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Original Research Paper

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Spatial Assessment of Ecological Vulnerability in Fuzhou District in China Using Remote Sensing and GIS

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ABSTRACT

With the growth of global population and intense land use changes, the problem of ecological vulnerability has become prominent. Assessment of ecological vulnerability bears significance in protection and restoration of the ecological environment. Assessment results for a given area can reveal regional characteristic differences in system vulnerability and provide basis for the rational use and protection of the natural environment. To analyse the ecological vulnerability in Fuzhou district in China and its causes, systematic assessment and zoning of ecosystem vulnerability were proposed. Using the remote sensing and geographic information system technologies, ecological vulnerability was spatially, explicitly, and comprehensively assessed. Results showed that the most vulnerable areas of Fuzhou district include Pingtan Comprehensive Experimental Area, Fuqing City, Fuzhou City and Changle City. Counties of Yongtai, Minhou and Minqing feature good vegetation coverages and low ecological vulnerability. In Fuzhou City, three zones, namely, Taijiang, Gulou and Cangshan Zones, feature high or extremely high percentage vulnerability. The other two zones comprise better ecosystems. Analysis of correlation coefficients between vulnerability value and various indices showed distinct factors of ecological vulnerability for each region. The main factors affecting the ecosystems in Fuqing, Jin'an Zone, and Changle City include climate, vegetation and soil, respectively, whereas the factors that simultaneously affect the ecosystem in Cangshan Zone consist of soil, land use, topography and vegetation. The key challenge in improving ecological vulnerability of these areas is optimization and coordination of land use/coverage under natural conditions. The results can provide basis and reference for future research and relevant formulation, such as the mode of selection of resource utilization and environmental protection, and improvement of key factors.

INTRODUCTION

Exploitation and utilization of natural resources become increasingly serious, leading to deterioration of the regional ecosystem environment. Serious problems, such as vegetation destruction, soil erosion and land use change, result in serious degradation of and irreversible changes in the entire ecosystem. Global and regional urbanization changes in the ecosystem occur ubiquitously and have been accelerating for decades. Vulnerability assessment has been studied for decades in some social fields, such as in assessment of poverty and food insecurity. Assessment of ecological vulnerability also has received significant attention (Lange et al. 2010). Vulnerability assessment was also applied to analysis of risks in ecology (Micheli et al. 2014), environment (Varis et al. 2012), agriculture (Jayanthi et al. 2013), sociology (Lee 2014), and economy (Armatas et al. 2017) and other natural risks (Ogunkunle et al. 2016).

Sources of regional vulnerability in different parts of the world exhibit diverse characteristics. Vulnerability reflects multiple stress and destructions that occur at different times and in given spatial scales. Vulnerability is a key and popular topic in the fields of ecology and environment and in social and economic fields. Vulnerability is not only a basic theoretical discipline but also an applied subject. Various factors should be considered in assessing ecological vulnerability. Assessment requires not only the studies of spatial scales and time but also those of structural and functional ecological relationships. The inherent intricacy of an ecosystem causes difficulty in selecting indices, determining weight, and quantifying vulnerability in assessment. Some experts have made remarkable achievements in the definition of ecological vulnerability, its characteristics, and evaluation indices and methods, which have brought new thinking in studies of the ecosystem (Song et al. 2015, Zhang et al. 2015). Ecological vulnerability assessment has become an important measure to assess global change and sustainable development.

Remote sensing (RS) and geographic information system (GIS) can provide a platform of multi-source information fusion and integration for the ecological vulnerability study. Remote sensing provides a powerful data source support for land use, vegetation cover, landscape changes and other parameters that usually have been used in the assessment of ecological vulnerability. Utilizing GIS spatial analysis and statistical functions enables the researchers quickly accomplish the results of evaluation. Vulnerability can be feasibly assessed using RS and GIS, because of the improving theories of vulnerability assessment and 3S (RS, GIS and GPS) applied technology (Song et al. 2015). Remote sensing (RS) and (GIS) have been widely used in geology, hydrology, ecology, forestry, environmental science and other fields (Zhang et al. 2015).

Thus far, the primary methods of determining weight rely on expert experience and several mathematical methods or their combination. Using mathematical methods, accuracy and consistency can be tested to reduce subjectivity and randomness. For a given region, determining weights through mathematical methods cannot achieve analysis of specific characteristics. On the other hand, combining expert judgment can increase flexibility of determining weights. Specific methods include expert consultation, index comparison, statistical average method, comparison method, sampling weight matrix method, step-wise regression method, grey correlation analysis, principal component analysis, and analytic hierarchy process (AHP). Sometimes several methods can be used simultaneously to determine weights in most literature (Alves et al. 2013).

Ecosystem degradation in Fuzhou district has exceeded the current level of socio-economic technology, putting pressure on ecological functions that can disrupt environmental recovery and cause irreversible damage (Fang et al. 2016). Previous studies showed that the main ecological threats in Fuzhou district include soil erosion, river flooding, coastal droughts, and urban tropical island effect (Chen et al. 2010). Fujian province is the first province to implement “ecological province construction” in China. Numerous works, such as state investigations (Wu et al. 2008), dynamic change monitoring (XU 2013), and ecosystem assessment (Jiang et al. 2012), have contributed significantly to the protection and improvement of the ecosystem and provided basis for subsequent regional ecosystem studies.

Overall, the ecological environment in Fuzhou and even Fujian Province has been paid more attention, but the study in the comprehensive evaluation of ecological vulnerability still needs to be further deepened. At the same time, it is necessary to find a suitable norm for the assessment of ecological vulnerability in Fuzhou, based on the differences between the characteristics and causes of the regional ecological vulnerability. The “norm” refers to the method of determining the indexes and weights, the idea of comprehensive zoning and result evaluation and so on that are suitable for this area. The results are not only able to expand the thinking of research for ecological vulnerability assessment, but also able to provide data support for the managers and planners in protecting regional eco-environment and controlling ecological vulnerability risks. Finally, the results of this study supply theoretical and technical reference to other study of ecological vulnerability in similar areas.

MATERIALS AND METHODS

Study Area

Fuzhou district is located between 25°16’-26°29’ North lati-

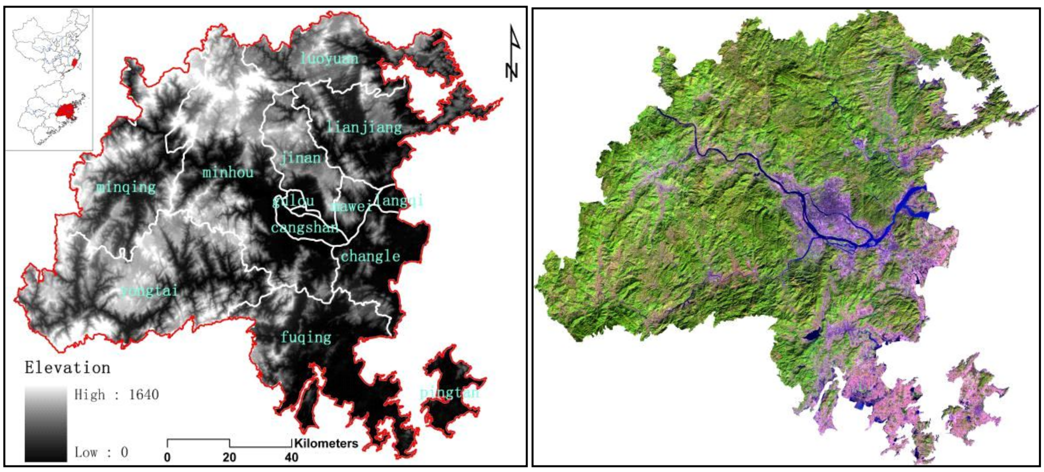

Fig. 1: RGB false colour composite image using bands 6, 5, and 4 of a Landsat 8 OLS image obtained in 2014 (left). Geographical location of the Fuzhou district study area and (right) its topography.

tude and 118°31'-120°13' East longitude, covers a total area of 11,462.41 km^2, and consists of 13 administrative subareas: Gulou Zone, Taijiang Zone, Jin'an Zone, Mawei Zone, Cangshan Zone, Minhou County, Minqing County, Yongtai County, Fuqing City, Changle City, Lianjiang County, Luoyuan County, and Pingtan Comprehensive Experimental Area (Fig. 1). In north, west and south of Fuzhou district, the landscape is dominated by mountains. In the east lies the Fuzhou Plain, which is a part of the Min River downstream plain landform. Fuzhou Plain features extensive and reticulated waterways and is home to most of the Fuzhou district's population. Fuzhou district experiences a humid subtropical climate, with high annual precipitation and temperatures.

Research Objectives and Design

In this study, the main ecological vulnerability of the study area was studied first. Then, each indicator was extracted on the basis of RS data and ground meteorological and landform data. Using AHP, weight coefficient of each index was acquired. Then, quantitative evaluation results were completed through the GIS technique. Finally, under different natural conditions, the main influencing factors of ecological vulnerability in the study area were analysed.

The objectives of this paper include (1) identifying threatening and sensitive indices, (2) constructing integrated assessment indices and presenting a systematic methodology, (3) determining the weight of all indices, and (4) analysing the ecological vulnerability for Fuzhou city. The present study aims to propose a systematic assessment and spatial zoning of ecosystem vulnerability.

Utilizing RS and GIS, ecological vulnerability indices in Fuzhou district were rapidly extracted and analysed. Overlaying calculation of ecological vulnerability was completed, whereas the weight of each index factor was obtained using AHP. The model was constructed by the following steps: (1) selection of indices, (2) data acquisition and processing, (3) determination of weights, (4) variable standardization of indices, (5) ecological vulnerability overlaying calculation, and (6) quantification of vulnerability. Fig. 2 illustrates the related flow diagram.

Ecological Threats

Terrain threat: The Fuzhou district features mountains and hills, which account for 32.41% and 40.27% of its total area, respectively. The proportions of mountains and hills are especially high in Yongtai, Minqing and Minhou County. Landslides, and soil and water erosions often occur in the steep mountains and hills of the district.

Uneven seasonal distribution of precipitation:

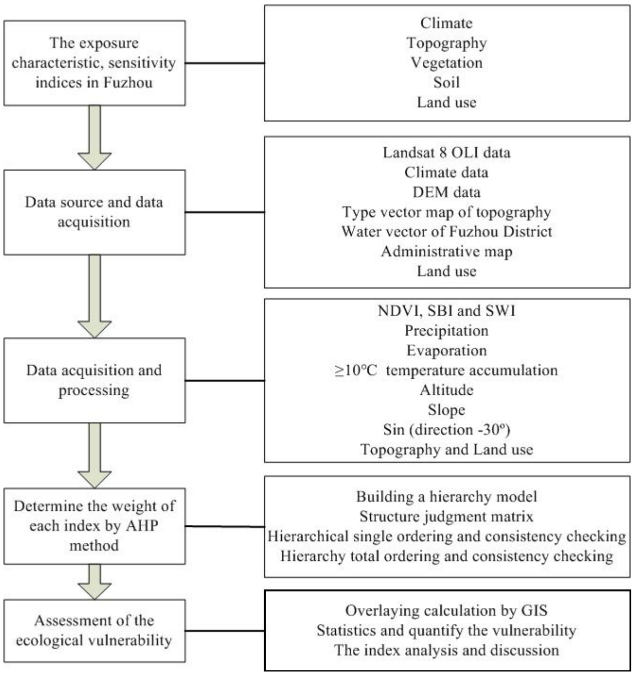

Fig. 2: Flow diagram of spatial assessment of ecological vulnerability in the Fuzhou district.

Precipitation intensity in the Fuzhou district strongly varies over the year. More than 80% of annual precipitation occurs in March to August accounts and accompanied by frequent typhoons and thunderstorms. During the rainy season, floods and mountain landslides occur frequently. Very little precipitation occurs, but evaporation is relatively strong, often resulting in serious droughts outside this period.

Large differences in precipitation evaporation ratios in Fuzhou district: Given that distribution of precipitation within a year varies widely, but evaporation does not, coastal cities often suffer net loss of water. Annual accumulation of ≥ 10°C growing degree days amounts to 6000°-6700°, providing excellent conditions for crop photosynthesis and biomass accumulation. However, as a result of flat topography around coastal cities and the rain shadow effect of Taiwan Strait, distribution of regional spatial precipitation varies drastically. Consequently, the ratio of annual precipitation to evaporation for Pingtan and Fuqing, which are located in the coastal area, reach 0.643 and 0.807, respectively. In normal years, these values result in net loss of water in these regions and subsequent droughts.

Population aggregation and land reduction: Human activities in the region have significantly changed land use/coverage over the past years. Fuzhou, as the capital city of Fujian Province, has experienced rapid population growth and industrial development, resulting in the reduction of land resources. According to dynamic changes in land use, construction land areas changed the most, followed by gardens, highways, unused lands, dry lands, paddy fields, water areas and forest land areas. The direction of expansion in Fuzhou district is to the east and south and to coastal areas along Min River (Yang et al. 2012). Land quality declines year by year, and human activities and settlements have also extended from the plain areas to the mountains and hill areas. Given the population growth, availability of per-person cultivated area decreased from 0.0365 hm^2 in 1978 to 0.025 hm^2 in 2009 (Hu et al. 2013).

Soil erosion and floods: Mountains in Fuzhou district mainly feature red and laterite soil types, resulting in barren, acidic, and sticky soil. Previously, high temperatures ensured high crop production. Now, high temperature is the main driver of soil erosion and mineral decomposition. During the rainy season, silt and clay from soil erosion are transported from mountains to rivers, resulting in sedimentation in these waters. Consequently, capacities of rivers for drainage and detention decrease, resulting in floods.

Environmental Impact Indices and Selected Indices

Vulnerability is a generalized concept that should be specifically addressed for a given region and investigated object. Most literature divide vulnerability studies into three parts: exposure characteristic, sensitivity and recovery capacity. For Fuzhou city and in this study, vulnerability is a set of ecosystems that include sensitivity and exposure to stress factors. The selected indices manifest the following characteristics: scientific, practical, representative, feasible, comprehensive and timely. This study was more inclined to assess vulnerability of regional climate, topography, land use and land cover, and other natural and physical hazard characteristics on a large administrative spatial scale. Five first-level indices were selected: climate, topography, vegetation, soil and land use.

Land use and vegetation coverage change constantly. Soil weathering becomes serious under high annual temperature accumulation of ≥ 10°C. Barren soil consequently continues to be eroded. Vegetation coverage and slope, combined with high temperatures and precipitation characteristics, are the main causes of ecological vulnerability in hills and mountains. The same conditions apply to plain areas.

The ratio of annual precipitation and evaporation adequately explains the dry conditions of coastal areas. We used the revised formula (Meng et al. 2004) of a Russian scientist of the Chinese Academy of Sciences to obtain the dryness index of Fuzhou district; this index can reflect constraints of precipitation and temperature accumulation on crop growth. The formula is as follows Eq. (1):

$$k = 0.16 \times \frac{\Delta T}{\Delta P} \qquad ...(1)$$

Where K is the dryness index, ΔT and ΔP are annual temperature accumulation of ≥ 10°C and annual precipitation of ≥ 10°C, respectively.

At the same time, human activities are concentrated in the hilly and low mountain or east plain areas, resulting in changes in vegetation coverage and the original ecosystem. That is, vegetation is the controlling factor, and combination of topography and climate is the triggering factor. Soil impoverishment is one of the underlying vulnerabilities. All indices are converted to dimensionless numerical values.

To validate our results, we performed ecological surveys in various directions and locations, such as in a northern line to Sun River, a southern line to Quanzhou, and an eastern line to the Langqi Island. The following were measured during these surveys (Zhang et al. 2014): GPS position, vegetation type, vegetation cover, soil type, topography type, land use and imaging characteristics. Based on the characteristics, geomorphologic type (N_{21} index) was assessed using grading standards, as presented in Table 1.

In the present study, we removed the water region using the water vector of Fuzhou district. Thus, the area of the study region totals 11462.27 km^2.

Data Acquisition and Processing

Given the results (Guettouche et al. 2013, Yao et al. 2016) of previous studies, each kind of index can be rapidly extracted by RS and GIS methods.

Obtaining site data on annual precipitation, evaporation, and ≥ 10°C temperature accumulations for 17 weather stations (including nine meteorological stations in Fuzhou district and eight stations around it) and extra 170 points in the study region, combined with ArcGIS topology processing, all site data were converted to raster data with a grid

Table 1: Vulnerability quantization value of land use and geomorphologic types.

Index	Index level value					
Geomorphologic type	Mesa	Valley alluvial plain	Moderate altitude mountain	Low mountain, Aeolian plain, etc.	High hill	Low hill
Index value	2	3	5	6	8	10

size of 30×30 m^2. From the average of nearly 30 years of meteorological data, accurate data were obtained for the 17 stations. A total of 170 extra points were selected from the contour map of 1:1,000,000 scale precipitation, evaporation, and ≥ 10°C temperature accumulations to facilitate the subsequent interpolation topology calculation.

From two Landsat 8-Operational Land Imager (OLI) images of Fuzhou district acquired on December 13, 2014 and December 22, 2014, we calculated two Normalized Difference Vegetation Index (NDVI) values for the images. Fragmentation of landscape ecology was used to represent ecological vulnerability of land use. Fragmentation was derived from classification results of OLI data. NDVI data were derived from RS imagery to represent vegetation coverage and biological capacity (Reeves et al. 2014). We deduced the soil brightness index (SBI) and soil wetness index (SWI) to represent soil conditions (Satir 2016), which can indirectly reflect vegetation coverage and soil moisture. NDVI and SWI were derived using Eqs. (2)-(4):

$$NDVI = \frac{\rho_{NIR} - \rho_{red}}{\rho_{NIR} + \rho_{red}} \quad ...(2)$$

$$\mathrm{SBI} = 0.31 \times B_2 + 0.28 \times B_3 + 0.47 \times B_4 + 0.56 \times B_5 + 0.51 \times B_6 + 0.19 \times B_7 \quad ...(3)$$

$$\mathrm{SWI} = 0.15 \times B_2 + 0.20 \times B_3 + 0.33 \times B_4 + 0.34 \times B_5 - 0.71 \times B_6 - 0.46 \times B_7 \quad ...(4)$$

Where, ρ_{NIR} and ρ_{red} are spectral reflect values of near-infrared OLI B_5 (0.845-0.885 μm) and red B_4 (0.63-0.68 μm), respectively. Landsat8 OLI image data were obtained from the United States Geological Survey and Geospatial Data Cloud websites (https://www.usgs.gov/ and http://www.gscloud.cn/).

From land use classification map of Fuzhou district (Qi, et al. 2016), we deduced a suitable landform and land use (Huzui et al. 2012) raster image with a 30×30 m^2 pixel size.

Using internal interpolation, we converted the 1:100,000 vector contour line data of Fuzhou district into a triangulated irregular network and subsequently to grid digital elevation mode and image data with a grid size of 30×30 m^2. From this information, we derived the image data for altitude, slope, and aspect to represent terrain information.

Variable Standardization

Ecological impact indices and ecological vulnerability form two kinds of relations: consistent and reverse relations. In a consistent relation, an increase in ecological impact index results in an increased ecological vulnerability, such as that with the land use index. In a reverse relation, an increase in ecological impact index results in a decreased ecological vulnerability, such as that with the NDVI. Calculations of ecological vulnerability for both relations also differ (Galicia et al. 2007). Several variables, such as the NDVI, featured negative contributions, whereas others, such as the land use index, exhibited positive contributions. Positive indices were standardized using Eq. (5), and negative indices were standardized using Eq. (6) with values ranging from 0 to 10. Calculation of ecological vulnerability for the consistent indices is as follows:

$$\mathrm{S_{ij}} = 10 \times \frac{(\mathrm{Xij\text{-}Xjmin})}{(\mathrm{Xjmax\text{-}Xjmin})} \quad ...(5)$$

Calculation of ecological vulnerability for the reverse indices is as follows:

$$\mathrm{S_{ij}} = 10 \times \frac{(\mathrm{Xjmax\text{-}Xij})}{(\mathrm{Xjmax\text{-}Xjmin})} \quad ...(6)$$

Where, i = 1, 2, … m; j = 1, 2, … n; i is the pixel number, j refers to the number of ecological impact indices, S_{ij} is the vulnerability value of unit I and index j, X_{jmax} is the maximum of index j, and X_{jmin} is the minimum of index j. Pixel numbers (i) range from 1 to 12,819,150. The number of ecological indices is n = 11.

Four consistent ecological indices and five reverse indices exist, namely, N_{12}, N_{23}, N_{24}, and N_{41}; and N_{11}, N_{13}, N_{22}, N_{31}, and N_{42}, respectively. The remaining two indices, N_{21} and N_5, are dimensionless standards (Huang et al. 2003, Wan et al. 2015).

AHP

AHP is a method or theory that involves pairwise comparisons for determining the weight of each index. Establishment of pairwise comparison matrices in AHP depends on expert judgment. AHP features flexible and intuitive advantage, which is the function of checking inconsistencies in judgments (Rahman et al. 2009). The built-in function that checks inconsistency of judgments ensures accuracy with different experts opinions. AHP is widely used in safety scientific research, such as those in coal mine safety assessment, safety of hazardous chemicals, capability evaluation during oil city disaster emergency, traffic safety evaluation, and other aspects. In environmental scientific research, AHP has been applied in the field of atmospheric environment, water environment, and ecological environment.

AHP uses expert judgment in classifying the degree of exposure and sensitivity. Vulnerability assessment strongly depends on expert judgment, but it can adapt to changes in space and hierarchical levels. Weights of all kinds of indices were obtained to complete our study using AHP

Table 2: Ecological vulnerability indices and their weights.

The first index (EV)	C_i	W_i	C_{ij}	The second index (IV)	Weight (W_{ij})
Climate	N_1	0.203	N_{11}	Annual precipitation/evaporation	0.474
			N_{12}	Dryness	0.474
			N_{13}	≥10°C temperature accumulation	0.052
Topography	N_2	0.203	N_{21}	Geomorphologic type	0.192
			N_{22}	Altitude (m)	0.077
			N_{23}	Slope (degree)	0.654
			N_{24}	sin (direction -30º)	0.077
Vegetation	N_3	0.466	N_{31}	NDVI data	1.000
Soil	N_4	0.042	N_{41}	Soil brightness index (SBI)	0.500
			N_{42}	Soil wetness index (SWI)	0.500
Land use	N_5	0.086		Land use extent index	1.000

All consistencies of the index weights meet RI < 0.1

(Wolfslehner et al. 2005).

Numerous ecological vulnerabilities around the world are similar in terms of drivers and processes. To characterize diversity in topography, soil, vegetation, land use and climate in the Fuzhou district, we set up a two-level system of indices consisting of five first-level indices and eleven second-level indices, which respectively reflect the performance and structure of the ecosystem. Using AHP, the weight of each index was determined (Table 2).

GIS Overlaying Calculation

Vulnerability assessment refers to quantification of vulnerability based on given calculations, such as GIS or mathematical methods, within a hazard condition (Lange et al. 2010).

In a specific period, spatial assessment of ecological vulnerability that is supported by GIS can achieve quantitative calculation results by calculating ecological vulnerability scores and displaying scores in a zoning map. All assessment indices must be spatially mapped. Grid cell data are mainly obtained by RS and GIS technologies, such as vegetation coverage index, terrain slope, and other data. In this study, the appraisal unit is a 30 m pixel, which is the resolution of the RS image. The overlaying map of vulnerability assessment was developed using weighted linear combination and the raster calculator in GIS Spatial Analyst functions. The overlaying calculator was based on Eqs. (7) and (8):

$$EV = \sum_{i=1}^{n}(W_i \times \sum_{j=1}^{m_i} W_{ij} \times C_{ij}) \quad ...(7)$$

$$IV = \sum_{j=1}^{m_i} W_{ij} \times C_{ij} \quad ...(8)$$

Where, EV is the ecological vulnerability of overlaying scores, *i* is the first-level index from 1 to 5, and W_i stands for the weight of every first-level index. IV is the *i*th vulnerability overlaying scores, W_{ij} is the weight of each second-level index determined by AHP, and C_{ij} is the standardized raster data value.

RESULTS

Investigation and statistics: On the basis of field investigation of land use, vegetation type, soil type and topography, we identified eight types of land uses/covers from the OLI images, which were obtained to analyse their spectral characteristics. Standardized training plots include urban structure, arable land, dry land or sand, permanent plant areas (e.g., orchards and wood production forests), woodland, grassland, little or no-vegetation coverage areas and coastal beach or inland waters. The classified ecological zone comprises urban lands, cultivated lands, dry or sand lands, permanent planting areas (orchards land), high-coverage forests, mixed forest with medium coverage, sparse forest with low coverage, shrub grass, few or now vegetation, coastal area, and inland water.

Quantitative calculation value of Fuzhou district changed from 0 to 8.83, and the average value was 3.43.

Ecological vulnerability value of natural vegetation areas totalled 2.46, whereas values of orchards and farmlands, which are strongly influenced by human activities, reached 3.39 and 4.34, respectively. Certain land use categories showed similar ecological vulnerability values; these categories included artificial construction-intensive areas, dry land or sand, and sparse vegetation cover areas, with mean vulnerability values of 5.57, 5.13, and 4.69, respectively.

Quantification of vulnerability: A framework was proposed for assessing ecological vulnerability in Fuzhou district using a semi-quantitative approach. The approach was used to describe relative vulnerability scale. Vulnerability can

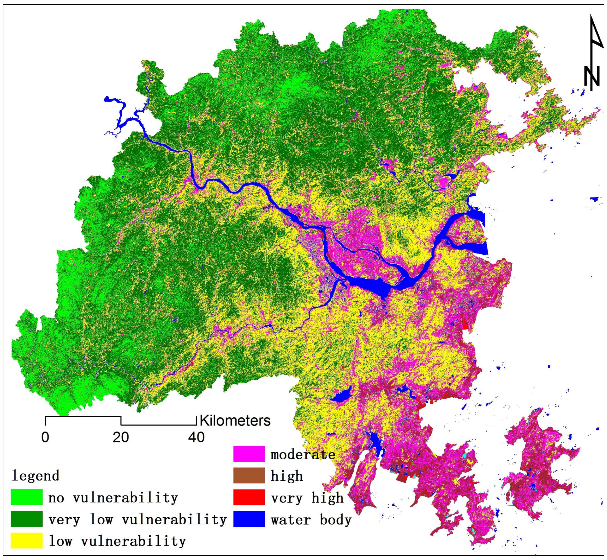

Fig. 3: Model output of ecological vulnerability analysis.

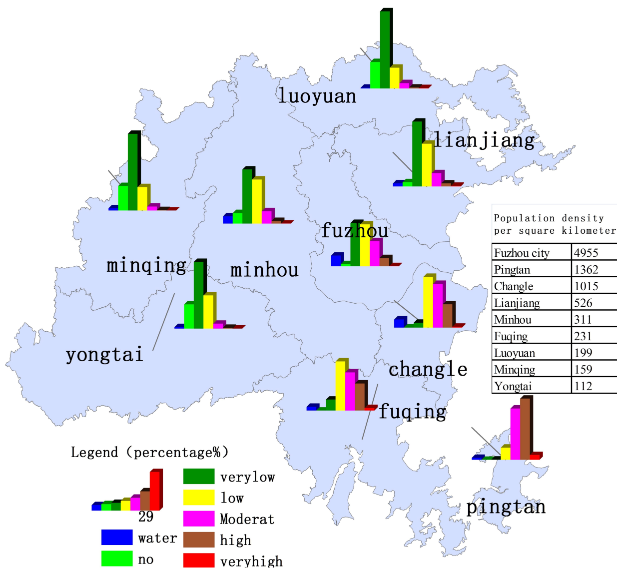

Fig. 4: Percentages of vulnerability classes in each of the studied subarea.

be classified as very low, low, moderate, high, and very high. In this approach, different scales were determined according to available data from the field surveys.

No or very low vulnerability is the condition of undistributed or very minor distortion, which is nearly typical for pristine conditions. This condition features relatively high recovery capability or ecological carrying capacity; these properties are suitable for reasonable resource development and utilization and essential for harmonious development of ecosystems, resources, and economic society. Low vulnerability presents a relatively low sensitivity and shows no remarkable ecological problems. This condition manifests relatively better recovery capability and ecological carrying capacity than the previous one. However, potential problems emerge when some primary conditions change, such as land use or soil state. Moderate vulnerability features higher sensitivity than low vulnerability, but its ecological pressure is still less, except for external interference. The ecosystem still exhibits good recovery ability once interference is eliminated. As long as human beings provide proper protection, they can return to their original ecological functions. High vulnerability can easily lead to potential ecological risks. Notable ecological problems and high ecological pressure accompany this condition. This condition also features poor recovery capability and ecological carrying capacity. Very high vulnerability is more serious; its sensitivity, recovery capability, and ecological carrying capacity are very weak.

According to cumulative statistics of the survey-point overlap vulnerability, we defined a range of vulnerability values between 2.5 and 8.83 in fragile ecosystems. This range of values was further subdivided into six levels: no vulnerability (0 to 2.50), very low vulnerability (2.50 to 3.25), low vulnerability (3.25 to 4.0), moderate vulnerability (4.0 to 4.75), high vulnerability (4.75 to 6.0), and very high vulnerability (6.0 to 8.83). Area proportions of each ecological vulnerability class reached 9.77%, 39.38%, 28.32%, 12.65%, 6.24%, and 0.49% of the total study area, respectively (Fig. 3 and Table 3).

Ecological vulnerability of Fuzhou district: For the entire Fuzhou district, the ecosystem of no, low, and very low vulnerability covers the largest proportion of 77.47%, accounting for an area of 8878.67 km^2. The ecosystem of Fuzhou district is desirable. We analysed the proportion of each vulnerability class in nine counties or cities. Ordered in decreasing proportions of no and very low vulnerability areas, the following areas were identified: Luoyuan County, Minqing County, Yongtai County, Minhou County, Lianjiang County, Minhou city, Fuzhou city, Fuqing City, Changle City, and Pingtan Comprehensive Experimental Area (Table 3 and Fig. 4).

Western and eastern coastal plain areas in Fuzhou district feature relatively large differences in terms of ecological vulnerability. In the entire district, percentages of moderate, high, and very high vulnerabilities were high in Fuqing and Changle cities, and percentage is the highest in Pingtan Comprehensive Experimental Area. The percentages totalled 51.47%, 51.57%, and 89.10%, respectively. The ecological environment is poor in these flat coastal

Table 3: Percentage of ecological vulnerability classes for different Fuzhou subareas (%).

Vulnerability	Water	No and very low	Low	Moderate	High	Very high	Total Area (km^2)
Fuzhou district	3.15	49.15	28.32	12.65	6.24	0.49	11462.27
Pingtan	1.5	0.16	9.24	38.94	46.52	3.64	262.76
Changle	6.2	3.65	38.58	33.19	17.71	0.67	672.59
Fuqing	2.84	8.32	37.37	29.01	20.56	1.9	1550.43
Fuzhou city	8.13	34.54	31.86	19.11	6.22	0.14	1012.89
Minhou	5.54	49.48	33.51	9.38	2.01	0.08	2129.04
Lianjiang	2.34	52.43	32.42	10.06	2.29	0.46	1066.61
Yongtai	1.18	69.14	25.27	3.75	0.6	0.06	2231.02
Minqing	1.73	76.97	17.84	3.07	0.35	0.04	1495.64
Luoyuan	0.56	78.68	15.74	4.04	0.7	0.28	1041.29

Table 4: Percentage of ecological vulnerability classes for the five zones (%).

Vulnerability	Water	No and very low	Low	Moderate	High	Very high	Total area (km^2)	Population (ten-thousand people)
Taijiang	19.13	0.33	9.65	50.08	20.67	0.14	17.38	44.69
Gulou	8.29	5.15	25.75	45.70	14.94	0.17	32.84	68.77
Cangshan	18.84	1.44	18.99	45.41	14.90	0.42	155.60	76.27
Mawei	11.61	14.29	48.94	17.88	7.11	0.17	245.17	23.19
Jin'an	1.18	55.55	30.14	10.68	2.40	0.05	561.90	79.25

regions. Vegetation has been largely destroyed and is almost barren due to long-term and intensive human activities. The coastal areas are exposed to intense sunlight, accumulate significant heat and evaporating soil moisture quickly. Annual precipitation is low and shows large seasonal variation. Very sparse vegetation, strong winds, low precipitation, and high evaporation combine to worsen fragile ecosystems. Yongtai, Minhou, and Minqing County, the three most western counties in the Fuzhou district, exhibit high percentages of vegetation coverage and low ecological vulnerability.

Ecological vulnerability of Fuzhou city: For the five zones of Fuzhou city, namely, Jin'an Zone, Taijiang Zone, Mawei Zone, Cangshan Zone and Gulou Zone, ecological vulnerability values also differ. Mean ecological vulnerability values reached 3.31, 4.56, 3.98, 4.52 and 4.24, respectively. In Fuzhou city, as the capital city of Fujian province, the proportion of non-fragile ecosystem is intermediate compared with those in other cities, because vegetation coverage is better in the north of Fuzhou city, thus benefiting the ecosystem.

Taijiang Zone, Gulou Zone and Cangshan Zone cover relatively small areas, 32.84, 17.38 and 155.60 km^2, respectively. However, percentages of high and very high ecological vulnerabilities are high. The three zones, where populations are concentrated and the main land use is urban construction, serve as economic, cultural and administrative centres of Fuzhou district, respectively. Table 4 summarizes vulnerabilities of the five zones.

Index analysis and discussion: Correlation coefficients between appraisal results and the five primary indices were separately obtained for the eight counties or cities and five zones. The correlation coefficient between vulnerability value and climate index in Fuqing is 0.469, which is higher than 0.203 for of the primary weight. This result shows that climate results in a more significant impact on ecological vulnerability of Fuqing City. The correlation coefficient between vulnerability value and vegetation reaches 0.618 in Jin'an Zone. Correlation coefficients between vulnerability value and soil total 0.421, 0.390 and 0.268 in Langqi Island, Cangshan Zone and Changle City, respectively. These results show that the main controlling factors differ in various regions of Fuzhou district. The main factor is climate in Fuqing, vegetation in Jin'an Zone, and soil in Changle City. The key factors are land use and topography in Gulou Zone and land use, soil and vegetation in Cangshan Zone.

The overall ecological system of Fuzhou District is good, and the area with high ecological vulnerability is in the eastern coastal city. On the other hand, vegetation coverage in the western hills is high, and overall vulnerability is small.

CONCLUSIONS

Fuzhou district, the capital city of Fujian Province, is located in the middle southeast of Fujian province. The district features rich precipitation, heat and high vegetation coverage but still possesses unique ecological vulnerability. This study analysed causes of exposure and susceptibility to ecological fragility in Fuzhou. To prevent deterioration of and to protect the ecosystem, correct appraisal must be conducted. The correlations between vulnerability value and the index are differentiated into regions. The government should consider the main factors of each region's vulnerability to protect the ecosystem.

Several environmental impact indices, such as precipitation, temperature and topography, used in this study for calculation of ecological vulnerability, are uncontrollable. To improve or to retain the ecological state of a certain area, we must focus on some indices that can be managed by man; such indices include land use and vegetation coverage. Efforts should also be exerted to raise public awareness. To adequately assess all aspects of ecological vulnerability, the following should be included: geography, ecology, climatology, pedology, geomorphology and regional planning or environmental planning. In this study, we only assessed the ecological vulnerability of 2014 in the Fuzhou district based on some natural factors. Other human behaviour and technological developments may pose more significant impacts on the ecosystem.

In future research, we will focus on monitoring of dynamical changes in the ecosystem to predict future ecological vulnerability trends and to continually study the impact of social and economic indicators on ecological vulnerability of Fuzhou district.

Several of the technologies used in this study, such as AHP, RS and GIS, featured significant advantages, such as timely assessments and high spatial resolutions. Further discussion and research on the choice of indices and weights are also necessary.

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