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Beyond inundation: a comprehensive assessment of sea level rise impact on coastal cultural heritage in China

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Abstract

The rise in sea levels, driven by global climate change, poses a significant threat to cultural heritage in coastal regions. Traditional risk assessment methods, focusing on direct inundation, often fail to consider the crucial impact of socio-economic factors, which are significantly vulnerable to sea level rise. To bridge this gap, this study introduces an innovative Sea Level Rise Cultural Heritage Impact Assessment Model (SLR-CHIA Model), a novel approach that integrates both land inundation and socio-economic aspects. This comprehensive model evaluates potential risks to various types of cultural heritage in coastal China, including intangible cultural heritage, relics, and traditional villages. The study's findings are striking: (1) About 7.79% of coastal villages, 53.94% of relics, and 2.53% of intangible cultural heritage are potentially at high risk in a 100-year sea level rise event; (2) Relics in the Eastern coast and villages in the Southern coast are most vulnerable; (3) Different types of cultural heritage rely on diverse principal factors for protection, resulting in varied risk levels under sea level rise conditions. The SLR-CHIA Model provides a vital methodological framework for evaluating cultural heritage risks in other global regions.

Keywords Sea level rise, Cultural heritage, China Coast, Risk assessment model, Intangible cultural heritage, Relics, Traditional villages

Introduction

As global climate change intensifies, sea level rise (SLR) has become an issue that cannot be ignored [1, 2]. It poses significant challenges to the development of coastal nations, impacts densely populated cities [3], and brings unprecedented threats to cultural heritage protection [4–8]. Based on simulations from the IPCC's Fourth Assessment Report [9] and paleo-temperature information [10], it is projected that ocean thermal expansion and extreme events will threaten over 19% of UNESCO World Heritage sites globally [8]. Cultural heritage exposed to SLR not only affects our common cultural assets but also challenges the cultural identity of nations and ethnic groups, posing hurdles to achieve sustainable development goals [4, 6, 11–13].

The impact of climate change on SLR is particularly severe in China [1, 14–16]. By 2050, ~ 57,000 km^2 of China's mainland coastal area is projected to be affected by extreme SLR event [17]. These regions are not only crucial for their rich cultural heritage concentration [18, 19], but also exhibit increased vulnerability under extreme marine events caused by storm surges and high tides [20]. Despite proactive national initiatives to combat SLR and stress the significance of coastal cultural heritage

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protection [21], the risks involved still carry substantial uncertainties.

Currently, the "direct inundation determination" method is widely used to assess SLR impact on cultural heritage [4, 6, 22, 23]. This approach considers cultural heritage sites as at risk primarily when forecasted to be submerged by future sea levels. For instance, it's estimated that a 1-m rise in sea level could inundate over 370 national-level heritage sites in China [4]. While effective in highlighting risks like water erosion, humidity fluctuations, salt intrusion, and microbial environmental changes to tangible heritage (relics, historic buildings, archaeological sites) [4, 8, 23, 24], it has notable limitations. First, it struggles to assess intangible cultural heritage (ICH), as the precise locations of ICH are difficult to pinpoint, challenging the determination of their susceptibility to submersion. Secondly, it overlooks critical factors such as population migration and economic shifts triggered by SLR [4]. These factors challenge the protection of some cultural heritage whose preservation relies on ongoing social activities [25–31]. That is to say, the direct inundation determination method may overlook the broader and more complex impacts of SLR on cultural heritage, potentially leading to an underestimation of its vulnerabilities.

Addressing this gap, our study introduces the Sea Level Rise Cultural Heritage Impact Assessment Model (SLR-CHIA Model). This model is designed for a comprehensive evaluation of the impact of SLR on various types of cultural heritage in China's coastal regions. Utilizing the Global Tide and Surge Reanalysis (GTSR) [32], alongside population and economic data from 2008 to 2020, and extensive cultural heritage records, this study uncovers the varied impacts of a 1 in 100-year SLR event on different types of cultural heritage, and provides a robust framework for crafting targeted heritage risk management strategies.

Comprehensive SLR impact assessment: beyond direct inundation

Cultural heritage encompasses both tangible heritage with historical, artistic, ethnic, and social significance (such as buildings, relics, and settlements) and intangible cultural heritage (ICH), including festivals, folk customs, traditional crafts, etc. Considering UNESCO's classification of cultural heritage, and acknowledging the distinct managing authorities and data accessibility in China, this study categorizes cultural heritage into three types: ICH, relics (including historic buildings, archaeological sites, grottoes etc.), and traditional villages. This categorization aids in observing the differential SLR's impacts on intangible, tangible, and settlement's cultural practices.

The impact of SLR on different types of heritage is not solely manifested in direct inundation; In fact, socioeconomic impacts induced by SLR can begin to indirectly affect the prioritization and execution of cultural heritage protection even before any actual inundation occurs [4, 8, 13].

According to human–environment relationship theory, cultural heritage is interlinked with socio-economic, demographic, and environmental factors, forming a complex adaptive system [31, 33, 34]. This study interprets these interconnected relationships within a framework that encompasses cultural, population, economic, industrial, and ecological subsystems [35, 36] (Fig. 1), recognizing that environmental resources, population dynamics,

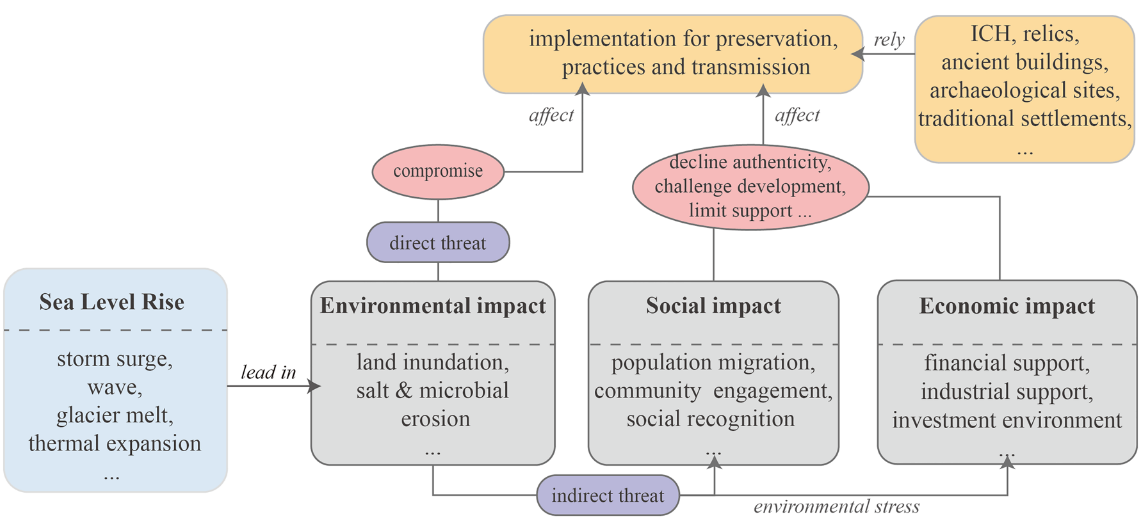

Fig. 1 Mechanism Diagram of SLR Impact on Coastal Cultural Heritage

and economic stability are essential for the robust protection and sustainable development of cultural heritage [28, 37–40]. These elements, highly sensitive to fluctuations caused by sea level rise, pose significant risks to the authenticity and continuity of cultural heritage, potentially triggering irreversible cultural transformations [13, 20].

The economic impact of SLR on coastal regions has a direct bearing on cultural heritage protection. In coastal provinces such as Guangdong, Zhejiang, and Liaoning, a primary challenge is balancing the substantial costs of maintaining relics with the looming economic threats posed by SLR [41]. Furthermore, the tertiary sector, encompassing tourism, service, cultural entertainment, and creative industries, plays a vital role in sustaining and revitalizing ICH and historical villages [42–45]. The economic shifts caused by SLR pose a threat to the preservation of these cultural heritages.

The population displacement triggered by SLR poses significant challenges to a range of cultural practices, impacting protective, hereditary, and practical work. Such demographic shifts can destabilize settlements [42, 45, 46], leading to the erosion of local beliefs and diminished engagement with cultural sites such as temples, shrines, and ancestral halls [47, 48]. Furthermore, the authenticity of ICH are at risk when communities sustaining these practices face relocation or demographic changes [49]. SLR could force coastal communities to relocate inland, resulting in village migration and potential significant transformations in living cultural traditions [1, 50].

Land inundation due to SLR brings significant challenges to the human–land relationship, especially in areas prone to storm surges and environments with high humidity and salinity [4, 12, 51]. This challenge is particularly acute in traditional settlements, where the essence of community life is intertwined with the surrounding natural environment. These settlements thrive on a dynamic equilibrium between their geographical context, occupational activities, and daily life, all of which are deeply embedded in agricultural traditions [52]. Furthermore, certain types of ICH, like craftsmanship and production skills, are closely tied to local ecological resources such as water sources, arable land, and forests [53]. The threat of SLR risks disrupting these agriculturally based cultural practices and the transmission of ICH, thereby undermining the sustainability and cultural identity of traditional villages.

Understanding the diverse dependencies of various heritage types on socio-economic, demographic, and environmental factors is essential. In response, we have categorized cultural heritage into three distinct types: ICH, relics (including historic buildings, grottoes, and archaeological sites), and traditional villages. To effectively identify and quantify the key factors influencing heritage protection, we introduce the SLR-CHIA Model.

Data and methods

Study area

This study focuses on all county-level regions along the coastline of Mainland China in 11 provinces, covering an area of ~ 1.3 million km^2. This area is primarily divided into three economic zones: the Northern coastal economic circle (involving coastal provinces such as Liaoning, Shandong, Tianjin, Hebei), the Eastern coastal economic circle (Jiangsu, Shanghai, Fujian), and the Southern coastal economic circle (Zhejiang, Guangxi, Guangdong, Hainan) (Fig. 2). The development of these three economic circles largely represents the highest level of China's economic development. However, due to their flat terrain, these areas are particularly sensitive to SLR, and in the past decade, storm surges and surging waves have become the main causes of direct economic losses due to natural disasters in these regions [52].

Using the ArcGIS Kernel Density tool, we demonstrate spatial differences in the distribution of different types of cultural heritage in coastline of Mainland China (Fig. 2). Observing the high-density areas, we find that the Northern coast has high-density of relics and medium density of ICH, but few traditional villages. In the Eastern coast, relics, ICH, and traditional villages all have the highest density areas, while the high-density of ICH is significantly smaller. In the Southern coast, traditional villages have highly concentrated areas, and relics and ICH are mainly concentrated in the Pearl River Delta area, albeit in smaller numbers. This highly concentrated and differentiated distribution implies that the impacts of SLR vary across these areas.

Data sources

Global tide and surge reanalysis dataset (GTSR)

The novel GTSR dataset consolidates storm surge and wave data from global tidal observations spanning 1979 to 2016, simulating and predicting the extreme sea level for a 1 in 100-year event (Fig. 4). The accuracy of GTSR has been validated and is suitable for digital elevation model (DEM) of SLR assessment [32]. It has shown effective results in Eastern Asia [54] and has been used in assessments of SLR threats to UNESCO World Heritage Sites and global infrastructure [6, 55].

Digital elevation model (DEM)

The DEM data, with a resolution of 30 m, was obtained from the Resource and Environment Science and Data Center of the Chinese Academy of Sciences. Combined

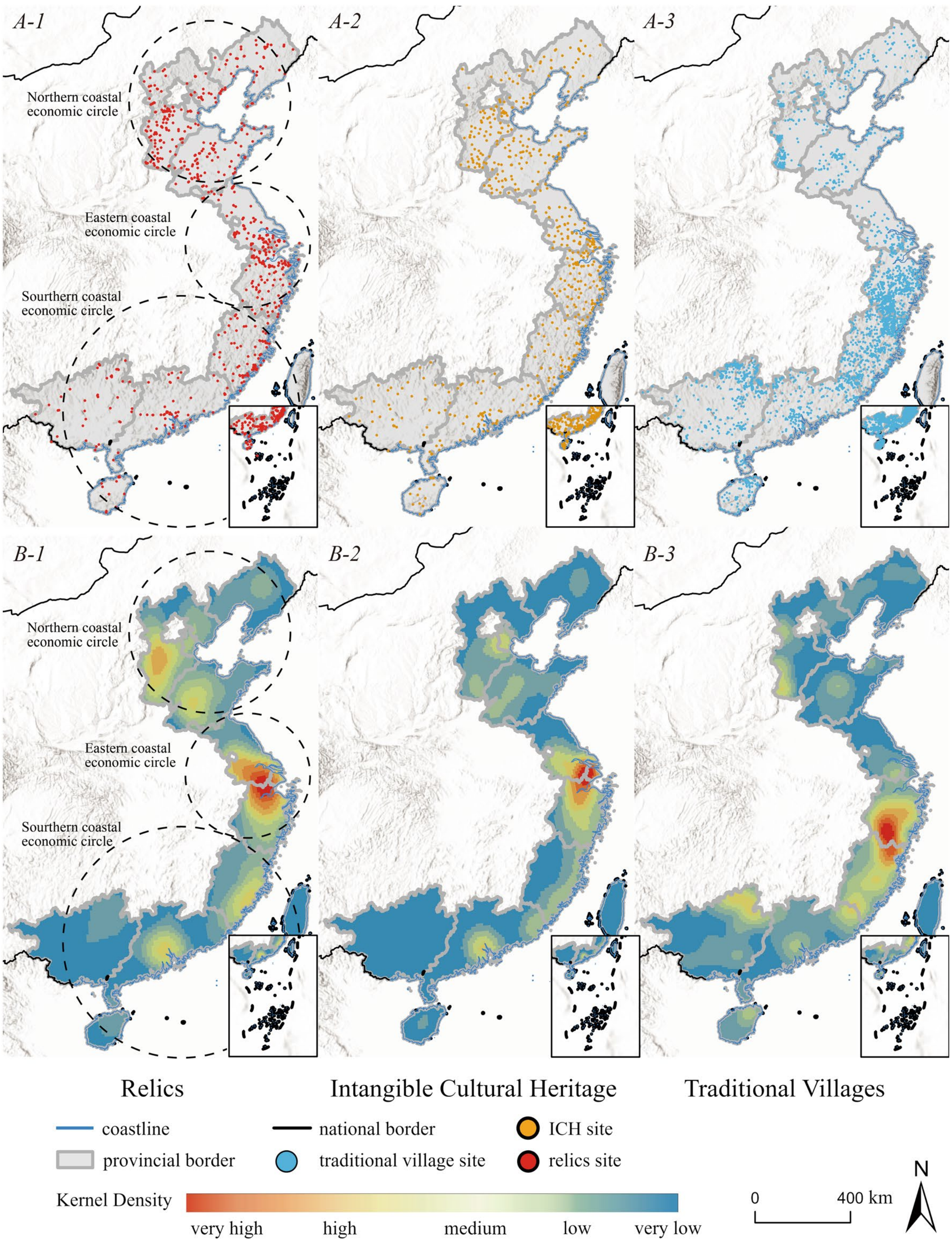

Fig. 2 Distribution and Kernel Density of Cultural Heritage along China's Mainland Coastline (**A1**: relics distribution; **A2**: ICH distribution; **A3**: traditional villages distribution; **B1**: kernel density of relics; **B2**: kernel density of ICH; **B3**: kernel density of traditional villages)

Table 1 Descriptive statistics of the variables under study

	Variable representation	Abbreviations	Obs	Mean	SD	Min	Max
Dependent variable	Annual ICH count	–	1469	9.728	10.010	0	93
	Annual relics count	–	1469	10.010	10.420	0	62
	Annual traditional villages count	–	1469	7.570	19.180	0	266
Explanatory variables	Gross Domestic Product	Econ_GDP	1469	16.840	0.942	14.180	19.770
	Tertiary industry of GDP	Econ_tert	1469	42.800	9.172	17.330	80.490
	Urban population of permanent population	Popu_urban	1469	58.432	14.711	24.643	100
	rural population of permanent population	Popu_rural	1469	41.567	14.711	0	75.354
	urban land in administrative area	Land_urban	1469	11.470	8.947	0.210	44.070
	ecological land in administrative area	Land_ecol	1469	43.020	28.860	0.420	94.780
Additional control variables	Books per 100 people	Lib	1469	68.610	69.170	2.120	1212
	Road length of administrative area	Road	1469	0.227	0.468	0.003	6.076
	Employment in culture & entertainment	Employ	1469	0.728	0.356	0.175	3.628
	Presence of 3A + scenic spots (1 = Yes, 0 = No)	Scen	1469	0.460	0.499	0	1
	Per capita education expenditure	Edu	1469	7.081	0.512	4.818	8.482
	Number of museums	Muse	1469	16.680	17.580	0	149

with GTSR data, it enables dynamic identification of inundation areas along China's coast.

Coastal county's economic, population development data (2008–2020)

Annual data for coastal counties was sourced from the national economic and social development bulletins. The timeframe of 2008–2020 corresponds with the reporting cycles for China's ICH and Traditional Villages, as well as the 6th to 8th national relics applications. This data including GDP per capita, Tertiary industry, Urban and Rural population, capita library holdings, road density, employment in cultural industries, number of major tourist attractions, per capita educational spending, and museum count. These indicators serve as control variables, contributing to identifying the key explanatory variables for the study (Table 1).

Land use data (2008–2020)

The land use data used in this study includes annual classifications of cultivated land, forest land, shrubland, grassland, water bodies, urban surfaces, wetlands, etc. [56]. These variables are instrumental in identifying the

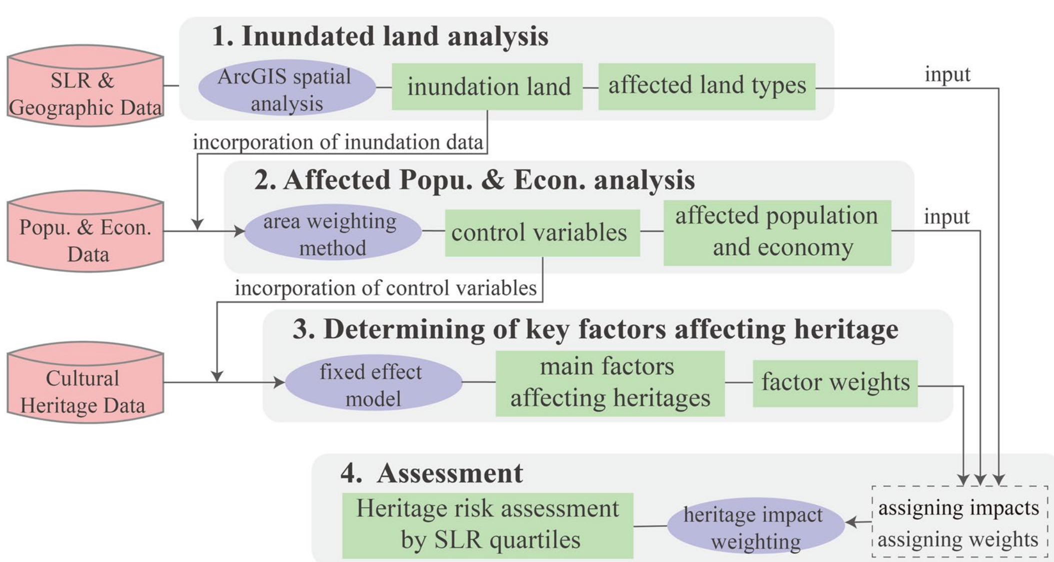

Fig. 3 Sea Level Rise Cultural Heritage Impact Assessment Model (SLR-CHIA Model)

key controlling factors for cultural heritage protection and quantifying their influence weights.

Cultural heritage data (2008–2020)

Three types of cultural heritage data for each coastal county from 2008 to 2020 was collected. The data on ICH and relics were obtained from the Ministry of Culture and Tourism (https://www.ihchina.cn/zhishichuang) and from various provincial culture and tourism departments. Data on traditional villages were sourced from the Ministry of Housing and Urban–Rural Development (https://www.mohurd.gov.cn). In total, 3990 relics, 21,921 ICH and 8,155 villages were collected. Spatial coordinates were retrieved using Google Maps (Fig. 2).

Research method

This study developed the SLR-CHIA Model (Fig. 3), which primarily comprises four parts: (1) analysis of inundated land; (2) analysis of population and economy affected by inundation; (3) determining key controlling factors; (4) assessment of the impact on cultural heritage.

Extraction of inundated land data affected by SLR

Utilizing the elevation-area method [17] and ArcGIS Pro, we extracted extreme sea level values for the Chinese mainland coastline from the GTSR dataset (Fig. 4, left). Areas below this sea level were identified as potentially inundated. Subsequently, we determined the potentially inundated area and the types of land affected within each county (see Fig. 4, right). Then, we calculated the area of inundated grid (Fig. 4, right) and different land types for counties, providing a detailed breakdown of land use impact.

Extraction of population and economic data affected by SLR

We used the area-weighted method [1, 17, 39] to evaluate the indirect impacts of inundated land on 2020's population and economic sectors, allocating the risks based on each county's percentage of potentially inundated land (from "Extraction of inundated land data affected by SLR"). The formula is as follows:

$$Y_{ai} = density_{ai} * subarea_i, \tag{1}$$

Y_{ai} represents the impact on the a factor in county i. $density_{ai}$ is the spatial density of factor a (km^2), and $subarea_i$ is the potentially inundated area of county i.

Determining key factors and weights for cultural heritage protection

Recognizing the diverse dependencies of different heritage types on socio-economic and environmental factors, we constructed a panel regression model using data from coastal cities spanning 2008–2020. This allowed us to pinpoint key factors influencing the protection of ICH, relics, and traditional villages and to calculate their weights. Variables and their descriptive statistics are detailed in Table 1. The regression model is expressed as:

$$y_{it} = \alpha + \beta_1 x_{it} + Control_{it} + \gamma_{it} + \varepsilon_{it}. \tag{2}$$

The dependent variable (y_{it}) represents the respective cumulative amount of ICH, relics and traditional villages for each category in $city_i$ for $year_t$. Each heritage type underwent separate regression analyses. The explanatory variables (x_{it}) for each category are the specific economic, demographic, and land-related variables of $city_i$ in $year_t$. $control_{it}$ denotes the set of control variables, while γ_{it} represents fixed effects for time and region, and ε_{it} is the random error term.

Key variables are: (1) Economic factors, represented by regional GDP (Econ_gdp) and the tertiary industry (Econ_tert), adjusted for inflation and log-transformed; (2) Demographic factors, reflected by the proportions of urban (Popu_city) and rural (Popu_rural) populations; (3) Land use factors, denoted by the proportions of urban (Land_city) and ecological (Land_ecol) land uses, with the latter including forests, grasslands, wetlands, and water bodies (derived in "Extraction of inundated land data affected by SLR") [57].

Additional control variables were incorporated to enhance accuracy, including per capita library holdings, road density, employment in cultural industries, number of major tourist attractions, per capita educational spending, and museum count (from "Extraction of inundated land data affected by SLR").

The model, validated through variance inflation, F-tests, and Hausman tests, utilized a double fixed effects approach for empirical analysis. The analysis highlighted the key factors (P value significant) and their respective weights, crucial for subsequent research phases.

Assessment of affected key factors on culture heritage

Building on the factors identified in "Extraction of population and economic data affected by SLR", we applied their coefficients as weights to assess the potential impact of extreme SLR on three types cultural heritage in each county, based on socio-economic and land use types data in 2020 (from "Extraction of population and economic data affected by SLR").The basic formula is:

$$CH_i = X_{i\_ICH} W_{i\_ICH} + X_{i\_heritage} W_{i\_heritage} + X_{i\_village} W_{i\_village}, \tag{3}$$

where CH_{iy} represents the comprehensive impact on heritage in $county_i$, X_i denotes the data for significant factors and W_i are its weight (coefficient from "Determining key factors and weights for cultural heritage protection").

The composite impact for each county in 2020 was then classified using a quartile method as 'very low', 'low', 'high', or 'very high'. Bivariate maps were created to visualize the spatial correlation between heritage density and impact levels (Fig. 5), and detailed maps were compiled to show the number of significantly affected heritages in each county, categorized as 'high' and 'very high' impact (Fig. 6).

Result

Impact of SLR on inundation extent and socio-economic factors

The area of China's mainland coastline potentially inundated by a 100-year SLR is ~ 56,800 km^2, including regions with an elevation equal to the extreme sea level (relative altitude difference of 0), considered high-risk areas, totaling around 81,100 km^2. This poses a threat to 223 counties across 11 provinces along the mainland coast (excluding Hong Kong, Macau, and Taiwan). The eastern coastal economic circle, particularly Jiangsu province and Shanghai, with their flat terrain and minimal elevation variance, is most susceptible to SLR. The northern and southern coastal economic circles also face variable impacts.

Utilizing spatial analysis tool in ArcGIS, it is estimated that an extreme SLR event could potentially impact ~ 17,200 km^2 of urban and 12,900 km^2 of ecological land across 223 coastal counties in mainland China. Based on socio-economic data from 2020 and using the area-weighted method, this scenario could place ~ 55.80 million urban and 15.99 million rural population at risk. The economic stakes are high, with a potential exposure of ~ 7,891.98 billion Chinese yuan in GDP, and the tertiary industry, contributing about 4320.19 billion Chinese yuan, could be the most affected.

Key factors and analysis of weights

This section highlights how economic, demographic, and land variables significantly impact the protection of ICH, relics, and traditional villages to varying degrees (Table 2).

Key controlling factors for relics: Tertiary industry, urban population, and urban land use all show a significant positive impact on relic protection, with regression coefficients of 0.060, 0.117, and 0.632, respectively.

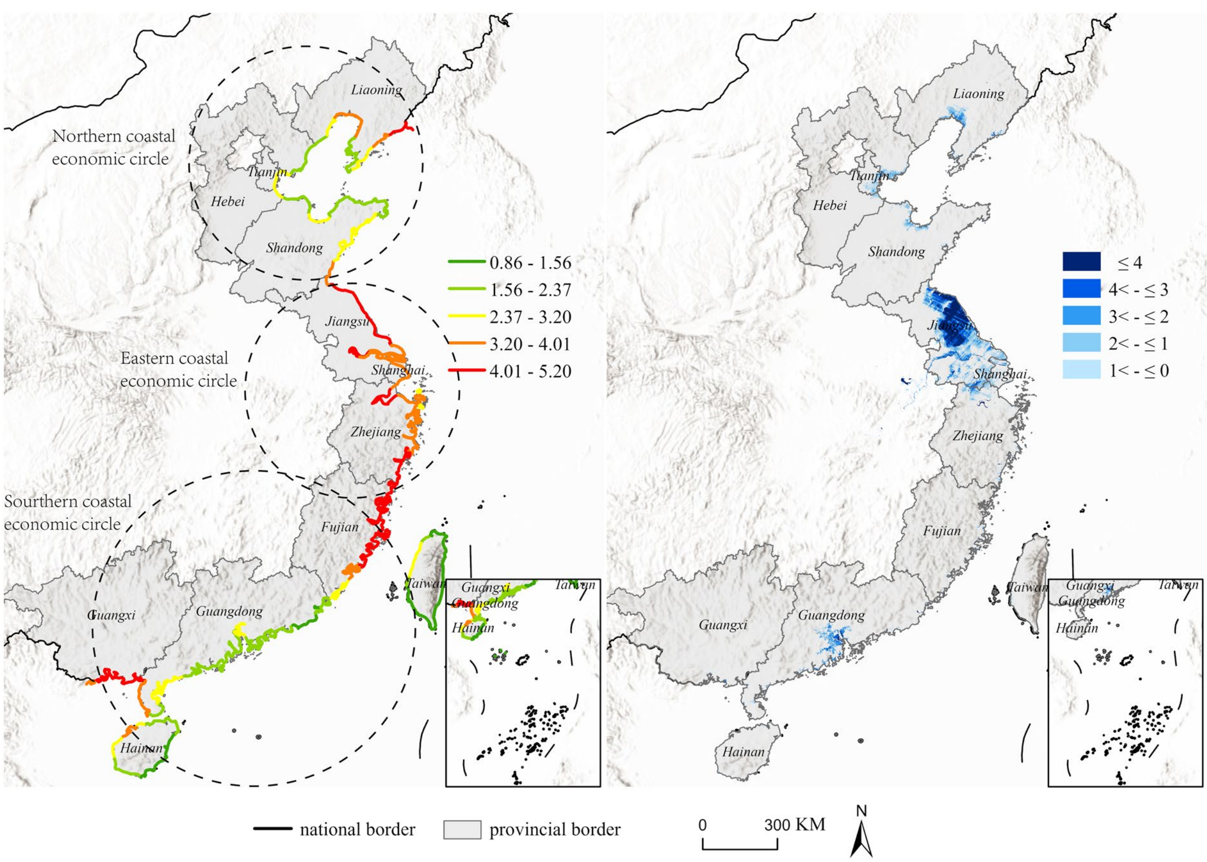

Fig. 4 Extreme sea levels (left) and inundation extent, depth (right) with a 100-years SLR (m)

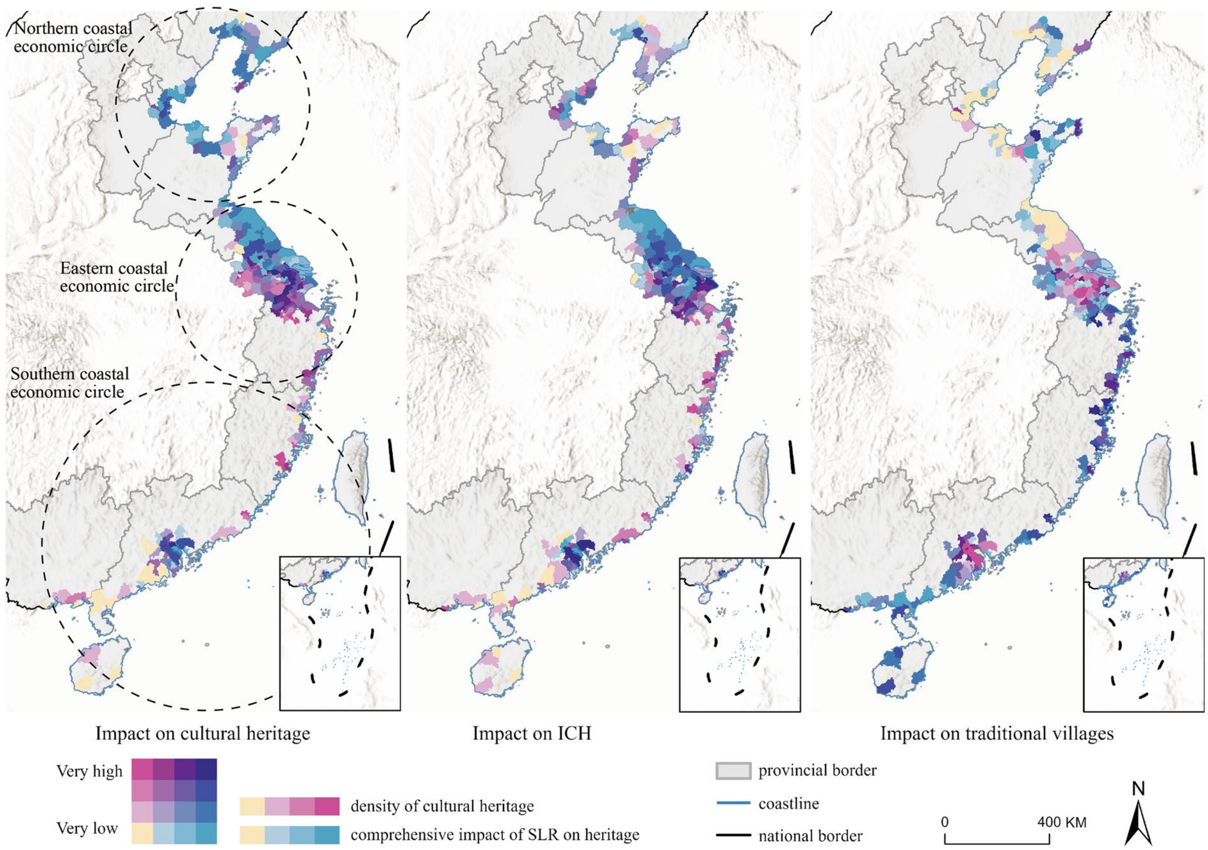

Fig. 5 Bivariate Map of Heritage Density and SLR Impact Severity in Affected Counties, 2020

Conversely, ecological land expansion negatively impacts relic protection, with a coefficient of − 0.195, likely due to space conflicts and environmental challenges posed to relics.

Key factors for ICH: Positive impacts are observed from regional GDP, tertiary industry, and urban land use, with coefficients of 2.646, 0.083, and 0.393, respectively. However, the proportion of urban population show negative impacts, with a coefficient of − 0.106, possibly because many ICH projects rely on rural livelihood. The expansion of ecological land also show negative impacts, with a coefficient of − 0.229, it implies that the transmission and application of ICH rely on city development to an extent.

Key factors for traditional villages: The expansion of regional GDP and urban population positively correlates with traditional villages protection, with coefficients of 10.826 and 0.221, respectively. Both urban and ecological land use negatively impact the protection of traditional villages, with coefficients of − 4.343 and − 1.930, indicating that traditional village conservation is highly sensitive to changes in land use.

SLR Impacts on cultural heritage

The repercussions of a 1 in 100-year SLR event on cultural heritage are primarily illustrated through detailed geographic analyses presented in Figs. 5 and 6. Our study delineates that:

Traditional villages—critical impact: A critical concentration of “very high” impact is observed along with China coast, especially in Southern coast, primarily affecting 109 traditional villages. This number could ascend to 208 considering “high” impact scenarios, accounting for 7.79% of total traditional villages samples in coastal heritage. Note worthy is Jiacheng area in Fujian province, a bastion of the Hakka community, with 34 national level traditional villages at heightened risk due to high socio-economic exposure. However, the mitigating topographical influence of the Daiyun mountain range restricts these impacts to the Fujian coastline, sparing more inland areas.

ICH—resilience: In contrast, ICH shows substantial resilience to SLR, with no entities recorded as ’very high’ impact. However, under ’high’ impact scenarios, the vulnerability becomes noticeable, affecting 35 ICH

Table 2 Key factors and their weights impacting cultural heritage protection (2008–2020)

Variables	ICH			Relics			Traditional villages		
	(1) Economy	(2) Population	(3) Land	(4) Economy	(5) Population	(6) Land	(7) Economy	(8) Population	(9) Land
Econ_GDP	2.646*** (0.486)			0.954 (0.732)			10.826*** (3.355)		
Econ_tert	0.083*** (0.019)			0.060** (0.029)			0.195 (0.133)		
Popu_urban		− 0.106*** (1.729)			0.117*** (2.592)			0.221* (11.988)	
Popu_rural.[a]		0.106*** (1.729)			− 0.117*** (2.592)			− 0.221* (11.988)	
Land_urban			0.393*** (0.068)			0.632*** (0.101)			− 4.343*** (0.455)
Land_ecol			− 0.229*** (0.046)			− 0.195*** (0.068)			− 1.930*** (0.308)
Lib	0.003** (0.001)	0.002** (0.001)	0.002 (0.001)	0.003* (0.002)	0.003* (0.002)	0.002 (0.002)	0.003 (0.008)	0.003 (0.008)	− 0.001 (0.007)
Road	0.906*** (0.318)	0.761** (0.319)	0.355 (0.322)	1.437*** (0.479)	1.663*** (0.478)	0.677 (0.482)	− 3.620* (2.195)	− 3.010 (2.209)	− 1.668 (2.168)
Employ	0.443 (0.302)	0.144 (0.302)	0.303 (0.300)	1.608*** (0.455)	1.773*** (0.453)	1.445*** (0.449)	− 2.205 (2.085)	− 2.339 (2.093)	− 0.093 (2.017)
Scen	− 0.117 (0.111)	− 0.076 (0.111)	− 0.019 (0.110)	− 0.371** (0.168)	− 0.364** (0.166)	− 0.262 (0.165)	− 0.550 (0.768)	− 0.500 (0.769)	− 0.693 (0.741)
Edu	− 1.119** (0.463)	− 0.525 (0.392)	− 0.101 (0.376)	− 1.730** (0.698)	− 0.752 (0.588)	− 1.611*** (0.564)	6.700** (3.202)	13.500*** (2.717)	11.430*** (2.533)
Muse	0.196*** (0.010)	0.194*** (0.010)	0.189*** (0.010)	0.179*** (0.015)	0.186*** (0.015)	0.164*** (0.015)	− 0.031 (0.069)	− 0.011 (0.069)	0.087 (0.067)
Constant	− 35.151*** (7.070)	12.739*** (2.837)	10.874*** (3.304)	− 4.762 (10.655)	0.587 (4.252)	14.910*** (4.949)	− 219.440*** (48.854)	− 90.533*** (19.665)	57.070** (22.247)
γ_t	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
γ_i	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,469	1,469	1,469	1,469	1,469	1,469	1,469	1,469	1,469
R-squared	0.527	0.528	0.539	0.589	0.594	0.604	0.238	0.234	0.293

Standard errors in parentheses, ***p < 0.01, **p < 0.05, *p < 0.1

[a] Due to multicollinearity, as urban and rural population percentages total one, separate regressions were performed, yielding identical results apart from the sign

Variables that are significant at the P-value are considered as Key factors, and their regression coefficients are determined as influence weight

entities, accounting for 2.53% of the coastal ICH inventory assessed. Specific areas with a high density of ICH, particularly Shanghai's Pudong district, which boasts 85 ICH items, demonstrate increased susceptibility due to both the concentration of heritage assets and the extensive areas at risk of inundation. This localized vulnerability highlights the need for targeted protective measures within these high-density zones.

Relics—substantial threat: The situation for relics is particularly grave, with 348 units under 'very high' impact due to SLR, escalating to 431 when considering those at 'high' impact. This alarming figure equates to 53.94% of all relics within the studied coastal counties, underscoring the severity of the threat they face. These figures highlight an urgent imperative for the development of robust protective strategies to mitigate the risks posed by SLR, particularly as it triggers profound economic and demographic shifts along the coast.

Discussion

In our study, we observed significant variations in the impact of SLR on cultural heritage along the coast. While all types are affected, the degree and nature of this impact vary significantly. This section aims to explore the underlying reasons for these disparities, focusing on three key factors: the differences in cultural heritage spatial distribution, the specific topographical characteristics of coastal areas, and the diverse dependencies of heritage types on socio-economic support.

Firstly, the distribution patterns of various cultural heritage types play a pivotal role in determining their susceptibility to SLR. These characteristics stem from more

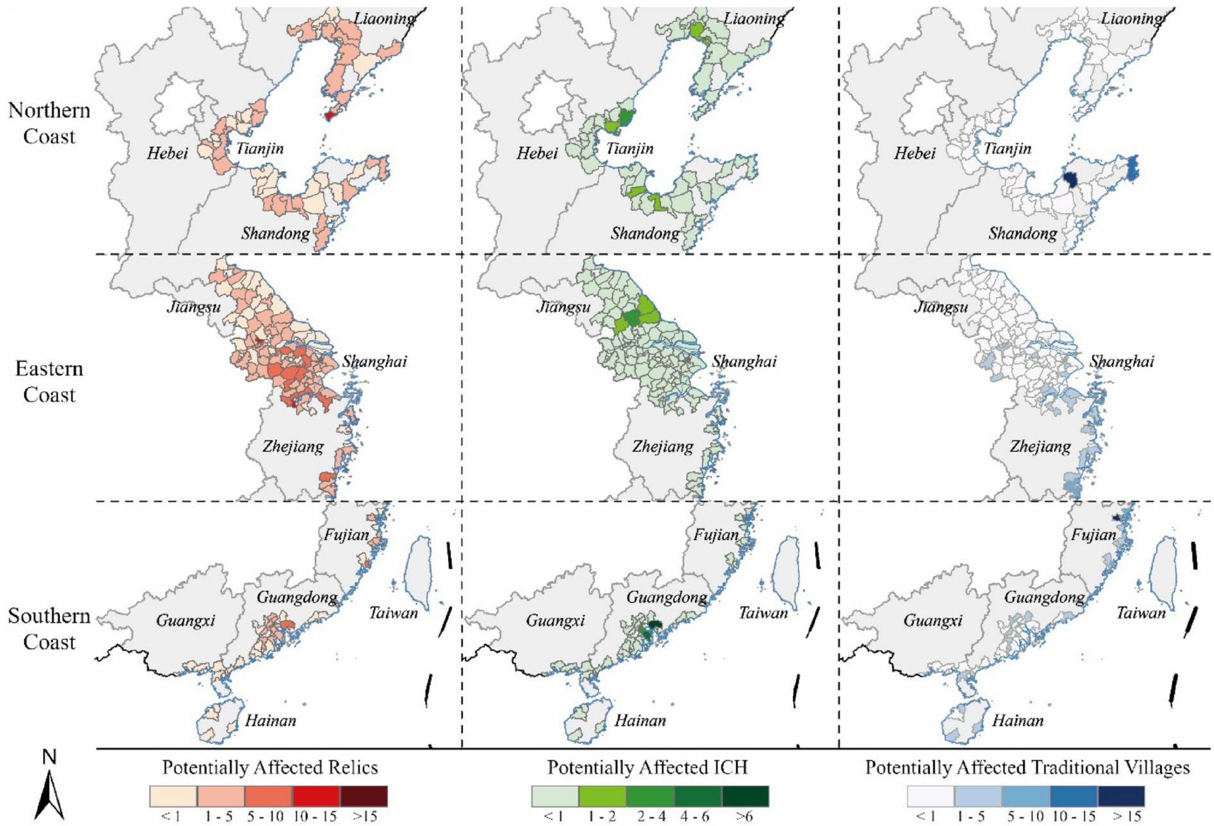

Fig. 6 The Number of Cultural Heritages in Each County Significantly Affected by SLR, 2020 ("Affected" refers to 'High' and 'Very High' comprehensive impact rankings as determined in "Assessment of Affected Key Factors on Culture Heritage")

than just geographical factors, but also influenced by a complex interplay of historical events, cultural evolution, and socio-political shifts. This complex background results in a scenario where similar extents of land inundation can impact different heritage types in vastly different ways, highlighting the need for nuanced assessments that consider the unique contexts and histories of each heritage type. For instance, the distribution density of traditional villages along the southern coast differs markedly from that of ICH in the same area. This difference necessitates region-specific protection strategies to ensure targeted and effective conservation against the challenges posed by SLR.

Second, the topography and landforms of coastal regions significantly influence their susceptibility to SLR-induced inundation. For instance, the eastern coast, including Jiangsu, features predominantly flat terrain, which, combined with higher predicted sea level elevations in a 100-year SLR event, places these regions at a greater risk of extensive land inundation. Contrastingly, the southern coast, influenced by the varied terrain of the Daiyun Mountain range, predominantly faces SLR risks in coastal counties, with its inland areas less affected despite significant projected sea level during a 100-year event. Areas at river deltas, such as the Yangtze River Delta, Pearl River Delta, and the Yellow River Estuary, face heightened impacts due to their proximity to waterways.

Third, different socio-economic factors exert varying degrees of influence on cultural heritage preservation efforts, leading to distinct vulnerabilities to SLR. This diversity is evident in several ways. For instance, our analysis indicates that economic upheavals caused by SLR might impact traditional village preservation more profoundly than demographic shifts, as evidenced in Table 2. This particular finding highlights the paramount importance of economic conditions in certain contexts. Additionally, some heritage types, such as ICH and relics, show negative responses to changes in ecological land use. This finding underscores the complex interplay between cultural heritage and their evolving environment, indicating an increasing interdependence with modern urban development. Similarly, the adverse effects of urban and ecological land use changes on traditional villages emphasize the need for a stable land environment for their sustenance and continuity. Collectively, these instances paint a picture of the multifaceted nature of SLR's impact on cultural heritage, underscoring the need for tailored and context-aware preservation strategies.

We acknowledge the limitations of our study. SLR-CHIA Model used the applications of cultural heritage protection as explanatory variables for assessing the weight of heritage protection. This approach helps assess the factors influencing the recognition and importance of cultural heritage, but it should not be equated directly with the impact on cultural heritage protection. Therefore, our findings should be interpreted cautiously in terms of their implications for cultural conservation. Moreover, the accuracy of SLR-CHIA Model depends on the completeness of cultural heritage application data. Thus, while SLR-CHIA Model can offer insights and be replicable for countries with well-established heritage protection system, it may be less applicable in regions lacking heritage data. Finally, it's important to emphasize that, due to data limitations, our study covers only a small subset of the vast cultural resources along the coast. The national and provincial ICH, national traditional villages, and relics included in our study represents only a fraction of the total. Consequently, the actual impact of SLR on cultural heritage could be much greater than our study suggests, underscoring the need for heightened attention to cultural heritage risk management in the face of global SLR threats.

Conclusion

Cultural heritage globally faces multifaceted threats from climate change and natural disasters, with SLR posing one of the most pervasive global challenges. However, traditional methodologies, primarily the direct inundation determination approach, struggle to encompass the varying impacts on different types of heritage and often overlook the indirect socio-economic impacts that SLR-induced inundation can have on the developmental needs of these heritages.

The study highlights that the impact of SLR on cultural heritage extends beyond mere inundation. In fact, negative impacts often predate actual inundation. In response, we developed the SLR-CHIA Model. This innovative model not only accounts for inundated areas and affected land types but also identifies and quantifies the key controlling factors upon which the protection of three types of cultural heritage depends. By assessing the impact of SLR events on these controlling factors, our model comprehensively evaluates the influence of environmental, economic, and demographic elements on cultural heritage protection under SLR conditions.

Our findings from the application of the SLR-CHIA Model reveal a nuanced landscape of vulnerability and resilience among various types of cultural heritage. Traditional villages in the southern coastal economic circle emerge as particularly vulnerable, whereas the impact on ICH is less severe, yet notable in regions like southern Suzhou and Shanghai. Relics located across the eastern, southern, and northern economic circles face substantial risks. These variations in impact are underpinned by the diverse distribution of cultural heritage, the different topographical features of the coastal regions, and the varying dependence of different heritage types on socio-economic and demographic factors.

It is important to note that our model's results indicate a broader spectrum of impacts on cultural heritage than previously studied, suggesting that the comprehensive effects of SLR are more profound than those resulting from "direct inundation determination" method. This further emphasizes the need for an integrated approach to assess the risks to cultural heritage from SLR. However, it is crucial to acknowledge that our study utilized only national and some provincial-level cultural heritage data. Given the vast and rich cultural heritage resources along China's coastline, the actual scope and severity of the impacts are likely to be more substantial. This accentuates the urgency for heightened attention and action towards risk management and protective strategies for cultural heritage in the face of escalating SLR threats globally.

Abbreviations

SLR	Sea level rise
DEM	Digital elevation model
GTSR	Global tide and surge reanalysis
SLR-CHIA Model	Sea level rise cultural heritage impact assessment model
Popu	Population
Econ	Economy
ICH	Intangible cultural heritage
Tert	Tertiary
Ecol	Ecology
Lib	Library
Scen	Scenery
Muse	Museum
Edu	Education
Ob	Observation

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Author contributions
ZHC was responsible for data collection, visualization creation, and analyzing the spatiotemporal characteristics of sea level rise impacts on heritage. ZHC also served as the primary author of the manuscript. QG and XWL jointly developed the model to identify key factors influencing heritage in the context of sea level rise. They also contributed to the creation and analysis of the study's tables. ZBW, the corresponding author, supervised the research process, ensuring its integrity and accuracy. All authors have read and approved the final manuscript.

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Availability of data and materials
The source of data used in the study is clarified in the article, and also are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

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