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GIS-Based Maritime Traffic Risk Identification and Assessment

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Abstract. Maritime traffic risk shows significant spatial and temporal differences among vessel activities, navigation conditions, and environments. The further development of Automatic Identification System (AIS) and Geographic Information System (GIS) provides useful tools to analyze vessel trajectories, accident hotspots and environmental risks. This paper reviews the major spatial data, GIS methods and applications used in maritime traffic risk identification and assessment. The main data sources include AIS data, historical accident records, environmental conditions and spatial data. GIS methods include traffic density and hotspot analysis, spatial overlay and spatial relationship analysis. Representative cases from the Malacca Strait, the Istanbul Strait and the Dover Strait, and the Bohai Sea show the different applications. This study employs GIS and various data sources to gain insight into the spatial distribution of maritime traffic and traffic hotspot areas, and historical accident data to identify accident-prone areas. Combining AIS, remote sensing and environmental data can also reveal the temporal and spatial distribution of maritime traffic risk. However, data quality, multi-source data matching and scale issues in space and time are still problems. Future research is needed to improve multi-source data fusion and dynamic risk analysis to further increase the reliability of maritime traffic risk assessment and risk management.

Keywords: geographic information system, automatic identification system, maritime traffic risk, spatial analysis, risk assessment

1. Introduction

Maritime transportation plays an important role in international trade. Intensive vessel activities are commonly observed around major ports, narrow waterways, and busy shipping routes. High levels of vessel activity also bring increasing challenges to maritime safety. Accidents such as collisions and groundings may cause human casualties, economic losses, and environmental damage. Therefore, it is important to know the spatial distribution of risk of maritime traffic.

Maritime traffic risk has been analyzed in the past by various spatial data and Geographic Information System (GIS) based approaches. AIS data have been extensively used to trace vessel motion, characterize traffic density and shipping routes [1-4]. Historical accident records have also been integrated with GIS techniques to investigate accident hotspots and spatial distribution [4]. More recent studies have also combined AIS with weather, environmental and remote sensing data

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to examine the relationship between navigation conditions and maritime risk [5]. However, most studies continue to address traffic density, accident hotspot or environmental factors individually. Not all the relationships between spatial datasets and risk factors have been explored thoroughly, particularly if risk varies over space and time.

This paper examines the use of GIS in maritime traffic risk identification and assessment. It summarizes the main spatial data sources used in maritime risk analysis, including AIS data, historical accident records, navigational information, and environmental data, together with commonly used GIS methods such as traffic density analysis, hotspot analysis, spatial overlay, and spatial relationship analysis. Case studies from the Malacca Strait, the Istanbul Strait and Dover Strait, and the Bohai Sea are then used to examine traffic density and hotspots, maritime accidents and collision risk, and environmental differences in maritime risk. The paper also discusses current problems related to data quality, multi-source data integration, and the interpretation of different risk indicators.

2. Data and GIS methods

2.1. Spatial data sources

Automatic Identification System (AIS) data are an important source of spatial information for maritime traffic analysis, providing real-time vessel locations and identification information. AIS continuously records information such as vessel position, speed, heading, and identity [1]. By connecting a series of AIS points for individual vessels, researchers can reconstruct vessel trajectories. When these trajectories are integrated into a GIS, they can be used to analyze traffic density, shipping routes, vessel encounters, traffic hotspots, and potential collision risks [2]. Therefore, AIS provides an important basis for the spatial analysis of maritime traffic and the identification of potential navigational risks.

Aside from AIS, accident data and navigational and environmental data also play a significant role in maritime traffic analysis. Typical information included in an accident record includes the location, time, type, and consequences of the accident [3]. These data, combined with a GIS, can be used to create a spatial analysis of historical accidents to find hotspots. Navigational data include information on the spatial conditions under which vessels operate, such as shipping channels, ports, coastlines, and water depth.

For instance, narrow channels can restrict the space available for vessel maneuvering, shallow areas can increase the likelihood of grounding, and ports and coastlines define the space between vessels and the land. Wind, waves, visibility, and sea ice are also environmental factors that can be used to describe conditions affecting ship navigation [2, 3]. These data, when combined in GIS, can be used for analyzing the relationships between the vessel traffic, historical accidents, and navigation and environmental conditions.

2.2. GIS analysis methods

The traffic density and hotspot analysis is primarily employed to determine sea areas where high vessel traffic occurs. Raw AIS data can be statistically analyzed by specific grid ranges and AIS traffic density maps can be produced. The density of vessels is generally higher in port entrances, important shipping routes and narrow channels [4]. Another method for analyzing the concentration distribution of vessel activities or maritime accidents is called Kernel Density Estimation (KDE). However, a high number of vessels does not necessarily translate to a high chance of an accident;

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other factors must be considered, such as historical incidents, the channel conditions, and the environment [6].

Spatial overlay can be used to relate the traffic density, accident locations, channel and environmental conditions as separate GIS layers in the same spatial extent. Some studies also apply weighted overlays on the basis of the relative importance of the various indicators to determine risk zones of different degrees. This makes it possible to see if there is a substantial overlap between the activities of the vessels, accident distributions, and environmental conditions in some areas, from which a spatial framework can be developed to identify high-risk zones [6].

Spatial relationship analysis could also be used for the study of distribution characteristics of maritime traffic risk in addition to density and overlay analysis. Spatial autocorrelation can help identify if accidents or high-risk areas are clustering in space. The relationships between traffic density, channel width, visibility, and maritime traffic risk can be further analyzed using spatial regression. If geographical locations vary, the underlying relationships may also differ, and Geographically Weighted Regression (GWR) can be applied to examine these spatial variations [7].

3. GIS applications in maritime traffic risk assessment

3.1. Traffic density and hotspot analysis

With the help of AIS data and ship trajectories, researchers can perform spatial statistics in various areas and determine the areas that have concentrated ship activity. High traffic density is primarily found along major shipping routes, port entrances, narrow channels, and where shipping routes intersect. These areas have more vessels, along with more collisions, crossings, and maneuvering [8, 9]. As such, traffic density and hotspot analysis is generally regarded as a fundamental technique for determining important areas of navigation and traffic complexity.

Liu et al. selected the Malacca Strait for study and analyzed the vessel traffic characteristics using AIS data from 2022 [9]. The study captured vessel location and navigation state from AIS and compared the speed and density of vessel traffic to traffic complexity in the various traffic zones. The Malacca Strait was segmented to create several traffic zones and a traffic zone matrix was created to help identify differences between traffic zones. The findings indicate that there is no uniform distribution of ship numbers, navigation status and traffic complexity among areas within the Malacca Strait. The shipping intensity in some water areas is much higher and the traffic situation is more complex. This zonal analysis reveals traffic flow patterns differ from site to site within a congested waterway; it also makes it easier to locate where vessel traffic is heavy.

The case study illustrates the spatial distribution of vessel traffic by integrating AIS data with GIS and allows for further comparison of the traffic characteristics of areas in narrow and busy waterways. The Malacca Strait itself is a place where the movement of ships is frequent and in some places the space for navigation is limited, which can be analyzed by assessing the traffic volume and complexity. However, when vessels operate in concentrated areas, it does not necessarily mean that the risk of accidents is greater. Study periods, vessel types and AIS data coverage may all have an impact on traffic density and hotspot identification results. Thus, historical data about accidents, navigational conditions, and environment must also be studied when evaluating maritime traffic risk.

3.2. Maritime accident and collision risk assessment

Historical maritime accident data can be analyzed to determine the distribution of accidents by sea areas. Accident data usually contain details of the location, time, type and effects of the accident.

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This information can be mapped geographically, so that it can be seen how many accidents are occurring in each area relative to others. Further integration of AIS vessel activity, channel locations and other navigational conditions could be used to investigate whether the distribution of accidents is related to the traffic situation and the navigation environment [10]. The analysis of such accidents is especially appropriate for gaining insight into the historical sea area accident characteristics and can also be used to identify sea areas that need special attention.

Yildiz et al. carried out spatial and statistical analysis of maritime accidents in the Istanbul Strait and Dover Strait [11]. This study used accident data from 2004–2020 covering collisions, groundings, and sinkings. The first step was to map the accidents using GIS and analyze the spatial distribution of the accidents in two very narrow waterways. Next, KDE was used to create plots of accident density and determine hotspots. The study also compared the relationship between the navigation and the type of accident, the severity of the accident, the density of the accidents, and based on this, the relation between the narrow waterways and the spatial distribution of accidents was then examined. Finally, the study also included the opinions of experts who knew the local navigation environment and were consulted to comment on some of the analytical results. These steps helped to establish a more complete picture of the accident location differences between the two straits and the relationships between each category of accidents and navigation conditions.

The results for the two straits can be further examined using GIS to establish a spatial framework for comparing accident locations, accident types, and navigational spatial conditions. The density map of the accidents clearly shows the historically dangerous areas, which can be used as a reference for maritime authorities in determining monitoring areas. However, the accidents occurring in accident hotspots are not indicative of the probability of future accidents unless the hotspot is actually an "accident hotspot" for that period. Completeness of accident records, accuracy of accident locations, the study time frame, analytical methods, and other factors may also affect analysis results. Historical accident hotspots are therefore more appropriate for detecting historical hotspot areas, while in a practical risk assessment, the vessel traffic and navigation conditions of the time of the risk assessment are also crucial.

3.3. Environmental conditions and spatial risk differences

Changes in environmental conditions also affect maritime traffic risks, in addition to vessel operations and sea conditions. Wind, waves, visibility, sea fog and sea ice may affect a vessel's actual navigation condition and the process of vessel encounters and avoidance maneuvers. Thus, the vessel traffic density could be the same at two locations, but the risk could be different. The correlation between environment and maritime traffic risks can be monitored on both spatial and temporal levels by combining AIS data with other meteorological, oceanographic, and remote sensing data.

Liu et al. selected the Bohai Sea of China as their study area, and they explored the spatial and temporal effects of sea fog on ship near-miss risks [12]. The study employed Himawari-8 satellite remote sensing data for sea fog identification, and vessel activity data and near-miss incidents were obtained using AIS data. To this end, machine learning and GWR methods were used to study the relationship between sea fog and vessel near-miss risk. Results indicate that sea fog has a significant regional variation in effects on near-miss risk. The relationship between sea fog and near-miss risk is stronger in the areas with dense vessel traffic (such as Tangshan Port and Tianjin Port) than in the relatively open waters of the central Bohai Sea. Seasonal variation is also observed; the relationship between sea fog and near-miss risk is stronger in autumn/winter and weaker in summer. This means

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that the risk posed by sea fog is not uniform in space and time, but is dependent on traffic situation and seasonal conditions.

The integration of remote sensing environmental data and AIS data on the same spatial scale will allow a more detailed understanding of the different effects of environmental factors in various water areas. This method is useful to understand why areas with the same traffic characteristics can have varying risk levels when the environment changes, compared to traffic density analysis or historical accident analysis. However, these analyses are also very sensitive to spatial resolution of environmental data and temporal alignment of datasets. The findings also may be affected by vessel type, navigation status and geographic variables. Thus, when discussing the impact of environmental conditions on the risk of maritime traffic, the scales of data and other possible influencing factors must be taken into consideration.

4. Challenges and future directions

GIS is widely used for maritime traffic risk analysis, but there are still some concerns in practical use related to reliability of the results. One of the primary concerns is data quality. AIS data can be incomplete, due to missing signals, abnormal trajectories, small vessels not being covered, and inconsistent time intervals. Historical accident data may also vary in terms of their location and reporting quality. These issues may impact vessel trajectory identification, traffic density and accident hotspots. The data available may not accurately represent actual vessel activity or accident conditions in some areas [13].

Typical data for maritime risk analysis are AIS data, accident data, remote sensing images, weather data and other environmental data. Direct integration can be challenging due to the different spatial dimensions, timescales and frequency of updates of these datasets. Observations of AIS may not correspond exactly with the time of weather or remote sensing data and differences in spatial scale can also impact the comparison of results. Another issue is that a single indicator does not fully capture the risk of maritime traffic. High traffic does not necessarily mean a high accident risk; an area with a large number of historical accidents does not always have the same degree of risk in the future. The traffic conditions, navigational environment, accident record and environmental factors should thus be treated as a combined factor [13].

Further research is needed in two directions: data quality and multi-source data integration. Enhancing the consistency and completeness of AIS data, and minimizing variance in data collection methods and reporting across data sources, are still needed. In addition to spatial consistency of data it is important to consider temporal consistency of data when integrating AIS, remote sensing, meteorological and environmental data. Maritime traffic risk assessment may also incorporate several indicators, including traffic intensity, historical accidents, navigation conditions and environmental factors to minimize judgment bias resulting from the use of a single indicator. High frequency of updates of AIS and environmental data allows more timely dynamic risk assessments that are closer to the actual changes in traffic risks from various periods and sea areas.

5. Conclusion

This paper analyzes the application of GIS in identifying and assessing maritime traffic risks, focusing on AIS data, historical accident records, navigation conditions and environmental data, as well as methods such as traffic density and hotspot analysis, spatial overlay analysis, and spatial relationship analysis. This review demonstrates that AIS data can be used to provide a description of vessel activity in various sea regions, and the number of ships involved in collisions can be

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estimated for different sea areas. Historical accident records can be used to identify areas with relatively high accident frequencies. In addition, remote sensing and environmental data can be used to study the relationships between wind, sea fog, and navigational risks. The use of multi-source data allows researchers to examine spatial variations in maritime traffic risks through different lenses, including vessel operations, past incidents, and environmental factors. The results show that GIS is effective in integrating various types of maritime information and in the analysis of the spatial and temporal features of maritime traffic risk. The analysis results, however, continue to be affected by the completeness of AIS data, the quality of accident data and inconsistencies between datasets with regard to spatial and temporal scales. Furthermore, traffic hotspots and previous concentrations of accidents cannot directly be interpreted as the likelihood of future accidents, leading to uncertainty in risk interpretation. Future research should enhance the coverage and consistency of maritime spatial data, improve the spatial and temporal consistency and completeness of AIS, accident and remote sensing data and sea environment data, and integrate multiple risk-related factors instead of a single indicator. Greater use of continuously updated vessel and environmental data may also support more dynamic and timely risk analysis, improve the reliability of GIS-based maritime traffic risk identification and provide stronger support for maritime safety management.

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