International Congress
INTERPRAEVENT 2002 in the Pacific Rim - MATSUMOTO/JAPAN
Congress publication, volume 1, pp.135-143

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# SURVEY ON MUDFLOW OCCURRENCE – NON-OCCURRENCE JUDGEMENT METHODS FOR VOLCANIC REGIONS

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**ABSTRACT**

In volcanic regions, the occurrence of mudflows is influenced by conditions such as the quantity of volcanic ash deposition and its permeability. It is, therefore, presumed that when predicting the occurrence of mudflows, it will be possible to predict mudflow occurrence locations more precisely by using a mudflow occurrence - non-occurrence judgement method that reflects the state of volcanic ash deposition. So in addition to rainfall and topography, the mean thickness of volcanic ash deposits in the drainage basin was added to causes of mudflows, and multiple discriminant analysis and the neural network method were used to judge whether mudflows would or would not occur at Usuzan Volcano from its eruption of 1977 until 1981. As a result, a comparison of the judgements of the occurrence or non-occurrence of mudflows made before and after the first use of the mean thickness of volcanic ash deposition in the drainage basin as a causal factor has shown that the precision of such judgements by multiple discriminant analysis has improved; to a maximum of about 20% for occurrence and about 30% for non-occurrence.

**KEYWORDS: Mudflow, volcanic ash deposition, mudflow occurrence - non-occurrence judgement, multiple discriminant analysis, neural network**

## INTRODUCTION

In regions where volcanic products are deposited by eruptions, rainfall causes frequent mudflows (this study only considers mudflows caused by rainfall, but does not include mudflows caused by snowmelt). Warning and evacuation systems must be established to protect the lives of the residents of these regions from such mudflows. There must, therefore, be a high precision method of predicting whether mudflows will or will not occur. It has been pointed out that in volcanic zones in particular, the occurrence of mudflows is related not only to rainfall, but also to the quantity of volcanic ash deposition and its permeability. Therefore, a mudflow occurrence - non-occurrence judgement method that reflects these factors is necessary. As a debris flow occurrence - non-occurrence judgement method that accounts for these factors other than rainfall, a method

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implemented by categorizing a number of factors such as topography, geology, etc. related to debris flow occurrence to judge the risk of a debris flow based on quantification II has been studied. But various problems with this method that have been pointed out are the difficulty of providing the level categorization with universal applicability and the fact that it does not adequately account for rainfall. So in order to solve such problems, debris flow occurrence - non-occurrence judgement methods using topographical factors and rainfall factors performed based on multiple discriminant analysis and based on the neural network have been proposed.

This survey took Hokkaido's Usuzan Volcano where mudflows occurred frequently after its 1977 eruption as a sample case to study the feasibility of applying debris flow occurrence – non-occurrence judgment methods using multiple discriminant analysis or a neural network as proposed by Araki et al. to perform mudflow occurrence - non-occurrence judgements in volcanic regions by reflecting volcanic ash deposition. Since almost no mudflows were caused by rainfall during the eruption of 2000, this period was not included in the survey.

## OUTLINES OF THE USUZAN VOLCANO AND THE MUDFLOWS FOLLOWING THE 1977 ERUPTION

The Usuzan Volcano, located on the north side of Uchiura Bay in south-western Hokkaido, is an active volcano with an altitude of about 700 m standing on the south side of the Toya Caldera that forms Lake Toya (Fig. 1). It is highly active, with historical reports of seven eruptions. The most recent eruption of 2000 continued intermittently from March to July in a western foothill. Four nearby municipalities suffered serious damage caused by the volcanic ash discharged in large quantities, by diastrophism, and inundation by muddy water presumably discharged from the eruptive crater.

**Fig. 1** Location of Usuzan Volcano

The previous eruption continued intermittently from August 1977 to October 1978 in the crater floor. Damage far worse than that of the 2000 eruption was caused in surrounding municipalities by volcanic ash and pumice stone discharged in large quantities, and by mudflows.

A total of about 30 mudflows occurred between 1977 and 1981, because the eruptions in 1977 and 1978 deposited a large quantity of volcanic ash in the surrounding region. The worst of these, which occurred on October 24, 1978, deposited approximately 150,000 $m^3$ of sediment at the Toya Lake Hot Spring and at the Sobetsu Hot Spring, resulting in two fatalities and one missing person.

## MUDFLOW OCCURRENCE – NON-OCCURRENCE JUDGEMENT METHOD BASED ON MULTIPLE DISCRIMINANT ANALYSIS

### Outline of multiple discriminant analysis

Araki et al., proposed the following debris flow occurrence – non-occurrence judgement method based on multiple discriminant analysis.

$$Z = -A_0 + \sum_{i=1}^{n} B_i X_i + \sum_{j=1}^{m} C_j X_j$$

Z: complex variable
$A_o$ : constant term
$B_i$ : coefficient of topographical factors
$C_i$ : coefficient of rainfall factors
$X_i$ : value of the topographical factor (i=1....n)
$X_j$ : value of rainfall factor (j=1.....m)

With this method, the topographical factors and the rainfall factors are used as explanatory variables for two populations: occurrence and non-occurrence of a debris flow. The judgement that a mudflow will occur or not occur is made by assuming that if $Z > 0$, it will occur and if $Z < 0$, it will not occur.

The constant term $A_o$ and coefficients $B_i$, $C_j$ are obtained to maximize the correlation ratio that is represented by the ratio of the overall variance of the complex variable and variance between the two populations. So if these are standardized so that the overall mean of the complex variable is 0 and the overall variance is 1 (the coefficient when this standardization was done is called the vector), it is possible to evaluate the degree that this factor influences the complex variable according to the size of this coefficient. The correlation ratio is set from 0 to 1, and the closer it is to 1, the better the judgement.

The rainfall factor and topographical factor were organized using documents obtained from a survey of the state of mudflow occurrences around Usuzan Volcano after the eruption of 1977, prior to the multiple discriminant analysis.

**Establishment of the rainfall factor**

The rainfall factor was assumed to be occurrence rainfalls and non-occurrence rainfalls from 1977 to 1981. The rainfall data that was used included long-term data within a range of 5 km from each torrent around Usuzan Volcano, and data obtained from the Usuzan Robot Observation Station (Meteorological Agency 1977 to November 1978) and the Lake Toya Hot Spring Observation Station (Nishi-iburi Fire Station, after December 1978) that was used for the task of predicting mudflow occurrences after the 1977 eruption. The times and places of their occurrence were designated using the results of surveys performed by Hokkaido Prefectural Office. Occurrence rainfall and non-occurrence rainfall were defined as explained below.

- Occurrence rainfall: It is defined as continuous rainfall including the day of the mudflow occurrence. But, a continuous rainfall is also rainfall that followed and preceded periods of 24 hours without rainfall.
- Non-occurrence rainfall: It is considered to be a rainfall with maximum hourly rainfall of 5 mm/h or more from among continuous rainfalls excluding rainfall that causes a mudflow (in order that occurrence rainfall is 5 mm/h or more).

And occurrence-rainfall and non-occurrence rainfall were organized as shown below with reference to a rainfall index used to predict the rainfall that causes debris flows.

- Short term rainfall: hourly rainfall, effective rainfall (half-life of 1.5 hours)

- Long term rainfall: cumulative rainfall (time of occurrence of maximum hourly rainfall, end of rainfall), effective rainfall (half life of 72 hours, abstraction of effective rainfall at time of occurrence of maximum hourly rainfall)

It was hypothesized that in cases where it is impossible to specify the precise time of the occurrence of mudflows in each torrent, mudflows occurred at the time when the maximum hourly rainfall was observed.

The hourly and cumulative rainfall of occurrence rainfalls have tended to increase since the largest mudflow of October 1978 (Fig. 2). There are no clear characteristics of the distribution of occurrence rainfall and non-occurrence rainfall that can be used to clearly distinguish between them (Fig. 3).

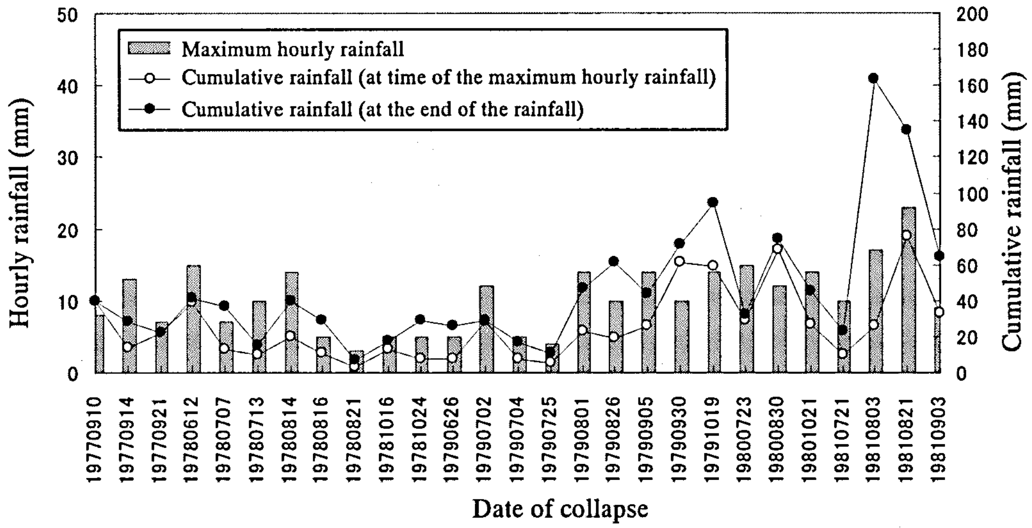


**Fig. 2** Change Over Time of Rainfall Causing Mudflows

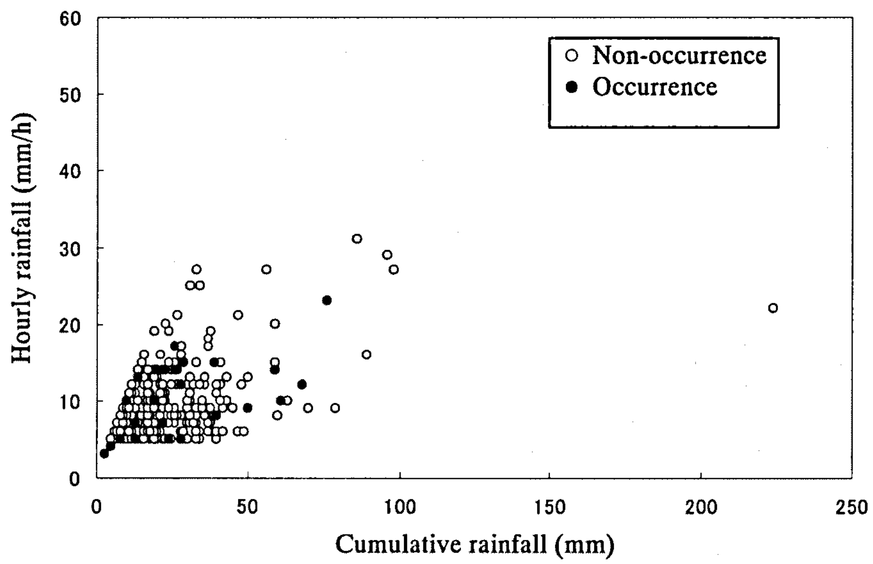


**Fig. 3** Mudflow Occurrence and Non-occurrence Rainfall Distribution Chart (Cumulative Rainfall – Hourly Rainfall Relationship)

## Establishment of the Topographical Factors

The topographical factors are those shown in Table 1 that were measured using a 1/2,500 scale topographical map of torrents throughout the Usuzan region with reference to the results of research by Araki et al.. The quantity of volcanic ash deposition is represented as the mean volcanic ash deposition depth in the drainage basin obtained by dividing the quantity of ash falling in each drainage basin obtained from a survey conducted by Hokkaido Prefectural Office by the drainage basin area. It should also reflect factors such as its permeability related to the physical properties of the volcanic ash, but because it was impossible to obtain detailed documents concerning this, it was not studied.

Mud flow occurrence was confirmed in all torrents with drainage basins of 0.25 $km^2$ or more by performing an examination using 1978 and 1979 topographical factors that permitted mud flow occurrence location to be grasped in detail (Fig. 4), but no clear tendencies were noted in others. This is presumably a result of the fact that if volcanic ash is deposited, mudflows occur regardless of the detailed topographical land forms.

**Table 1.** Items Measured Using Topographical Maps

| .Factor | | | Reason for selection |
|---|---|---|---|
| Topographical factors | Torrents | Drainage pattern | Form of the flow of the water (min. torrent length/main torrent length) |
| | | Mean gradient of torrent (°) | Likelihood that a debris flow will flow down the torrent |
| | | Steepest gradient of torrent (°) | Likelihood of the riverbed moving (measured within a vertical range of 30 m) |
| | | Main torrent length (km) | Distance the water flows downstream |
| | | Drainage basin area ($km^2$) | Size of the collection area |
| | | Drainage basin length (km) | Drainage basin shape |
| | | Drainage basin width (km) | Ditto |
| | | Drainage basin shape ratio | Ratio of the drainage basin shape (drainage basin width/drainage basin length) |
| | | Valley depth ratio | Degree of development of the valley (main torrent length/drainage basin length) |

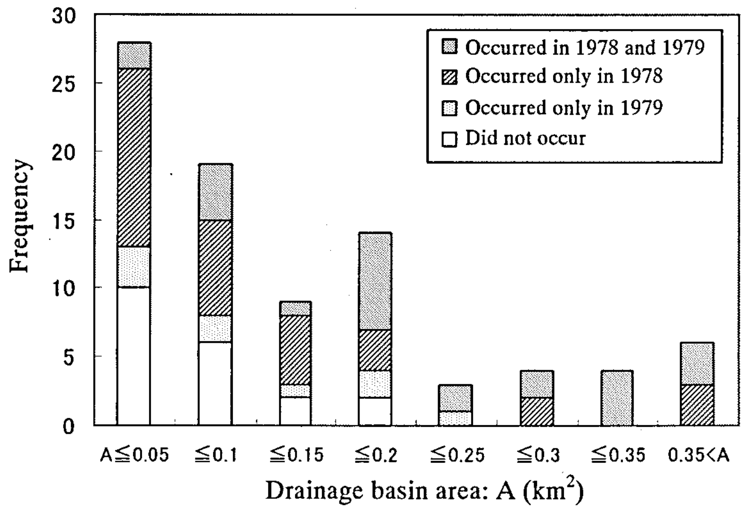


**Fig. 4** Drainage Basin Area – Mudflow Occurrence Frequency Relationship

## Results of Mudflow Occurrence – Non-occurrence Judgements Based on Multiple Discriminant Analysis

To obtain the rainfall indices that can be used to most precisely judge whether mudflows will or will not occur from indices that represent short term rainfall and long term rainfall, the combination of rainfall indices for Case 3 was used to perform multiple discriminant analysis only of rainfall factors based on the rainfall indices organized as explained above (Table 2). Since the result showed that the occurrence and non-occurrence judgement rate for Case 1 was the best, the hourly rainfall and cumulative rainfall were used as the rainfall indices (Table 3).

**Table 2.** Combinations of Rainfall Factors

| Rainfall index | | | Case 1 | Case 2 | Case 3 |
|---|---|---|---|---|---|
| Short term rainfall | Hourly rainfall | | ○ | ○ | |
| | Effective rainfall | Half-life: 1.5 hours | | | ○ |
| Long term rainfall | Cumulative rainfall | | ○ | | |
| | Effective rainfall | Half-life: 72 hours | | ○ | ○ |

The rainfall index used for the occurrence rainfall was the mudflow occurrence time (including estimates) and that for the non-occurrence rainfall was the maximum hourly rainfall time.

**Table 3.** Results of Judgements Based Only on Rainfall Factors

| | | | Case 1 | Case 2 | Case 3 |
|---|---|---|---|---|---|
| Vector | Long term | Hourly rainfall | 0.205272 | | 0.224408 |
| | | Half-life 1.5 hours | | 0.15337 | |
| | Short term | Cumulative rainfall | 0.49681 | | |
| | | Half-life 72 hours | | 0.004069 | 0.003906 |
| Constant term | | | -2.289802 | -1.517934 | -1.81371 |
| Correlation ratio | | | 0.028 | 0.0327 | 0.0366 |
| Correct judgement rate | | Occurrence | 15/21 | 14/21 | 15/21 |
| | | (%) | 71.4 | 60.6 | 71.4 |
| | | Non-occurrence | 218 / 337 | 307 / 479 | 213/337 |
| | | (%) | 64.6 | 64.1 | 63.2 |

Next, multiple discriminant analysis using rainfall factors and topographical factors was performed. Because cases where the locations of the occurrence of mudflows in the drainage basins have been identified in detail are limited to 1978 to 1979, the multiple discriminant analysis for topographical factors was performed using data only for 1978 and 1979.

The results are shown in Table 4. Empty spaces on the chart show that as a result of analysis of the correlation between various factors performed during the multiple discriminant analysis calculations, factors with higher coefficients of correlation were removed. The results of multiple discriminant analysis performed using both rainfall and topographical factors are inferior to the results of judgements based only on rainfall factors (Table 3).

Then the multiple discriminant analysis was performed using data for occurrences from 1977 to

1981. However, because only occurrence torrents are known, preventing detailed identification of topographical factors in years other than 1978 and 1979, the topographical factors used were the drainage basin area, drainage basin length, drainage basin width, and as the effects of the volcanic ash, the mean volcanic ash deposit depth in the drainage basin. As a result of performing multiple discriminant analysis using the above data, mudflow occurrence judgment and mudflow non-occurrence judgement rates of approximately 90% and 99% respectively were obtained: showing that far more precise judgements of both occurrence and non-occurrence than those based on multiple discriminant analysis using only rainfall factors (Table 5) can be obtained. This is presumed to be a result of the fact that among factors that effect the occurrence of volcanic mudflows, the quantity of ash deposited has a much greater influence on the occurrence of mudflows than the drainage basin topographical factors explained above. The empty spaces in the table are the result of removing factors whose vector values becoming negative during the multiple discriminant analysis calculations.

**Table 4.** Results of Multiple Discriminant Analysis Using Topographical Factors and Rainfall Factors(1978, 1979)

| | | | |
|---|---|---|---|
| Vector | Topography | Drainage basin area | |
| | | Main torrent length | |
| | | Drainage basin length | 0.182 |
| | | Drainage basin width | 0.368 |
| | | Mean drainage basin gradient | 0.183 |
| | | Maximum torrent bed gradient | 0.437 |
| | | Minimum torrent length | |
| | | Drainage pattern | 0.255 |
| | | Drainage basin shape ratio | 0.453 |
| | | Valley depth ratio | 0.196 |
| | | Mean volcanic ash deposit depth in the drainage basin | 0.361 |
| | Rain-fall | Hourly rainfall | 0.162 |
| | | Cumulative rainfall | 0.375 |
| Correlation ratio | | | 0.003 |
| Correct judgement rate | | Occurrence | 451/682 |
| | | % | 66.1 |
| | | Non-occurrence | 999/2450 |
| | | % | 40.7 |

**Table 5.** Results of Multiple Discriminant Analysis using Topographical Factors and Rainfall Factors (1977 – 1981)

| | Case | 3-3-1 | 3-3-2 | 3-3-3 |
|---|---|---|---|---|
| Vector | Drainage basin area | — | — | — |
| | Drainage basin length | — | — | — |
| | Drainage basin width | — | — | — |
| | Volcanic ash deposit depth | 0.238 | 0.226 | 0.232 |
| | Maximum hourly rainfall | 0.952 | 0.921 | 0.952 |
| | Half-life 1.5 | — | — | — |
| | Cumulative rainfall | — | 0.317 | — |
| | Half-life 72 | — | — | 0.196 |
| | Correlation ratio | 0.562 | 0.588 | 0.564 |
| Correct judgement rate | Occurrence | 105/116 | 105/116 | 104/116 |
| | (%) | 90.5 | 90.5 | 89.6 |
| | Non-occurrence | 84/85 | 84/85 | 85/85 |
| | (%) | 98.8 | 98.8 | 100.0 |

# MUDFLOW OCCURRENCE – NON-OCCURRENCE JUDGEMENT METHOD BASED ON THE NEURAL NETWORK

## Outline of Mudflow Occurrence – Non-occurrence Judgement System Based on the Neural Network

Using data for rainfall and topography in 1978 and 1979, and with reference to the results of research by Araki et al., a three-layer neural network consisting of an input layer, a hidden layer, and an output layer was used to judge the occurrence and non-occurrence of mudflows (Fig. 5).

The results show the certainty factor from 0.0 to 1.0 in the output layer, with 0.5 or higher indicating occurrence and less than 0.5 indicating non-occurrence. And the closer to 1.0, the higher the reliability of the occurrence judgement, and the closer to 0.0, the higher the probability of the non-occurrence judgement. The sigmoid function was used as the input-output function of the neurons and back propagation was applied as the learning method to optimize the network.

## Results of Mudflow Occurrence – Non-occurrence Judgements Based on the Neural Network

The judgement capabilities of the neural network judgement system when the mean volcanic ash deposit depth in the drainage basin was used as a causal factor and when it was not used were compared. In each case, first the system learned using 2/3 of all data as the learned data, then used the remaining 1/3 as the test data to confirm the system's judgement capability.

Examining the results based on the judgement rate of the test data reveals that when the mean volcanic ash deposit depth in the drainage basin was used as a causal factor, the non-occurrence judgement rate is only 66% that is less than the 84% obtained when the mean volcanic ash deposit depth in the drainage basin is not used, but inversely, the occurrence judgement rate is 80% when it is used, but 76% when it is not (Table 7).

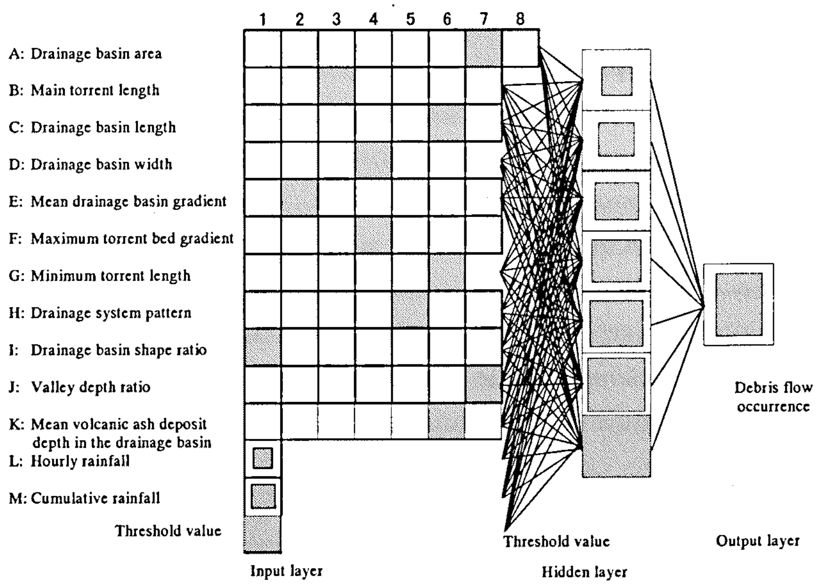


**Fig. 5** Model of the Neural Network

**Table 7.** Results of the Neural Network Based Judgements

| | | Mean volcanic ash deposit depth in the drainage basin Not used | | Mean volcanic ash deposit depth in the drainage basin Used | |
|---|---|---|---|---|---|
| Data | | Teacher | Test | Teacher | Test |
| Judgement results | Occurrence | 450/455 | 172/227 | 455/455 | 182/227 |
| | (%) | 98.9 | 75.8 | 100 | 80.2 |
| | Non-occurrence | 170/174 | 73/87 | 159/174 | 57/87 |
| | (%) | 97.7 | 83.9 | 91.4 | 65.5 |
| Repetition number | | 10000 | | 10000 | |
| Square mean error | | 0.013840 | | 0.023421 | |

## CONCLUSION

The results of performing mudflow occurrence – non-occurrence judgements at Usuzan Volcano from the time of the eruption of 1977 till 1981 based on multiple discriminant analysis and on a neural network have shown that when the mean volcanic ash deposit depth in the drainage basin was used as a causal factor, the precision of both the mudflow occurrence and non-occurrence judgments are improved. This is particularly conspicuous when multiple discriminant analysis is used. A comparison of the results when the approximate shape of the drainage basin and the mean volcanic ash deposit depth in the drainage basin are used as causal factors and the results when the mean volcanic ash deposit depth in the drainage basin is not used as a causal factor shows that its use improves the occurrence judgement rate by 20% and the non-occurrence judgement rate by about 30%. But further tests of these methods must be done at many volcanoes to assess their wide applicability. In this case, only the mean volcanic ash deposit depth in the drainage basin was used to represent the effects of volcanic ash deposition, but further studies also accounting for changes in the permeability of volcanic ash that are assumed to directly influence the way it is discharged must be carried out in volcanic product deposition regions.

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