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EDITED BY
Song Ding,
Zhejiang University of Finance and Economics, China

REVIEWED BY
Jianqiang Zhang,
Zhejiang Gongshang University, China
Le Ma,
Wuhan University, China

*CORRESPONDENCE
Rui Han
hrui1995@163.com
Xin Dai
daixin@caas.cn
Huishang Li
lihuishang@caas.cn

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Economic footprint assessment of storm surge disasters in China based on disastrously-extended input-output analysis

Rui Han[1,2*], Kedong Yin[3,4,5], Xin Dai[1*], Huishang Li[1*] and Shiwei Zhou[2,3]

[1]Agricultural Information Institute, Chinese Academy of Agricultural Sciences, Beijing, China, [2]School of Economics, Ocean University of China, Qingdao, China, [3]Ocean Development Research Institute, Major Research Base of Humanities and Social Sciences of Ministry of Education, Ocean University of China, Qingdao, China, [4]School of Economics, Shandong University of Finance and Economics, Jinan, China, [5]Institute of Marine Economics and Management, Shandong University of Finance and Economics, Jinan, China

Introduction: Escalating climate change has intensified storm surge disasters in China, whose economic repercussions are not confined to coastal areas but cascade nationwide through industrial supply chains. However, existing research overlooks these nationwide implications.

Methods: To address this gap, this paper proposes an innovative assessment framework for evaluating the economic footprint of storm surge disasters, quantifies the indirect economic losses inflicted by storm surge disasters in China from 2011 to 2020 and further trace the diffusion of these losses across various industries and regions by developing a disastrously-extended input-output model.

Results: The findings reveal that indirect economic losses constituted over 60% of the total economic losses from storm surge disasters during the aforementioned period. Interestingly, regions remote from the direct impact of the storm surge disasters were not immune to their effects. Among these, Henan Province emerged as the inland area most severely impacted by storm surge disasters, while the northwest and southwest regions typically experienced minimal indirect economic losses. Furthermore, the majority of the indirect economic losses originated from the Resource Processing Industry and Service Department of the directly affected regions, and the secondary industry of the potentially affected regions.

Discussion: These findings demonstrate the inadequacy of localized disaster policies and underscore the urgent need for a nationwide resilience strategy focused on critical supply chain vulnerabilities.

KEYWORDS

storm surge disasters, economic footprint, disaster prevention and mitigation policy, economic loss diffusion, input-output model

1 Introduction

The extreme weather events and meteorological disasters frequently occur under the background of global climate change (Sun P. et al., 2023). The prevalence of meteorologically-related catastrophes has seen a surge of nearly 35% since the 1990s, and an alarming 83% of worldwide natural disasters during the 2010s were attributed to intense weather and climate events such as floods, cyclones, and heatwaves. These events impacted approximately 1.7 billion individuals and precipitated 410,000 fatalities globally (Freebairn et al., 2020). Natural disasters have the potential to instantly obliterate capital and social progress that have been accumulated over decades, consequently exacerbating household poverty and seriously impeding the sustainable development of the economy and society (Felbermayr and Gröschl, 2014). In 2020, storms constituted 22% of all catastrophic disasters worldwide, being second only to floods. However, storms incurred the largest direct economic losses, amounting to a staggering 93.2 billion USD. A storm surge is an abnormal rise of water mainly caused by storms (Muis et al., 2016). Studies have shown that the increase in extreme weather, such as storms and sea level rise caused by climate change, will further aggravate the frequency of storm surges (Vousdoukas et al., 2016; Wang et al., 2018), which had devastating impacts on the economies and societies of the coastal regions (Martzikos et al., 2021).

As a prominent maritime nation, the marine economy is a new economic growth of China, which is also seriously influenced by marine disasters (Han et al., 2021). The damage inflicted by storm surges on China's coastal regions surpasses that caused by other marine disasters (Fang et al., 2017), posing a significant impediment to the socio-economic development of these areas (Khan et al., 2020). As per the Bulletin of China Marine Disaster, between 1998 and 2020, storm surges occurred 399 times in China's coastal regions, 188 of which caused damage. These incidents led to a cumulative death toll of 962 and direct economic losses amounting to 224.624 billion RMB, accounting for over 90% of all direct economic losses from marine-related disasters. Despite a decrease in fatalities over time, potentially attributable to enhanced warning and forecasting systems in coastal areas (Shi et al., 2015), the asset loss has not followed a similar downward trend due to the rapid urbanization and continuous wealth accumulation in coastal areas (Malvarez et al., 2021).

Previous research on the socio-economic impacts of storm surges in China has primarily focused on putting forward disaster prevention and mitigation policies from the perspective of short-term consequences and direct economic losses (Kentang, 2000; Guo and Li, 2020; Du et al., 2022). However, in today's interconnected world, with increasingly close urban relationships facilitated by the flow of people, information, materials, and energy, the impacts of natural disasters are increasingly crossing regions and industries (Mendoza et al., 2020; Tian et al., 2023). The storm surge disasters are no exception, which may have profound economic and social consequences. Shughrue et al. (2020) have confirmed the socio-economic impacts of cyclones spreading through urban trade networks worldwide. Davlasheridze et al. (2021) assessed the economic impact of the storm surge disaster events in the United States, revealing that the storm surge event caused by Hurricane Ike in 2008 had a sustained and adverse long-term effect on the economy of Texas, with ripple effects and spatial spill-overs of local impacts spreading to other parts of the country. However, the economic impact of storm surge disasters in China, particularly the effects of their spread across regions through urban trade and industry networks, remains largely unexplored, except for a few assessments of indirect economic losses involving local industrial relations in the province where the storm surge disasters occurred (Jin et al., 2020; Lin et al., 2023).

Therefore, this paper focuses on proposing post-disaster mitigation policies by studying the nationwide spread of storm surge disasters based on regional trade and industrial networks. We aim to develop a storm surge disastrously-extended input-output (DEIO) model by distinguishing the directly affected and potentially affected regions, as well as the directly affected and potentially affected sectors to assess the economic footprint of the storm surge disasters. Our objective is to clarify and analyze the temporal and spatial trends in the economic footprint of storm surge hazards. Specially, we identify the year and the region with the most severe economic impacts, which includes both directly affected regions and potentially affected regions. Furthermore, we identify the diffusion of storm surge economic losses among eight regions in China, as well as the diffusion of storm surge economic losses from directly affected regions to potentially affected regions. Additionally, we identify the sectors that with the most deliver diffusion of storm surge economic loss in directly affected regions and the most receive diffusion in potentially affected regions. Accounting for the economic footprint referred to the effects of storm surge disasters spreading across the regions plays a vital role in tackling global climate change, enhancing disaster prevention and mitigation, and realizing high-quality sustainable development of China.

This paper contributes to the literature in three ways. Firstly, the study proposes an economic footprint accounting and analytical framework for storm surge disasters. Unlike conventional assessments that largely focus on direct, localized damages, our framework systematically quantify the indirect economic losses that propagate through inter-regional supply chains, offering a more holistic view of storm surges' true economic consequences. Secondly, the paper constructs a storm surge DEIO model specifically for China. Previous single-region approaches were inherently incapable of tracing how economic shocks spill over from an affected area to the rest of the region. Our multi-regional model overcomes this by explicitly mapping the inter-provincial trade linkages, allowing us to quantitatively track the diffusion pathways of indirect losses across the entire national economic network. By doing so, we identify critical sectors and regions that are systemically at risk despite being geographically distant from the coast. Third, the findings shift the paradigm for disaster mitigation policy. By illuminating the critical role of indirect economic loss diffusion, our research moves beyond traditional, site-specific defense strategies. We provide actionable insights for developing network-based, collaborative resilience policies that can preemptively manage and mitigate the cascading economic fallout from storm surges across the entire nation.

The remainder of the paper is organized as follows. In Section 2, we review the related research and provide a strong rationale basis for the current study. Section 3 presents economic footprint accounting and analytical framework and constructs the DEIO model. Section 4 describes and discusses the results and provides policy advice. And in Section 5, we conclude the paper with implications and insights for future research.

2 Literature review

2.1 Storm surge disaster prevention and mitigation

Research on natural disaster prevention and mitigation primarily focuses on two aspects: pre-disaster prevention and post-disaster reduction. Pre-disaster prevention emphasizes the investigation of the physical attribute of natural disasters, aiming to proactively mitigate damages through early monitoring and alerts (Wang et al., 2024). Post-disaster research, on the other hand, delves into the societal attribute of natural disasters, utilizing post-disaster loss assessments to implement adaptive measures that alleviate the socio-economic impacts caused by such disasters. In recent years, the social attribute of disaster has also become a hot research issue (Karimiziarani et al., 2022; Guo et al., 2024; Li et al., 2024). Regarding storm surge disasters, existing studies primarily put forward storm surge disaster prevention policies from perspective of numerical simulation, disaster-causing mechanisms and risk assessment. Numerical simulation analyses delve into the dynamic process of storm surge formation (Jian et al., 2021; Wang N. et al., 2021; Sun Z. et al., 2023). Research on disaster-causing mechanism of storm surge hazard incorporates the disaster-bearing body into the framework to examine the disaster-causing process (Wang et al., 2020; Zhang et al., 2023). Risk assessment studies evaluate potential disaster scenarios by considering factors such as hazard of disaster-causing factor, exposure of disaster-bearing body, damage of the disaster, and adaptive capacity (Heck et al., 2021; Fu et al., 2023; Wei et al., 2024). The above research aims to propose pre-disaster warning and mitigation measures by studying the physical properties of storm surge disasters. Studies on the socio-economic impacts of storm surge disasters, focusing on their social attributes, proposes disaster reduction policies for storm surge disasters by exploring the impact of storm surge disasters on social and economic systems (Fang et al., 2014; Yan et al., 2016). And the socio-economic impacts of storm surge disasters are post-disaster studies (He and Zhuang, 2016; Furman et al., 2021). Although pre-disaster studies are essential for storm surge hazard monitoring and warning, post-disaster research is equally vital for disaster prevention, mitigation, and sustainable development due to the escalating frequency and the globally spread risk of storm surge disasters with climate change (Shughrue et al., 2020).

Coastal regions serve as significant hubs for population, economic, and social progress, while also being susceptible to natural calamities. Storm surge is a significant natural disaster in coastal regions, often resulting in substantial property losses and casualties in coastal areas (Von Storch and Woth, 2008; Sui et al., 2023). Moreover, storm surge events have significant negative effects on the natural environment, economy, and society of coastal regions (Lin et al., 2012). Verdon-Kidd et al. (2016) highlighted the destructive potential of storm surge landfalls, which can cause extensive damage to infrastructure, communities, and lead to direct economic losses due to high winds, heavy rainfall, and coastal erosion. Jin et al. (2018) investigated the relationships of various influencing factors to the direct economic losses, agricultural losses, fishery losses, human resource losses, engineering facility losses and amenity losses of storm surge disasters. Yi et al. (2021) identified that the implementation of green marine technology innovation can help alleviate the upward pressure of economic development on storm surge disaster losses and proposed to reduce storm surge disaster losses by increasing investment in green innovation and strengthening environmental regulation. Guo et al. (2022) proposed a novel prediction system for direct economic losses of storm surge disasters, encompassing three modules: storm surge hazard reduction, forecasting, and assessment. Wang et al. (2022) conducted spatial distribution predictions of direct economic losses caused by typhoon-induced storm surge disasters. Therefore, it is evident that storm surge disaster losses are crucial to study the socio-economic impacts of storm surge disaster and to propose post-disaster mitigation policies, while the current proposed mitigation policies are based on direct economic losses and local socio-economic impacts.

However, the impacts of storm surge disasters transcend the immediate affected areas and can spread from city to city worldwide through urban trade networks. Shughrue et al. (2020) identified the vulnerability of cities' social economies to storm surge disasters, even if they are geographically distant from the direct hit location. These adverse secondary impacts are up to even three-quarters of the maximum impacts of storm surge disaster. Besides, cities that heavily rely on global trade networks but have limited suppliers are particularly susceptible to adverse secondary effects of hurricanes. Jin et al. (2020) only evaluated the indirect economic losses from storm surge disasters in Guangdong Province. But in fact, assessing the long-term socio-economic impacts and spatial spillovers associated with coastal storm surges is important to accurately assess the severity of the economic consequences caused by storm surge disasters and to inform future mitigation policies (Davlasheridze et al., 2021). Considering that current research only focuses on the immediate and local damage caused by a storm surge disaster in China, it fails to take into account the secondary economic impacts that spread from the original affected area to various cities across the country. Therefore, this study aims to investigate the economic impacts of storm surge disasters from the perspective of spatio-temporal socio-economic linkages and to propose mitigation policies.

2.2 Accounting for the economic footprint of disasters

Disaster footprint describes the traces left by the impacts of disaster events on the human economy and society. Currently, there is no standardized and precise definition of the economic footprint of disasters. However, it generally refers to the economic losses caused by disaster events, including both direct economic losses in the affected area and indirect economic losses that propagate along the supply chain (Wang D. et al., 2021). The assessment of direct economic losses from natural disasters is typically conducted by government departments or insurance firms through primary post-disaster data surveys and interviews (Botzen et al., 2020). Alternatively, disaster models can be used to calculate these losses based on the physical properties of the disaster-bearing bodies considering the intensity of natural disasters (Liu et al., 2022). However, the assessment methods of indirect economic losses of natural disasters are still underdeveloped.

The assessment models for indirect economic losses of disasters generally encompass econometric models (Molinari et al., 2014), input-output methods (Jiang et al., 2023), and Computable General Equilibrium (CGE) models (Brouwer et al., 2008). However, econometric models are characterized by their simplistic functional form and subjective parameter setting, making it difficult to capture the intricate interrelationships within the economic system. Input-output method and CGE model reflect the economic structure by considering the connections between industries and regions. These models can measure the ripple effect and cascade effect of disasters on various sectors of the social economy, facilitating the analysis and comparison of their impacts (Rose and Liao, 2005). Although CGE model can overcome the limitations of the Input-Output model, such as linear and static assumptions (Carrera et al., 2015; Kajitani and Tatano, 2018), its practical application in the indirect economic loss assessment of natural disasters is challenging due to the availability of parameter estimation for primary data (Okuyama and Santos, 2014; In et al., 2015).

Therefore, the Input-Output model has emerged as a widely used approach for assessing indirect economic loss resulting from rapid-onset disasters due to its advantages, including its ability to work with limited data, its simplicity, and its applicability to specific regions (In et al., 2015). Mendoza-Tinoco et al. (2017) developed an accounting framework for flood footprints, utilizing the input-output model to measure the overall direct and indirect economic effects of floods on various factors such as production, infrastructure, and residential capital. It was observed that the economic impacts of flood events spilled over to the entire economic system, and some of the most affected sectors may be those that are not directly damaged. To further enhance the flood footprint model, Yin et al. (2021) integrated it with global climate models and hydrological models, creating an integrated disaster risk assessment model. This model was applied to evaluate the economic and industrial chain impacts of sudden flood events under different future climate change and socio-economic development scenarios of six developing countries. Wang D. et al. (2021) assessed the economic effects of the 2018 California wildfires based on an input-output model with a combination of physical and epidemiological models. Their research also revealed that the majority of economic impacts associated with the disaster event are likely to be indirect, usually affecting industry sectors and locations far from the disaster.

It can be seen from the above that existing research on the economic impacts of storm surge disasters has made significant progress, primarily in risk assessment based on physical attributes. Although some studies have begun to employ methods like the Input-Output model to investigate indirect economic impacts, the analytical scope of the extant literature is largely confined to the directly affected areas, focusing on local and short-term economic shocks. This research paradigm, however, significantly overlooks the cross-regional cascading effects and spatial spillovers that arise from disaster shocks propagating through tightly interconnected urban trade networks in a modern economy, which can lead to substantial secondary economic losses in cities geographically distant from the disaster. Consequently, the current academic understanding and quantification of storm surge disasters' economic footprint remains incomplete. To address this critical gap, this study constructs a DEIO model designed to accurately capture the indirect economic losses that spread along multi-regional industrial chains. Subsequently, a systematic analysis of this economic footprint is conducted from both regional and industrial perspectives, aiming to provide a scientific basis for formulating comprehensive disaster prevention and mitigation policies.

3 Methodology

3.1 Economic footprint accounting and analytical framework

The economic footprint of storm surge disasters provides a comprehensive accounting of the storm surge, which consists of direct and indirect economic losses. The direct economic losses pertain to the damages incurred in the directly affected regions caused by the reduction of the value of the hazard-affected bodies after the storm surge disaster, including farmland losses, aquaculture losses, coastal engineering losses, house losses, ship losses and other losses. The indirect economic losses refer to the potential losses of the economy resulting from the supply-chain disruptions triggered by storm surge disasters. These disruptions encompass delays in production, depletion of capital stock, and interruptions in transportation along the production chain. It is important to highlight that the indirect part of the economic footprint of storm surge disasters was designed to estimate the potential supply-chain losses assuming that other factors remain constant.

The analytical framework and the structure for economic footprint accounting of storm surge disasters are illustrated in Figure 1. Initially, we identifies the directly affected and potentially affected regions, as well as the hazard-affected bodies of storm surge disaster from the China Marine Disaster Bulletin. Subsequently, sectors related to the hazard-affected bodies were determined based on information from the Natural Disaster Statistics Bulletin. To construct the DEIO table, we utilized the multi-regional input-output (MRIO) table obtained from the Carbon Emission Accounts & Datasets (CEADs) database. Finally, the DEIO model was employed to assess the indirect economic losses resulting from storm surge disasters.

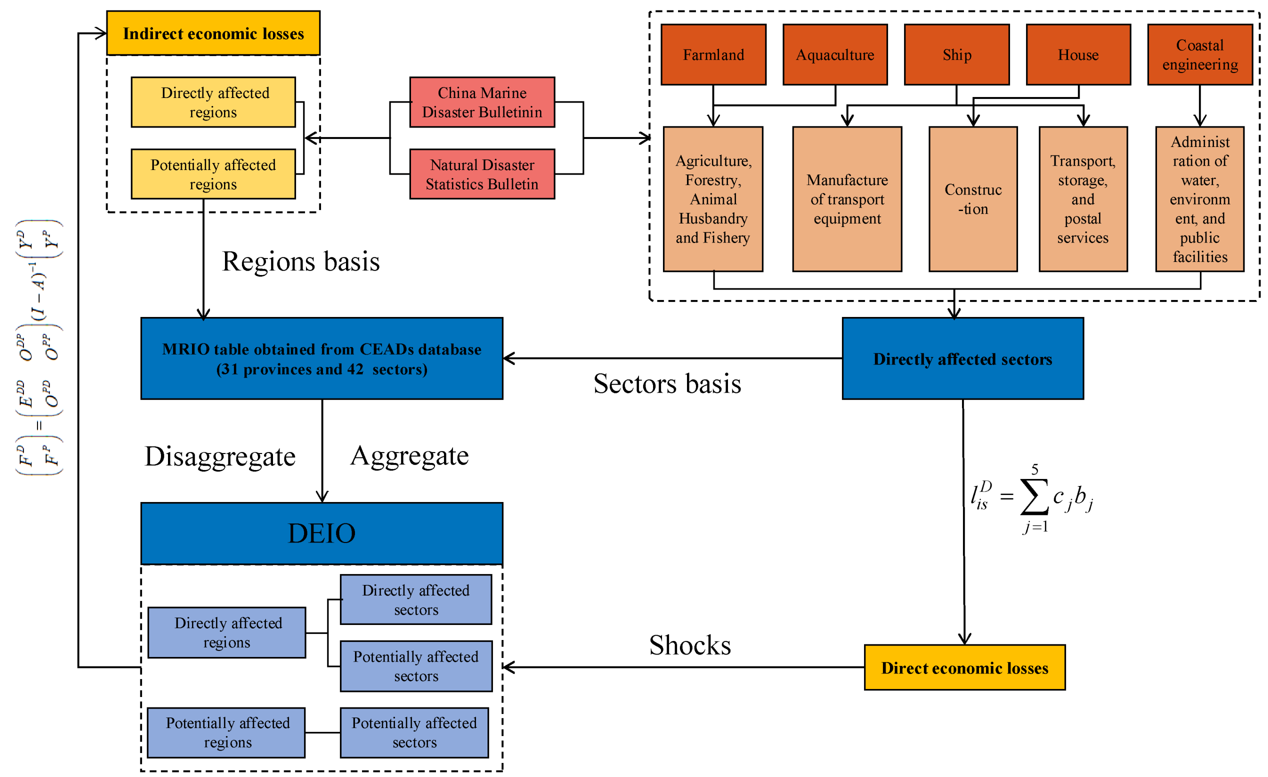

FIGURE 1
The analytical framework and structure for economic footprint of storm surge disasters.

3.2 DEIO model construction and indirect economic impact assessment

3.2.1 DEIO model construction

The MRIO model, derived from Leontief's economic input-output model (Leontief, 1986), is a tool designed to characterize economic activities and their interconnections across multiple regions. Building upon traditional input-output models, it extends the analytical scope by integrating production, consumption, and trade activities from different regions into a unified framework. This approach effectively reveals inter-regional economic dependencies, making it particularly valuable for studying cross-regional economic linkages, resource flows, and environmental impacts. As such, the MRIO model is widely applied in fields like trade analysis, environmental economics, and regional development research. The DEIO model is a methodology for measuring the spread of economic losses resulting from disasters across various industries and regions based on input-output relationships. The DEIO model categorizes regions into directly affected regions and potentially affected regions, and sectors into directly affected sectors and potentially affected sectors, which is as illustrated in Table A1. Essentially, the DEIO model functions as a MRIO model.

For the storm surge disasters in China, we utilized the China MRIO table in CEADs database as the basis for the DEIO table. This table is constructed based on the entropy theory and gravity model, covering 31 provinces and 42 socio-economic sectors (Zheng et al., 2020). The MRIO table is already balanced, eliminating the need for additional balancing procedures. To construct the DEIO table for storm surge disasters in China, we made modifications to the CEADs data by disaggregating and aggregating bilateral trade data between industries based on the geographic distribution and the type of hazard-affected bodies. Specifically, we made adjustments to the MRIO table obtained from the CEADs database in the following three aspects.

First, we conducted data collection and analysis on storm surge disasters in China from 2011 to 2020. We compiled information on the locations where these disasters made landfall, their tracks, the regions they affected, and the resulting losses. This allowed us to identify the annual direct disaster regions (for the DEIO of storm surge disasters of China, $k \leq 11$ and $m \geq 20$ in Figure A1) and the direct hazard-affected bodies that were directly affected by the storm surge disasters.

Second, we merged directly hazard-affected bodies into the related sectors according to the Natural Disaster Statistics Bulletin formulated by the National Bureau of Statistics and Ministry of Emergency Management of the People's Republic of China. Specifically, farmland and aquaculture are mapped to the Agriculture, Forestry, Animal Husbandry and Fishery sector; ships are mapped to the Manufacture of transport equipment sector and Transport, storage, and postal services sector; houses are mapped to the Construction sector; and coastal engineering are mapped to the administration of water, environment, and public facilities sector.

Third, the 42 socio-economic sectors based on MRIO in CEADs database were aggregated into 9 sectors. Simultaneously, for the regions directly affected by storm surge disasters, we extracted and disaggregated the sectors corresponding to the directly hazard-affected bodies, which were then merged into the directly affected sectors of storm surge disasters. Table A2 presents a complete list of the sectors classification in DEIO table of storm surge disasters in China, which was mapped to sectors and sub-sectors.

3.2.2 Event matrix

The Event Matrix is a crucial tool for systematically assessing the economic, social, and environmental impacts of natural disasters. By collecting and integrating loss data across various sectors after disaster events, it provides a comprehensive perspective for analyzing multifaceted disaster impacts (Faturay et al., 2020). The primary step in constructing a Disaster Event Matrix involves obtaining detailed disaster loss information and data, typically sourced from government reports, assessments by non-governmental organizations, and academic research. Direct economic losses covered by the matrix primarily include property damage and infrastructure destruction, such as losses to residential and commercial buildings, farmland, aquaculture facilities, transportation networks, and communication infrastructure. These direct losses manifest immediately after a disaster and exert substantial impacts on the economic and social fabric of affected regions. To describe the impacts of storm surge disasters on the national social and economic system, we used the direct losses data of storm surge disasters over the years to construct the event matrix of the directly affected regions.

According to the Bulletin of China Marine Disaster and Bulletin of Natural Disaster Statistics, the five primary types of directly hazard-affected bodies by storm surge disasters are farmland, aquaculture, coastal engineering, houses, and ships. The basic calculation method for determining direct economic losses can be expressed as follows:

$$l_i^D = \sum_{j=1}^{5} c_{ij} b_{ij}$$

where l_i^D is the direct economic losses of storm surge disaster in direct disaster region i, $c_{ij}$is the actual value of hazard-affected body $j$before damage in direct disaster region i, b_{ij} is the damage rate of hazard-affected body $j$in direct disaster region i.

The degree of damage in direct disaster region i can be calculated as $e_i = l_i^D / y_i$, where e_i is the degree of damage in direct disaster region i, y_i is the added value of directly affected sectors of storm surge disaster in region i.

At the same time, considering other seven industrial sectors in each directly affected region, the shock vector of each region is $E_i = (0, \cdots, 0, e_i)^T$, where E_i is the shock vector in direct disaster region i.

The following formula can obtain the event matrix of storm surge disasters in the directly affected regions $E = diag(E_1, \cdots, E_k)$, $k \le 11$, where E is the event matrix, $diag(E_1, \cdots, E_k)$represents the diagonal matrix.

3.2.3 Indirect economic impact assessment

In our indirect economic impact assessment and analytical framework of storm surge disasters, although the storm surge disasters only caused damage to the hazard-affected bodies in the coastal areas, the impacts of the disasters would spread to the whole country through the industrial chain due to the highly interconnected and interdependent economies of various regions in China. We assumed that, without considering the planning of post-disaster reconstruction, the damage to the hazard-affected bodies caused by storm surge would only be recovered by reducing the final demand. Then the storm surge shocks (see Figure 1) were introduced and injected into the final demand block. Furthermore, since the focus of this paper is to analyze the annual impact of storm surge disasters on the economic system, we assume that the economic structure of each province remains fixed in the given year. Following Liu et al. (2023), we align the input-output structure with the year closest to the analyzed period. Specifically, for the years 2011–2014, we use the 2012 multi-regional input-output table; for 2015 and 2016, we adopt the 2015 table; and for 2017–2020, we apply the 2017 multi-regional input-output table. It is worth noting that the actual economic and social system includes plans for storm surge disaster reconstruction, which would influence the distribution of economic elements' supply and demand. However, this aspect is out of the scope of our study in this work.

Assuming that there are m regions and k sectors in each region of directly affected regions, n regions and l sectors in each region of potentially affected regions of storm surge disasters, the mathematical structure of the DEIO model of storm surge disasters is composed of $(m \cdot k + n \cdot l)$ linear equations. For the directly affected regions, the regional production activities have the following balance:

$$x_q^{D(i)} = \sum_{i'=1}^{m}\sum_{r=1}^{k} z_{qr}^{DD(i\to i')} + \sum_{j=1}^{n}\sum_{r=1}^{l} z_{qr}^{DP(i\to j)} + \sum_{i'=1}^{m} y_q^{DD(i')} + \sum_{j=1}^{n} y_q^{DP(j)}$$

where $x_q^{D(i)}$ denotes the total output of sector q of a directly affected region i, $z_{qr}^{DD(i\to i')}$represents the intermediate input from sector q to sector r between the directly affected regions, $z_{qr}^{DP(i\to j)}$ represents the intermediate input from sector q to sector r between the directly affected regions and the potentially affected regions, $y_q^{DD(i')}$denotes the input of the sector q in the directly affected regions to the final demand in the directly affected regions, $y_q^{DP(j)}$ represents the input of the sector q in the directly affected regions to the final demand in the potentially affected regions.

In the same way, for the potentially affected regions, the regional production activities have the following balance:

$$x_r^{P(j)} = \sum_{i=1}^{m}\sum_{q=1}^{k} z_{rq}^{PD(j\to i)} + \sum_{j'=1}^{n}\sum_{q=1}^{l} z_{rq}^{PP(j\to j')} + \sum_{i=1}^{m} y_r^{PD(j\to i)} + \sum_{j'=1}^{n} y_r^{PP(j')}$$

where $x_r^{P(j)}$ represents the total output of sector r of a potentially affected region, $z_{rq}^{PD(j\to i)}$ denotes the intermediate input from sector r to sector q between the potentially affected regions and the directly affected regions, $z_{rq}^{PP(j\to j')}$ represents the intermediate input directly affected regions, $y_r^{PD(j\to i)}$represents the input of the sector r in the potentially affected regions to the final demand in the directly affected regions, $y_r^{PP(j')}$denotes the input of the sector r in the potentially affected regions to the final demand in the potentially affected regions.

The direct input coefficient represents the direct input from the sector q in one region to the sector r in another region. The calculation formula is as follows $a_{qr}^{DD} = z_{qr}^{DD}/x_r^{DD}$, $a_{qr}^{DP} = z_{qr}^{DP}/x_r^{DP}$, $a_{qr}^{PD} = z_{qr}^{PD}/x_r^{PD}$, $a_{qr}^{PP} = z_{qr}^{PP}/x_r^{PP}$, where a_{qr}^{DD} is the direct input coefficient of sectors of the directly affected regions, a_{qr}^{PD} is the direct input coefficient of sectors between the directly affected regions and the potentially affected regions, a_{qr}^{DP} is the direct input coefficient of sectors between the potentially affected regions and the directly affected regions, $a_{qr}^{PP}$is the direct input coefficient of sectors of the potentially affected regions.

To sum up, we obtain the equation described as $X = AX + Y$, where X represents the whole total output matrix, A denotes the whole direct consumption matrix, and Y represents the whole final demand matrix of DEIO. We then obtain that $X = (I - A)^{-1}Y$, where I is the identity matrix, $(I - A)^{-1}$ represents Leontief inverse coefficient.

The economic footprints of storm surge disasters are calculated using DEIO analysis. Based on the event matrix of storm surge disasters, the economic footprint transfer matrix of storm surge disasters among regions can be determined as follows:

$$\begin{pmatrix} F^D \\ F^P \end{pmatrix} = \begin{pmatrix} E^{DD} & O^{DP} \\ O^{PD} & O^{PP} \end{pmatrix} (I - A)^{-1} \begin{pmatrix} Y^D \\ Y^P \end{pmatrix}$$

here,

$$A = \begin{pmatrix} A^{DD} & A^{DP} \\ A^{PD} & A^{PP} \end{pmatrix}$$

E^{DD} represents event matrix, and O^{DP}, O^{PD}, O^{PP}represent zero matrix, $F^D$is the indirect economic impacts in the directly affected regions and $F^P$is the indirect economic impacts in the potentially affected regions of storm surge disasters. Furthermore, the representation above considering Taylor expansion of the Leontief inverse matrix is

$$\begin{pmatrix} F^D \\ F^P \end{pmatrix} = \begin{pmatrix} E^{DD} & O^{DP} \\ O^{PD} & O^{PP} \end{pmatrix} \left(I + A + A^2 + A^3 + \cdots\right) \begin{pmatrix} Y^D \\ Y^P \end{pmatrix}$$

which enables precise track the cascading effects of storm surge-induced economic losses.

3.3 Data sources

In this study, the storm surge disasters data used for the economic footprint accounting of storm surge disasters are from the Bulletin of China Marine Disaster spanning from 2011 to 2020. The primary input-output table data are derived from the CEADs database (Zheng et al., 2020), specifically the MRIO table encompassing 42 sectors across 31 regions in China for the years 2012, 2015, and 2017. For the convenience of the research, we have consolidated the 42 sectors into 8 sectors in the directly affected regions and 9 sectors in the potentially affected regions based on considering the sectors directly affected by storm surge disasters (refer to Table A2 for further details).

4 Results and discussion

4.1 Temporal and regional distribution analysis of economic footprint of storm surge disasters

4.1.1 Temporal analysis of direct economic loss

The storm surge disasters mainly caused damage to farmland, aquaculture, coastal engineering, house and ship. Figure 2 illustrates the direct economic losses incurred by these affected assets from 2011 to 2020. Over the past decade, the storm surge losses in China have exhibited a fluctuating trend, with an estimated average direct economic loss of 8082.1091 million RMB.

Moreover, it is important to note that the direct economic losses incurred in the years 2012, 2013, 2014, and 2019 exceeded the average direct economic loss, while in the remaining years, they were lower than the average. Notably, the highest direct economic loss was observed in 2013, amounting to 15,396 million RMB, whereas the lowest occurred in 2020, totaling 810 million RMB. The ratio of direct economic loss to GDP exhibited a similar trend to the direct economic loss, experiencing a significant decline after 2015, despite a notable increase in 2019. Comparing the direct economic losses in 2012 and 2019, it is evident that the direct economic loss in 2012, amounting to 12,629 million RMB, accounted for 0.0463% of the GDP in the directly affected regions. Conversely, the direct economic loss in 2019, totaling 11,638 million RMB, only accounted for 0.0282% of the GDP. This suggests that although the absolute value of direct economic loss resulting from storm surge disasters remains relatively high due to their sudden, random, and uncertain nature, the proportion of direct economic loss to GDP in the directly affected regions is consistently decreasing. This phenomenon may be attributed primarily to the implementation of disaster prevention policies and advancements in science and technology in China (Shi et al., 2015; Lin et al., 2023).

4.1.2 Provincial indirect economic loss analysis and comparison

The distribution of indirect economic losses caused by storm surge disasters in the 31 provinces of China for each year from 2011 to 2020 is presented in Figure 3. The data is displayed in logarithmic form to provide a clearer representation of the loss distribution. The highest indirect economic loss occurred in 2013, amounting to 38,012.39 million RMB. The second-highest and third-highest indirect economic losses were observed in 2012 and 2014, totaling 34,648.85 million RMB and 33,275.95 million RMB, respectively. It is worth noting that this distribution differs slightly from the distribution of direct economic losses depicted in Figure 2.

In terms of each province's annual indirect economic losses, certain regularities can be observed. The highest indirect economic loss still occurred to the directly affect regions. For instance, in 2013, Guangdong incurred a direct economic loss of 7420 million RMB, leading to an indirect economic loss of 13374.84 million RMB. Similarly, in 2019, Zhejiang suffered a direct economic loss of 8726 million RMB, resulting in an indirect economic loss of 11812.29

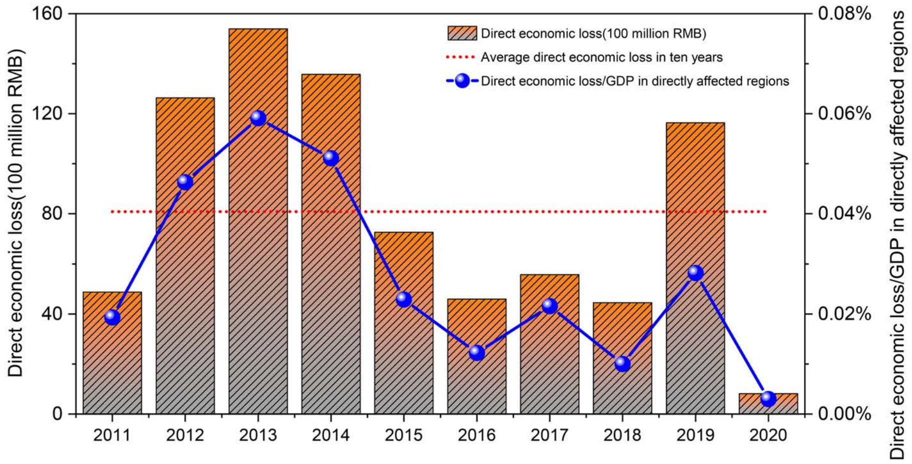

FIGURE 2
The direct economic losses of storm surge disasters in China from 2011 to 2020.

million RMB. The ratio of indirect losses to direct losses for Guangdong and Zhejiang was 180.25% and 135.37% respectively. This finding is consistent with Hallegatte's research (Hallegatte, 2008), which indicates that indirect losses can range from 50% to 250% of direct losses.

Potentially affected regions are also impacted to some extent by storm surges. Coastal regions usually take measures to respond to these disasters, while inland regions often neglect them. However, inland regions are prone to being affected by storm surges as well. From 2011 to 2020, Henan, Anhui, Jiangxi, Shaanxi, and Beijing consistently ranked among the top eight inland regions severely affected by storm surge disasters. Furthermore, regions like Hunan, Chongqing, Jilin, and Shanxi also experienced severe impacts from storm surges. Among them, Henan was the most severely affected inland region. In contrast, Tibet, Qinghai, and Ningxia consistently ranked among the top three inland regions with minimal impact from storm surge disasters.

We assessed the spread degree of storm surge damage by analyzing the ratio of indirect economic loss to total economic loss and the ratio of indirect economic loss in potential disaster regions to indirect economic loss. These ratios provided insights into the diffusion of economic losses at both national and regional levels. The total economic loss, referred to as the economic loss footprint, encompassed national direct economic loss and national indirect economic loss. At the national level, the ratio of indirect economic loss to total economic loss remained relatively stable at around 72% from 2011 to 2016, around 65% from 2017 to 2020 except 2018, and for a peak of 73.30% in 2015. This turning point may be attributed to the implementation of the National Comprehensive Disaster Prevention and Mitigation Planning (2016-2020) by the Chinese government. This plan emphasized the enhancement of natural disaster relief policies, the establishment of information sharing mechanisms for disaster prevention, mitigation, and rescue, and the cultivation of market participation in disaster management. These measures effectively curtailed the spread of storm surge damage. At the regional level, the ratio of indirect economic loss in potential disaster regions to indirect economic loss fluctuated around 15% from 2011 to 2020, indicating that these regions consistently suffered from storm surge damages. Notably, the lowest ratio of 7.15% was observed in 2014, while the highest ratio of 26.33% occurred in 2018. This was because Hainan Province, as not directly affected region by the storm surge disaster in 2018, was also largely affected by the storm surge disaster, whose indirect economic loss reached 1955.74 million RMB and accounted for 18.53% of the indirect economic loss that year.

4.1.3 Regional distribution analysis of the direct and indirect economic loss

Taking into account the intensity, time span, distribution of losses, and size of storm surge disasters, a detailed comparison and comprehensive analysis were conducted, focusing on the storm surge disasters that occurred in 2012, 2015, 2017, and 2020 (the same below). The economic losses among the 31 affected regions in China were depicted in the regional distribution maps presented in Figure 4, which were classified based on the quantile method.

Figure 4A illustrates the distribution of direct economic losses in 2012. Zhejiang, Shandong and Hebei (the darkest region) were the most strongly affected region, accounting for 74.91% of direct economic losses. The distribution of the other regions includes Guangdong with 13.83%, Jiangsu with 4.87%, Guangxi with 4.22%, Fujian with 2.09%, Shanghai with 0.05% and Tianjin with 0.03%. Additionally, the storm surge disasters had a ripple effect on regional industrial chains, resulting in an additional 34648.85 million RMB of economic losses, as shown in Figure 4B. Consequently, the economic footprint of the 2012 storm surges in China amounted to 47277.85 million RMB, equivalent to 0.09% of China's GDP that year. Among the affected regions, Zhejiang experienced the highest indirect economic losses, accounting for 25.48% (8828.38 million RMB) of the total. Henan was identified as the most vulnerable potential disaster region, with 1.79% (618.67 million RMB) of indirect economic losses among all potentially

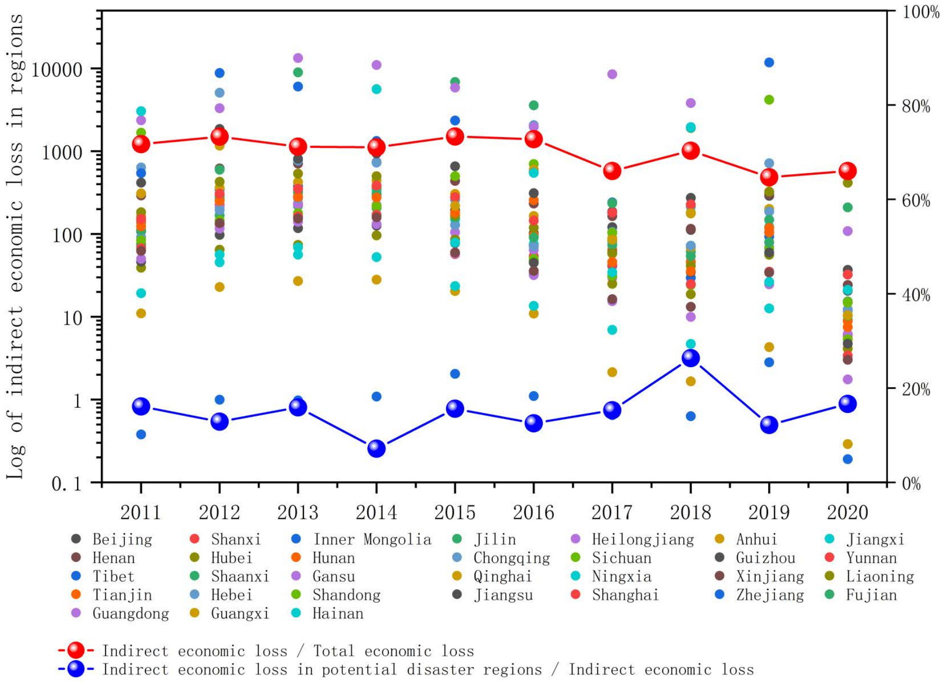

FIGURE 3
The indirect losses of storm surge disasters in China from 2011 to 2020.

affected regions. In contrast, Tibet was the least affected potential disaster region, with only 0.003% (0.10 million RMB) of losses. Noteworthy regions also include Shandong and Hebei, which represented 40.03% (13870.57 million RMB) of national indirect economic losses, as well as Guangdong (9.54%, 3307.19 million RMB), Jiangsu (5.36%, 1856.65 million RMB), and Guangxi (3.38%, 1169.74 million RMB).

Figure 4C illustrates the distribution of direct economic losses resulting from storm surges in 2015. The southeastern coastal regions of China, namely Fujian, Guangdong, and Zhejiang, bore the brunt of the damage, accounting for 42.40%, 39.60%, and 14.42% of the national direct economic losses, respectively. Conversely, other affected regions outside the southeast coast, such as Shandong, Jiangsu, Shanghai, Guangxi, and Hainan, collectively experienced less than 3% of the national direct economic losses. The geographical distribution of indirect economic losses is presented in Figure 4D. Notably, Fujian suffered the largest proportion of indirect losses, surpassing one-third of the national indirect economic losses (6873.47 million RMB). Henan emerged as the most vulnerable potential disaster region, contributing 14.10% of the indirect economic losses among all potentially affected regions, similar to the situation in 2012. Figures 4E, F depict the distribution of direct and indirect economic losses in 2017, respectively, while Figures 4G and H illustrate the same for 2020. A detailed analysis and description of these figures will not be reiterated here. However, it is worth mentioning that in 2017, Guangdong accounted for 96.13% (5361 million RMB) of the national direct economic losses from storm surge disasters and also experienced the largest indirect economic losses (8507.22 million RMB). Additionally, although Jiangsu and Shanghai were not directly impacted by storm surges in 2017 and 2020, they ranked among the top two potentially affected regions with the highest indirect economic losses, followed by Henan.

Based on the comparative analysis presented in Figure 4, it can be inferred that the southeastern coastal regions of China experienced a significantly greater impact from storm surge disasters compared to the northern coastal regions. This finding aligns with the research conducted by Wang K. et al. (2021). Additionally, the indirect economic losses in different regions varied greatly and reflected the response to storm surge disaster in some way. This discrepancy may be related to the regional economic structures (Mendoza-Tinoco et al., 2020). In economies that are more interconnected, industries heavily rely on intermediate inputs to sustain production, rendering them more susceptible to disasters that disrupt intermediate production through direct shocks to industrial capital, and leading to higher losses along the production chain (Shughrue et al., 2020).

4.2 Diffusion of economic footprint of storm surge disasters analysis

Before analyzing the diffusion of storm surge disaster loss flows between sectors and regions, the diffusion ratios of storm surge disasters were analyzed and discussed, as presented in Table 1. Shandong exhibited the highest diffusion ratio within the region in 2012, accounting for 88.66%, followed by Fujian and Hebei with diffusion ratios within the region of 84.33% and 83.11%,

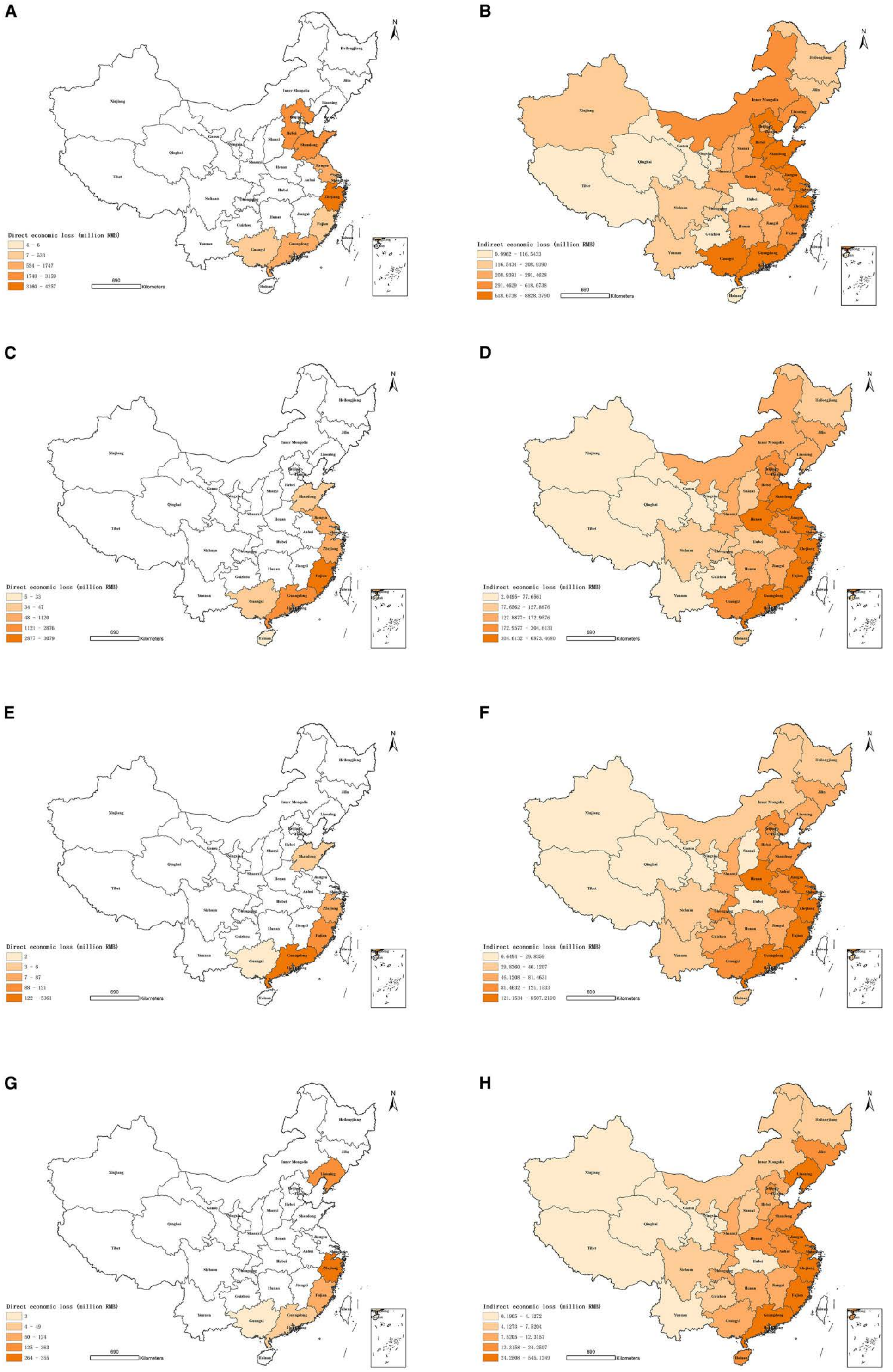

FIGURE 4
Regional distribution of the direct and indirect economic loss of storm surge disasters in China. **(A, C, E, G)** indicate the direct economic loss of storm surge disasters in 2012, 2015, 2017, and 2020, respectively. **(B, D, F, H)** show the indirect economic loss of storm surge disasters in 2012, 2015, 2017, and 2020, respectively.

respectively. This indicates that the economic production of Shandong, Fujian and Hebei in 2012 relied heavily on the intermediate input within the province, resulting in the predominant spread of storm surge disaster losses within the province. Regarding the diffusion ratio within the coastal regions, Shandong, Fujian, and Hebei remained in the top three. Comparing the diffusion ratio within the region and the diffusion ratio within the coastal regions of storm surge disasters, it is evident that the economic structures of Shanghai and Tianjin were closely interconnected with the rest of the coast, leading to the

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TABLE 1 Diffusion ratio of storm surge disaster losses in the directly affected regions.

Direct economic loss and diffusion ratio		Liaoning	Tianjin	Hebei	Shandong	Jiangsu	Shanghai	Zhejiang	Fujian	Guangdong	Guangxi	Hainan
2012	Direct economic loss (million RMB)	/	4	2044	3159	615	6	4257	264	1747	533	/
	Diffusion ratio within the region	/	72.33%	83.11%	88.66%	75.53%	59.84%	72.00%	84.33%	73.92%	79.69%	/
	Diffusion ratio within the coastal regions	/	86.33%	90.61%	93.08%	85.68%	79.52%	84.87%	91.63%	86.54%	89.87%	/
2015	Direct economic loss (million RMB)	/	/	/	44	58	5	1120	3079	2876	47	33
	Diffusion ratio within the region	/	/	/	90.15%	73.38%	62.39%	59.08%	84.72%	74.63%	77.97%	55.75%
	Diffusion ratio within the coastal regions	/	/	/	94.82%	84.16%	81.26%	78.01%	91.89%	87.51%	89.99%	79.10%
2017	Direct economic loss (million RMB)	/	/	/	6	/	/	87	121	5361	2	/
	Diffusion ratio within the region	/	/	/	86.68%	/	/	77.13%	87.56%	81.65%	78.27%	/
	Diffusion ratio within the coastal regions	/	/	/	93.64%	/	/	89.07%	93.09%	90.14%	89.71%	/
2020	Direct economic loss (million RMB)	263.36	/	/	/	/	/	354.83	124.03	49.19	3.25	15.30
	Diffusion ratio within the region	79.75%	/	/	/	/	/	77.16%	87.59%	81.68%	78.30%	72.76%
	Diffusion ratio within the coastal regions	89.99%	/	/	/	/	/	89.07%	93.10%	90.15%	89.71%	86.12%

(1) Diffusion ratio within the region refers to the proportion of the indirect economic loss in the region directly affected by storm surge disaster to the total indirect economic loss induced from the directly affected region. (2) Diffusion ratio within the coastal regions refers to the proportion of indirect economic losses in whole coastal regions that spread from the region directly affected by storm surge disasters to the total indirect economic losses induced from the directly affected region. Here, the whole coastal regions include Liaoning, Tianjin, Hebei, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, Guangdong, Guangxi, and Hainan. (3)/indicates that the storm surge did not cause direct economic losses to the region in that year.

propagation of storm surge damage losses to the surrounding coastal areas. In 2015, the diffusion ratios within the region and the diffusion ratios within the coastal regions of all directly affected regions, except Zhejiang, remained almost unchanged compared to 2012. Specifically, the diffusion ratio within the coastal regions of Zhejiang decreased from 84.87% in 2012 to 78.01% in 2015, while the diffusion ratios of Zhejiang to Henan and Anhui increased from 2.81% and 1.32% in 2012 to 5.25% and 2.61% in 2015, respectively. This indicates that the economic structures of Zhejiang underwent adjustments, strengthening the economic relationships with inland regions and consequently expanding the spread of storm surge disaster losses to the inland regions along the regional industrial chain. Comparing the data from 2015, the diffusion ratios within the region of Zhejiang and Guangdong in 2017 exhibited an upward trend, particularly in Zhejiang, which may be related to supply-side structural reform. In 2020, the diffusion ratios within the region and the diffusion ratio within the coastal regions of Zhejiang, Fujian, Guangdong, and Guangxi remained similar to those in 2017, largely due to the utilization of the same input-output structure for the calculations and the relatively stable industrial structure in coastal regions.

In addition, the diffusion of economic losses caused by storm surges across the entire nation was further discussed. To facilitate the presentation and analysis of findings, 31 provinces and cities were aggregated into eight regions. Figure 5 illustrates top 3 diffusion flows of storm surge economic loss from North Coast, East Coast and South Coast during the years 2012, 2015, 2017, and 2020.

Figure 5 illustrates the diffusion of storm surge economic loss embodied in domestic trade within China. It is evident that the North Coast, East Coast, and South Coast regions are particularly susceptible to storm surges and consistently experience the most severe impacts yearly. Furthermore, in 2012, 2015, 2017, and 2020, the primary destinations which storm surge economic losses transmitted from the North Coast, East Coast, and South Coast regions directed toward are the North Coast, East Coast, South Coast, Central, and Inland North regions. Conversely, the Northwest and Southwest regions generally exhibit lower levels of indirect economic losses resulting from storm surge disasters. In detail, the North Coast experienced the most significant indirect economic loss in 2012, amounting to 14550 million RMB. The East Coast propagated substantial economic losses to the North Coast and Central regions, with losses amounting to 1072 and 918 million RMB, respectively. In 2015, the South Coast bore the brunt of the highest indirect economic loss, which was estimated at 13043 million RMB. This region also spread economic losses to the East

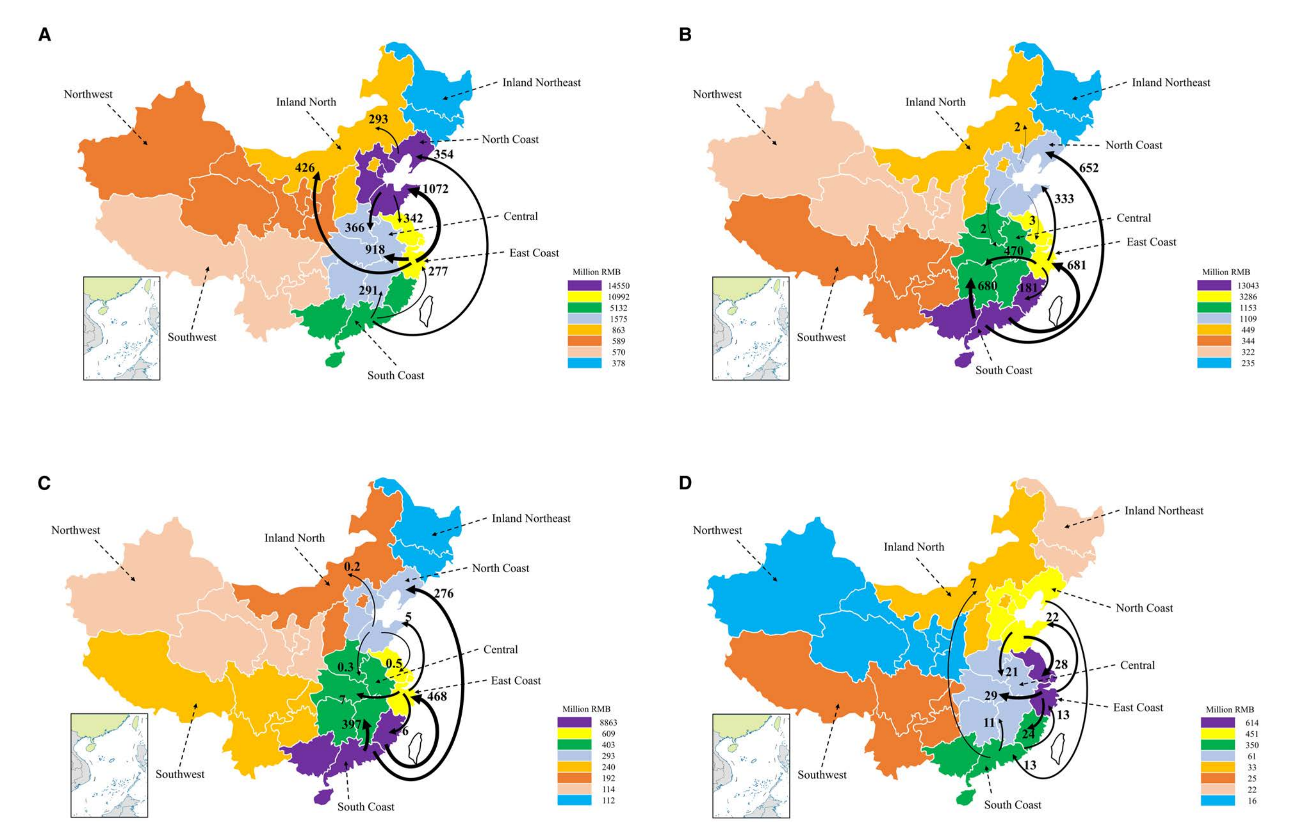

FIGURE 5
The diffusion of storm surge economic loss among eight regions. Inland Northeast includes Heilongjiang and Jilin; North Coast includes Liaoning, Tianjin, Hebei and Shandong; East Coast includes Jiangsu, Shanghai and Zhejiang; South Coast includes Fujian, Guangdong, Guangxi and Hainan; Inland North includes Inner Mongolia, Beijing and Shanxi; Central includes Henan, Anhui, Jiangxi, Hubei and Hunan; Northwest includes Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang; Southwest includes Chongqing, Sichuan, Guizhou, Yunnan and Tibet. For clarity, the top 3 diffusion flows of storm surge economic loss from North Coast, East Coast and South Coast of 2012, 2015, 2017 and 2020 were indicated in **(A–D)**, respectively.

Coast, Central regions, and North Coast, with losses amounting to 681, 680, and 652 million RMB, respectively. In 2017, due to Guangdong's contribution of 96.13% to the national direct economic loss from storm surge disasters, the majority of indirect economic losses were disseminated from this region. As a result, the South Coast suffered the highest indirect economic loss, amounting to 8863 million RMB, who's top 3 regions spread remained the same as in 2015. In 2020, the East Coast experienced the highest indirect economic loss, amounting to 614 million RMB, and primarily disseminated the economic loss to the Central regions, with losses amounting to 29 million RMB. As previously mentioned, it can be seen that the Central regions, due to their geographical bordering to the North Coast, East Coast, and South Coast, were significantly impacted by the diffusion of economic losses from storm surge disasters (Ning et al., 2019). Consequently, the Central regions became the potentially affected region that were most seriously hit by the storm surge disasters.

4.2.1 Economic loss diffusion sectoral analysis within directly affected regions

The diffusion of embodied storm surge disaster losses across various sectors in directly affected regions is depicted in Figure 6. As indicated in Table 1, the diffusion ratio within the region in the directly affected regions consistently surpassed 50% across all years. The top three pairs of embodied storm surge disaster loss flows (as illustrated in Figure 6) were consistently found in S8 of the top three directly affected regions, with the exception of 2017. These pairs were Zhejiang-ZhejiangS8, Shandong-ShandongS8, and Hebei-HebeiS8, with losses amounting to 5217.78 million RMB, 4207.87 million RMB, and 2509.12 million RMB in 2012, respectively. In 2015, the pairs were Fujian-FujianS8, Guangdong-GuangdongS8, and Zhejiang-ZhejiangS8, with losses of 3675.02 million RMB, 3499.64 million RMB, and 1409.07 million RMB, respectively. In 2017, the pairs were Zhejiang-ZhejiangS8, Liaoning-LiaoningS8, and Fujian-FujianS8, with losses of 420.75 million RMB, 331.65

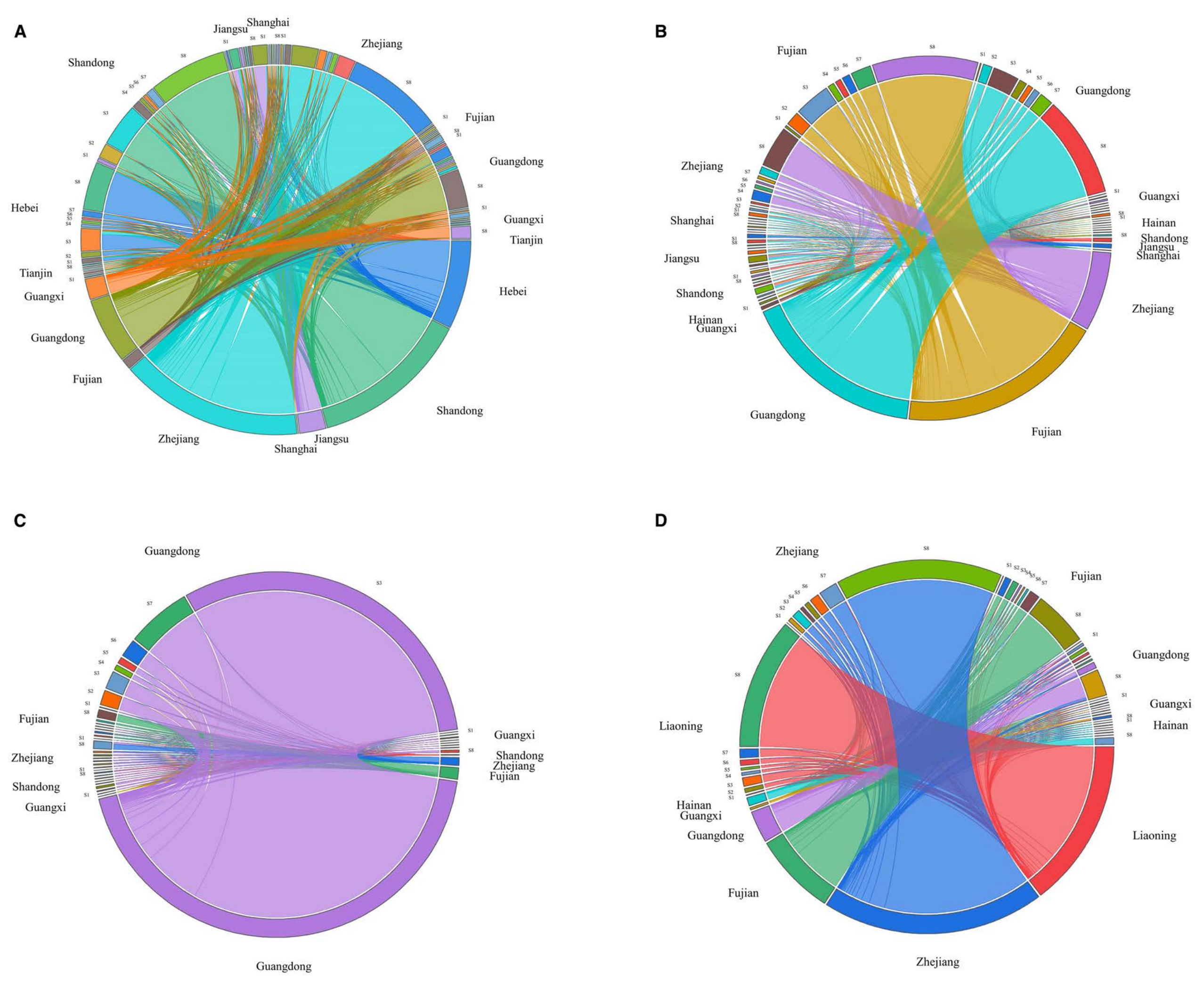

FIGURE 6
The diffusion of storm surge economic loss among different sectors in the directly affected regions. **(A–D)** indicate the diffusion of storm surge economic loss among different sectors in the directly affected regions in 2012, 2015, 2017, and 2020, respectively.

million RMB, and 140.95 million RMB, respectively. However, in 2017, due to Guangdong contributing 96.13% to the national direct economic losses from storm surge disasters, the top three embodied storm surge disaster loss flows pairs were found in Guangdong-GuandongS8, Guangdong-GuangdongS7, and Guangdong-GuangdongS3, with losses of 6240.80 million RMB, 1150.11 million RMB, and 318.58 million RMB, respectively.

From the perspective of the sectoral diffusion ratio of storm surge disasters, the embodied loss diffusion with the top three highest proportions typically transpired in S8, S3 (Resource processing industry shown in Table A2) and S7 (Service department shown in Table A2). The sectoral diffusion ratios within the region, such as Jiangsu-JiangsuS8, were around 50% in 2012 and 2015, escalating to over 60% in 2017 and 2020. This suggests that the propensity for disaster losses to permeate other potentially affected sectors is diminishing with the enhancement of disaster prevention and mitigation capabilities. The inter-provincial sectoral diffusion ratios within the directly affected regions were also notably large in S3 and S8. Specifically, the top three embodied storm surge disaster loss flow pairs among inter-provincial sectors were observed in Shanghai-HebeiS3, Shanghai- ShandongS3 and Zhejiang-HebeiS3, accounting for 2.61%, 2.21% and 2% respectively in 2012. In 2015, these were observed in Zhejiang-JiangsuS3, Hainan- GuangdongS3 and Hainan-JiangsuS3, accounting for 2.25%, 2.14% and 2.12%, respectively. In 2017, these were observed in Zhejiang-GuangdongS8, Guangxi-GuangdongS8 and Guangxi-GuangdongS3, accounting for 1.26%, 0.91% and 0.73%, respectively. In 2020, these were observed in Zhejiang-GuangdongS8, Guangxi-GuangdongS8 and Hainan-GuangdongS3, accounting for 1.27%, 0.92% and 0.87% respectively. By accounting the embodied loss diffusion of storm surge disasters among sectors in directly affected regions, it is evident that S8, S3, and S7 are the pivotal sectors governing the diffusion of storm surge damage loss in these inter-provincial sectors. Therefore, optimizing the industrial structure of provinces and bolstering the resilience of the industrial chain plays a crucial role in mitigating the loss diffusion of storm surge disasters (Lu et al., 2022).

4.2.2 Economic loss diffusion analysis from directly affected regions to potentially affected regions

The regions potentially impacted by storm surge disasters, which were not directly and immediately affected, were often overlooked in the analysis of the social and economic impacts of storm surge disasters. The diffusion flows of economic losses from storm surge disasters, from the directly affected regions to the potentially affected regions, are illustrated in Figure 7. Henan, a non-coastal province, consistently emerged as the most severely potentially affected region in 2012 and 2015. In 2012, 54.61% (337.83 million RMB) of Henan's indirect economic loss was disseminated by Zhejiang, with 13.28% (82.18 million RMB), 10.29% (63.64 million RMB), and 9.98% (61.75 million RMB) being attributed to Guangdong, Hebei, and Shandong, respectively. In 2015, the proportions of Henan's indirect economic loss disseminated from Zhejiang, Guangdong, and Fujian were 45.39%, 29.91%, and 21.89%, respectively. Jiangsu, a coastal province not directly impacted by the storm surge disaster in 2017 and 2020, consistently emerged as the most severely potentially affected region in these years. In 2017, approximately 96% of the indirect economic losses in Jiangsu, Shanghai, and Henan were diffused from Guangdong, because Guangdong contributed the majority of the country's direct economic losses from storm surge disasters. In 2020, Jiangsu, Shanghai, and Henan, similar to 2017, were the top three potentially affected regions most impacted by storm surge disasters, with their indirect economic losses primarily originating from Liaoning and Zhejiang. Notably, Liaoning, despite being located on the North Coast, still disseminated indirect economic losses amounting to 8.69 million RMB to Henan, which constituted 35.84% of Henan's total indirect economic losses. Furthermore, Liaoning was the primary source of indirect economic losses in Jilin, Heilongjiang, and Xinjiang, accounting for 44.99%, 42.45%, and 41.31% of their losses, respectively, even if these regions having relatively low indirect economic losses. Zhejiang was the primary source of indirect economic losses in Shanxi, Inner Mongolia, and Shanghai.

Based on the aforementioned analysis, it can be seen that coastal regions, which were not directly impacted by storm surge disasters, such as Jiangsu, often emerged as the most potentially affected regions. In addition, Henan typically emerged as the most severely impacted inland region. Specially, Guangdong-JiangsuA4, Guangdong-HenanA4, Guangdong-HenanA8 and Zhejiang-HenanA4 usually are the main economic loss diffusion pathways. This phenomenon can be attributed to the regional trade structure under the backdrop of China shifting from over-reliance on external demand to emphasizing domestic inter-regional trade (Xin et al., 2023). Additionally, storm surge disasters predominantly hit the southeast coastal areas directly. On the other hand, the proportions of intra-regional trades in China surpass those of inter-regional trades. Consequently, the potentially affected regions in the eastern coastal areas often suffer from substantial indirect economic losses from storm surge disasters. Furthermore, despite the large circular gravitation within the Central regions and the relatively small proportions of extra-regional trades, their trade partners are primarily concentrated in the coastal regions. Henan, being at the heart of China's inter-provincial trade cycle (Li and Liu, 2022), thus becomes the recipient of the diffusion of economic losses instigated by storm surge disasters in coastal regions.

4.2.3 Indirect economic loss analysis of the three major industries in potentially affected regions

Figure 8 show the impacts of storm surge disasters on three industries in the potentially affected regions. And it further delineates the proportional distribution of the primary industry losses, the secondary industry losses and the tertiary industry losses.

In 2012, Henan suffered the most tremendous indirect economic loss among potentially affected regions, amounting to 618.67 million RMB. The distribution of these losses was as follows: 8.03% were attributed to primary industry losses, 77.83% to secondary industry losses, and 14.14% to tertiary industry losses (as depicted by the blue circle in Figure 8A). In contrast, Beijing, which suffered the fifth largest loss at 291.46 million RMB, had 51.57% of its losses in the secondary industry and 47.58% in the tertiary industry, with a mere 0.85% in the primary industry

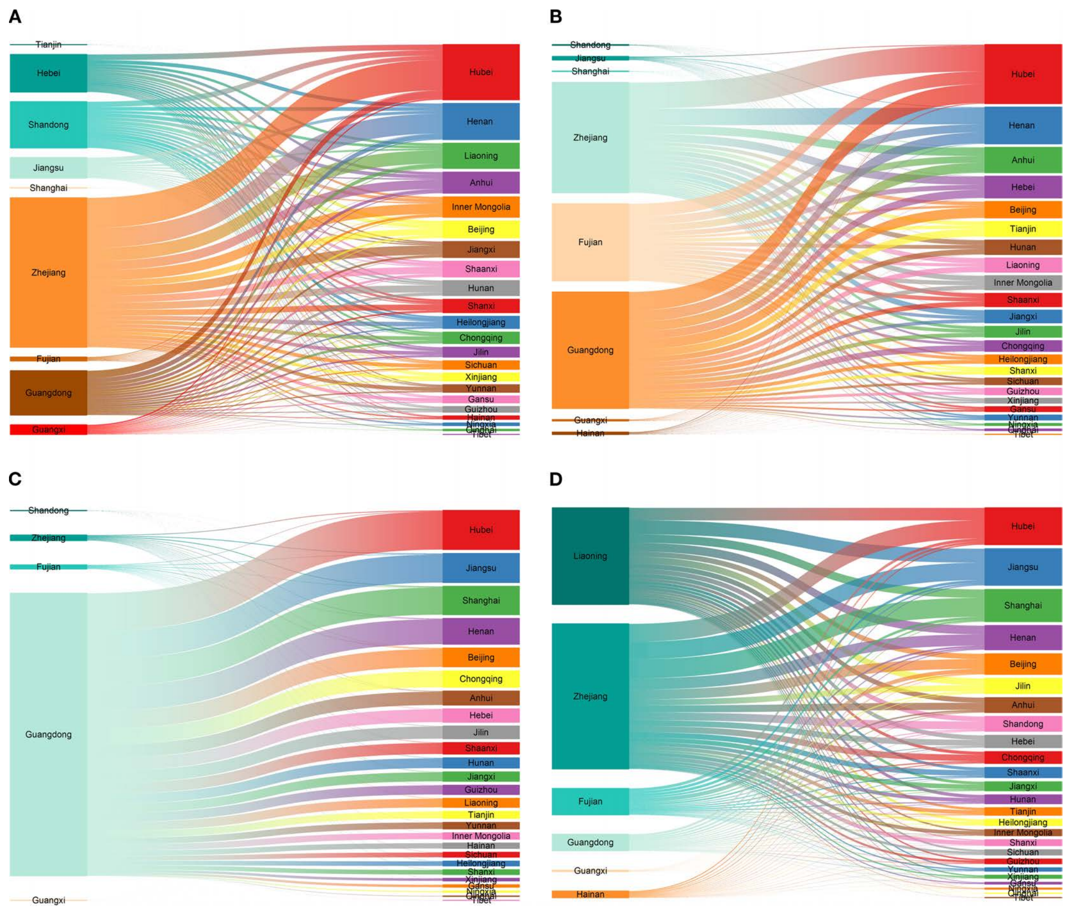

FIGURE 7
The diffusion of storm surge economic loss from the directly affected regions to the potentially affected regions. **(A–D)** indicate the diffusion of storm surge economic loss from the directly affected regions to the potentially affected regions in 2012, 2015, 2017, and 2020, respectively.

(represented by the red circle in Figure 8A). The affected sectors in other potentially affected regions were predominantly concentrated in the secondary industry (Figure 8A).

In 2015, Henan continued to bear the brunt of indirect economic losses (438.69 million RMB) among potentially affected regions. Of these losses, 5.39% were associated with the primary industry, 77.81% with the secondary industry, and 16.80% with the tertiary industry (blue circle in Figure 8B). In Beijing, 66.45% of economic losses were attributed to the tertiary industry, surpassing the proportion of losses in the secondary industry at 32.98%. Moreover, the industrial structures of the affected sectors in other potentially affected regions in 2015 had shifted compared to 2012, with the proportions of losses in the secondary industry having almost universally decreased (Figure 8B). The industrial structures of the affected sectors in potentially affected regions in 2017 (Figure 8C) and 2020 (Figure 8D) mirrored those in 2015, possibly due to the Supply-side structural reform policy aimed at reducing inventory (Green and Denniss, 2018).

However, it is noteworthy that Jiangsu experienced the most significant indirect economic loss among potentially affected regions, with 71.14% and 69.14% of losses associated with the secondary industry in 2017 and 2020, respectively. The industrial structures of the affected sectors in Shanghai in 2017 and 2020 were relatively similar to those in Beijing, with sectors impacted by storm surge disasters being more concentrated in the tertiary industry and less so in the primary industry. Specifically, 56.07% of economic losses from storm surge disasters in Shanghai (the second largest at 181.90 million RMB) in 2017 were in the secondary industry, and 43.86% were in the tertiary industry, with a negligible 0.07% in the primary industry (Goldenrod circle in Figure 8C). In 2020, 51.32% of Shanghai's economic losses (the second largest at 32.43 million RMB) were in the secondary industry, and 48.59% were in the tertiary industry, with only 0.09% in the primary industry (Goldenrod circle in Figure 8D). But, the primary industry most affected by storm surge disasters was in Heilongjiang, which accounted for 24.88% and 25.89% of indirect economic losses in 2017 and 2020, respectively.

4.3 Policy implications

Storm surge disasters have the potential to cause significant losses to resources, environment, people, and property in coastal areas. These losses are spread to other areas through inter-regional trade, thereby posing a serious challenge to China's sustained economic and social development. Given the sudden, random, and unpredictable nature of storm surge disasters (Contento

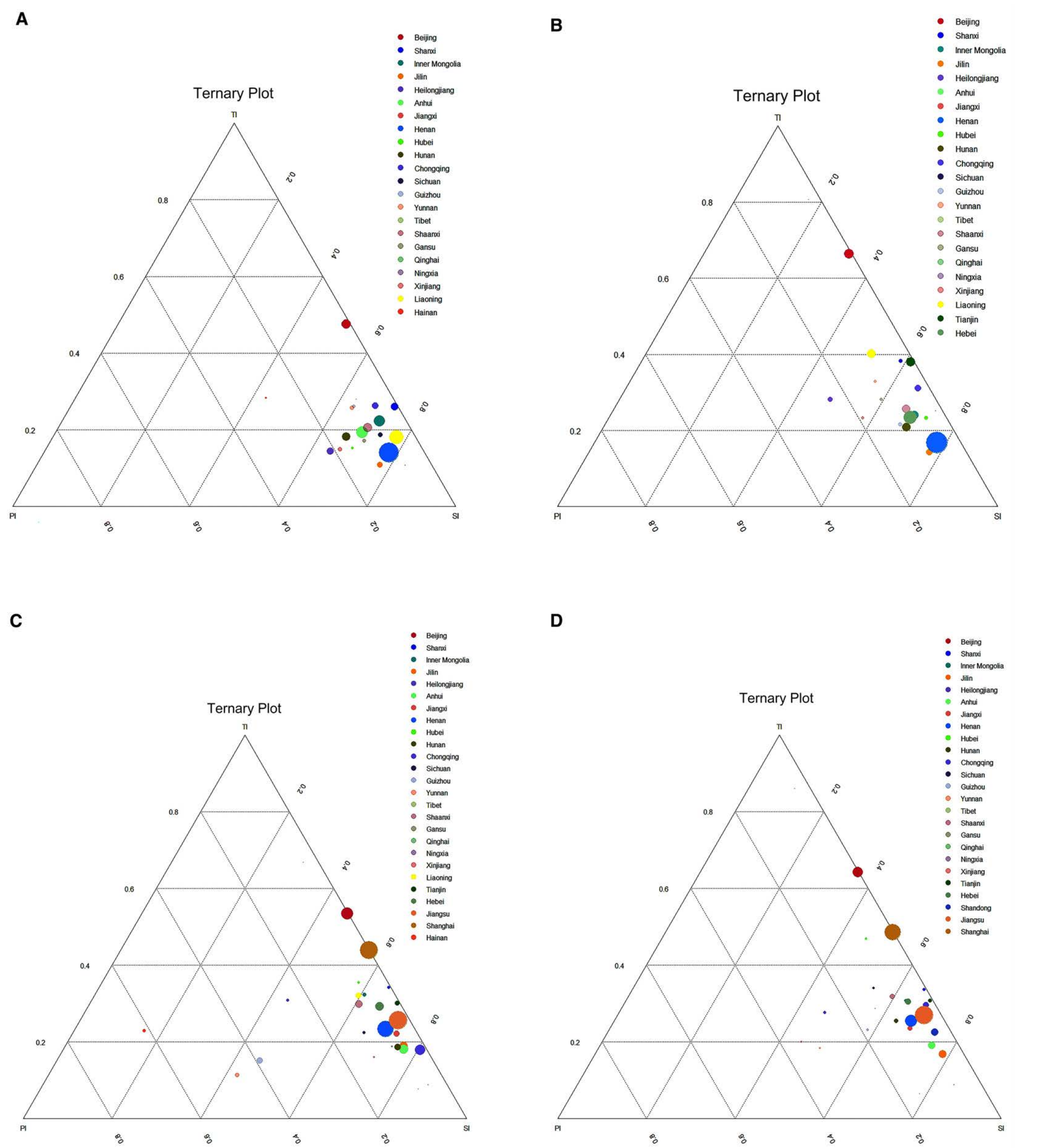

FIGURE 8
Indirect economic loss of storm surge disasters on three major industries in the potentially affected regions. Ternary plots show the magnitude of storm surge disasters impacts on three industries in the potentially affected regions of China (size of circles) as well as the relative shares of the primary industry losses, the secondary industry losses and the tertiary industry losses (positions of circles). **(A–D)** indicate the indirect economic loss of storm surge disasters on three major industries in the potentially affected regions in 2012, 2015, 2017, and 2020, respectively.

et al., 2020), there is inherent uncertainty in the directly affected areas. However, due to the relatively stable economic development structure of each region, the directly affected and potentially affected areas can take necessary disaster prevention and mitigation measures to minimize the impact of storm surge disasters on the economic and social aspects.

4.3.1 Disaster mitigation countermeasures from the perspective of coastal resilience

From the research findings, it is evident that the proportion of direct economic losses caused by storm surge disasters to the GDP of the affected areas has been decreasing. However, the absolute value of the direct economic loss is still high (Figure 2). The regions most affected by these losses are primarily located in the southeast coastal areas such as Zhejiang, Fujian, and Guangdong. It is important to note that the impact of storm surge disasters can extend beyond these regions through interregional industrial linkages, resulting in significant indirect economic losses (Figure 3). These losses pose a major obstacle to the sustainable development of China's economy and society.

To tackle this challenge, a comprehensive approach is proposed, focusing on the establishment of a robust first-line defense system aimed at preventing and mitigating the impact of storm surges. First, utilize satellite data for enhanced forecasting (Liu et al., 2023).

Leveraging the wealth of satellite data is crucial for developing highly refined and precise typhoon forecast models. By harnessing cutting-edge technology, we can significantly improve the accuracy of storm surge predictions. This improvement equips communities with the necessary time to implement preventive measures and evacuate vulnerable areas, thereby minimizing potential loss of life and property. Secondly, bolster coastal protection standards. Advocating for the implementation of standardized seawall projects introduces a consistent and dependable barrier against storm-driven surges. These engineered defenses, designed with resilience in mind, can serve as a formidable shield for coastal communities. In addition, acknowledging the delicate balance between development and conservation, a holistic perspective necessitates a reevaluation of coastal spatial planning. This reexamination allows us to harmonize the demands of development with the imperative of preserving the coastal ecosystem (Barbier, 2016; Shokatian-Beiragh et al., 2024). Striking this equilibrium involves careful consideration of sustainable coastal development practices, minimizing the ecological footprint while still facilitating growth. Finally, effective communication and community engagement are essential components of preventing disasters strategy. Not only educate communities about storm surge risks and the importance of preparedness measures, but also encourage community involvement in disaster planning and response efforts.

4.3.2 Disaster mitigation countermeasures from the perspective of industrial diffusion

In terms of the inter-industrial diffusion of storm surge disaster losses, the Resource processing industry and Service department were the sectors most severely affected by storm surge disasters in the directly affected regions (Figure 6). Apart from Beijing, Shanghai, and Heilongjiang, the industries most impacted by storm surge disasters in the potentially affected regions were typically concentrated in the secondary industry. Specifically, the tertiary industry was most affected in Beijing and Shanghai, while the primary industry was most affected in Heilongjiang (Figure 8).

To enhance the resilience of the industrial chain, with the resource processing industry at its core, a comprehensive strategy is proposed. First, strengthen the foundation of basic manufacturing. Emphasis should be placed on bolstering the foundational elements of the basic manufacturing industry. This involves enhancing the position of basic manufacturing within the industrial chain. Additionally, improving support structures and infrastructure throughout the industrial chain will be crucial. Secondly, the industrial system should be perfected, and industrial clusters should be optimized. A concerted effort should be made to perfect the industrial system surrounding resource processing, which includes refining processes, improving efficiency, and optimizing resource allocation. Special attention should be given to optimizing industrial clusters, fostering collaboration, and promoting synergy among related industries. By clustering related businesses together, economies of scale can be achieved, and knowledge sharing can be facilitated. Third, breakthroughs in core technology should be made to realize diversification of the industrial chain. Investment in research and development is essential to drive innovation and develop new products, processes, and applications, which will enable the expansion of the industrial chain into new sectors and markets. In addition, resilience planning also should be a priority, with measures in place to mitigate the impact of disruptions such as natural disasters and supply chain disruptions.

4.3.3 Disaster mitigation countermeasures from the perspective of regional diffusion

In terms of the inter-regional diffusion of storm surge disaster losses, inland areas have also been significantly affected. From 2011 to 2020, Henan, Anhui, Jiangxi, Shaanxi, and Beijing consistently ranked among the top 8 inland areas with severe storm surge disaster losses (Figure 3). Among them, Henan experienced the most severe impacts (Figure 7). The Central region, which is usually influenced by its geographical location and economic structure, was the most vulnerable to storm surge disasters (Figure 5). However, coastal areas often implement specific measures to deal with these disasters, while inland areas tend to overlook them.

To mitigate the spread of impacts from storm surge disasters, a multifaceted approach is proposed, focusing on financial innovation and regional collaboration. These measures aim to enhance resilience and minimize the socioeconomic repercussions of such events. Firstly, innovate the financial system and improve insurance mechanisms. To address the financial burden of storm surge disasters, innovation within the insurance sector is imperative. Proposing a government-led, commercially operated storm surge disaster insurance system can provide coverage for affected individuals and businesses. Additionally, implementing a national reinsurance loss sharing mechanism can spread the financial risk and reduce overall losses. Secondly, it is essential for the Central region to enhance its awareness of storm surge disaster prevention. Establishing safety reserves of raw materials and intermediate products can help mitigate disruptions to supply chains during and after a storm surge event. This proactive measure ensures continuity of production and minimizes economic losses. In addition, strengthening the resilience of the supply chain through measures such as diversification of suppliers and distribution channels further fortifies the region against the impacts of disasters. Lastly, it is important for the Central region to enhance its inter-regional trade network. The Central region can play a pivotal role in facilitating industrial transfers from coastal areas, thereby reducing vulnerability to storm surge risks while promoting economic diversification. By expanding its ability to undertake industrial transfers from coastal areas and facilitating trade exchanges with the Western region under the background of Dual Circulation Strategy, this will foster a collaborative and synchronized development among the Eastern, Central, and Western regions.

5 Conclusions and prospects

5.1 Main conclusions

In this study, we proposed an assessment framework for evaluating the economic impact of storm surge disasters. We constructed a DEIO model specifically designed for storm surge disasters, which takes into account both the directly affected regions and sectors, as well as the potentially affected ones. By using this model, we were able to calculate the indirect economic losses caused by storm surge disasters in China from 2011 to 2020. To illustrate the diffusion of storm surge disaster losses, we focused on the years 2012, 2015, 2017, and 2020. We analyzed the spread of these losses at both the regional and industrial levels. Through our analysis, we have drawn several key conclusions.

Firstly, the indirect economic losses constitute a major part of the economic footprint of storm surge disasters. From 2011 to 2020, indirect economic losses from storm surge disasters accounted for over 60% of the total economic losses in China. Secondly, the influence of storm surge disasters in the southeast coastal regions of China is considerably higher than in the northern coastal regions. The economic impact on potentially affected regions also exhibits significant differences, possibly due to regional economic structures. The research findings indicate that in 2012, 2015, 2017, and 2020, the top three diffusing flows of economic losses of storm surges from the North Coast, East Coast, and South Coast predominantly flowed to the North, East Coast, South Coast, Central, and Inland North, respectively. Among inland regions, Henan was the most severely impacted by storm surges, while the indirect economic losses from storm surges in the Northwest and Southwest were typically low. Thirdly, the majority of indirect losses occur in basic heavy industries, which are centrally positioned in the industry chain and have strong interconnections with other industries. Among the directly affected regions, the Resource Processing Industry and Service Department are the sectors with the largest indirect economic losses from storm surge disasters, while most of the indirect economic losses in potentially affected regions occur in the secondary industry.

5.2 Limitation and future work

This study provides data support and a theoretical basis for formulating storm surge disaster prevention and mitigation policies in China, which is of great significance to the sustainable development of China's social economy. In future research, scenarios such as post-disaster labor restriction, post-disaster capital restriction, and post-disaster reconstruction should be considered. Conducting a more specific simulation and analysis using a major storm surge disaster event as an example would be beneficial. Additionally, it is important to explore the influencing factors of economic losses diffusion of storm surge disasters among regions and sectors.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding authors.

Author contributions

RH: Conceptualization, Writing – original draft, Methodology. KY: Data curation, Writing – review & editing, Supervision. XD: Visualization, Writing – review & editing. HL: Formal analysis, Writing – review & editing. SZ: Investigation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2025.1673928/full#supplementary-material

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