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Sustainable Management of a Mountain Community Vulnerable to Geohazards: A Case Study of Maolin District, Taiwan

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Abstract: This study investigates community-based landslide mitigation planning. The combination of a landslide susceptibility index (LSI) model, landslide inventory datasets, and field work is used to identify hazard-prone areas in Maolin District, Taiwan. Furthermore, to identify the challenges and opportunities affecting the sustainable development of mountain communities, a pilot survey was conducted in three such communities (Dona Village, Wanshan Village, and Maolin Village). The results reveal that there are two types of significant mass movement in such areas: debris avalanche and debris flow. The results also show that the LSI map and multi-temporal landslide inventory datasets correlate with landslide locations. Meander is identified as an important factor in landslide activity. The questionnaire results show that the residents of the study area lack awareness of and access to information related to landslide activity. Similarly, the local residents favor increased environmental protection, working within their community, and additional government spending in regard to managing geohazards. To increase the resilience of the community, an improved landslide susceptibility map is proposed based on the output of the results. Thus, this research improves upon the process of identifying, supporting, and bettering the management of communities prone to landslides.

Keywords: geohazards; remote sensing; landslide susceptibility index (LSI); questionnaire; GIS; rural development

1. Introduction

There are two categories of natural disasters that affect Taiwan: climatic-related disasters, such as typhoons and floods, and geological hazards, which include mass movements or slope failures and earthquakes. The historical records reveal that from 1958 to 2007, 270 natural disaster events occurred in Taiwan, including typhoons (71.1%), flooding (15%), earthquakes (8.5%), torrential rainfall (2.2%), windstorms (1.5%), mountain flooding (0.7%), and landslides (0.7%) [1]. In particular, 89% were related to heavy rainfall, and 97% were directly or indirectly related to landslides. Thus, typhoon-induced landslides pose the greatest threat to southern Taiwan [2].

Typhoons are common meteorological events during the summer and fall months in Taiwan. Taiwan is located at 23–25° N, which places the island in the pathway of western North Pacific tropical cyclones [3]. Approximately 30 tropical cyclones form annually, with an average of 4.5 events affecting Taiwan and an average of 1.8 making landfall [4]. Warm, moist air produced by typhoon formation causes continuous torrential rain on windward-sloping terrain [5,6]. As a result, heavy rainfall persists even after a typhoon leaves Taiwan [7]. Moreover, typhoons often engage in tremendous changes in motion and structure when approaching or moving across an island [8,9], making their paths difficult to forecast.

The direct impact of natural disasters on the indigenous people of Taiwan is very apparent, as the majority reside in the highlands and mountainous regions. The mountainous regions of southern Taiwan are the homelands of the Rukai, Bunan, and Paiwan tribes. These mountain groups are continuously exposed to increased risk as a result of residing in such hazard-prone environments. For example, Typhoon Morakot caused significant destruction in the indigenous communities in the highlands, severely damaging property and incurring heavy death tolls [10,11]. Moreover, post-disaster reconstruction initiatives and assistance typically do not address the actual needs of such communities [12].

The term "sustainable development" is a common phrase used in relation to the economic, social, and environmental development taking place in society. The Brundtland Commission [13] defines sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs", which is the most widely accepted definition. The vision of "sustainable mountain communities" in Taiwan has garnered the attention of local and national governments, as well as non-governmental organizations [14]. In practice, the term "sustainability" has become a catch phrase for government involvement in community development [15]. Moreover, the encroachment of development—aiming to improve the local economy—into the highland areas of southern Taiwan has, in turn, created negative environmental consequences. Such practices include land use alterations on steep sloping terrain for agricultural development and regulated tourism development, such as resort construction.

Devastating events such as Typhoon Morakot reveal the complexities of preparing for natural disasters in a sustainable way. Mountain communities must balance the need to minimize the harmful impact of natural disasters on their citizens while finding ways to utilize their natural wealth to improve the local economy; indeed, increased agricultural production and tourism can bring many economic benefits to such communities [16]. The International Union of Geodesy and Geophysics (IUGG)'s Commission on Geophysical Risk and Sustainability has identified the need for integration of knowledge concerning environmental, social, and economic processes [17]. Furthermore, the integration of such diverse data streams can improve the understanding of the natural phenomena associated with disasters, develop prediction model capabilities, and generate and analyze timely and accurate information needed by decision makers and the public. Therefore, more multidisciplinary research programs should be developed to facilitate this goal.

The combination of Taiwan's complex geology and unpredictable weather creates conditions for extreme natural disaster events to occur on a fairly regular basis. The island is often the victim of natural hazards, causing loss of life or immeasurable property damage. Small remote villages typically have poorly developed economies that rely on agriculture and tourism and have limited capacities for resilience in the wake of such extreme events. Natural disasters can severely disrupt the tourism industry, which is heavily dependent on daytrips made by out-of-community visitors. Similarly, agricultural activity can be significantly impaired or destroyed by flooding or landslides. With such limited economic diversification, mountain communities have low capacities to adapt to disturbances caused by natural hazards. Therefore, such communities remain unsustainably vulnerable to the impacts of future natural disasters. The loss of economic opportunities such as job creation and business development further exasperate social problems, including alcohol abuse, depression, anxiety, and domestic violence [18]. The combination of poor environmental, economic, and social conditions creates a vicious cycle that communities are unable to overcome.

The objectives of this study are as follows: (1) to use a landslide susceptibility index (LSI) map to identify landslide zones; (2); to evaluate the accuracy of the developed LSI map by overlapping Formosat-2 imagery of pre- and post- typhoon events, along with multi-temporal landslide inventory data; (3) to analyze the variations in highly susceptible landslide areas using field investigation; (4) to examine the geomorphic and geologic factors that influence landslides; and (5) to collect—via a pilot survey—and analyze the views of inhabitants of mountainous communities on sustainable development in geohazard-prone areas.

2. Materials and Methods

2.1. Maolin District

The study area of Maolin District, Taiwan (Figure 1) is dominated by steep mountainous terrain, which abruptly rises from the western plain, with elevations of 230–2000 m in the eastern district boundaries. Three townships (Maolin Village, Wanshan Village, and Dona Village) are located in the Jhoukou River watershed, which is a tributary of the Laonong River—a sub-water watershed of the Gaoping River basin. The total population of the three villages is approximately 1800 residents. Maolin District encompasses a 35-km-long section of the Jhoukou River. The most apparent fluvial formation in the study area is an incised meander along the length of the river.

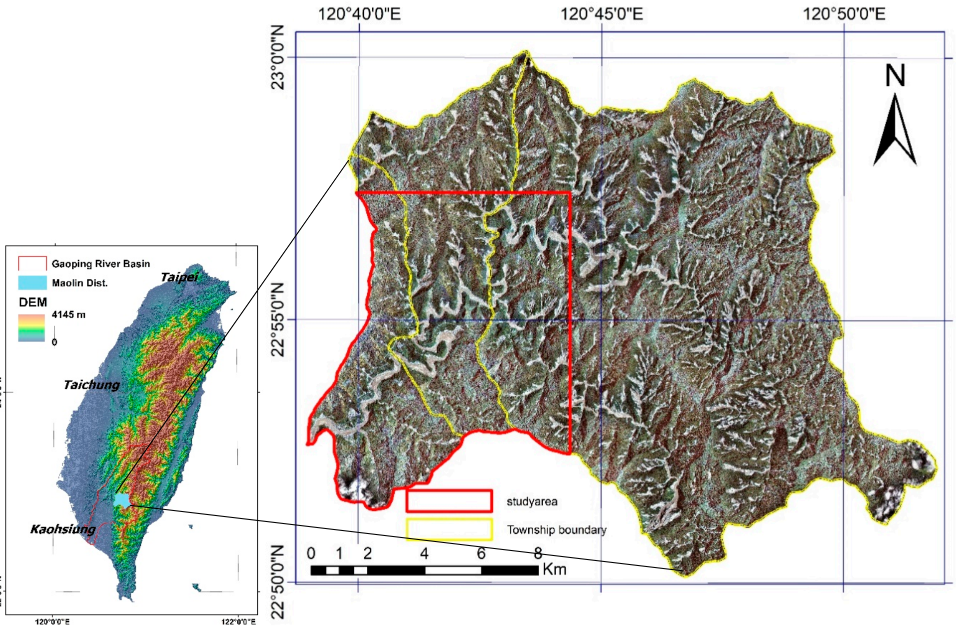

Figure 1. The geographical location of Maolin District, Taiwan.

The geology of Maolin District is dominated by the Lushan formation, comprising slate, sandstone, and phyllite that have been proven to date back to between the Miocene period and the early Miocene period [19]. Furthermore, the significant soil types include colluvial- and lithosol-type soils.

Maolin District is a designated national scenic area, which lacks diversified economic activity due to the rugged terrain conditions. Furthermore, this area is designated as a wintering ground for migrating purple butterfly species [20]. The annual butterfly migration occurs between November and March. The combination of these unique mountain and ecological resources has resulted in the development of ecotourism, which contributes significantly to the local economy. The local communities also continue to use the limited arable land to farm, using crop rotation guided by the traditional farming calendar [21].

2.2. Framework

This study proposes the use of a multidisciplinary approach to better understand the sustainability and resiliency issues arising in mountain communities facing geohazards and to identify information gaps that need attention. Our proposed framework encourages communities to be both sustainable and resilient [14]. The typical framework for sustainability evaluates social, economic, and environmental factors in order to assess sustainable development. In this study, we adapted the traditional sustainability framework and tailored it to Maolin District, using factors that reflect the local conditions in the communities there. Our proposed framework consists of three major criteria: (1) safety; (2) information and awareness; and (3) economy and natural capital (Figure 2).

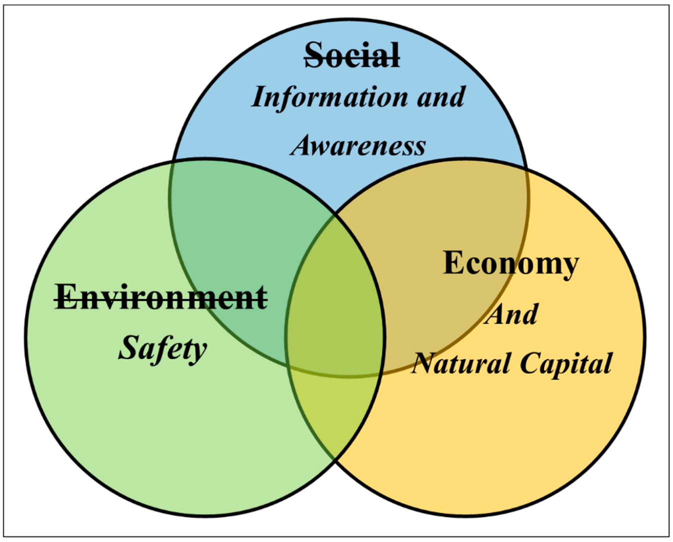

Figure 2. Adapted sustainability framework for Maolin District, Taiwan.

In our framework, we substituted "safety" criteria for the "environment" criteria, because the environment surrounding the local community is directly influenced by geomorphic processes and meteorological conditions that create hazardous circumstances for the residents. Similarly, we replaced the "social" factor in the traditional framework with "information and awareness" criteria to develop a more effective method of improving awareness of landslide susceptibility in the community. This can be achieved by communicating relevant information to the local community, enabling local citizens to become well informed about the state of their community and facilitating community participation in landslide mitigation planning. Furthermore, "natural capital" criteria were added to the economy criteria, because Maolin District has an abundant amount of natural resources, including clean water, forests, plants, animals, and hot springs, and high potential to capitalize on land-based activities (e.g., fresh air, pristine nature, visitor memories).

2.3. Landslide Susceptibility Index (LSI)

In developing a landslide susceptibility index (LSI), it is common to use a statistical approach that combines landslide inventory data and causative factors to assess and map areas prone to landslide activity [22]. This study builds upon an inventory-based susceptibility model that was used to identify and evaluate susceptibility factors in order to improve development in the Gaoping River Basin [23]. In this study, four bivariate models were examined: a linear combination (LC) model, a geometric mean (GM) model, and two mixed models (MX1 and MX2), which integrated the multiplication and addition of factors. Datasets were obtained from the Soil Water Conservation Bureau (SWCB) and the Forestry Bureau of Taiwan, which included information regarding geology, land use, soil classification, slope, drainage, distance to river, watershed boundaries, digital elevation models (DEM), landslide inventory data, and Formosat-2 (FS-2) imagery. The five most representative factors were chosen (slope, soil type, curvature, rock strength, and stream buffer) to reflect the land conditions of Maolin District. An information value (IFV) was calculated for each class of parameters based on the number of pixels identified as representing a landslide within the parameter class. This was based on the assumption that landslides occur where the land conditions have resulted in landslides previously. The IFV values ranged from 0 to 2, with 0 indicating no landslide activity and higher values showing landslide activity within the parameter class.

The results of this research reveal that the modulating effects between factors of slope and rock strength and drainage and curvature increased with multiplication. Importantly, MX2 represented well the unique land conditions of Maolin District, and it was used to derive the LSI maps used in this study. For further details on the LSI model, see Harrison et al. (2017). MX2 is defined as follows

$$\text{MX model 2}: LSI = IFV_{slope}\ x\ IFV_{lith} + IFV_{riv}\ x\ IFV_{curv} + IFV_{soil} \quad (1)$$

2.4. Landslide Inventory

Landslide inventory maps were obtained from the Forestry Bureau of Taiwan, which were generated by extrapolating data from Formosat-2 imagery [24] with the use of an automatic image processing system (FS-2 AIPS) [25]. The Expert Landslide and Shaded Area Delineation System (ELSADS) [26,27] uses values of reflectance in the red and near–infrared spectra to develop a normalized difference vegetation index (NDVI) to represent the geospatial changes in the vegetation cover. Because landslide activity is common on sloping terrain, the ELSADS enables the interpretation of images with the support of a digital terrain model (DTM) for the corresponding area. The ELSADS enables users to assess other geospatial information maps (e.g., geology maps, land use maps, previous imagery) to clearly interpret non-landslide, shadow, and dark areas and to confirm that a non-vegetated area is correctly interpreted as a landslide polygon [26]. Furthermore, image processing involves acquiring two suitable image sets with temporal differences—typically "before" and "after" images that can be overlain to determine differences in vegetation that has been disturbed as a result of landslide activity. For example, the output inventory map of Maolin District shows (Figure 3) landslide polygons identified in non-vegetated areas on sloping terrain, while differentiating the landslides from flat terrain, roads, riverbeds, and buildings. In this study, a nine-year landslide inventory dataset (2004–2012) was examined.

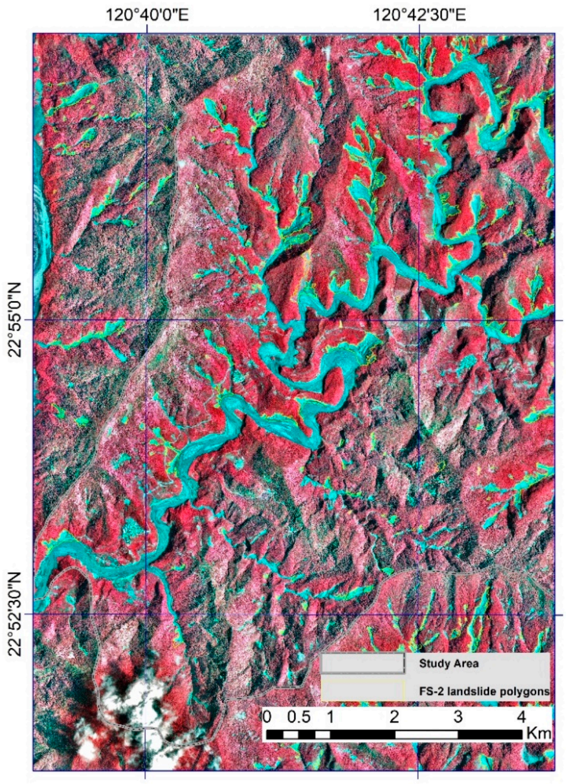

Figure 3. Normalized difference vegetation index (NDVI) output example showing landslide polygons, Maolin District, Taiwan (base image: Formosat-2 (FS-2), 20101121).

2.5. Field Work

Field visits were conducted to further identify areas prone to landslide activity. Approximately 114 locations (Figure 4) were documented on the FS-2 base images. FS-2 is a daily revisit satellite managed by the National Space Organization of Taiwan. The imaging capabilities of FS-2 include 2-m resolution in a panchromatic band and 8-m resolution in four multispectral bands ranging from visible to near–infrared [28]. The field investigation sites were chosen based on evidence of slope failure identified in the landslide inventory datasets. An expert approach to site analysis was used, which included a walking survey of the entire slope failure to verify the cause of the slope failure. Further investigation included an analysis of the surficial lithology.

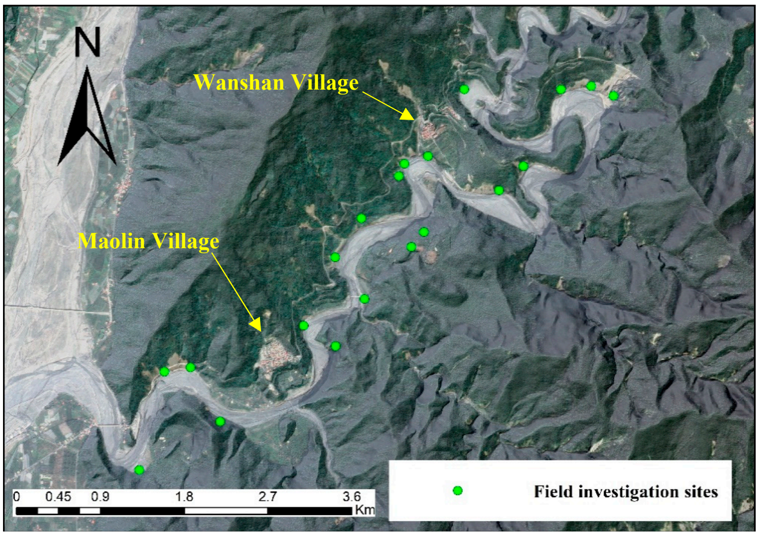

Figure 4. Field investigation site examples in Maolin District, Taiwan (base image: FS-2, 20101121).

To evaluate the sustainability of a mountain community, it is necessary to gauge the perspective of the inhabitants [29]. Important research questions include knowledge, behavior, perception, and classification [30]. Cultural information regarding the local tribes was obtained from the Council of Indigenous Peoples, Executive Yuan, as well as face-to-face interviews with the local residents.

In this study, we developed a questionnaire that contained two major categories of sub-topics: "information and awareness" and "economy and natural capital". The goal of the questionnaire was to gather the residents' perspectives on the following issues: (1) the personal routines of the residents; (2) how the residents define natural disasters and how the residents believe natural disasters impact their community; (3) the status of the disaster prevention techniques currently used; (4) how the government is performing with respect to relief and reconstruction efforts; and (5) the priorities of a sustainable community.

A total of eleven questions were designed with logical wording and sequence [30]. The questionnaire length was limited to eleven questions to ensure that participants would not be inconvenienced by completing the survey. The questionnaire participants were restricted to the residents of Maolin District (i.e., Maolin Village, Wanshan Village, and Dona Village). The survey questions (Supplementary Materials, Table S2) were distributed face to face in the three villages in the study area. Distribution of the questionnaires involved calling upon households; visiting community centers, clinics, restaurants, police stations, churches, government offices, farms, hostels, and hotels; and approaching individuals on the street. Similarly, mandarin was used as the delivery language of the questionnaire. An English translation of the questionnaire was generated upon completion of the data collection. A total of 130 residents were selected at random, representing 7.1% of the total population of Maolin District.

3. Results and Discussion

3.1. Combination of Landslide Inventory and Field Work Analysis

A total of six zones (A, B, C, D, E, and F) were identified to facilitate the analysis of Maolin District (Supplementary Materials, Figure S1). In zones A and B, slope failures occurred along the base of the river channel near the outer bend. Similarly, the field investigation showed that mass movements also occurred within confined ephemeral gullies. The dominant types of mass movement identified within these zones were debris flows (confined channels) and debris avalanches (unconfined flows). Zone D showed similar processes and geomorphic features to the previously mentioned zones. In zone D, the most significant mass movement was located west of Wanshan Village (Figure 5). Zone D can be classified as a debris flow-dominated channel based on the basin shape, size, slope, and confined channel. The zone E results show significant mass movements at the base of the outside bend of the Jhoukou River channel. The type of movement was identified as debris avalanche. Interestingly, the location of this movement was directly opposite to the landmark known as Snakehead Mountain. The zone F analysis shows mass movements with confined channels that show possible debris flow characteristics.

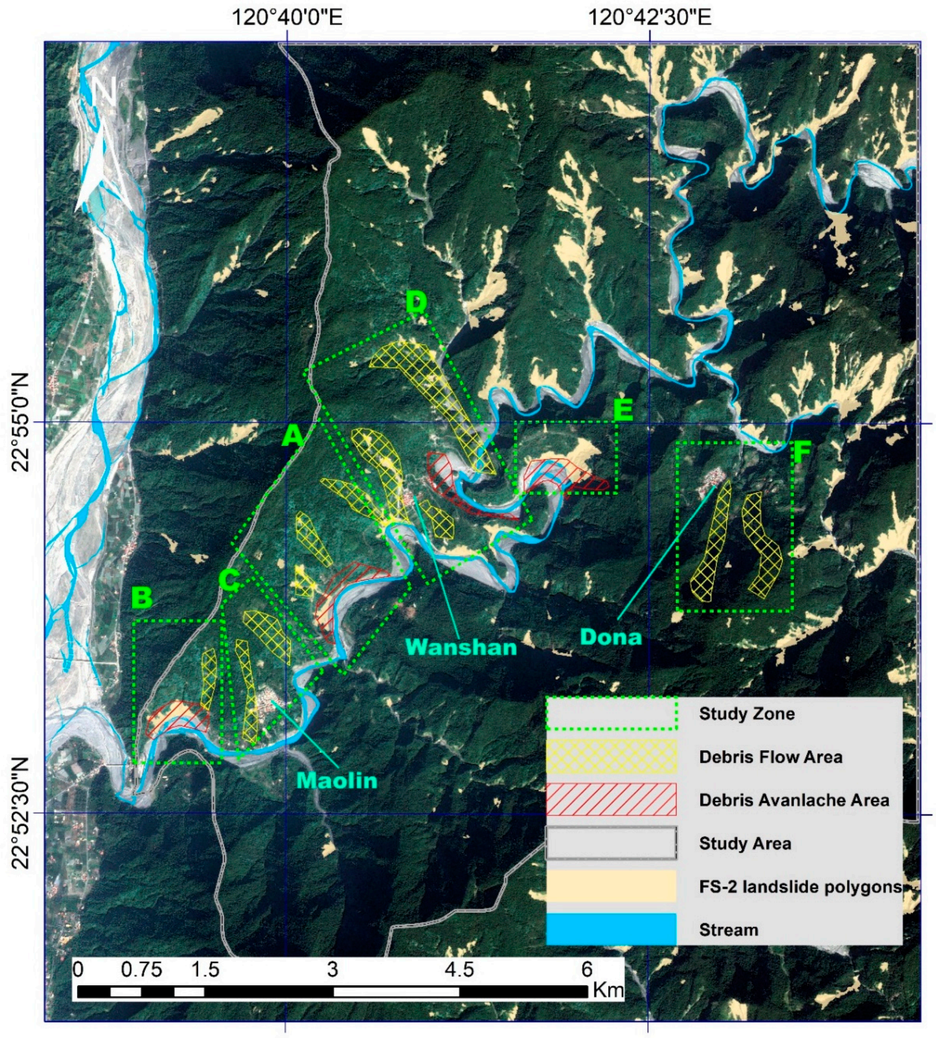

Figure 5. Location of significant mass movements, Maolin District, Taiwan (base image: FS-2 20101121).

The analysis of the geology and geomorphology of Maolin District reveals that the combination of the two factors played an important role in the frequency and location of the slope failure activity in the study area. The geologic influences indicate that three major rock types are present there: slate, sandstone, and phyllite. Similarly, soil conditions in the study area are generally shallow, poorly sorted, and lacking defined soil horizons. For example, poorly sorted colluvial-type sediments are shown in Figure 6.

Figure 6. Outcrop of colluvial-type sediments, Maolin Village.

This slope failure was also documented in the landslide inventory analysis (Supplemental Materials, Figure S1) as E1/E2 slope failure. The geologic context also seemed to contribute to the landslide activity of Maolin district. As previously stated, the Lushan formation is primarily composed of highly fractured and deformed bedrock that has been heavily weathered from precipitation. Such geologic conditions allow for unlimited sediment to be supplied to the gullies and channels in the study area. During high precipitation events, the sediment is available to be transported downhill. This pattern is seen throughout Maolin District. Small gullies show little sign of sediment being completely flushed from the channel system. Figure 7 shows an example of a gully with unlimited sediment availability, which is representative of the condition of the confined gullies in the study area.

Figure 7. Gully with an unlimited sediment supply, Maolin Village.

As shown in the imagery analysis (Supplemental Materials, Figure S1), a significant proportion of landslide activity occurred along the outer bends of meanders along the Jhoukou River. Furthermore, Figure 8a,b shows the influence of meanders as a geomorphic response to the hydrologic conditions of the Jhoukou River as a result of periods of peak flow, such as during the rainy season or during typhoons. After Typhoon Morakot, significant landslide activity occurred (Figure 8b) along the outer meander bends. This hydrogeomorphic relationship caused continued incising of the outer banks of the valley walls, thus destabilizing otherwise stable portions upslope from the meander [31,32].

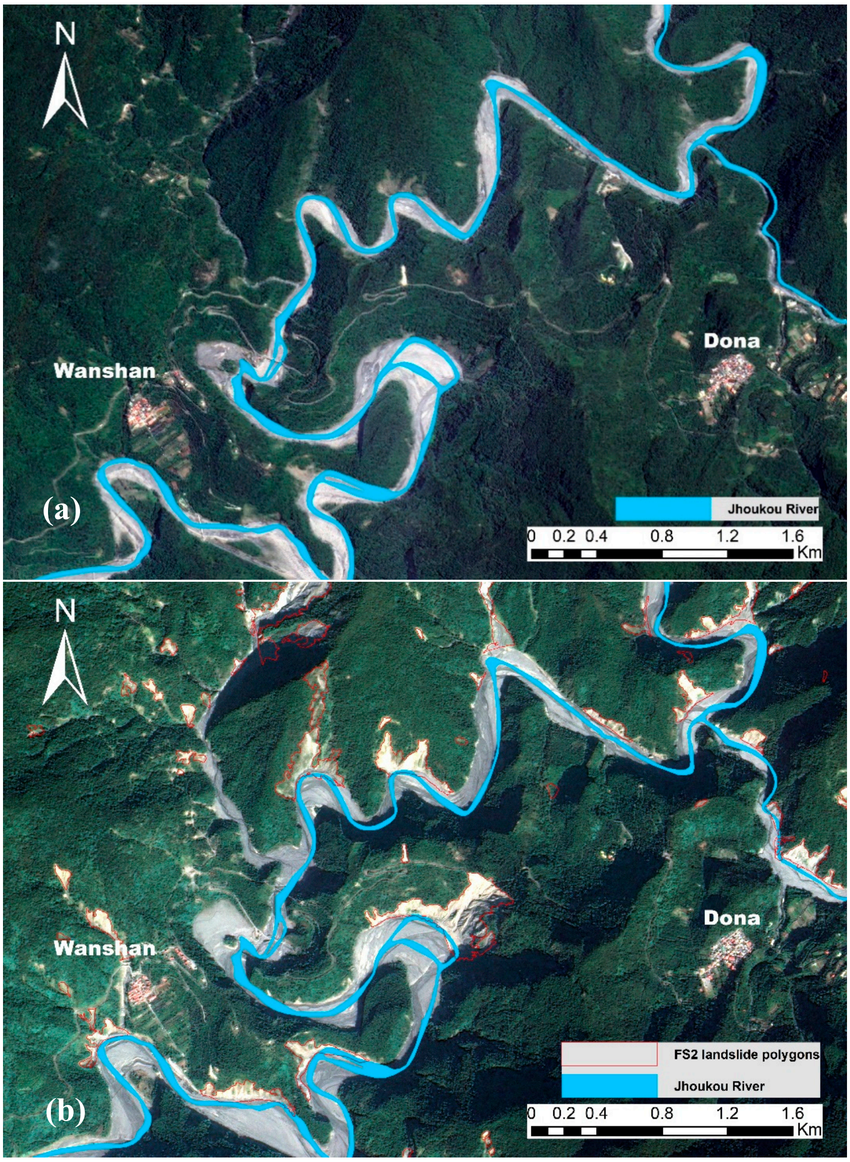

Figure 8. FS-2 images of the study area after Typhoon Morakot (**a**) FS-2 image (20080622); (**b**) FS-2 image (20101121). Meander examples and related landslide polygons, Wanshan Village.

Questionnaire Results

The results of the pilot questionnaire (Supplementary Materials, Table S2) reveal the awareness levels of landslides, disaster prevention knowledge, and perceptions of the concept of sustainability in the community of Maolin District. Most questions were multiple choice and required participants to select one answer; therefore, the total number of replies corresponds to the total number of questionnaires, and the percentage per reply relates to the proportion of the residents surveyed. Other questions allowed for more than one response; therefore, the percentage shown refers to the total number of replies as compared to the total number of possible replies for the individual question. Because the goal of the study is to assess preliminary views, the bias caused by allowing multiple answers is not viewed as significant [33].

The analysis of the survey results was organized under two topics: "information and awareness", and "economy and natural capital". The topics were chosen based on trends found in the initial data analysis. The questions were selected based on their relevance to the previously mentioned topics. A scale was developed to evaluate the "risk to sustainability" for each topic, which allowed for each response to be ranked high, medium, or low. For the topic, "information and awareness", the following ranking criterion is defined in Table 1. Generally, residents who lack accurate and reliable information regarding geohazards are less likely to be aware of the danger they face in their community. Improved information sources can further reduce vulnerability and lower the risk of dangerous conditions. For example, residents who know the locations of evacuation shelters and how to receive landslide bulletin updates are more likely to make informed decisions.

Table 1. Criteria for the information and awareness scale.

Risk to Sustainability	Criteria
High	No awareness of geohazards, highly vulnerable.
Medium	Some awareness of geohazards, somewhat vulnerable.
Low	Sufficient awareness of geohazards, low vulnerability.

With respect to the topic of "economy and natural capital", the ranking criteria are defined in Table 2. Table 3 (Supplemental Materials, Table S2, question 1) shows that the residents did not have a clear concept of where dangerous landslides or debris flows occur in their community; therefore, weak confidence intervals are reported. Similarly, a high risk to sustainability ranking was assigned to the three most common responses, because the wide breadth of responses indicates that the residents may have had some knowledge of where to obtain this information; however, the source of information may not have been trustworthy. When the residents were asked about how and where to evacuate, a higher confidence interval was reported for the responses that answered "yes" (Supplemental Materials, Table S2, question 2, response A). This answer was assigned a low risk to sustainability ranking, because it reveals that the residents had knowledge of how to evacuate. However other respondents answered that the government would make evacuation arrangements or that they would simply depend on the government for evacuation. Such answers were assigned a high risk to sustainability ranking due to the fact that responsibility seemed to be shifted away from the individual and towards the government. With respect to the survey question regarding computer access, the results were assigned a low risk to sustainability ranking (Supplemental Materials, Table S2, question 3).

Table 2. Economy and natural capital scale.

Risk to Sustainability	Criteria
High	No job, must travel elsewhere for work, no adaptive capacity.
Medium	Some have jobs, have limited adaptive capacity.
Low	Can support themselves within their own community, have sufficient adaptive capacity.

Table 3. Summary results for the questionnaire on information and awareness.

Question	Risk to Sustainability	Conclusion
1. Landslide locations	High	No clear understanding of location
2. How to evacuate	Medium	Knew of shelters, but depended on government
3. Computer Access	Low	Tool to gain information
4. Trusted person for landslide information	Medium	Not one trusted information source
5. Evacuation plan	Medium	Good overall understanding
6. During typhoon, where is safe?	Medium	Varied responses

The high confidence interval indicates that citizens had reliable access to the internet. However, analysis of question 4 indicates that trusted information sources were scarce Many residents chose individuals, such as their husbands, wives, or grandparents, as trusted information sources (Supplemental Materials, Table S2, question 4). Similarly, the wide range of answers may also indicate that community members had a lack of trust in the government. For example, the offices of the tribal leaders and government representative do not share the same space. Anecdotal evidence from village members reveals that elders were often approached regarding, and had the final say on, decisions related to the conditions of the mountains and river flow during storm events. This may further support the responses recorded for question 4. There was no clear answer when the residents were asked if they understood their evacuation plan. This was also reflected in the confidence interval values for response B of question 4. This response, although not significant, showed the highest CI value of the three choices. These results show that the residents did not think their evacuation plan is good enough and felt there is room for improvement. This is interesting due to the events of Typhoon Morakot, which still would have been fresh in the locals' minds. It could be assumed that because of this recent disaster, the residents would have shown heightened awareness of their evacuation plan. However, anecdotal evidence indicates that, during Typhoon Morakot, some residents felt that evacuation was not needed and that the outside agencies were more concerned about the residents of Maolin than was necessary. Furthermore, when the residents were asked to identify a safe place to seek refuge during a typhoon, a wide range of responses were recorded. These results also show that the idea of a safe place may be viewed differently by researchers, out-of-community agencies, and government departments than by the local residents. Anecdotal results show that elderly residents felt that their home and the church were safer than the government shelters. This point of view was also observed among the younger community members as well.

The second survey topic, "economy and natural capital" (Table 4 and Supplemental Materials, Table S2), shows significant results. A high confidence interval was reported for the question regarding the employment status of the residents. Many of them indicated that they work within their community. This response was assigned a low risk to sustainability ranking. Indeed, the respondents believed that it is a more sustainable solution for the residents to work within their community and to avoid leaving and traveling outside their community for employment. However, the results also show that, in fact, many residents do not have employment. This was ranked a high risk to sustainability. If the residents are unemployed, they are more likely to become dependent on government assistance or, in some cases, have to relocate to a new community. Question 2 focused on the secondary benefits of construction on their community, especially in terms of creating jobs. Surprisingly, a significant number of residents believed that there could be added benefits from construction projects in the study area, such as increased hiring of local residents; however, they did not have personal knowledge of this happening. The third question asked the residents what they hoped for the future of their community. A significant number of residents responded that environmental protection should be a priority for their community. This result was ranked a low risk to sustainability, because there is an underlying understanding within this community that the preservation of cultural and natural resources is necessary. The final question asked the residents how the government could reduce the risk of the landslides that affect their community. Many residents responded that the government needs to increase the budget for construction, road work, and afforestation programs. This was classified as a medium risk to sustainability, because there has already been a significant amount of money spent on projects to improve roadways and infrastructure. Similarly, anecdotal information from the local residents indicates that the current government does not know the local terrain well and that the quality of bridge construction is quite poor compared with that of 50–60 years ago.

Table 4. Summary of the results for the economy and natural capital questionnaire.

Question	Risk to Sustainability	Conclusion
1. Work location	Medium	Most working in Maolin District, but many answered "no job"
2. Benefits from reconstruction (hiring locals)	High	New roads, no new work
3. Future of Maolin District	Low	Environment/culture is a priority
4. Travel out of community	High	Increased risk when going outside of the community often
5. Lower risk of landslides	Medium	Want more money to be spent

3.2. Landslide Susceptibility Index Map Evaluation

The results of the landslide susceptibility index modeling of Maolin District show that the land conditions of slope, curvature, distance to river, and rock strength strongly influenced hazard-prone areas (Figure 9). Low LSI values indicated low landslide susceptibility, whereas high values represented areas of high susceptibility. Furthermore, very low (dark green 3–8) to low (green 8–10) LSI values occurred along the riverbed, which corresponded with the low slope gradient found along the base of the Jhoukou River channel. The very low to low LSI values followed a pronounced meander pattern as the river drained to the southwest. Similarly, in the upper reaches, very low to low LSI values were confined to very narrow sections of the river channel; however, as the river drained to the southwest, the river channel widened, as did the meander, which created a broad channel morphology. Medium LSI values (yellow 10–13) dominated the study area model. Such values were located in hilly terrain away from the main river channel. Similarly, medium values occupied the mountain ridge lines that run parallel to the drainage pattern of the study area. High (orange 13–15) to very high (red 15–18) LSI values were located in areas where steep gullies were present. In the upper reaches of the basin, there was a dendritic pattern visible in relation to the high to very high LSI values. Further investigation indicates that such a pattern corresponded with steep first- or second-order channels found in this portion of the study area. Importantly, high to very high LSI values were found along the margin of very low to low values, as well as near the inner and outer bend of meanders along the Jhoukou River channel.

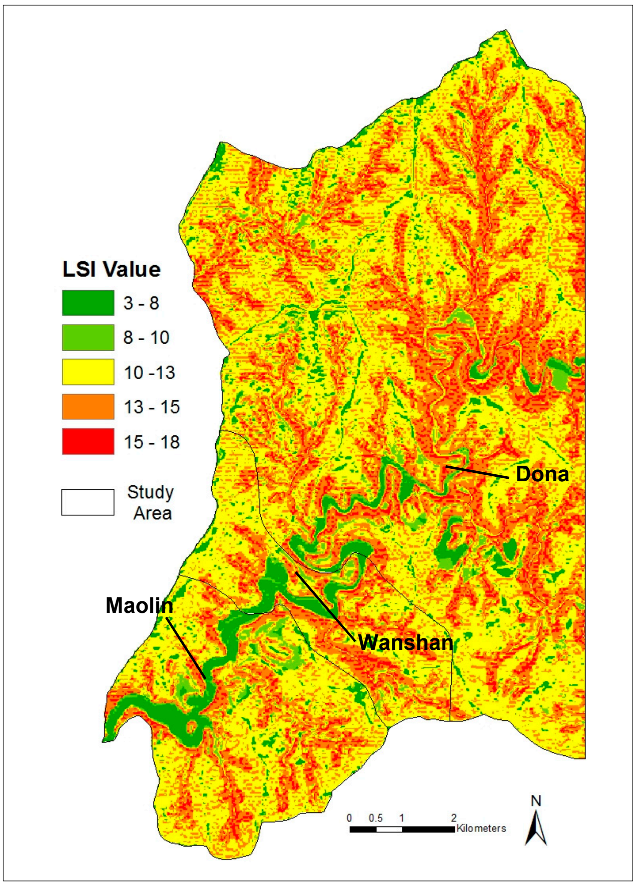

Figure 9. Landslide susceptibility index (LSI) results for Maolin District (Maolin Village, Wanshan Village, and Dona Village).

Moreover, this was also seen when comparative analysis of the LSI map and landslide inventory results were conducted (Supplemental Materials, Figure S2). For example, Figure 10 shows the Jhoukou River channel (green) with a low LSI value. Along the outer bend of the river, the section was classified as high to very high susceptibility (Figure 10a). A landslide polygon was added (Figure 10b) from the landslide inventory results of 2011 to show that undercutting from the meander caused further upslope instability in zones classified as low to medium susceptibility.

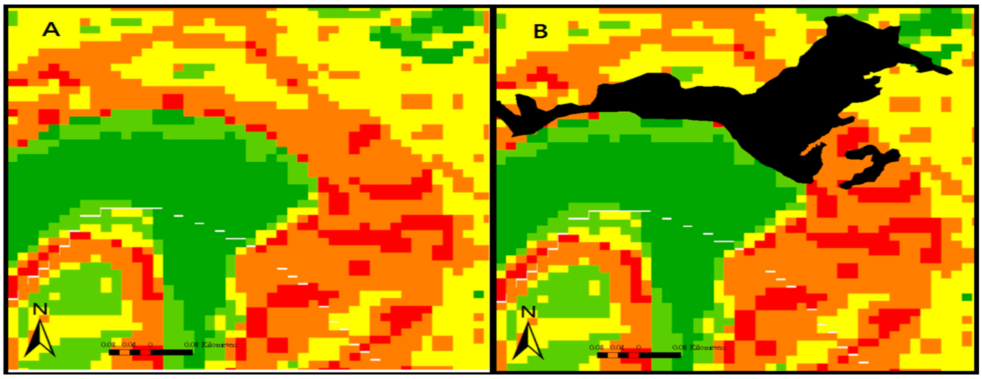

Figure 10. LSI results showing the influence of meander on landslide activity. The polygon represents the locations of past landslides. (**A**) Outer meander bend without landslide polygon (**B**) Outer meander bend with overlaid landslide polygon (black polygon).

3.3. Landslide Zone Map Results

The results from the LSI analysis and the landslide inventory results allowed for the identification of locations susceptible to landslides in Maolin Village, Wanshan Village, and Dona Village. Our field investigation also verified the location of and processes involved with the slope failures near the communities. Importantly, using an LSI map to identify areas prone to landslide activity is not valuable to untrained users, such as the local residents. Such a technical map has little information value to residents that have limited knowledge of the geologic units, statistics, mathematics, and computer software involved. Therefore, this study presents a simplified landslide zone map.

The landslide zone map was generated (Figure 11) by using a FS-2 base image of the three villages. The LSI results, landslide inventory results, and field work findings were overlaid, and polygons were created to identify terrain conditions where landslides are likely to occur, using an expert approach to identify verifiable landslide zones. Two zones were identified: a general "landslide zone" (green) and "landslide zone (meander)" (yellow). Zonal boundaries were highlighted with a simple outline to ensure ease of use and understanding.

Four emergency shelters (safe zones), at least one within each village, were included on the map. The goal was to produce a map for residents, stakeholders, and visitors that is clear, simple, and without the clutter and jargon of a technical hazard map. With this in mind, this map can help establish a safety standard as an additional aspect of community development and resilience.

3.4. Sustainability Framework

To integrate these diverse data streams and to improve our understanding of the natural and human phenomena associated with communities facing geohazards, we proposed here a framework for analyzing sustainability. Within this framework, three core criteria were identified, which should be considered with respect to the communities in Maolin District. This framework can serve as a tool for stakeholders to improve their community's resilience to future landslides.

This sustainability framework combines these three core criteria (Figure 12) to achieve a safe and sustainable community. There is a significance behind the linkage of the criteria. Each criterion is dependent on the other to successfully attain community sustainability. If one or more is not met, the community may face increased vulnerability and lower resilience to landslide activity. This framework requires data streams to be integrated from scientific and social science fields to fully develop a multidisciplinary management plan.

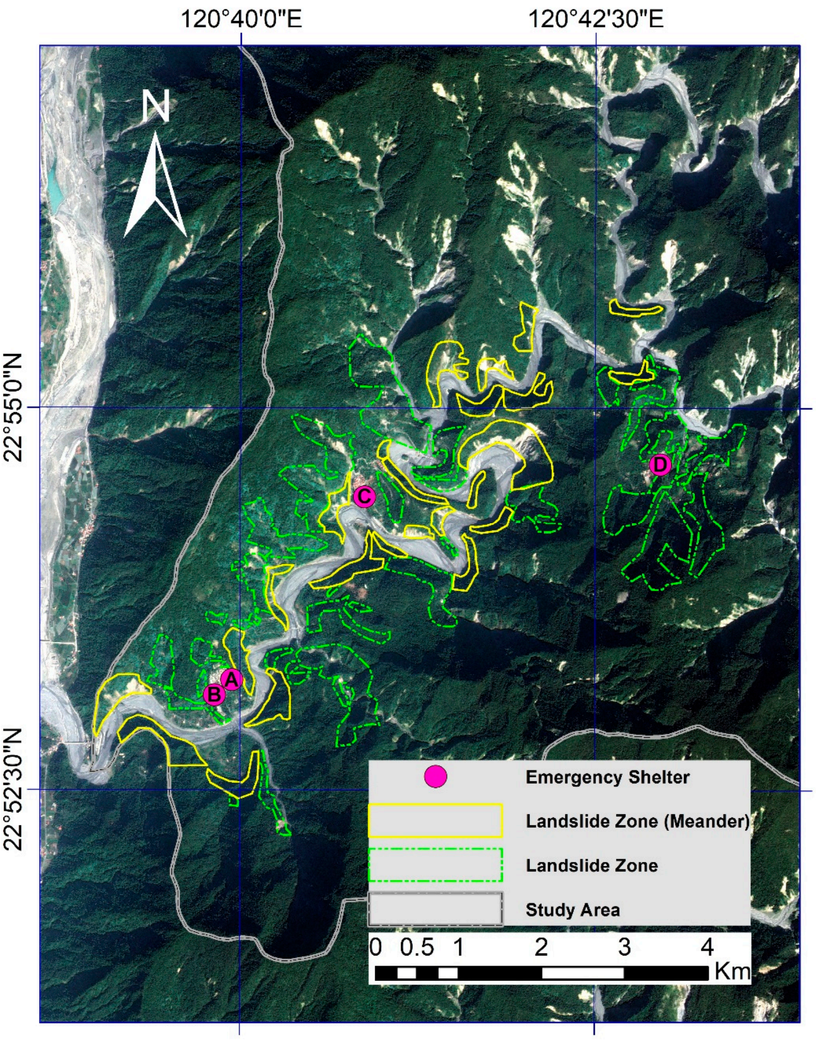

Figure 11. Landslide zone map with emergency shelter locations: A—Maolin Presbyterian Church; B—Maolin Elementary School; C—Wanshan Refuge House; and D—Dona Community Center and Dona Elementary School, Maolin District (base image: FS-2, 201011).

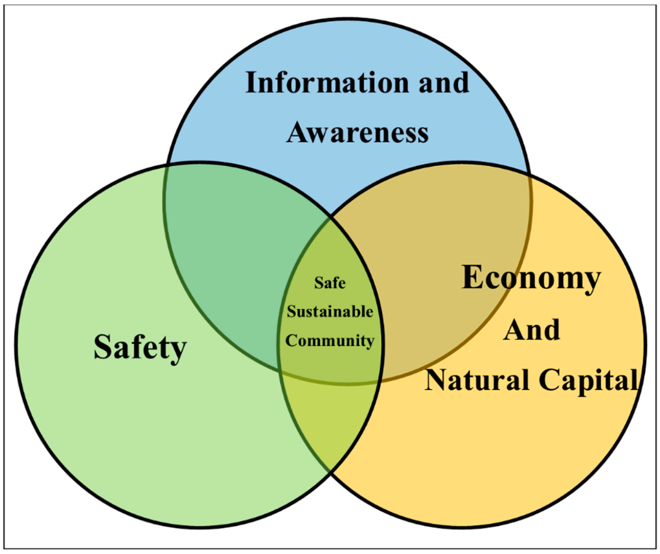

Figure 12. Sustainable community framework for Maolin District, Taiwan.

3.5. Discussion

The questionnaire results show that there is a need to further develop the flow of information available to the local residents of Maolin District. The vague responses observed during the questionnaire analysis further support the need for an improved and reliable source of geohazard information. This study also revealed that the residents demonstrated a lack of faith in non-local nongovernmental organizations and government departments alike. Thus, information should be made available within the established outlets of the community, such as the church or community halls. Simplified, easy to understand pamphlets should be distributed to the local residents that contain information on evacuation routes, emergency shelters, and hazard zones. The promotion of internet use as a source of local information should also be a point of discussion in this community. Similarly, based on the questionnaire findings, reliable sources of information were shown to be scarce. Tribal leaders or trusted individuals should be given responsibility for communicating accurate information to community members. Streamlining the chain of command could efficiently allow for improved information flow in the community.

To achieve sustainability, the local economy must also be developed to be more resilient [34]. A community must be able to prepare for, withstand, and recover from the impacts of a landslide. Working within the community was identified as an important factor for the survival of this community. Even when faced with the threat of geohazards, the anecdotal information reveals that the residents described this area as their "home" and that they preferred to remain in the community. However, the economic conditions within the villages revealed an ecotourism industry in its infancy, lacking vision, support, and direction from the community. The potential benefits (positive effects) versus the costs (negative effects) must be considered carefully by the community prior to implementing new development initiatives [35]. Environmental protection was viewed as a priority by the residents; however, from the perspective of the residents, the government needs to spend more money on road development and environmental and cultural preservation programs. Therefore, it is clear that development strategies are required for the short, middle, and long term [36]. Moreover, there is a need for a value-added approach to tourism development in Maolin. Such initiatives can follow the success of small-scale coffee growers [37]. Furthermore, there is much room for improvement; visitors stay for a short period of time in the study area. Anecdotal reports from the residents indicate that they perceive that visitors feel that there are limited activities in Maolin.

Furthermore, anecdotal evidence reveals that there are several locations suitable for the extraction and development of hot springs; however, based on the local residents' opinion, the government does not want to support drilling for this resource. Careful consideration is required to ensure that this area's infrastructure can carry the capacity of the influx of tourists expected as the reconstruction work nears completion. Future plans must use the natural capital within this area conservatively. This should include the development of trail networks for biking, walking, and hiking. The relative remoteness of the villages from major urban centers leaves the villages lacking access to local shopping and procurement of supplies on a daily basis. There is a need for further development of community-based distribution centers that would allow for goods to be purchased by locals for locals. Similarly, there is further need for the enrichment of the cultural activities and products available for tourists to experience and purchase. This should include bilingual information for international visitors, as well as the further diversification of the quantity of locally made crafts.

4. Conclusions

This study evaluated of the sustainability of a mountain community in Southern Taiwan. The use of an LSI map, landslide inventory datasets, and field work analysis were used to identify areas susceptible to landslides. The results of this study show that an LSI map is an effective tool for identifying landslide zones. Multi-temporal landslide inventory analysis and expert field investigation further improved the process of identifying landslide activity in highly susceptible landslide zones.

A community-based participation questionnaire was also distributed to the local residents to evaluate their awareness of landslides and sustainability.

The questionnaire results indicate that the residents had moderate awareness of and access to information related to landslides. Similarly, the residents were in favor of increased environmental protection, working within their community, and increased government spending to improve their community's preparedness for natural disasters. In this study, we proposed a sustainability framework that is based on the integration of three core criteria: safety, information and awareness, and economy and natural capital. This framework presents guidance that is useful for land use management and the development of safe, resilient, and sustainable communities.

Furthermore, the fluvial feature of meander was identified as an important factor influencing the distribution of slope failures in the study area. Similarly, the complex geologic conditions of the study area significantly contributed to the reoccurrence of mass movements, especially debris flows and debris avalanches.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/11/15/4107/s1, Table S1. Eleven questions developed and delivered to the residents of Maolin District; Figure S1. Land inventory results for Maolin, Wanshan, and Dona; Figure S2. LSI vs. landslide inventory (2004–2012) results, Maolin District; Table S2. Questionnaire results.

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