# Uncertainty in assessing landslide hazard and risk

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## ABSTRACT

Landslide identification and mapping are the fundamental steps in every attempt to assess landslide hazard and risk. Comparison of landslide maps produced by different investigators or through different techniques indicates the inherent uncertainty related to this task. When landslide data are aggregated into slope units, mapping errors are greatly reduced, with an acceptable loss of spatial resolution. All methods for manipulating instability factors and evaluating hazard and risk levels are also error-prone; the statistical one, although having some limitations, proves to be the most feasible. This is particularly true when GIS technologies are used for data acquisition, processing and analysis. As with other natural catastrophes, the prediction of landslide occurrence in space and time remains a problem that requires a renewed interdisciplinary effort.

In many countries, landslides—widespread in space and time—generate a yearly loss of property greater than that from any other natural disaster, including earthquakes, tornadoes and floods [27, 3]. This is largely true for Italy, where the interaction of geologic, geomorphologic and climatic factors has led to a geomorphic evolution of the slopes, controlled mainly by mass movement. Thus throughout the hilly and mountainous areas of the country, hundreds of failures take place every year, damaging infrastructures, dwellings and crops [12, 4].

Different methods and techniques for evaluating landslide occurrence have been developed or proposed. Some of them aim at predicting the behaviour of individual slopes through surface and subsurface measurements of soil/rock geotechnical properties and mechanical modelling of slope instability conditions. Others attempt to assess actual and potential landslide incidence over large areas or whole countries on the basis of geologic and geomorphologic observations and models.

Despite the conflicting views among some earth scientists and engineers, it can be stated that both approaches have significant advantages and limitations [29, 15, 2, 21]. Depending on the technical and economic constraints of the investigation, either approach may be better suited to solve some slope instability problems or to fulfill the requirements of a specific project.

In this paper, our discussion will be confined to the advantages and limitations in predicting landslide hazard and risk on a regional scale, namely the assessment of actual and potential mass movement over large areas derived from earth science information and modelling.

Since a review of the studies worldwide on the topic is beyond the scope of this work, the considerations presented in the following sections reflect mainly the authors' experience gained from some long-term investigations in southern and central Italy.

## LANDSLIDE MAPPING AND HAZARD ZONATION

Over the past 20 years, many scientists have attempted to assess landslide hazard and produce maps portraying its spatial distribution (landslide hazard zonation). "Hazard" indicates "the probability of occurrence within a specified period of time and within a given area of a potentially damaging slope-failure" [29]. "Zonation" refers to the division of the land surface into "homogeneous" areas or domains and their ranking according to degrees of actual/potential hazard caused by mass movement [29]. As discussed below, these terms are somewhat equivocal and imply the collection of information, such as the recurrence period of landslide movements, which can rarely be acquired. In addition, there has been no general agreement to date on methods or even the scope of these investigations [2, 8].

Despite the methodological and operational differences, all methods proposed are founded upon a single basic conceptual model. This model requires, first, the identification and mapping of a set of geologic-geomorphologic factors (such as rock composition and structure, bedding attitude, slope steepness and morphology, stream evolution, vegetation cover, etc) which are directly or indirectly correlated with slope instability. It then involves both an estimate of the relative contribution of these factors in generating slope failure and the classification of the land surface into zones of different hazard degree.

The model outlined—based on the well-known and widely applied principle "the past and present are keys to the future"—implies that slope failures in the future will be more likely to occur under those conditions which led to past and present instability [29]. Thus the preliminary step of the operation implies the identification and mapping of all landslide phenomena over a training area which must be as representative as possible of the different geologic and geomorphologic features of the region to be investigated (target area).

## UNCERTAINTY IN LANDSLIDE MAPPING

The experience gained from hundreds of surveys carried out in different parts of the world [29, 2, 15, 3] has demonstrated that well-trained investigators are able to detect and map many or most landslides oc-

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curring in an area by applying aerial photo interpretation techniques and systematic field checks [26, 30]. However, old, dormant landslide bodies, landslide areas intensively modified by farming activity or covered by dense vegetation cannot be easily identified and correctly classified. This introduces a factor of uncertainty that cannot be readily evaluated and explicitly incorporated in the subsequent phases of the analysis, being largely dependent on the skill of the surveyor, and the quality and scale of the aerial photographs and base maps used. Three examples follow.

During a recent study carried out in a small (17 $km^2$) portion of the La Honda basin, California, two landslide maps (Figures 1 and 2) were produced independently by two equally experienced investigators. The experimental area is underlain mainly by clay-rich rocks, with slopes partly cultivated and partly forested. Most of the failures are of the slide-flow type and, most important, more than 50 percent appear to be old or very old and dormant or stabilized.

Landslides were identified and mapped using black-and-white 1:18,000 scale aerial photographs and 1:24,000 scale base maps. Before starting this operation, the first investigator (investigator "A") had the opportunity to visit the area. He mapped only those landslides for which an adequate number of features (constituting the geomorphic signature [22]) of a failed slope (*ie*, scarp lines, hummockey surfaces, undrained depressions, drainage line patterns, etc) could be detected (Figure 1). Investigator "B" included also those movements that could be only inferred from equivocal geomorphologic evidence (Figure 2). Comparison should therefore be confined to the common "certain" data of the maps.

A visual inspection indicates that the overall spatial distribution of landslides in the two maps is fairly similar, the percentages of "certain" unstable areas being rather close (13.5 percent and 16.8 percent, respectively; see Table 1). The intersection (A∩B) of the two maps (Figure 3) indicates, however, that less than 10 percent of the landslide area is common to both maps. In addition, their union (A∪B) indicates that more than 20 percent of the area was classified as unstable by either the first or second investigator.


**FIGURE 1** La Honda basin (California) test area. Landslide map prepared by surveyor A using 1:18,000 scale black-and-white aerial photographs and a few field checks


**FIGURE 2** La Honda basin (California) test area. Landslide map prepared by surveyor B using 1:18,000 scale black-and-white aerial photographs without field checks

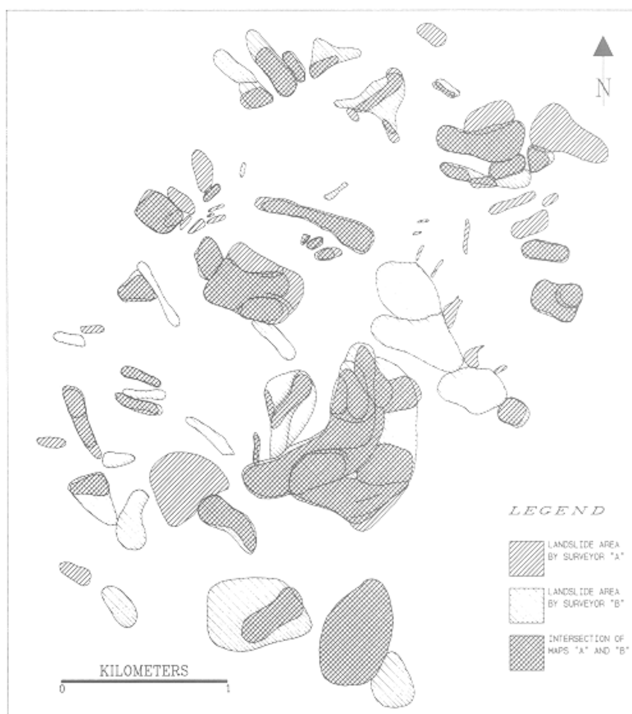


**FIGURE 3** La Honda basin (California) test area, overlay of maps A and B (Figures 1 and 2)

**TABLE 1** La Honda basin (California) test area, comparison of landslide maps produced by two equallly experienced surveyors using comparable mapping methods (test area = 17 $km^2$)

| | | *Unstable area (%)* |
|---|---|---|
| Surveyor A | | 13.5 |
| Surveyor B | all data | 24.5 |
| | "certain" data | 16.8 |
| Intersection A and B | | 9.9 |
| Union A and B | | 20.3 |

Overall mapping error: 51.5 %

From these figures, the overall mapping error can be calculated as:

$$\text{Error} = [(A \cup B - A \cap B) / A \cup B] \times 100$$

which yields a value of 51.5 percent. This represents the total error associated with landslide identification, interpretation, classification, topographic location, and aerial photograph-to-map data transfer and drafting. This simple experiment suggests that when dealing with old, dormant landslides the degree of uncertainty in their identification, classification and mapping is significantly high.

A second example comes from the Umbria region (central Italy), where a regional survey to map the landslides of the whole area was carried out in 1986-1988 [14]. The task was performed using (1954-55) 1:33,000 scale black-and-white standard aerial photographs, 1:25,000 scale topographic maps, and a limited amount of field checking in relevant zones. Figure 4 shows the portion of the landslide map covering the Tascio basin area (approximately 60 $km^2$). As described in detail elsewhere [9, 10], the slopes of this basin are underlain mainly by clay-sandstone sequences, clayey limestone and limestone. Landslides are abundant and most of them are slides and slide-flows [28]; old, dormant features prevail throughout. It is worth noting that slope morphology is modelled each year by intensive farming.

More recently, a new detailed survey was carried out in this basin. Interpretation of high-quality, 1978 colour aerial photographs at scale 1:13,000, topographic sheets at scale 1:10,000, and systematic field observations permitted the identification of almost 250 landslides (Figure 5). For each failure, the degree of certainty in its identification was estimated on the basis of the type and number of detected features characterizing a failed slope. Consequently, most landslides were classified with a high (63 percent) or fairly high (24 percent) certainty. The remaining ones (13 percent), consisting mainly of old, dormant, large slides, could be only inferred [9, 10].

Comparison of the two maps (Figure 6) yields the results listed in Table 2A. Since the landslide surface common to the two maps is only 7.8 percent (intersection) and the total area is 20.4 percent (union), the resulting overall mapping error is high, almost 62 percent.


**FIGURE 4** Tescio basin (central Italy) test area, landslide map obtained using 1:33,000 scale black-and-white aerial photographs and some field checks

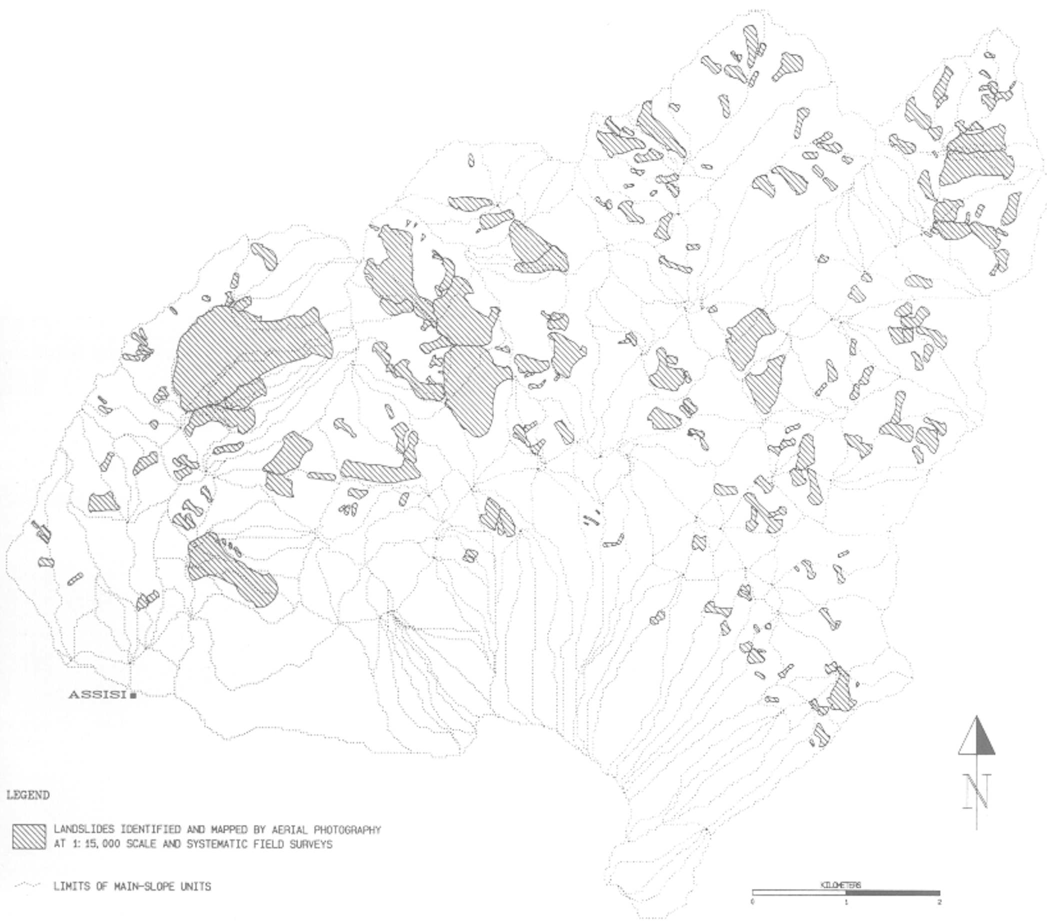


**FIGURE 5** Tescio basin (central Italy) test area, landslide map obtained using 1:13,000 scale colour aerial photographs and systematic field checks

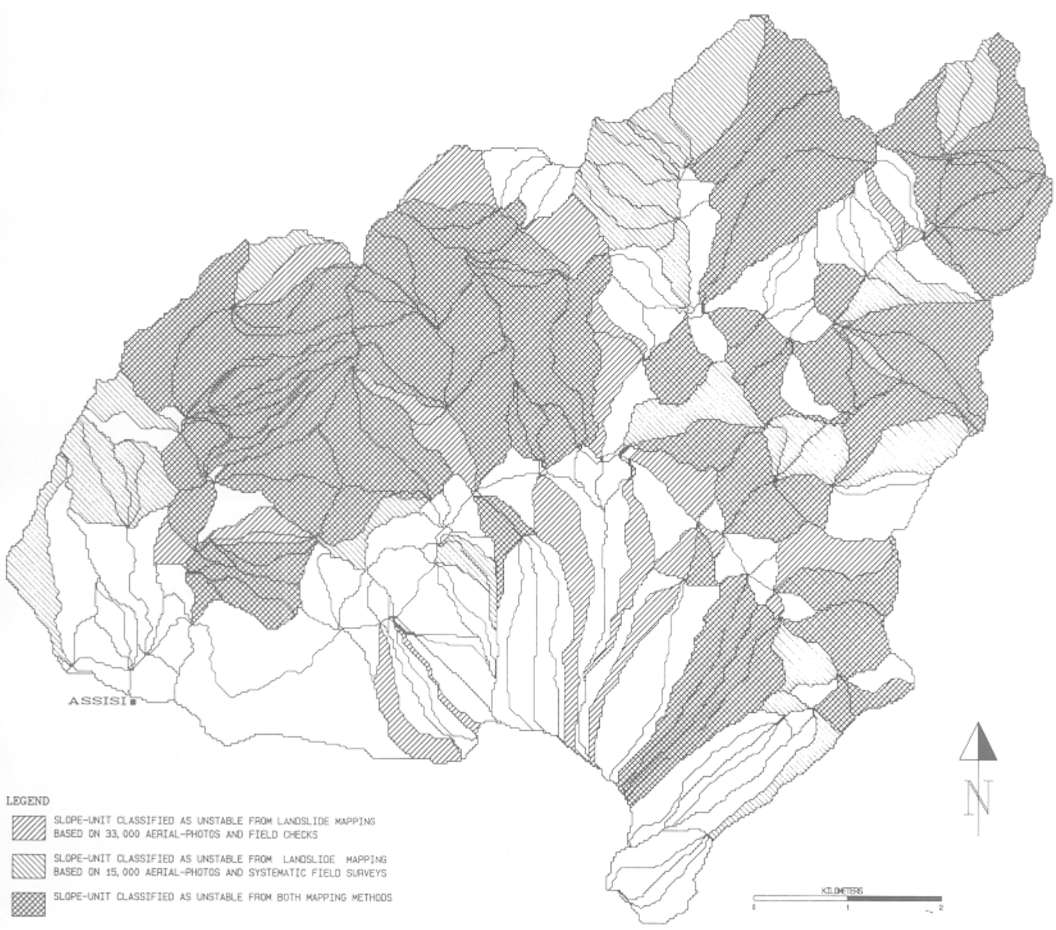


**FIGURE 6** Tescio basin (central Italy) test area, overlay of stable and unstable slope units derived from landslide maps of Figures 4 and 5

**TABLE 2A** Tescio basin (central Italy) test area (60 $km^2$). Comparison of landslide maps of Figures 4 and 5, produced by the same surveyors but using different methods

| | *Unstable area (%)* |
|---|---|
| Mapping method 1 | 15.4 |
| Mapping method 2 | 12.8 |
| Intersection maps 1 and 2 | 7.8 |
| Union maps 1 and 2 | 20.4 |

Overall mapping error: 61.8 %

**TABLE 2B** Comparison of mapping methods 1 and 2, data grouped into slope units

| | | *Method 1* Stable (153) | *Method 1* Unstable (113) |
|---|---|---|---|
| *Method 2* | Stable (148) | 122 | 26 |
| | Unstable (118) | 31 | 87 |

Overall mapping error: 21.4 %

**Method 1:** Interpretation of 1:33,000 scale aerial photographs and field checks
**Method 2:** Interpretation of 1:13,000 scale aerial photographs and systematic field surveys

The third example refers to a portion of the Marecchia basin, near the town of San Marino (northern Italy). The area (46 $km^2$) consists of clayey terrains very prone to landslides. Most of the slope failures are old, dormant-to-active flows or slide-flows. A large part of the area is farmed.

As part of a regional reconnaissance mapping project carried out in the late 1970s, landslides of this area were mapped using aerial photographs (at unknown scale), base maps at scale 1:25,000 and field investigations (Figure 7). No information is available to us about the experience of the first team who mapped the area. The area was recently remapped using 1954-55 1:33,000 scale aerial photographs, 1:25,000 scale topographic sheets and some field checks (Figure 8). Table 3 lists the results of the intersection (Figure 9) of the two landslide maps. It is apparent that in this case the extent of disagreement is so great (overall error almost 80 percent) that it seems the two teams aimed at mapping different morphologic features. It is tentatively assumed that the first team attempted to detect and portray the active, most damaging portions of landslide masses, whereas the second tried to trace out the geomorphic evolution of the area, outlining the overall extent of past and present landslide bodies. The aims of the studies and the mapping methods were so different that every comparison becomes difficult or unsuitable.


**FIGURE 7** Marecchia basin (northern Italy) test area. Landslide map prepared by team A using field investigations and aerial photo interpretation


**FIGURE 8** Marecchia basin (northern Italy) test area. Landslide map prepared by team B using aerial photo interpretation and some field checks


**FIGURE 9** Marecchia basin (northern Italy) test area, overlay of maps of Figures 7 and 8

**TABLE 3** Marecchia basin (northern Italy) test area (46 $km^2$). Comparison of landslide maps produced by two teams of surveyors using different mapping methods

| | Unstable area (%) |
|---|---|
| Team A | 8.1 |
| Team B | 10.3 |
| Intersection A and B | 3.3 |
| Union A and B | 15.1 |

Overall mapping error: 77.9 %

Since the errors obtained by simple map overlay appeared to be too pessimistic, they were re-examined. For the La Honda test area, we attempted to separate the errors caused by differences in surveyors' interpretation and judgement from other more trivial sources of error, such as inaccuracies in topographic data location, and data restitution, drafting and digitizing. Thus a corridor (buffer) was traced around each landslide mass. The resulting maps were processed following the procedure described above. This operation was repeated four times using corridors 25, 50, 100 and 200 m wide. As shown in Figure 10, first the error decreases at a slow rate and then declines more rapidly. Because of the scales of the aerial photographs and base maps used, and the standard inaccuracy in subsequent data digitizing, the total error associated with such operations can be accounted for by a corridor at least 50 m in width. This leads to an error of approximately 5 percent (Figure 10). The remaining 46 percent should represent the actual error attributed to the different geomorphologic interpretations of the two surveyors.

As discussed below, by tracing a "confidence belt" of, say, 150 m around landslide bodies, maps produced by different surveyors may become comparable, with an acceptable uncertainty (about 30 percent error).

At present, may hundreds of maps of landslides or their deposits have been produced throughout the world. With a few exceptions, their overall accuracies and reliability remain largely unevaluated—information on the criteria on which the failed masses were identified being insufficient or absent.

Despite these limitations, inventory maps remain—in general—very useful for a preliminary assessment of the actual instability conditions of a region.

## UNCERTAINTY IN HAZARD ZONING

As outlined above, a further step towards hazard zonation would require the identification of the conditions leading to slope failure, their systematic and consistent mapping, and the evaluation of their relative contributions to mass movement. This is not an easy task. In fact, the causes of each slope failure are many, complex, and sometimes unknown. Conversely, there are not many geologic-morphologic factors that are both relevant to the prediction of landslide hazard *and* mappable at effective cost over a wide region [8]. Table 4 provides a tentative list of the main factors controlling slope failure in the most

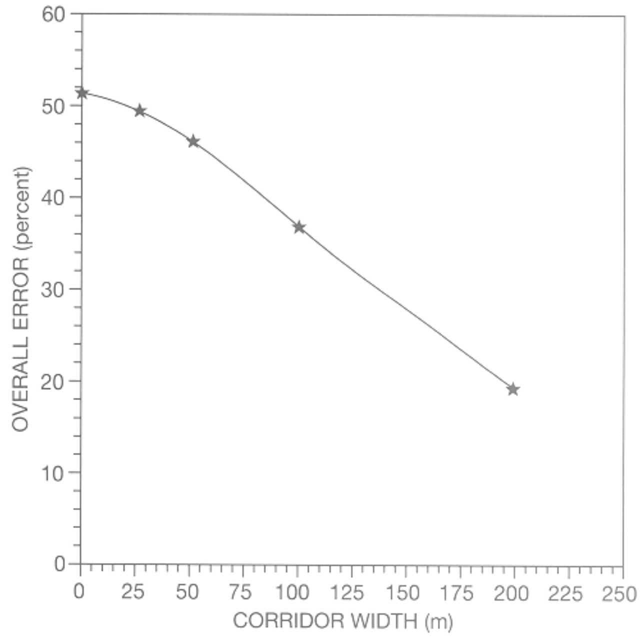


**FIGURE 10** La Honda basin (California) test area, estimated mapping errors obtained by adding "uncertainty" corridors of different widths to landslide bodies

common geomorphic settings, along with the uncertainty associated with their collection. It is apparent that the most important determinants of instability, such as the hydrogeologic conditions, are among the most elusive in a quantitative measurement.

Even worse, time and financial constraints frequently induce project managers and investigators to collect basic data from existing poorly reliable topographic and geologic maps or to obtain them by extrapolating a small number of site measurements of rock or soil properties to large areas. The resulting information is thus largely inadequate for (reliable) prediction of hazard.

Other major problems refer to the methods commonly used in ranking slope instability factors and assigning the different hazard levels [2, 15, 8]. The most important of these procedures or methods are (1) geomorphologic, (2) deterministic, (3) index (heuristic) and (4) statistical. All incorporate significant advantages and drawbacks.

The main advantage of the geomorphologic ap-

**TABLE 4** Main factors controlling instability conditions and tentative estimated degree of uncertainty associated with each

| Factor | Uncertainty |
|---|---|
| Geodynamic setting | High |
| Rock composition | Low |
| Rock structure | Intermediate |
| Groundwater conditions | High |
| Surface water conditions | Low |
| Slope geometry and angle | Low |
| Slope geomorphic processes | Interm/high |
| Land use | Low |
| Human activity | Intermediate |
| Present climatic conditions | Intermediate |
| Past climatic conditions | Interm/high |

proach lies in the capability of a skillful surveyor to estimate actual and potential slope failure, taking into consideration a large number of factors detected in the field or on aerial photographs [30]. In addition, local or unique slope instability conditions can be identified and assessed. In general, the time and resources required for this type of work are not excessive. The major drawback of the approach concerns the high subjectivity that characterizes all phases of the geomorphologic investigation. This is particularly true for the final step, when areas of potential failure have to be identified on the basis of an empirical model founded solely on the surveyor's skill.

Since the degree of uncertainty associated with this crucial step cannot be evaluated, it is difficult or impossible to compare landslide hazard maps produced by different surveyors. The outcome of the nationwide "Zermos" project in France [13] seems to point out clearly this limitation.

Deterministic (geotechnical) approaches are based on a set of physical laws or models controlling slope stability. Being process-driven models, they may provide significant insight on the causes of landslides. Their limitations include the fact that very few geotechnical data can be collected over a large region at reasonable cost; an example is provided by the recent work of Mulder [19]. In general, the spatial variability of the data is not controlled for, and reliable mechanical models are not yet available for several types of structurally complex rock units [21].

The index (or heuristic) method is based on a priori knowledge of the causes of landslides in the area under investigation. Clearly, its reliability is directly dependent on how much is known—and how well—of the acting geomorphologic processes. Since this knowledge can be formalized into rules, the method could somewhat take into account local geomorphic variability or unique conditions leading to slope failure. It could also be exported to neighbouring areas as long as the rule set holds true. In addition, the approach is readily suitable for applications pertaining to the realm of expert systems. This means that future developments in computer technology may enhance the diffusion of this method.

Pitfalls refer to the fact that in most cases the body of knowledge available on the causal relations between environmental factors and landslides is inadequate, and the resulting rules are too simple to predict correctly landslide distribution in space and time. At present, maps obtained by this method cannot be readily evaluated in terms of reliability or certainty.

The advantages and disadvantages of the statistical approach are similar to those of the previous method, with a fundamental difference: landslide hazard evaluation becomes as objective an operation as possible, since the instability determinants and their interrelations are evaluated on the basis of a multivariate statistical model. Clearly the strength of this functional model is directly dependent on the quality and quantity of data collected. Being data-driven, it cannot provide a clear physical insight of the processes involved in generating slope failure. In addition, a model designed for a certain region cannot readily be extrapolated to the neighbouring ones.

Finally, it can be stated that the uncertainty associated with all these methods ranges from intermediate (*ie*, the statistical approach) to high (*ie*, the geomorphologic one), but a quantitative estimate of the error magnitude associated with each method is possible only for the statistical one.

In the light of the above, in the following sections the discussion will be confined mainly to the applications of statistical models.

## UNCERTAINTY IN STATISTICAL MODELS

To date, few investigators have attempted to predict landslide hazard through multivariate models or other geomathematical methods [20, 23, 6, 1, 9, 10]. This is quite surprising, since the problem of forecasting landslide occurrence is conceptually and operationally similar to that of predicting other geologic phenomena, such as oil traps or ore bodies, both of which have been extensively attempted using various geomathematical techniques [10, 11]. In all cases the phenomenon to be identified is the result of the interplay of a large set of interrelated factors, many of which are unknown or unmappable.

The task of creating geologic-morphologic multivariate models for identification of unstable slopes was attempted in three sample zones of Calabria (southern Italy). The results demonstrated that these black-box models were capable of predicting actual and potential landslides in each study zone [6, 8]. The main pitfall of the method concerned the large amount of time required for digitizing, encoding, validating and processing the basic spatial and non-spatial data.

More recently, by taking advantage of the potentials of modern GIS technologies, a new attempt was carried out in the Tescio basin. Through new techniques in automated cartography, a high-fidelity digital terrain model (DTM) was created and the study area was automatically partitioned into subbasins and main slope units (right/left sides of subbasins) [5, 7]. Such units became the homogeneous land units or domains to which all subsequent zoning operations were referenced.

The morphologic parameters of each slope unit, merged with relevant lithologic, structural and hydrogeologic data, were used as input for a discriminant function which enabled the successful prediction of the spatial distribution of stable and unstable basin slopes [9, 10]. The outcome of this investigation makes it possible to draw some conclusions on the advantages and disadvantages related to landslide hazard zoning in general, and the feasibility of the statistical approach in particular.

First, the automatic subdivision of a basin into sub-basins and main slope units allows selection of a reference land unit which is morphologically meaningful, namely the geomorphic processes, such as landsliding, are spatially bounded by their limits [10]. This is not the case when the region to be investigated is subdivided into purely geometric units, suchs as grid cells, which do not bear any relationship with slope form and process. Nevertheless, the grid-cell approach is still widely accepted by many investigators for studies aimed at assessing landslide hazard on the basis of statistical or heuristic models [1, 22].

A second advantage refers to the significant reduction in landslide mapping errors. As shown above (Figures 4 and 5, Table 2A), the error derived from the use of different mapping techniques proved to be significantly high (62 percent). When landslide bodies are aggregated at the slope unit level (Figure 6, Table 2B), the overall error is reduced to 21 percent. This improvement has a cost in terms of spatial resolution: the resolution will decrease as slope unit mean size increases. For most small- to medium-scale regional landslide assessments, however, it is more significant to classify as stable or unstable morphologically-bounded land units (such as slope units or sub-basins) than to attempt to trace out questionable boundaries of landslide bodies which will eventually vary depending on climatic conditions and farming activities. All of this could be interpreted as an operation aimed at treating the data as a fuzzy set instead of a crisp set [18].

The use of slope units, although conceptually and operationally feasible, does not lack pitfalls. First, the selection of the main size of the slope unit is not straightforward. The appropriate size should be dependent simply on the average size of the landslide bodies present in the study area. This criterion does not hold, however, when dealing with zones in which two or more groups of landslides, generated in different morpho-climatic or geodynamic environments, exhibit different mean sizes. In such circumstances, it would be necessary to subdivide the region with different degrees of generalization and build up different hazard models for each genetically and typologically different landslide set.

A second type of problem arises when the study area is not bounded by morphologic limits (*ie*, basin divide), but administrative or topographic geometric boundaries. This circumstance, unfortunately very common, requires extension of the investigated area to reach some high-order drainage divides in the neighbouring zones. This step, if conceptually and technically suitable, may become infeasible in terms of the extra cost and time required.

Another way to compare errors and uncertainty related to different hazard mapping methods consists of building up hazard models for each different landslide dataset (Figures 4 and 5). Table 5A lists the results of the discriminant model based on the detailed landslide map (Figure 5); Table 5B shows the same for the landslide data of Figure 4. In both cases, the discriminant function was obtained starting from the same geologic-morphologic factors. It is apparent that the use of less accurate and reliable landslide information (Figure 4) leads to a less efficient hazard model (75 vs 83 percent of slopes correctly classified). In terms of a cost/benefit analysis, however, the choice between low-quality and high-quality landslide input data may be an open question.

The discriminant model developed for the Tescio basin does not explicitly incorporate any time dimension and thus cannot be classified as an actual hazard model [29]. This basic limitation is imposed by the fact that for this region, as for many other areas worldwide, information on the exact dates of past

**TABLE 5A** Tescio basin (central Italy) test area (60 km$^2$). Classification of stable and unstable slope units by discriminant analysis; landslide data derived from map of Figure 5. Slpoe units wtih an arera less than 0.01 km$^2$ were excluded from this analysis

| *Actual Slope Group* | *Number* | *Predicted Group Membership 1 (%)* | *2 (%)* |
|---|---|---|---|
| 1 Stable | 131 | 84.7 | 15.3 |
| 2 Unstable | 116 | 18.1 | 81.9 |

"Grouped" cases correctly classified = 83.40 %

**TABLE 5B** Classification of stable and unstable slope units by discriminant analysis; landslide data derived from map of Figure 4. Slope units with an area less than 0.01 km$^2$ were excluded from the analysis

| *Actual Slope Group* | *Number* | *Predicted Group Membership 1 (%)* | *2 (%)* |
|---|---|---|---|
| 1 Stable | 138 | 76.8 | 23.2 |
| 2 Unstable | 109 | 27.5 | 72.5 |

"Grouped" cases correctly classified = 74.9 %

activation or reactivation of landslide bodies is difficult or impossible to collect. This hampers the modelling of the time relationship between the most common triggering mechanisms, such as extreme rainfall or severe earthquakes, and widespread slope failure. Consequently, time uncertainty in landsliding constitutes the main drawback of all statistical (and heuristic) hazard models.

This limitation notwithstanding, in many geomorphic environments, landslides take place more frequently on slopes that have experienced past movements. By "predicting" the past/present spatial concentration of landslides, the discriminant model may indicate, under this assumption, the slope units in which failures will be more likely to occur in the future. This type of information, although incomplete and somewhat inadequate, may still be very useful for planning purposes.

The last test concerns the comparison of different statistical models. The present investigation was limited to comparison of the results yielded by discriminant analysis and logistic regression analysis.

Although a detailed discussion of the respective characteristics of these two techniques is beyond the scope of this paper, it is worth noting that both methods are widely used for a variety of applications, such as the prediction of a binary dependent variable from a set of independent variables. In discriminant analysis, this is obtained through a linear function of the independent variables whose coefficients are such that the discriminant score ratio of between-groups-variance/within-groups-variance is maximum. In logistic regression, the coefficients are estimated using a maximum-likelihood method; since the logistic model is nonlinear, an iterative algorithm is required.

Although discriminant analysis is a "robust" method, departure from some assumptions (namely: multivariate normality of the independent variables, equal variance-covariance matrices of the groups, etc) may of unstable area within the slope unit); $A_d/A_s$ is the ratio of inhabited area to slope unit area (*ie*, the expected size of dwelling area within the slope unit); $D_L$ is the degree of damage caused by landslide (*ie*, the expected loss of dwellings in a slope unit if effected by a landslide).

$H_L$ was provided by the discriminant function. Since the discriminant model does not explicitly incorporate time, $H_L$ was tentatively assigned a recurrence interval of 25 years, *ie*, the return period of heavy rains in the region. Equally questionable was the definition of $A_L$. After different attempts, a rather crude approach was selected: slope unit unstable surface was, indeed, obtained simply by curvilinear regression using as predictors slope unit area and its square term for those slopes that had a hazard ($H_L$) greater than 0.5 (115 of 266 cases). As illustrated in detail elsewhere [10], $A_d/A_s$ was determined taking into consideration the safety effect of houses located along ridge crests of the sub-basins. In addition, independence of inhabited areas ($A_d$) and unstable areas ($A_L$) could be assumed. Last, using a very conservative approach, $D_L$ was set equal to 1, which means total destruction of a building if effected by landslide.

By comparing the results of this operation (Figure 11) with reports on the frequency of house damage caused by landslides over the past 50 years, the simple approach selected appears to provide a fairly adequate model of the existing landslide risk throughout the study area (see Figure 12).

## CONCLUDING REMARKS

The tests performed under different conditions on different sample areas proved that landslide identification and mapping is an error-prone operation which is dependent on the skill of the surveyor and the technical tools selected. Overall errors may well be greater than 50 percent. A similar error magnitude is expected to be associated with many other geologic and geomorphologic interpretations.

Unfortunately, most of landslide maps published worldwide do not provide any insight into the criteria used and their reliability; thus these data have to be interpreted and used taking into consideration their inherent limitations.

Since uncertainty is frequently greater in detecting landslide boundaries than in the broad identification of the zone where failure took or is taking place, instability classification based on slope unit limits may significantly increase reliability, with an acceptable loss of spatial resolution.

Landslide hazard zoning can be performed using different approaches (geomorphologic, deterministic, index and statistical); although all exhibit advantages and limitations, each one may be best suited to solve a specific landslide assessment problem.

On the basis of the experiments illustrated in this paper and elsewhere [6, 8, 10], it has been demonstrated that the statistical models, based on a set of relevant geologic-morphologic variables mappable over


**FIGURE 11** Tescio basin (central Italy) test area, comparison of hazard maps obtained from discriminant and logistic regression analyses

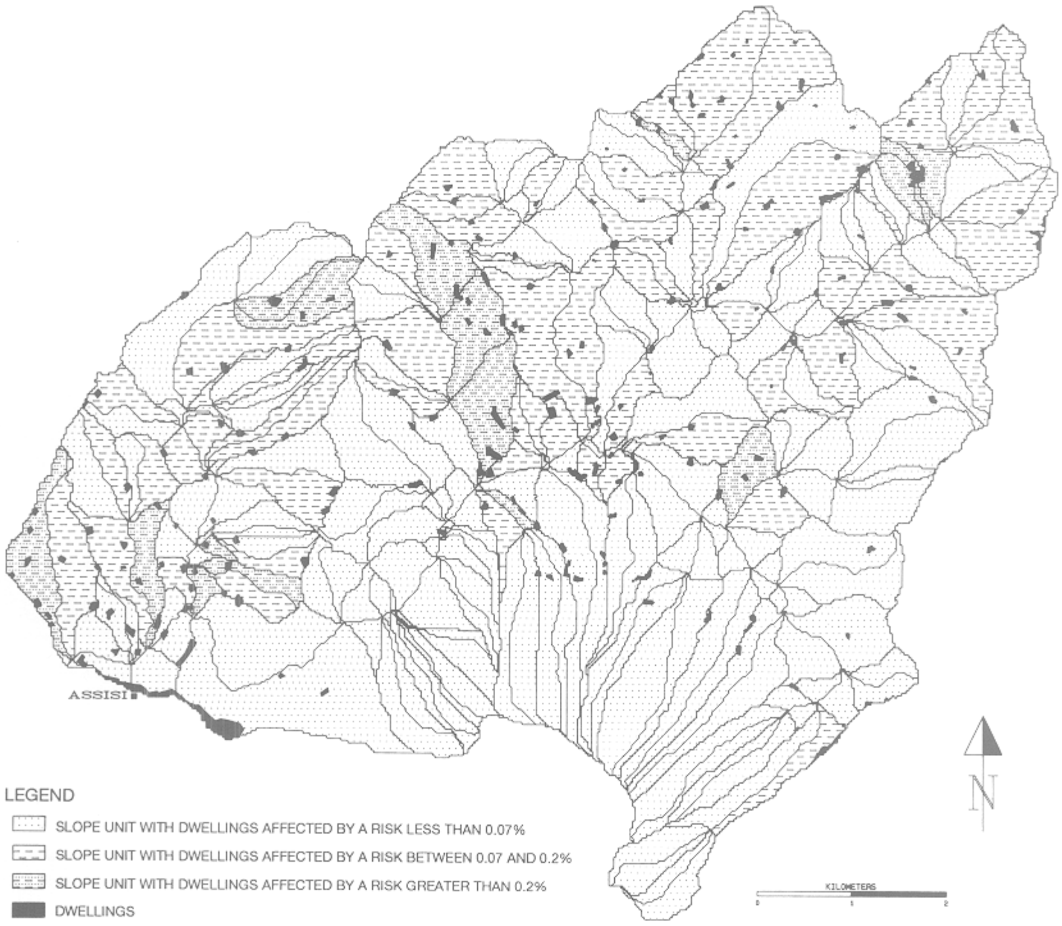


**FIGURE 12** Tescio basin (central Italy) test area, landslide risk assessment

large areas, are able to successfully predict stable and unstable slope units in a variety of geomorphologic environments. The sources of error associated with these models are many; they refer to the nature, quality and quantity of the input data, and the way such data are processed and manipulated.

Nevertheless, the experiments showed that the error magnitude related to data processing and statistical modelling is far smaller than that associated with data collection operations, *ie*, landslide mapping. This result points out the need for an effort towards more accurate and reliable field/laboratory work.

Although statistical models appear to be the most feasible approach to hazard and risk assessment, they do not lack intrinsic limitations. Being black-box models, they do not readily unravel the internal structure of the process involved. They remain basically too simple to fully explain slope failure distribution, which is always the result of the interaction of many factors, most of which are complex and some unknown. Likewise, extrapolating these functional models from training areas to large target areas may be difficult or sometimes impossible without an unacceptable increase in uncertainty.

In many cases the magnitude of potential slope failures and the vulnerability of property or lives cannot be readily determined, leading to a great uncertainty in risk assessment. Thus the resulting information cannot be used at local scale without further detailed site investigations.

This review of potentials and drawbacks of landslide evaluation may be concluded with the following remarks.

The application of geomathematical methods to environmental hazards has always required a great deal of time and personnel for collecting, encoding and digitizing the large amount of data needed to build up multivariate models of the spatial distribution of landslides, floods and other natural catastrophes. To facilitate the acquisition, handling and manipulation of these data, efficient GIS-based techniques are available. The Tescio basin case study clearly demonstrated the effectiveness of such an automated approach. Furthermore, sophisticated data capture/display electronic devices, faster computers and better GIS modules will profoundly influence the methods and techniques for acquiring and handling spatial data.

As with other natural catastrophes, prediction of landslide hazard and risk remains a problem at both regional and local scales. Its solution would require a renewed interdisciplinary effort from research institutions, at national and international levels, supported by a financial commitment of the interested countries.

## ACKNOWLEDGEMENTS

Figures 4, 5, 6, 11 and 12 were prepared by the national group for prevention of hydrogeologic haz-

ards, which includes (in addition to the authors) R Detti, V Pasqui and P Reichenbach.

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## RÉSUMÉ

L'identification et la cartographie des éboulements sont les étapes fondamentales dans tout essai de répartition de hasard et risque d'éboulement. Une comparaison de cartes d'éboulements produites par différents chercheurs ou à travers différentes techniques montre l'incertitude inhérente à ce travail. Lorsque des données d'éboulement sont agrégées en unités de pente, les erreurs cartographiques sont considérablement réduites, avec une perte acceptable de résolution spatiale. Toutes les méthodes pour manipuler des facteurs d'instabilité et évaluer des niveaux de hasard et de risques sont sujettes à erreurs; la méthode statistique, bien qu'ayant certaines limites s'avère être la plus fiable. Ceci est particulièrement vrai lorsque les technologies SIG sont utilisées pour l'acquisition de données, le traitement et l'analyse. Comme dans toute catastrophe naturelle, la prévision d'éboulements dans l'espace et le temps demeure un problème qui exige un effort interdisciplinaire renouvelé.

## RESUMEN

La identificación y el mapeo de los deslizamientos son pasos fundamentales en cada intento de evaluación de los riesgos. La comparación de mapas de deslizamientos producidos por distintos investigadores o a través de distintas técnicas indican la incertidumbre inherente a esta tarea. Cuando se agregan datos del deslizamiento a las unidades de pendiente, los errores en el mapeo se reducen considerablemente, con una aceptable pérdida de resolución espacial. Todos los métodos para manejar factores de inestabilidad y evaluación de niveles de riesgo también están sujetos a error; el estadistico, aunque tiene algunas limitacones, prueba ser el más viable. Esto es especialmente cirto cuando tecnologías SIG son empleadas para la obtención, procesamiento y análisis de datos. Como en todas las catástrofes naturales, la predicción de la ocurrencia de deslizamientos en tiempo y espacio continúa siendo un problema que requiere de un renovado esfuerzo interdisciplinario.