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Original Research

Environmental Stress in Coastal Areas: Scale Effects and Vertical Management from Pollution Sources

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Abstract

Analyzing environmental sustainability from pollution sources is crucial for reducing pollution and advancing carbon peak and neutrality goals. This study uses Zhejiang Province, a typical coastal area in China, to develop a pollution source classification system, assess environmental stress intensity, and identify spatial patterns. The study also proposes a hierarchical control approach that integrates control levels and strategies. The findings reveal significant spatial variation in environmental stress across Zhejiang, with coastal cities facing higher stress than inland areas. Industrial sources in counties show a greater environmental impact. A classification system with 7 secondary categories and 21 tertiary categories is proposed, with the environmental stress index ranging from a maximum of 0.432 to a minimum of 0.013. The system emphasizes controlling "point" sources in urban and rural residential areas and industrial and mining production areas, "linear" sources in mobile transportation, and "planar" sources in agricultural planting and production breeding areas. The control levels for typical regions – dominated by industrial, agricultural, domestic, or ecological sources – range from Level IV to Level 0, requiring tailored environmental control strategies. The graded control measures based on environmental stress intensity and spatial characteristics can be effectively integrated with other environmental functional zoning systems, enhancing the precision of environmental management.

Keywords: environmental stress, pollution source assessment, environmental control, coastal areas

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Introduction

Coastal areas, where land and sea meet, are important regions where natural environments and human activities interact. These areas are rich in natural energy, have high biological productivity, and are of great economic importance. Many researchers have used various data sources, such as remote sensing images, field samples, and historical statistics, to study coastal areas [1-3]. These studies focus on various perspectives, such as coastal resource and environmental changes, ecosystem services, territorial spatial planning, human-environment interactions, land-sea coordination, and resilience [4-6]. Since China introduced its maritime power strategy, the marine economy has expanded quickly, leading to a significant increase in coastal socio-economic activities. However, some of this growth has been inefficient, disorganized, and extensive, resulting in negative environmental impacts [7]. Preliminary research shows that maritime activities contribute about 20% to the marine environmental impact, while land-based socio-economic activities account for more than 60% [8, 9]. These include various pollution sources – such as those from production, daily living, urban and rural areas, and mobile sources – along with growing inter-regional and intra-regional pollution [10]. It is urgent to explore the environmental effects and spatial differences caused by different structures of human activities, focusing on pollution sources. There is also a need to shift from a single-element approach to a comprehensive one, and from end-of-pipe control to source control, to better address the complexity of regional environmental issues.

Accurately calculating environmental stress intensity across various production and living processes is crucial for understanding pollution loads and spatial control. Single-factor stress intensity measures the total emissions or emissions per capita/area in specific sectors under certain socio-economic conditions [11-13]. It is often analyzed using methods like emission factor analysis, principal component analysis, or direct measurement to determine pollutant levels and their sources [14-16]. By combining multiple pollutant indicators, comprehensive evaluation models like the entropy method are used to analyze pollution more holistically [17, 18]. Understanding the spatial distribution and temporal changes of pollution loads can clearly show the characteristics of pollution emissions in a region [19]. However, the local emission intensity often affects the overall intensity of the region, so downscaling pollutants at a regional level can reveal spatial variations in environmental stress.

Based on the spatial differences in environmental systems, their state, and functions, zoning technology can be used to assign environmental functions and protection goals to specific areas [20]. This approach helps create tailored regional environmental management policies, which play a key role in protecting and managing the environment. Researchers have developed environmental quality indicators or pollution inventories and used them to define zoning criteria based on spatial differences, which guide coordinated development across society, the economy, and ecology [21-23]. Countries in Europe, America, and China also implement differentiated control and monitoring for pollution sources, such as point sources and non-point sources, and apply targeted pollution control measures in different areas [16, 24, 25]. However, more work is needed to integrate pollution source classification with spatial planning and apply it to micro-level environmental regulation to avoid weak control and confusion in enforcement.

Zhejiang Province, a typical coastal region in China, faces complex pollution source structures due to its high-intensity human activities and unique terrain [26]. This study aims to address the ongoing ecological degradation in coastal areas by focusing on pollution sources. Using Zhejiang Province as a case study, we will first reconstruct the pollution source classification system, then estimate the environmental stress intensity for each category. Additionally, we will identify spatial distribution patterns of pollution sources and develop a micro-scale environmental control model to mitigate the impacts effectively.

Experimental

Study Area

Zhejiang Province is located on the southeast coast of China, bordered by the East China Sea to the east and the southern part of the Yangtze River Delta (Fig. 1). It spans latitudes from 27°02′N to 31°11′N and longitudes from 118°01′E to 123°10′E. It covers an area of 105500 km^2, with 74.6% of the land being mountainous, 5.1% covered by water, and 20.3% consisting of plains. The terrain gradually slopes from southwest to northeast, with mountains in the southwest, hills in the central region, and low-lying alluvial plains in the northeast. The province's sea area spans 260000 km^2 and includes several bays, such as Hangzhou Bay and Xiangshan Port. Zhejiang's coastline stretches 6715 km, with 2218 km of mainland coastline, the longest in China. The province has a dense network of waterways and numerous lakes, such as Qiantang, Tiaoxi, and Yongjiang Rivers, and also boasts 2878 islands, the most of any province in the country.

Zhejiang Province is divided into 11 prefecture-level cities, 7 of which are coastal. By 2023, Zhejiang had a permanent population of 66.27 million, with 49.19 million living in urban areas and 17.08 million in rural areas. The GDP reached 825.53 billion yuan, marking a 6% year-on-year increase. The industrial structure is divided into 2.8% primary, 41.1% secondary, and 56.1% tertiary sectors, with manufacturing and services, especially e-commerce and the digital economy, driving rapid growth. Zhejiang is rich in marine resources and has been focusing on developing

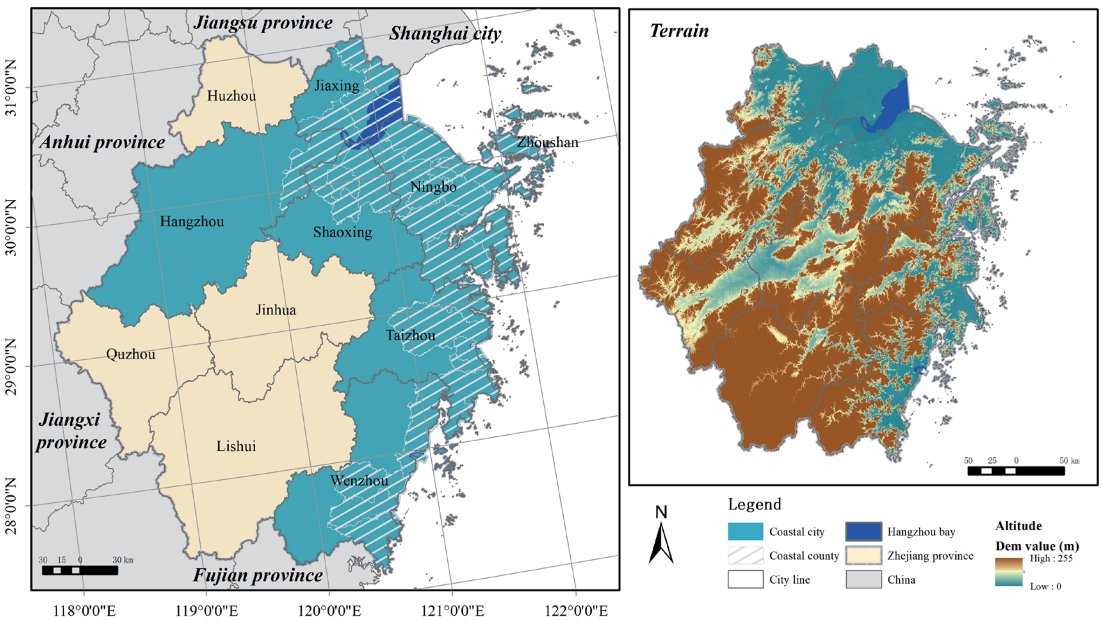

Fig. 1. Location map of Zhejiang Province, China.

its marine economy. The Zhoushan Fishing Ground, one of China's largest, contributes significantly to the marine economy, which has a total value of 920 billion yuan.

With increasing human activities, the ecological pressure on Zhejiang's coastal areas is rising. Understanding the emission characteristics of various environmental pollutants and the resulting environmental stress, as well as implementing targeted control measures, is crucial for promoting sustainable development in the province's economy, society, and environment.

Data Sources

The research data primarily consists of two types: (1) Geographic feature data, which includes the Digital Elevation Model (DEM), land use map, and administrative division map. DEM data, with a resolution of 30m grid, is sourced from the Geographical National Monitoring Cloud Platform (http://www.dsac.cn/). The land use map is derived from the land use change data (2018) provided by the local natural resources management department, the third land use status survey data (2019), and remote sensing data from the Resources and Environment Science and Data Center of the Chinese Academy of Sciences (http://www.resdc.cn/), which has been converted from vector to 30m precision raster data. The administrative division map, which includes boundaries for provinces, cities, and counties, is extracted from the land use map and is available in vector format. (2) Socio-economic and pollutant emission data, including urban and rural population, tourist population, livestock and poultry breeding, agricultural planting, and industrial production, are sourced from official reports and publications, including the China Environmental Statistical Yearbook (2023), the Second National Pollution Source Census Report of Zhejiang Province (2018), Environmental Quality Reports (2023) and Statistical Yearbooks (2023) of prefecture-level cities and the Zhejiang Province. Additionally, field research conducted in Zhejiang Province and coastal cities during July and August 2022 helped supplement and collect missing data from the statistical and map data.

Research Method

Classification System and Spatial Identification of Environmental Pollution Sources

Environmental pollution sources are the places or activities where pollutants that harm the environment come from [27]. These sources are generally categorized into two main types: anthropogenic pollution sources and non-anthropogenic pollution sources. Based on regional functional types and variations in production and living behaviors, and the characteristics of pollutants, the anthropogenic pollution sources can be identified as production sources and living sources, along with non-anthropogenic pollution sources, primarily ecological sources [28, 29]. These can further be divided into 3 main categories, 7 subcategories, and 21 tertiary categories, forming a three-level classification system that is based on the current national pollution source classification standards and environmental spatial control system.

From an environmental control perspective, the depth of control varies by level, forming a vertical structure. At the regional and provincial levels, the focus is on strategic coordination, with pollution source control mainly concentrated on the first and second levels. At the city and county levels, the emphasis shifts to implementation, with pollution source control focusing on the third level. Given the rapid urbanization and industrialization since 2000, human activities have significantly impacted the coastal ecological environment, with anthropogenic pollution sources becoming the primary cause of local environmental degradation. Hence, in this study, we will focus on anthropogenic pollution sources for pollutant emission measurement and vertical control.

By combining this system with land use classification standards, pollution source spaces can be reclassified and extracted on a GIS platform. These spaces are defined as areas that discharge harmful substances or have detrimental environmental effects. Within each pollution source space, pollutants' types, properties, and treatment measures are generally consistent. The steps for identifying spatial patches are as follows: first, using the land use map as the base, land units of the same pollution source type are processed into uniform spatial units through spatial analysis techniques like cutting and merging. Next, spatial units not identified in the land use map are supplemented by overlaying POI data and field survey, refining the initial map. Finally, ecological protection areas, identified by provincial authorities, are incorporated to further refine the final spatial distribution of pollution sources, as shown in Fig. 2.

Environmental Stress Assessment and Integration

The environmental stress assessment of anthropogenic pollution sources is based on the emission factor method [30, 31], referencing the pollution source emission coefficient manuals from China and Zhejiang Province. The emission objects, emission coefficients, and decontamination efficiency of various pollutants under different pollution behaviors are determined, and the basic formula is refined twice to optimize the environmental stress assessment formula specifically for Zhejiang Province. Environmental pollutants are classified into three categories based on the types and characteristics of pollutants generated during human production and consumption: solid waste, water pollutants, and air pollutants. Solid waste includes urban and rural household waste, industrial solid waste, and agricultural solid waste; water pollutants consist of domestic sewage, industrial wastewater, and agricultural runoff, with primary pollution indicators such as COD, $NH_3 - N$, TN and TP; Air pollutants include SO_2, NO_x, $PM_{2.5}$, NH_3, etc. The emission factor method is based on the following principle:

$$EM_{i,l,t} = \sum_{j,k} A_{i,j,k,t} \times EF_{j,t,l} \times \sum_{z}(1 - \delta_z) \quad (1)$$

where EM represents the amount of pollutant emissions; EF is the baseline emission factor for pollutants; A is the emission target quantity, such as urban and rural permanent population, energy consumption, product

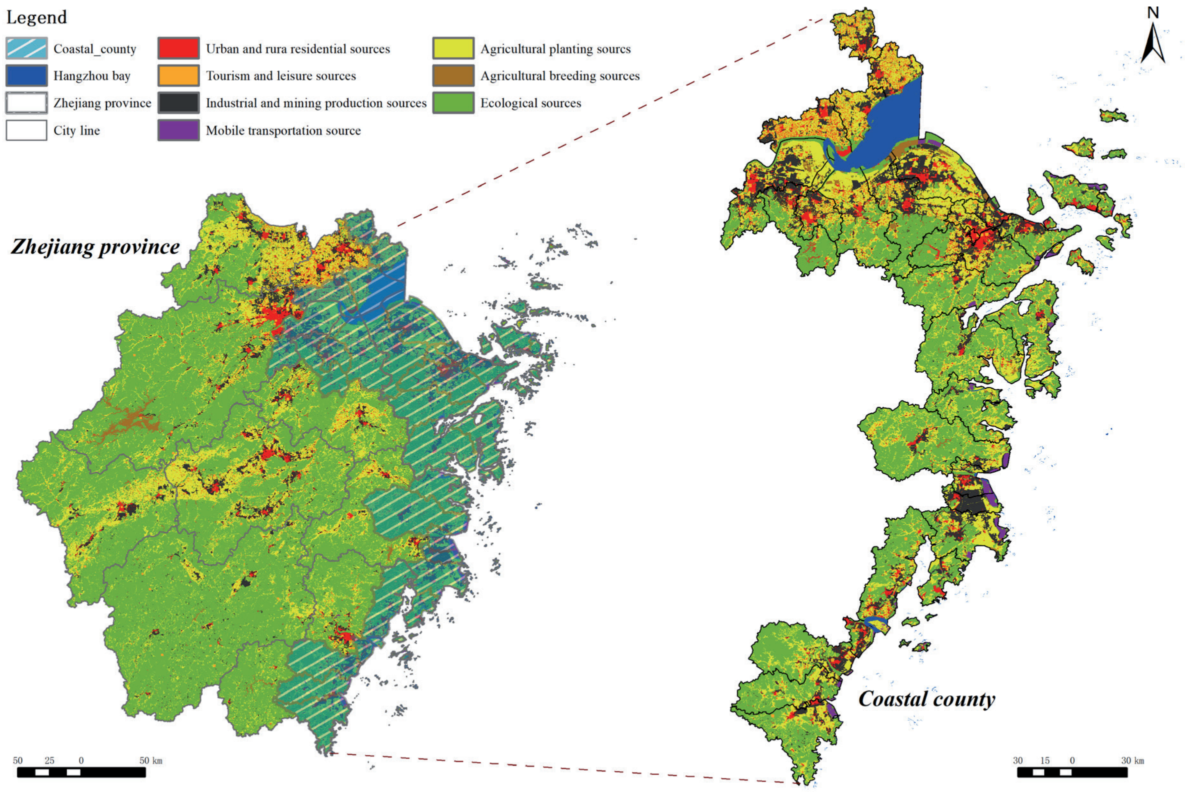

Fig. 2. Spatial distribution of pollution sources in Zhejiang Province and along the coastal zone.

output, or livestock and poultry counts; δ is the efficiency of pollution removal; i represents partition type, j represents anthropogenic pollution behavior, k represents emission object type, t represents time interval, l represents pollutant type, and z represents pollution control measures.

The living source mainly covers the pollutants generated by urban and rural residents using fuel in their daily lives, as well as temporary pollutants generated by visitors from other regions. Its formula can be expressed as:

$$EL_{i,l} = N_T * P_i * EF_{l,i} \tag{2}$$

where $EL_{i,i}$ is the pollutant emission amount; N_T is the emission duration, such as the average stay time of visitors or the number of days residents stay (typically 365 days); $EF_{i,i}$ is the baseline emission factor for pollutants; P_i is the emission subject amount, such as the resident population or the number of visitors at the end of the year; i represents the pollution source type; l represents the pollutant type.

The pollutant emission process from production sources is more complex than that from living sources. Among them, the pollutants emitted during industrial production are primarily generated by fuel combustion, and the corresponding calculation can be performed using formula (1). Agricultural production includes both crop planting and livestock breeding. The calculation formulas for the pollutants generated during the crop planting process, such as straw waste, organic matter in water bodies, and nitrogen fertilizers converted to ammonia, are given in formulas (3), (4), and (5), respectively.

For straw waste:

$$EP_{F,solid} = P_F \times \mu \times (1-\rho) \tag{3}$$

where $EP_{F,solid}$ is the quantity of straw waste; P_F is the food production output; μ is the straw conversion ratio; ρ is the comprehensive utilization rate of straw.

For organic matter in water bodies:

$$EP_{F,water} = A \times \beta \times EF_{F,w} \tag{4}$$

where $EP_{F,water}$ is the organic matter emission in water; A is the cultivated area; β is the comprehensive correction factor for farmland; $EF_{F,w}$ is the standard farmland source strength coefficient.

For nitrogen fertilizer conversion to ammonia:

$$EP_{F,air} = \sum_{m=1}^{n} P_m \times H_m \times EF_{F,a} \tag{5}$$

where $EP_{F,air}$ is the amount of nitrogen fertilizer converted to ammonia; P_m is the number of livestock; H_m is the standard conversion ratio for housing; m is the type of livestock; $EF_{F,a}$ is the standard emission coefficient for pigs.

In addition, another special mobile source generates mobile pollutants due to the movement of motor vehicles and other mechanical vehicles, primarily air pollutants. In the calculation, these are combined as pollutants uniformly generated by transportation spaces. The formula is as follows:

$$EP_{V,air} = \sum_{h=1}^{J} V_h \times EF_{V,a} \times VKT_{V,a} \times \left(1 - \frac{d}{365}\right) \tag{6}$$

where $EP_{V,air}$ is the amount of air pollutants emitted by motor vehicle operation; V_h is the number of the h-th type of motor vehicle; $EP_{V,a}$ is the emission coefficient; $VKT_{V,a}$ is the average annual mileage; J is the total number of motor vehicle types; d is the number of dust-free days.

While different environmental pollutants possess unique properties and cannot be directly combined, they do have cumulative effects on the overall environmental system. Using the enhanced emission factor method, individual pollutant emission characteristics from various anthropogenic pollution sources can be calculated [32]. In comprehensive evaluations, these single characteristic values can be weighted, summed, and combined to obtain the integrated emission characteristic values for pollutants from various sources. The integrated characteristic value for the i-th anthropogenic pollution source space is given by:

$$E_i = \omega_1 \overline{ES_\iota} + \omega_2 \overline{EW_\iota} + \omega_3 \overline{EA_\iota} \tag{7}$$

where E_i represents the integrated characteristic value of the i-th anthropogenic pollution source space; $\overline{ES_\iota}$, $\overline{EW_\iota}$, $\overline{EA_\iota}$ are assigned spatial level values for solid waste, water pollutants, and air pollutants emissions in the i-th anthropogenic pollution source, respectively; ω_i is the weight assigned to the l-th pollutant.

For vertical control, the control level for different pollution source spaces can be determined based on the integrated characteristic values, the spatial distribution of anthropogenic pollution sources, and environmental pollution characteristics. With reference to the ecological protection red line plan, special control areas will be designated in zones with integrated characteristic values of 0, indicating high ecological value.

Results and Discussion

Provincial Variations in Characteristic Pollutants

Under the combined influence of industrial, agricultural, and living pollution sources, Zhejiang Province experiences significant emissions of solid waste, water pollutants, and air pollutants. In 2022, the total solid waste discharged in Zhejiang Province reached 94.32 million tons. Among water pollutants,

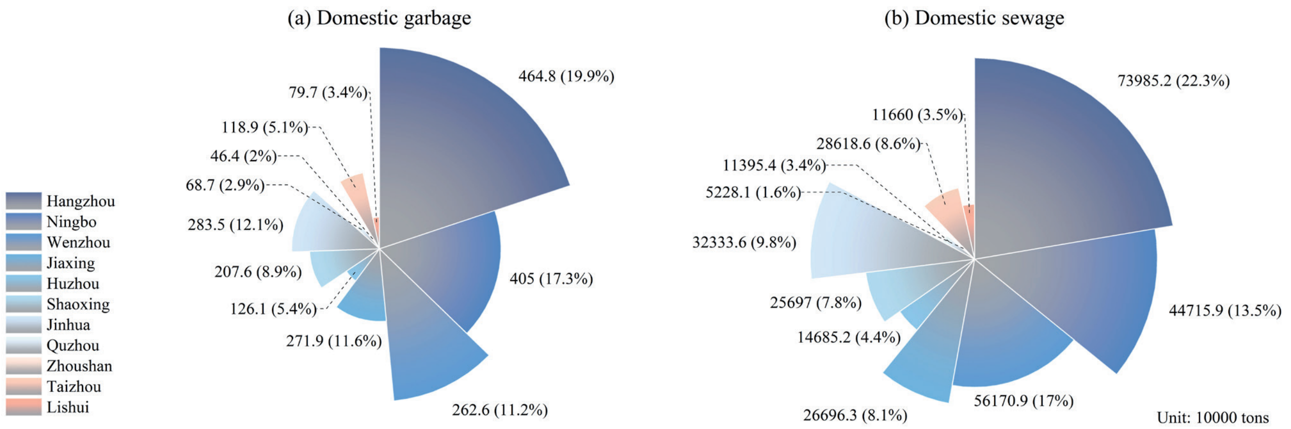

Fig. 3. The emissions of domestic pollution sources in cities of Zhejiang Province.

TN emissions were the highest at 358.33 million tons, followed by *TP* at 52.07 million tons. For air pollutants, NO_x had the highest emissions at 30.55 million tons, followed by SO_2 at 12.38 million tons. Emissions of $PM_{2.5}$, VOC_S, and NH_3 were relatively lower.

The spatial distribution of pollutant emissions reflects the differentiated contributions of industrial production, agricultural activities, and living sources, shaping the overall emission patterns. Industrial sources primarily contribute to solid waste and certain air pollutants, with emissions concentrated in pollution-intensive industrial sites and general manufacturing production areas. Agricultural sources, on the other hand, play a dominant role in water pollution emissions, as *TN* and *TP* discharges are mainly found in grain and agricultural production zones, as well as forestry, fruit, and tea cultivation areas. Living sources significantly impact urban areas, where NO_x and SO_2 emissions are primarily associated with waste treatment facilities, while domestic sewage and solid waste discharges are closely linked to population size.

The characteristic pollutant emissions between typical coastal cities in Zhejiang Province – Hangzhou, Jiaxing, Shaoxing, Ningbo, Zhoushan, Taizhou, and Wenzhou – and inland cities show notable differences. These seven coastal cities, which account for 82.5% of Zhejiang's population, are responsible for a large-scale discharge of domestic sewage and solid waste. As shown in Fig. 3, domestic sewage discharge in Hangzhou, Wenzhou, Ningbo, Jinhua, and Taizhou ranks among the top five in the province, collectively accounting for 71.2% of the province's total discharge. Additionally, domestic waste emissions in Hangzhou, Ningbo, and Jinhua are among the top three in the province, with Wenzhou and Taizhou contributing 11.2% and 5.1%, respectively. Due to its smaller population, Zhoushan's characteristic pollutant emissions are relatively insignificant in comparison.

Significant Internal Differences Among Coastal Cities

City-level Differences: Significant Internal Variations Among Coastal Cities

Building on the differences in pollutant emissions between coastal and inland cities, a further analysis reveals notable county-level disparities within the seven coastal cities, as shown in Fig. 4. Overall, the emission of characteristic pollutants is mainly concentrated in counties where industrial production is the primary regional function. Among these, Ningbo, Shaoxing, Taizhou, and Zhoushan exhibit highly concentrated emission characteristics. In Ningbo, pollution discharge is mainly concentrated in Zhenhai and Beilun, which have developed industries and large freight turnover. In Shaoxing, the pollution discharge is concentrated in Keqiao, where the printing, dyeing, and chemical industries are well-developed. In Taizhou, pollution is concentrated in Yuhuan, which houses many heavy polluting industries such as valves, automotive parts, and non-ferrous metals. In Zhoushan, the pollution discharge is concentrated in Daishan, which hosts the majority of the city's industrial production capacity.

In contrast, Hangzhou, Jiaxing, and Wenzhou show a more diverse range of characteristic pollutant emissions with more balanced discharge volumes. In Hangzhou, large-scale emissions occur in Xiaoshan, Qiantang, and Jiande, where traditional industries like textiles, chemical fibers, automobile manufacturing, metal products, chemical raw materials, and chemical product manufacturing dominate. In Wenzhou, the main pollution sources are Rui'an, which specializes in automobile and motorcycle parts, machinery and electronics, polymer synthetic materials, and fashion and light industry; Yueqing, which is rich in mineral resources and has numerous water-related pollution industries, such as metal surface treatment and circuit boards, as well as organic waste gas pollution industries like surface spraying and casting;

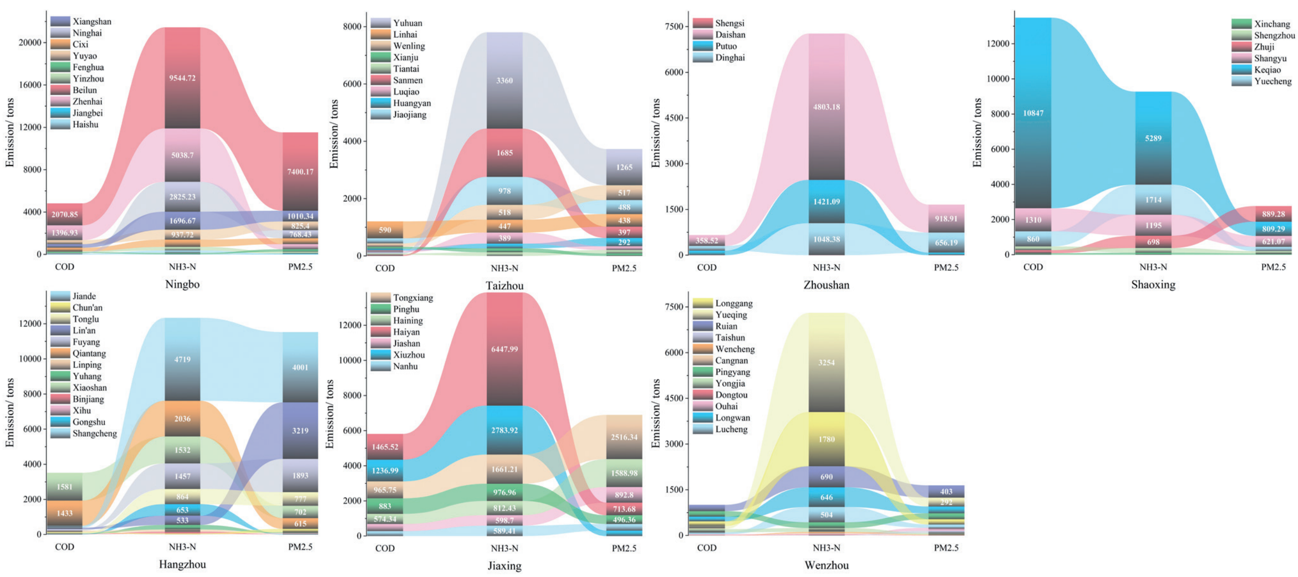

Fig. 4. County-level distribution of characteristic pollutant emissions in coastal cities of Zhejiang Province.

and Longgang, which is known for its railway, highways, ports, and is one of the major printing and packaging industry hubs in China, showcasing relatively high industrial differentiation among these regions. In Jiaxing, pollutant emissions are distributed in Haiyan, which is primarily focused on grain production; Xiuzhou, known for its developed textile and dyeing industries; and Haining, which has a very high annual coal consumption.

In addition, the central urban areas, characterized by high human activity intensity and relatively high population density, also bear a significant amount of characteristic pollutant emissions. Due to the relatively consistent pollution behaviors resulting from residents' daily life and tourist activities, the types of pollutants tend to be simpler. In contrast, the peripheral counties, which are mainly engaged in agricultural production and ecological protection, experience lower human activity intensity and, as a result, have relatively low pollutant emissions. For example, Gongshu, the area with the highest population density in Hangzhou, has higher NO_x emissions than other counties due to the impact of residents' production, daily life, and transportation. Chun'an, home to the Qiandao Lake Reservoir, places strong emphasis on environmental protection, and its pollutant emissions are among the lowest. Putuo in Zhoushan City, which houses 32.9% of the city's population and is densely populated with a focus on tourism development, ranks second in terms of characteristic pollutant emissions. Shengsi, with only 86 km^2 of land area and a population of 65000, accounting for just 5.5% of the city's total population, produces negligible characteristic pollutant emissions. Huangyan, Tiantai, and Xianju in Taizhou, as well as Yongjia and Cangnan in Wenzhou, are located in hilly areas where mountainous terrain covers more than 80% of the region. Their development is primarily based on agricultural activities, resulting in lower characteristic pollutant emissions.

Localized Patterns of Pollution Source Emissions

Point-Pattern of Pollution Source Emissions

The spatial concentration of human activities in Zhejiang Province is relatively high. The three-level spatial units of anthropogenic pollution sources, including pollution-intensive production sites, general manufacturing production sites, urban residential sites, rural residential sites, leisure and recreation sites, and garbage disposal facilities, are often "point-like" distributions in the central areas of cities and towns (Fig. 5a).

Zhejiang Province has a resident population of 66.27 million, with 49.19 million urban residents, accounting for 74.2% of the total population. The spatial distribution of population density shows a "point-band-zone" structure, with high-value points in economically developed cities like Hangzhou, Ningbo, and Wenzhou, connected by transportation corridors and expanding outward to areas with good transportation facilities, decreasing layer by layer. Also, the population agglomeration effect along the eastern coastal area is significant. The Hangzhou Bay urban agglomeration, including six cities – Hangzhou, Ningbo, Jiaxing, Huzhou, Shaoxing, and Zhoushan – accounts for 56.59% of the total population of the province, with a population density of 786 people per km^2. Water pollutants in urban and rural residential areas are primarily *COD* and *TN*, with emissions of 303600 tons and 37600 tons, respectively. The main air pollutants are $PM_{2.5}$ and VOC_S, with emissions of 24400 tons and 127700 tons, respectively. The comprehensive environmental stress indexes for urban and rural residential areas are 0.1128 and 0.0300, respectively.

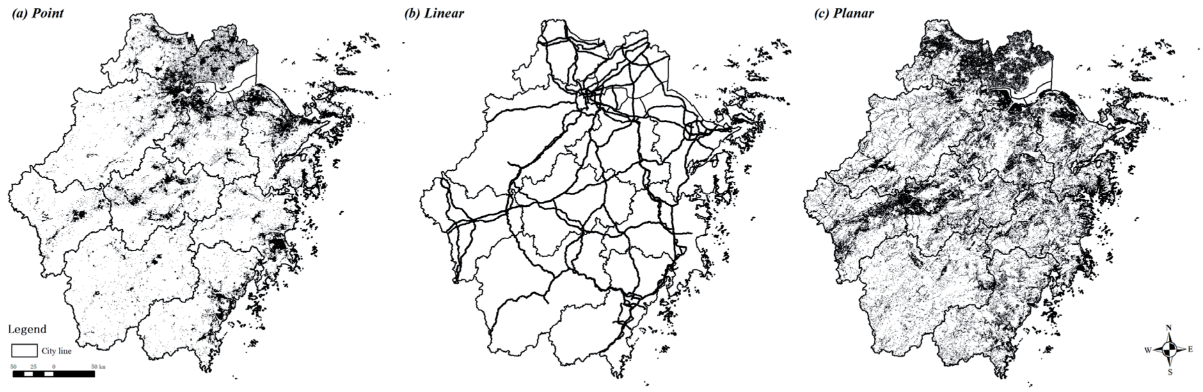

Fig. 5. Point-linear-planar patterns of pollution source emissions in Zhejiang Province.

In terms of industrial and mining production, Zhejiang Province has a large scale of industrial enterprises across 38 sectors, including non-metallic mining and dressing, agricultural and sideline food processing, food manufacturing, and textiles. These enterprises are distributed across various cities in the province, creating a widespread industrial layout. Pollution-intensive industries, in particular, exhibit strong spatial concentration and are still primarily concentrated in the traditional "Hangzhou Bay". The main water and air pollutants in industrial and mining production areas are COD and VOC_S, with emissions of 58300 tons and 548100 tons, respectively. The environmental stress indexes for pollution-intensive production sites and general manufacturing production sites are 0.0813 and 0.4342, respectively.

Linear-Pattern of Pollution Source Emissions

Zhejiang's transportation system is centered around the comprehensive transportation network of the Hangzhou metropolitan area, with Ningbo-Zhoushan Port, Yiwu international transportation, and Wenzhou regional transportation as key hubs. The five major transportation corridors are the coastal route, Shanghai-Hangzhou-Ningbo, Jinhua-Wenzhou-Yiwu, Hangzhou-Shaoxing-Ningbo, and Jinhua-Lishui-Wenzhou. This transportation system has led to increased traffic volume, dense settlement patterns in villages and towns along the routes, and significant pollutant emissions resulting from human activities, creating a linear pollution distribution (Fig. 5b). By the end of 2022, the total expressway mileage in Zhejiang Province had reached 5096 km. The highway density in major cities like Hangzhou, Ningbo, and Wenzhou, as well as their surrounding areas, is relatively high, with the province having 20.51 million motor vehicles. The primary pollutants in transportation areas are NO_x and VOC_S, with emissions of 300100 tons and 112100 tons, respectively.

Zhejiang Province, with its dense river network, also faces water pollution challenges. Factories and residential areas along rivers or waterways often discharge untreated or substandard wastewater and domestic sewage, contributing to water pollution. Additionally, chemical substances such as fertilizers and pesticides from agricultural activities enter rivers and waterways through runoff and infiltration, further exacerbating pollution. The road network in Zhejiang overlaps heavily with the river system, leading to pollution sources such as oil spills and chemical leaks during transportation, which threaten water quality. Furthermore, the distribution of the road network impacts river flow directions, disrupts wetlands and ecological balance, and intensifies water environment stress.

Planar-Pattern of Pollution Source Emissions

The agricultural production model in Zhejiang Province remains relatively traditional, with a significant reliance on chemical fertilizers, pesticides, and other chemicals. Livestock and poultry farming also contribute to water pollution, as manure and wastewater are often discharged directly without treatment or fail to meet treatment standards, leading to both water pollution and pesticide residue contamination. This results in a typical planar distribution of pollution across the region (Fig. 5c).

Regarding agricultural planting, Zhejiang has 12261 km^2 of arable land and 55550 km^2 of garden areas. The main pollutants in the planting industry are NH_3–N, TN, and TP, with emissions of 4.2 million tons, 356 million tons, and 52 million tons, respectively. It indicates severe nitrogen and phosphorus pollution in water bodies in farming areas, with pollutant discharge roughly correlating to the scale of agricultural production in each city. The primary air pollutant in the planting sector is NH_3, with an emission of 4200 tons. In livestock and poultry breeding, the average annual number of live pigs, poultry, and sheep at a provincial scale was 6.5 million, 85.1 million, and 1.6 million, respectively. With a growing demand for livestock products, large-scale breeding has become an inevitable trend. This has led to a significant increase in animal waste, with a total of 12.3 million tons of solid waste generated. The main water pollutants produced are *COD* and *TN*, which total 24500 tons and 2100 tons, respectively.

Zhejiang's rich coastal and water resources, along with its favorable climate, have fostered rapid development in aquaculture. However, pollutants such as feed residues, biological excreta, drugs, and disinfectants from aquaculture operations enter the water environment, causing eutrophication and organic pollution. Key pollution sources in the aquaculture areas of Zhejiang include the Tiaoxi Stream Basin, Yueqing Bay in Wenzhou, Ningbo coastal waters, Hangzhou Bay, Taizhou Bay, etc. In these regions, high aquaculture density and unlicensed enclosures are common. The water pollutants from aquaculture are mainly *COD* and *TN*, amounting to 35000 tons and 4600 tons, respectively.

Vertical Control of Environmental Pollution Stress

Considering the earlier analysis of emission intensity and spatial distribution characteristics, a combination of qualitative and quantitative methods was used to assess and manage pollution sources in Zhejiang Province, taking into account both the level of pollution they cause and the vulnerability of the local ecosystem. As shown in Table 1, pollution sources with a comprehensive index over 0.1 include pollution-intensive production sites, urban residential areas, waste treatment facilities, grain and agricultural production areas, and livestock and poultry breeding areas. These sources cover the main contributors to pollution from both production and daily life. The control measures for each pollution source are aligned with the intensity of environmental stress they cause. The sources are categorized into four control levels: IV (highest priority), III, II, and I (lowest priority). Pollution sources that require ecological protection are given a separate classification, labeled level 0. The goal of environmental control is to focus on the areas where pollution is generated, considering both how much pollution is being emitted and the spatial impact. Based on the spatial interaction patterns and environmental stress characteristics of pollution sources in Zhejiang Province, four typical control types have been identified: industrial source-oriented, agricultural source-oriented, life source-oriented, and ecological source-oriented. For each type, a tailored environmental management approach has been proposed to ensure targeted and effective control, addressing the specific needs and challenges of these pollution sources (Fig. 6).

The typical distribution of industrial source-oriented areas shows high density and significant emissions, which creates notable environmental stress. Industrial parks, where many production units are concentrated, are the main sites for industrial and mining activities. While this boosts industrial agglomeration, it also makes these areas the primary source of industrial pollution. To manage this, the following measures can be taken: First, improve the environmental infrastructure in industrial areas, optimize buffer zones, and implement a comprehensive plan to control industrial pollutant emissions. Second, encourage individual businesses to adopt greener practices and upgrade their technologies, using a combination of regulations and incentives, such as pollution discharge standards and fees, to reduce emissions and improve efficiency. Lastly, accelerate the use of clean or renewable energy in industrial operations and apply targeted measures for high-pollution industries like steel, petrochemicals, shipbuilding, and textiles, such as performance-based control systems.

Agricultural source-oriented areas are primarily distributed in plains and river valleys that are suitable for farming and livestock breeding, such as the Hangjiahu Plain, Wenzhou-Taizhou Coastal Plain, and Jinhua-Quzhou Basin. These areas are key

Table 1. Environmental stress index of pollution source in Zhejiang Province.

Environmental pollution source	Solid waste stress index	Water stress index	Air stress index	Comprehensive stress index
General Manufacturing Production Sites	0.1872	0.0002	0.0564	0.0813
Pollution-Intensive Production Sites	1.0000	0.0013	0.3013	0.4342
Waste Treatment Facilities	0.0005	0.2560	0.6000	0.2855
Transportation Spaces	0.0000	0.0000	0.0535	0.0178
Grain and Agricultural Product Production Areas	0.0325	0.7500	0.0070	0.2632
Fruit and Tea Planting Areas	0.0001	0.0699	0.0025	0.0242
Livestock and Poultry Breeding Areas	0.2413	0.0007	0.2000	0.1473
Aquaculture Areas	0.0000	0.0009	0.0000	0.0003
Urban Residential Areas	0.2895	0.0045	0.0443	0.1128
Rural Residential Areas	0.0665	0.0036	0.0200	0.0300
Cultural Recreation Areas	0.0342	0.0005	0.0053	0.0133

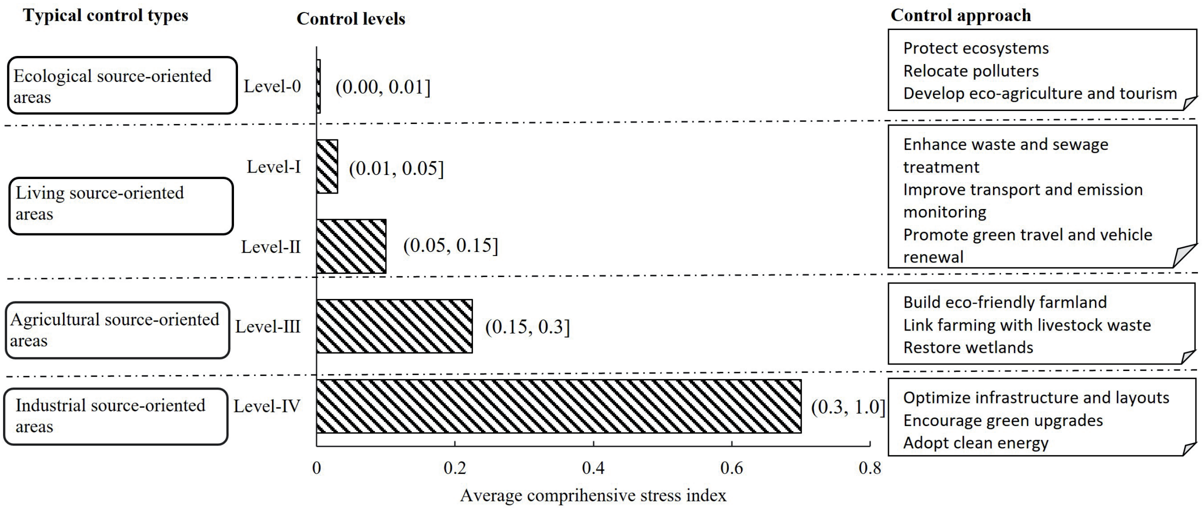

Fig. 6. Vertical environmental control system for pollution source.

production zones for grains, fruits, tea, and livestock. However, flat terrain suitable for intensive agriculture is relatively scarce, accounting for only 20.3% of the province's total land area. Agriculture, especially crop cultivation, is the primary source of water pollution, with chemical fertilizers and soil erosion contributing to non-point source pollution that is highly mobile and difficult to control. Meanwhile, large-scale livestock and aquaculture operations are centralized, which helps confine pollutants to specific areas. However, insufficient waste treatment in these operations creates potential risks for ecological damage. To address these challenges, the following control strategy can be implemented: First, the construction of high-standard farmland should be promoted, utilizing low-cost composting to convert livestock manure into natural fertilizer or biogas fermentation to produce combustible gas for resource reuse. Second, large-scale livestock farms should be located near agricultural areas, enabling treated manure to serve as fertilizer for crops and creating a closed-loop system that integrates agriculture and animal husbandry. Finally, unused land near farmland drainage areas can be converted into artificial wetlands or forests to filter irrigation runoff and mitigate eutrophication. This integrated approach ensures sustainable agricultural production while effectively managing pollution sources.

The typical areas dominated by living sources are closely aligned with population distribution, primarily concentrated in central urban areas and major towns within each city. These areas are characterized by diverse urban functions, including residential, commercial, leisure, and recreational activities, which result in a variety of pollution sources such as urban and rural residential spaces, recreational zones, and transportation networks. Environmental stress in these regions is mainly point-like, supplemented by linear sources, covering relatively small areas with moderate pollution emissions. However, the rear-end controllability of these sources is relatively strong. Some stresses are dynamic and shift with human activities, increasing the complexity and risk of pollution control. To address these challenges, the following management strategies can be adopted: prioritize the construction and improvement of solid waste classification systems and sewage treatment processes in residential areas, while encouraging residents to actively participate in environmental management and promoting waste-free city initiatives across the province. Rational planning of large-scale infrastructure such as railways and highways should be complemented by the development of low-grade roads connecting villages and towns, alongside improvements to remote sensing networks for monitoring motor vehicle emissions. Furthermore, green and low-carbon travel should be encouraged by promoting public transportation, phasing out high-emission vehicles, facilitating vehicle upgrades, and fostering green consumption habits. These measures aim to mitigate environmental stress, enhance pollution control, and support sustainable urban and rural development.

The typical areas dominated by ecological sources are primarily distributed in the hilly and mountainous regions of western and southern Zhejiang, as well as the coastal zones of eastern Zhejiang, showcasing distinct land and sea characteristics. These regions are mainly composed of national parks and nature reserves, with eco-tourism serving as a supplementary function. Human-induced pollutant emissions in these areas are minimal; however, tourism development leads to seasonal fluctuations in environmental stress, with higher intensity during peak tourist seasons and lower intensity during off-peak periods. To manage these areas well, ecological protection should come first, based on natural resources and land features. This includes setting boundaries for ecological protection on both land and sea, with national parks playing a key role in strengthening ecosystem stability. Efforts should also focus on addressing the main causes of ecological damage. This includes relocating or closing chemical factories in sensitive areas like rivers, lakes, and bays, strictly limiting non-ecological development along shorelines, and setting up strong ecological monitoring and early warning systems. Additionally, the Hangzhou-Ningbo ecological economic belt should be developed carefully to support the growth of specialized agriculture and forestry industries. Eco-cultural tourism in Jiangnan water towns should be planned to create economic benefits while protecting nature, ensuring a balance between development and ecological conservation.

Conclusions

Zhejiang Province's ecological environment faces significant stresses from industrial, agricultural, and residential sources, with considerable spatial variation across different scales. At the city level, over 71.2% of pollutant emissions are concentrated in seven coastal cities. In contrast, mountainous regions, primarily focused on ecological protection, experience lower environmental stress. At the county scale, pollutant emissions are concentrated in industrial hubs like Ningbo and Shaoxing, while cities like Hangzhou and Wenzhou show more balanced emissions.

Pollution sources in Zhejiang can be categorized into three primary types: industrial, agricultural, and living sources, with 21 subtypes in point, linear, and planar patterns. Industrial and mining areas, as well as urban and rural living spaces, mainly face point-like stress, accounting for 90% of the province's air pollutant emissions due to urbanization and industrialization. Transportation areas are subject to linear-like stress, with pollutants spreading along transportation routes, often overlapping with river networks. Agricultural areas, livestock farms, and aquaculture zones experience planar-like stress, with significant water environment pressures in the Tiaoxi River Basin and coastal waters.

Environmental control is prioritized based on pollution source type. Industrial sources are primarily grade IV, with a focus on technological upgrades and emission controls. Agricultural sources are grade III, with pollutant reduction methods such as tailwater irrigation and low-cost composting. Living sources are grade II and I, targeting waste reduction, vehicle updates, and greener lifestyles. Ecological areas are classified as grade 0, prioritizing ecological security and sustainable development.

Due to data limitations, this analysis examines environmental stress characteristics from a single phase in 2022, resulting in low temporal resolution and the exclusion of indicators such as carbon emissions. Future research should integrate pollution source structures with other environmental divisions to optimize the allocation of production and living spaces in coastal areas. Additionally, leveraging AI, field investigations, and big data analysis will help expand socio-economic and environmental data across time, revealing long-term spatial patterns of environmental stress. By accurately categorizing pollution sources, the classification system allows for more targeted control measures, enhancing the efficiency and sustainability of pollution management. As environmental conditions evolve, the system can be refined to support flexible, data-driven pollution control strategies.

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Conflict of Interest

The authors declare no conflict of interest.

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