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Hazard Ratings of Debris Flow Evacuation Sites in Hillside Communities of Ershui Township, Changhua County, Taiwan

Szu-Hsien Peng

Department of Spatial Design, Chienkuo Technology University, No. 1, Chieh-Shou N. Rd., Changhua City 500, Taiwan; shpeng@cc.ctu.edu.tw; Tel.: +886-4-711-1111 (ext. 2256); Fax: +886-4-711-1126

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Abstract: Global warming in recent years has resulted in climate change. To cope with future climate change and natural environment changes, much of our planning and thinking needs to be adjusted. To this end, safety and rapidness of evacuation have become primary research goals. In this study, geographic information and fuzzy expert systems are applied to debris flow evacuation sites in Ershui Township, Changhua County, for evaluating their hazard ratings. After a geographic information system is used to overlay the environmental sensitivity, FLO-2D is applied to simulate debris flow situations, and the results are utilized to establish a fuzzy expert system that successfully evaluates the hazard ratings of such sites in hillside areas. For future applications, another evaluation reference based on original evacuation sites and routes or evacuation mechanisms and disaster prevention models is proposed as a source of essential assistance to relevant sectors.

Keywords: hazard rating; debris flow evacuation site; environmental sensitivity; fuzzy logic system; geographic information system (GIS)

1. Introduction

The phenomenon of global warming and its climate change impacts are becoming increasingly apparent. Taiwan was seriously affected by Typhoon Morakot in August 2009 [1–4]. Along the route of Morakot, much torrential rain fell, causing disastrous results owing to the high stationarity and effects of its southwesterly flow. Various types of disasters such as floods, shallow slope failure, debris flow, deep-seated landslides, and dammed lakes resulted from the long duration, high intensity, and extensive rainfall. To cope with climate and natural environment changes in the future [5], much of our planning and thinking needs to be adjusted, and research on risk evaluation for evacuation sites neighboring frequent disaster areas is urgently required. Current disaster management includes provisions for evacuation sites and routes; however, such areas might be prone to debris flow risk, which needs to be assessed. An important component of risk assessment is the hazard rating assessment of debris flow evacuation sites.

The slopeland of Changhua County covers Changhua City, Fenyuan Township, Huatan Township, Dacun Township, Yuanlin Township, Shetou Township, Tianzhong Township, and Ershui Township on the Bagua Plateau, with a total area of 13,200 hectares. In recent years, the saturation of land use in urban areas and the development of non-agricultural use of slopeland have caused soil erosion loss and increased surface runoff [6,7]. Whenever there is a typhoon or torrential rainfall, a large amount of rain that is not promptly drained causes floods or debris flow flooding in downstream areas and further endangers the safety of hillside communities.

Generally, risk is a potential damage that can be calculated from the probability of a dangerous event (or hazard), the values of elements-at-risk, and the respective vulnerabilities of elements to a specific event. Traditional evacuation methods [8–16] have been substantially developed for different types of disasters such as hurricanes, floods, landslides, and earthquakes. Existing shelters often consist of schools, community activity centers, or other existing facilities, but these are often not completely evaluated for safety, and, in many cases, they might be affected by disasters.

In this study, a FLO-2D model was used to conduct the simulations of debris flow disasters. The model was executed for different return periods, disaster occurrence strengths, and disaster likelihoods, which were available at different degrees of hazard levels (high, medium, and low). Disasters with longer return periods and higher intensities may occur at the same time, but the probability of such occurrences is lower; conversely, the probability of the occurrence of disasters with shorter return periods and lower intensities will be higher [17,18].

Most traditional numerical simulations can only be employed for a single disaster pattern. Through this study, different types of disasters such as landslides and potential debris flows are combined using fuzzy logic expert systems, producing results that can be folded into a complex potential disaster map. This model can be used to establish a preliminary safety assessment for debris flow disaster prevention or evacuation sites for hillside communities. This evaluation methodology can offer a reference for relevant actors in the disaster prevention planning community.

2. Material and Methods

A fuzzy expert system was established in this study to implement the security evaluation of debris flow disaster prevention evacuation sites in hillside communities in Changhua County. As a feed-in to the expert system, a geographic information system (GIS) was used to analyze landforms, geology, and soil conditions in order to assess environmental sensitivities in hillside communities. The GIS data were integrated with potential debris flow torrent map data provided by the Soil and Water Conservation Bureau (SWCB) to develop numerical situation simulation for evacuation sites that would provide decision support analysis to the fuzzy expert system. A flow chart of this study is shown as Figure 1.

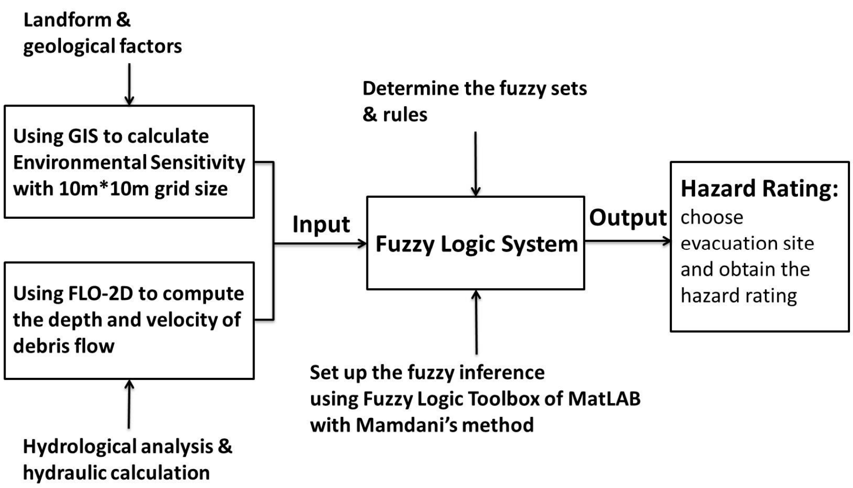


Figure 1. The flow chart of this study.

2.1. Environmental Sensitivity

In accordance with the Technical Regulations for Soil and Water Conservation Articles 147 and 148, the landform homogeneous region in the studied area was divided into several land units based on the Evaluation of Simprecise Method [19], and parameters including slope, slope erosion, engineering properties of rock masses, rock structure, and soil depth were filled into the land units to calculate environmental risk [20]. In this case, landform and geology were mainly considered in determining environmental risk. Numerical factors encoding slope and slope erosion were applied to landforms while geological factors were encoded based on a combination of environmental geology parameters (see Table 1). The set of geological factors in Table 1 includes three codes found in Tables 2–4. The environmental risk was then calculated as the sum of landform and geological factors. An example of this calculation is given as follows.

For a land unit with a slope of 15%–30%, an erosion score corresponding to land surface with erosion marks, volcaniclastic rock mass engineering properties, unstratified rock structure, and soil depth below 1 m, the environmental risk calculated based on Tables 1–4 in accordance with the Technical Regulations for Soil and Water Conservation [20] as 6 (see Figure 2).

Table 1. Environmental landform and geological factors.

Numerical Factor	Slope (%)	Numerical Factor	Erosion	Numerical Factor	Geological Factor
0	⩽5	1	Flat slope	1	I0A, I1A, I2A, [I3A (without free end) *]
1	5–15	2	Erosion mark	2	I0B, I1B, I2B, [I3B (without free end) *] II0A, II1A, II2A, [II3A (without free end) *]
2	15–30	3	Shallow gully	3	I0C, I1C, I2C, [I3C (without free end) *] II0B, II1B, II2B, [II3B (without free end) *]
4	30–40 40–55	4	Deep groove	4	I3A, I4A, II0C, II1C, II2C, [II3C (without free end) *]
6	55–100	5	Previous landslide, cinder pile	5	II3A, II4A, I3B, I4B
8	>100	6	New landslide	6	I3C, I4C, II3B, II4B, II3C, II4C

Note: * implies that field investigation is needed to distinguish whether exposure exits or not.

Table 2. Classification of engineering properties of rock mass.

Rock Type	Engineering Property Grade	Rock Name
Sedimentary rock	I	Hard sandstone; Dense limestone; Well-cemented conglomerate
	II	Poorly cemented sandstone, Alternations of sandstone & shale, shale, mudstone; Porous limestone; Tuff; Gravel layer or poorly cemented conglomerate; Fragmentation of hard rock
Igneous rock	I	Lava, intrusive rock, well-consolidated volcaniclastic rocks
	II	Poorly consolidated volcaniclastic rocks
Metamorphic rock	I	Gneiss; Marble; Quartz schist; Slate, Phyllite, Green schist
	II	Shattered zone; Split developed in the slate, phyllite, schist black, and green schist

Note: I implies hard rock; II implies soft rock.

Table 3. Hillside rock structure classification.

Code	Slope Type (Hillside Rock Formations)
0	Non-ramp (unstratified rock)
1	Oblique slope
2	Reverse slope (cliff)
3	Dip slope (strata dip more than 10 degrees)
4	Shattered zone

Table 4. Soil depth classification.

Code	Soil Depth
A	One meter or less
B	More than one meter to four meters
C	More than four meters

Risk is actually a measure of potential damage (= value × danger × vulnerability), and applying the term "sensitivity" to the above results may be more suitable. However, official documents [20] have used the term "environmental risk," which is therefore used in this study. Environmental sensitivity in the context of this study is an index that increases with the environmental risk index value. Our grading of environmental sensitivity is shown in Table 5; based on environmental sensitivity, the potential hazard ratings are graded Extremely Low, Low, Medium, High, and Extremely High.

Table 5. Environmental sensitivity grading.

Environmental Risk	Environmental Sensitivity	
Below 5	1	Extremely Low
6–7	2	Low
8–9	3	Medium
10–11	4	High
Above 12	5	Extremely High

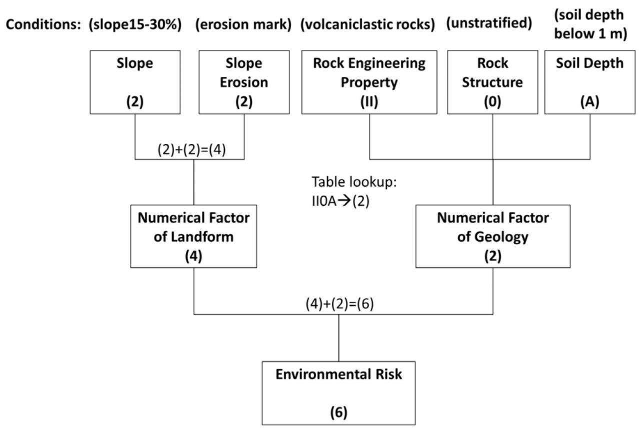


Figure 2. Example of the environmental risk calculation.

McHarg *et al.* (1969) effectively improved the overlay analysis technique and applied it to various land use suitability analyses [21]. Overlay analysis has gradually become a major method for analyzing environmental characteristics in regional planning. The overlay analysis technique became a general function in the GISs that were developed in the 1980s [22–26]. The overlay analysis function in GIS can be used to overlay environmental risks onto specific layers to aid enquiry; for example, potential debris flow torrent map data provided by the SWCB in Taiwan have been combined with numerical situation simulation results to allow for efficient searching for environmental sensitivities and potential debris flow disasters within a given region. In this study, the grid size for calculation is 10 m × 10 m, which matches with the conditions of numerical simulation.

2.2. Numerical Model for Debris Flow

Numerical scenario simulation is fed by FLO-2D model output. The FLO-2D model was developed by the University of Colorado for research on debris flow and flooding, and an enhanced version was developed by the FLO-2D Company as commercial software that has been approved by the United States Federal Emergency Management Agency (FEMA). FLO-2D programs can calculate two-dimensional simulations of flooding or debris flow using shallow water equations to obtain the average velocities u and v on the x- and y-axes, respectively, as well as the water depth h. The governing equations are shown as follows [27]:

Continuity equation:

$$\frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x} + \frac{\partial (vh)}{\partial y} = i \tag{1}$$

Equations of motion:

$$S_{fx} = S_{bx} - \frac{\partial h}{\partial x} - \frac{\partial u}{g\partial t} - u\frac{\partial u}{g\partial x} - v\frac{\partial u}{g\partial y} \quad (2)$$

$$S_{fy} = S_{by} - \frac{\partial h}{\partial y} - \frac{\partial v}{g\partial t} - u\frac{\partial v}{g\partial x} - v\frac{\partial v}{g\partial y} \quad (3)$$

where h is water depth; u and v are velocities along the x- and y-axes, respectively; i is rainfall or lateral inflow; and g is the acceleration of gravity. The variables h, u, v, and i are functions of time, t. In this study, the inflow hydrograph was employed instead of rainfall as the boundary condition for the calculation.

Equations (2) and (3) are the equations of momentum equilibrium in the x and y directions, respectively. From left to right, the equations describe the friction slope (rheology model) affected by the strength of materials, the bed slope of gravity, the pressure gradient, the local acceleration term, and the convective acceleration term in the inertial contact force.

Based on physical interpretations of the sub-items of the governing equations, FLO-2D proposed three models to simulate the physical problem, each aiming at distinct requirements: the dynamic wave model, which is used as the overall equation of momentum in Equations (2) and (3); the diffusion wave model, which ignores items 3–5 to the right of the equality sign in Equations (2) and (3); and the kinematic wave model, which ignores items 2–5 to the right of the equality sign in Equations (2) and (3). The more items that can be ignored, the more operation time can be reduced. However, the kinematic wave model is not suitable for areas with gentle slope, and based on current growth in computing capability and the need to accurately model mechanical behavior over the simulation, the more accurate dynamic wave model is generally used for analysis.

A runoff hydrograph of inflow is required in order to simulate debris flow. In this study, a triangular unit hydrograph is utilized for this calculation. The relation among the triangular unit hydrograph base period T_b, the peak discharge Q_p, the peak arrival time T_p, and the watershed topographic factors is shown in the following equations [28]:

$$Q_p = \frac{0.208AR_e}{T_p} \quad (4)$$

$$T_p = \frac{D}{2} + 0.6T_c \quad (5)$$

$$T_c = \frac{L}{W} \quad (6)$$

$$W = 72\left(\frac{H}{L}\right)^{0.6} \quad (7)$$

$$T_b = T_p + T_r = 2.67T_p \quad (8)$$

where R_e is the unit rainfall excess (mm), T_p is the time of rise to peak flow (h), T_r is the rainfall excess unit time (h), Q_p is the peak discharge (cms), T_c is the time of concentration (h), T_b is the discharge hydrograph base period (h), L is the watershed mainstream length (km), H is the watershed vertex-control point head (km), W is the flood delivery velocity (km/h), A is the watershed area (km^2), and D is the effective rainfall duration (h).

From the above equations, T_r = 1 hr and unit rainfall excess R_e = 10 mm are used for calculating the peak discharge. A triangular unit hydrograph matched with a design hyetograph is utilized in this study as the numerical simulation condition for estimating the inflow runoff hydrograph of the potential debris flow torrent in Ershui Township. The modeling results can be used to predict potentially inundated areas as well as flow depth and velocity of debris flow.

2.3. Fuzzy Logic System

Fuzzy logic is a convenient way to map an input space to an output space using a primary mechanism consisting of a list of if-then statements called rules. All rules are evaluated in parallel and the order in which they are implemented is unimportant. The rules themselves are useful because they refer to variables and to the adjectives that describe the interaction of a set of variables. Fuzzy logic starts with the concept of a fuzzy set, which is a set without a crisp or clearly defined boundary. Fuzzy sets can contain elements with only a partial degree of membership as defined by a membership function, which is a curve that delineates how each point in the input space is mapped to a membership value (or degree of membership) between 0 and 1. Fuzzy sets are extensions of classical sets; if X is the universe of discourse and its elements are denoted by x, then a fuzzy set A in X is defined as a set of ordered pairs as follows [29,30]:

$$\mathrm{A} = \{x,\ \mu_{\mathrm{A}}(x) \,|\, x\,\mathrm{X}\} \tag{9}$$

where $\mu_{\mathrm{A}}(x)$ is called the membership function of x in A. The membership function maps each element of X to a membership value between 0 and 1.

Because fuzzy sets and fuzzy operators are the subjects and verbs, respectively, of fuzzy logic, these if-then rule statements are used to formulate the conditional statements that comprise fuzzy logic. In general, one rule alone is not effective; two or more rules that can play off one another are needed. The output of each rule is a fuzzy set, and the fuzzy sets output by each rule are aggregated into a single output fuzzy set. Fuzzy inference refers to the process of formulating a mapping from a given input to an output using fuzzy logic. Mamdani's fuzzy inference method, which is the most commonly used fuzzy methodology, was among the first control systems built using fuzzy set theory. A Mamdani-type fuzzy inference system was employed to set up the fuzzy expert system used in this study.

The Fuzzy Logic Toolbox in MatLAB was applied to establish the fuzzy expert system for hazard rating of debris flow evacuation sites in this study (Figure 3) [31]. Environmental sensitivities and potential debris flow disasters were used as input parameters, with the output parameter being a hazard rating in which environmental risks (0–20) were divided into five grades—very low (VL), low (L), medium (M), high (H), and very high (VH)—potential debris flow was divided into four grades (0–3)—NA, Low, Medium, and High—and hazard rating was divided into four grades (0–100)—Safe, Medium, Unsafe, and Dangerous (Figure 4). The classification (0–3) of potential debris flow in Figure 4b is based on the results of numerical simulation. Zero implies no debris flow. Flow depth > 1.5 m or velocity > 1.5 m/s would correspond to a grade High, with score 3. If the flow depth < 0.5 m and velocity < 0.5 m/s, the grade would be Low, with score 1; all other parameter combinations would be Medium with score 2. As it is a two-to-one system (two inputs producing one output), these fuzzy rules can be described as a 5 × 4 matrix of input variables [29], *i.e.*, as 20 rules, as listed in Table 6. When the fuzzy rules of an expert system are established, the Fuzzy Logical Toolbox can be utilized for calculating the relationship between environmental risk, potential debris flow and hazard rating (Figure 5) [30]. Thus, this model can be used to hazard rate debris flow evacuation sites by simply inputting environmental risks and the positions of potential debris flows (based, e.g., on GIS overlay analysis results). For future application, relevant map data could be used to create a database into which users could input the coordinates of evacuation sites in order to automatically screen the input parameter for calculation.

Table 6. Logic rules of fuzzy expert system.

Input 1 (Environmental Risk)	Input 2 (Potential Debris Flow)	Output * (Hazardous Rating)
VL	N/A	Safe
VL	Low	Safe
VL	Medium	Medium
VL	High	Unsafe
L	N/A	Safe
L	Low	Medium

Table 6. *Cont.*

Input 1 (Environmental Risk)	Input 2 (Potential Debris Flow)	Output * (Hazardous Rating)
L	Medium	Medium
L	High	Unsafe
M	N/A	Medium
M	Low	Medium
M	Medium	Unsafe
M	High	Unsafe
H	N/A	Medium
H	Low	Unsafe
H	Medium	Unsafe
H	High	Dangerous
VH	N/A	Unsafe
VH	Low	Unsafe
VH	Medium	Dangerous
VH	High	Dangerous

Note: * For example: If (Input 1 is VL) and (Input 2 is N/A) then (Output is Safe).

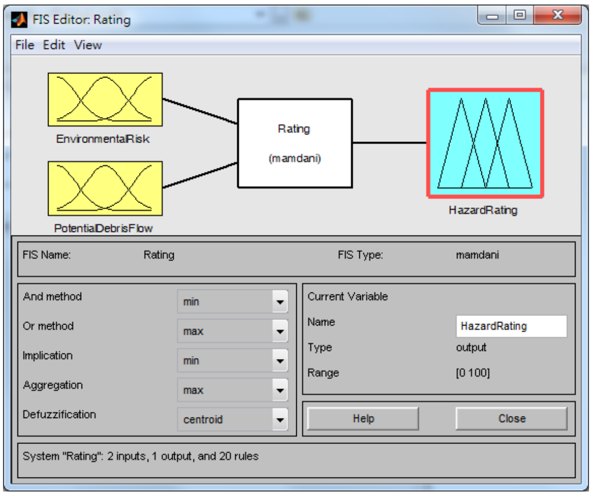
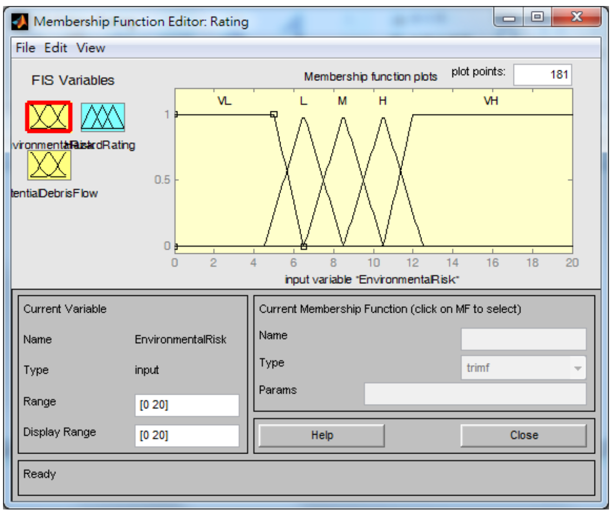
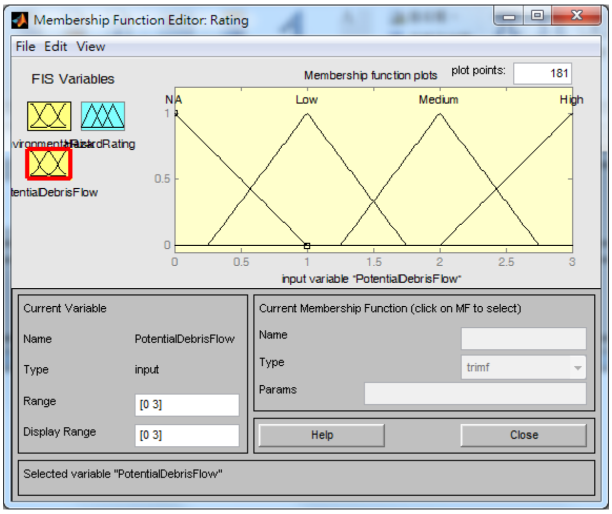


Figure 3. Fuzzy expert system for hazard rating.



(a)

Figure 4. *Cont.*



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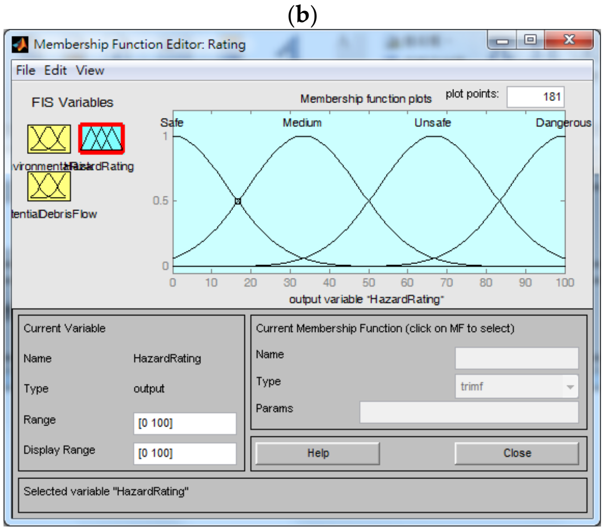


(**c**)

Figure 4. Fuzzy condition setting of input and output parameters. (**a**) Environmental risk; (**b**) potential debris flow; (**c**) hazard rating.

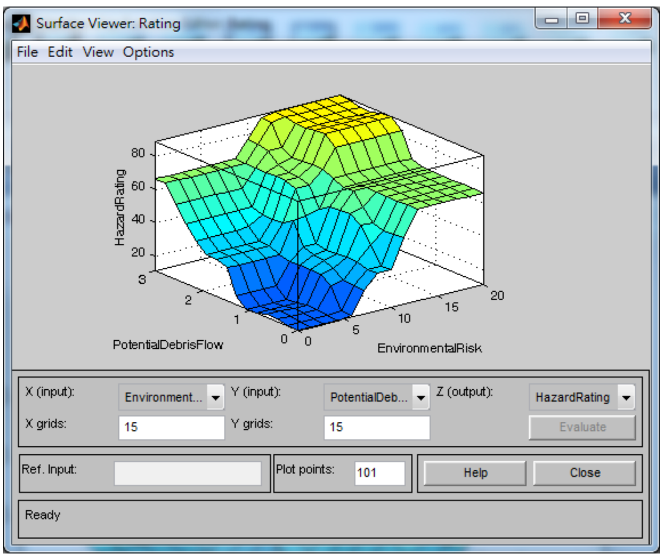


Figure 5. Operation result of fuzzy expert system.

3. Results and Discussion

3.1. Study Area

Located in the middle of western Taiwan, Changhua County is a roughly trapezoidal piece of land with a north–south distance 44 km, a northern east–west width of about 12 km, a southern width of about 40 km, and an area of 1074.40 km^2. Located in the southeast end of Changhua County, Ershui Township has a total area of 29.44 km^2, an east–west width of about 8.75 km, and a south–north length of about 5.00 km. Ershui Township has a landscape consisting of plains and plateau landforms with the slope of the Bagua plateau in the northeast and the alluvial plains of the Chuoshui River in the southwest. The slopeland geology in Ershui Township reveals mainly lateritic plateau deposits, Lichi formation, and alluvium (Lichi formation is a standard melange composed of thick mudstone and mixed with a variety of exotic blocks). Most rock formations are aligned in the north–south direction and their degree of weathering is medium, with a few steep and exposed riverbank sections along the river. Reddish brown and yellow-red lateritic soils and alluvial soils are the major soil types; most areas with protruding relief contain reddish brown lateritic soil but little yellow-red lateritic soil; alluvial soil has developed into flood land or alluvial fans in the river valley [32].

3.2. Numerical Simulations of Potential Debris Flow

According to the potential debris flow torrent information provided by the Soil and Water Conservation Bureau, a total of seven potential debris flow torrents appear in Changhua County; five of these are distributed among Dayuan Village, Yuanchuan Village, and Changhe Village in Ershui Township (Table 7). The three villages in the Ershui Township of Changhua County are therefore investigated in this study. A situation simulation of potential debris flow torrents (numbered DF001-DF005) is detailed in this section.

Table 7. Potential debris flow torrent in Ershui Township, Changhua County.

Number	Village	Potential	Households May Be Affected	Rainfall Alert Value during 24 h (mm)
DF001	Dayuan Village	Low	1~4 households	500
DF002	Dayuan Village	Medium	More than 5 households	500
DF003	Yuanchuan Village	Low	More than 5 households	500
DF004	Changhe Village	Medium	More than 5 households	500
DF005	Changhe Village	Medium	More than 5 households	500

A hyetograph must be designed before estimating the discharge hydrograph. The Horner formula [33] of the Liufenliao Station provided by the Water Resources Agency (Figure 6) is used for hyetograph design in this study, and a triangular unit hydrograph [28] is applied to calculate the 24 h inflow discharge hydrograph based on a daily rainfall 500 mm (Figure 7). The 500 mm daily rainfall figure and 50-year recurrence are suggested by the SWCB of the Council of Agriculture in Taiwan [28].

As the most significant differences between debris and hyperconcentrated flows stem from larger differences in solid sediment contents, fluid sediment volume concentration is the most direct measure for defining debris flow. Except for a few field-observed values, the design values of sediment volume concentration were calculated using the Takahashi Theory equation as the criterion. Based on Bagnold's concept of dilatant fluid, Takahashi [34] established the debris flow sediment volume concentration using the following equation:

$$C_D = \frac{\gamma_w \tan\theta}{(\gamma_s - \gamma_w)(\tan\varphi - \tan\theta)} \quad (10)$$

The above equation is suitable for calculating the saturated (balanced) sediment concentration at a debris flow forefront. In the equation, φ is the sediment internal friction angle, which is closely correlated with sediment characteristics and has values between 26° and 48°; θ is the bed slope; γ_s

is the soil particle unit weight; and γ_w is the clear water unit weight. According to Equation (10), the simulated debris flow concentration is between 17% and 44% and the reasonable range of debris flow sediment volume concentration is between 0.33 C_* and 0.9 C_* (where C_* is the sediment volume concentration of stacked soil in the riverbed). Although there is no field measurement for testing, the current calculation results still appear to be within a reasonable range as compared to the area affected by debris flow announced by SWCB [35].

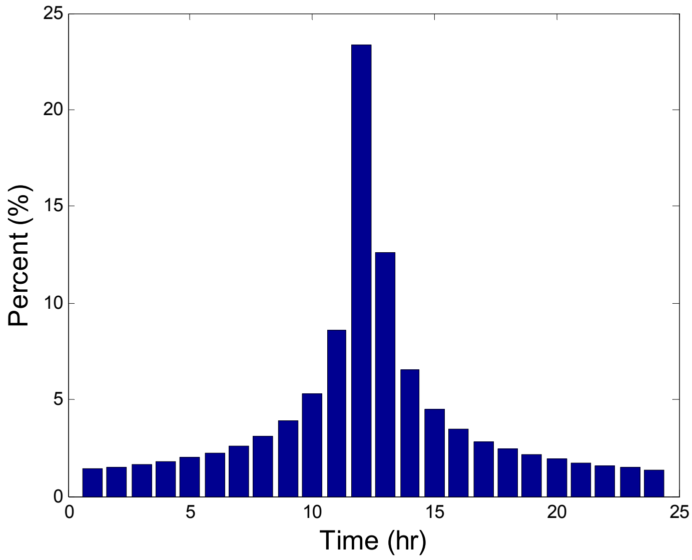
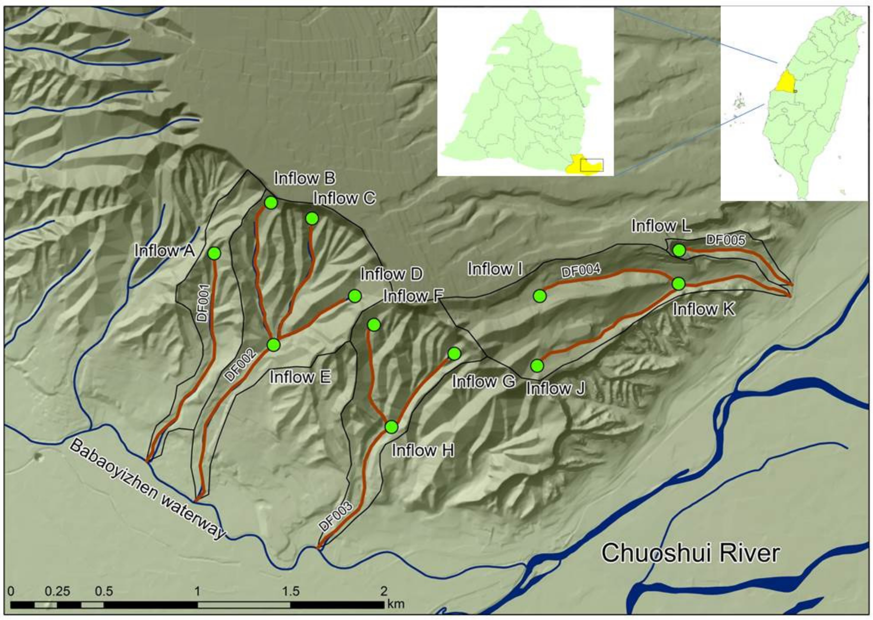
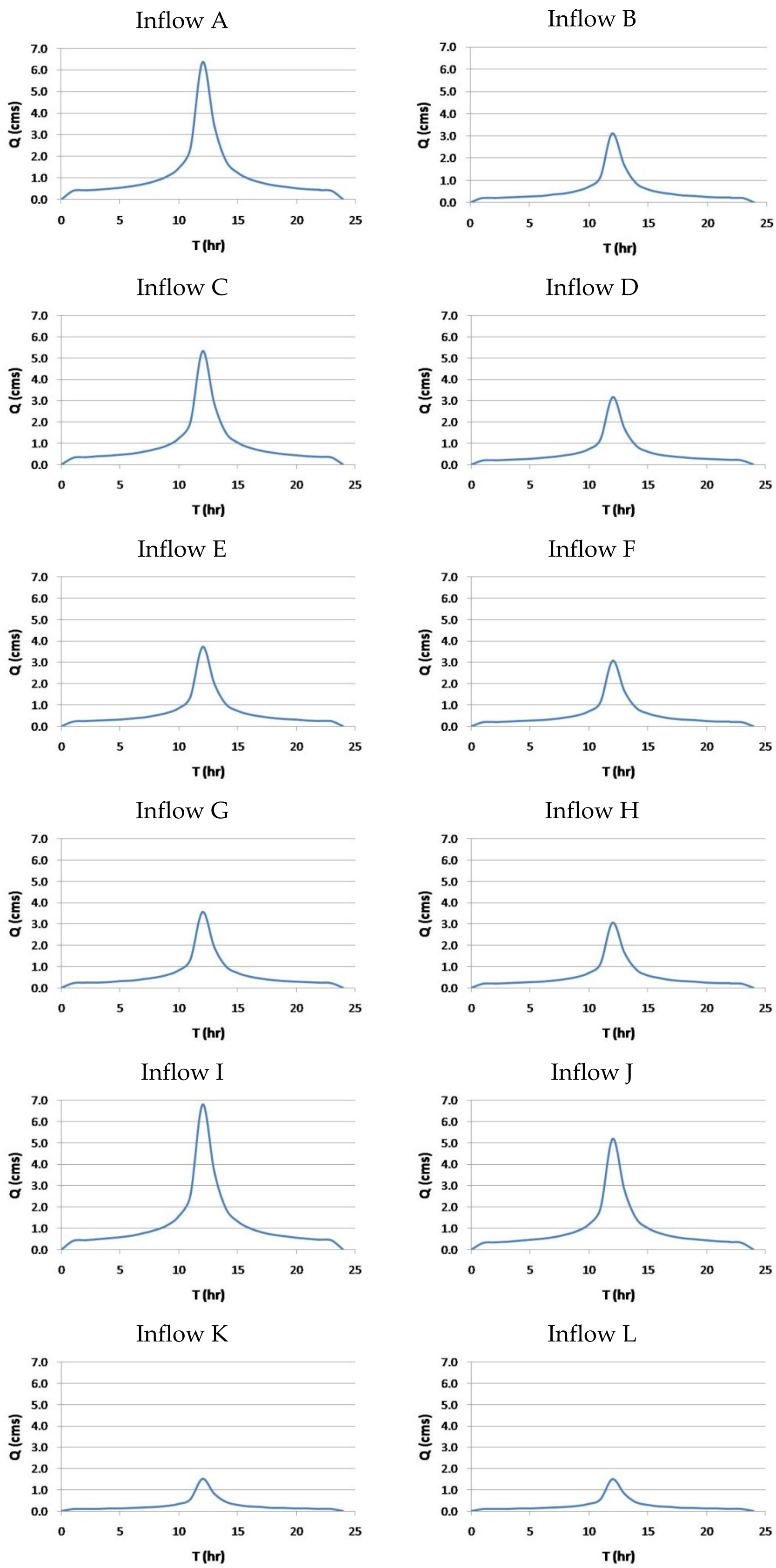


Figure 6. Horner hyetograph of 50-year recurrence interval in Liufenliao Station.



(**a**)

Figure 7. *Cont.*



(**b**)

Figure 7. Simulation of inflow discharge hydrograph: (**a**) sub watersheds; (**b**) Inflow hydrographs A–L.

The debris flow rheological parameter is estimated using equations suggested by the FLO-2D users' manual [36]:

$$\tau_y = \alpha_1 e^{\beta_1 C_v} \quad (11)$$

$$\eta = \alpha_2 e^{\beta_2 C_v} \quad (12)$$

where τ_y is the yield stress; η is the viscosity coefficient; C_v is the debris flow volume concentration; and α_1, β_1, α_2, and β_2 are coefficients calculated with empirical formula. Because there is no empirical formula of debris flow rheological parameters for the Changhua areas, the testing results Jan *et al.* [37] obtained using a tube rheometer for Shenmu Village in Nantou County, Taiwan in 1997, as organized by a previous study [38], are used: $\alpha_1 = 0.811$, $\beta_1 = 13.72$, $\alpha_2 = 0.00462$, and $\beta_2 = 11.24$. The inflow hydrograph and rheological parameters above are utilized for simulating the debris flow in Ershui Township (Figure 8).

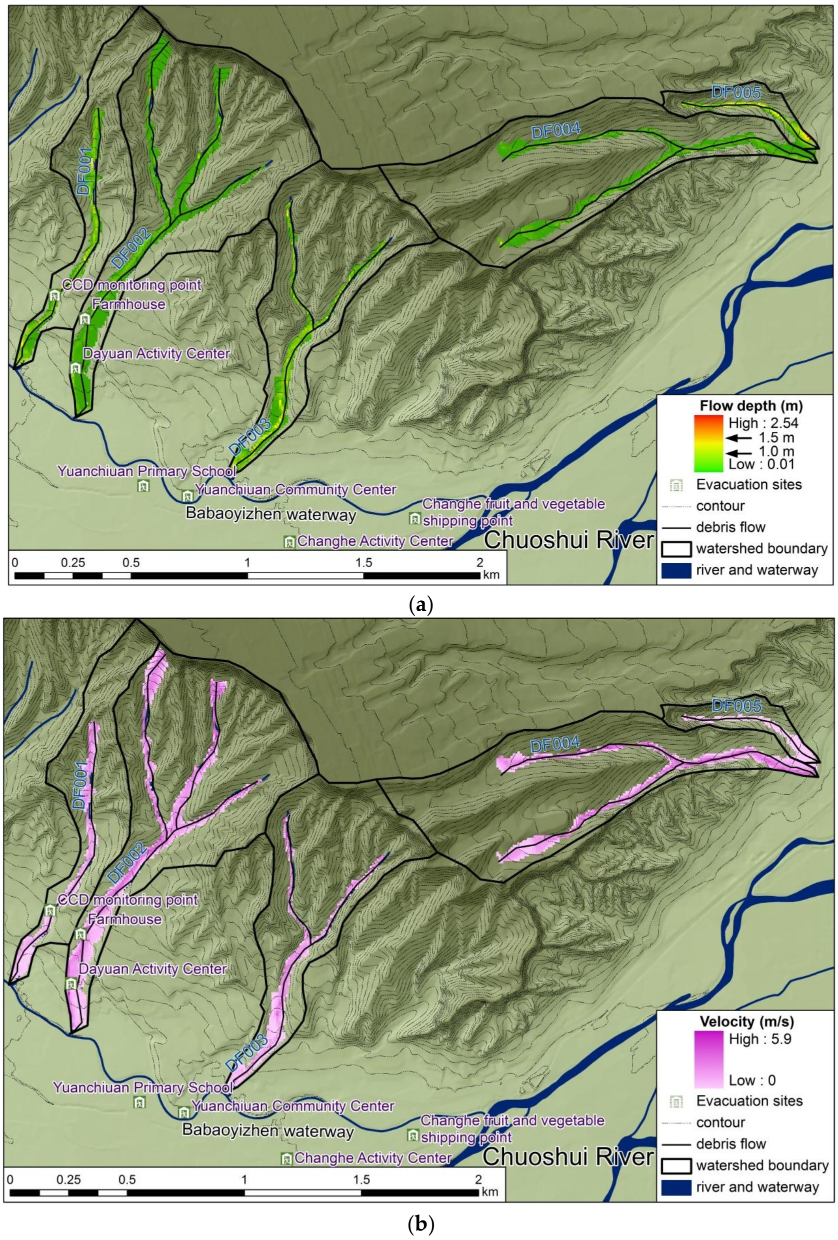


Figure 8. FLO-2D simulation result. (**a**) Simulation of maximal flow depth; (**b**) simulation of maximal flow velocity.

3.3. Hazard Assessment of Debris Flow Evacuation Sites

Mapped soil, geology, and digital elevation model (DEM) data were collected and a previous environmental evaluation was obtained using an ArcGIS overlay analysis (ESRI Company). The environmental risk overlay result is shown in Figure 9, which covers all watersheds of debris flow in Ershui Township. The figure indicates the final environmental risk using a multicolor GIS overlay; as the GIS uses same grid elements as the FLO-2D simulation, environmental risks can be determined from this result by exporting the grid positions or coordinates. Possible evacuation sites for potential debris flow torrents in Ershui Township (numbered DF001–DF005) are listed in Table 8. The fuzzy expert evaluation results can be obtained by inputting the location of each evacuation site into the established model.

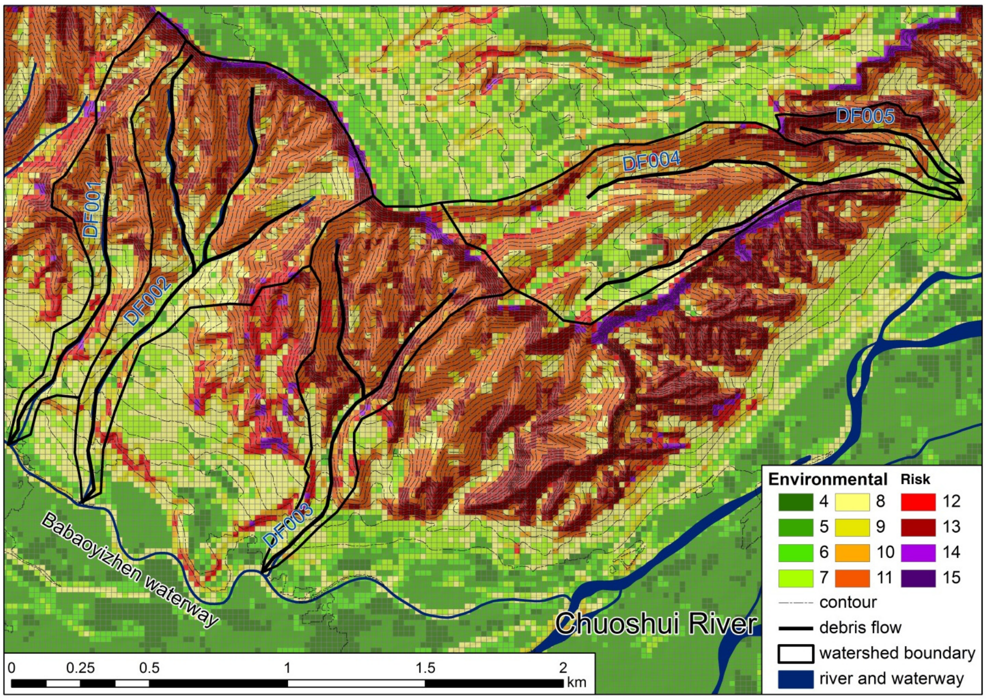


Figure 9. Environmental risk overlay in research area.

Table 8. Hazard assessment of debris flow evacuation sites.

No.	Name	Position X	Position Y	Environmental Risk	Potential Debris Flow	Hazard Rating
1	Yuanchiuan Primary School	213,624	2,632,953	4	0	11.0
2	Yuanchiuan Community Center	213,814	2,632,909	8	0	32.6
3	Changhe fruit and vegetable shipping point	214,792	2,632,813	5	0	11.0
4	Changhe Activity Center	214,250	2,632,687	4	0	11.0
5	Dayuan Activity Center	213,332	2,633,460	8	3	66.3
6	CCD monitoring point	213,243	2,633,773	12	1	66.3
7	Farmhouse	213,372	2,633,672	9	3	67.4

In this assessment system, users input the coordinates of evacuation site positions and the corresponding environmental risks based on Figure 9 in order to obtain potential debris flow grades calculated according to the classification system in Section 2.3 (Figure 10). These results are used as inputs to the fuzzy logic system, with the outputs shown in Figure 11. The first column in Figure 11 lists the operation of the 20 fuzzy rules for environmental risk, while the operation of fuzzy rules for potential debris flow is listed in the second column. The third column shows the assessment results of the fuzzy logic system; for instance, a hazard rating of 66.3 for the Dayuan Activity Center.

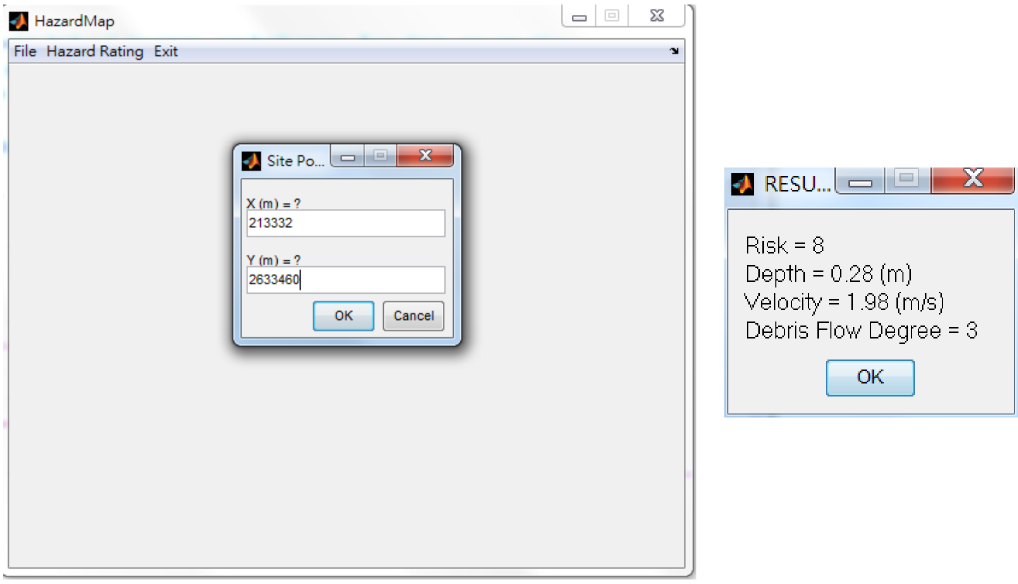


Figure 10. Calculation of environmental risk and potential debris flow grade with GIS overlay (the example of Dayuan Activity Center).

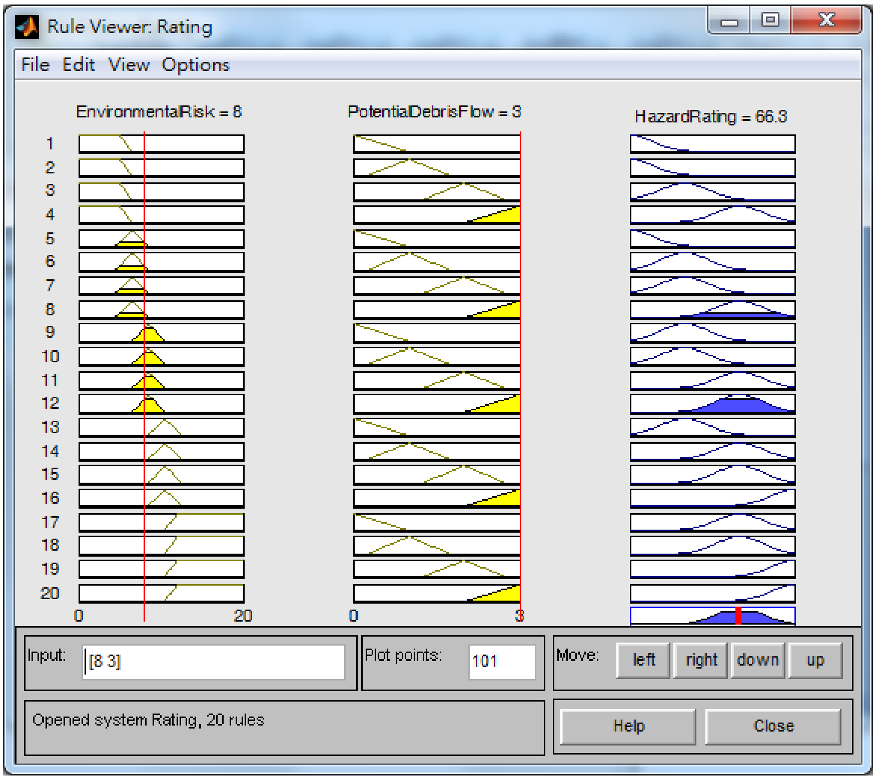


Figure 11. Hazard rating evaluated with fuzzy expert system (example for Dayuan Activity Center).

A comprehensive comparison of the sites (Yuanchiuan Primary School, Yuanchiuan Community Center, Changhe fruit and vegetable shipping point, Changhe Activity Center, and Dayuan Activity Center) is given in Table 8. The Yuanchiuan Primary School, Changhe fruit and vegetable shipping point, and Changhe Activity Center each scored hazard ratings of 11. The Dayuan Activity Center scored 66.3; as this is over 50, it is not suitable as an evacuation site. The Yuanchiuan Community Center scored 32.6, which is slightly higher than the Yuanchiuan Primary School, Changhe Activity

Center, and Changhe fruit and vegetable shipping point, but still acceptable. These evaluation results match those for the debris flow evacuation sites announced by SWCB, which only suggests four sites (No. 1–No. 4 in Table 8) for debris flow evacuation on its disaster prevention maps. A position is suggested for the installation of a charge-coupled device (CCD) debris flow monitoring alert system to be preset by the Changhua County Government; this point presents a high possibility of debris flow and is near farmhouses next to a steep river, which have high hazard ratings.

The occurrence, scale, and timing of natural disasters cannot be accurately predicted at the present stage of technology, and the benefits of relying entirely on engineering methods to reduce the damage of natural disasters are inconsistent with the cost in terms of human and economic aspects. Using territorial planning and disaster prevention to achieve mitigation, on the other hand, is feasible. In line with this, the methodology of establishing environmental indicators for hill tribe risk assessment [39] and debris flow evacuation refuge decision-making model [40] are often mentioned. However, current methods for blending GIS and fuzzy expert system outputs in order to hazard rate debris flow evacuation sites are limited. This study proposes a concept and set up an assessment approach and model in which, for a selected target area, users can input position coordinates of facilities and then quickly obtain hazard rating results output by an expert system. This represents a convenient methodology for use by managers or disaster rescue personnel that can be expanded, for example, to houses of residents. Furthermore, local governments can also determine emergency priorities for sites before debris flows occur.

4. Conclusions

Major typhoons and flood disasters frequently occur in Taiwan, resulting in serious losses. To cope with future climate and natural environment change, our thinking about disaster planning needs to be refined and expanded. In the face of natural disasters and the need to better plan for emergency relief, this study took the viewpoint of ensuring local safety and resilience as an impetus to investigate evacuation sites in hillside communities facing frequent disasters. The result of the study was a fuzzy expert system for the hazard rating of debris flow evacuation sites in Ershui Township, Changhua County, Taiwan, which was coupled to a GIS using numerical simulations of potential debris flow disaster. This system can quantify evaluation results in order to provide essential assistance for evacuation sites neighboring disaster areas or to help in the evaluation of evacuation mechanisms and disaster prevention models. The study combined analysis of geological conditions with the numerical simulation of potential debris flows and utilized an innovative fuzzy logic system to successfully establish an evaluation model for debris flow evacuation sites. The assessment results were in close agreement with the results of field investigations, suggesting that this method is a feasible approach that is worthy of continued research in the future.

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