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Contents

PART 1 Slopes and Landslides

1 Stability Analysis of Prediction Models for Landslide Hazard Mapping

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ABSTRACT

This chapter discusses the influence of causal factors for landslide hazard mapping and stability of the prediction results. Among many quantitative models, we consider a model based on the theory of fuzzy sets with the algebraic sum operator. In the model, layers of geoscience maps represent the spatial information used for the prediction of areas in which the geomorphologic setting is similar to the ones in which a particular type of mass movement has taken place. One of the main challenges in the selection of these causal factors is that of how to compare two prediction models based on two different sets of casual factors. In the application discussed here, a study area in the Rio Chincina region of central Colombia is considered in which a spatial database was constructed for hazard mapping of 'rapid debris avalanches'. In the database eleven map-layer causal factors were selected, and the landslides of rapid debris avalanches were divided into two subsequent periods, PRE-1960 (prior to 1960) and POST-1960 (after 1960). For the prediction, the eleven layers of information were integrated as evidence toward a proposition that 'points in the study area will be affected by future mass movement'. The analysis discussed here assesses the stability of the predicted hazard map with respect to the introduction or removal of each causal factor, i.e. of each map layer, according to the following steps.

1. A prediction map using all eleven causal factors was first constructed. Eleven prediction maps were generated by subsequently eliminating different single factors. Difference or DIF-maps were computed between the eleven maps and the prediction map using all the eleven factors. All prediction maps were obtained using the PRE-1960 landslides only. A 'matching rate' was then defined as a quantitative indicator associated to the DIF-map.
2. Using the matching rates, the causal factors were divided into two groups: the 'influent factor group' and the 'non-influent factor group'. For each of the three prediction maps based on the influent factor group, non-influent factor group and all eleven factors, a prediction-rate curve was obtained by comparing the prediction map and the distribution of the POST-1960 landslides. The prediction power of the factors used in each prediction

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was measured by the statistics from the comparison. The subsequent investigation was on the prediction differences between the two groups as fully described by the prediction-rate curve.
3. The influent factor group was also studied in terms of its relevance in the prediction.

The results of the study led to the following conclusions for the study area. (i) Although the division of two groups was rather artificial, only six causal factors were considered as 'influent factor group'. The prediction power of the prediction map based on these six factors is as good as that of the map using all eleven factors. The six factors are lithology, distance to valley head, aspect, slope angle, elevation and relief patterns. The first three factors have stronger influence in the prediction. (ii) The prediction power of the final map based on the six influent causal factors was illustrated by the corresponding prediction-rate curve. Comparing with the prediction map based on all eleven factors, the prediction map was stable enough to be used for land-use planning.

1.1 INTRODUCTION

About one-quarter of the natural disasters in the world appear to be directly or indirectly related to landslides, due to rainfall, local downpour, earthquakes and volcanic activities. Human interventions by constructing social infrastructure are often the trigger of the landslide phenomena. 'When', 'Where' and 'What scale' are important aspects of landslides in the prediction of geomorphologic settings and conditions in which landslides are likely to occur. The problem is critical in developing countries where warning and protection measures are particularly difficult to implement due to the limitation of economic conditions (Hansen 1984). The aim of this contribution is to predict where landslides may occur and analyse the stability of the predictions.

Many research activities have been carried out for landslide prediction, using various kinds of map data (e.g. Carrara 1983; Carrara *et al.* 1992; Kasa *et al.* 1991; Chung and Fabbri 1993; Chung and Leclerc 1994; Fabbri and Chung 1996). Recently, the analysis of satellite remotely sensed data has also been applied to the slope stability evaluation (Obayashi *et al.* 1995). Some of the difficulties were:

1. the selection of causal factors (usually specially compiled map data) for landslide prediction;
2. the analytical procedure to test the influence of each causal factor in a prediction;
3. the interpretation of the results from a prediction.

In this chapter, we plan to provide a systematic procedure to identify and evaluate the influence of causal factors on landslide prediction, in a study area. The difference or DIF-maps represent an initial approximation of spatial correspondence between two prediction patterns in a study area. While more complete comparisons can be easily computed for all the classes of predicted values between pairs of predictions, the four-class DIF-maps between two corresponding binary patterns used here facilitate the identification and visualization of discrete spatial patterns.

In Figure 1.1, three hypothetical binary predictions (A, B and C) are considered, and the accompanying three maps (D, E and F) show three DIF-maps. The prediction maps were based on three models and the pair-wise DIF-maps of the three prediction maps were generated from them. The black ellipses represent ten unknown 'future' landslides to be

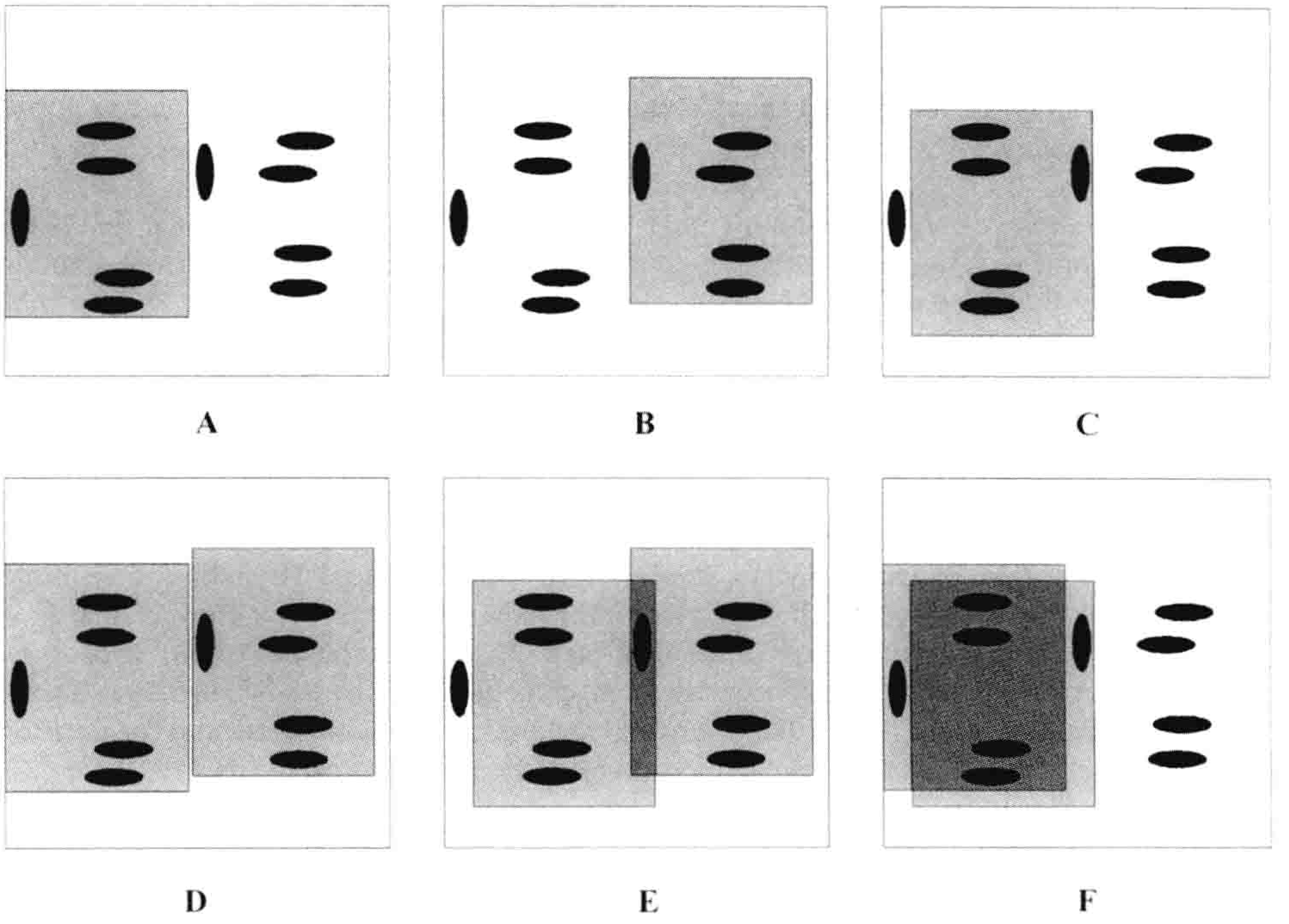

Figure 1.1 Prediction maps based on three models and the corresponding pair-wise difference or DIF-maps. The black ellipses represent ten 'future' landslides to be predicted by the prediction models. In each prediction map, the grey rectangle represents the hazardous area and it occupies 25% of the whole study area. The prediction powers of three prediction maps are identical, in that each map predicts five future landslides (50%) of ten landslides to come, i.e. each grey hazardous rectangle intersects five ellipses. (A) Prediction map from Model 1. (B) Prediction map from Model 2. (C) Prediction map from Model 3. (D) DIF-map between Model 1 and Model 2. (E) DIF-map between Model 2 and Model 3. (F) DIF-map between Model 1 and Model 3

predicted by the prediction models. In each prediction map, the grey rectangle represents a hazardous area and it occupies 25% of the whole study area. Each map predicts five future landslides (50%) of the ten landslides to come, i.e., each grey hazardous rectangle intersects five ellipses. It implies that the prediction powers of three prediction maps are identical. The DIF-map in Figure 1.1D shows no overlapping area and hence Model 1 (Figure 1.1A) and Model 2 (Figure 1.1B) are distinctly different. However the DIF-map in Figure 1.1F has much common area between the two models (Figure 1.1A and C). On one hand, if two models generate two prediction maps with the corresponding DIF-map shown in Figure 1.1D, then it would be very difficult to make a land-use map by combining two prediction maps. On the other hand, if two models generate the DIF-map shown in Figure 1.1F, it would be easy to combine two prediction maps because the two maps have a reasonably stable pattern. In this situation, we may be able to conclude that we can present a combined prediction from Model 1 and Model 3 with a certain confidence. As a quantitative indicator on a DIF-map, the following 'matching rate' was defined as:

Matching rate = common area (dark grey) / predicted hazardous area (light and dark grey)

If two maps match perfectly, then the matching rate is 1. If two maps do not match at all, then the matching rate is 0. Higher matching rates mean similar results in map 1 and map 2. A lower matching rate means that the two maps are very different. The matching rate for the DIF-map in Figure 1.1D is obviously 0, but the rate for DIF-map in (Figure 1.1F) is about 75%.

From an empirical study, assuming that two prediction maps have similar prediction powers, we came to a conclusion that the matching rate should be at least 75% to combine and subsequently interpret two prediction maps effectively. Otherwise two prediction maps are informing two different descriptions of the landslides. However, if the matching rate is lower than 75% and one prediction has much larger prediction power than the other map, then we may ignore the prediction map with the lower prediction power.

Neither the DIF-maps nor the associated matching rates themselves provide any valid measure of prediction power. It is only through the corresponding 'prediction rates curve' that we will provide that measure.

From the viewpoint of a land planner, the dark grey area in Figure 1.1E and F can be termed the 'stable hazardous' areas. On the other hand, the light grey areas in Figure 1.1E and F are termed 'non-stable hazardous' areas in the DIF-map. The 'non-stable hazardous' areas mean that we do not have much information on these pixels concerning the studied landslide hazard. According to Kasa *et al.* (1991, 1992) more supporting information is essential for decision-making in carrying out landslide prevention plans in the non-hazardous areas.

1.2 STUDY AREA, DATA SETS AND PREDICTION MODEL

1.2.1 Study Area and Causal Factors

The catchment of the Rio Chincina, located on the western slope of the central Andean mountain range (Cordillera Central) in Colombia, near the Nevado del Ruiz volcano, was used as a test for various landslide hazard zonation techniques. Van Westen (1993) made an extensive study of the region and constructed the database of the study area. Since then the database was made available as a case-study data set for many kinds of exercises and experiments on landslide hazard zoning by van Westen *et al.* (1993), with the name GISSIZ: training package of Geographic Information Systems on Slope Instability Zonation. It is on that data set that Chung *et al.* (1995) have developed several multivariate regression models for landslide hazard mapping.

The input data for landslide hazard mapping usually consist of several layers of map information. Each layer may be the result of map updating by experts, of field verification and of interpretation of aerial photographs. The resulting maps describe surficial and bedrock geology, soil type, slope, land use, geomorphology, mass movements, distance from active faults and other features, including man-made ones, that are relevant to slope instability. In addition, the identification of types and dates of landslide phenomena is critical to the application of predictive techniques.

Among many layers of spatial data constructed by van Westen (1993), he has suggested that the following seven data layers are 'causal factors' and are significantly related to landslide hazard: (1) bedrock lithological map; (2) geomorphological map; (3) slope-angle map; (4) land-use map; and three maps containing distances from the nearest valley head (5), from roads (6) and faults (7). In particular, translational mass movements termed 'rapid debris avalanches' (or 'derrumbes' in Spanish) were studied and predicted using the above causal factors. The initial seven maps and four additional ones derived from the elevation map are described in Table 1.1.