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Conceptual Framework for the Development of an Indicator System for the Assessment of Regional Land Subsidence Disaster Vulnerability

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Abstract: This paper aims to develop a set of valid and reliable indicators to evaluate the regional land subsidence disaster vulnerability. The proposed indicator system can provide effective theoretical support for further land subsidence risk evaluation and risk management. This study transfers the qualitative analysis of land subsidence vulnerability to quantitative evaluation by developing a universal land subsidence vulnerability indicator system and outlining a corresponding vulnerability analysis framework. The land subsidence vulnerability analysis in Xixi-Chengnan area, Jiangsu Province, China used as the case study to prove the applicability and the simplified use of the proposed system. Based on the flexibility of the proposed universal indicator system, indicators can be added into and deleted from the system, according to the actual situation in a certain study area.

Keywords: vulnerability assessment; land subsidence; factor identification; indicator system; indicator information

1. Introduction

Land subsidence has long been recognized as a problem in China. It causes aquifer system compaction by continuously increasing the extraction of groundwater from unconsolidated aquifers, causing the associated groundwater level to decline. It is estimated that there are over 150 cities in the world with serious problems related to subsidence due to excessive groundwater withdrawal. The land subsidence disaster discussed in this paper is aimed at that which is caused by groundwater overexploitation.

Land subsidence disaster vulnerability originates in difficult-to-capture dimensions, making it even harder to measure and evaluate. To be measured, the dimensions, characteristics or variables that define and influence land subsidence disaster vulnerability have to be assigned with a crisp value, meaning they need to be scaled using indicators [1]. An indicator is a single measure of a characteristic. An appropriate indicator can effectively translate complex data or phenomena into concise, understandable and manageable units of information for assessing achievement, change, and performance [2]. Simpson and Katirai [3] assert that indicators are attractive because of their ability to summarize a considerable amount of technical information in a way that is easy for people to understand [4]. The use of indicators has been primarily applied to adaptive capacity [5–8], as well as to vulnerability [9]. The indicators are created for a better understanding of the land subsidence and its vulnerability by condensing this complex system into simple terms through numerical data [10,11]. Birkmann [12] also names the abilities to set priorities, to give a background for action, to raise awareness, and to analyze trends as the most important functions of indicators. Therefore, the necessity of building a uniform, comprehensive and action-oriented land subsidence vulnerability indicator system that can be used in different temporal-spatial scales is widely recognized.

The remainder of the article is organized as follows: Section 2 discusses and defines vulnerability, disaster vulnerability, and land subsidence disaster vulnerability. Section 3 presents an analytical framework of land subsidence disaster vulnerability. Section 4 uses the developed analysis framework to analyze the land subsidence disaster vulnerability in the Xixi-Chengnan area. Section 5 concludes with the new conceptual framework and its implications, usage, and advantages.

2. Land Subsidence Vulnerability

2.1. The Concept of Vulnerability

There is no common conceptualization of vulnerability [13]. In several studies, the conceptual development of vulnerability suffers from the lack of a clear relationship between the theory and the empirical work [14], and that vulnerability is place-based and context-specific [15]. However, there are significant efforts to develop and to improve the concept in different contexts [16–18].

The most commonly used vulnerability definitions can be divided into two types: (1) the "potential for loss" [19–22]; and (2) "a predictive variable". The latter is a measure of possible future harm. These definitions are dynamic and forward concepts that specifically address uncertainty and probabilities. Specifically, the United Nations Disaster Relief Organization even defines vulnerability as "the degree of loss to a given element or set of elements at risk, resulting from the occurrence of a natural phenomenon of a given magnitude". Cutter et al. [23] used the human element as the "property of life"—the main potential risk factor related to disasters occurring. Adger [24] defines vulnerability as a powerful analytical tool for describing states of susceptibility to harm, physical and social systems, and for guiding normative analysis for risk reduction. Social scientists often have different interpretations of vulnerability, and most of them tend to view vulnerability as a set of socio-economic factors [25,26].

2.2. The Concept of Disaster Vulnerability

Maskrey [27] defines disaster vulnerability as the possibility of damage caused by extreme events, but this definition confuses vulnerability and hazard without indicating the essential attributes of the elements at risk. The UN defines natural disaster vulnerability as the degree of loss caused by potential damage phenomena in a given area with a value from 0 to 1. According to Panizza [28], disaster vulnerability may be directly or indirectly sensitive to material damage caused by human intervention. Tobin and Montz [29] regarded disaster vulnerability as "the potentiality of loss", which reflects partial attributes of elements at risk. The definition of disaster vulnerability given by Deyle et al. [30] is the sensitivity of human settlement to the harmful effects of natural disasters. Liu et al. [31] are of the opinion that disaster vulnerability should represent the risk tolerance of people and the economy in a specific society under the action of disaster risk.

The above definitions vary greatly in topics and expressions, but can be divided into the following two categories:

(1) The possible loss or loss degree of an element at risk is stressed without considering the capacity of disaster prevention and alleviation. The correlation between disaster vulnerability and the physical exposure of the element at risk is investigated in this category. It indicates that the vulnerability will be influenced by outside activities–especially human interactions.
(2) The essential characteristics, status or sensitivity of being vulnerable to disaster for elements at risk are emphasized. In this category, disaster vulnerability is considered a systematic dynamic property. It changes with the natural environment and social-economic conditions.

The two categories of disaster vulnerability are different for three reasons: (1) the epistemology and methodology are different; (2) the analysis of the relationships between disasters and corresponding vulnerability are different; and (3) the researched disaster types and chosen study areas are different.

The two categories of definition divide the disaster vulnerability into "external" and "internal" parts. The terms "external" and "internal" are used to describe the external load acting on a system and the internal factors affecting the system, respectively.

2.3. The Concept of Land Subsidence Disaster Vulnerability

The land subsidence disaster risk is determined by hazard and vulnerability, where hazard and vulnerability depend on natural factors and human factors, respectively. In this paper, land subsidence vulnerability is underlined as an inherent state of a certain area at risk. It is derived from the inherent properties of interactional physical, social, economic, and environmental systems.

3. Analytical Framework

3.1. Factor Identification

Historically, some vulnerability assessments were quite narrow in focus [32]. Recently, more and more researches have recognized the need to combine the effect of coupled human environment systems [33–36]. Although such researches are often place-based, Luers et al. [33] argued that the vulnerability assessment should not focus on selected factors of concern and specific sets of stressors.

The land subsidence disaster vulnerability system refers to a wide range of profiles. Many factors are involved in land substance vulnerability assessment, including society, economy, environment, education, politics, and human lifestyle. The most common factors have been generalized in the References [37–42] and can be divided into the following four categories [43]:

(1) Physical factor: mainly assesses the sensitivity of architecture, infrastructure, and lifeline projects.
(2) Social factor: emphasizes the effect of land subsidence disaster on human life and production or the response capacity of human power to land subsidence disaster. This factor generally assesses population density, population composition, poverty degree, and the situation of education.
(3) Economic factor: mainly indicates the sensitivity of the economic system to land subsidence disaster and refers to the production link, distribution link, and consumption link. Generally, this factor can be characterized by the gross domestic product (GDP).
(4) Environmental factor: describes the sensitivity of the eco-environment to land subsidence disaster, where land resources are deemed as the main indicator type in most research.

3.2. Indicator Selection

Building an indicator system is the basis of land subsidence disaster vulnerability assessment. The reasonability of the indicator selection is directly related to the reliability of the assessment results. To express the coordination between land subsidence disaster vulnerability and physical, social, economic, and environmental systems, the indicator system should be comprehensive and operational. However, an indicator system covering all of the involved indicators will be complex and redundant. It is therefore necessary to select only essential indicators based on the selection criteria.

3.2.1. The Criteria of Indicator Selection

Specifically, the indicators should be selected in terms of the following principles:

(1) The principle of operability: The selected indicators should be the most sensitive and easily expressed. They should represent the main idea of coordinating the development of physical, human, social, economic, and eco-environmental systems. Furthermore, the connotation, dimension, and transformation of each indicator should be clear, all of the indicator data should be easily accessible and comparable, and the dimensions of all the normalized indicators should be accordant.
(2) The principle of measurability: As mentioned above, the land subsidence disaster vulnerability is defined as a composite system of physics, society, economy, and environment. Compared to

qualitative analysis, quantitative analysis is more intuitive. It can reflect the regional land subsidence disaster vulnerability situations. It also can describe the physical, social, economic, and environmental sub-systems in a certain area at risk. Based on the quantitative analysis results, the early warning can be made and preventive measures can be taken. Therefore, the metrizability of selected indicators is an important criterion.

(3) The principle of completeness: The indicator system created should systematically and completely express the complex land subsidence disaster vulnerability system. It should also demonstrate the regional land subsidence disaster vulnerability situation hierarchically.

(4) The principle of validity: Each selected indicator should be independent. In the screening process, if two or more indicators refer to similar or overlapping aspects of the regional land subsidence disaster vulnerability system, only one indicator can be selected.

3.2.2. The Framework of the Indicator System

Rationality of the developed indicator system framework plays an increasingly important role in improving the efficiency and accuracy of land subsidence vulnerability assessment. In this paper, the framework of the indicator system is constructed as a hierarchical structure, which contains an object level, a factor level, and an indicator level from bottom to top. There is only one indicator on the object level and four on the factor level. The indicator level consists of specific assessing indicators. The structure of the indicator system is shown in Figure 1.

Figure 1 shows that regional land subsidence disaster vulnerability is the assessing object, is the only indicator or index on the object level (level-A). The assessing object can be obtained by aggregating all indicators and factors step-by-step. The factor level (level-B) uses four influence factors to represent physical, social, economic, and environmental systems, and they are physical factor (B1), economic factor (B2), social factor (B3), and environmental factor (B4). The indicator level (level-C) is the foundation for describing each factor (B1~B4) in level-B, and each indicator in level-C is the basic and specific element of the built indicator system.

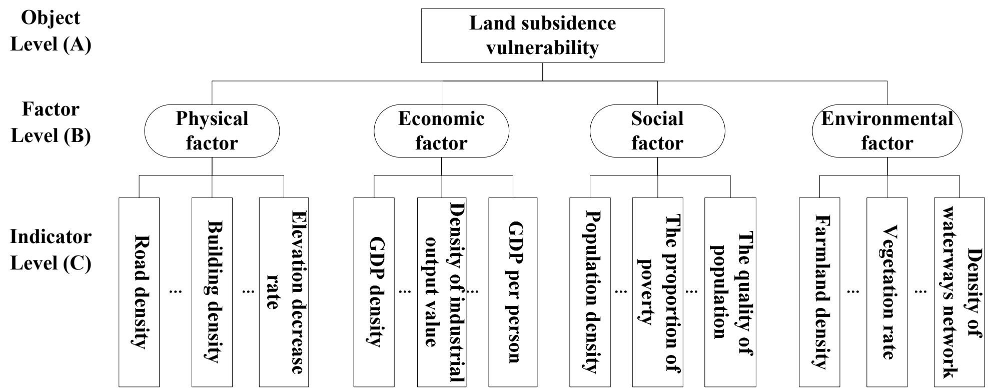

Figure 1. Framework diagram of the land subsidence vulnerability indicator system.

There are numbers of indicators in level-C, and Table 1 lists the universal indicators of land subsidence disaster vulnerability assessment. The concrete elucidation is as follows:

(1) Fundamental indicators of physical factors consider the architecture and infrastructure (including water supply, power supply, transportation, communication, and some other projects closely related to normal circulation of regional social life). It takes the building density (C4), density of flood control facilities (C5), elevation decreasing rate (C6), road density (C1), bridge density (C2), and underground pipeline density (C3) as universal fundamental indicators of the physical factors. Describe the infrastructure projects and lifeline projects in the area at risk. Building density (C4) reflects the distributional attributes of regional buildings. Density of flood control facilities (C5) reflects the capacity of disaster prevention and alleviation with respect to regional flood control

and drainage. Subsidence rate (C6) reflects the loss of ground elevation caused by regional land subsidence, and is equal to elevation decreasing rate. The loss of ground elevation results in the invalidation of benchmarks. It also leads to some ground facilities being built according to the original benchmarks. The increment in building costs and the loss of ground elevation may lead to the decrement of the flood dam standard and even aboveground rivers. This will only intensify waterlogging disasters. Lifeline projects refer to many contexts, but in this paper, based on the hysteresis regarding land subsidence disasters, only the two aspects of transportation and water supply are considered. Road density, bridge density, and underground pipeline density are chosen as the representative indicators. Road density (C1) reflects regional transportation accessibility; bridge density (C2) reflects regional connectivity of sea and overland; and underground pipeline density (C3) reflects capacities of regional water delivery and drainage.

Table 1. Indicator system of land subsidence disaster vulnerability assessment.

Object Level (A)	Factor Level (B)	Indicator Level (C)	
	Factor and Code Name	**Indicator and Code Name**	**Note**
Land Subsidence Disaster vulnerability	Physical factor (B1)	road density (C1)	the ratio of road mileage to area
		bridge density (C2)	the ratio of bridge number to area
		underground pipeline density (C3)	the ratio of underground pipeline length to area
		building density (C4)	the ratio of building area to area
		density of flood control facilities (C5)	the ratio of flood control facility number to area
		subsidence rate (C6)	the ratio of accumulative subsidence to corresponding subsidence years
	Economic factor (B2)	GDP density (C7)	the ratio of GDP to area
		density of industrial production (C8)	the ratio of industrial production to area
		density of agricultural production (C9)	the ratio of agricultural production to area
		investment density of fixed assets (C10)	the ratio of fixed asset investment to area
		GDP per person (C11)	the ratio of GDP to regional population
		annual growth rate of GDP (C12)	the ratio of GDP variation to GDP of last year
	Social factor (B3)	population density (C13)	the ratio of regional population to area
		the proportion of non-agricultural population (C14)	the ratio of non-agricultural population to total population
		the proportion of poverty (C15)	the ration of population living at or below the poverty line to total population
		the proportion of floating population (C16)	the ration of floating population to total population
		the quality of population (C17)	① $\gamma = P_1/P_2$
	Environmental factor (B4)	farming density (C18)	the ratio of farming area to area
		vegetation rate (C19)	the ratio of vegetation vertical projection area to area
		drainage network density (C20)	the ratio of the total river length to unit river basin area

①: γ is the index of population quality; P_1 is population with qualifications of technical secondary school or college or higher for every 10,000 persons; P_2 is the number of illiterate and semiliterate persons for every 10,000 persons.

(2) Fundamental indicators of economic factors consider the sensitivity of economy performance to land subsidence disasters in the disaster-bearing area. Regional economy performance refers to the size, growth or decrease rate, and level of the economy in a certain area at risk. It is a way of measuring the status and potentiality of regional economy development. GDP density (C7), GDP per person (C11), and annual growth rate of GDP (C12) are key indicators that measure economic sustainable development. The scope of GDP accounting covers nearly all sectors of the national economy. The indicators related to GDP reflect the overall level of the economy or reveal the structure of each trade. GDP density (C7)—which is expressed as GDP per square kilometer and can be calculated by multiplying GDP per capita of an area by the population density of that area—reflects the distribution attribute of the regional economy. The bigger the GDP density is, the more vulnerable the regional economy to land subsidence disaster. GDP per person (C11) reflects the development level and development degree of the regional society. It is the main material basis of income per capita and the living standard of a regional resident. Furthermore, GDP per person focuses on the relationship between the population or labor force and the GDP in a certain area at risk, while directly determining and affecting the regional investment orientation, investment capacity, and investment level. The annual growth rate of GDP (C12) reflects the development rate of the regional economy and is the most commonly used indicator for measuring the economic development rate. The calculation of the indicator is based on the following general formulation:

$$growth\ rate\ of\ GDP\ =\ \frac{GDP\ of\ this\ period\ -\ GDP\ of\ last\ period}{GDP\ of\ last\ period} \times 100\% \tag{1}$$

Investment of fixed assets is the economic activity of constructing and purchasing fixed assets. It is the main means of reproducing social fixed assets. Investment density of fixed assets (C10) is the investment of fixed assets per unit area in a certain region at risk, the workload of fixed asset activities built and purchased in terms of money per unit area, and a comprehensive indicator reflecting investment size, investment rate, investment proportion and use of fixed assets.

Industrial production is the total industrial output in a certain period, which is always expressed in money. Agricultural production is the total output of farming, forestry, ranching and fishing trades, expressed in money, and reflects the total size and result of agricultural output in a certain period. The two items of production can be expressed in the form of a unit area and are denoted by two indicators of industrial production density (C8), which reflects the total size and level of regional industrial production. They are also denoted by the density of agricultural production (C9), which reflects the regional agricultural production situation. Although the scope of GDP accounting contains industry and agriculture, the simultaneous selection of C7, C8, and C9 is feasible. On one hand, the gross annual production of industry and agriculture—the main indicator for measuring the economic development level—is characterized by universality and importance for the indicator-determinance of an economic factor within land subsidence disaster vulnerability. On the other hand, the accounting scope of the gross annual production of industry and agriculture is limited, so it cannot refer to each sector of the national economy. Thus, the related indicators of GDP are necessary.

(3) Fundamental indicators of social factors emphasize the effect of land subsidence disaster on human beings from three aspects: the structure of the population, the quality of the population, and the urbanization level. The structure of population can be described by the following indicators: population density (C13), the proportion of non-agricultural population (C14), the proportion of poverty (C15), and the proportion of floating population (C16). The quality of the population is generally demonstrated by the population quality index (C17).

Humans are the undertakers of disasters. The population is increasing with the development of society, and an increasing number of people flock into cities or societies with developed economies. Consequently, the risk of disaster loss is increased by the greater population density. Therefore, the first indicator of the social factor is population density (C13), which reflects the distribution attributes of the regional population. The larger the population density in the disaster-bearing area is, the more vulnerable the disaster-bearing area is.

The special indicator of the proportion of the non-agricultural population (C14) has been chosen to reflect the urbanization level of regional societies. The urbanization level is increased by adjusting the industrial structure. The proportion of agriculture population decreases, or the proportion of non-agriculture population increases greatly. This is good in the cases of urbanization and modernization.

The proportion of poverty (C15) is an intuitive indicator for measuring living standards in the disaster-bearing area.

The proportion of floating population (C16) is an indicator characterizing the development stage of the region's society. Particularly at the underdeveloped stage, the size of the floating population is small. And at the developing stage, with the prosperity of the economy and the development of urbanization, the floating population grows rapidly. As the types become increasingly abundant, the structures become fragmented, and the expansion of the population puts extreme pressure on the underdeveloped city and transportation systems. Finally, at the developed stage, the size of the floating population further expands with the perfection of the urban transportation system.

The quality of population (C17) is a key component within the social factor of land subsidence disaster vulnerability. It reflects various social functions together with the influence expressed as the structure and the combined status of the population. It also indicates the regional achievements in regard to satisfying basic human needs.

(4) Fundamental indicators of environmental factors emphasize the vulnerability of the eco-environmental subsystem caused by a potential land subsidence disaster and take land resources or land use types as the main research subjects for selecting an indicator. Farming density (C18)—a way of measuring ground vegetation and changes in the eco-environment—is chosen as a representative indicator. The greater the farming density is, the more vulnerable the disaster-bearing area becomes. Vegetation rate (C19) reflects abundance of forests and the afforestation level.

Drainage network density (C20) expresses the quantity of drainage networks on a given territory in a certain area at risk. It is one of the features of the river system that varies with climate, geology, landscape, soil, and vegetation. A larger drainage network density can indicate a higher possibility of waterlogging. The drainage network density is closely related to the climate conditions and the underlying surface conditions. From a climate aspect, corresponding drainage networks are shaped due to the timely discharge of surface runoff, and the networks inevitably reflect the regional rainfall and runoff characteristics. The drainage network density increases with the increase in precipitation. From an underlying surface aspect, the drainage network density is also affected by soil permeability. With the increase of permeability, the drainage network density decreases. Therefore, the drainage network density reflects the precipitation and underlying surface conditions. Classically, the drainage network density (C20) tends to be higher in areas with more precipitation and less permeable soil.

The indicator system has several functions, which are as follows:

(1) Evaluation: the system can be used to reasonably and comprehensively assess the land subsidence disaster vulnerability in the area at risk by combining the processes of weight and aggregation.
(2) Verification and prediction: based on the spatial and temporal flexibility of the proposed indicator system, the past, current or future land subsidence disaster vulnerability level in a certain area at risk can be assessed by aggregating the determined indicator system. The assessed level can be used to review, scan, or forecast the regional land subsidence disaster vulnerability situation.
(3) Comparability: it is feasible to compare the land subsidence disaster vulnerability levels for different areas at risk or for different time intervals. The comparison results can reveal the spatial distribution and time-variation of land subsidence disaster vulnerability levels.
(4) Decision support: comparing the land subsidence disaster vulnerability levels in different areas at risk or in different time intervals has contributed to the land subsidence disaster risk zoning, further layout, and risk prevention, and alleviation plan-making. An integrated assessment result,

in terms of vulnerability level, is obtained by determining the indicator system, then collecting and analyzing the indicator data, and finally by weighing and aggregating all indicators and factors in the indicator system on a level-by-level evidence. The results can be used by decision-makers and risk managers to formulate corresponding programs, both short and long-term, for land subsidence disaster risk prevention and alleviation. As the results can also be used to arrange the sustainable development of nature, economy, society and environment.

If a possible decision-maker has to make his choice based on the above proposed indicator system of land subsidence disaster vulnerability assessment, one possibility is to provide objective motivations. The information should include (but is not limited to):

(1) possible causal chains and how to recognize them;
(2) assessment of uncertainties;
(3) how to address eventual data inhomogeneity; and
(4) list of indicators of the same type.

3.2.3. The Analysis of Indicator Data

A necessary step needs to be taken after determining the assessing indicators: analyzing the connotation of the indicator data.

First, the reference state is defined to judge the vulnerability level of each indicator to determine the vulnerability level and level thresholds of each indicator according to correlative criteria. Then the correlation coefficients of the vulnerability level sequence of each indicator are calculated using the rank correlation analysis method. Finally, the correlation degrees of every two vulnerability level sequences of the indicator are obtained.

The rank correlation coefficient is a non-parametric measure of correlation—it can assess how well an arbitrary monotonic function describes the relationship between two variables without any assumptions about the frequency distribution of the variables. In practice, illustrating the relationship between two things (or two variables) is better for analyzing problems and making decisions. There are two calculation methods for the rank correlation coefficient (or rank coefficient for short): Spearman's correlation coefficient method and Kendall's correlation coefficient method. The former is more common.

For a two-dimensional random vector sample of size n, the n raw scores X_i, Y_i are converted to rank x_i,y_i [44]. If $X_i = Y_i$ is tenable for all i, then the two ranks are completely positively correlated. If $X_1 = Y_n, X_2 = Y_{n-1}, \ldots, X_n = Y_1$ are tenable for all i, the two ranks are completely negatively correlated.

Spearman's correlation coefficient focuses on calculating the difference of $D_i = X_i - Y_i$. The linear correlation coefficient of rank orders can be calculated in terms of the following formula:

$$r_s = 1 - \frac{6\sum {D_i}^2}{n(n^2-1)} \quad (2)$$

where r_s is the rank correlation coefficient between two variables, n is the size of sample, and D_i is the rank difference of the sample, which is used to measure the completely positively/negatively correlated departure degree between a pair of ranks. The values of r_s range from -1 to 1, and the following statements apply: if the ranks of two compared sequences are the same and both are in ascending order or descending order, the rank correlation coefficient of the two compared sequences is 1, and if the ranks of two compared sequences are different and one is in ascending order and the other is in descending order, the rank correlation coefficient of the two compared sequences is -1.

4. Case Study

4.1. The Study Area

To demonstrate the practicability and applicability of the developed land subsidence disaster vulnerability indicator system in Section 3, the Xixi-Chengnan area (Figure 2) in China, located between 31°35′40″ and 31°51′02″ N and 120°5′27″ and 120°35′47″ E, was taken as the study area as an example for other area at risk studies. The case study is limited, however, to the current spatial and temporal scales due to the limitations of the obtained study material and data. Xixi is located in the north of Wuxi city, and Chengnan is located in the south of Jiangyin city, Jiangsu Province, China. Land subsidence was first observed here in the 1960s. Withdrawals of groundwater from the confined aquifers led to large decline in water levels, associated compaction of the aquifer system, and gradual subsidence of the land surface. The total subsidence area is 690 km^2 and covers 10 townships that are administratively divided into 3 districts (Figure 2) [43].

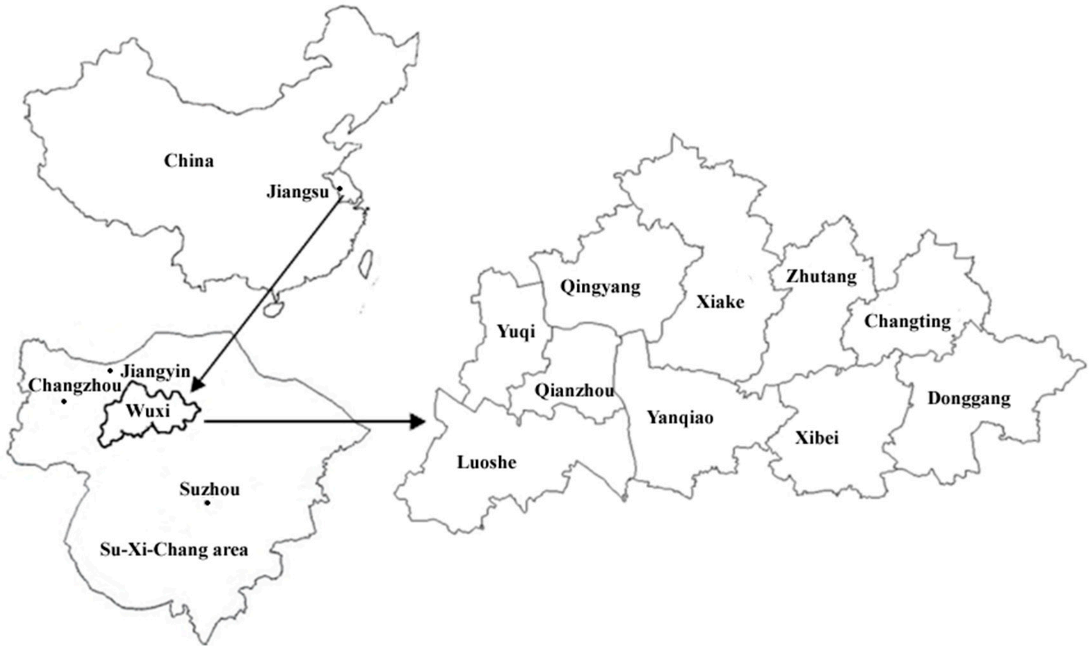

Figure 2. Location of the study area.

4.2. The Indicator Selection

For a certain area, the indicators should be significant for evaluating regional land subsidence disaster vulnerability performance and for reflecting the major characteristics and actual situations of the physical, economic, social, and environmental vulnerability. In this study, the logical analysis method [45] and the geological experience method were applied to select indicators from the proposed universal indicator system. The indicators can be selected from a universal indicator system by analyzing the connotation and extension of each indicator in indicator system, judging the relationship between indicators, evaluating the availability of statistical information, and discussing the particularities of the study area. These relationships between indicators are as follows:

(1) Causal relationship: A causal relationship appears in terms of different causal forms, such as one result-multiple causes, one cause-multiple results, and multiple causes-multiple results. The causal relationship between indicators can be identified in terms of the mechanism of interaction between indicators and the chronological order of the compared indicators. For example, there is a certain causal relationship between the density of industrial production, the density of agricultural production, and GDP density: the greater the densities of industrial

production and agricultural production, the greater the GDP density. There is also a causal relationship between the proportion of non-agricultural population, the proportion of poverty, and population quality: the larger the agricultural population and poverty population, the lower the population quality.

(2) Equivalent relationship: The relationships between indicators of the same type are basically or completely equivalent. For these indicators with equivalent relationships, only one indicator needs to be chosen. For instance, the development level of a regional macro-economy is affected by many fields with various development trends, whereas GDP is the most cognizable indicator for measuring and comparing regional economic development levels. Specifically, GDP density, GDP per person, and the annual growth rate of GDP are all key indicators for measuring the level of economic sustainable development of the same kind. Thus, it is sufficient to choose only one of these three indicators. For different study areas, the selected indicators based on indicator selection criteria are different due to various reasons, including the availability of statistical information and the specificity of the studied area at risk. GDP per person is usually used to measure a region's standard of living and the situation of economic development. It can be used as a fundamental indicator of economic factor because it is an effective tool in understanding and controlling the macroeconomic situation in a certain region. Compared to GDP per person, GDP density can reflect the regional development degree and economic concentration degree. GDP density is a measure of economic activity by area. It can be used as a fundamental indicator of economic factor by demonstrating the effects of geography on economy. The GDP annual growth rate is driven by the four components of GDP: (1) personal consumption; (2) business investment; (3) government spending; and (4) exports and imports. These components do many things: measure how quickly the economy is growing, reflect the change in degree on economic development levels within a specific period, show the required time period of improving levels of living, and reflect the increase in productivity arising from technological innovation and the accumulation of human and physical capital. This study chose GDP density as the fundamental indicator of economic factor, which mainly depends on the idea that all indicators (besides subsidence rate) are expressed in terms of density.

(3) Progressive relationship: Regarding the indicators in the same causal chain, each one has an identical influence on the indicator located at the beginning. For instance, GDP per person, which is the middle indicator in the causal chain, can be calculated via GDP density and population density. The original cause indicators should therefore replace GDP per person.

The use of the logical analysis method can determine partial indicators, but in actual research, indicator selection is also limited by the incompleteness of statistical information and geographical data. To select indicators that summarize the leading factors of land subsidence disaster vulnerability, the natural, social, and economic attributes in Xixi-Chengnan area, as well as the predecessors' work experience, should be combined. Using the geological experience method to rescreen the indicators listed in Table 1. Eventually, five indicators are selected, they are the most related to the research object of the study area. The five indicators, their units and operational definitions are listed in Table 2.

Table 2. Operational definition of land subsidence disaster vulnerability indicators.

Code	Indicator	Unit	Operational Definition
C_1	GDP density	10,000 Yuan/km^2	regional GDP/the regional area
C_2	Population density	people/km^2	regional population/the regional area
C_3	Farmland density	m^2/km^2	regional farmland area/the regional area
C_4	Building density	m^2/km^2	regional industrial and civil architecture area/the regional area
C_5	Subsidence rate *	mm/a	accumulative subsidence/corresponding subsidence years

* The quality of subsidence rate is equal to that of the elevation decreasing rate.

GDP density reflects the economic situation per unit area in the region at risk. The population density represents the sensitivity of regional life to land subsidence disasters and is more widely applicable than absolute population figures. Generally, the density of the main land use type is regarded as the main environmental vulnerability component. Farmland is the chief land use type in the study area, and farmland density can illustrate the sensitivity of the environment to land subsidence disasters. Building density indicates the distribution attributes of regional industrial and civil architecture. The subsidence rate directly affects the structural integrity of roads and buildings and other infrastructure and is therefore an important indicator.

4.3. Data Sources and Data Extraction

All indicators (besides subsidence rate) listed in Table 2 are expressed in terms of density, even if they are unrelated to the location and size of the study area. They can be taken as continuous variables. These indicators aim to show the number of main fundamental elements of physical, social, economic, and environmental factors per unit of area for the study area. These kind of expressions contribute to regionalizing the vulnerability assessment results.

The subsidence rate cannot be quantified according to administrative regionalization. A worst-case method is adopted, and it is feasible in places where a numerical value of a given variable is not available. This method, however, can be adapted to compare the characteristics of the variable on different areas in a qualitative way. The gathered data of each indicator are based on the natural and socioeconomic characteristics of each township published in both the Xishan and Huishan Statistical Yearbook 2008. The normalized results are shown in Table 3.

Table 3. Normalization of land subsidence disaster vulnerability indicators.

Township	GDP Density	Building Density	Population Density	Farmland Density	Subsidence Rate
Yanqiao	0.104	0.000	0.290	0.000	0.000
Qianzhou	0.533	0.754	0.920	0.191	0.000
Yuqi	1.000	0.685	0.905	0.154	0.000
Luoshe	0.434	0.738	1.000	0.143	0.000
Xibei	0.000	0.176	0.000	1.000	0.500
Donggang	0.205	0.562	0.291	0.879	1.000
Changting	0.059	1.000	0.645	0.107	0.000
Zhutang	0.178	0.677	0.549	0.004	1.000
Xiake	0.087	0.737	0.496	0.044	1.000
Qingyang	0.116	0.821	0.574	0.055	0.000

In this study, each indicator of land subsidence disaster vulnerability in Xixi-Chengnan area was divided into five grades of "very low", "low", "medium", "high", and "very high". The threshold ranges of each grade are listed in Table 4, and according to the table, each selected indicator can be zoned in terms of the grade division (shown in Figure 3). The evaluated indicators are presented using a graphical display method for each cluster of indicators for each township. They are used to illustrate the physical, social, economic, and environmental system status in the Xixi-Chengnan area.

Table 4. Grading land subsidence vulnerability indicators.

Grading	Very Low	Low	Medium	High	Very High
Normalization	<0.2	0.2–0.4	0.4–0.6	0.6–0.8	>0.8

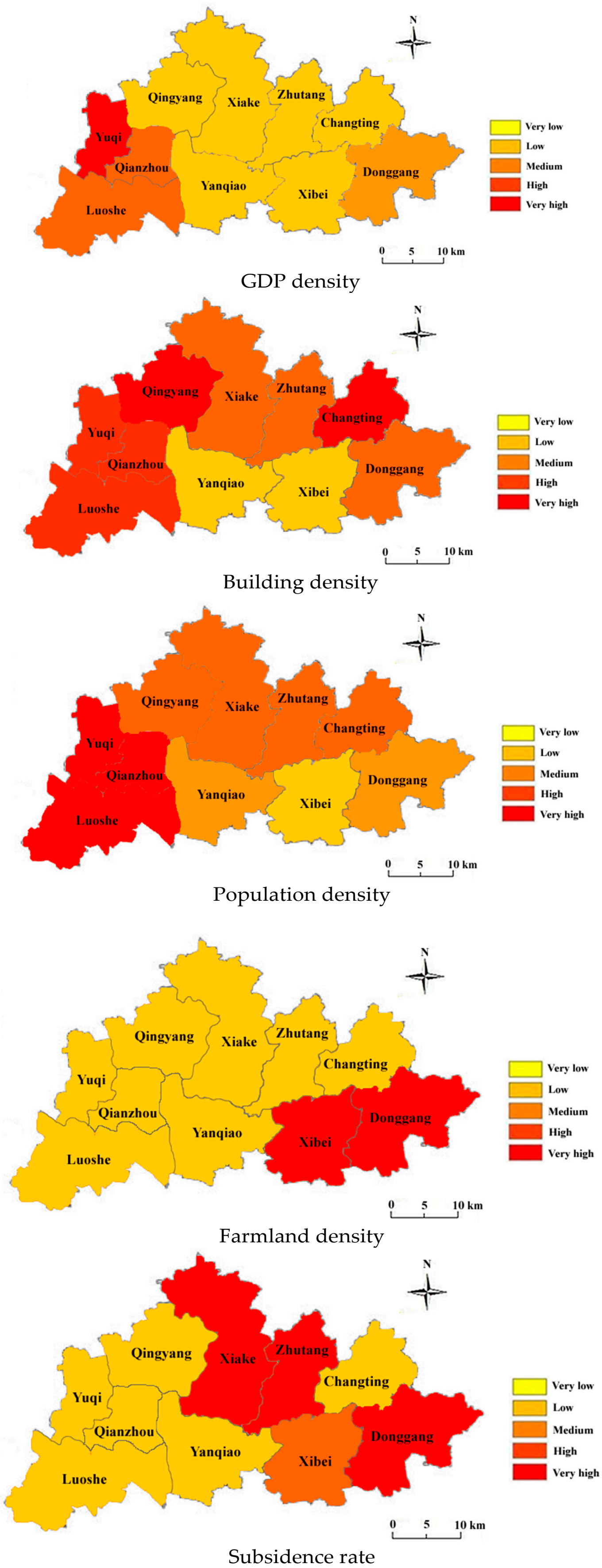

Figure 3. Vulnerability grade zoning of each indicator in the study area.

Based on the grade zoning of the land subsidence disaster vulnerability indicators in the Xixi-Chengnan area, the Spearman rank correlation matrix of the five indicators can be obtained, as shown in Table 5. The correlation matrix demonstrates that there are strong positive correlations between GDP density and building density as well as between GDP density and population density. There is a strong negative correlation between population density and farmland density. For a certain township, there is therefore a higher vulnerability grade of population density, GDP and building density but a lower vulnerability grade of farmland density.

Table 5. Spearman rank correlation matrix of the indicator vulnerability grades.

Indicator Vulnerability Grade	GDP Density	Building Density	Population Density	Farmland Density	Subsidence Rate
GDP density	1.000	0.276	0.679	−0.049	−0.326
Building density		1.000	0.659	−0.494	−0.555
Population density			1.000	−0.685	−0.469
Farmland density				1.000	0.498
Subsidence rate					1.000

5. Conclusions

A reasonable indicator system can provide an efficient method or guidance for measuring regional land subsidence disaster vulnerability situations. It plays a central role for risk managers and decision-makers who determine the performance of physical, economic, social, and environmental systems in particular at-risk areas. It allows them to make and conduct specific disaster prevention and alleviation plans.

The land subsidence disaster vulnerability is relative, changes with human activities, and is a key breakthrough point of decreasing land subsidence risk. The proposed indicator system can be used to analyze the land subsidence vulnerability state in a certain area at risk from physical, economic, social, and environmental perspectives. One important advantage of the proposed indicator system is its flexibility. It (1) is easy to be extended or contracted (i.e., if we need to build a special indicator system based on the proposed universal indicator system for a certain area at risk, new indicators can be added even if they are not in the universal indicator system, and the future integrations of indicator-level and factor-level all are kept feasible), and (2) can be used at different spatial and temporal scales and in various land subsidence disaster scenarios. The indicator system can also be used by local governments to manage and monitor the local land subsidence disaster vulnerability situations in a comprehensive and sustainable manner from four aspects: (1) the architecture, infrastructure, and lifeline projects within a region; (2) the well-being of individuals and communities; (3) the economic resources of individuals or communities; and (4) the state of the eco-environment within a region.

Vulnerability is embedded into the concept of risk generally in terms of the equation Risk = Hazard × Vulnerability. In addition to hazards, vulnerability contributes to the generation of risk. Therefore, the proposed indicator system can be used to explain why the same hazardous land subsidence disaster event has different effects on each element at risk. As a part of the risk assessment, the indicator system can provide a comprehensive view of land subsidence disaster vulnerability and technologically support the development of a comprehensive risk assessment hierarchical framework with associated risk factors and risk indicators.

Indicators enable a comparative analysis of vulnerability and have been used increasingly to rank regional vulnerability levels with the objective of aiding governments and other organizations in the allocation of resources for vulnerability reduction. To complete the comparative analysis, a logical future step is need, which would be to aggregate the proposed indicator system. By aggregating the indicators (that is, aggregating the normalized and weighted indicator values into an overall composite index value) of the built indicator system, the vulnerability levels (ranging from 0 to 1) within predefined space and time scales could be calculated, which is the basis of comparison and ranking. The indicator system's application to map the vulnerability enables the comparison of land subsidence disaster vulnerability between sub-areas in a certain administrative area at risk. It should be noted that low vulnerability degree does not necessarily imply low risk degree because the risk also depends on the hazard degree of the land subsidence disaster. This model may also be transferred to and combined with an existing quantitative hazard model, and a relative risk value can be obtained by multiplying the hazard value by the vulnerability value. In this regard, the combined model can describe the components and the whole of the regional land subsidence disaster risk. For regions with identical land subsidence disaster hazard levels, the relative risk levels would be proportional to the relative vulnerability levels.

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