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Contributions and Resistances to Vulnerability of Rural Human Settlements System in Agricultural Areas of Chinese Loess Plateau since 1980

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Abstract: The vulnerability evolution of human settlements system on the micro-scale is a direct indicator of the local impact of global environmental change. Traditional agricultural areas are most vulnerable to climate and market changes. Due to the lack of historical statistics, micro-scale quantitative studies on the historical evolution of vulnerability are extremely scarce. From the perspective of the socio-ecological system, this study conducted field investigations along with quantitative assessment and an ethnographic approach to explore the vulnerability change of rural human settlements system since 1980 in Jia County, an agro-pastoral interlocking area. The study found that the vulnerability of natural, dwelling and social systems has continued to decrease, while human system vulnerability increased. At present, the RHSS is characterized by the poor quality of the river, a depressed rural population and a large gap between the rich and poor as weaknesses, and is characterized by sandstorm disaster reduction, more robust rural roads, adequate water for domestic use and high social security as strengths. Results revealed that ecological projects, increased precipitation, market changes, urbanization siphoning and farmer behaviors are key drivers to the vulnerability change since 1980. The study findings can be directly applied to rural revitalization strategies, vulnerability mitigation and adaptive management practices in China. In addition, the vulnerability evolution under multiple perturbations can provide guidance for settlement planning and construction in traditional agricultural areas among developing countries under global changes.

Keywords: human settlement ecology; vulnerability; TOPSIS; contribution and barrier models; Chinese Loess Plateau

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1. Introduction

Rural development is a worldwide topic. The current global climate change, market competition and changes, urbanization and industrialization processes have a profound impact on rural development [1–5], while extreme risk events and uncertain future changes consistently threaten the sustainability of rural development [6–8]. Traditional farming areas are characterized by economic vulnerability and remoteness, and agricultural production, farmers' livelihoods and settlements are extremely sensitive to external environmental changes and policy interventions [9–11]. Based on the perspective of human and environmental vulnerability, the research exploring the evolution of human settlements over a long time series can be strong evidence for mapping the impact of environmental changes on local places [12]. In addition, the development and transformation with respect to agricultural or vulnerable rural areas are also significant issues in the topic of sustainable rural development and human welfare.

Human settlement science aims to study the relationship between human beings and the environment in the context of human settlements (including villages, towns, cities, etc.) [13]. In the 1950s, Dosadias, a Greek urban planner, proposed the concept of "human settlements", which marked the formation of human settlement science focusing on urban planning [13]. In China, Lianyong Wu was inspired by the theory of Daosadias and created the "science of human settlements" with China's national conditions, which standardized the framework of human settlement research [14]. After that, Chinese scholars from the fields of architecture and urban planning conducted theoretical exploration and practice of human settlements around the creation of a desirable habitat. For example, the existing research focuses on the design and ecological problems of rural human settlements [15], explores the strategies and methods of rural settlement system planning [16] and conducts rural spatial guidance planning [17]. In recent years, the integrated perspective of human–earth systems and spatial analysis technology has provided a very broad space for geographers to participate in human settlements research [18]. Among the global studies, the contents focus on the following four aspects: First, the characteristics and evolution of rural settlements and landscapes have been focused on [19,20]; Second, poverty, social conflicts, housing and infrastructure development in urban and rural development have attracted the interest of scholars [21,22]; Third, the quality of urban and rural human settlements at different scales has been assessed [23,24]; Fourth, a few studies have explored the correlation between human settlements and economic development, urbanization, population distribution, etc. [25,26].

The issue of human settlement improvement has received continuous attention from international organizations. The United Nations Centre for Human Settlements (UNCHS) was established in 1978 and clearly put forward the concept of sustainable habitat development in the "Istanbul Declaration", which stressed the sustainable development of cities, towns and villages at different levels. In 2004, a new "rural-urban linkage concept" was established, which re-emphasized the importance of urban–rural linkage development and suggested that efforts should be made to increase the infrastructure, public services and employment opportunities in rural areas, not only to improve urban habitats. At the same time, UNCHS joined hands with the World Bank and other international organizations to conduct experiments on human settlement construction in developing countries in the form of project assistance.

For a long time, the urban centrism of human settlements research was obvious, and the study of rural human settlements was limited to the generalization and summary of phenomena, such as settlement location and morphology, land use and rural landscape [27]. Since the 1950s, after urbanization in Europe and the United States, the problems of rural poverty and inequality attracted the attention of a group of scholars, and rural social geography based on "humanism" began to occupy an important position in the study of rural human settlements. For example, researchers explored the impact of urbanization on rural areas from the perspective of urban–rural linkage and urban–rural integration, focusing on hot topics such as rural poverty, infrastructure construction, rural population mobility and the urban–rural gap [28]. At present, planning, architecture and national governments have carried out more practical work on habitat engineering, but mostly focus on the hardware aspects of settlements, such as building facilities, settlement planning and sanitation improvement. For example, "Optimize rural habitat and carry out comprehensive improvement of rural environment" has become an important slogan for China's rural environmental improvement work.

However, the above perspectives ignore the systemic attributes of rural human settlements. The rural human settlements system (RHSS) is a dynamic and complex mega-system covering the living environment related to lives, residences and basic production activities involved in the settlement of residents [29]. Among the existing studies, there is still a lack of research efforts based on an integrated systems perspective. The current research works from a systems perspective are again focused on exploring the natural suitability, satisfaction and integrated quality by using official statistics [24]. Due to the lack of micro-historical data, there are relatively few studies exploring the evolution of rural human settlements at the community or village scale with ground truth characteristics and "human experience". In addition, the micro-scale research mainly concentrates on satisfaction and comprehensive quality assessment [30,31], and less focus on the vulnerability, adaptation and resilience of the RHSS under global changes.

Vulnerability, initially used in the study of risks and hazards, is the degree to which a system, subsystem, or system component is likely to experience harm due to exposure to a hazard, either a perturbation or stress/stressor [32]. RHSS vulnerability refers to the state in which the environment related to housing, living and basic production activities of the inhabitants in a rural area is vulnerable to negative impacts or damages due to exposure to disturbances from natural and human conditions. In the 1980s, the term "vulnerability" was introduced into the field of geosciences by Timmerman [33], and has been extended to various areas of study of human–environment relationships, such as climate impacts and socio-ecological systems [34–37], livelihood and poverty [38], social transformation [39,40] and health and welfare [41–44]. It has gradually become a new research perspective and an important analytical tool for global environmental change and sustainability science.

Studies on the vulnerability of human–environment relationships have attracted the attention of scholars from ecology, geography, economics, sociology and other disciplines. Current research focuses on the following four aspects: first, numerous analytical frameworks have emerged to explore the causes and interaction relationships, such as SLA (sustainable livelihoods analysis) [45], the human–environment coupled system analytical framework [32], VSD (Vulnerability Scoping Diagram) and ADV (Agents Differential Vulnerability) integration assessment framework [46,47]. Secondly, vulnerability studies with respect to different perturbations have received more attention, and are characterized by an expansion from focusing on natural hazards to social threats or multiple disturbances [39,48–50], while the current research achievements are fewer for human–land system vulnerability based on multiple disturbance factors. Third, a wealth of research has been generated in vulnerability assessment and impact factor analysis, and has focused on typical human–environment system types, such as social-ecological systems [50–53], economic systems [54,55], human–water systems [56], and livelihood systems [57,58]. Fourth, the studies at different scales, such as household, community, region and global, have been addressed. For the global and national scales, vulnerability assessments and spatial differentiation analyses based on sustainable development perspectives have been conducted [59]. For the regional and urban scales, the research objects are more diversified, such as integrated vulnerability [60], or focusing on social or institutional vulnerability [40]. For the community and household scales, the characteristics and formation processes of livelihood and poverty vulnerabilities with respect to the specific disturbances are more delicately explored [34,48].

In summary, the concept and connotation of vulnerability terminology has been enriched and developed in a large number of case studies. Among the existing studies, a rich set of case studies based on the Sustainable Livelihoods Framework or PICC assessment framework has been developed, whereas there is a relative lack of vulnerability studies focusing on the coupled mega-system of rural residents' productions and habitats. In particular, the vulnerability of rural settlements under the disturbance of urbanization and climate change needs urgent attention. Our study aimed to focus on the traditional farming areas in the Chinese Loess Plateau. Rather than previous studies in which researchers independently determined the characterization indicators, our study proposes a vulnerability measurement index system for the RHSS with the participation of residents and experts. On the other hand, instead of using official statistics to portray the temporal evolution of the RHSS from a macro-scale or to qualitatively describe the evolutionary process, we experimentally combine historical village data with residents' recall questionnaires to explore the evolution of RHSS vulnerability since 1980. Such research covers the perceptions and experiences of the residents and can fully reflect the local meaning and characteristics.

The Loess Plateau is one of the regions characterized by the highest concentration of human–land conflicts in China [61]. Over the past 40 years of China's reform and opening up, the relationship between humans and the land on the Loess Plateau has changed dramatically. On the one hand, the implementation of a series of ecological construction and livelihood projects has contributed to the reduction in soil erosion, the increase in vegetation cover, the obvious improvement of ecosystem service capacity and the success of rural facilities in the region [62]. On the other hand, the traditional farming areas have long been disturbed by climate change, lack of water resources, frequent natural disasters and fragmented landscapes [63–65]. Additionally, the local development has shown the characteristics of low industrialization of agriculture, lagging development of non-agricultural industries and reliance on national financial support [66]. In addition, under the siphoning of urbanization, rural capital and resources are continuously lost, and the vulnerability of rural systems such as hollowing out has become obvious [50,67]. Therefore, it is urgent for us to interpret the changes to rural human–land systems in the Chinese Loess Plateau over the past 40 years in the context of multiple perturbations and uncertainties.

The strategy of rural revitalization has become the Chinese national strategy. Supporting the demands of the major national strategy is an essential practice for the localization of vulnerability theory. This study delicately explores the vulnerability evolution in the RHSS over 40 years at the micro-scale based on first-hand data, using Jia County as a typical case area. Specifically, the analysis focuses on addressing three questions: First, the changes in the vulnerability of the RHSS and composition from 1980 to 2017; Second, the spatial and temporal variation characteristics of functional vulnerability factors, including contributions and resistances; Lastly, the evolutionary impacts of key events on RHSS vulnerability.

2. Materials and Methods

2.1. Study Area and Representative Years

2.1.1. Study Area and Sample Villages

The Loess Plateau, characterized by low precipitation, ecological fragility and economic poverty, covers a total area of 646,200 km^2 [61]. Jia County is located in the middle reaches of the Yellow River, the northern farming-pastoral ecotone, which belongs to both the national key ecological function area and the key practice area for poverty alleviation (Figure 1). Since 1980, Jia County has faced common problems of traditional agricultural areas on the Loess Plateau, such as frequent natural disasters, topographic and ecological constraints, declining villages under the impact of urbanization, as well as individual problems of unsustainable livelihoods in date palm forests under the disturbance of climate change [66,67]. Authors explored the evolution of the vulnerability of RHSS since 1980, using Jia County as a typical area of traditional farming areas on the Loess Plateau.

The study area covered 2029.3 km^2, with 12 towns and 1 street office, 8 communities, 330 administrative villages and a total population of 269,400 in 2017. The climate is continental arid and semi-arid, with frequent natural disasters such as drought, frost and hail. The annual average temperature is 10.2 °C and the annual average precipitation is 386.6 mm, with precipitation mainly concentrated in July to September. The topography is characterized by high in the northwest and low in the southeast. The complex topography can be categorized into 3 regional types with obvious differences in landforms [68], namely, the northern Windsand Region, the Loess Hilly and Gully Region in the southwest and the Earth-Rock Mountainous Region along the Yellow River (Figure 1). As for agricultural production, food crops mainly include beans, potatoes, corn, millet, sorghum, etc.; livestock categories mainly contain pigs, sheep, poultry, etc., while economic forests are dominated by jujube trees.

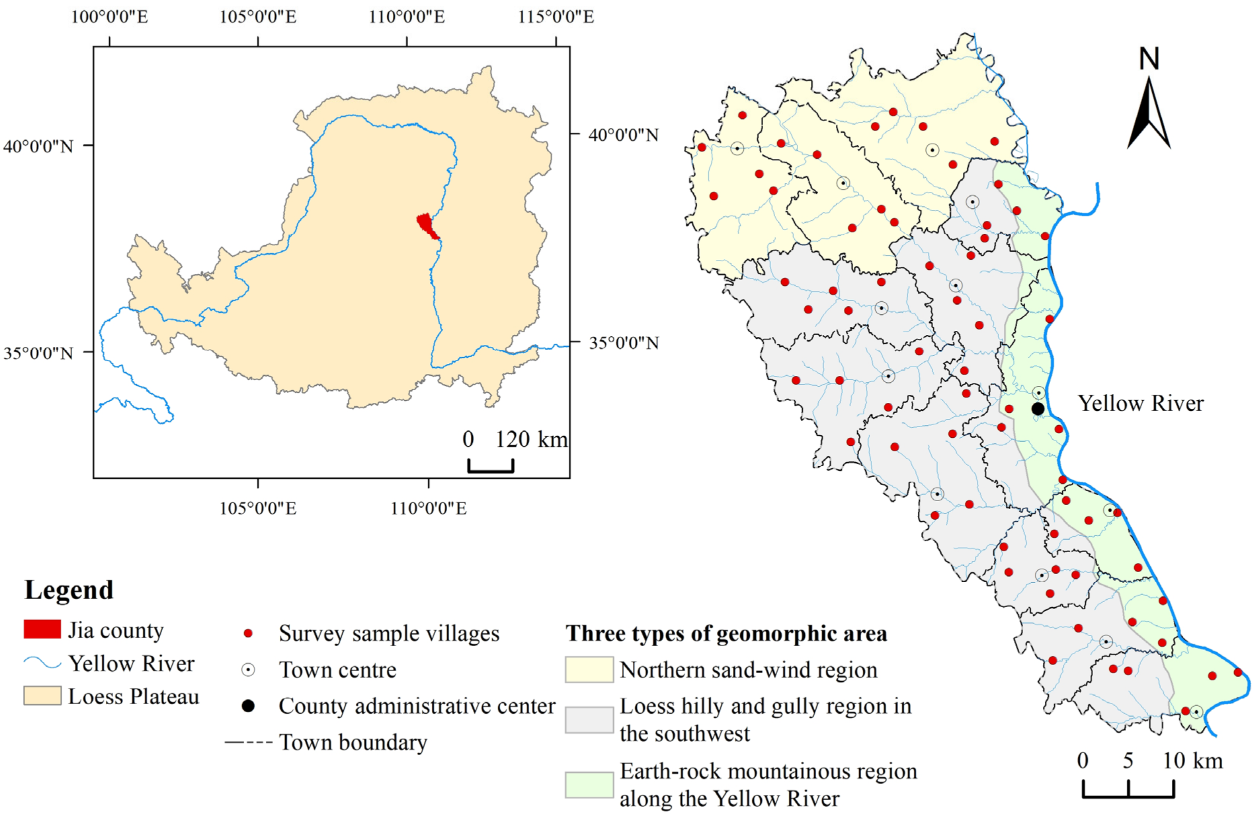

Figure 1. Schematic diagram of survey sample village in Jia County, Chinese Loess Plateau.

2.1.2. Identify Representative Years for the Study

Since 1980, the development of rural areas in Jia County on the Loess Plateau, including changes in the state of residents' lives, production and living environment, has been influenced by government policies and projects such as the Household Contract Responsibility System (since 1979), Grain for Green Project (since 1999), Extending Radio and TV Broadcasting Coverage to Every Village Project (since 1999) and the New Rural Cooperative Medical Insurance (since 2007). Among them, Jia County piloted the Household Contract Responsibility System in 1979, and it was fully implemented in 1980, which increased farmers' enthusiasm for production, and the agricultural production and rural economy began to flourish [68]. In April 2007, Shaanxi Province listed Jia County as a project county for New Rural Cooperative Medical Insurance, and local residents were impressed by the promotion phase of the new rural cooperative medical work [68]. Therefore, we selected the years when national projects with strong influence were implemented as a representative historical time section for the study. That is, four representative years of 1980, 2000, 2008 and the current 2017.

In order to strive for clear recall of respondents and to ensure the accuracy and comparability of indicator data among different respondents, recall guide words were selected for prompting in the questionnaire. In addition, in terms of questionnaire design, we designed questions with clear memory, such as questions involving slow change features, significant change features and perceptual experience [69]. Finally, the researcher entered the answers into the questionnaire according to uniform rules. For 1980, the recall guide words were "when the household contract responsibility system started", "30 years ago" and "80s". For 2000, "at the turn of the century" and "when the pilot project of grain for green was launched" were used as recall guide words. For 2008, "08 Beijing Olympic Games" and "new rural cooperative medical insurance" were used as recall guide words. For 2017, "information in last year" was filled in.

2.2. Field Investigation and Data Collection

In order to explore the evolution of RHSS vulnerability in Jia County since 1980, the research team conducted several field surveys. Despite some constraints of collecting the required data in such remote, hollowed-out and aging rural settings, we opted to collect information scientifically using a variety of survey methods, such as oral historical interviews, structured questionnaires for household sampling and village questionnaires. The data used in this study were mainly obtained from the field investigation. Stratified random sampling method [70] was used to select 5 sample villages for each of the 13 towns in the study area, and finally determined 65 sample villages by collecting latitude and longitude through GPS, as shown in Figure 1.

2.2.1. Ethnographic Approach with Oral Historical Interviews

The interview materials obtained and local chronicles [68,71] were used to conduct ethnographic research [72,73], which was designed to analyze the evolutionary impacts of key events on RHSS vulnerability in the context of climate change, market changes, urbanization perturbations, policy interventions and households' adaptation. From 22 to 29 October 2017, the research team conducted the first oral historical interviews [74] in Jia County. Three towns were selected for each of the three types of landscape areas, three villages were selected for each town. In each village, multi-stakeholders, including farmers, village administrators and rural elites, were selected for in-depth interviews, and 52 valid interview recordings were harvested. From 16 July to 2 August 2018, oral history interviews were conducted again for the 65 sample villages (Figure 1), and 61 audio recordings of multi-stakeholder interviews and 2 transcripts of government symposiums were obtained.

The multi-stakeholder interviews were assisted by the village head to provide a list of interviewees, and then the researchers sampled one to two respondents from the list in each sample village. Each interview ranged from about 0.5 to 1 h in length and was audio-recorded for preservation and analysis. Referring to the "ground-truthing" qualitative approach successfully used by Smith et al. [75], our interviews covered 6 questions.

(1) What changes have occurred in each area of the village or settlement since 1980?

(2) What were the reasons for these changes? Have farmers or local governments contributed to the changes?

(3) Have farmers adapted to the above changes in their villages? How did they respond to the negative changes?

(4) What were the most unsatisfactory and satisfactory aspects of the village or settlement systems since 1980?

(5) What will be the future changes in the village? What are the bottlenecks that limit the future development of the village?

(6) What are your suggestions for the development of the village? Or what kind of help would you like the national or local government to provide?

Question (4) could also be used for the identification of vulnerability measurement elements for RHSS.

2.2.2. Structured Questionnaire

We developed structured questionnaires to survey households and villages from 16 July to 2 August 2018. As for village questionnaires, information in sample villages was obtained by collecting village statistics and supplementing them with interviews with current and retired village leaders or clerks. The information included the natural ecological environment, demographic changes and infrastructure and services. Finally, one valid village questionnaire was generated for each sample village, totaling 65 questionnaires.

As for household questionnaires, we randomly selected 7 households in each sample village; a total of 455 questionnaires were distributed and 455 were collected, of which 451 were valid, with an efficiency rate of 99.1%. Each questionnaire was limited to 45–60 min in length. The contents of the questionnaire are shown in Appendix A, and the basic information of householders is shown in Table A1.

2.2.3. Geographic Information Systems Data Sets

The river systems, administrative divisions at all levels and road networks required for this study were obtained from the National Geographic Information Resources Catalogue Service and the 1:1 million national basic geographic database (www.webmap.cn, accessed on 1 January 2018). The latitude and longitude information of the sample villages was collected via handheld GPS.

2.3. Vulnerability Assessment Framework for the RHSS

2.3.1. Elements and Domains of Vulnerability Measurement for the RHSS

The RHSS is actually a manifestation of the coupled system of human and environment in the rural area. In this study, elements to measure the vulnerability of RHSS were selected from five major subsystems: natural, human, dwelling, support and social [13]. Different from previous studies where elements were selected independently by researchers or expert groups, for this study, a combination of farmer participatory assessment and expert approval was used to determine the underlying characterization elements [76]. A brief implementation process is as follows.

Based on 52 in-depth interview texts, the textual keywords were coded according to the responses to the question "What were the most unsatisfactory and satisfactory aspects of the village or settlement systems since 1980?". Next, the keywords were categorized into natural, human, dwelling, support and social subsystems according to the subsystem to which they belonged. Finally, we extracted the top four keywords for each subsystem based on response frequency. If keywords with the same ranking appeared in the fourth place, the choices were made by 5 experts. The results are as follows:

- As for natural system, the elements were natural disasters, land use, fertilizer use and ecological environment;
- As for dwelling system, the elements were housing construction, home appliance facilities, drinking water problems and communication conditions;
- As for human system, the elements were family size, population burden, population growth and population quality;
- As for support system, the elements were basic education, health care, traffic roads and retail outlets;
- As for social system, the elements were economic (income) growth, industry (livelihood) diversity, government services and social inequality issues.

From the above elements, it can be seen that natural, human and dwelling systems mostly have sensitive-exposure properties, while support and social systems mostly reflect properties in terms of coping and adaptive capacity. The above element sets can be used to guide the construction of vulnerability assessment index systems for RHSS at different scales.

2.3.2. Vulnerability Assessment Index System for RHSS at Village Scale

The characterization factors at the village scale needed to satisfy the following requirements, firstly, they should highlight the habitat characteristics of the village unit and focus on the behavior, psychology and experience of the residents. Secondly, they should be both spatially differentiated and historically comparable. Finally, considering that some of the data will come from household sampling questionnaires and will use retrospective survey methods to obtain information for multiple historical years, the slow-change variables, macro-change variables and perception-type variables will be mainly considered in the indicators to ensure the feasibility and scientific validity of the retrospective [69].

In summary, a three-level vulnerability assessment index system for RHSS at the microscale was constructed based on the elements of vulnerability in five subsystems, with indicators determined around slow-change variables, such as land use, household facility environment, village construction and socio-ecological environment perception-type variables (As shown in Table 1).

Table 1. Indicator system and data sources for characterizing the vulnerability of RHSS at village scale.

Subsystems	Factors	Calculation Description	Direction
Natural system vulnerability	Forest Cover	Share of forest land in total land	–
	Land Cultivation	Ratio of abandoned land to total land	–
	Sandstorm	Five-point scale values, impact degree of wind and sand disaster: Very low 1; Low 2; Medium 3; High 4; Very high 5	+
	Fertilizer Use	Average fertilizer use on household contracted land	+
	River Quality	Five-point scale values, perceived quality of river and canal water: Perennial clearness 1; Relatively clean 2; River breakage, medium quality 3; Muddy, polluted with garbage 4; Highly polluted, smelly 5	+
Human system vulnerability	Permanent Population	Five-point scale values, permanent population profile in villages: Crowded and well-structured 1; Appropriate demographic structure 2; Less youths and children 3; Few youths 4; Highly depressed 5	+
	Dependency Ratio	Ratio of non-working-age population to working-age population; working age is defined as between 15 and 64 years old	+
	Household Size	Number of people per household, calculated by the ratio of village population to number of households	–
	Labor Literacy	Five-point scale values, education level of the labor force: Illiterate 1; Elementary school 2; Junior high school 3; High school 4; University or above 5	–
	Festival Crowd	Five-point scale values, crowds at traditional festivals: Less crowded and cold 1; Few people, no festival atmosphere 2; Medium, no feeling 3; People flow, with festive atmosphere 4; Very crowded and hot 5	–
Dwelling system vulnerability	House Structure	Five-point scale values, vulnerability grading of housing structures: A building of two or more stories 1; single-story house 2; Stone cave house 3; Earthen cave house 4; Decrepit house 5	+
	Housing Size	Number of rooms per capita	–
	Durable Goods	Sum of the values for consumer durables, values for each consumer good: Electric fan, Washing machine, TV, Refrigerator 1; Motorcycle, Bicycle 2; Car, Water heater, Air conditioner, Computer 3	–
	Communication	Four-point scale values, best communication devices for home ownership: No 1; Landline telephone 2; Non-Smart mobile phones 3; Smartphone 4	–
	Domestic Water	Four-point scale values, ways to use water at home: In-house tap water 1; Well water without entering the house 2; Going out to obtain water 3; Use of rainwater 4	+
Support system vulnerability	School Distance	Distance to the nearest primary school. If the elementary school is located in the village, the value was assigned as 0.5 km	+
	Village Doctor	Total number of doctors in the village or available for home visits	–
	Road Condition	Condition of trunk road in village, calculated by the multiplied product of the value for road technical class and the value for pavement type; value for the road technical level: Provincial-level road 1; County-level road 2; Township-level road 3; Village-level road 4; Value for the pavement level: Hardened 1; Unhardened 2	+
	Retail Store	Total number of retail stores or kiosks in the village	+
	Garbage Disposal	Four-point scale values, ways to dispose of domestic garbage: Dumped into the garbage pond dedicated to cleaning and transport 1; Local centralized incineration or burial disposal 2; Concentrated pile to wasteland, no disposal 3; Dump into gullies or rivers 4	+

Table 1. *Cont.*

Subsystems	Factors	Calculation Description	Direction
Social system vulnerability	Livelihood Diversity	Number of household livelihood types. There are six types of livelihoods: agriculture, forestry, ranching, labor, business and employment in public institutions or state-owned enterprises.	−
	Household Income	Household income per capita	−
	Village Security	Five-point scale values, village security level: Very poor 1; Poor 2; Average 3; Better 4; Very good 5	−
	Village Management	Five-point scale values, ability and attitude to deal with general affairs in village management: Poor attitude and ability 1; Indifferent attitude, average ability 2; Good attitude but difficult to handle issues 3; Good attitude, slow to handle issues 4; Good attitude and promptness 5	−
	Wealth Disparity	Five-point scale values, disparity of wealth between households within the village: Very small 1; Small 2; Medium 3; Big 4; Bigger 5	+

Note: Indicator "Road Condition", the required technical road grade data from the detailed road statement and the traffic road network map of different periods provided by Jia County Traffic Bureau. For indicators assigned on a four- or five-point scale, village values were taken from the sample household averages. Data on support, population and land were obtained from thematic village statistical questionnaires which were answered by village leaders or respected elderly people over 60 years old. In indicator direction, "+" means that the system vulnerability value increases as the indicator value increases, "−" means that the system vulnerability value decreases as the indicator value increases.

2.3.3. Assessment Model for RHSS Vulnerability

Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) is an important method in multi-attribute decision making [77]. The basic principle of this method is to construct the optimal and inferior solutions of each index of a multi-attribute problem and calculate the relative proximity of each evaluation sample to the optimal and inferior solutions which are used as the basis for evaluating the advantages and disadvantages of each solution [78].

First, the index data were standardized by applying the extreme value standardization method. Among them, the positive-type indicators were processed using Equation (1) and the negative-type indicators were processed using Equation (2).

$$x'_{ij} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)} \quad (1)$$

$$x'_{ij} = \frac{\max(x_j) - x_{ij}}{\max(x_j) - \min(x_j)} \quad (2)$$

In Equations (1) and (2), x_{ij} denotes the value of the index j for the sample i, and x'_{ij} denotes the corresponding standardized value.

Second, with n factors for each evaluation object, a dimensionless data matrix was constructed, as shown in Equation (3). Next, the matrices of the optimal solution $\mathbf{X}^{+}$ and the inferior solution $\mathbf{X}^{-}$ were determined, as shown in Equation (4).

$$\mathbf{X} = \left(x'_{ij}\right)_{m*n} \quad (3)$$

$$\mathbf{X}^{+} = \left(x_j^{+}\right)_{1*n};\ \mathbf{X}^{-} = \left(x_j^{-}\right)_{1*n} \quad (4)$$

In Equation (4), variable m refers to the sample to be evaluated, n refers to the evaluation index and x_j^{+} and x_j^{-} refer to the optimal and inferior solutions of indicator j, respectively.

Third, the distance between each evaluation sample with the optimal value and with the inferior value was calculated separately, as shown in Equation (5). In this case, equal weights were used in the formula, which was to ensure that there was no change in the information conveyed by the composite index or any change in the contribution of the variables caused by the difference in weights.

$$d_i^+ = \sqrt{\sum_{j=1}^{n} w_j \left(x'_{ij} - x_j^+\right)^2} \; ; \; d_i^- = \sqrt{\sum_{j=1}^{n} w_j \left(x'_{ij} - x_j^-\right)^2} \tag{5}$$

In Equation (5), d_i^+ and d_i^- refer to the distance from the optimal value and from the inferior value, respectively. The w_j refers to the weight of indicator j.

Lastly, Equation (6) was used to calculate the relative closeness of each evaluation sample to the optimal value, which was the vulnerability index, and a larger value of C_i means a larger vulnerability index for the evaluation sample.

$$C_i = \frac{d_i^-}{d_i^- + d_i^+} \tag{6}$$

2.4. Identifying the Functional Compositions

2.4.1. Contribution and Barrier Models

Identifying the main contributors and main resistances to vulnerability is the key to reducing vulnerability and improving robustness. The contribution factor refers to the promotion of the rise in vulnerability of RHSS, and the contribution model is shown in Equations (7) and (8).

$$E_j = \frac{F_j \times I_j}{\sum_{j=1}^{n} F_j \times I_j} \times 100\% \tag{7}$$

$$D_r = \frac{W_r \times K_r}{\sum_{r=1}^{5} W_r \times K_r} \times 100\% \tag{8}$$

In these equations, I_j refers to the standardized value of the original factor, F_j denotes the weight of the j-th factor on the target layer and E_j denotes the contribution of the j-th factor to the vulnerability of the target layer. K_r refers to the subsystem vulnerability value, W_r denotes the weight of the r-th subsystem to the target layer and D_r refers to the contribution of the r-th subsystem to the vulnerability of the target layer.

Resistance factor refers to the inhibition of the rise of vulnerability of RHSS, and the barrier model is shown in Equations (9) and (10).

$$O_j = \frac{F_j \times \left(1 - I_j\right)}{\sum_{j=1}^{n} F_j \times \left(1 - I_j\right)} \times 100\% \quad j = 1, 2, \ldots, n \tag{9}$$

$$U_r = \frac{W_r \times (1 - K_r)}{\sum_{r=1}^{5} W_r \times (1 - K_r)} \times 100\% \quad r = 1, 2, 3, 4, 5 \tag{10}$$

In these equations, O_j refers to the resistance of the j-th factor to the target layer vulnerability, and U_r refers to the resistance of the r-th subsystem to the target layer vulnerability.

2.4.2. Recognition and Grading for Contributions and Resistances

Based on the measurement results of the contribution model, the factor/subsystem with the highest contribution value was identified as the contribution factor/subsystem to the vulnerability of RHSS in the sample villages. Similarly, based on the results of the barrier model, the factor/subsystem with the highest resistance value was identified as the resistance factor/subsystem to the vulnerability of RHSS in the sample villages.

In addition, the contribution factor/subsystem and the resistance factor/subsystem were further classified into three levels of low, medium and high according to their values. The grading criteria are shown in Table 2.

Table 2. The levels for contributions and resistances of factors/subsystems to RHSS vulnerability.

Levels	Value Range for Contributions/Resistances	
	Subsystems	**Factors**
Low	<0.2 [a]	<0.04 [b]
Medium	0.2–0.25	0.04–0.08
High	>0.25	>0.08

Note: [a] For 5 subsystems, 0.2 is the average value. [b] For 25 factors, 0.04 is the average value.

3. Results

3.1. Evolution of the RHSS Vulnerability

Based on the assessment of five subsystems and 25 factors, there were different trends of vulnerability change (see details in Table 3, Figure 2).

Table 3. Average values for factor/subsystem vulnerability of the RHSS among 65 sample villages in 1980, 2000, 2008 and 2017.

Factors (Systems in Bold)	1980	2000	2008	2017
Forest Cover	0.818	0.525	0.425	0.418
Land Cultivation	1.000	0.925	0.841	0.468
Sandstorm	0.702	0.520	0.326	0.177
Fertilizer Use	0.177	0.441	0.539	0.383
River Quality	0.500	0.510	0.602	0.558
Natural system vulnerability	**0.595**	**0.569**	**0.541**	**0.418**
Permanent Population	0.153	0.305	0.598	0.822
Dependency Ratio	0.476	0.289	0.179	0.241
Household Size	0.356	0.432	0.570	0.718
Labor Literacy	0.779	0.742	0.581	0.376
Festival Crowd	0.246	0.309	0.464	0.615
Human system vulnerability	**0.421**	**0.427**	**0.480**	**0.544**
House Structure	0.788	0.694	0.649	0.587
Housing Size	0.857	0.782	0.680	0.526
Durable Goods	0.868	0.785	0.691	0.415
Communication	0.983	0.869	0.506	0.128
Domestic Water	0.656	0.469	0.251	0.095
Dwelling system vulnerability	**0.798**	**0.697**	**0.549**	**0.379**
School Distance	0.002	0.037	0.298	0.406
Village Doctor	0.818	0.757	0.788	0.803
Road Condition	0.786	0.573	0.419	0.197
Retail Store	0.881	0.731	0.765	0.794
Garbage Disposal	0.973	0.973	0.961	0.632
Support system vulnerability	**0.618**	**0.575**	**0.613**	**0.545**
Livelihood Diversity	0.708	0.452	0.390	0.623
Household Income	0.974	0.863	0.616	0.336
Village Security	0.426	0.443	0.310	0.210
Village Management	0.740	0.749	0.589	0.363
Wealth Disparity	0.201	0.338	0.668	0.786
Social system vulnerability	**0.582**	**0.558**	**0.514**	**0.472**
RHSS vulnerability	**0.655**	**0.604**	**0.565**	**0.454**

Note: The values for the factors were standardized by applying the extreme value standardization method.

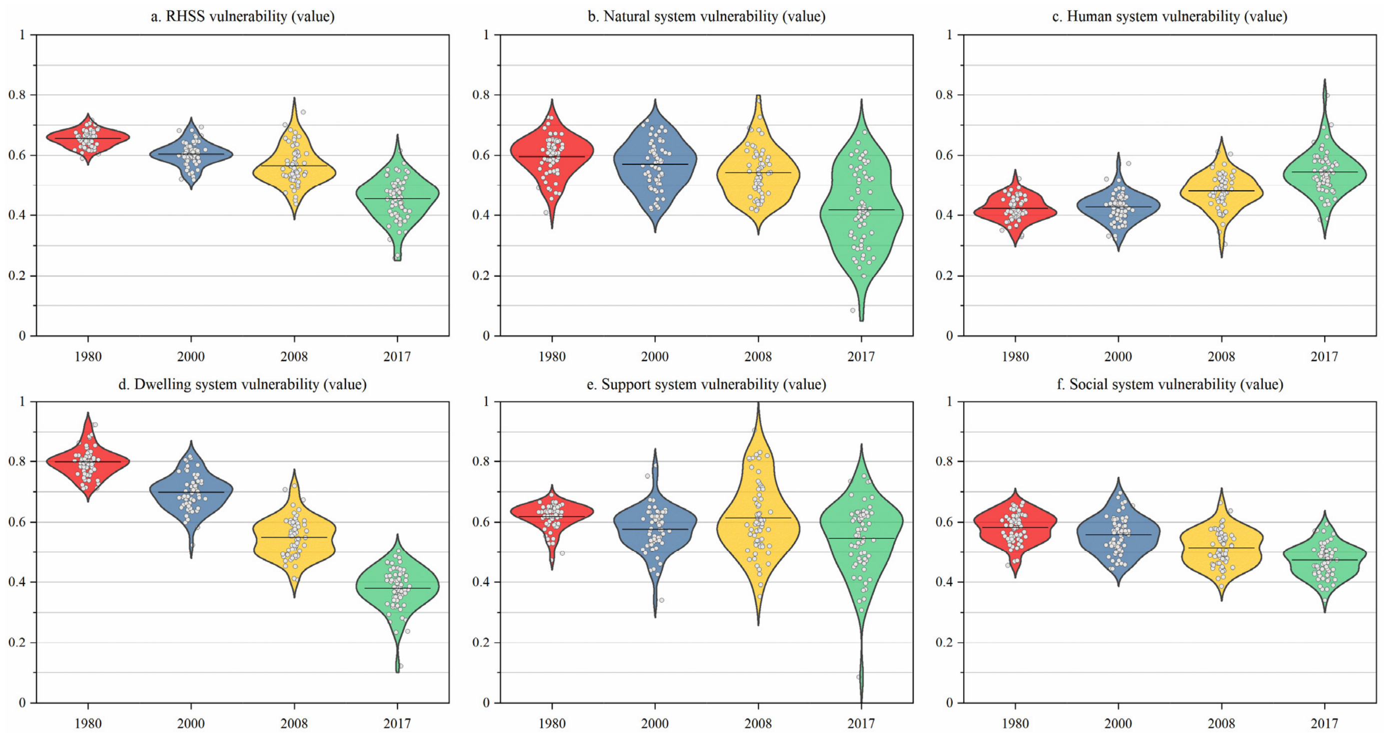

Figure 2. Violin plot for the distribution of vulnerability indices of RHSS and subsystems in 65 sample villages from 1980 to 2017.

3.1.1. Gradually Decreases but Differences Widened in RHSS Vulnerability

The distribution of the RHSS vulnerability indices is shown in Figure 2a, which shows a gradual decrease in RHSS vulnerability from 1980 to 2017, but with increasing variation. In the 1980, the RHSS vulnerability indices in all 65 sample villages was very high, concentrated in the range of 0.6–0.7. By 2000, the vulnerability index decreased slightly and was mainly concentrated in the range of 0.5–0.7. In 2008, the distribution range of vulnerability indexes widened, with most sample villages concentrated in the range of 0.5–0.6, and a few villages shown below 0.5. However, there were also a large number of villages with an index above 0.6 and even above 0.7. In 2017, the vulnerability of the RHSS was significantly reduced, with the indexes for the vast majority of villages below 0.5, in which some villages were below 0.4 and some villages even had very low vulnerability (below 0.3).

3.1.2. Continued Reduction in Vulnerability for Natural, Dwelling and Social Systems

The natural system for sample villages maintained a high level of vulnerability in the 1980, 2000s and 2008, but the vulnerability indices decreased slightly period by period in the vast majority of villages until 2017, when the mean value of the vulnerability indices decreased significantly with a significant increase in spatial variation. The indices for a part of the villages were below 0.3, while some villages were above 0.6 (Figure 2b).

A significant downward trend in the vulnerability indices for the dwelling system was observed between 1980 and 2017, with the extent of reduction increased period by period. During the period 1980–2000, the mean value of the vulnerability indices decreased from 0.8 to 0.7, and the vast majority of villages remained in a highly vulnerable state. By 2008, the vulnerability indices mitigated to a moderate level, mainly concentrated in 0.5–0.6, with a slight increase in spatial disparity. By 2017, the vulnerability indices for most villages were significantly reduced to a lower level, with the indices below 0.3 for some of the villages (Figure 2d).

The social system vulnerability indices showed a slow reduction trend, with the mean value decreased to below 0.5 in 2017. In addition, the distribution range of vulnerability indices was very concentrated in each period, with a concentration in the range of 0.5–0.7 in 1980 and in the range of 0.4–0.6 in 2017. It can be seen that the rural social system in the study area is relatively stable and changes slowly (Figure 2f).

3.1.3. Increased Vulnerability in Human System and Increased Gaps in Support System

Figure 2c shows that the human system vulnerability has increased significantly since 2000 with increased distribution gaps, where the indices in some villages have exceeded 0.6 and even reached extreme vulnerability (over 0.7). In contrast, in the 1980 and 2000s, the vulnerability indices of almost all the sample villages were below 0.5, and a large number of villages were in low vulnerability (under 0.4).

For the support system, the mean value of the vulnerability indices was consistently above 0.5 and even exceeded 0.6 in 1980 and 2008. At the same time, the distribution difference of the vulnerability indices widened significantly, from a concentrated distribution range of 0.5–0.7 in 1980 and 2000 to a range of 0.3–0.8 in 2008 and 2017. It is worth pointing out that the vulnerability of the support system was extremely high in 2008, with the indices even exceeding 0.8 in some villages (Figure 2e).

3.2. Spatio-Temporal Evolution of the Functional Composition in RHSS Vulnerability

The functional compositions for RHSS vulnerability, including contribution/resistance subsystems and the contribution/resistance factors in each subsystem, were diagnosed for 65 sample villages in 1980, 2000, 2008 and 2017 based on the contribution and barrier models.

3.2.1. Contribution and Resistance Subsystems for RHSS Vulnerability

As shown in Figure 3a–d, the contribution subsystems of RHSS vulnerability were gradually transformed from the full occupation of the dwelling system to the dominance by the support and human systems. In 1980, with the exception of only two villages where the contribution subsystems were the support system, all others were the dwelling system. In 2000, natural or support systems replaced the dwelling system as the contribution system of some villages, among which the natural system mostly belonged to the contribution subsystems in northern villages. By 2008, a dramatic change had occurred in the spatial pattern of the contribution subsystems, with the distribution of the support system expanding across the board, the dwelling system distribution narrowing to the southwest gully area and the natural system becoming the main contributing subsystem in the northern Windsand Region. In 2017, the share of human system distribution among the contribution subsystems significantly increased from 1.5% to 27.7%, which together with the support system became the widely distributed contribution subsystems.

As shown in Figure 3e–h, the resistance subsystems showed a gradual shift from full occupation by the human system to a pattern of occupation in the southern and northern regions by the natural and residential systems, respectively. The human system as the resistance covered almost all the sample villages from 1980 to 2000, but the level of resistance decreased. In 2008, while the resistance subsystems were still widely distributed by the human system, the level of resistance generally decreased, and the natural and social systems became the resistance subsystems in a large number of sample villages. In addition, there was no distribution of the natural system in the Northern Windsand Region, and the sample villages with the support system as the resistance were all close to the township administrative centers.

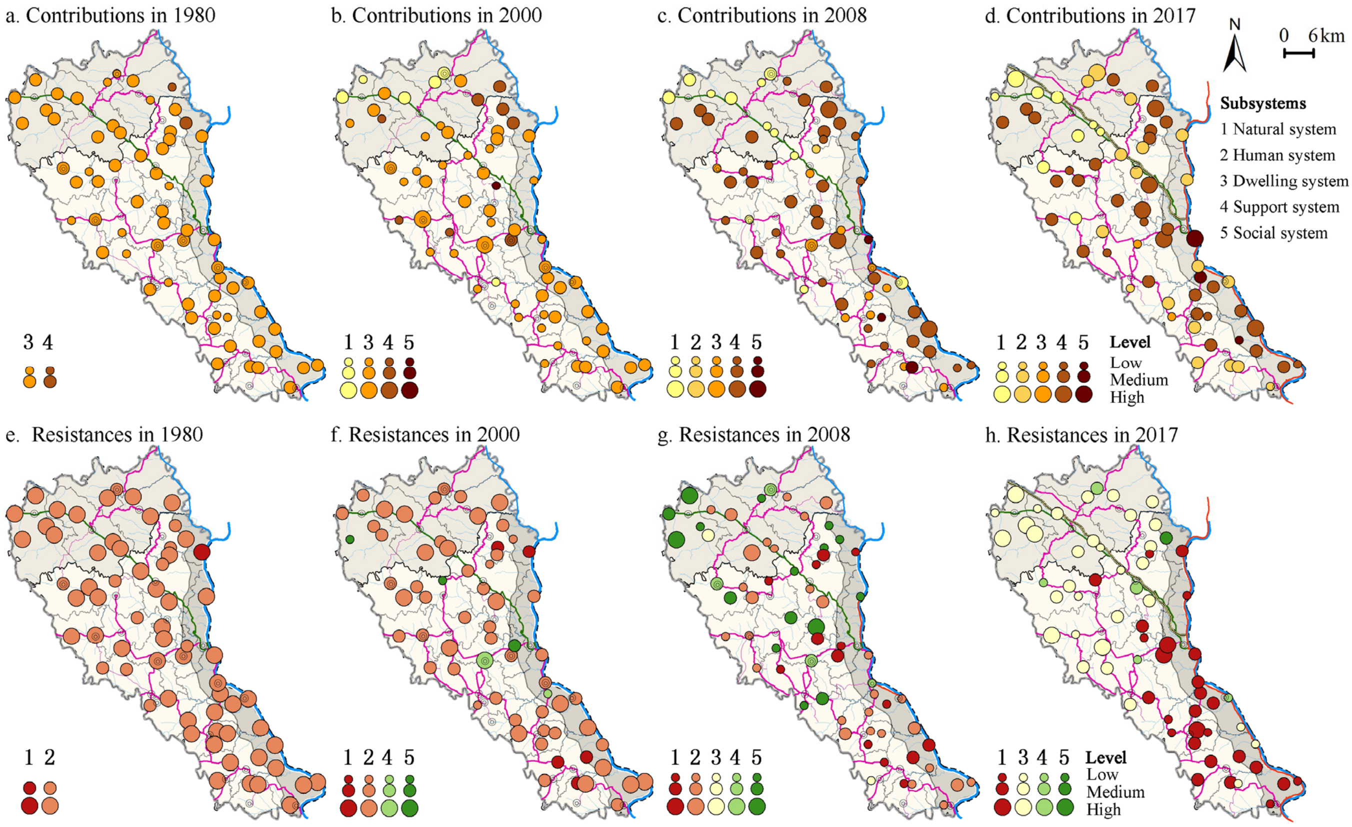

Figure 3. Spatio-temporal divergence of contribution and resistance subsystems to RHSS vulnerability in 65 sample villages from 1980 to 2017. Note: '—' refers to the River, '—' refers to the Tourist Highway along the Yellow River, '═' refers to the Expressway, '—' refers to provincial highways, '—' refers to county roads.

3.2.2. Contribution and Resistance Factors

(1) Factors in the natural system

The contribution factors of the natural system vulnerability experienced a spatial evolution from a full regional coverage of Land Cultivation with a joint influence of Sandstorm or Forest Cover in the northern region to a dominant distribution of River Quality. It can be seen that there were multiple factors within the natural systems in the northern villages that were all extremely vulnerable in the 1980s. From 1980 to 2008, Land Cultivation was always the most widely distributed contributor, while Sandstorm gradually decreased, and Fertilizer Use and River Quality gradually increased. By 2017, River Quality became the most widely distributed contributor. In addition, Land Cultivation, Forest cover and Fertilizer Use were still contributors in some villages (Figure 4a–d).

As for the resistance factors, they showed a shift from Fertilizer Use occupying the whole region with high resistance to the widespread occupation by Sandstorm with low resistance. Since 2000, the Forest Cover and Sandstorm as resistance factors gradually spread, until the extensive coverage of Sandstorm in 2017. It is noteworthy that Land Cultivation became the resistance factor of the natural vulnerability in a few villages in 2008, attributed to the abandonment of farming (Figure 4e–h).

According to the interviews, perennial drought, frequent sandstorms and low vegetation cover were the main impressions of the respondents about the natural ecological environment in the 1980s and 1990s. Local residents noted: '*In the 1980s, the traffic conditions were not good, so it was not convenient to buy things and go out, and all the land was planted and hardly sold because it was not enough to eat by itself. At that time, there was no fertilizer and no irrigation, so when there was a drought, there was no harvest*'. In the 2000s, reforestation and extensive planting of jujube trees were the most common agricultural practices. After 2010, respondents clearly perceived a significant improvement in air quality, but there were also changes such as more garbage in the river and the river breaking and drying up. Residents point out that '*there are few dust storms, the mountains are full of trees, there is more rain, the air quality has become better, there is no sand and wind" The jujube trees have grown up and cannot be planted with crops under the forest. In addition, the return on jujube is not good, and the jujube lands were not even cultivated*'.

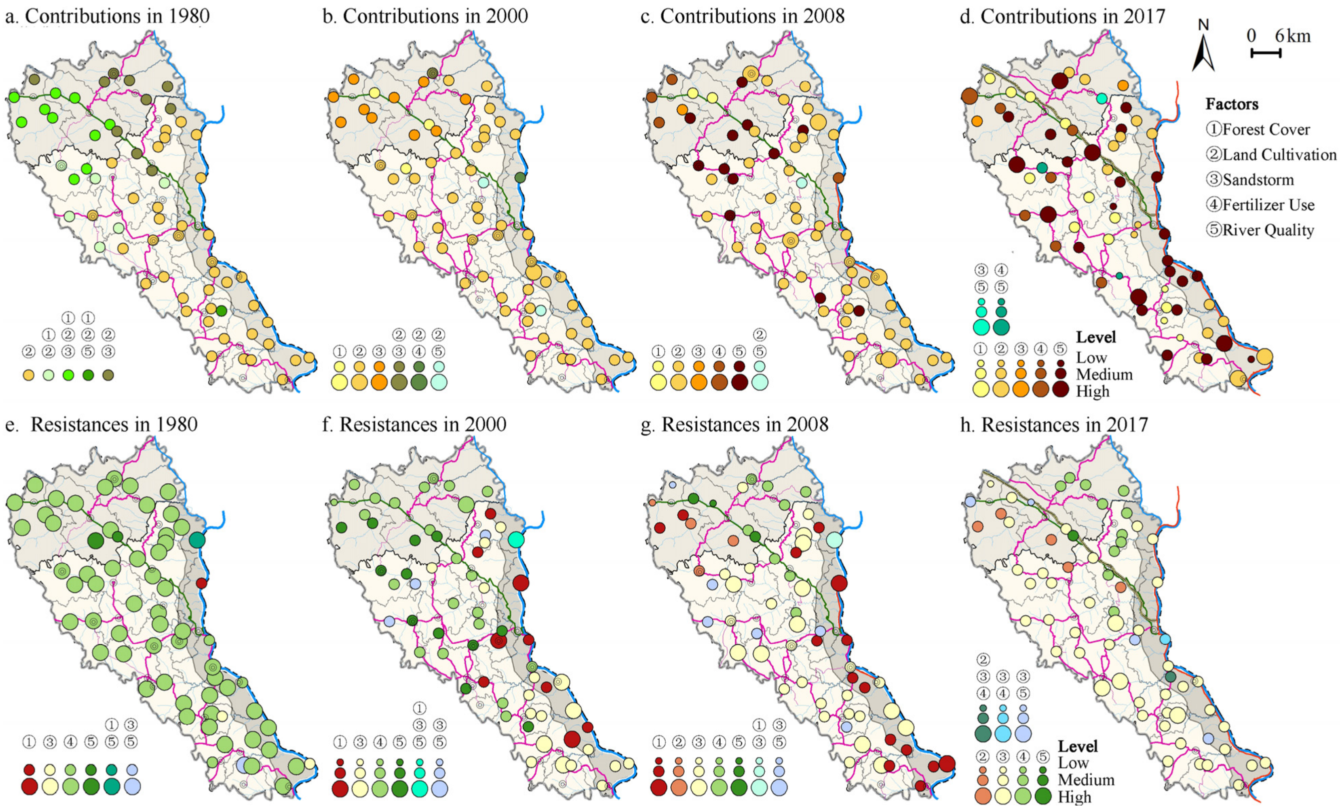

Figure 4. Spatio-temporal divergence of contribution and resistance factors to natural system vulnerability in 65 sample villages from 1980 to 2017. Note: '——' refers to the River, '——' refers to the Tourist Highway along the Yellow River, '══' refers to the Expressway, '——' refers to provincial highways, '——' refers to county roads.

(2) Factors in the human system

As shown in Figure 5a–d, the study area was almost entirely dominated by Labor Literacy as the contributor factor to human system vulnerability in 1980 and 2000. Since 2008, the distribution of the Permanent Population and Household Size factors gradually expanded, with Permanent Population becoming the most widely distributed contributor by 2017. At the same time, Festival Crowd began to appear among the contribution factors, while Labor Literacy disappeared.

As shown in Figure 5e–h, since 1980, Permanent Population and Festival Crowd gradually disappeared among the resistance factors, while Dependency Ratio and Labor Literacy have gradually covered the whole region. In the 1980s, the vast majority of villages showed Permanent Population as the resistance factor with a high level of resistance. By the 2000s, most of the villages shifted to Dependency Ratio as the resistance factor. At the same time, the distribution of Festival Crowd had widened. In 2008 and 2017, Dependency Ratio became almost the dominant resistance factor in the study area. The distribution of Labor Literacy also increased, which used to be the vulnerability contributor that dominated the whole region from 1980 to 2008.

According to the interviews, a large population, an abundant young labor force, and a large household scale were the typical characteristics of rural populations in the 1980s and

1990s. One respondent pointed out that: 'the village was crowded and lively, and people would come to help anyone who needed help or during the busy farming season.' Since 2000, there has been a gradual exodus of young rural laborers to the cities, and '*80% of the people in the village are working outside*'.

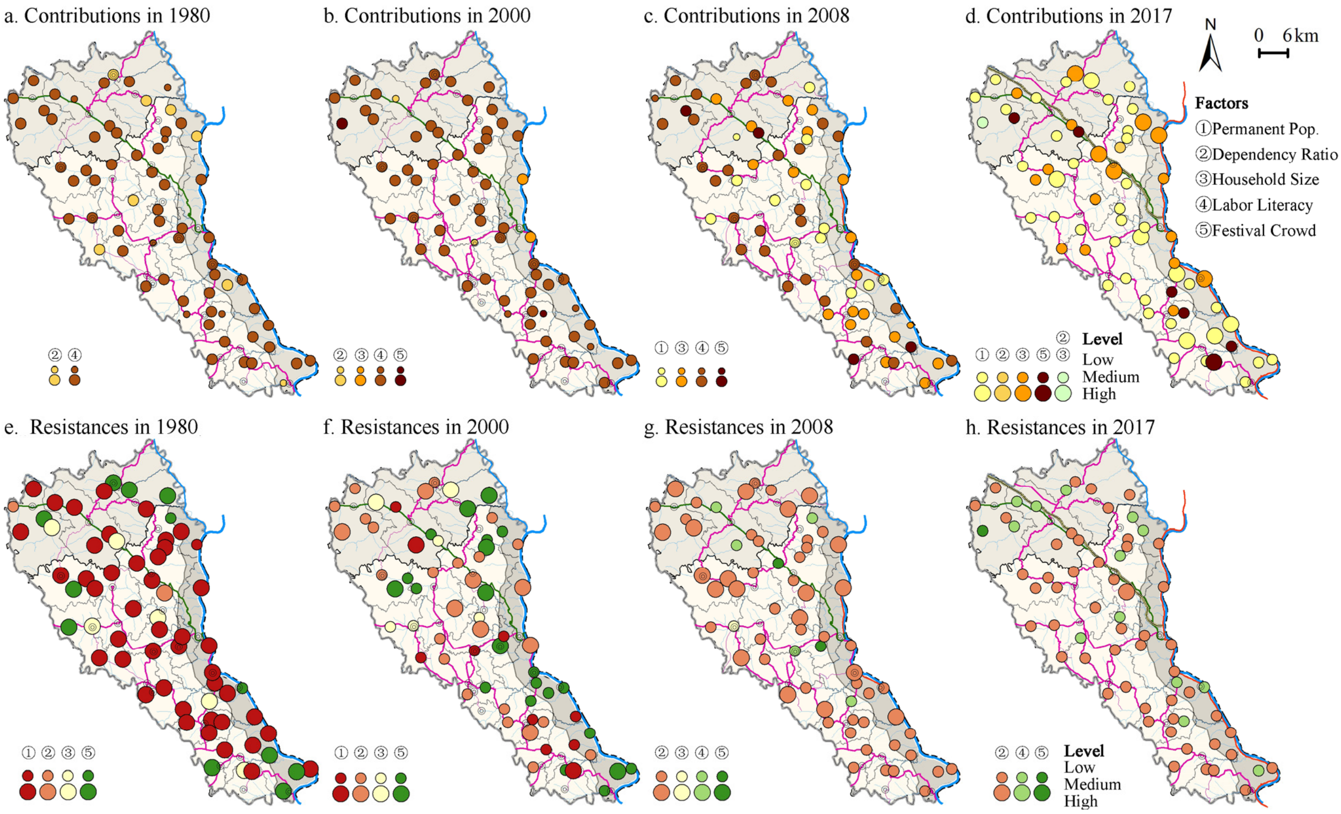

Figure 5. Spatio-temporal divergence of contribution and resistance factors to human system vulnerability in 65 sample villages from 1980 to 2017. Note: '—' refers to the River, '—'refers to the Tourist Highway along the Yellow River, '═' refers to the Expressway, '—' refers to provincial highways, '—' refers to county roads.

(3) Factors in the dwelling system

There was a shift in the contribution factor to dwelling system vulnerability from the dominance of Communication to the staggered distribution of House Structure and Household Size. In 1980 and 2000, the Communication factor almost occupied the whole region, and the distribution of Household Size and Durable Goods gradually widened, whereas in 2008, significant shifts and spatial differences in contribution factors were observed, with House Structure, Household Size and Durable Goods becoming the main distribution factors. By 2017, the Durable Goods factor narrowed in distribution, while the House Structure factor widened (Figure 6a–d).

Domestic water was the vulnerability resistance factor that dominated the whole region during 1980–2017, and the resistance level gradually increased. Of course, by 2017, there was a significant increase in the distribution of Communication as the resistance factor, which was the vulnerability contributor that dominated the whole region in 1980 and 2000 (Figure 6e–h).

According to the interviews, in the 1980s and 1990s, the dwelling environment was mainly characterized by poor housing conditions, mostly kilns with adobe structures and no home appliances. The migration relocation project began in 1999, and the housing system was characterized by newer housing, more household appliances and more convenient access to water, but the housing structure in non-migrant relocation villages was still relatively fragile. One resident mentioned that '*after the resettlement, the households were modernized with running water, drainage pipes, and solar energy*'.

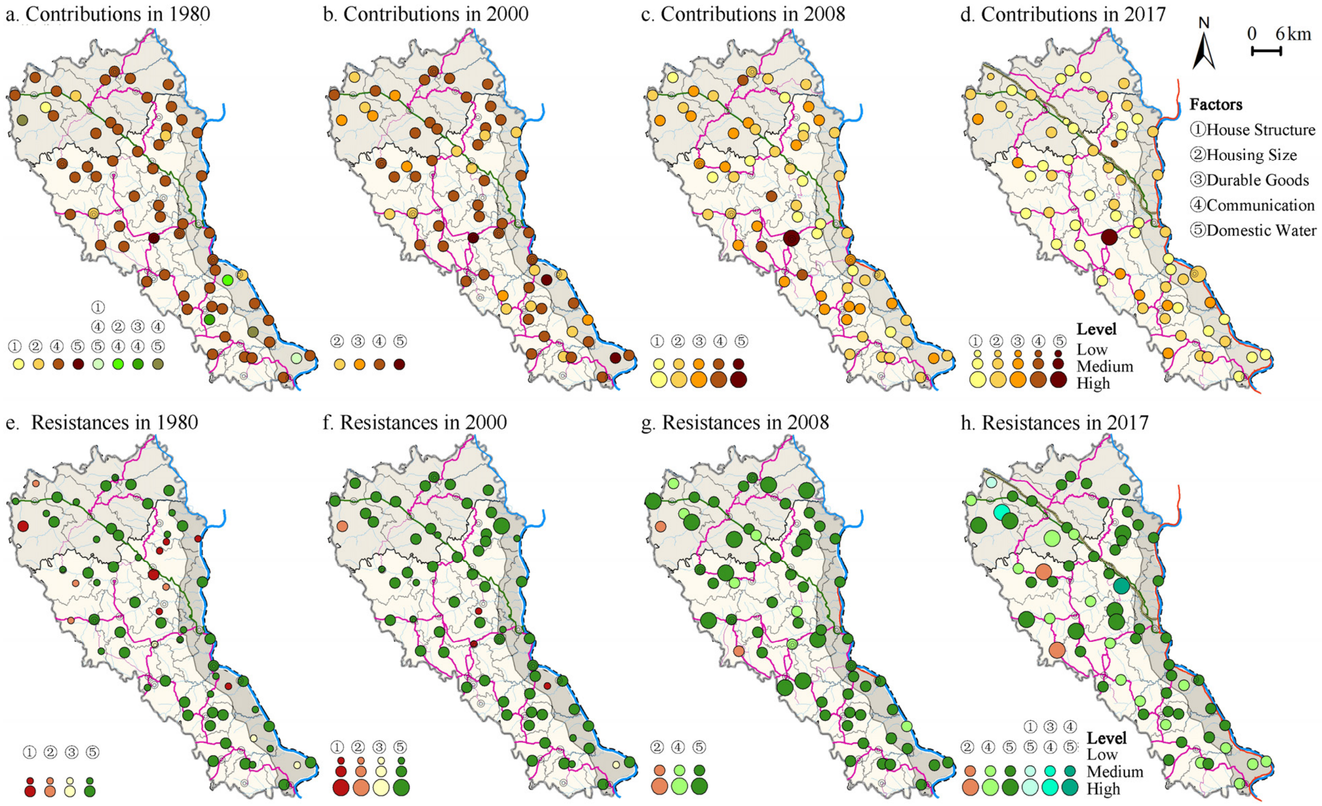

Figure 6. Spatio-temporal divergence of contribution and resistance factors to dwelling system vulnerability in 65 sample villages from 1980 to 2017. Note: '——' refers to the River, '——' refers to the Tourist Highway along the Yellow River, '——' refers to the Expressway, '——' refers to provincial highways, '——' refers to county roads.

(4) Factors in the support system

The vulnerability contributors in the support system exhibited multi-factor coexistence characteristics in the sample villages due to the synchronous development of infrastructure in the Loess Plateau's rural areas. From 1980 to 2008, Garbage Disposal was the contribution factor that occupied the whole region, and there were widespread co-contributors, such as Retail Store and Village Doctor, in agricultural villages outside the township centers. By 2017, the number of co-contributors to the support system vulnerability decreased in each sample village, but regional differences and diversity characteristics were still significant (Figure 7a–d).

As for resistance factors, the distribution of School Distance covered the whole region between 1980 and 2000, while it narrowed to the township centers by 2017. The distribution of Road Condition has gradually broadened since 2008 and became a widely distributed factor by 2017. In addition, Garbage Disposal began to become the resistance factor to vulnerability in some villages along the road (Figure 7e–h).

According to the interviews, in the 1980s and 1990s, residents were deeply impressed by the difficulty of traveling, accessing medical care and purchasing supplies. Residents noted: '*almost all the roads in the countryside are dirt, and you go out on foot or by ox cart*' '*It is not convenient to go to towns, and there are only barefoot doctors in the village*' '*it is inconvenient to buy things, so we grow all our own food*'. Since 2005, school consolidation, closure of grocery stores and closure of individual health clinics have become the imaginary scenes in the village support system. Yet, traffic conditions improved significantly as roads were extended to villages and hardened.

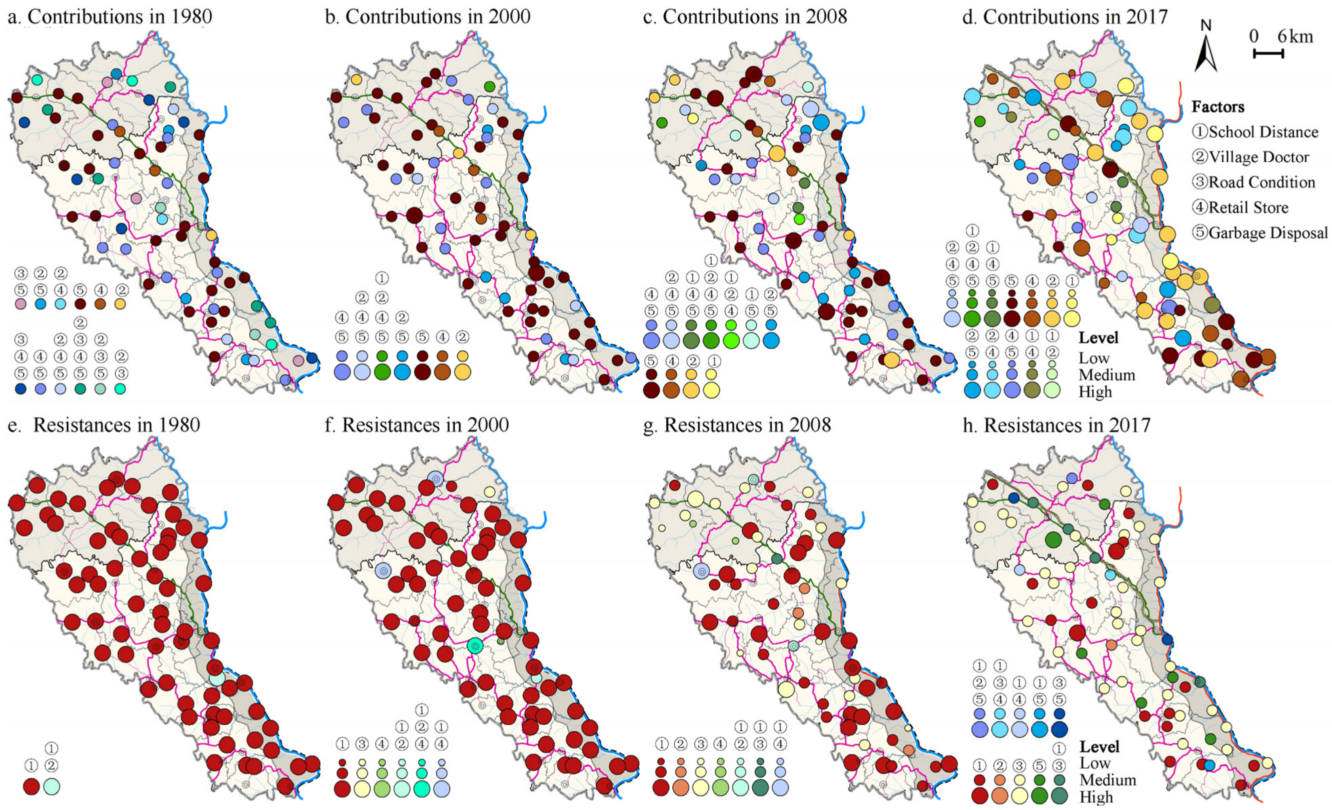

Figure 7. Spatio-temporal divergence of contribution and resistance factors to support system vulnerability in 65 sample villages from 1980 to 2017. Note: '——' refers to the River, '——'refers to the Tourist Highway along the Yellow River, '══' refers to the Expressway, '——' refers to provincial highways, '——' refers to county roads.

(5) Factors in the social system

The vulnerability contribution factor in the social system experienced a gradual shift from Household Income to Wealth Disparity. Of course, Village Management was also more widely distributed in 2000 and 2008, and Livelihood Diversity started to become the vulnerability contributor in a large number of sample villages by 2017 (Figure 8a–d).

Vulnerability resistance factors showed an increased spatial divergence, with a shift from full coverage of Wealth Disparity to a dominant distribution of Village Security and Household Income. However, Household Income had been a widely distributed vulnerability contributor from 1980 to 2008. On the other hand, Livelihood Diversity as the resistance factor increased in distribution from 2000 to 2008, but became the contribution factor for a portion of the villages in 2017 (Figure 8e–h).

According to the interviews, overall poverty and low income were prominent features during the 1980s and 1990s, with residents pointing out that: '*grains and cereals were all planted, just enough to eat, we had almost no income, and occasionally did odd jobs at the village*' '*none of the households in the village had income, so there was no gap between rich and poor*'. In the recent decade, some households lost their livelihood channels of jujube fruits, and the gap between rich and poor increased, but residents generally reported that household income had improved significantly.

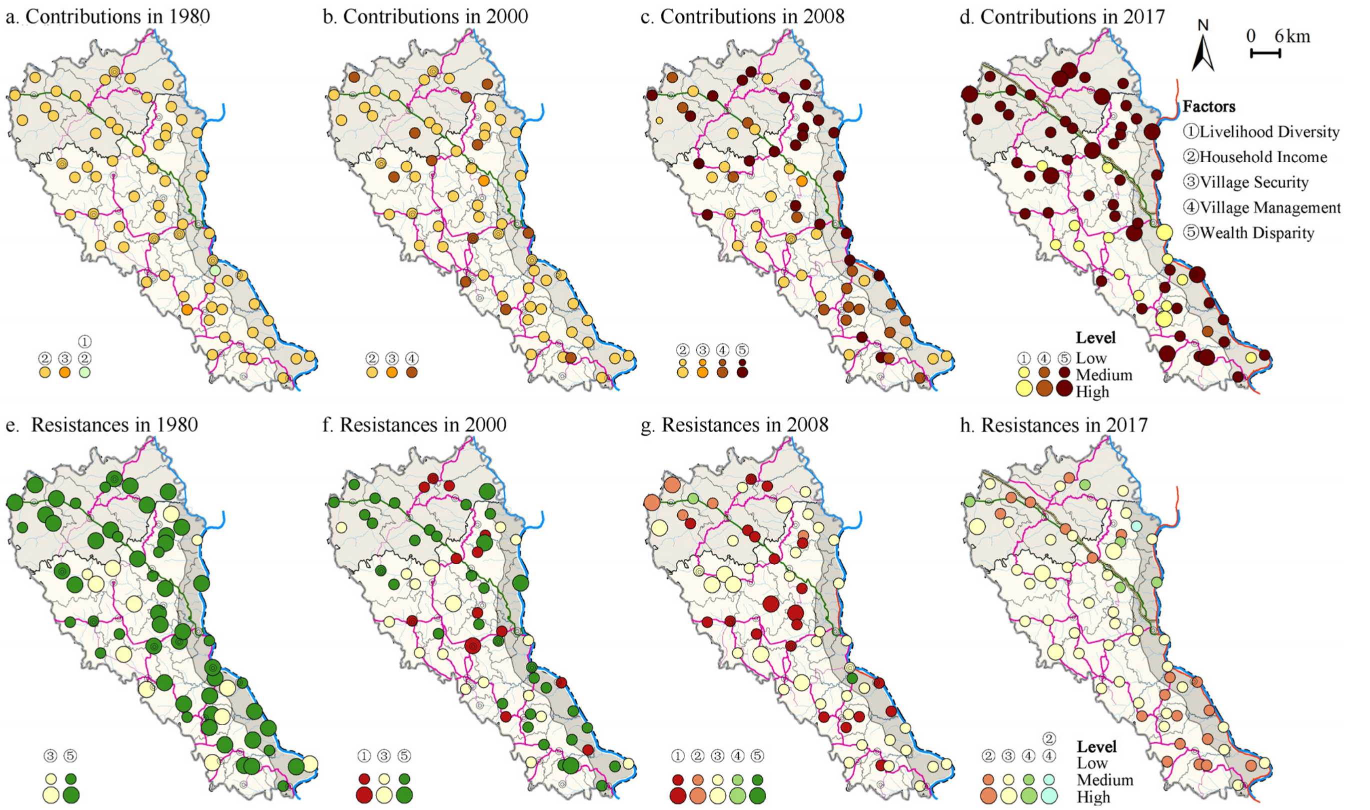

Figure 8. Spatio-temporal divergence of contribution and resistance factors to social system vulnerability in 65 sample villages from 1980 to 2017. Note: '—' refers to the River, '—'refers to the Tourist Highway along the Yellow River, '—' refers to the Expressway, '—' refers to provincial highways, '—' refers to county roads.

3.3. Transition in Functional Compositions of RHSS Vulnerability

3.3.1. Changes in Subsystems

Table 4 shows the distribution of the resistance and contribution among subsystems to RHSS vulnerability in the 65 sample villages during 1980–2017. The contribution subsystem with the widest distribution changed from the dwelling system to the support system, with the proportion of sample villages decreasing from 96.9% to 50.8%. The human system remained as the most widely distributed resistance subsystem until 2008, but the proportion of sample villages gradually decreased from 98.5% in 1980 to 44.6% in 2008. By 2017, the dwelling system became the most widely distributed resistance subsystem (49.2%), followed by the natural system (41.5%). That means that the contribution or resistance subsystems to RHSS vulnerability among 65 sample villages changed from a homogeneous system in 1980 to multi-category systems.

Table 4. The distribution changes of contribution and resistance factors/subsystems to RHSS vulnerability in 65 sample villages during 1980–2017.

Factors (Subsystems in Bold)	**Contributions in Villages**				**Resistances in Villages**			
	Percentage (%)				**Percentage (%)**			
	1980	**2000**	**2008**	**2017**	**1980**	**2000**	**2008**	**2017**
Forest Cover	24.6	4.6	3.1	20	3.1	15.4	24.6	0
Land Cultivation	**100**	**80**	**70.8**	23.1	0	0	6.2	9.2
Sandstorm	30.8	16.9	1.5	4.6	4.6	**33.8**	**53.8**	**73.8**
Fertilizer Use	0	1.5	6.2	13.8	**89.2**	**33.8**	12.3	20
River Quality	1.5	3.1	20	**43.1**	6.2	24.6	13.8	7.7
Natural system	0	7.7	18.5	13.8	1.5	7.7	21.5	41.5

Table 4. *Cont.*

Factors (Subsystems in Bold)	Contributions in Villages				Resistances in Villages			
	Percentage (%)				Percentage (%)			
	1980	2000	2008	2017	1980	2000	2008	2017
Permanent Population	0	0	20	**61.5**	**69.2**	15.4	0	0
Dependency Ratio	12.3	3.1	0	3.1	3.1	**41.5**	**87.7**	**78.5**
Household Size	0	3.1	29.2	27.7	9.2	9.2	1.5	0
Labor Literacy	**87.7**	**90.8**	**44.6**	0	0	0	7.7	20
Festival Crowd	0	3.1	6.2	9.2	18.5	33.8	3.1	1.5
Human system	0	0	1.5	27.7	**98.5**	**84.6**	**44.6**	0
House Structure	3.1	0	16.9	**46.2**	10.8	4.6	0	1.5
Housing Size	7.7	21.5	**43.1**	40.0	6.2	1.5	3.1	3.1
Durable Goods	1.5	9.2	32.3	10.8	4.6	1.5	0	1.5
Communication	**90.8**	**64.6**	6.2	1.5	0	0	10.8	27.7
Domestic Water	6.2	4.6	1.5	1.5	**78.5**	**92.3**	**86.2**	**70.8**
Dwelling system	**96.9**	**76.9**	15.4	3.1	0	0	3.1	**49.2**
School Distance	0	1.5	10.8	10.8	**100**	**96.9**	**61.5**	38.5
Village Doctor	29.2	18.5	30.8	30.8	1.5	3.1	7.7	3.1
Road Condition	29.2	0	0	0	0	1.5	32.3	**58.5**
Retail Store	43.1	30.8	32.3	32.3	0	6.2	4.6	3.1
Garbage Disposal	**89.2**	**90.8**	**84.6**	**84.6**	0	0	0	15.4
Support system	3.1	12.3	**60.0**	**50.8**	0	3.1	6.2	7.7
Livelihood Diversity	1.5	0	0	21.5	0	20	32.3	0
Household Income	**98.5**	**80.0**	35.4	0	0	0	7.7	30.8
Village Security	1.5	1.5	1.5	0	18.5	26.2	**56.9**	**61.5**
Village Management	0	18.5	24.6	1.5	0	0	1.5	9.2
Wealth Disparity	0	0	**38.5**	**76.9**	**81.5**	**53.8**	1.5	0
Social system	0	1.5	4.6	4.6	0	4.6	24.6	1.5

3.3.2. Changes in Key Factors

(1) River Quality, Permanent Population, House Structure, Garbage Disposal and Wealth Disparity became the key contributors.

Table 4 shows the distribution of the vulnerability contribution factors in each subsystem among the 65 sample villages. In the natural and human systems, Land Cultivation and Labor Literacy remained as the most widely distributed contribution factors until 2008, respectively. In 2017, the distribution proportion of River Quality (43.1%) and Permanent Population (61.5%) reached the highest, respectively, followed by Land Cultivation (23.1%) and Household Size (27.7%).

Communication was the contribution factor with the highest distribution proportion in the dwelling system in 1980 and 2000, after which Housing Size (43.1%) and House Structure (46.2%) became the factors with the highest proportions in 2008 and 2017, respectively. That is, at present, housing structural vulnerability and overcrowding are the key vulnerability components of the dwelling system.

Garbage Disposal remained as the contributor with the largest share in the support system. In addition, the distributions of Village Doctor and Retail Store were both high, exceeding 30% by 2017. As for the social system, Household Income was the highest-weighted contributor until 2008, after which it changed to Wealth Disparity, and the proportion reached 76.9% in 2017. In addition, the proportion of Livelihood Diversity increased from 0 to 21.5% from 2008 to 2017. It indicates that the type of rural livelihood activities in the study area decreased significantly during this period.

(2) Sandstorms, Dependency Ratio, Domestic Water, Road Condition and Village Security became the key resisters.

Since 2000, Fertilizer Use replaced Sandstorm, and Dependency Ratio replaced Permanent Population as the key resistance factors in the natural and human systems, respectively, with the proportion of both factors increasing continuously to more than 70%. Domestic Water was sustained as the most widely distributed resistance factor in the dwelling system, with shares remaining above 70%. The most widely distributed resistance factor in the support system changed from School Distance to Road Condition during 2008–2017, and that in the social system switched from Wealth Disparity to Village Security during 2000–2008.

3.4. Impact Events on the Evolution of RHSS Vulnerability

Based on the local chronicles [68,71] and oral historical interviews with different stakeholders, such as farmers, village chiefs and local governments, we further analyzed the key impact events that led to the changes in vulnerability characteristics, and formed a vulnerability evolution path diagram for the RHSS by combining the vulnerability characteristics at four historical periods (Figure 9). This diagram can be considered as a scenario overview showing the evolution of RHSS vulnerability for the traditional farming areas on the Chinese Loess Plateau since 1980.

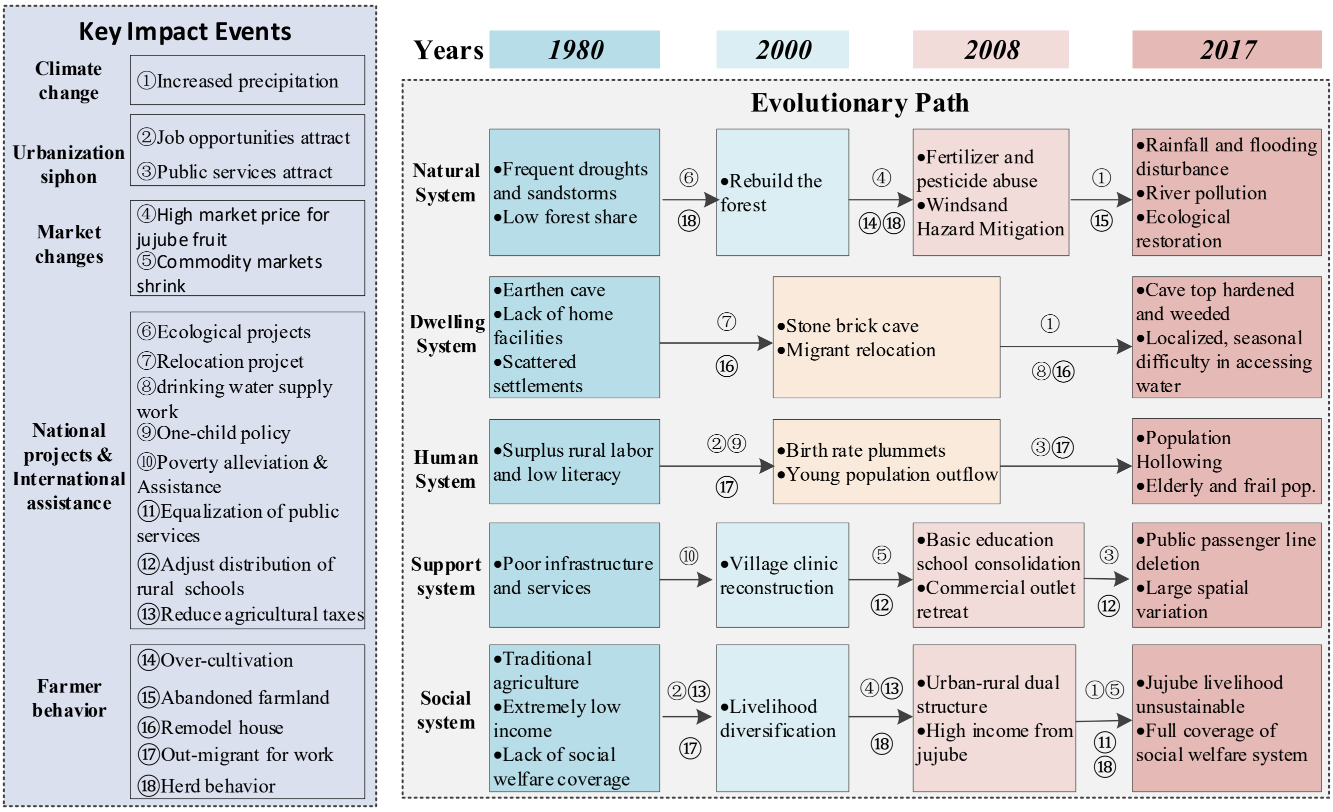

Figure 9. Evolutionary paths of RHSS vulnerability in traditional farming areas of the Loess Plateau, China, 1980–2017.

3.4.1. Ecological Projects and Off-Farm Employment Drive Natural Systems toward Ecological Restoration

In 1980, prominent drought, frequent sandstorms and an extremely low proportion of forests were the typical vulnerability characteristics of natural systems in traditional agricultural areas on the Loess Plateau. Since the 1980s, with the implementation of national projects for ecological protection and repair such as afforestation, wind and sand control and small watershed management, and World Bank loan projects for soil and water conservation, the forests have begun to be rebuilt and soil and water conservation has achieved important results [79]. On the other hand, the positive response of farmers to national policies and local government calls, such as spontaneous return of farmland to forests and extensive planting of jujube trees, has accelerated the restoration of the local ecological environment.

Farmers pointed out, "*Originally, our mountains were bare and treeless, that is, in the 1980s, but since the GfG Project, the mountains have become green*". "*Since 2000, every household has planted jujube trees, and the government has paid for one jujube sapling, two or three yuan*".

The large amount of land abandoned or abandoned fertilization has contributed to the natural recovery for the ecological system in the Loess Plateau agricultural area. Since 2010, in the study area, under the background of global climate change, autumn precipitation has increased significantly, and heavy rainfall disasters have become the main disasters of natural systems, while drought and wind-sand disasters have almost disappeared [66]. At present, the production environment is less disturbed by drought and sandstorms, as perceived by farmers.

Several farmers indicated that afforestation and greening was one of the important reasons for local climate change and increased precipitation, "*The temperature has gotten warmer, the farmland on the mountains has been abandoned and full of weeds and shrubs. Now there are more and more trees, which may also lead to more rainfall*".

At the same time, increased precipitation during the maturity of jujube fruit led to mold and yield reduction, which together with the shrinking of the acquisition market led to the fact that the representative jujube livelihood has become unsustainable [66]. Under the multiple perturbations of climate change and the shrinking market size, as well as high returns from off-farm employment, farmers travel to abandon farming and fertilizer behaviors, and young laborers shift to off-farm industries [80].

An old farmer reluctantly pointed out that "*the young people have gone out to work, and the old people are unable to farm because of old and sick, so the land is basically abandoned*".

3.4.2. Rainstorms and Dropped Groundwater Levels as New Disturbances to Dwelling System

The annual precipitation and the precipitation in the mature period of jujube fruit in Jia County have shown an obvious upward trend since 1980 [66]. Since 2010, the study area has experienced a high incidence of summer rainstorms, autumn rains and other disaster events. Frequent floods have caused the destruction of water pipes and roads in residential areas, and the impact of high-intensity rainstorms has caused substantial damage to the cave dwelling structure, with frequent leakage from the cave roof. To cope with the water leakage problem, local residents, with government subsidies or on their own initiative, hardened the cave roof to a concrete or steel roof, which had long been covered with meadow vegetation.

In Moutouyu Village, an ancient village of caves, the village director pointed out that "*the village vegetation has been seriously damaged, the climate has changed, rainfall has increased, the roofs of every house used to grow grass, standing on the hillside to see a green piece, but now due to the increase in rainfall, every house is forced to do hardening, all become bare*".

The trade-off between carbon sequestration and water production poses a major challenge to the ecological benefits of the fallowing project, and over-planting has become a major cause of soil drying in the Loess Plateau [81]. Between 2000 and 2010, the reduction in soil water (2.4 ± 0.9 mm a^{-1}, $p = 0.08$) and runoff (0.5 ± 0.3 mm a^{-1}, $p = 0.06$) in the Loess Plateau area due to the return of farmland to forestry was equivalent to a $67\% \pm 53\%$ increase in evapotranspiration [62]. The dropped groundwater level further caused the drying up of wells and the cutting off of rivers in the northern wind and sand area.

A resident mentioned that "*the wells have no water, the river dried up long ago . . . summer also no water, the willows on the river bank for 100 years have withered*".

3.4.3. Urbanization Siphoning and Non-Farm Transformation Drive Rural Hollowing Out

Since 1980, under the effect of urbanization and industrialization, the employment opportunities in urban areas have increased, and the surplus labor force in rural areas has moved to cities [68]. Nowadays, the rural population continues to migrate to the cities and the transformation to non-farm livelihoods has become a dominant trend [80]. In this context, the aging population is left behind, with the loss of doctor and teacher resources becoming huge vulnerable features of the human system, and further lead to undesirable changes in the support system.

Interviewed households commonly describe the current situation in negative terms, such as "*the young people have all left, the children were taken away by their parents, and there are only old people around 70 and 80 years old*" and "*people have gone to the cities, there is nothing left in the countryside*".

3.4.4. Vast Impact in Village Access and Facility Layout Adjustment

In October 1998, the State Council issued a document approving the request of the State Planning Commission for the construction and renovation of rural power grids, after which the national system project of Village Access, covering infrastructure such as highways, electricity, drinking water, telephone networks and cable TV networks, was vigorously promoted. By 2003, the study area was connected to roads in villages, and in 2004, Mobile and Unicom networks covered every township and village in the county [68].

In 1996, with the support of the World Bank loan "Disease Prevention Project—Immunization Subproject", the study area began to re-build village health offices [68]. Since 2002, the government has gradually increased investment in rural medical and health facilities, and the medical and health conditions have gradually improved. At present, each administrative village has set up a standardized village clinic.

On the other hand, due to population loss and the decrease in the amount of school-age children, the Jia County Primary and Secondary School Layout Adjustment Program was developed and implemented in 2005, and a total of 271 rural elementary school and 13 9-year consistent schools were abolished in that year. The vicious cycle was formed by the removal of schools and the shrinking student population. Additionally, a wave of closures of retail outlets, etc., attached to schools was also formed during the period of school removal and consolidation. With population loss and aging leading to a dramatic drop in rural consumer demand, the grocery stores have closed, private clinics have shut down, passenger routes have shrunk, and rural commercial services have also tended to withdraw.

Several residents pointed out that "*The town does not even have a middle school, and now it is very inconvenient to get to school*" "*People who live in the village are very far from the bus route, you have to walk to town and then take the bus*" "*There are no more retail stores in the village, you can only go to the town to buy. There are also mobile vendors who drive to the countryside to sell goods, sold and left, but nothing you can do if you are cheated*".

3.4.5. Increased Precipitation and Market Changes Lead to Unsustainable Livelihoods in Forested Villages

The rural areas in the Loess Plateau have experienced a transformation from traditional agricultural livelihoods to new agricultural livelihoods and, currently, to non-farm livelihoods [66]. In Jia County, social welfare, government administration, mechanization and the development of a non-farm economy are becoming robust, whereas the vulnerability characteristics in the social system are gradually concentrated in specific household structures, farm household types and geographic spaces. The livelihoods with jujube fruits in the forestry villages have become unsustainable under the dual disturbance of climate change and market changes. The higher the precipitation in the mature stage, the higher the rotten rate of jujube pulp, whereas the annual precipitation in the mature period remained above 100 mm from 2007 to 2017. Additionally, since 2010, the jujube market changed dramatically. The market price of jujube fruit, generally, has been approximately 0.4 CNY/kg in 2017, compared with 2 CNY/kg in 2008.

Farmers who have planted jujube sadly mentioned, "*Every year, when the annual harvesting period of jujube fruit comes, it suffers from continuous precipitation. The more rain and the longer it lasts, the more serious the jujube mildew will be. Furthermore, even the part of the jujube fruit that is not moldy also cannot be sold for much money. Now, the land is full of jujube trees, but the income is not acceptable*".

Villages in the loess hills and northern windsand landscape in the study area are transforming to modern agriculture with the benefit of high-standard farmland and mountain apple projects, while the Earth-Rock Mountainous Region along the Yellow River, lacking farmland, has developed into featured jujube forest areas. In such areas, for families with sufficient labor, non-farm income to a certain extent resisted the cliff of the jujube fruit livelihood income.

4. Discussions

4.1. Discoveries, Limitations and Prospects in RHSS Evolution Research

The vulnerability of the RHSS in the traditional agricultural area on the Loess Plateau, represented by Jia County, showed a mitigating trend stage by stage in the results. The degrees of vulnerability of the natural, dwelling and social systems have all continued to decrease, while on the other hand, the vulnerability of the human system has increased significantly and the spatial variation of vulnerability on the support system has proliferated. The vulnerability in natural subsystems showed a significant trend of reduction, characterized by an increase in vegetation cover, a decrease in wind and sand hazards and an increase in abandoned land. This finding is consistent with the vast majority of studies on the Chinese Loess Plateau, such as that the Loess Plateau has gradually turned green and its ecological service capacity has been greatly improved [62–64,79]. In addition to the contribution of ecological projects, the widespread abandonment of farming by farmers is also an important reason for the natural restoration of the Loess Plateau's ecology [66,80]. The research findings point to a significant increase in the vulnerability of human systems, characterized by a decrease in resident population and a reduction in household size. In parallel, the vulnerability of village support systems along transportation routes was significantly reduced, and remote villages were highly vulnerable due to inadequate facilities. This also matches the development trajectory of traditional rural villages in China since the reform and opening up, that is, from traditional backwardness and closure to openness and convenience, while under the impact of urbanization, the traditional rural areas continue to lose population and tend to be hollowed out [82–85]. Moreover, it is shown in our findings that village security and household income are the resisters of social vulnerability, and wealth disparity and livelihood diversity become the contributors of vulnerability. The opinion on resisters is consistent with the findings on the effectiveness of poverty eradication in rural China, confirmed by existing studies [22,38], but the point on contributors differed somewhat from existing studies, such as the enrichment of livelihood channels [86]. It is worth stating that the decrease in livelihood diversity in the study area is due to the unsustainable livelihood of jujube under increased precipitation and cold markets, which is an important local manifestation of agricultural and livelihood vulnerability under global environmental change [10,11], particularly in traditional agriculture or remote disadvantaged rural areas [9].

However, limited by the population loss and aging in the study area, although the research team conducted the sample survey as meticulously as possible and standardized the retrospective questionnaire method to ensure the quality of the questionnaire, there are still shortcomings, such as insufficient sample households, and the retrospective questionnaire may deviate from the authenticity. Of course, except for long-term follow-up research, retrospective questionnaires and oral history interviews have become the main methods for studying rural evolution at the microscopic scale. On the other hand, the research team also further explored the consistency of the quantitative vulnerability assessment results with the local reality over 40 years using ground-truthing methods [75] and local chronicles [68,71]. As can be seen from Section 4.1, the quantitative results of the evolution of the vulnerability in natural, human, social, dwelling and support systems are consistent with the local reality.

As shown by the identification of key events in the evolution of RHSS vulnerability, the outcomes of vulnerability changes in the five subsystems were inextricably linked to the large-scale and long-term ecological and welfare projects implemented in the Loess Plateau by the Chinese government, as well as urbanization siphoning and other disturbances. This result also further matches with the research on the effectiveness of agricultural practices and the reforestation projects in the Loess Plateau region. For example, under the influence of agricultural practices such as building terraced fields, returning farmland to forest land and grassland, all have had positive and significant impacts on farmers' livelihood assets, strategies, outcomes and vulnerabilities [79,86–88], and the ecological indicators have improved dramatically [62]. However, although the research group carefully explored the identification of key events by using ethnographic approaches with historical oral interviews, there are still shortcomings and work to be continued. In future research, the research team will further explore the response of farmers' behavior to key events, and will focus on measuring the degree of impact based on key quantitative indicators such as behavioral indicators and livelihood capital indicators. In addition, the research team will also pay more attention to the issue of heterogeneity in multi-stakeholders' adaptation, especially the vulnerability and adaptation of elderly and weak groups, and poor households.

4.2. Change in Natural, Human, Dwelling, Social and Support Systems with Ground-Truthing

(1) Differentiated improvement in natural systems, reduced vulnerability in dwelling and social systems under the national ecological and welfare project

Since the 1970s, China has implemented a series of ecological construction projects and governance measures in the Loess plateau region, such as the 3-North Shelter Forest Program, the Green for Grain Project, the Natural Forest Protection Project and the Soil Erosion Control Project. The Loess Plateau turned green, showing the evolutionary characteristics of increasing vegetation cover and improving ecosystem service capacity [89]. Wu et al. points out that Loess Plateau has achieved "win-win" gains of restoring the environment and promoting socioeconomic development: a 56.7% increase in grain output along with increased vegetation cover, soil conservation and solid services [79]. In contrast to the significant ecological improvements in macro-regional or single factors, however, studies based on the micro-case and habitat perspectives showed a dramatic increase in spatial variation in the vulnerability of the natural system [62,90]. For these reasons, habitat-based studies are more concerned with soil and river pollution caused by fertilizer abuse, littering and livestock farming in villages [91]. These environmental problems are also habitat issues that need to be urgently addressed in agricultural and rural development. As for the enlarged spatial differences in study area, these can be attributed to the differences in the three types of landform areas, among which the Northern Windsand Region has a gentle topography, more arable land resources and higher cultivation intensity, and suffers from wind and sand attacks from the Mu Us Desert. In contrast, in the Southeast Soil-Rock Mountain Region along the Yellow River, almost all of the areas are forestry villages with jujube, which are characterized by thin soil layers that are unsuitable for cultivation, and are less affected by wind and sand. More importantly, the habitat activities in the area are controlled by the current policy of ecological protection and restoration of the Yellow River.

Since 1998, the Chinese government has proposed the Extending Radio and TV Broadcasting Coverage to Every Village Project, which was further expanded into a national system project that includes roads, electricity, domestic and drinking water, telephone networks, cable TV networks, the Internet, etc. Since 1996, Jia County, the study area, has been implementing the Manna project, Fluorine Prevention and Water Improvement project and Human Drinking Safety project, and by 2005, one-third of the administrative villages had universal access to piped water [68]. In addition, during the 12th Five-Year Plan period, the study area implemented the Cave Dwelling Renovation project, Poverty Alleviation and Relocation project and Universal Access to Piped Water project. Under diverse welfare projects, the residential facilities environment for rural households in the study area has improved significantly, and the dwelling system achieved the greatest reduction in vulnerability by 2017, followed by the social system.

(2) Increased vulnerability in the human system and highlighted problems in the support system due to rural depopulation and hollowing out.

Hollowing out under the siphoning effect of urbanization has become a major problem for China's rural development [84]. The main symptoms are the loss of rural population and the aging and weakening of the population, which further causes the loss of various resources in the countryside [82,83]. In other words, population loss and aging and weakening are both the human systemic manifestation of rural depression and the root cause of continued rural decline [85]. In the study area, the vulnerability of the RHSS has developed from low to high since 1980.

Most of the interviewees pointed out that "*the young people have run away from the villages, the children have been brought to the city with them. People have gone to the city, there is nothing left in the countryside*", "*In our village, 80% of the people are working outside, there are only elderly people over 70 years still staying in the village*".

Interviewees repeatedly mentioned the difficulty of marrying a wife, "*the pressure of bride price expenses is very high, it is difficult to meet the requirements of the girl's family to buy a house and a car*".

Reduced population size has led to a further reduction in the rural student supply as well as the market demand for public transportation and merchandise retail, with school consolidation, deletion of public passenger transportation lines and withdrawal of stores becoming typical problems in current rural support systems. Remote villages and less-advantaged families are extremely vulnerable in terms of accessibility of children to school, public transportation and material procurement. As a result, different from the dwelling system, the support system vulnerability was not significantly reduced during the period from 1980 to 2017, and showed significant spatial heterogeneity.

Interviewees pointed out that "*I do not know which school my grandchildren will be attending, the school in village, no children study, has been merged*".

4.3. Changes in the Strengths and Weaknesses of the RHSS

Based on the identification of the contributions and resistances to RHSS vulnerability, the research team further sorted out the shifts in the strengths and weaknesses of the RHSS, which can provide direct guidance for the planning and construction work of regional habitats.

Figure 10 shows the changes in the strength and weakness characteristics of the RHSS over four historical periods from 1980 to 2017. The dwelling system became the strength system, while the support system became the weakness system. The strength system in the RHSS on the Loess Plateau traditional farming area changed from the human system in 1980-2008 to the dwelling system in 2017. On the other hand, the weakness system shifted from the dwelling system in 1980 and 2000 to the support system in 2008 and 2017.

As for the specific characteristics, within the natural system, the strengths changed from less fertilizer use to sandstorm disaster reduction, and the weaknesses changed from high intensity of land cultivation to poor river quality. Within the human system, the abundance of the permanent population in villages was a superior feature in 1980, while the depression has become a significant disadvantage by 2017. In addition, low dependency ratios have become an advantage in the current period and the educational levels of the labor force are no longer a disadvantage. Within the dwelling system, the availability of water for domestic use has always been a strength, while the weaknesses have changed from poor communication conditions to overcrowding and aging of the houses. Within the support system, the disadvantage has always been the lack of hazard-free garbage disposal, while the advantage has changed from the proximity of elementary schools to the improvement of road conditions. Within the social system, the wealth disparity factor shifted from an advantage in 1980 and 2000 to a disadvantage in 2008 and 2017, while low household income disappeared as a disadvantageous feature. Currently, the excellent security environment in the rural areas has become a significant advantage.

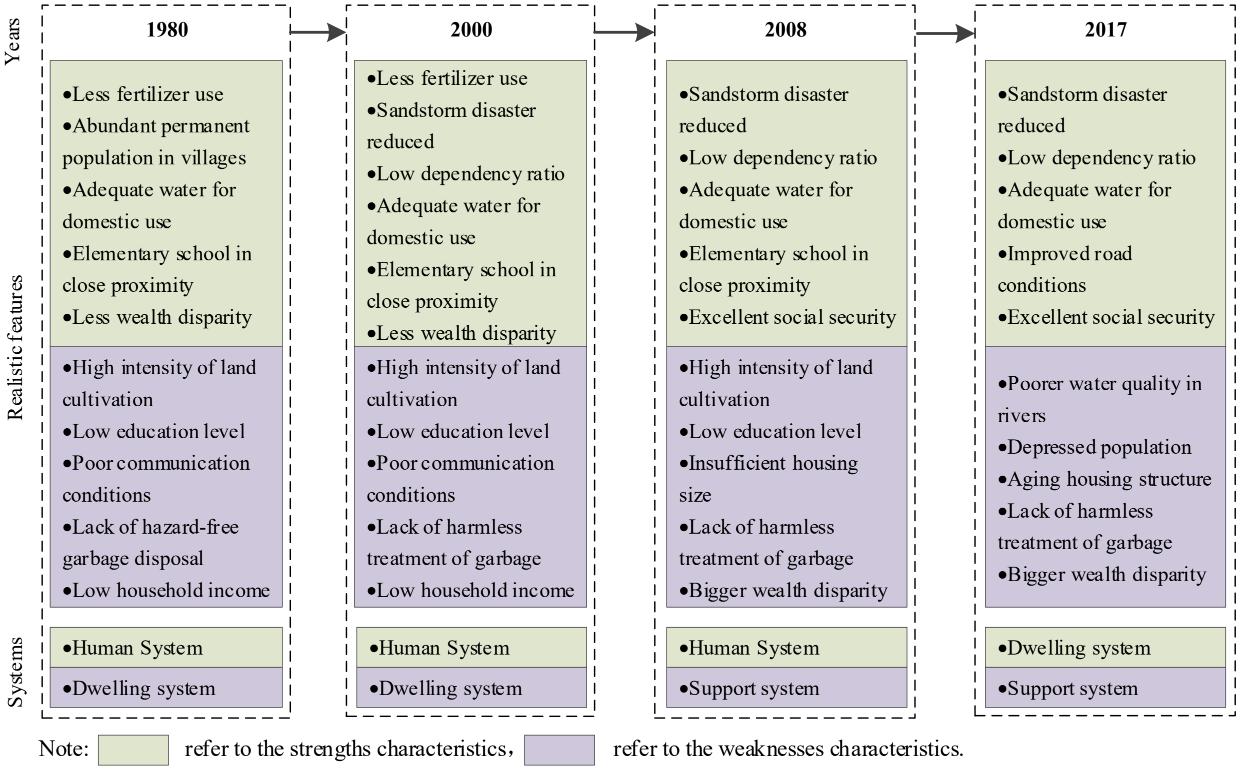

Figure 10. Changes in strengths and weaknesses of rural human settlements system in the Loess Plateau since 1980.

5. Conclusions

This study explored the evolution of RHSS vulnerability in traditional farming areas on the Chinese Loess Plateau since 1980 based on microscopic surveys and in-depth interview work. The conclusions are as follows: (1) The vulnerability of natural, dwelling and social systems has continued to decrease, while human system vulnerability increased and the spatial differentiation of vulnerability in the support system has intensified. (2) The most widely distributed subsystem contributing to vulnerability has shifted from the dwelling system to the support system, while the resistance subsystem has shifted from the human system to the dwelling system. (3) The weaknesses of the RHSS in the historical period were low vegetation cover, low education level, poor communication, lack of hazard-free garbage disposal and low income, while the strengths were aspects such as less fertilizer use, sufficient rural population, good accessibility to elementary schools and less gap between the rich and poor. At present, RHSS is characterized by the poor quality of the river, a depressed rural population and a large gap between the rich and poor as weaknesses, and sandstorm disaster reduction, more robust rural roads, adequate water for domestic use and high social security as strengths.

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Appendix A

The survey included seven parts:

(1) Basic household information, population structure and livelihood sources;
(2) Changes in the natural system, including land use, natural disasters, ecological conditions, etc.;
(3) Changes in the housing system, such as housing renewal, housing structure and facilities;
(4) Changes in the support system, including village infrastructure, public services, etc.;
(5) Changes in the human system, including individual behavior, psychological perception, etc.;
(6) Changes in the social system, including social interaction, village social environment perceptions, government service evaluations, etc.;
(7) Coping strategies, such as adaptation to the effects of climate change, strategic choices in the context of village depression and perceptions of natural disasters and coping strategies.

Table A1. The basic information of the householder for the 451 surveyed households in 2017.

Basic Indicators	Category	Number	Basic Indicators	Category	Number
gender	male	419	employment	pure farming	197
	female	32		mainly farming, part-time jobs	40
age	25–44	31		mainly for work, part-time farming	34
	45–64	252		pure work	39
	65–74	126		do business	26
	75–82	42		student and soldier	0
household size	1–2	193		work in public institutions	13
	3–5	205		non-employment	102
	6–12	53	working experience	construction worker	108
health condition	healthy	299		manufacturing worker	4
	diseased	132		catering and accommodation attendant	5
	disabled	20		driver	4
labor capacity	complete	338		mining worker	8
	incomplete	87		skilled worker	13
	incapacity	26		home services and property management service	2
education years	<6	140		no working experience	307
	6–8	126			
	9–11	135			
	>11	50			

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