

Comparing Landslide Maps: A Case Study in the Upper Tiber River Basin, Central Italy

F. GUZZETTI*

M. CARDINALI

P. REICHENBACH

CNR-IRPI

Perugia, Italy

A. CARRARA

CNR-CSITE

Bologna, Italy

ABSTRACT / The preparation of landslide maps is an important step in any landslide hazard assessment. Landslide maps are prepared around the world, but little effort is made to assess their reliability, outline their main characteristics, and pinpoint their limitations. In order to redress this imbalance, the results of a long-term research project in the Upper Tiber River basin in central Italy are used to compare reconnaissance and detailed landslide inventory maps, sta-

tistical and geomorphologically based density maps, and landslide hazard maps obtained by multivariate statistical modeling. An attempt is made to discuss advantages and limitations of the available maps, outlining possible applications for decision-makers, land developers, and environmental and civil defence agencies. The Tiber experiment has confirmed that landslides can be cost-effectively mapped by interpreting aerial photographs coupled with field surveys and that errors and uncertainties associated with the inventory can be quantified. The experiment has shown that GIS makes it easy to prepare landslide density maps and facilitates the production of statistically based landslide hazard models. The former supply an overview of the distribution of landslides that is easily comprehended but do not provide insight on the causes of instability. The latter, giving insight into the causes of instability, are diagnostically powerful, but are difficult to prepare and exploit.

Maps are the tools that earth scientists prefer in order to portray geological information and convey it to other scientists, decision-makers, and the public. In the realm of natural hazards, maps are prepared to show where catastrophes have happened or where they are expected to occur and can be used to divide up land areas into zones of different hazard or risk levels.

Cartography is a crucial aspect of landslide hazard assessment, and landslide maps have been prepared for different parts of the world (Brabb and Harrod 1989, Brabb 1991). However, little work has been done to assess the reliability of landslide maps, compare different types of such maps, or discuss their advantages and drawbacks (Carrara and others 1992). The present paper will attempt a critical analysis of these problems.

This study focuses on the Upper Tiber River basin, which extends over about 4100 km² in central Italy and is covered by landslide inventory, landslide density, and hazard maps. Hence, a comparison among them is feasible, with emphasis on their applications by scientists, planners, decision-makers, and land developers.

KEY WORDS: Map; Landslide; Inventory; Density map; Hazard assessment; Central Italy

*Author to whom correspondence should be addressed.

Landslide Maps

Landslide maps can be loosely grouped into three classes: inventory maps, density maps, and hazard maps. Inventories are the simplest form of direct landslide mapping and show the location of known landslides (Hansen 1984a). Density maps attempt to portray the spatial abundance of landslides (DeGraff 1985) through indirect mapping (Hansen 1984a). Hazard maps show the inferred or computed degree of landslide hazard obtained by modeling or by direct mapping (Carrara and others 1995, Guzzetti and others 1999). The methods and techniques used to prepare the different types of landslide maps vary quite substantially, and so do their information content and applications.

Inventory Maps

Inventory maps record the location of all landslides that have left discernible features in an area. They may also report the date of occurrence and the type of mass movement (Hansen 1984a, Wiczeorek 1984). In the later case a classification is adopted whose application fits the technique used to complete the inventory. Most commonly, a simplified version of the classification of mass movements proposed by Varnes (1978) is used (Antonini and others 1993, Cardinali and others 1990). Inventories can be prepared by different methods depending on scope, available resources, and scale of

the investigation. They can be prepared by collecting historical information on landslide events or from the analysis of aerial photographs coupled with field surveys. The former is a means of constructing a landslide archive (IGS-WPWL 1990) and reports the location of sites where landslides are known to have occurred (Guzzetti and others 1994). The latter are geomorphological maps that portray the distribution of landslide deposits (Hansen 1984a, Wiecek 1984). They may show all landslides triggered by a single event, such as an earthquake, rainstorm, or snowstorm (Agnesi and others 1983, Ellen and Wiecek 1988, Govi 1976, Harp and others 1981) or show the cumulative effects of many events over a period of several hundreds or even thousands of years (Guzzetti and Cardinali 1989, Cardinali and others 1990, Antonini and others 1993). Most commonly a single map is used to portray all different types of landslides. Alternatively, a set of maps can be prepared, each map showing a different type of failure (e.g., deep-seated slides, shallow failures, debris flows, rock falls, etc.; see Cardinali and others 1990).

Small-scale inventories (<1:200,000) are compiled from data captured from the literature (Radbruch-Hall and others 1982); by literature survey; through inquiries to public organizations and private consultants (Nemčok and Rybář 1968, Inganäs and Viberg 1979); by searching chronicles, journals, and technical and scientific reports; by interviewing landslide experts (Guzzetti and others 1994, 1996a, Reichenbach and others 1998a); and by the analysis of aerial photographs (Cardinali and others 1990). A proposal for a small-scale worldwide landslide inventory was made by Brabb (1993) as a contribution to the International Decade for Natural Disasters Reduction (IDNDR).

Medium-scale inventories (1:25,000–1:200,000) are prepared through the systematic interpretation of aerial photographs at print scales that range from 1:60,000 to 1:20,000 and by integrating local field checks with historical information. Large-scale inventories (>1:25,000) are prepared for limited areas, using both the interpretation of aerial photographs at scales greater than 1:20,000 and extensive field investigations, which make use of a variety of techniques and tools that pertain to geomorphology, engineering geology, and geotechnical engineering (Wiecek 1984, Brand 1985, Agostoni and others 1997). In Italy, examples of large-scale inventories in urban and suburban areas are given by the SCAI (Study of Urban Slope Instability) atlases prepared for four Italian regions (Agostoni and others 1997, Rossetti 1997, Felicioni and others 1994, Annovi and Simoni 1993, Luino and others 1993).

The application of landslide inventories depends on their scale and the techniques used to compile them.

Small-scale inventories made by interpreting aerial photographs can be used for regional planning, to identify broad areas where landslide processes are concentrated, for the production of small-scale susceptibility maps, and for regional geomorphological studies (Guzzetti and others 1996b). Synoptic inventories achieved by a literature search or study of historical records have many applications, including the planning of detailed research projects, the portrayal of a national distribution of failures (Nemčok and Rybář 1968, Radbruch-Hall and others 1982, Guzzetti and others 1996a, Reichenbach and others 1998a), investigation of the awareness of landslide phenomena, evaluation of the type of damage and the structures most vulnerable to landsliding (Guzzetti and others 1996a), and construction of frequency–magnitude curves (Fell and Hartford 1997, Evans 1997, Morgenstern 1997).

Medium- and large-scale inventories find application in geomorphological studies, for the analysis of the regional distribution of landslide types and patterns (Guzzetti and others 1996b), and as databases for the statistical appraisal of landslide hazard and risk (Berknopf and others 1988, Carrara and others 1991, 1995, Soeters and van Westen 1996, Guzzetti and others 1998b). Large-scale inventories are used to report the ground effects of natural catastrophes such as meteorological or seismic events (Agnesi and others 1983, Ellen and Wiecek 1988, Govi 1976, Harp and others 1981), or to map in detail individual sites affected by slope movements, mostly to plan geotechnical studies and remedial measures (Agostoni and others 1997, Rossetti 1997, Felicioni and others 1994, Annovi and Simoni 1993, Luino and others 1993, Brand 1985, Brand and others 1982).

The limitations of landslide inventories refer to their subjectivity and to the difficulty of measuring their reliability. The reliability of archive inventories depends largely on the quality and abundance of information sources (Reichenbach and others 1998b, Glade 1998, Cruden 1997, Ibsen and Brunnsden 1996, Guzzetti and others 1994). For geomorphological maps, the experience gained from surveys carried out in different parts of the world has shown that trained investigators can reliably detect landslides by standard photointerpretation techniques coupled with systematic checks in the field (Speight 1977, Cotecchia 1978, Rib and Liang 1978, Crozier 1984, Varnes and others 1984, Brabb and Harrod 1989, Turner and Schuster 1996). However, the reliability of geomorphological inventories depends on the type and scale of the aerial photographs used; the experience and skill of the interpreter; the scale of the final map; the complexity of the geological, morphological, and land-use setting; and the persistence of land-

slide morphology within the landscape (Carrara and others 1992, Fookes and others 1991, Mulder 1991, Rodolfi 1988, Hansen 1984b, Roth 1983, Rib and Liang 1978).

Density Maps

Landslide density (or frequency) maps attempt to measure quantitatively the spatial distribution of slope failures (DeGraff 1985). Density maps are used to show a synoptic view of landslide distribution for large regions or entire nations (Radbruch-Hall and others 1982, Reichenbach and others 1998a), to portray a first-order overview of landslide abundance (Campbell 1973, Wright and others 1974, Wright and Nilsen 1974), or to show the magnitude of slope failures triggered by severe storms (Campbell 1975, Ellen and Wieczorek 1988) or seismic events.

Depending on the type of mapping unit, landslide density maps can be based on statistical or geomorphological criteria. In statistically based maps, the mapping unit is most commonly a cell, i.e., a regular square (a grid or raster). Density is determined by counting the percentage of landslide area within a moving window of predefined size and shape. This is equivalent to a moving average filtering technique. Window size is generally 10–100 times larger than grid size and its shape is square or nearly circular. Additional filtering or weighting techniques can be applied to improve map consistency and readability. By interpolating equal quantity (isopleth) lines, a statistically based density map can be portrayed as a contour map (Wright and others 1974). The latter is the favored method for showing landslide density (Campbell 1973, 1975, Wright and Nielsen 1974, DeGraff 1985).

Statistically based landslide density maps rely on the assumption that landslide occurrence is a continuous variable that can be spatially interpolated (Schmid and MacCanell 1955, Wright and others 1974, Guzzetti and others 1999). Hence, they perform best in homogeneous terrain, where lithology and morphology do not change abruptly. This assumption holds true only as a general approximation, at small scale, and in homogeneous physiographic environments. At larger scales, the assumption of spatial continuity does not take into account the existing relations between slope failures and the local morphological or geological settings. As an example, where layered rocks crop out, slope forms and processes are influenced by the attitude of bedding planes. In susceptible geologic environments, landslides are often larger and more abundant where bedding dips toward the slope free face. Conversely, where bedding dips into the slope (reverse slope) terrain is steep and landslides are less abundant (Guzzetti

and others 1996b). In such conditions, an isopleth map prepared without considering the presence of streams or divides will be misleading, particularly on reverse slopes. This limitation is partly overcome by selecting a mapping unit that bears a physical relation to the geomorphology of landsliding (Carrara and others 1995, Guzzetti and others 1999).

Main slope units (as defined in Carrara and others 1991) appear to be particularly suited to the determination of landslide frequency. They partition the territory into domains bounded by drainage divides and stream lines, using manual techniques or automatic selection from a digital terrain matrix (DTM) that acts as a computerized representation of topography (Carrara 1988). Slope units, therefore, correspond to the actual slopes on which slope failures take place. The percentage of landslide area within each slope unit, as counted, is equivalent to the percentage of failed area on each slope. The landslide density in this case is the percentage of the slope unit that is occupied by the landslides. As they are delimited by morphological boundaries, slope units avoid the pitfall of forecasting high landslide densities in areas that are mapped as essentially landslide free but are close to known failures (for example, across the divide of an asymmetric ridge that is controlled by the attitude of bedding). In addition, slope units mitigate the effects of possible identification and mapping errors. As landslide density is computed for the entire mapped area, possible mapping or drafting errors made within each slope unit are averaged (Carrara and others 1992).

The advantage of morphological soundness and the limitation of mapping errors is counterbalanced by the loss of resolution. The resolution of slope-unit-based density maps is usually lower than that of grid-based or contour-based maps, unless the grid or contour spacing is particularly large for the amplitude of the terrain under study. As a result of interpolation procedures, landslide density is a derivative of the spatial distribution of landslides (i.e., the inventory). Interpolation inevitably causes information to be lost. Indeed, even if landslides were mapped in great detail, nothing could be said about the exact location of any single landslide within a slope unit. However, if the size of slope units is chosen in relation to the size of landslides to be studied, the loss of resolution is only apparent and does not correspond to a loss in the applicability and utility of the map (Carrara and others 1992, 1995, Guzzetti and others 1999).

Errors and inconsistencies associated with the definition of slope units from DTMs, to the geometrical consistency between slope units and landslide boundaries, to the size of slope units compared to the extent of

landslide deposits, and to the correspondence between slope units and the actual geometry of the slopes, may limit the use of such mapping unit in properly counting and displaying landslide density.

Alternative mapping units can be selected in order to determine landslide density. These include the unique condition units, which are obtained by sequentially overlying various thematic layers (Chung and others 1995). If slope units are further subdivided by intersecting them with lithological, morphological, or land-use boundaries, unique domains are singled out whose size and location may fit closely to the known, or mapped, distribution of landslides (Carrara and others 1995).

Landslide Hazard Maps

Several methods and techniques have been proposed and tested in order to evaluate landslide hazard and risk, but no general agreement has yet been reached about the methods used to produce such maps. Methods for zoning land areas into domains of different hazard levels can be qualitative or quantitative and direct or indirect. A review of the literature (Guzzetti and others 1999) shows a predilection for indirect and quantitative approaches. Recent successful attempts are based on statistical (i.e., probabilistic) or process-driven (i.e., geotechnical) modeling. The former relies on the analysis of functional relations between instability factors (thematic variables) and on the past and present distribution of slope failures (landslide inventory). The latter relies upon the understanding of the physical laws that control slope instability. At present, geotechnical modeling shows promise for quantitative investigation of the influence of instability factors on landslides, but it appears to be useful only in areas of limited extent, due to the difficulty of collecting geotechnical data with appropriate resolution over larger regions. Conversely, the statistical approach is the one that is currently pursued to assess landslide hazard over large regions.

Regardless of the method used to ascertain the nature and extent of landslide hazards, how hazard domains are displayed on a map is of paramount importance. Restricting the discussion to statistical and geotechnical approaches, model results often exhibit variations, including errors and uncertainties, i.e., they do not match the known, or mapped, distribution of slope failures (the inventory). No multivariate statistical model will be able to classify all mapping units perfectly. In geotechnical modeling the mismatch between model results and the known distribution of slope failures may be a result of shortcomings in the model, local instability conditions, inaccuracy in data collection, imprecision in landslide mapping, or the spatial variability of factors that determine slope instability.

Multivariate models work best where the proportion of mapping units that is free of landslides and is nearly equal with that which is affected by landsliding. If the input factors include both good and poor predictors (i.e., some of the input variables do not have a clear relationship with landslides), statistical procedures may generate unreliable results. High and low values of hazard probability indicate hazardous and safe mapping units, respectively. Intermediate values (i.e., values close to 50% of probability) fail to add any additional information to the original landslide inventory (Carrara and others 1995).

The reliability and meaning of hazard classes derived from statistical scores should be clearly explained in the hazard map. Areas predicted to be stable (with a probability exceeding, say, 60%) and found to be landslide free, or predicted to be unstable (again, with a probability exceeding 60%) and having landslides, can be confidently mapped as such, but mapping units that are classified at intermediate levels of probability should most correctly be mapped as unclassified and placed in domains in which, given the available information furnished by forecasting variables, the model cannot provide any additional insight with respect to the known distribution of landslides.

A related problem is that of misclassification in models. The map becomes inaccurate where units are predicted to be unstable where no landslides were found, where there is change in land use or farming activities, the influence of some unidentified factor, or to landslides so extensively modified by erosion that they cannot be determined with the available tools. Conversely, mapping units that are predicted as stable but where landslides were actually recognized indicate either mapping errors or a model that fails to take account of the factors that cause failure in that specific environmental setting. Statistically sound multivariate procedures will yield an approximately equal proportion of the two types of misclassification. The first type of mismatch (type A error) must be interpreted as hazardous, whereas the second (type B error) is equivocal; it requires further investigation, and should be displayed accordingly.

The Upper Tiber River Experiment

The Tiber River basin is located in central Italy and drains into the Tyrrhenian Sea (Figure 1). The upper basin extends for about 4100 km² and is underlain by the limestone and marl of the Umbria-Marche stratigraphic sequence, by flysch deposits of the Tuscan and Umbrian sequences, and by lake and continental deposits of Pliocene to Holocene age. The attitudes of

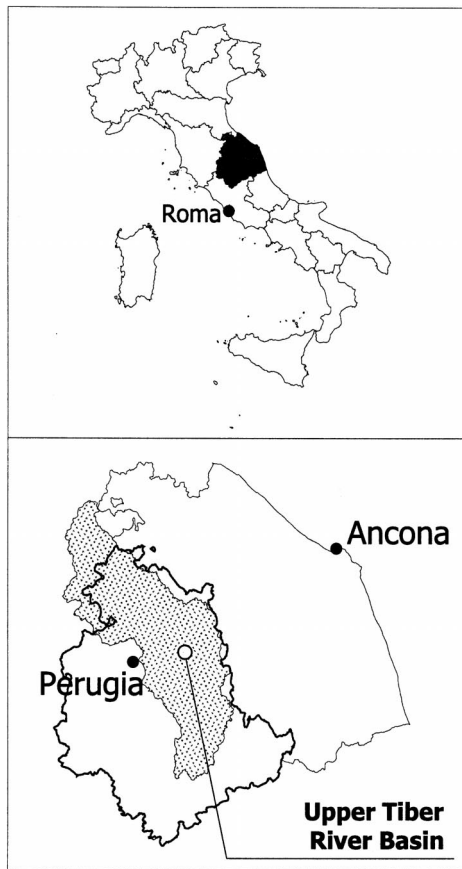


Figure 1. Location of the Upper Tiber River Basin (central Italy).

lithology and bedding largely control the location, abundance, and pattern of landslides. Mass movements found in the area include falls and topples in hard rocks, soil slips in the colluvial cover that mantles slopes underlain by soft or weak rocks, rotational slides in homogeneous and mostly soft rocks, and earth flows or complex and compound slides where alternating hard and soft rocks crop out (Guzzetti and others 1996b).

Landslides were mapped in the Upper Tiber River basin as part of a long-term effort to evaluate landslide hazard and associated risks (Guzzetti and others 1999). Preliminary reconnaissance mapping was carried out over the years 1987–1998 (Guzzetti and Cardinali 1989, 1990) and partially updated in 1989–1991 (Antonini and others 1993) through the interpretation of medium-scale (1:33,000) black-and-white aerial photographs taken in 1954–1956 (Figure 2). More recently, a new inventory was prepared by reinterpreting 1:33,000-scale aerial photographs and, over the 35% of the area where continental and lake deposits crop out, by using 1:13,000 color aerial photographs taken in 1977 (Figure 2). Detailed field checks were carried out in six pilot areas

in the basin or very close to it. In these areas, landslides mapped from aerial photographs were checked individually in the field (Carrara and others 1991, Barchi and others 1993, Toppi 1993, Cardinali and others 1994, Lambrugo and Lattuada 1996). Other checks were performed randomly in order to test the reliability of the inventory and to solve localized problems of interpretation.

In preparing the new inventory, interpretation of aerial photographs was carried out by a team of two interpreters who completed, not only the landslide inventory, but also a photogeological map and a map of bedding attitudes. Although it was demanding and time-consuming, this work allowed the interpreters to gain a better understanding of the local geological and morphological settings and to prepare a more reliable landslide map. Landslides were classified as shallow or deep-seated, and no attempt was made to determine their types, age, or degree of activity, as was done for the reconnaissance inventory (Guzzetti and Cardinali 1989, Antonini and others 1993) and the pilot areas (Carrara and others 1991, Barchi and others 1993, Toppi 1993, Cardinali and others 1994, Lambrugo and Lattuada 1996). Landslide depth varies depending on rock strength and lithology. In general, shallow failures involve surface deposits, soils, and the colluvial cover, whereas deep-seated landslides involve the bedrock.

The time and resources needed differed between the reconnaissance study and the new landslide inventories. Table 1 shows the comparison with additional reference to detailed studies that were carried out in pilot areas. The time needed to acquire data and complete maps was similar to that reported elsewhere in the literature (Campbell 1985, Cardinali and others 1990, Brabb 1993) and shows that landslide inventories can be prepared with few resources and in a reasonably short space of time, even for large areas.

A test was made to compare the reconnaissance maps with the new inventory. The former mapped about 4000 landslides over about 270 km², which represented 7% of the entire area (Figure 2). The proportion increases to about 9% if only hilly or mountainous terrain is considered, by removing floodplains and intermountain basins from the analysis. The new inventory recognized 17,600 slope failures that covered a total of 514 km² (Figure 2). This indicates that landslides cover 12.5% of the study area, a figure that increases to 14.8% if floodplains and intermountain basins are excluded from the analysis. The latter values agree with figures obtained from detailed studies carried out in pilot areas of the Upper Tiber River basin and its immediate surroundings (Carrara and others 1991, Barchi and

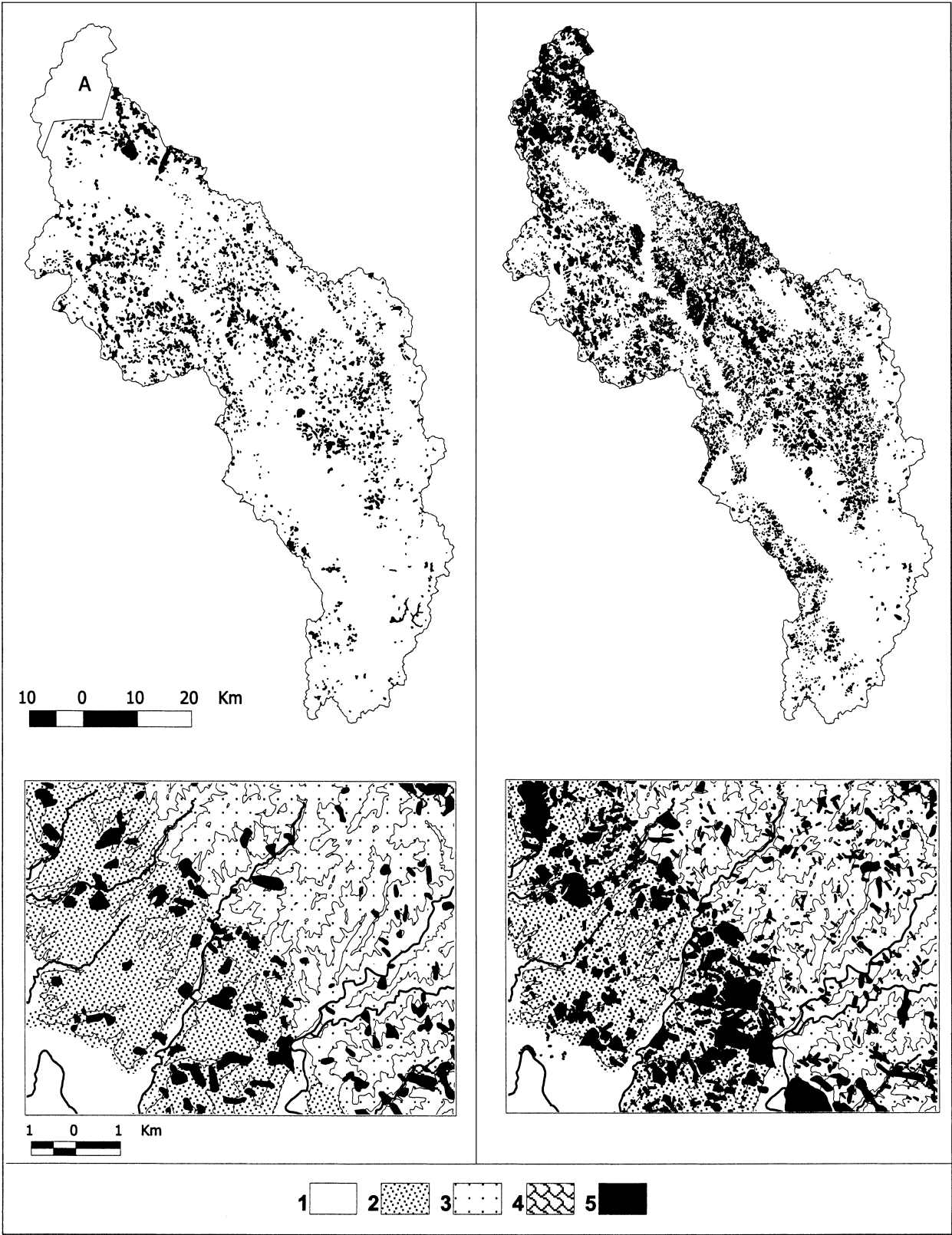


Table 1. Comparison of the time and resources needed to complete landslide inventories and other thematic maps at various scales in Central Italy

Area	Extent (km ²)	Aerial photographs			Data acquisition scale	Team (N.) ^c	Final map scale	Product	Time for photo inter- pretation (months/ man) ^d	Field check	Total time (months/ man) ^e
		B&W ^a	Color ^a	Total ^b							
Umbria Region ^f	13,000	1085		1085	1:25,000	2	1:100,000 ^j	Inventory map	18	Very limited ^l	24
Marche Region ^g	14,600	1100		1100	1:25,000	3	1:100,000 ^j	Inventory map	18	Very limited ^l	24
UTRB ^h	4150	400	600	1000	1:25,000	3	1:50,000 ^k	Inventory map	10	} Limited ^m	36
								Photo-geological map	14		
Pilot areas ⁱ	30–100	5–10	15–35	20–45	1:10,000	2–3	1:10,000 ^k	Inventory map Geological map Land use map	3–8	} Extensive ⁿ	6–12

^aBlack and white aerial photography at 1:33,000 scale taken in 1954–1956. Color aerial photographs at 1:13,000 scale taken in 1977.

^bTotal number of interpreted photographs.

^cNumber of geomorphologists carrying out photo interpretation in the team.

^dIncluding map drafting.

^eTime for map completion, including interpretation of aerial photographs, field checks, drafting, digitisation, and map publishing.

^fFrom Guzzetti and Cardinali (1989; 1990).

^gFrom Antonini and others (1993).

^hUpper Tiber River Basin, from Guzzetti and others (1999).

ⁱTescio basin (Carrara and others 1991), M. Coscerno area (Barchi and others 1993), Carpina basin (Cardinali and others 1984), Fosso Bianco (Toppi 1993), Mercatale area (Lambrugo and Lattuada 1996), and Carpinella (unpublished) areas.

^jPublished by Guzzetti and Cardinali (1989) and by Antonini and others (1993).

^kUnpublished work.

^lField checks were performed randomly, mostly along roads, in less than 5% of the study area.

^mField checks were performed in about 20% of the study area by geological survey or by random tests.

ⁿGeological and morphological maps were prepared through field mapping for the entire area.

others 1993, Toppi 1993, Cardinali and others 1994, Lattuada and Lambrugo 1996).

The mismatch of maps (Carrara and others 1992) between the two inventories is about 71% and is not evenly distributed. The highest mismatch is found

where lake and continental deposits crop out (Figure 2). The reasons for this are manifold, and they include interpreter errors in one or both maps that may arise from the different experience of the interpreters in how to recognize (subtle) landslides features on aerial photographs, different background information on landslide types and processes, and different amounts of time and resources that were available for the two investigations. The experience and knowledge of landslide types and processes and the time and resources available to the interpreters were increased in the second study with respect to the reconnaissance mapping exercise. Hence, the new landslide map is considered to be more reliable and accurate than the reconnaissance inventory.

Historical information on landslides in the Upper Tiber River basin was collected as part of a nation-wide attempt to compile an archive of mass movements and floods (Guzzetti and others 1994, 1996a, Reichenbach and others 1998b). For the 76-year period between 1918 and 1994, 329 pieces of information were collected on

Figure 2. Upper Tiber River Basin (central Italy). Comparison of landslide inventory maps. Left: Reconnaissance inventory carried out through the interpretation of medium-scale (1:33,000) black-and-white aerial photographs taken in 1954–6. The A shows the area where the reconnaissance inventory was not available. Right: New inventory prepared by re-interpreting 1:33,000 scale aerial photographs and, where continental and lake deposits crop out, by using 1:13,000 color aerial photographs taken in 1977. Original map scale is 1:100,000; figure scale is about 1:900,000. Lower maps are enlargements at about 1:50,000 scale. Contour lines and major streams are shown as thin and thick lines, respectively. 1) Recent alluvial deposits 2) Lake and continental deposit, Pliocene to Holocene in age 3) Flysch deposit of the Umbrian sequence; 4) Olistostrome; 5) Landslide.

single or multiple landslide events at a total of 249 sites. The historical catalog was compared with the new landslide inventory. Due to the different techniques used to complete the two inventories and, most importantly, to the difficulty in accurately locating historical events, it was not considered appropriate to overlay the maps directly. Instead, the distance was measured between each landslide that was identified historically and the nearest landslide mapped in the new inventory. It was found that about 75% of all historical events lay on or within a distance of 300 m to the nearest mapped landslide.

With respect to the study area, landslide density maps were prepared for both the reconnaissance survey and the new landslide inventory. For the latter, grid-based statistical maps and slope-unit based density maps were compiled (Figure 3). The grid-based density map was prepared by counting the percentage of landslide area within a circular moving window of about 1 sq km. The grid size used was 25 m, which is equal to the resolution of the DTM used to prepare the slope unit map. The slope-unit-based density map was prepared by counting the percentage of landslide area within each slope unit. Terrain where landslides were not expected (i.e., large floodplains and intermountain basins) were taken out of the analysis. The two maps were compared by ranking both with respect to the same density classes (<2%, 2%–10%, 10%–35%, and >35%; see Figure 3). Table 2 shows the result of the comparison. When compared to the grid-based maps, the slope-unit-based maps resulted in larger density values for both the very low and the high density classes, and appear to better fit the landslide inventory. This is confirmed by values for the high class (>35%) that are lower, but close to the average (regional) percentage of landslide area. The effect of excluding fluvial plains and intermountain basins is clearer for the very low (<2%) class that was reduced 6.2% and 4.2%, for grid-based and slope-unit-based maps respectively.

A landslide hazard map has not yet been constructed for the entire Upper Tiber River basin. However, landslide hazard was assessed from the statistical modeling of morphological, lithological, geological, structural, and land-use data for about 1130 km² in the most northerly section of the basin (Guzzetti and others 1999). The hazard map classifies about 72.4% of the 5604 slope units that partition the basin (Figure 4). Model mismatch resulted in 17.1% of type A errors and 10.5% of type B errors. As the two values correspond fairly closely with each other, the validity of the statistical model is confirmed: type B errors (the worst case) are less than type A errors (the conservative case). About 24.2% of all slope units have statistical scores that are

close to 0.5 (0.4–0.6), which indicates that the model is unable to classify land areas with absolute certainty.

Given the outcome of the statistical model, the study area was ranked into five hazard classes: (1) slope units classified as stable, with a probability $\geq 60\%$; (2) slope units classified as unstable, with a probability $\geq 60\%$; (3) slope units that are unclassified and have probabilities that lie between 40% and 60%; (4) slope units that are predicted as unstable but do not contain recognizable landslides (misclassification of type A); and (5) slope units that were predicted as stable but do have landslides (misclassification of type B).

Discussion

The value of a map refers to its information content, which depends largely on the type of data shown, their quality, and the extent to which the information is new and essential. A map is valuable when the data shown are useful to the user, i.e., when the map is both relevant and understood by the user.

A carefully designed inventory map that shows landslides as recognized by the interpreter, without any modification apart from scale or graphical constraints, is a basic map. A landslide density map obtained by interpolating an inventory map without any additional information is a derivative map. A landslide hazard map obtained from an inventory is also a derivative map but, if it includes additional information on factors such as lithology and morphology that are used to build the hazard model, it has an information content that is superior to that of the input maps, including the inventory.

Landslide inventory maps are easy for both experts (such as geomorphologists) and nonexperts (such as decision-makers and planners) to understand. Such maps are easily prepared by trained geomorphologists and do not require large investments. Only limited resources are required for their completion, namely aerial photographs, base maps, and a stereoscope.

Figure 3. Upper Tiber River Basin (central Italy). Comparison of landslide density maps. Left: Grid-based density map prepared by counting the percentage of landslide area within a circular moving window of about 1 square kilometer. Grid size was 25 meters. Right: Slope-unit based density map prepared by counting the percentage of landslide area within each slope unit. Terrain where landslides were not expected (large floodplains and intermountain basins, white on the maps) were taken out of the analysis. Figure scale is about 1:900,000. Lower maps are enlargements at about 1:25,000 scale. Density classes: 1) Nil 2) <2% 3) 2–10% 4) 10–35% 5) >35%. 6) Landslide.

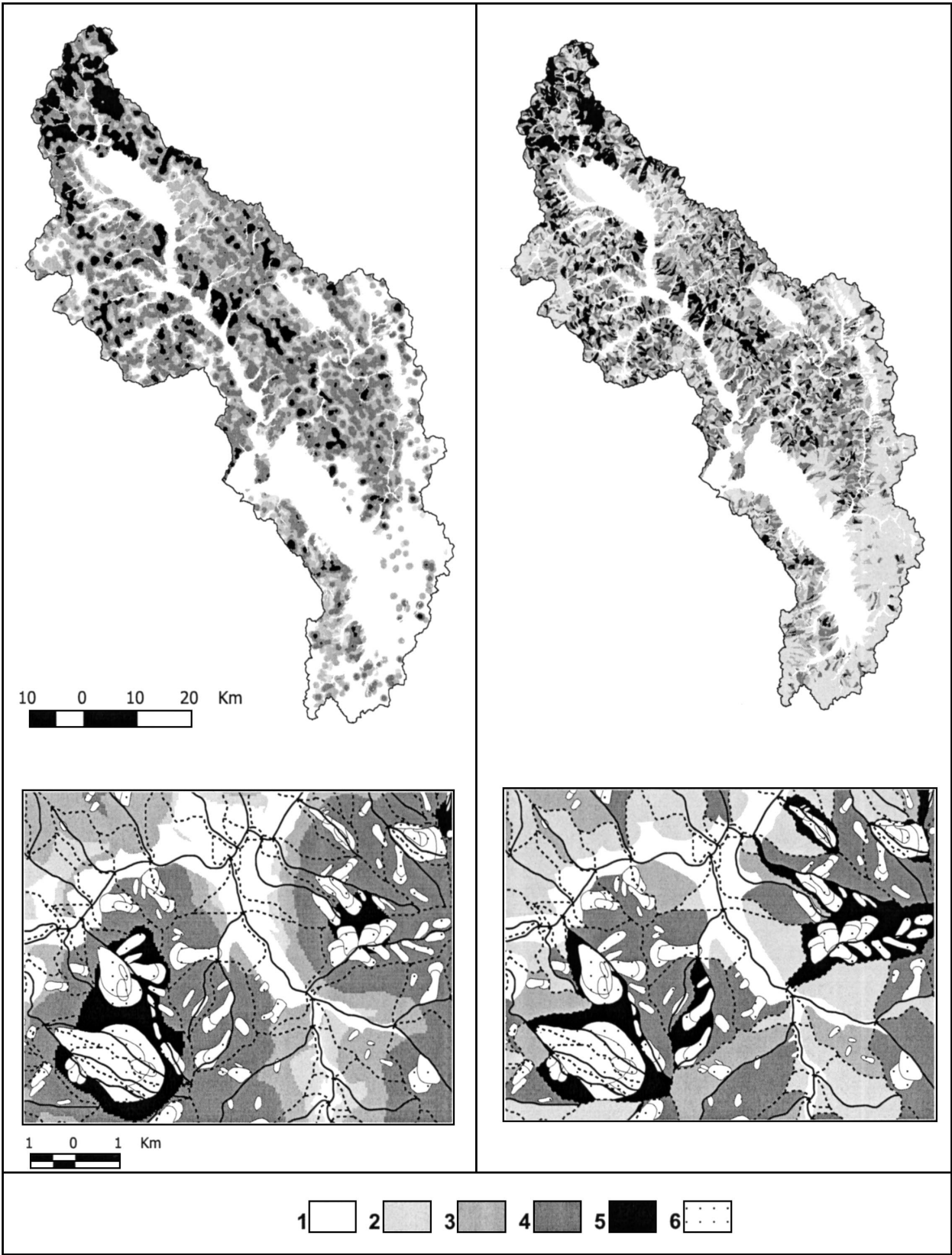


Table 2. Comparison of grid-based and slope-unit-based density maps^a

Density map	Domain	Density			
		Very low <2%	Low 2%–10%	Medium 10%–35%	High >35%
Grid-based density map	Entire area	34.7	25.7	29.9	9.7
	Without valley bottoms	28.6	26.7	33.5	11.2
Slope-unit-based density map	Entire area	46.2	20.0	22.0	11.8
	Without valley bottoms	41.9	20.1	24.4	13.6

^aIn the grid-based density map, grid size was 25 m, consistent with the resolution of the DTM used to compute slope units.

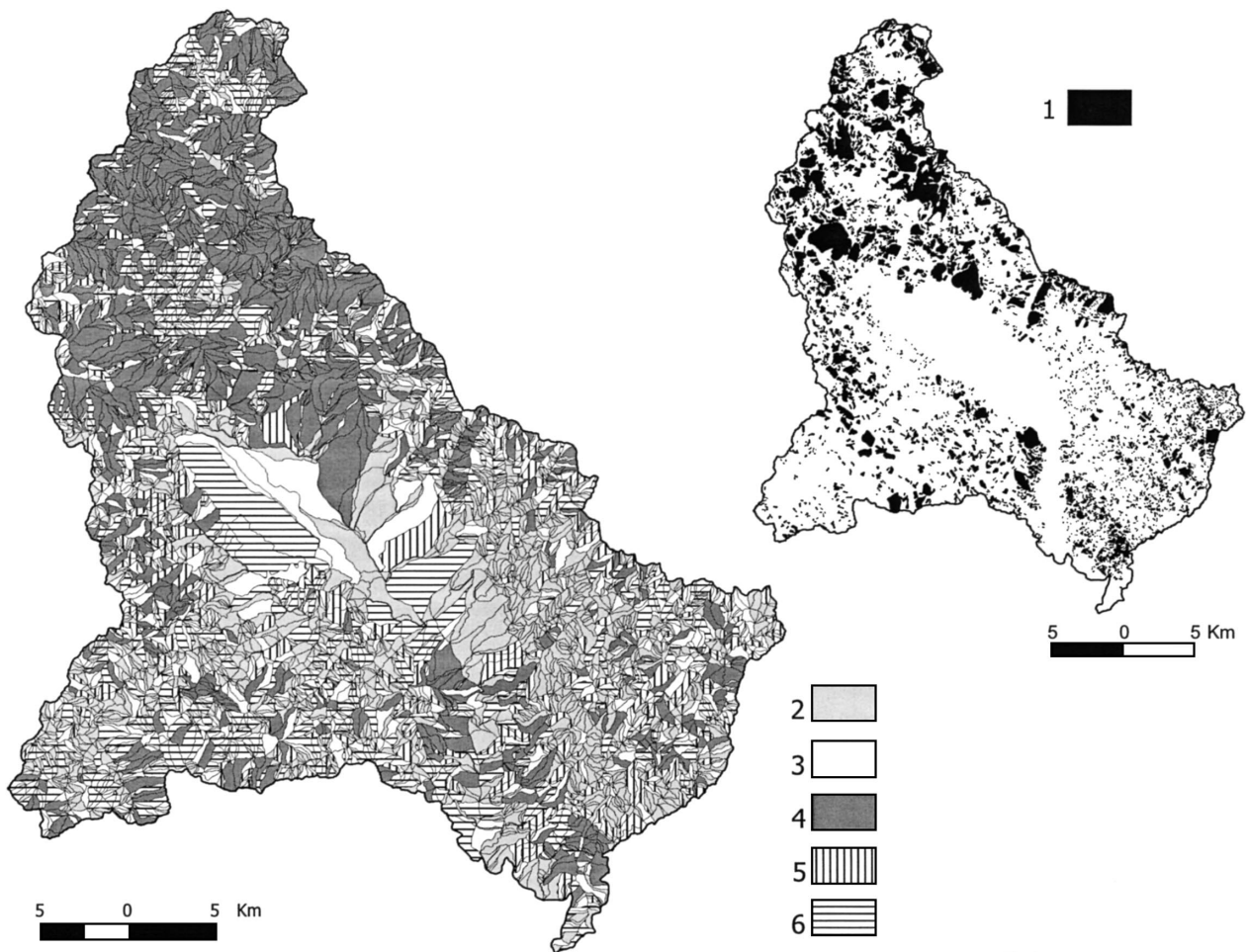


Figure 4. Upper Tiber River Basin (central Italy). Landslide hazard map for the most northerly section of the basin. The map to the left was prepared through the statistical modelling of morphological, lithological, geological, structural and land-use

data. Hazard, i.e., the probability of finding a landslide within any given slope unit, is shown in 5 classes. The map to the right shows the new landslide inventory. 1) Landslide 2) Stable area 3) Unclassified 4) Unstable area 5) Error of type A 6) Error of type B.

Despite the ease with which they are prepared, and their immediateness, landslide inventories are not yet very common. Inventory maps are available for only a few countries and mostly for limited areas (Brabb and Harrod 1989, Brabb 1993). This is surprising because inventories provide fundamental information on loca-

tion and size that is necessary in any assessment of slope stability.

The reasons for this shortcoming are manifold and depend on general and local conditions. There is a certain inability of environmental and planning agencies and of national and regional geological surveys to

understand the value of regional inventories for planning purposes (Brabb 1996). This is often coupled with an inability or lack of resolve in preparing landslide inventories for large regions, which has the effect of limiting knowledge of landslide distributions, types, and patterns. Indeed, some planning agencies prefer to ignore where landslides are located: lack of knowledge in this case represents a degree of freedom. The opinion that landslide mapping, and in particular inventory making, is not scientific finds advocates even among earth scientists (Sassi and others 1998). Indeed, preparing landslide inventories, particularly from aerial photographs with or without field surveys, is a subjective operation that requires skills and training. Maps prepared by personnel not sufficiently trained or experienced or who lack the proper resources may be wrong and unreliable. The subjectivity and the difficulty in assessing (quantitatively) its reliability, make landslide inventory maps somewhat unreliable in the eyes of some potential users. Lastly, in recent years there has been a general, unjustified preference for “high-tech” remote sensing techniques, which are not yet capable of mapping landslides efficiently over even small areas (Soaters and others 1991).

The experiment in the Upper Tiber River basin has confirmed that landslides can be cost-effectively recognized and mapped by skilled geomorphologists through the interpretation of aerial photographs. As it is a detailed update of a previous reconnaissance mapping, the new inventory has greatly improved the quality and spatial resolution of mass-movement information. A recent test carried out in a limited portion of the basin has shown that, despite possible cartographic and mapping errors, the new inventory was able to predict about 80% of the more than 3500 landslides caused by a severe snowmelt event in January 1997.

Results of the reconnaissance and detailed mappings showed that the vast majority of failures were soil-slips, slide-earth flows, and complex and compound landslides (Guzzetti and others 1996b) that, for hazard assessment purposes, could be considered as two landslide types: shallow and deep-seated. Previous surveys also showed that landslide age and activity were difficult to determine consistently across morphological and geological boundaries without checking failures singularly in the field (Antonini and others 1993). This is why in the new inventory landslides were mapped as shallow or deep-seated and no attempt was made to determine type, age, or degree of activity.

The Upper Tiber River basin experiment has also shown that, quite apart from the landslide inventory, the production of photogeological maps locally increases the quality of both kinds of map and thus limits

the risk of geological misclassification. On the other hand, the process is more time-consuming and demanding on the interpreters.

The number, size, and total extent of mapped landslides depend on many factors, including the skill of the interpreter and the scale and quality of aerial photographs. The Upper Tiber River basin experiment has shown that a reconnaissance mapping, carried out with medium-scale aerial photographs in a limited time, provides a good overview of the distribution of landslide deposits at the regional scale, allowing for general discussions on landslide types and patterns in different lithological and physiographic environments. The new inventory, completed by reinterpreting the same medium-scale aerial photographs with less time constraints and improved knowledge on the lithological, structural, and morphological settings prone to failures, show more landslides and an increased landslide area. Landslides are mapped more accurately, and landslide boundaries follow more precisely the actual landslide geometry, better fitting morphological and lithological constraints (i.e., drainage lines, lithological boundaries, faults, bedding attitude, etc.).

Limited to the outcrop of lake and continental deposits, where large-scale (1:13,000 scale) aerial photographs of a different vintage (1977) were used in addition to the medium-scale photographs (1954–1955), the marked increase in the number and of the total area of landslides mapped is due to the larger scale of the photographs that allowed for the recognition of smaller landslides. Recent tests performed in limited areas where flysch deposits crop out have shown that interpretation of large-scale (1:13,000 scale) aerial photographs (1997) added limited new information, better defining only the internal subdivisions of large landslide deposits.

Even if it is very accurate and precise, a landslide inventory map cannot show all slope failures that have occurred in an area. The landslide map will show only slope failures that have left discernible morphological signs on the date and at the scale of the investigation. Thus, the quality of a landslide inventory depends on the persistence of landslide morphology within the landscape and the ability of the interpreter to properly understand the geomorphic evolution of the slopes. In the areas that are mapped as having landslides, interpreters are confident that landslide scars and/or deposits exist, but nothing is said about the reliability of such statement, i.e., the veracity of the map. Additionally, where landslides are not shown, most commonly nothing is said about the potential presence or absence of slope failures. Indeed, authors of inventory maps often state that areas not mapped as landslides cannot be

considered free of mass movements, but rather represent domains where the interpreter was not able to identify a failure (Guzzetti and Cardinali 1989, 1990, Antonini and others 1993). No effort is made to distinguish areas that are landslide free (such as large alluvial plains, valley bottoms, flat ridge tops, and stable ground) from areas where landslides could exist but either are not present or were not recognized.

This imprecision limits the value of landslide inventory maps and may jeopardize their usefulness for planning, land development, and decision-making. Indeed, where landslides are recognized, actions can be taken and proper regulations can be established before planning or land development takes place. Much less clear is what to do where landslides are not recognized, particularly in the vicinity of existing mass movements or in terrain that is prone to slope failures.

As an example, on 5 May 1998 rainfall-induced shallow failures were triggered on the steep slopes mantled by volcanic deposits of the Pizzo d'Alvano area (Campania, Italy). The resulting debris flows killed 137 people in the village of Episcopio (Sarno). Twenty-three additional casualties were reported at Quindici, Siano, Braciliano, and San Felice a Cancellò. Inspection of medium-scale (1:33,000) aerial photographs showed that prior to the event little could be said about the exact location of the source area of debris flows. However, on the basis of the overall geological and geomorphological settings, slopes could be interpreted to be highly susceptible to failures. Archive data confirmed that the region suffered similar catastrophic landslides in historical and recent times.

To improve the accuracy with which future landslides are predicted, the density of slope failures can be determined within predefined domains or mapping units. Density is a clearly definable and easily comprehended quantitative measure of the spatial distribution of slope failures. Regardless of the geological setting, where landslides are abundant, density is high and, conversely, where landslides are sparse, density is low.

Landslide density maps are fillers of space. They provide insight on the expected (or inferred) occurrence of landslides in any part of the investigated area without leaving unclassified areas. A density map does not show where landslides are located but this (apparent) loss in resolution is compensated for by improved map readability and reduced cartographic errors (Carrara and others 1992). Additionally, landslide density is independent of the extent of the study area, which makes comparison between different regions straightforward. Such characteristics make density maps appealing to decision-makers and land developers.

In the Upper Tiber River basin the inventory and

density maps were combined. This was achieved by overlying the landslide inventory on top of the density map based upon slope units. The resulting map retains the advantages of a landslide inventory map (i.e., it shows where failures were recognized by the interpreter) and fills spaces, thus providing insight into the distribution of slope failures. The use of slope units guarantees a match with the local morphological setting. The map was further improved by clipping out of the frequency count the areas that were known to be landslide free (e.g., large valley bottoms). The combined inventory and density map gains in readability and applicability to decision-making and planning.

Despite all possible improvements, landslide density maps do not incorporate any physical relation between slope failures and the landscape. Thus, they cannot be used to establish the factors that control landslide occurrence. Indeed, density maps can be used to decide where landslides are more abundant but not why this is so. They can be of help in specifying where subsequent studies have to be made but not to model the effects of remedial works. This is the goal of landslide hazard modeling.

Regional landslide hazard models are the most sophisticated and complex forms of landslide cartography. As they are derived from the analysis of many instability factors, hazard models help explain why landslides are abundant or sparse and help model the effects of hazardous events and remedial works. Given that landslides take many different forms and result from the interplay of a variety of causes (Schuster and Krizek 1978, Crozier 1986, Dikau and others 1996, Turner and Schuster 1996), different hazard models can be prepared that take into account the main instability factors (rock composition, structure, etc.) and the various landslide types (deep-seated slide, shallow failure, debris flow, rock fall, etc.). Additionally, models of different forms and reliability can be prepared for the same area, depending on the type and quality of the available information.

Although they are diagnostically powerful and are potentially superior to more simple approaches such as inventory and density maps, landslide hazard models are complex tools that can be difficult to master and exploit. They need to be applied with care to planning and land development, and only by experienced geomorphologists, who will often be the same people who helped build them. This is particularly relevant for areas that were either misclassified by hazard models or where the model was unable to classify the terrain. In these places, it is essential to understand how a model behaves before it can be put to any practical use. A landslide hazard model should always be used in combi-

nation with all the information that was used to build it. This can be readily done if the information is available in digital format in a properly organized GIS.

As a drawback, statistical models of landslide hazard are difficult to prepare. They require large efforts to collect and validate input data that are often not readily available. They also need interaction between expert geomorphologists and statisticians in order to process data in such a way as to avoid statistically sound but geomorphologically unrealistic or erroneous results. Lastly, they are negatively influenced by the extent of the investigated area, which makes it difficult to compare hazard classes from different locations (Carrara and others 1991, 1995, Guzzetti and others 1999).

In the Upper Tiber River basin the landslide hazard model proved quite efficient in classifying the terrain as potentially stable or unstable. About 30.8% of the land surface was classified as unconditionally stable and 43.0% as unconditionally unstable. The remaining part (about 26.2%) had a statistical score close to 0.5 and was of uncertain hazard classification. In these areas further investigation and additional information are needed in order to assess landslide hazard.

Uncertainties and errors in preparing a landslide inventory will reflect on the derived products: density and hazard maps. If errors are large because of the lack of interpreter's experience, misunderstanding of the geological or geomorphological setting and evolution, or if one or more landslide type is not recognized and mapped, all subsequent landslide maps will be partly or totally erroneous. The effects of limited, nonsystematic errors will vary. Density maps, being a simple interpolation of the inventory, will be negatively affected and will provide erroneous results. Negative effects will be less severe for maps prepared using physically based mapping units. Wrong or inaccurate mapping is reflected in (robust) statistically based hazard models as errors (of type A or B) that can be quantified and dealt with separately. This is a major advantage of hazard models compared to landslide density or landslide direct mapping.

For planning and decision-making, a single landslide map (whether it be an inventory, density, or hazard map) is seldom considered adequate (Guzzetti and others 1999, Brabb 1995, 1996, Swanson and Schuster 1989, Ahlberg and others 1988, Godefroy and Humbert 1983). To exploit the map potential to the full, a protocol (i.e., a set of regulations) must be established that links terrain domains to proper rules. For landslide inventories (Figure 5A) only one set of regulations can be used for the areas mapped as landslides. Little can be said about the remaining territory, unless a distinction is made between the areas that are free of landslides and

those where landslides were not recognised (Cardinali and others 1990).

Designing regulations for density maps may be somewhat easier (Figure 5B). In these the land area that is potentially hazardous is not classified as totally free of landslides. A single rule, either loosely or tightly enforced, or a set of rules of escalating complexity can be designed to depict increasing density of landslides. The combination of landslide and density maps shows information of different utility and requires two sets of rules: one for the areas mapped as having landslides and one for the remaining land area. The latter will be based on the abundance of landslides.

It can be very difficult to design a protocol for landslide hazard maps (Figure 5C). Rules can be made that take model reliability into consideration and deal differently with domains classified as unconditionally stable or unstable and those for which further investigation is required. Development of a thorough protocol may be aided by GIS technology. Within a GIS environment encompassing all the information (or themes) used to build the hazard model, rules can be defined that consider information such as topography, morphology, lithology, urban expansion, and land use, which is not readily available from landslide inventory or density maps. As different hazard models are prepared for varying landslide types, and more than a single hazard model can be prepared for the same landslide type, a comprehensive protocol would probably be linked to different scenarios. A complex set of regulations is feasible, and it would cover areas mapped as having landslides, those that the model defines as landslide-prone or stable, those of uncertain definition, and areas that were mapped erroneously by the model.

Conclusions

It should be noted that any sufficiently wealthy society may be willing to take cost-effective actions where a problem exists (in this case where landslides have been recognized). The same society will be unwilling to act where a problem is not recognized (i.e., landslides were not mapped), even if this does not preclude landslides from occurring the future. The misconception may be caused by lack of knowledge or an erroneous perception of natural hazards and by the inability of earth scientists to provide the correct perspective to decision-makers or the general public. This highlights the role of landslide maps and the need for a renewed effort to find ways to transfer information on landslide occurrence to decision-makers and the public.

Landslide mapping is a form of geomorphological

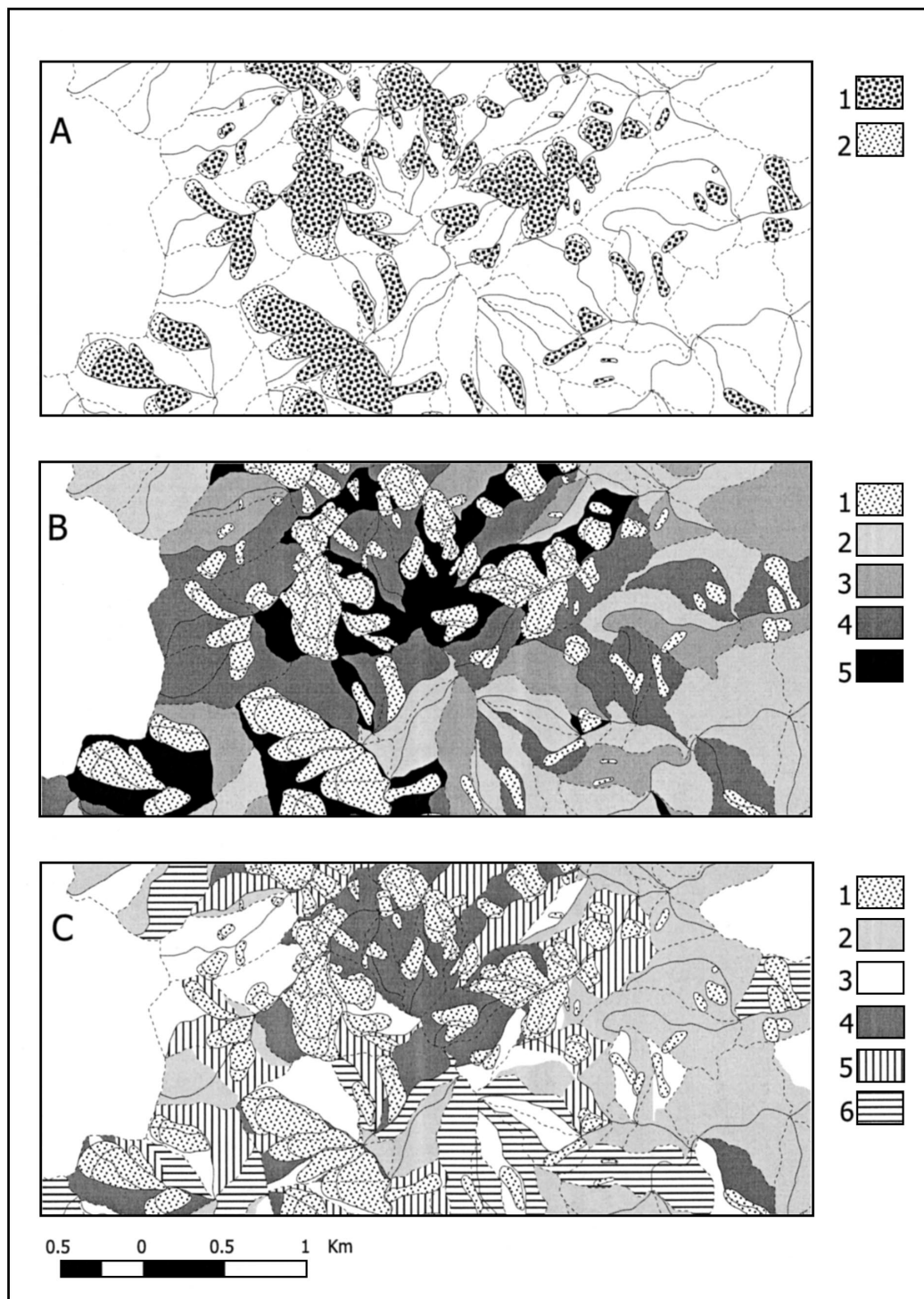


Figure 5. Upper Tiber River Basin (central Italy). Comparison of landslide maps. Continuous lines are drainage and dashed lines are divides. A) New inventory map (see Figure 2). 1) Landslide deposit, 2) Landslide crown area. B) Slope-unit based density maps (see Figure 3). 1) Landslide, 2) <2%, 3) 2-10%, 4) 10-35%, 5) >35%. C) Landslide hazard maps (see Figure 4). 1) Landslide, 2) Stable area, 3) Unclassified, 4) Unstable area, 5) Error of type A, 6) Error of type B.

cartography that has been pursued by individuals and institutions for many years. Landslide inventory, density and hazard maps can be prepared by different techniques and have a variety of possible applications. Despite the efforts, no agreement has yet been reached on the techniques and methods for their preparation, which makes it difficult to compare results achieved by different authors. Moreover, the goals of landslide cartography tend to be heterogeneous. There is a definite need for new efforts designed to experiment with new mapping techniques and to test their applications.

In synthesis, the long-term experiment in the Upper Tiber River basin has confirmed that landslides can be cost-effectively mapped by experienced geomorphologists at different scales by interpreting aerial photographs and field surveys. The collection of historical information on past landslide events from archive and chronicles has also proved to be effective. However, it is not easy or straightforward to compare different types of inventory. Errors and uncertainties associated with the inventory process can be large and need to be quantified.

The Tiber experiment has also shown that GIS technology makes it easy to prepare landslide density maps from landslide inventories. If a geomorphologically based mapping unit is selected, density maps provide an overview of the distribution of landslides. However, as they bear no physical relation to slope processes, landslide density maps cannot provide insight into the causes of slope failures.

In addition, the experiment has shown that statistically based landslide hazard models can be successfully prepared for large areas at scales that are suited to regional and municipal planning. They can provide insight into the causes of landsliding and will thus foster knowledge of slope processes. However, rigorous hazard models are hard to prepare and difficult to exploit: for this reason they should be used with care. Further work is needed in order to test methods of displaying the outcome of hazard models that take into account model shortcomings and local variability.

Finally, the Tiber experiment has shown that, even where it is required by law, landslide cartography cannot fully satisfy the needs of decision-makers, planners, real estate agents, environmental and civil protection agencies, utility companies, and the insurance industry. Regulations are needed that link the terrain domains outlined by inventory, density, or hazard maps to required actions. Designing, testing, and enforcing such regulations may prove to be the most difficult part of any landslide hazard assessment project.

Acknowledgments

The research was supported by CNR IRPI and CNR GNDICI grants. Authors are grateful to David Alexander, Earl Brabb, and Andy Hansen for reviewing the manuscript. The report is CNR-GNDICI publication no. 2048.

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