits in small-scale geographic areas, the numerical coverage of natural data is limited, so the interpolation processing is required. And data quality issues should also be noted, such as data on wave heights, which may be nulls near the shore.

2. The indicators of mitigation capacity layers need to be more comprehensive and accurate. The existing indicators of mitigation capacity layers are mostly determined qualitatively and are limited by the expert knowledge and existing cognitions, which have resulted in the numerical descriptions of the indicators failing to be comprehensively and accurately determined. In addition, it is necessary to strengthen the research on the indicators’ spatial influence to realize the spatial mapping of the indicators.

5 Conclusion

Based on the risk theory, this study screened the risk factors of key nodes of sea lanes from three risk categories (hazard, vulnerability and exposure, and mitigation capacity) and constructed a security risk assessment index system for key nodes of sea lanes to achieve the integration of natural and humanity factors. In this study, the weights of indicators were determined by the combination of AHP and GRA. After the indicator values were ranked, the multi-criteria spatial mapping layers were formed by the geospatial analysis and then, the layers were weighted and superimposed to realize the risk visualization in strait areas. Compared with previous studies, this study improved their limitations which mainly included insufficiently considering the complex humanity and politic factors in the criteria (Zhou et al. 2020) and lacking the risk visualization of key nodes of sea lanes in geospatial scale (Li et al. 2018). This study took into account the influence of humanity factors to conduct the comprehensive assessment and analysis of the natural and humanity environment risks of key nodes. Furthermore, the study used geospatial analysis technique to acquire risk mapping and spatial visualization of key nodes of sea lanes. From the case studies of the Tsugaru Strait and the Makassar Strait, it can be seen that the high-risk areas are located in the central areas and the southwest of the Tsugaru Strait and the overall risk of the Makassar Strait is low except for the western areas. These indicate that the methods can effectively display the spatial distribution of security risks in key node areas, identify high-risk areas in key nodes and analyze the security situation of key nodes of sea lanes. Based on the assessment results and the objective conditions of the straits, important factors affecting security risks can be confirmed, including the piracy and maritime terrorism, wind, wave, visibility, water depth and width in the hazard layer; the vessel traffic density, military bases, distribution of obstructions to navigation and distribution of ports and terminals in the vulnerability and exposure layer; the emergency response capability in the mitigation capacity layer can mitigate or respond to the process of transforming risks into accidents. Due to the spatial heterogeneity of straits, each important factor in different straits will have different performance.

This study focuses on the key nodes of sea lanes, improves the status of straits that lacks the basic research and monitoring by visualizing risks in spatial scales and grasps the basic
conditions and risk status of the key nodes of sea lanes. In this way, the risk mapping and analysis of the navigation environment in the straits have been formed, which can provide certain references for the decision-making of vessels in the strait and strengthen risk prevention to reduce the blockage of straits. What’s more, it is conducive to the channel planning in straits, ensure the safety of maritime transportation and maintain the stability of the global supply chain. However, the existing researches on the assessment of the risk status of key nodes cannot achieve the dynamic real-time tracking of risks. Therefore, it is necessary to further carry out the dynamic risk assessment of key nodes to explore the dynamic mechanism of security risks of key nodes of sea lanes, in order to better ensure the maritime safety.

Author contributions All authors contributed to the study conception and design. Methodology, software, writing—original draft preparation and visualization were performed by LX. Conceptualization, resources, writing—reviewing and editing were performed by SC. SX and PQ conducted supervision. Investigation was carried out by TW. YG and NL conducted writing—reviewing and editing. All authors read and approved the final manuscript.

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Declarations

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