

The application of genetic algorithm in debris flows prediction

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Abstract Debris flows caused serious loss of human lives and damages to properties in Taiwan for the past decades. A number of methods for prediction of debris flows have been studied including numerical method, statistic method, experiment method and neural network method in recent years. This study proposed a genetic algorithm (GA) model for occurrence prediction of debris flows. A total of 154 potential cases of debris flows collected in eastern Taiwan were fed into the GA for training and testing. The average ratio of successful prediction reaching 90.4% demonstrates that the presented GA model can provide a stable and reliable result for prediction of debris flows in the hazard mitigation and guarding system.

Keywords Genetic algorithm · Debris flows · Prediction

Introduction

In Taiwan Island about three-fifths area is occupied by mountains. Therefore, most rivers are short and flow fast. In recent years many hillsides near metropolitan cities in Taiwan have been developed and became residential regions due to economical growth and with high density of population. Typhoons strike Taiwan during the summer period from June to October every year brings bountiful

rainfall inducing serious landslide and debris flows. Figure 1 displays the main spread of debris flows in Taiwan. Table 1 shows a list of some debris flows that occurred in Taiwan from 1979 to 2003 and most of them were induced by typhoons (Lin and Jeng 2000). In addition, rainstorms frequently caused debris flows in mountain areas. For example, during the period from June to September 1999, rainstorms had induced debris flows in many areas from north to south such as Hsihtien, Neihu in Taipei, Shengmu in Nantou, Meishan in Chiayi, Shandi, Lion, and Wutai in Pingdong. As a result of debris flows many human lives have been lost, buildings collapsed, and properties damaged. Besides, in watershed areas water pollution induced by debris flows severely shortens the lifetime of dams and affect purity of water. Without pure water, the daily life of people can be very inconvenient; so also, the agricultural irrigation and industrial usage. For example, typhoon Aere hit Taiwan on 24 August 2004 and triggered the debris flow causing the aforementioned disasters and water pollution that left many thousands of residents without water supply for several days in northern Taiwan (Table 2).

To verify the occurrence of debris flow, experts and researchers utilize topography, air photos, satellite images as well as site investigation. It is a time-consuming and tedious work for monitoring debris flows and data collection. Therefore, how to predict the occurrence of debris flows becomes an important and challenging task in Taiwan.

Chen (1984), Chang and Hsieh (1996, 1997), and Chang (1998) investigated the debris flows in potential creeks around the developed residential areas in Taiwan. Chang and Ru-Jen (2006) used Back-propagation of Neural Networks (Negnevitsky 2002; Russell and Norvig 2003; Schalkoff 1997) to treat nonlinear problems for build a model on the occurrence of debris flow that study proposed

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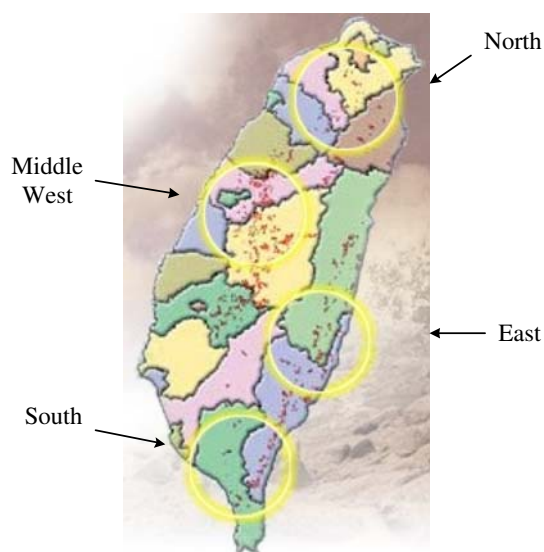


Fig. 1 Spread of debris flows in Taiwan

well results. Chyan-Deng Jan et al. (2004), defined as a debris-flow rainfall-triggering-index (RTI), using the product of rainfall intensity and effective accumulated rainfall to predict debris flow. Preprocess for critical precipitation line is quite complicated and is not a simple work. Chang and Lee (1997) analyzed the instant rainfall intensity in the areas of debris flows using group method of data handling (GMDH) with artificial neural networks (ANN) introduced by Ivakhnenko (1970).

Senoo et al. (1985) and Chan and Haung (1987) took rainfall indexes for early warning and evacuating program of debris flow. Keefer et al. (1987) used a precipitation duration and intensity data, to predict the occurrence of debris flow. Also Wieczorek (1987) and Hirano and Moriyama (1993) took intensity duration to control debris flows. Hsieh et al. (1995) used rainfall data about the debris flow hazard, which had been collected in Taiwan to obtain the function of critical line of the two groups, rainfall data of debris flow occurrence and non-occurrence. Fan and Tsai (2003), used Fisher's discriminate function of multivariate statistical analysis to analyse the occurrence of debris flow. The occurrence predictions of debris flows with instant rainfall intensity could not always produce very good and stable results, which explains that the instant rainfall intensity was not the only factor causing debris flows.

Slope stability is another important factor causing debris flow (Johnson and Rodine 1984). Besides rainfall and slope factors, soil weight and water level are also important factors (Wang 1994). Chang and Hsieh (1996) had investigated the debris flow occurrence in the eastern Taiwan and pointed out some important factors such as length,

slope, watershed area, effective rainfall intensity and cumulative rainfall. The length, slope, watershed area, and effective rainfall intensity, were also identified as important factors of debris flows by Fang and Yao (1997). Lee and Chang (1995) presented a fuzzy model for prediction of debris flows, but did not consider the cumulative rainfall was an important factor. Still, after defuzzification, this fuzzy model did not tell a clear and specific lower bound (or a crisp value) that can be used for the indication of debris flows.

The authors of this study believe that the causes of debris flow are not only related to current rainfall but also related to previous rainfall. An effective cumulative rainfall contains two parts: (1) the previous effective cumulative rainfall and (2) the current effective cumulative rainfall (Hsieh 1993). A continuous rainfall can be defined as a period of precipitation during which, there is no rainfall more than 24 h before and after this period. The previous effective cumulative rainfall is 1 week (168 h) before the current continuous rainfall. The current effective cumulative rainfall is a period of rainfall and debris flows occur within that period. It is hard to determine the exact time of occurrence of a debris flow except by continuously recording observations. Therefore, an effective cumulative rainfall can be defined as a continuous rainfall from the time point A reaching 4 mm/h to the time point of occurrence of debris flow (Hsieh 1993). Usually, the time of occurrence of debris flow is the first peak rainfall during a continuous rainfall period.

Obviously, the slope is an essential and important factor for the occurrence of debris flows. About 86% of debris flows occurred in the slope within the range from 10° to 25° in eastern Taiwan (Chang 1995). The length of streams is also an important factor for debris flows. A total of 77% debris flows occurred in the streams within the length ranging from 500 to 2,000 m in eastern Taiwan (Chang 1995).

The size of effective watershed area is related to the rainfall that can be collected. A larger effective watershed area can collect more rainfall. Therefore, a larger watershed area has a higher chance to induce the debris flow. About 59% of effective watershed areas from 10 to 120 ha (10,000 m²) are the potential debris flows in eastern Taiwan (Chang and Hsieh 1996).

The shape factor could be another influence factor on debris flow. The shape factor, F , is defined as $F = A/L^2$, where L is the length of mainstream and A is the watershed area. The shape factor is closely related to the distribution of flow rate hydrograph. A narrow and long watershed area has a smaller shape factor and the shape of its flow rate hydrograph is flat. A watershed area with a large shape factor has higher chance to cause the occurrence of debris flow if other conditions are the same.

Table 1 Some debris flows in Taiwan

Date	Typhoon/rainstorm	Location (village, stream)	Town/country	City/county	Region
1979/08/15	Oumin		Shiuhding	Taipei	North
1981/07/19	Maury	Chiunglin,	Chiunglin	Hsinchu	North
1981/07/19	Maury		Sanhsia	Taipei	North
1981/07/19	Maury		Shiuhding	Taipei	North
1982/08/11	Cecil		Linkou	Taipei	North
1985/10/04	Beth		Kuonliau	Taipei	North
1987/10/25	Lynn		Reifun	Taipei	North
1987/10/25	Linen		Shanchih	Taipei	North
1994/08/08	Doug	Datrucon	Reifun	Taipei	North
1996/09/28	Storm	Anyi road		Keelung	North
2000/11/01	Xangsane	Datrucon	Reifun	Taipei	North
2000/11/02	Xangsane	Chunher	Jinshan	Taipei	North
2001/08	Toraji	Naiwan	Geolan	Miauli	Middle West
2001/08	Toraji	Dili	Hsinyi	Nantou	Middle West
2001/08	Toraji	Fongchiu	Hsinyi	Nantou	Middle West
2001/08	Toraji	Bisheih	Hsinyi	Nantou	Middle West
2001/08	Toraji	Sanmuon	Hsinyi	Nantou	Middle West
1998/05	Otto	Fongchiu	Hsinyi	Nantou	Middle West
1998/05	Otto	Irbu	Suali	Nantou	Middle West
1998/05	Otto	Sanbu	Suali	Nantou	Middle West
1996/07/31	Herb	Fongchiu	Hsinyi	Nantou	Middle West
1996/07/31	Herb	Bisheih	Hsinyi	Nantou	Middle West
1996/07/31	Herb	Sanmuon	Hsinyi	Nantou	Middle West
1985/08	Nelson	Fongchiu	Hsinyi	Nantou	Middle West
2001/09/16	Nari	Whahsan	Gouken	Yunlin	South
2001/09/16	Nari	Fonghsan	Alihsan	Chiai yi	South
2001/09/16	Nari	Duanlu	Chuchi	Chiai yi	South
2001/08	Toraji	Jeanchin	Wanlun	Hualien	East
2000/08	Bilis	Dahsing	Kuanfu	Hualien	East
1994/07	Tim	Dahsing	Kuanfu	Hualien	East
1991/09	Nat	Dahsing	Kuanfu	Hualien	East
1990/09	Dot	Dahsing	Kuanfu	Hualien	East
1990/06	Ofelia	Tonmen	Showlin	Hualien	East
1990/06	Ofelia	Dahsing	Kuanfu	Hualien	East
1989/09	Sarah	Dahsing	Kuanfu	Hualien	East

The occurrence of debris flows is also related to the grain size of deposit in the riverbed around watershed areas. In general, a small grain-size of soil only needs a shallow water to cause debris flow and a large grain-size of soil needs deeper water. The grain-size of soil can be obtained from the deposit in the riverbed (Chang 1995).

The objective and motivation of this study is to demonstrate a simple, rapid, and convenient analytical model for the debris flow prediction without performing a complicated, and non-linear mathematical and mechanical analysis (e.g. Takahashi 1977; Chang 1995). As mentioned before, previous research could not always get a stable and

reliable result because they selected fewer factors for prediction. In order to get a stable and reliable prediction, the authors analyzed the geological and environmental conditions and chose seven factors including rainfall intensity, creek length, slope, effective watershed area, shape coefficient, median size of soil, and effective cumulative rainfall for prediction. The seven factors constructed a GA model using genetic algorithm (GA) for debris flows analysis and prediction. After training, the adjusted weight can be directly utilized for debris flow prediction. This model can be used to assist in the hazard mitigation and warning systems.

Table 2 Locations of selected samples from risky rivers in eastern Taiwan

Location	Observation station	Coordinates
Fawha Mountain	Beimen	E304.7, N2653.8
Tonmen Village	Tonmen	E299.1, N2651.8
Fonlin Creek	Mataiein	E293.1, N2627.0
Shoufon Creek	Shihlin	E292.9, N2635.6
Nanchin Creek	Dapin	E288.1, N2615.6
Honyen Creek	Lisan	E282.2, N2604.5
Fushin Creek	Fonbean	E290.3, N2607.4
Chinshui-chionliang Creek	Chuolu	E277.8, N2573.4
Chuo Creek	Miaupu	E279.2, N2583.0
Chiuain Creek	Minli	E380.0, N2567.5
Dongshin	Fonbean	E303.5, N2614.9

Theory of genetic algorithm

Genetic algorithm is a kind of search algorithm established by simulating the genetic and evolution processes of biological field for acquisition of the near-optimal solution of a certain problem. It presents the competitive mechanism of “competition for survival, victory to the superior and elimination of the inferior, survival of the fittest.” GA is an algorithm receiving close attention when applied to search, optimization and mechanical learning. This algorithm has been extensively applied to solving different kinds of problems. It is proved to be effective and efficient in solving the optimization problems of different aspects.

The basic idea of GA is to start searching from the search space a group of randomly produced initial solutions, which are called a “population.” In the population each individual is a solution of a problem, or termed as “chromosome.” Through the “fitness function” of chromosome, the quality of chromosome can be rated. The chromosome with great fitness function has a high probability of being selected. On the contrary, the chromosome with small fitness function has a low probability of being selected. The selected chromosome is brought to the next generation. Through such genetic operations as crossover and mutation, the chromosomes of the next generation produce new chromosome, which is called the “next generation.” Having gone through several generations, the algorithm is converged at the best chromosome, which is just the optimal solution or near-optimal solution of problem.

The calculation procedures of GA can be summarized as GA (crossover and mutation) and evolution algorithm (selection). GA simulates the reproduction process of new generation by genes in each generation, and evolution algorithm is a process of continuous renewal of population through competition.

Comparing the typical GA and the traditional optimization algorithm, their characteristics are summarized as follows:

1. GA is a calculation of the code of solution set, instead of a calculation of solution set itself.
2. The search of GA is originated from a population of solutions, instead of certain individual solutions.
3. GA only uses fitness function for rating whether a solution is good or bad.
4. GA adopts probability search, instead of path search (Goldenberg 1989; Fogel 1998)

When solving special problems, GA has to possess five elements as follows (Michalewicz 1999):

1. An application of genes to express the possible solution to a problem.
2. A creation method of the initial population of the possible solution.
3. An evaluation function that plays the role of the environment, rating solutions in terms of their “fitness.”
4. How genetic operators change the tissue of sub-generation.
5. The variables that GA has to use, such as the number of populations, probability of the use of genetic operators.

The procedures of GA motion can be described according to the following procedures:

1. Randomly produce initial population.
2. Rate the chromosome by using fitness function.
3. Select the chromosome with high fitness function for rating.
4. Produce new chromosome through genetic and mutation operations.
5. Repeat steps 2 to 4 continuously until the preset evolution algebra is reached.

First of all, this study uses real numbers and strings to demonstrate the commencement of the use of model for optimization. Simple GA brings out quite good results in solving many practical problems. It has three operators, including reproduction, crossover and mutation. Reproduction is an independent string acquired through the duplication of fitness function value. For the duplication of fitness function value, the string with better fitness capability has higher probability to reproduce the next generation. The whole reproduction process is carried out according to Darwin’s Evolution Theory.

After the reproduction procedure, select a pair of strings from the crossover pool, and then randomly produce an integer L from the range $(1, K - 1)$, where K denotes the length of string. The two strings exchange all the characters

from positions $L + 1$ to K . Taking the two strings, $S1$ and $S2$ for example:

$S1 = 1\ 23\ 8\ 35\ 21\ 9\ 47$
 $S2 = 43\ 0\ 5\ 84\ 2\ 17\ 44$

Randomly produce an integer $L = 4$ from the range $(1, 7 - 1)$. Then the strings $S1'$ and $S2'$ after crossover are indicated as follows:

$S1' = 1\ 23\ 8\ 35\ 2\ 17\ 44$
 $S2' = 43\ 0\ 5\ 84\ 21\ 9\ 47$

Although reproduction and crossover can effectively re-group and search strings, some useful genes may be probably missed. Therefore, the mechanism in simple GA

with lower production probability can be used. Through the upper and lower bounds of problem, mutation randomly produces new string.

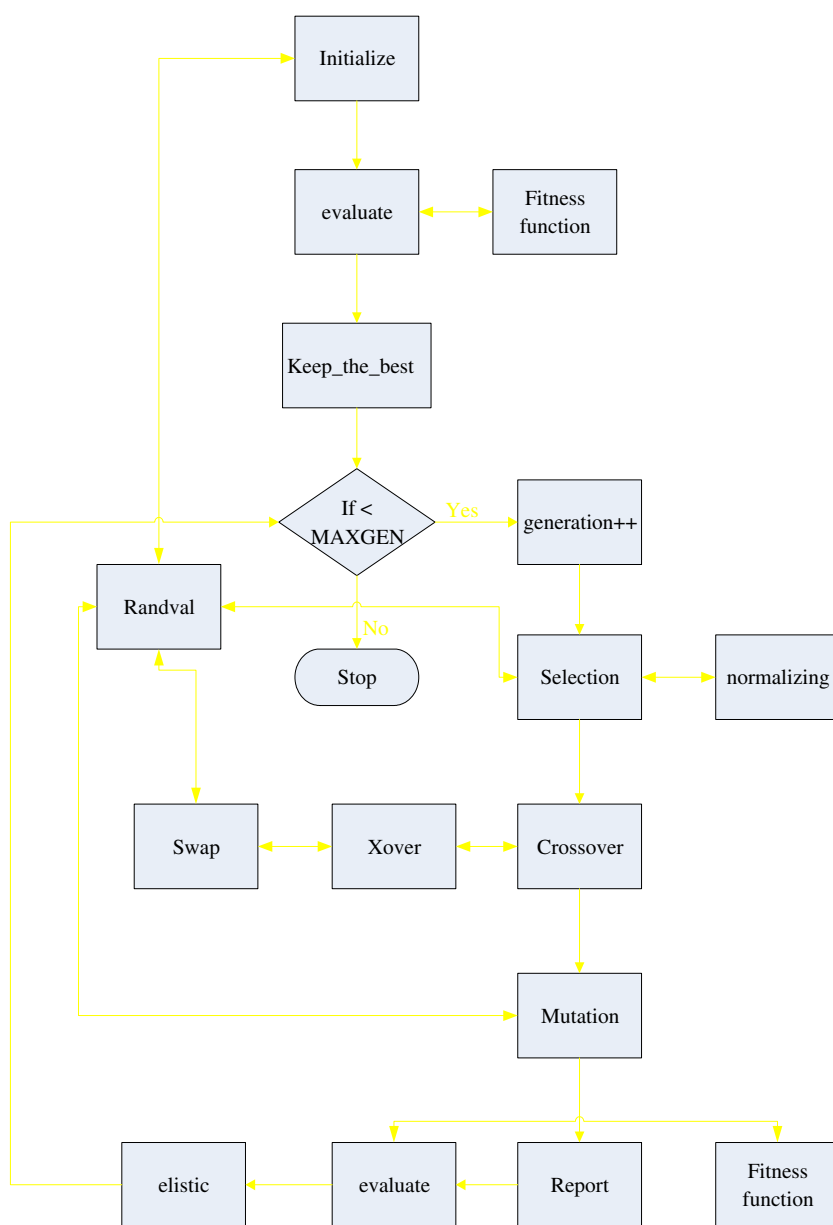
The GA flow chart of this paper is shown in Fig. 2.

Cases study and results

The occurrence of debris flow is a complicated non-linear problem, and the factors of debris flow are caused at random. In view of no fixed rule to follow in the design of fitness function, this study designs a fitness function F_x , as shown in Eq. 1–4.

Equation 1 is defined as the coefficient function f for the factors of occurrence of debris flow. In order to acquire the

Fig. 2 Structure of genetic algorithm (GA)



optimal group of coefficients, fitness function F_x takes the related minimum square error (MSE) of the group of coefficients randomly selected in each generation as the criterion.

$$f = \sum_{i=1}^7 b_i \times A_i \tag{1}$$

$$f_{jk} = \sum_{i=1}^7 b''_{ik} \times A_i \tag{2}$$

$$R_k = \text{SQRT} \left[\frac{\sum_{j=1}^m (f_{jk} - \bar{f}_{jk})^2}{m - 1} \right] \tag{3}$$

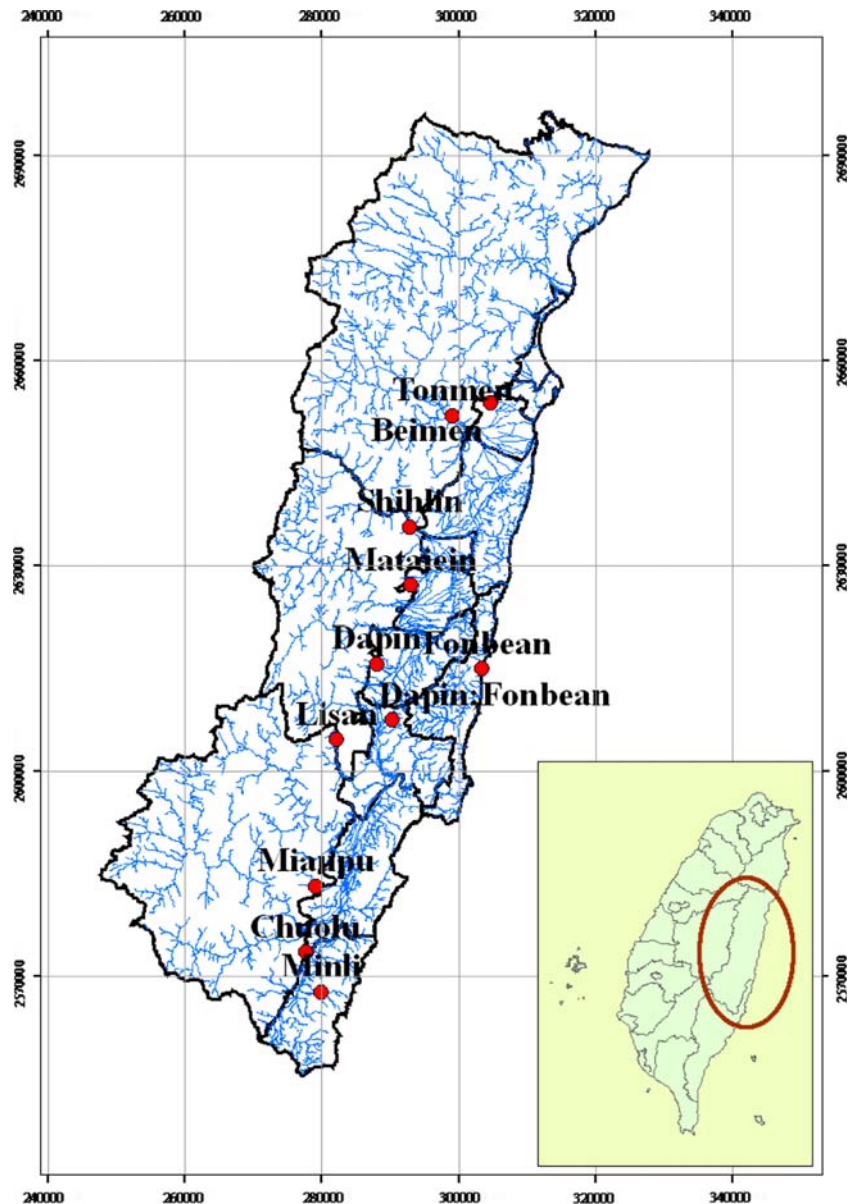
$$F_k = \text{MAX} \left(\frac{1}{R_k} \right) \tag{4}$$

where:

- A_i : factors of occurrence of debris flow
- b_i : coefficient, $i = 1 - 7$
- m : number of training groups
- k : population size
- b'' : coefficients randomly selected

The range of genetic search in this study covers: upper bound = 10 (or 100 for effective cumulative rainfall), lower bound = 1, population = 2,000, generation = 800, $P_x = 0.8$ (probability of crossover), $P_m = 0.01$ (probability

Fig. 3 Distribution of debris flows in study area



of mutation), Roulette wheel for the selection process, GA code modified from “Genetic Algorithms + Data Structures = Evolution Programs” (Michalewicz 1999).

Data-pre-processing

This study employs the seven influencing parameters of debris flow mentioned above, namely the length of creek, average slope, effective watershed area, shape coefficient, median size of soil, effective cumulative rainfall, and effective rainfall intensity. Since the numerical values of these parameters range from as small as less than 1 to as large as above 3,000, such a great difference of numerical values makes it difficult to control and determine the range of search solutions, or the upper and lower bounds of solution during the GA application. Therefore, it is necessary to normalize the original data, and make all the data mutate between one and ten.

This study took 154 debris fall cases that occurred in eastern Taiwan (as shown in Fig. 3) in the past years as the samples. In the data group there were 29 groups of debris flow data, which were divided into two parts in times of calculation. Among them, 24 groups served as the test group, and the rest of the 5 groups served as the testing group that acquired optimal combination coefficient by using GA. Finally, the 125 groups without occurrence of debris flow were taken as the prediction group (Fig. 4).

Normalizing

In the evolution process, due to the adoption of elite policy, some individuals occupy the whole individual appearance probability too early. Perhaps these individuals are not the optimal values. However, to maintain a reasonable difference of fitness among individuals, the reliability during the selection of individuals has to be considered. It implies that selective pressures should be appropriately released. This

study employs a normalizing process of the individuals in each generation so as to release the selective pressures, as indicated in Eq. 5.

$$f'_k = (f_k - f_{\min} + \gamma) / (f_{\max} - f_{\min} + \gamma) \tag{5}$$

- f_k : individual value of current generation
- f_{\min} : minimum value of the individual value of current generation
- f_{\max} : maximum value of the individual value of current generation
- γ : positive number which is not equal to 0 and is smaller than 1.

The processing of GA in this study is as follows:

1. By means of random way, use the upper and lower bounds of each parameter to acquire k (population size) groups of gene $b''_{ik}, i = 1 - 7$.
2. Calculate the related function values of each group of genes, and m (number of training groups) function values are acquired:

$$f_{jk} = \sum_{i=1}^7 b''_{ik} \times A_i.$$

3. Fitness function F_x takes the MSE of the m (number of training groups) function values in each generation as the criterion. Select the genetic groups with the greatest F_x in this generation for survival to the next generation:

$$R_k = \text{SQRT} \left(\frac{\sum_{j=1}^m (f_{jk} - \bar{f}_{jk})^2}{m - 1} \right) \quad F_k = \text{MAX} \left(\frac{1}{R_k} \right).$$

\bar{f}_{jk} : mean of m (number of training groups) function values.

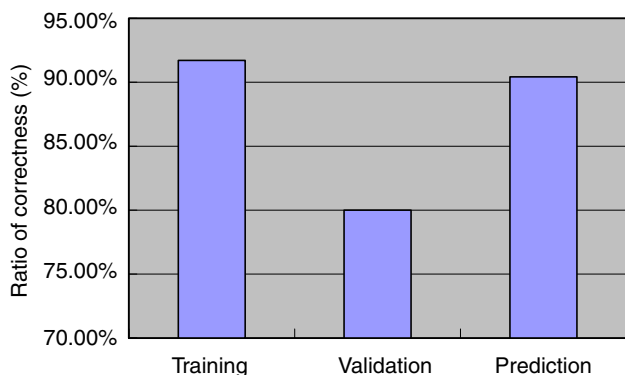


Fig. 4 Ratio of correctness in different phases in GA analysis

Table 3 The ten results in GA phase

N	Percentage of success in training (%)	Percentage of success in verification (%)	Percentage of success in test (%)
1	91.67	80	89.6
2	91.67	80.0011	90.4
3	91.67	80.0012	88.8
4	91.67	80.0011	88
5	91.67	80.0012	90.4
6	91.67	80.0011	90.4
7	91.67	80.0013	90.4
8	91.67	80.0011	89.6
9	91.67	80.0011	90.4
10	91.67	80.0011	88.8

Table 4 Mean of results after 10 times of genetic algorithm

Determination criterion	Training group (occurring) (%)	Testing group (occurring) (%)	Prediction group (not occurred yet) (%)
$<1.5\sigma$ (debris flow occurs)	91.7 (success rate)	80 (success rate)	9.6 (failure rate)
1.5σ (debris flow not occurred yet)	8.3 (failure rate)	20 (failure rate)	90.4 (success rate)
Average success rate	87.4		

4. Randomly select the group of genes of the next generation according to normalizing principles.
5. Process the genetic exchange and mutation.
6. Repeat steps 2 to 6 until the iteration frequency is greater than the preset value.
7. Calculate the optimal genetic group acquired in the last generation, and substitute it for the data of each training group to obtain the function value of training group.
8. Calculate the function value of each training group and the difference of means of function values in each training group. The difference, if greater by 1.5 times the standard deviation, is taken as the statistical critical value. The difference being less than 1.5 times of standard deviation is preset as a situation when debris flow occurs. The difference being greater than 1.5 times of standard deviation is preset as a situation where debris flow has not occurred yet.

When performing GA for 10 times, the authors calculated the mean and standard deviation of the function values in 24 training groups each time, as well as the difference between the function values and the means of 5 testing groups and 125 prediction groups. The authors also made a statistics on the proportion of the number of standard deviation with difference being smaller than 1.5 times to the number of standard deviation with difference being greater than 1.5 times. The results of algorithm done for 10 times are indicated in Table 3 For the results of the 10 times' algorithm, the predicted success rate of debris flow is 91.7% in average in training group, and 80% in testing group. With GA being applied to the prediction group with no occurrence of debris flow, the success rate is 90.4% in average. The average success rate of these three groups is so high to reach 87.4% (Table 4). Apparently, this method is able to obtain very good prediction results.

Summary and conclusions

This study presents a simple and easy model by using GA model for debris flows analysis and prediction. The application of GA can achieve optimized network structure rapidly. In order to get a stable and reliable prediction, seven significant factors of debris flows were chosen for

input. These seven factors are : (1) length of creek, (2) average slope, (3) effective watershed area, (4) shape coefficient, (5) median size of soil, (6) effective cumulative rainfalls, and (7) effective rainfall intensity.

A total of 154 potential debris flow cases in Taiwan were collected and used for analysis and prediction. In a randomly selected run, the ratio of success in training, testing and prediction reaches 91.7, 80 and 90.4%, respectively. The average ratio of correctness is 87.4%. This demonstrates that the presented model of GA is stable and reliable, and can be used to predict the occurrence of debris flows in hazard mitigation systems.

References

- Chan L, Huang M (1987) A study of the artificial intelligence system for debris flow warning system. In: The Proceedings of 10th Hydraulic Engineering Conference, Taipei, Taiwan, ROC, H2–H7
- Chang TC, Ru-Jen C (2006) Application of back-propagation networks in debris flows. *Eng Geol* 85:270–280
- Chang FJ, Lee SP (1997) A study of the intelligent control theory for the debris flow warning system. In: Proceedings of the 1st debris flows conference, Taipei, Taiwan, ROC, pp 109–123
- Chang TC (1995) Study of model for hydrograph of debris flows. The proceedings of 10th National Conference of Technology and Vocational Education, Industry (V), pp 265–272
- Chang TC, Hsieh CL (1996) Site investigation and analysis for debris flows in eastern Lan-Yun District. *Chin Water Soil Reserv Rep Taiwan* 27(2):139–150
- Chang TC, Hsieh CL (1997) Field investigation and analysis of debris flow in central Taiwan. *J Chin Agric Eng Taiwan ROC* 43(3):31–46
- Chang TC (1998) Field investigation and analysis of potential debris flow in northern Taiwan. *J Chin Agric Eng Taiwan ROC* 44(3):51–63
- Chen SH (1984) Study of investigation method for debris flow hazard. The Department of Forest, National Taiwan University, pp 99–101
- Chyan-Deng J et al (2004) A debris-flow rainfall-based warning model. *J Chin Soil Water Conserv* 35(3):275–285
- Fang CC, Wu MF, Pon GC (1999) Study in critical precipitation line of debris flows in Fongchui. *Geotech Technol Taiwan* 74:39–46
- Fang CC, Yao CS (1997) Preliminary study of hydrology and geology conditions in occurring region of debris flows in eastern Taiwan. The 1997 Agricultural Engineering Conference, Taiwan, ROC, pp 521–531
- Fan JC, Tsai IT (2003) Real-time evaluation and test for the occurrence probability of debris flows of the first order streams in the Nan-Tou Area, Thesis of master at Taiwan University
- Fogel DB (ed) (1998) *Evolutionary computation*, IEEE Press, New York

- Goldenberg DE (1989) Genetic algorithms in search, optimization and machine learning, Addison Wesley, Reading
- Hirano M, Moriyama T (1993) Prediction of occurrence and runoff analysis of debris flows. In: Proceedings of National Conference on Hydraulic Engineering, ASCE, pp 1780–1785
- Hsieh CL (1993) Debris flow warning system II, Project of Council of Agriculture, Executive Yuan, Republic of China
- Hsieh CL, Lu YC, You BS, Chen LR (1995) Methodology for critical precipitation line of debris flows occurrence. Chin Water Soil Reserv Rep Taiwan ROC 26(3):167–172
- Ivakhnenko AG (1970) Heuristic self-organization in problem of engineering cybernetics. Automatica 6:207–219
- Johnson AM, Rodine JR (1984) Debris flow. In: Brunsden D, Prior DB (eds) Slope instability. Wiley, New York
- Keefer DK, Wilson RC, Mark RK, Brabb EE, Brown WM, Ellen SD, Harp EL, Wiczorek GF, Alger CS, Zarkin RS (1987) Real-time landslide warning during heavy rainfall. Science 238:921–925
- Lee SP, Chang FJ (1995) A study of fuzzy control theorem for debris flows warning system. J Chin Soil Water Conserv 26(2):145–154
- Lin ML, Jeng FS (2000) Characteristics of hazard induced by extremely heavy rainfall in central Taiwan–Typhoon herb. Eng Geol 58(2):191–207
- Michalewicz Z (1999) Genetic algorithms + data structures = evolution programs, Springer, Berlin
- Negnevitsky M (2002) Artificial intelligence: a guide to intelligent systems. Addison Wesley, Harlow
- Rumelhart DE, Hinton GE, William RJ (1986) Learning representations by back-propagation errors. Nature (Lond) 323:533–536
- Russell S, Norvig P (2003) Artificial intelligence—a modern approach, 2nd edn. Prentice Hall, Englewood Cliffs
- Schalkoff RJ (1997) Artificial neural networks. International Editions, McGraw-Hill, New York
- Senoo K et al (1985) Rainfall indexes for debris flow warning evacuating program. Shin-Sabo 38(2):16–21
- Takahashi T (1977) A mechanism of occurrence of mud-debris flows and their characteristics in motion. Ann Disaster Prey Res Inst Kyoto Univ V20B-2:405–435
- Wang DS (1994) Study of mechanism of debris flow occurrence, Thesis in Department of Civil Engineering, National Taiwan University
- Wiczorek GF (1987) Effect of rainfall intensity and duration on debris flows in central Santa Cruz Mountains, California, 9 flows/avalanches: Process, Recognition and Mitigation, Geological Society of America. Rev Eng Geol 7:93–104