Geogr. Fis. Dinam. Quat.
28 (2005), 63-80, 9 figg., 4 tabb.

PAOLO MORA (*), MARCO GUALDRINI (**) & MASSIMO FABRIS (***)

PHOTOGRAMMETRIC DEMS AND SPATIAL ANALYSIS TECHNIQUES IN LANDSCAPE EVOLUTION STUDIES

ABSTRACT: MORA P., GUALDRINI M. & FABRIS M., *Photogrammetric DEMs and spatial analysis techniques in landscape evolution studies*. (IT ISSN 1724-4757, 2005).

The comparison of multitemporal Digital Elevation Models (DEMs) of the same area is a powerful tool in an integrated approach for studying Earth surface features and their evolution. At the same time, the differences in the techniques used to generate different datasets and the presence of artefacts constitute an important problem that must be solved in order to allow a meaningful study of the geomorphologic evolution of the area.

Geographic Information Systems (GIS) tools can be of great help in this approach, allowing users to obtain significant morphometric parameters from co-registered DEMs and giving at the same time the possibility to estimate artefacts in the datasets, to evaluate differences between ground surfaces in the different years and to validate results through geostatistical processes.

In this study photogrammetry has been applied to extract multitemporal DEMs datasets of a hydrographic basin affected by landslides (Bologna, Italy) and GIS techniques have been used for morphologic enquiry on the test site.

A time series of stereo digital images, derived from aerial photogrammetric surveys (1976, 1986, 1988 and 1993), was analysed and processed for obtaining high spatial resolution DEMs through softcopy photogrammetric techniques. DEMs accuracies, strictly related to the quality of images, to the adopted systems and strategies and to the morphologic features of the test area, were estimated.

The analysis of the derived data in a GIS environment allowed the generation of correction maps and shaded relief maps for each dataset, evidencing various types of 3-Dimensional (3-D) artefacts in the models. After appropriate filtering of data, in order to make datasets comparable, geomorphologic features of the site were studied by means of 3-D raster analysis techniques. GIS functions were applied to the DEMs in order to display morphometric parameters for each dataset (elevation, slope, aspect, curvature) and to compare the ground surfaces, generating differential elevation maps for the whole of basin.

Generally, differential movements inside the landslide areas in the basin appear to be comparable to the movements of the whole of basin in the considered time span: these differences must otherwise be weighted and validated, considering the accuracy of the different datasets and the limits of these comparison techniques.

KEY WORDS: Landscape evolution, Digital Elevation Models, Digital photogrammetry, Geographic Information Systems, Spatial analysis.

INTRODUCTION

A Digital Elevation Model (DEM) is a digital representation of continuous variation of ground relief over space (Burrough, 1986; Burrough & McDonnel, 1998). DEMs provide a description of the physical surface of the Earth and represent a powerful tool for many applications. In particular, DEMs have been useful with respect to the mapping of morphologic variations and areas involved in crustal deformations, the study of induced gravitative instability phenomena and the control of eruptive events (Achilli & *alii*, 1997; Kääb & Funk, 1999; Baldi & *alii*, 2000; Baldi & *alii*, 2002; Mora & *alii*, 2003; van Westen & Lulie Getahun, 2003) show the importance of multitemporal DEMs datasets (Pesci & *alii*, 2004).

DEMs can be extracted by applying selected methodologies based on specific surveying approach like aerial and terrestrial photogrammetry, kinematic Global Positioning System (GPS), airborne and terrestrial laser scanning and Interferometric Synthetic Aperture Radar (InSAR) systems (Pesci & *alii*, 2004).

DEMs come in different scales and resolutions and are organized as ordered arrays of regularly gridded numbers representing terrain elevations for ground positions. Internal accuracy is related to the survey method, field working conditions and depends on the quality of data, morpho-

(*) *Alma Mater Studiorum - Università di Bologna, Dipartimento di Scienze della Terra e Geologico-Ambientali, via Zamboni 67 - 40127 Bologna (BO), Italy.*

(**) *GEOgrafica, via Fornarina 3 - 48018 Faenza (RA), Italy.*

(***) *Alma Mater Studiorum - Università di Bologna, Dipartimento di Fisica, Settore Geofisica, viale Berti Pichat 8 - 40127 Bologna (BO), Italy.*

This research was supported by Italian MIUR 2001 National Research Program: «Hydro-geological hazard control in sites of high societal value through the integration of remote-sensing and monitoring techniques».

We are indebted to M. Berti, M. Ciabatti and G.A. Pini for reviewing an earlier version oh the manuscript and for their helpful suggestions.

Special thanks to Leica Geosystems SpA for providing hardware and software support in the improvement of specific data managing procedures.

logic features of the measured area and on the systems and strategies adopted for data management and processing.

In fact, DEMs often present terrain elevation errors due to problems encountered during data collection and/or handling and/or processing. Complete error elimination is difficult to plan and achieve, although several methods for correction of these errors have been developed and improved.

The availability of stereo aerial photo coverage of the whole of Italy since the 1950's allows us to generate 3-D datasets essential for the assessment of morphological changes which occurred over the last 50 years. Time sequences of multiscale aerial photogrammetric surveys performed over the same area represent a powerful tool for obtaining reliable information.

Using standard procedures, elevation difference time series between DEMs, characterized by comparable model accuracy, can be calculated (Pesci & *alii*, 2004) in order to monitor surface deformations, to detect morphological changes and to evaluate mass volumes involved in different events (Mora & *alii*, 2003). Different DEMs need to be registered in a unique spatial reference system. The co-registration of different DEMs can be obtained through ground control points or surface matching procedures (Pilgrim, 1996; Mitchell & Chadwick, 1999; Li & *alii*, 2001).

Geographic Information Systems (GIS) offer the possibility of managing DEMs in a useful way. In particular, the different elevation datasets, together with other geographic data (raster images, orthophotos, vector and raster topographic bases, vector and raster land cover data with database attributes, 3-D points, labels) can be treated in the same georeferenced system. This allows overlay, direct query and comparison and to approach data analysis in an integrated way. This approach makes it possible to analyse data keeping a global view on the area and on the phenomena of interest.

The analysis can be conducted using several methods to evaluate different parameters directly available in the DEMs or derived through simple or complex algorithmical operators.

Many geomorphologically significant variables, such as slope distribution, surface convexity and drainage, can be automatically extracted and compared each other and with other geographic data to obtain new informations and modelizations of the landscape evolution processes, providing an understanding of these processes in qualitative and quantitative terms (Pike, 1995; Longley & *alii*, 2001; Arrel, 2002).

Results are directly related to the dataset accuracy and scale: it is impossible to obtain information with a general accuracy higher than that of the original data. Furthermore, as landforms and processes are scale-dependent (Schumm & Lichty, 1965), the choosing of an appropriate work scale is important for obtaining significative results for the investigated processes.

In this study multitemporal DEMs datasets, extracted by means of digital aerial photogrammetry on the test area, have been checked and managed with spatial analysis techniques.

GEOLOGICAL SETTING AND MORPHOLOGIC FEATURES

The study area is located in a hydrographic basin affected by landslides in the Reno River basin (Northern Apennines of Italy). The Northern Apennines are a mountain chain formed by fold-and-thrust belts, thrust sheets and nappes, in general verging toward NE. They developed during the continuous convergence between the European and the Adriatic plates (Elter & *alii*, 2003; Regione Emilia-Romagna, 2004, and references therein).

Two main tectonics units, mostly corresponding to different paleogeographic domains, have been recognized: the Tuscan-Umbria-Romagna units and the Ligurian nappe. The Tuscan-Umbria-Romagna units are the deepest structural units and share a common stratigraphy, from Upper Triassic evaporites, to Jurassic-Cretaceous carbonatic succession, up to Oligocene-Upper Miocene foredeep turbiditic deposits (Macigno, Mt. Cervarola Sandstones, Mt. Falterona Sandstones, and Marnoso-arenacea Formation) (see, among many others, Vai, 2001, and references therein; Pini & *alii*, 2004; Regione Emilia-Romagna, 2004). They have been organized as structural units and are internally deformed by several deformation phases of Oligocene, Miocene, Pliocene and Pleistocene ages (Vai & Castellarin, 1993; Cerrina Feroni & *alii*, 2002).

The Ligurian nappe is the uppermost structural unit and its basal contact upon the Umbria-Romagna units is evident along the «Sillaro line». It is composed by Subligurian, Ligurian and Mesoligurian units. The Ligurian units are made up by Middle Jurassic ocean crust (ophiolites) and Upper Jurassic-Middle Eocene deep marine sediments (Pini & *alii*, 2004). A sequence is recognizable in the latter with clayey complexes hosting calcareous and siliciclastic turbidites in the lower part (Palombini Shale, Varicoloured Shale, Ostia and Scabiazza Sandstones) and thick turbiditic successions, known as «Helminthoid flysches», in the upper part (Bortolotti & *alii*, 2001; Elter & *alii*, 2003; Pini & *alii*, 2004; Regione Emilia-Romagna, 2004).

The Subligurian units derive from deformation of stratigraphic units deposited onto a thinned continental margin close to Ligurian oceanic domain and are mainly constituted by Paleocene-Middle Eocene shaly calcareous turbidites («Canetolo complex») (Regione Emilia-Romagna, 2004).

The Mesoligurian units (Calvana and Sillaro units, «Modino basal complex»), representing an intermediate paleogeographic domain between the Subligurian and Ligurian ones, are characterized by stratigraphic features intermediate between the Subligurian and the Ligurian units and shared the same structural evolution as the Ligurian units in eoalpine and mesoalpine tectonic phases (Cerrina Feroni & *alii*, 2002; Pini & *alii*, 2004).

The overthrust of the Ligurian nappe onto the Tuscan-Umbria-Romagna units continued from upper Aquitanian to Lower-Upper Pliocene. A thick lithostratigraphic succession has been deposited onto the Ligurian nappe in the so-called satellite or piggy-back basins (Ori & Friend, 1984; Ricci Lucchi, 1986). In the geological literature these sedimentary sequences, characterized by prevailingly marine sediments (Monte Piano, Ranzano, Antognola, Bismantova, Termina and Gessoso-solfifera Formations) and deposited from Middle Eocene to Lower Messinian, have been referred to as Epiligurian succession (Ricci Lucchi, 1986).

The emplacement of the allochthonous complex (Ligurian nappe) at the Apennines-Po Plain border occurred in the Pliocene and in some cases the Pleistocene. Alongside the main divide of the chain, the geometric relationships described above have been cut and overturned by out-of-sequence overthrusts, starting from the Upper Miocene-Lower Pliocene up to the Middle Pleistocene. An important phase of normal faulting related to crustal extension characterized the south-western part of the chain (facing the Tyrrhenian Sea) (Carmignani & *alii*, 2001; Martini & *alii*, 2001, and references therein). This extensional tectonics is now active alongside the Apenninic watershed and is extending towards the Po Plain. The actual Apennine front is now buried by the alluvial deposits of the Po plain (Pieri & Groppi, 1981).

A large part of the Subligurian, Mesoligurian and Ligurian units at the latitude of Bologna has been long considered in the geological literature as chaotic assemblages of rocks of uncertain, and therefore strongly debated, origin (see Cowan & Pini, 2001, and references therein). These rock units, referred to as «*argille scagliose*» («scaly clays») and later as «*caotico eterogeneo*» or «*complesso caotico*» («Chaotic Complex») are characterized by a prevailing block-in matrix texture. Moreover, a thick weathered carapaces and the cover of recent mudflows tend to homogenize the feature of the rocks and to give a common, chaotic aspect.

More recent studies (Bettelli & Panini, 1989; Castellarin & Pini, 1989) pointed out that the «*argille scagliose*» can be subdivided in two distinct group of rock units/bodies: 1) broken to completely disrupted formations, which have been strongly deformed as a consequence of intense continuous tectonic stresses, but which still maintain their lithostratigraphic identity (tectonosomes, Pini, 1999), and 2) deposits by debris flows and avalanches related to both the Epiligurian and the Ligurian/Mesoligurian units (argillaceous breccias, or olistostromes, Bettelli & Panini, 1992; Pini, 1999).

The main morphologic features change substantially in relation to the geological and physical characteristics of the terrain. The most important variations are associated with the evolution of the slopes. In fact, the sandstone outcrops (i.e. Macigno, etc.) are characterized by steep slopes, while the clayey formations (i.e. Subligurian and Ligurian Units, etc.) present lower acclivity with more gentle hilly aspect.

The Subligurian and Ligurian Units (Palombini Shale, Varicoloured Shale, «*argille scagliose*» *Auctt.*) and the sedimentary breccias of the Epiligurian succession are affected by the largest number of landslides. This situation depends mainly on their chaotic structures and on the predominance of clayey materials with low shear strength values.

In the Emilia-Romagna region, where landsliding appears to be an important process of past and present morphologic evolution, over 32000 landslides bodies have been recognized. Twenty-six percent of them had activity between 1982 and 1995 (Regione Emilia-Romagna, 1999; Regione Emilia-Romagna, 2004) with velocities varying from slow to rapid according to Cruden and Varnes's classification (Cruden & Varnes, 1996).

Many are «complex» landslides (according to the Working Party on World Landslide Inventory classification, WP/WLI, 1993a; WP/WLI, 1993b), with a «style of activity characterized by the temporal succession of different mechanisms». In fact these landslides are mainly characterized by multiple retrogressive rotational-translational slides in the upper sector, subsequently evolving in earthflows with an increase of internal deformation.

The majority of these phenomena have to be considered as «reactivated landslides» (WP/WLI, 1993a; WP/WLI, 1993b). The cause of their reactivation can be related to periods of intense or prolonged rainfalls and, in some cases, with snowmelt in the spring (Bertolini & Pellegrini, 2001). Real-time monitoring reveals that water pressure increases as a consequence of direct infiltration from the surface during the wet season (Simoni & *alii*, 2004).

TEST SITE

The study basin, located 40 km South of Bologna, on the western side of the Reno River basin, extends for about 2.5 square kilometres with an average slope of about 13 degrees: a 3-D perspective view of test site and surrounding area is shown in figure 1.

The land cover consists mainly of agricultural areas (heterogeneous agricultural areas), forests and semi-natural areas (forests, shrub and/or herbaceous vegetation associations, open spaces with little or no vegetation), while artificial surfaces (urban fabric) characterize a small portion of the site (McGwire & Estes, 1991; Bossard & *alii*, 2000; EEA, 2001).

The area is characterized by the presence of clay soils, derived from deep weathering of the bedrock and made of stiff and highly fissured mudshales (Palombini Shale and Varicoloured Shale).

A significant portion of the hydrographic basin is affected by erosion processes related to runoff in addition to instability phenomena.

The main landslide body at Rocca Pitigliana affects the central-lower sector of the hydrographic basin, extending for more than 35000 square metres. The first historical information about this landslide dates back to March 6th 1934, when several buildings were destroyed. Further reactivations, generally starting with small roto-translational movements in the crown area, subsequently evolving in earthflows, occurred in 1939, 1965, 1994, 1999. Following the last parossistic event (1999) that caused the interruption of the main road, the public administration planned emergency intervention aimed at correcting the local hy-

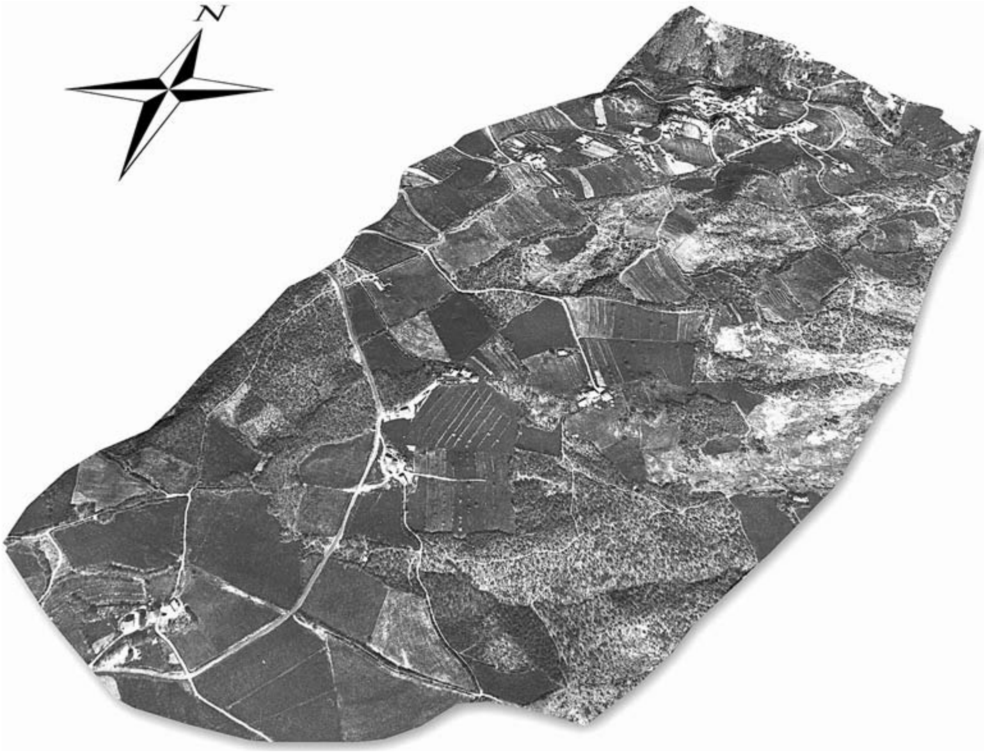

FIG. 1 - 3-Dimensional perspective view of test site (approx. 2.5 square kilometres) and surrounding area based on 1976 data.

drogeological instability and erosion and prepared the slope for permanent consolidation. Several inclinometers and piezometers were installed in the landslide body to monitor deformations and groundwater levels. They indicate a slip surface located between 6 and 11 m depth from the surface where post-failure deformation intermittently progresses. The headscarp was partly reactivated in March 2004 by means of retrogressive slidings. In 2003-2004 a drainage system made of longitudinal and transversal trench drains (up to 7 m deep) and surficial sewers was established along the slope. The landslide body was also smoothed to improve runoff and prevent rainfall infiltration.

Near the end of 2002 an experimental site was installed close to the landslide headscarp, whose morphology and sub/surface water circulation scheme were unaffected by human intervention. Pressure sensors, tensiometers, soil moisture sensors and a raingage were installed and are still working. The automatic monitoring of rainfall and pore pressure response in both saturated and unsaturated soils is providing valuable experimental data used for defining the subsurface flow field and for relating slope movements to rainfall events. A wire extensometer, installed in October 2002 and still in operation, allows detecting possible failures.

Permanent GPS stations were installed during December 2002. They provide continuous observation of landslide surficial movement. The result of this observation (ended in March 2004) has given a quite null surficial velocity (0.56 +/– 0.13 cm/yr).

GPS kinematic surveys, terrestrial laser scanning and photogrammetric campaigns were conducted for obtaining high accuracy DEMs of the area. Aerial photogrammetric techniques were also extensively applied to obtain multitemporal datasets of the whole hydrographic basin.

ADOPTED METHODOLOGIES: GENERALITIES

Digital aerial photogrammetry

Photogrammetry is defined as «the art, science, and technology of obtaining reliable information about physical objects and the environment» (Thompson & Gruner, 1980; Chandler, 1999) by means of photographs or imagery stored on tape or disk taken by electronic means. Products are represented by point coordinates, graphic and/or numeric maps and rectified images (Thompson & Gruner, 1980). Digital photogrammetry applies the same principles and methods as traditional analogic photogrammetry (Kraus, 1993; Kraus, 1997) and represents an efficient and precise means for the automatic generation of DEMs.

During aerial photogrammetric missions images are acquired using full precision mapping cameras, either traditional cameras that use film to capture and store images or digital cameras (Janesick, 2001; Cramer, 2004; Ferrano & *alii*, 2004; Ziemann & Grohmann, 2004) that use line sensors or array sensors.

In order to be used for digital photogrammetric applications, aerial photographs exposed in a traditional camera have to be translated into digital format by using radiometrically and geometrically precise scanners; the most applied methodology to perform this operation is to scan from diapositive transparencies by using so called photogrammetric scanners which transform each photograph into a digital form.

Softcopy workstations, today also employed as mapping instrumentation, perform precise photogrammetric procedures (Shenk, 1999; USACE, 2002): orientation processes (interior, relative and absolute orientation and aerial triangulation); stereomapping; production (DEM generation, orthophoto computation, planimetric features extraction, perspective views preparation, raster images production).

The digital photogrammetric procedure starts from image orientation (Ackermann & Schade, 1993; Hellwich & *alii*, 1994; Tang & Heipke, 1996; Heipke, 1997; Dowman, 1998). During stereo model set up, models must be georeferenced to the ground for measuring or mapping using well defined ground control points, unambiguously identifiable in the images (natural and/or artificial points). Typically, aerotriangulation methods are utilised «to extend the field surveyed horizontal and vertical control to a network sufficient to set up each stereomodel within the study area» (USACE, 2002).

The stereomapping process provides substantially planimetric features, contour lines and DEM data. During this process, the operator, observing a single 3-D model on the monitor screen, guides the reference mark over the surface of the stereomodel by using a cursor and can register the observed points.

The processing of stereo digital images can be automated using digital image correlation. This process amounts fundamentally to a direct comparison of patches of pixels on conjugate images or to an indirect comparison of information derived from the digital images (Ziemann & Grohmann, 2003). Image matching procedures, based on well-defined comparison techniques related to shape and grey/colour levels in the corresponding zones of the images are employed (Heipke, 1995; Kraus, 1998; Mora & *alii*, 2003). The application of digital image processing using matching algorithms based on different techniques can provide a large number of 3-D points at a specified cell size. High spatial resolution DEMs can be generated (Ackermann, 1996; Bacher, 1998; Karras & *alii*, 1998). Digital photogrammetric systems can provide for some accuracy indicators, although global accuracy indicators generally give values that are too optimistic and quality indicators for each grid point may not give reliable information (Baltsavias & Käser, 1998). To improve accuracy of calculation, the operator can conduct point measurement activities on the stereo images; it is possible to introduce interactively necessary informations and/or corrections to the model by collecting planimetric (roads, etc.) and topographic features (lines of equal elevation - contours, break lines and single height points) to ensure that the vertical location of all points is on the earth surface at the specified location (USACE, 2002).

The final accuracy of digital photogrammetric processes depends mainly on the camera-object distance, on the image quality and on the pixel dimension; other factors affecting the final accuracy of the digital products are the presence of shadows, water bodies, snow fields, the morphology and the land cover of the surface (Achilli & *alii*, 1997; Baldi & *alii*; 2000; Mora & *alii*, 2003). Certainly, a key role in the automatic processing of the digital images is played by the correlation algorithm that can work at subpixel level.

Spatial analysis techniques and Geographic Information Systems

Spatial analysis techniques applied to geomorphologic fields are designed to describe the landscape evolution processes in a quantitative way, allowing an objective multitemporal analysis of shapes. For this purpose, it is necessary to operate a parameterisation of the physical surface (Speight, 1974; Evans, 1988) that can be intended as the numerical description of continuous surface form (Pike, 1993) or, in a more closely geomorphologic sense, «a set of measurements that can describe topographic form well enough to distinguish topographically disparate landscapes» (Pike, 1988). Terrain modelling and ground surface quantification by means of numerical models are of great help for obtaining this parameterisation (Pike, 2000).

A digital model of the land describes the topographic field as a surface developed in a 3-D coordinate system through the identification of known coordinate points (Pfaltz, 1976): these points can be evenly distributed or scattered in a non-homogenous pattern. If the points are irregularly distributed, the numerical surface can be easily described by irregular triangles that connect the points: this surface is called Triangulated Irregular Network (TIN) (Peucker & *alii*, 1978; Fowler & Little, 1979). If the points are evenly distributed with a fixed distance in *x-y* plane, the terrain is well described by a regular grid characterised by square cells (Neteler & Mitasova, 2004). In both cases, the model is defined as a 2.5-Dimensional (2.5-D) model; it is represented by a two dimensions surface, composed by planar elements that develop in a 3-D space without thickness and volume (Turner, 1997). The use of a 2.5-D model is appropriate for the analysis of surface characteristics in geomorphologic fields, as the attention is particularly focused to the surface as a bi-dimensional plane developed in three dimensions.

In order to use the earth surface model in an effective geomorphologic analysis, appropriate and geomorphologically significant parameters must be derived (Evans, 1972; Collins, 1975; Evans, 1981; Gardner & *alii*, 1990). In particular, these parameters have to be functions not only of geomorphologic shapes but also of geomorphologic processes (Wood, 1996a).

The chosen parameters have to be associated with each element of the model (each triangle for a TIN and/or each cell for a grid) (Kumler, 1994).

Furthermore, it is advisable that the surface parameters are small in number, allowing them to be used in the wider range of cases and containing at the same time the most of information possible (Wood, 1996a). In particular, five terrain parameters (Evans, 1980) that can be always defined for a continuous 2.5-D surface, can be assumed as significant: elevation; slope; aspect; profile convexity; plan convexity.

Elevation can be defined as the distance, measured on the *z* axis, of a point above or below a reference surface or datum (generally mean sea level): this is the basic information that constitutes the earth surface model (ESRI, Inc., 1996).

Slope is the steepness of a surface. On a TIN surface, the slope is, for each triangle, the slope of the plane defined by the triangle; on a grid surface, the slope for each cell is the steepest downhill slope of a plane defined by the cell and its eight surrounding neighbours. Slope can be measured in degrees from horizontal (0°-90°) or percent slope. Mathematically, slope is referred to as the first derivative of the surface (ESRI, Inc., 1996).

Aspect is defined as the direction in which a slope or surface faces, especially in the context of exposure or insolation. Aspect can be calculated by many GIS software packages and is usually expressed in degrees relative to North: for example North is 0 degrees, and South is 180 degrees (Krzanowski & *alii*, 1995).

Profile convexity and plan convexity are related to curvature of the terrain. Mathematically, convexity is referred to as the second order derivate of the surface. In order to evaluate this parameter, measures must be derived on an intersecting plane, reducing the expression to an ordinary differential one (Wood, 1996a). There are several convexity or curvature parameters that can be evaluated, depending on the orientation of the intersecting plane.

In profile convexity, the second order derivate of the surface is calculated on the intersection of the surface with the plane passing for *z* axis and aspect direction: this parameter describes the rate of change of slope in profile. In plan convexity, the second order derivate of the surface is calculated on the intersection of the surface with the *x-y* plane: so, this parameter describes the rate of change of slope in plan (Wood, 2004).

Generally, these parameters can be easily estimated, managed and compared if the terrain surface model is built on a regular structure; therefore, the use of a raster grid provides results that are very suitable.

A comparison between the elevation in the different times can be simply obtained, defining different grids with cells of the same size for different temporal instants, by means of an algebric sum between the various 2.5-D surfaces; the result is represented by a map of variations on the *z* axis along time. In the same way, the estimation of volume variations can be obtained considering the volume enclosed between two 2.5-D surfaces, representing two considered instants in time.

The acquisition process of elevation data is performed through different methods that operate a discretization of the *continuum*. In several cases raw data are irregularly distributed and the grid generation procedure (gridding) is obtained through an interpolation that can introduce an alteration of the sampled data (Lam, 1983). This factor must be considered and kept under control during the different steps of morphometric analysis in order to avoid errors or estimations without statistical significance (Guth, 1992).

Important variables to be considered are the data detail and the scale at which the parameterisations have been executed (Church & Mark, 1980; Chang & Tsai, 1991; Carter, 1992). Sampling window size and interpolation method can also influence the analysis and the results, leading to incorrect conclusions. Therefore, the choose of an appropriate analysis scale and the use of parameterisation methods that take into account the dependency of shapes from the DEM resolution are very important (Wood, 1996b; Wood, 1998). Sensitivity analysis techniques, which check how a given parameter reacts to the variation of another parameter, can be used for this purpose (Hamby, 1994; Arbia & *alii*, 1998).

The management of multitemporal grids representing the same area is extremely simplified by the use of GIS systems. A Geographic Information System is an information management system of geographically referenced data. The system, based on hardware and software, provides tools for displaying, manipulating and analysing spatial data from many sources in an integrate way (Burrough, 1986; Neteler & Mitasova, 2004). Data are of two different types: data with a geographic position and/or extension, and alphanumeric data, usually the attributes of the geographic data. The geographic data are usually derived from remote sensing, aerial photogrammetry, field surveys or paper cartography. The alphanumeric data, descriptive of particular features or parameters, are associated with specific geographic objects and as such get a geographic position in the system.

Database software manages the relations between the geographic/spatial and alphanumeric datasets. Usually, information is grouped into layers of homogenous datasets, defined by a unique set of attributes (categories or fields of the database). GIS analysis helps identifying relationships between separate but overlapping layers of information: spatial relationships (proximity, connection, crossing, if an object contains another or is within another, etc.) are considered and the topology of the features is managed by specific functions and tools (Verbyla, 2002).

The management of geographic information can be obtained in different ways, especially when information that has a shape on the terrain is considered. Geographic features can be described in software as vectors representing their edges or as rasters subdividing the whole of area in cells of fixed size and giving an attribute for each cell. A vector model shows where features occur and gives a location to every object, drawing its shape as defined by points, lines or polygons (defined by *x*, *y* coordinates in space). A raster model shows what occurs everywhere and assigns a value to each place in the area. Raster models could represent a point as a single cell, a line as a continuous series of cells, and a polygon as an area of continuously touching cells (NOAA, 2004).

The two different methods of information management are both effective, but each one can be more useful in a specific application field. Vector based tools are more efficient in managing quantized and discrete geographic informations (single points, edges, etc.), while raster based tools can describe more easily parameters that change with continuity in space, without sharp transitions (density of a value, distribution of a parameter, variation of morphologic surface are among these kind of data). Raster GIS coverages also allow analytical comparisons between different parameters on the same area simply by comparing for each cell of the coverage different attributes in the same cell. Usually, the most used estimation functions of the quoted morphometric parameters are software standard tools, while more complex parameters can be evaluated with the use of analytic functions, providing the possibility of deriving new information (Dymond & *alii*, 1995).

MATERIALS AND METHODS: TEST SITE INVESTIGATION

DEMs generation and checking

The Rocca Pitigliana site has been investigated using four aerial photogrammetric surveys performed in 1976, 1986, 1988 and 1993 (tab. 1).

TABLE 1 - Principal characteristics of the photogrammetric data

Characteristics	1976 survey	1986 survey	1988 survey	1993 survey
Aerial photogrammetric camera	RMK A 15/23	RMK A 15/23	RC 10	RC 20
Focal length (mm)	153.15	153.33	153.26	153.20
Mean image scale	1:17000	1:37000	1:34000	1:36000
Resolution (dpi)	2116	2116	2116	2116
Pixel dimension (μm)	12	12	12	12
Ground pixel dimension (cm)	20	45	41	44
Ground control points number	9	7	9	10
Tie points RMS: E; N; H (cm)	0.8; 1.3; 1.9	0.3; 0.4; 0.3	0.1; 0.1; 0.2	0.1; 0.6; 0.5
Ground control points RMS: E; N; H (cm)	9.0; 10.8; 2.9	4.5; 7.0; 4.8	4.2; 5.3; 2.1	4.8; 5.8; 1.2
DEM cell size (m)	1	1	1	1
DEM grid size	1526x1641	1166x1212	1503x1484	1647x1526

Images were analysed using Wehrli and LH Systems photogrammetric systems.

Multi temporal images were scanned using the Wehrli Raster Master RM2 at a resolution of about 2116 dpi, which results in a pixel size of 12 μm (tab. 1) corresponding to a ground pixel dimension ranging from twenty (1976 survey) to forty-five centimetres (1986 survey) (tab. 1) (Wehrli & Associates, Inc., 2000). The imagery was characterised by good quality. Four diapositive transparencies of the earliest two surveys (1976 and 1986), although affected by some imperfections, were of a quality that produced images suitable for the intended purpose.

Digital images were processed by means of the Digital Photogrammetric Workstation (DPW) 770 Helava using the LH Systems SoftCopy Exploitation Tool Set (SOCET SET) software (Helava, 1988a; Helava, 1988b; Dowman & *alii*, 1992; Heipke, 1995; LH Systems, LLC, 1999) release 5.0. This software, designed to support image-based softcopy applications, provides friendly image exploitation tools and supports the generation of data-bases and products such as reports, DEMs, vector databases, orthophotos, image maps and image mosaics (Mora & *alii*, 2003).

Images were oriented using well defined ground control points (natural points), unambiguously identifiable in the whole image blocks and located in stable areas. The locations of the points, essential to orientate images and not available *a priori*, were surveyed to centimetre accuracy with GPS static surveys providing the same common reference system for co-registering all the models.

An internal bundle adjustment program, allowing adjustment of image parameters, was used to perform the aerial triangulation of the blocks of images. Root mean square of residuals of control points ranged from a few centimetres to several centimetres for the considered aerial photogrammetric surveys (tab. 1).

The image correlation module (Automatic Terrain Extraction, ATE) was used for DEMs generation. Several trials were conducted applying available methods (Adaptive ATE and Non-Adaptive ATE). A number of multitemporal test DEMs at variable resolutions (1 m, 2 m and 4 m cell sizes) were computed for several selected zones using different strategies (Bacher, 1998; Felicísimo & *alii*, 2004). In order to check the resulting matching accuracies, comparisons with reference datasets of the selected zones (check point data) were performed (Baltsavias & Käser, 1998; Baltsavias & *alii*, 2001; Gooch & Chandler, 2001). On the basis of findings, the adaptive method was selected and regular spaced (1x1 m) grid DEMs of the whole hydrographic basin were automatically extracted. The automatic correlation algorithm works at sub-pixel level, even for 1/3 pixel, and a DEM accuracy ranging from forty (1976 survey) to eighty centimetres (1986, 1988 and 1993 surveys) can be achieved (Baldi & *alii*, 2000).

The Helava Digital Photogrammetric Workstation 770 computes the so-called Figures Of Merit (FOM), numerical values assigned by the terrain extraction process to each grid point. These values are used to estimate the correlation quality and consequently the resultant height quality (Baltsavias & *alii*, 1995; Baltsavias & *alii*, 2001). FOM are not reliable measures of the matching accuracies; they represent a quality criterion and are proportional to the correlation coefficient (the larger the numerical value, the better the measurement). Ordinarily, FOM numbers equal or greater than 33 point out successful automatic correlation (LH Systems, LLC, 1999), while posts characterized by a FOM number less than 33 are considered to be poor (Baltsavias & Käser, 1998).

The percentages of points with poor FOM were different for the considered surveys: 51.91% for the 1976 survey; 55.87% for the survey performed in 1986; 34.40% for the 1988 survey; 21.94% for the 1993 survey (tab. 2). The mean values of FOM were the following: 43.68 for 1976 dataset; 35.20 for 1986 one; 51.28 for 1988 dataset; 66.83 for 1993 dataset. FOM planimetric distribution for each

TABLE 2 - Principal characteristics of the Digital Elevation Models

Characteristics	1976 DEM	1986 DEM	1988 DEM	1993 DEM
DEM points number	1287290	801190	958402	1167698
Points with FOM < 33 (number)	668219	447670	320111	668219
Points with FOM < 33 (%)	51.91	55.87	34.40	21.94

automatically generated DEM dataset has been represented with relative range maps (fig. 2a).

The stereo-operator checked the automatically generated DEMs and performed several editing operations for increasing the accuracy of the calculation; these actions have been accomplished to establish the height of points on the earth surface with maximum accuracy.

Editing was extensively performed on the models. Areas characterised by the presence of points with poor FOM were inspected and stereoscopically remeasured by visually adding breaklines and contour lines. Point measurements activities were also conducted on other parts of the models not exactly correlated by the ATE. The creek and the roads were edited out and, for obtaining final photogrammetric models representing the bare earth surface, a bridge over the Marano Creek, the buildings and the trees/forest were removed. The stereo operator introduced interactively measurements by comparing the automatically generated DEM with the stereoscopic model, collecting contours and break lines and measuring the ground coordinates of single points.

An estimation of height corrections for each survey was performed, comparing elevation values of automatically extracted DEMs and the correspondent values of edited DEMs. The resulting range maps, represented in figure 2b, show the planimetric distributions of height corrections.

Comparative analysis of the range maps (FOM planimetric distributions of automatically generated DEMs datasets and height corrections planimetric distributions) for each survey was conducted. Most of the editing was carried out in areas characterised by a presence of points with poor FOM; however, both minor and major height corrections were also introduced in posts characterized by FOM numbers equal or greater than 33.

Edited DEMs were loaded in the ArcView 9 GIS with ArcGIS 3d Analyst extension (ESRI, Inc., 2004).

Models were represented in shaded-relief (Yoeli, 1967; Brassel, 1974) by applying artificial illumination to the terrain, generating shading according to the surface morphology (smoothness or roughness). Resulting planimetric maps (fig. 3) show that some areas are affected by the presence of several morphologic artefacts (steps, terraces, geometrical ridges) characterised generally by an elevation component similar to the expected accuracy and a planimetric extension of several times the cell pitch; these features, not referred to natural processes, can be ascribed to problems associated in data collecting and/or managing and/or processing.

Comparisons between artefact trends and planimetric distributions of either FOM and height corrections were performed for each survey by means of topological overlay. Systematic interdependences were not established from data analysis. Maps of the comparisons are shown in figure 4.

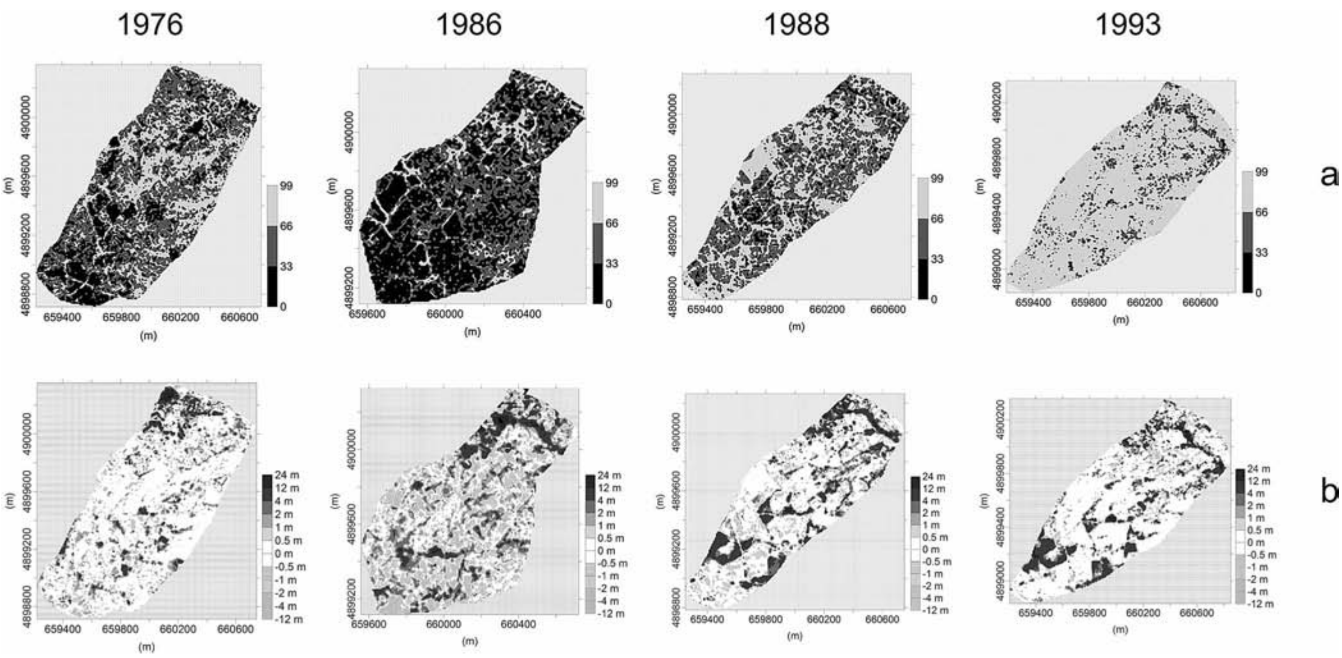

FIG. 2 - a) FOM planimetric distributions (UTM coordinates) of automatically generated DEMs datasets; b) Differential elevation maps (UTM coordinates) obtained by comparing datasets: automatically generated DEMs and corresponding edited DEMs (bare earth surface models).

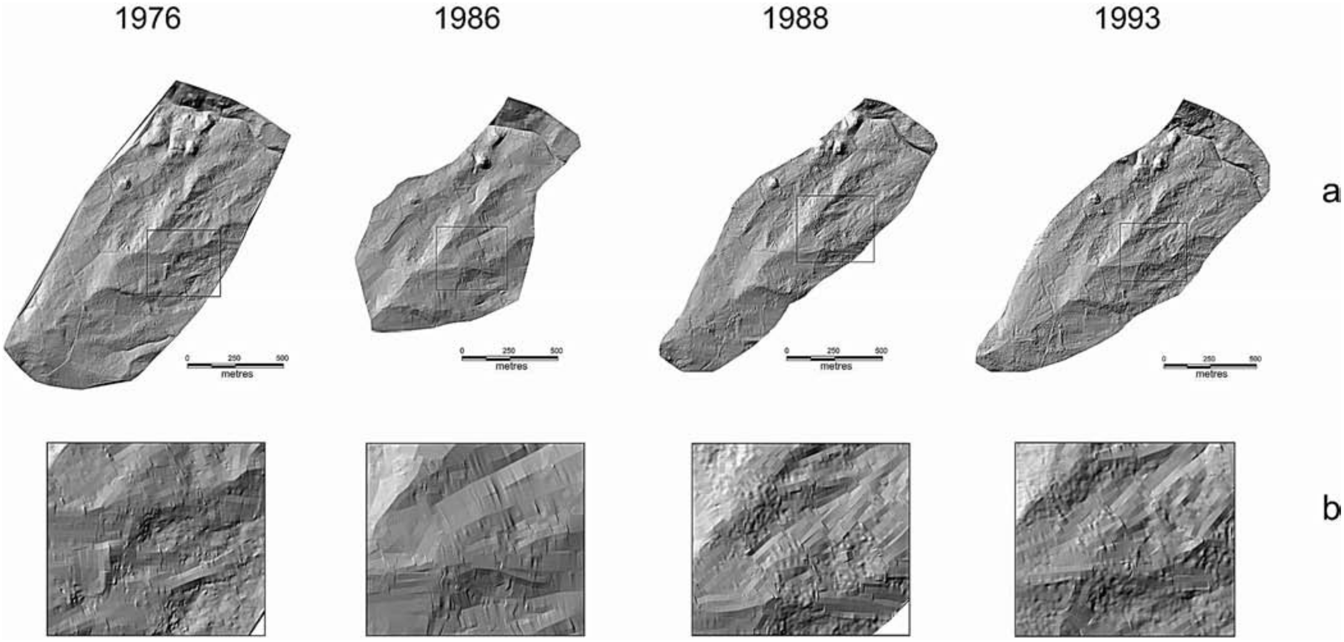

FIG. 3 - a) Shaded-relief representations of bare earth surface models derived from stereo aerial images; b) details of bare earth surface models corresponding to boxes in a).

DEMs filtering and comparison

Multitemporal DEMs (1976, 1986, 1988 and 1993), extracted by means of digital aerial photogrammetry on the Rocca Pitigliana study area and co-registered, have been analysed with spatial analysis techniques. In order to reduce the effects of evidenced artefacts and to allow a numerical comparison of the different datasets, a filtering method was applied to DEMs to reduce high frequency structures (noise) while at the same time maintaining the general morphologic characteristics of the area.

DEM filtering is normally obtained through interpolation of elevation values of cells, using specific algorithms, i.e. weighted moving average, bicubic splines, kriging and others (Burrough, 1986; Schenk & *alii*, 2000; Mitchell & *alii*, 2002). Each interpolation technique generates new values for the grid by averaging the elevation values in a window around the original cell.

For geomorphologic purposes it is important to note that the smoothing can significantly modify the morphologic features present in the considered digital model. These filtering procedures usually generate altered and smoothed versions of the original data. DEMs accuracies after the interpolation process can be checked with simple random sampling, comparing original and interpolated values in significant areas, or using mathematical methods that try to identify surface trends or markers (outliers) of significant errors that deviates so much from the original data to be identified as errors (Hawkins, 1980; Brovelli & *alii*, 1999; Brovelli & *alii*, 2000; Habib & *alii*, 2001).

In the present study, the smoothing procedure was applied to reduce the effect of artefacts in the definition of each surface model and therefore to allow a multitemporal DEMs comparison of morphologic shapes. Particular attention was devoted to choosing a smoothing technique suitable for maintaining the main morphometric shapes at the work scale. As geomorphologic structures are a function of representation scale and sampling cell size, a smoothing threshold for each dataset was defined, below which no significant shape alteration at the work scale is introduced. For this purpose, specific functions present in the open source software Landserf 2.1 (Wood, 2004) were employed. This surface visualization and analysis software can handle multiple datasets (DEMs, TINs, vector coverages, etc.) in a georeferenced system. DEMs are stored as raster grids, and can be interpolated with a quadratic approximation process. This method can be considered as suitable and effective due to its capability to model the surface relying on a relatively low number of data points, while providing good accuracy in the fit between the model and the true surface. For each cell of the interpolated DEM an elevation value is calculated by defining a square set of cells around the considered one and «fitting the most appropriate continuous quadratic function through them» (Wood, 1996a). Landserf can calculate the most significant morphometric parameters (elevation, aspect, slope, curvature) on the defined surface in each cell from the quadratic function on the considered cells set; the larger the number of cells considered for quadratic approximation, the higher the filtering and smoothing effect on the DEM. As morphologic structures are scale-dependent, artefacts can be eliminated using a sufficiently wide sampling window, but, in the case of a window that is too

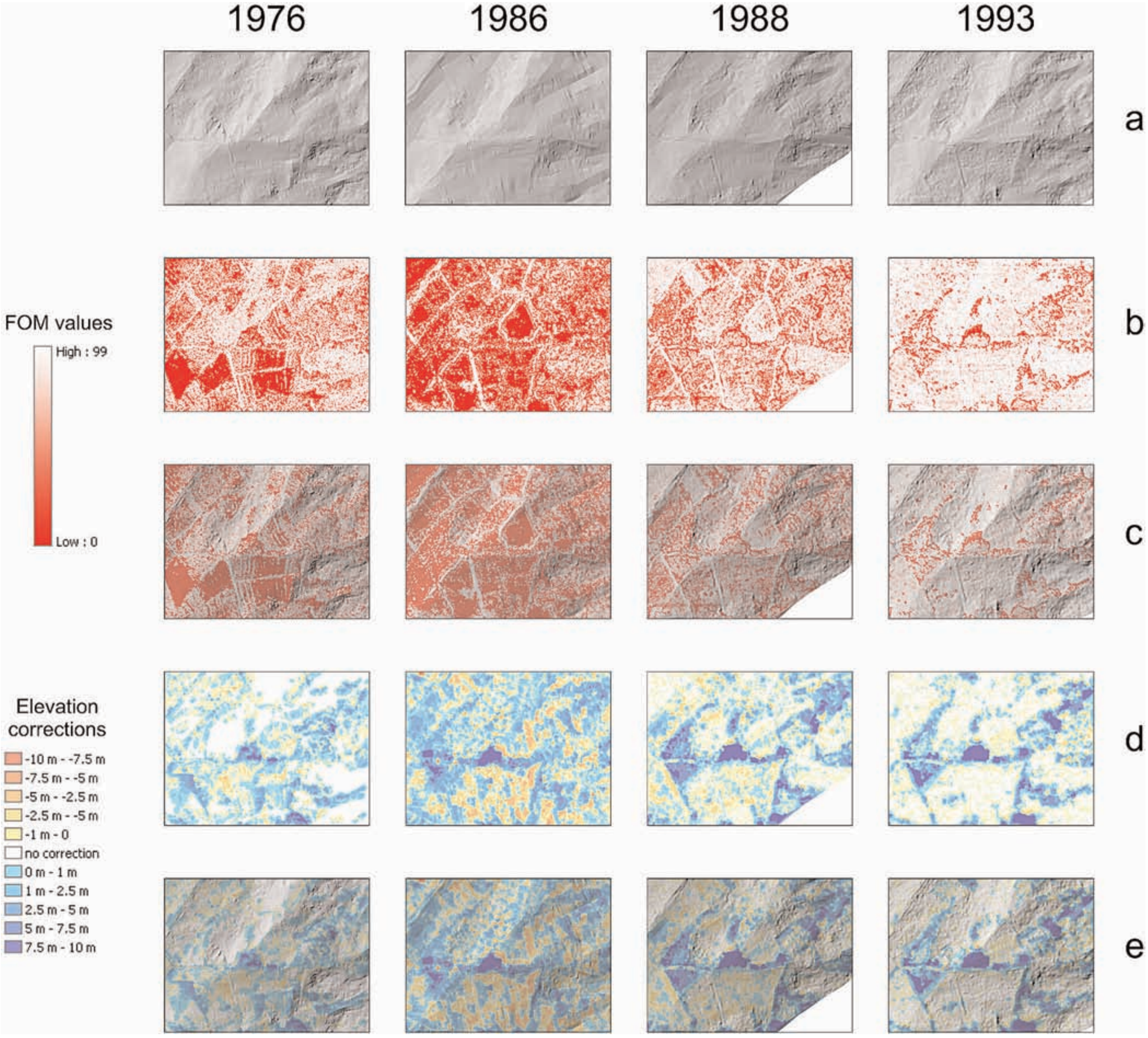

FIG. 4 - Comparison overview of artefact trends, FOM distributions and height corrections distributions for the same sectors of photogrammetric DEMs datasets. a) shaded-relief representations of bare earth surface models; b) FOM distributions; c) topological overlay of shaded-relief representations of bare earth surface models and FOM distributions; d) height corrections distributions; e) topological overlay of shaded-relief representations of bare earth surface models and height corrections distributions.

coarse, it is possible to significantly alter and smooth terrain shapes.

In order to find an acceptable compromise, i.e. the correct threshold value to eliminate only artefacts and not important morphologic features, it is possible to perform a qualitative sensitivity analysis to check the variation of morphometric parameters on the same areas of the surface, corresponding to different sampling window sizes, i.e. different smoothing intensities. When, at a given sampling size, the considered morphometric parameter starts deviating significantly from the values of the original dataset, it can be assumed that the scale of smoothing is comparable to the scale of interesting morphologic features: increasing the sampling window above that value can result in a deletion of the morphologic detail of the model.

The Landserf Multiscale query function makes it possible to interactively query the DEM about a specific parameter sampling the surface and obtaining the value of the chosen parameter (aspect, slope, plan curvature, profile curvature) at different smoothing window sizes and in different areas of the DEM. The result is shown as a diagram in which the parameters are represented at different sampling sizes.

An overview of the inspected parameters for 1976 dataset (bare earth surface model) is presented in figure 5. Figure 5a shows a shaded-relief representation of a specific investigation area (sampling size: 25x25 cells).

Figure 5b shows the variation of aspect parameter using a quadratic interpolation window ranging from 3x3 to 25x25 cells. Aspect is expressed in degrees from North, therefore the diagram is a goniometric circle from 0° to 360°, with different circles representing the different sampling sizes; the aspect values for the chosen points are represented by a curve that connects the values at different scales. If the curve maintains a constant trend, that is a constant angle referred to the axis origin (rectilinear shape), the interpolation at different sampling sizes doesn't modify significantly the aspect at that point. This can be interpreted as indicating that aspect is scale-invariant for the given window sampling size. If an inflection in the curve is shown at a certain sampling window size, the interpolation, starting from that value, has an influence on the morphometric parameter and on the morphologic structures. This can be interpreted as showing that they are scale-dependent for the given sampling window. An implication is that by increasing the interpolation window, it is possible that some significant terrain structures are erased.

Figure 5c shows the variation of slope parameter: in this case the value can vary between 0° and 90°. The diagram presents the window sampling size on the *x* coordinate and slope angle on the *y* coordinate. The interpolated line represents the slope variation at the different sampling sizes: like the aspect diagram, important changes in the inflection of the curve represent significant influences of the sampling scale on the parameter value, resulting in major deviations of the interpolated surface from the original model.

Similar diagrams corresponding to plan curvature and profile curvature are presented in figures 5d and 5e. In these cases the value represented on the *y* axis is a dimensionless number, positive in case of convexity and negative in case of concavity. On the *x* axis the different sampling window sizes are represented.

The interactive multiscale query tool was used on the DEMs to identify critical scale values for morphologic parameters compared to the smoothing scale: variations were checked in different and interesting areas of the study site. The high frequency artefacts generated in the DEM creation process were filtered, interpolating the original dataset with the quadratic approximation method and defining an optimum sampling window size for each dataset. Appropriate sampling windows can smooth the noise and maintain the important shapes for the area. In the present study the chosen values are: 11x11 cells for 1976 dataset; 17x17 cells for 1986 one; 15x15 cells for 1988 dataset; 13x13 cells for 1993 dataset.

The accuracies of the filtered DEMs were checked comparing the elevations of filtered datasets with the corresponding elevations of non filtered ones: this operation

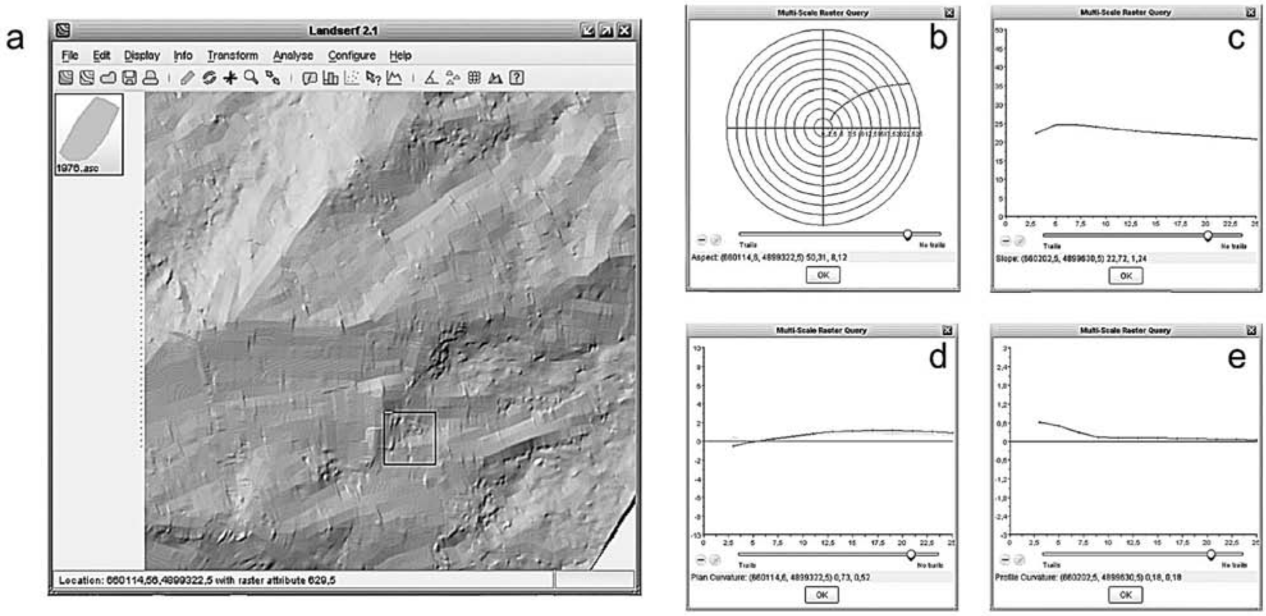

FIG. 5 - Example of Landserf Multiscale raster query of morphometric parameters on 1976 dataset (bare earth surface model). a) shaded-relief representation of a specific investigation area: sampling size of 25x25 cells; b) aspect variation diagram at different sampling sizes; c) slope variation diagram at different sampling sizes; d) plan curvature variation diagram at different sampling sizes; e) profile curvature variation diagram at different sampling sizes.

TABLE 3 - Classification statistics of elevation differences between final models derived from stereo aerial images (bare earth surface) and corresponding filtered models

Characteristics	1976	1986	1988	1993
Mean (m)	–0.01	–0.08	–0.02	–0.02
Standard deviation (m)	0.11	0.23	0.12	0.12

was performed in ArcView 9 with the Single Output Map Algebra function by subtracting the corresponding grids. The resulting values represent the approximation introduced by filtering procedure. Frequency distribution histograms are presented in figure 6: values closely follow a bell-shaped curve, suggesting a normal (Gaussian) data distribution. Classification statistics for datasets are shown in table 3. The mean values are very close to zero and standard deviations are in the order of 0.1 m for 1976, 1988 and 1993 datasets, and in the order of 0.2 m for 1986 datasets (1 σ): these values are smaller than expected accuracies of the photogrammetric models. Therefore, the filtering process does not significantly change the accuracy of the original datasets and resulting surfaces can be assumed as representative of the bare earth surface models photogrammetrically derived. Shaded-relief planimetric maps of filtered DEMs for each dataset (fig. 7) display the effect of smoothing process on morphologic artefacts and shapes. Figure 8 shows comparisons between shaded-relief representations (final photogrammetric models and filtered models) for the same sectors of DEMs datasets.

The filtered DEMs were used in DEMs comparison process to identify, in the relevant time span, variations of the morphologic surface and to analyse the landscape evolution of the area (Zevenbergen & Thorne, 1987). The comparisons were performed in ArcView 9, subtracting the corresponding model elevations; differential elevation maps between pairs of models (1986-1976, 1988-1986, 1993-1988, 1993-1976) are shown in figure 9. Classification statistics for elevation differences are summarized in table 4:

TABLE 4 - Classification statistics of elevation differences between pairs of filtered models (1986-1976, 1988-1986, 1993-1988, 1993-1976)

Characteristics	1986-1976	1988-1986	1993-1988	1993-1976
Minimum (m)	–18.55	–10.74	–12.17	–14.18
Maximum (m)	14.04	22.76	7.72	5.99
Mean (m)	0.62	–0.33	–0.65	–0.42
Standard deviation (m)	1.96	1.68	1.15	1.10

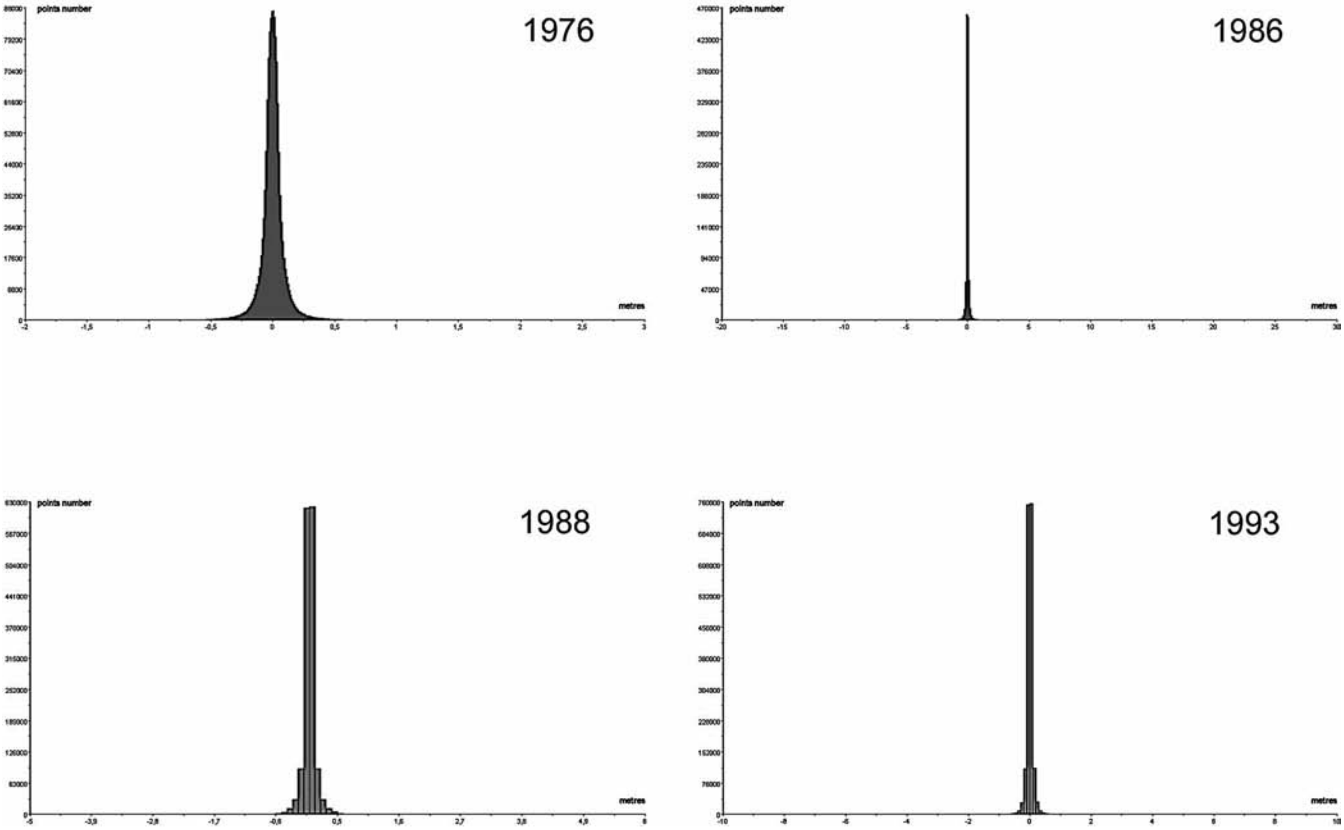

FIG. 6 - Frequency distribution histograms of elevation differences between final photogrammetric models (bare earth surface models) and corresponding filtered models.

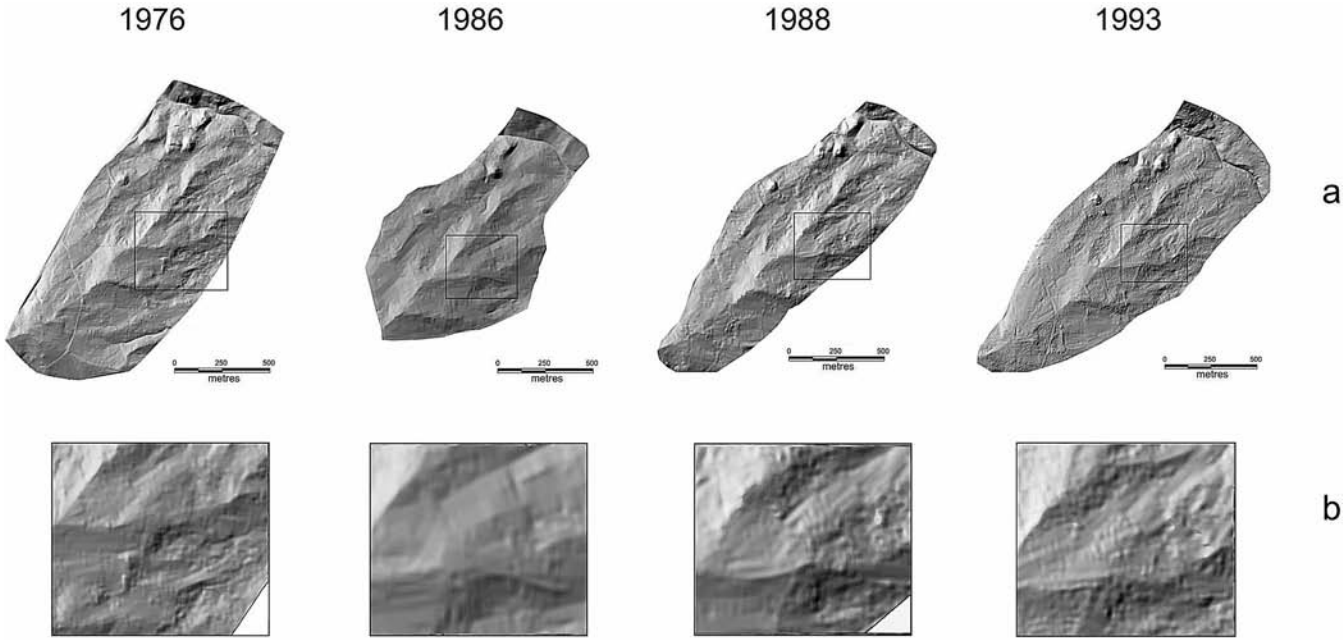

FIG. 7 - a) Shaded-relief representations of filtered models; b) details of filtered models corresponding to boxes in a).

mean values of differences in elevation are in the order of 0.6 m for 1986-1976 comparison, and of –0.5 m for the other comparisons, while standard deviations range between 1.1 m and 2.0 m. The highest values of standard deviations are relative to DEMs comparisons considering 1986 dataset.

RESULTS AND DISCUSSION

Digital photogrammetry has been applied to reconstruct the detailed morphology of a hydrographic basin affected by landslides and its evolution over a defined time span (1976-1993).

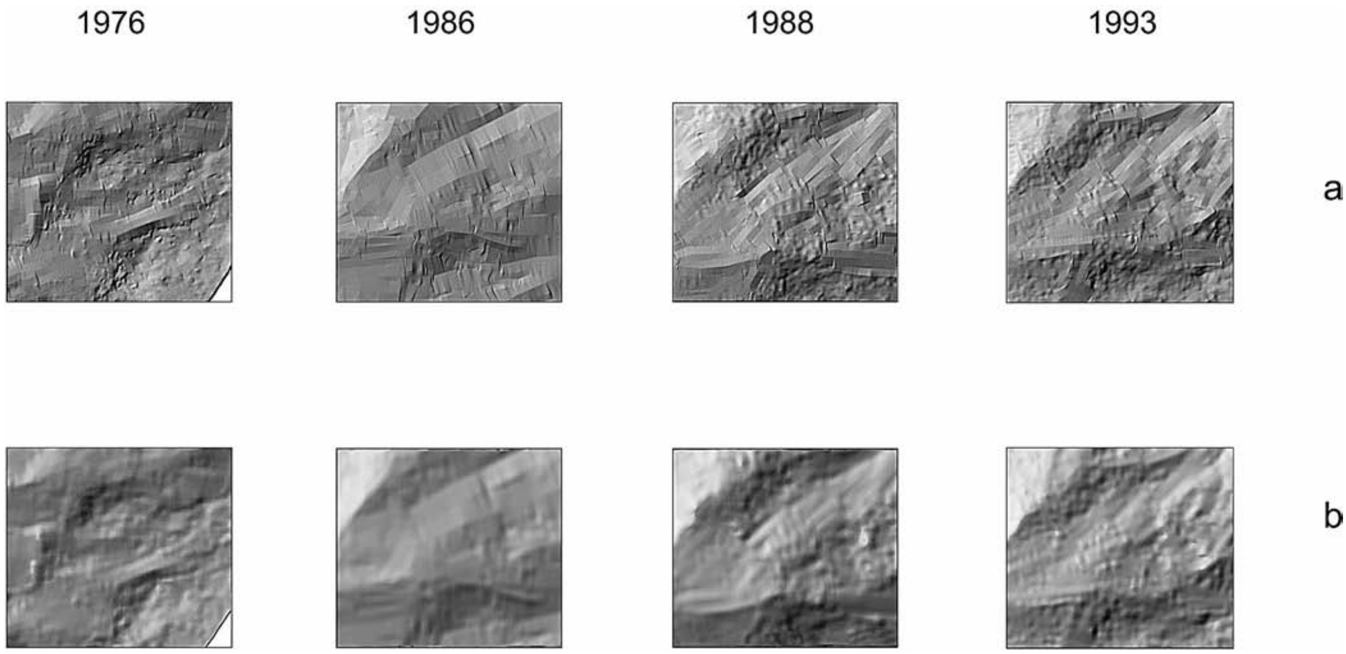

FIG. 8 - Comparisons between shaded relief representations for the same sectors of DEMs datasets. a) bare earth surface models derived from stereo aerial images; b) filtered models.

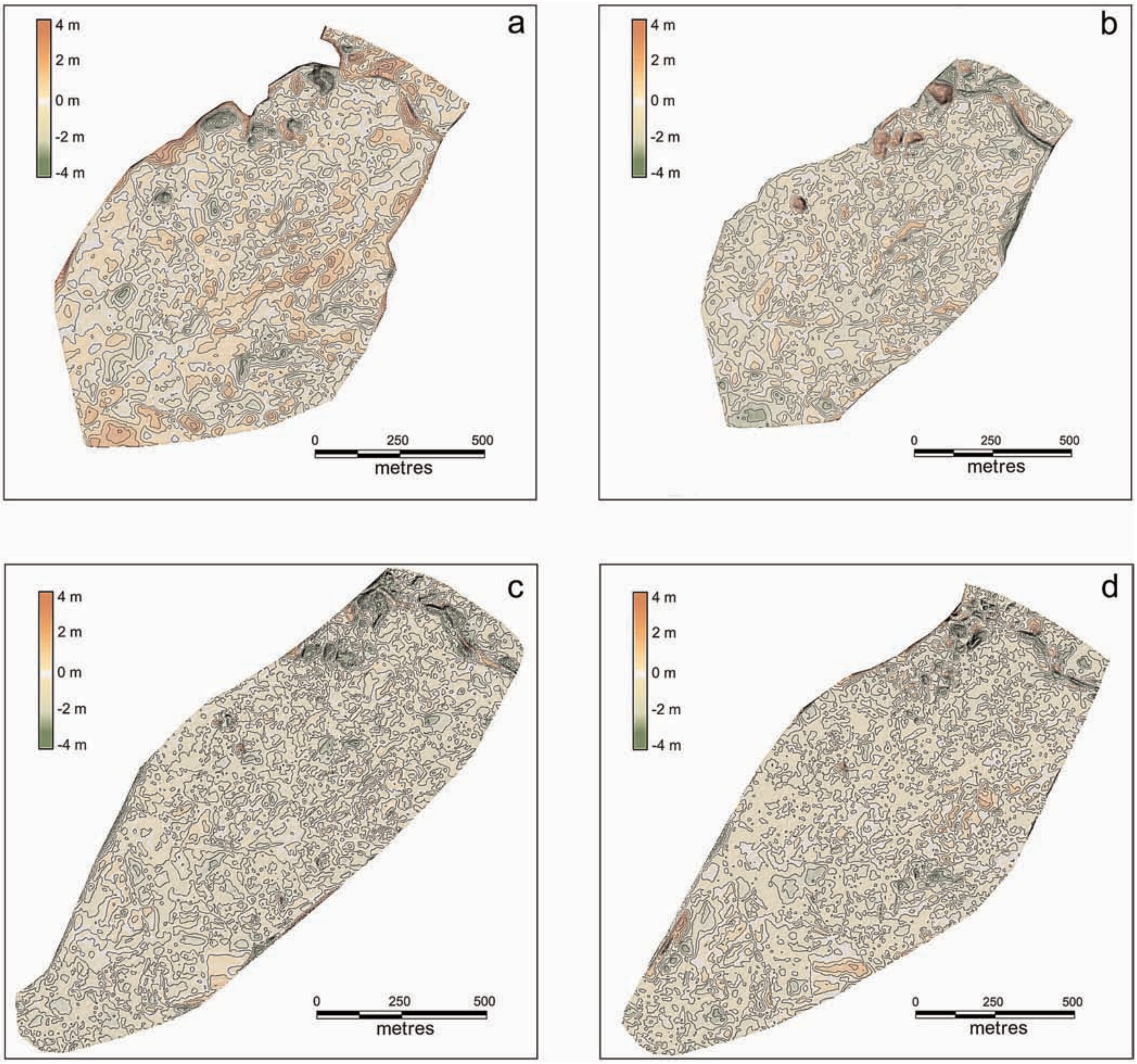

FIG. 9 - Differential elevation maps between pairs of filtered models (contour line interval: 1 m). a) comparison between 1986 and 1976 datasets; b) comparison between 1988 and 1986 datasets; c) comparison between 1993 and 1988 datasets; d) comparison between 1993 and 1976 datasets.

Aerial images were translated into digital format using a precision scanner.

Automatic DEMs extraction procedures were performed and checked. Results show that many matching errors occurred in zones characterised by the presence of low texture, occlusions and/or shadows, surface discontinuities, large perspective differences, steep terrain conditions (points at and/or close to buildings, trees, bridge; steep slopes; rugged terrains) and water bodies (small ponds). Significant point measurement activities have been performed; software and stereo operator editing was used to edit large amounts of data. Most of these editing operations have been carried out in areas characterised by the presence of points with low numerical values of the correlation quality indicator (FOM) for increasing DEMs accuracies, although blunders have been detected and eliminated in other zones.

Edit tools were applied on other parts of the models to obtain the final photogrammetric DEMs representing the bare earth surface of the hydrographic basin. Principally, editing work was performed stereoscopically in areas characterised by the presence of objects that are not ground features.

The use of GIS tools and relief shading techniques has shown the presence of morphologic artefacts in the edited DEMs. Elevation components of these features are characterised by low values and fit to within the expected accuracies; planimetric components show considerable values, extending over areas of several times the cell size. A quadratic approximation filtering technique was applied to the edited DEMs to reduce the effect of artefacts on morphologic structures. A qualitative sensitivity analysis approach was performed; a multiquery analysis of the variation of morphometric parameters at different filtering intensities allowed the selection of an optimum smoothing value for each dataset. This approach eliminates high frequency noise and allows the generation of filtered DEMs that can be used as representative of the bare earth surface models: larger scale shapes in the whole of basin are kept and the general accuracy in elevation is maintained.

Filtered DEMs were compared by means of algebric sums, in order to identify variations in the ground surface over the project time span. Resulting maps show different patterns in terms of soil loss and accumulation. Generally, the detected variations in elevation are small considering the complex dynamics of the basin, ranging between zero m and +/– 4.0 m. As the elevation accuracies of the datasets are in the order of 0.4 m - 0.8 m, variations in elevation between zero m and +/– 0.8 m - 1.2 m have not been considered in relation to their statistical significance. Elevation differences values less than –4.0 m and greater than 4.0 m, identified in specific zones of the basin and ascribed to human activity, have not been taken into account in examining landscape evolution.

On the whole of basin scale, the analysis of the data does not indicate a clear trend of ground surface variations due to landslide activity. In fact, the entire area is characterised by general instability. Movements in the main landslide area overlap each other, masking or deleting previous movements effects. Moreover, landslide movements are mostly translational (slab slide and earthflows) with minor elevation components in the short time. Local phenomena are still evidenced in the comparisons, more clearly in certain time intervals (i.e. 1993-1988 and 1993-1976 comparisons): these specific effects are due to well defined and spatially confined landslide movements that have been remobilised in the study area.

Mass wasting due to sheet, rill and gully erosion apparently can not be quantified since the time scale of these processes is too large to be seen in the few decades that our data cover.

CONCLUSIONS

This paper has described and tested a combination of techniques for an integrated approach to landscape analysis. Digital photogrammetric systems, spatial analysis techniques and GIS tools were used for morphologic enquiry on a test area. The study utilized multitemporal photographic images, captured by employing analog cameras and subsequently digitised to obtain high spatial resolution DEMs through photogrammetric processes. Spatial analysis procedures have been used for DEMs analysis. Results are based on the adopted materials and methods and are applicable to areas characterised by complex morphologic features. In particular, DEMs extraction procedures, filtering techniques and morphometric parameterisations resulted to be effective in studying earth surface features and their evolution. Certainly, developments in digital photogrammetry and GIS will enhance the quality of information that can be obtained by the proposed approach.

Ongoing improvements in digital photogrammetry will provide rapid and continuous progress. Advances in high resolution digital aerial cameras can supply image collection systems that will become the most used in the near future. These new systems can play an important role in strengthening the approach described in this paper. Developments in the field of digital image correlation provide scientists, researchers and technicians with powerful tools for DEMs extraction. Automatic derivation of high density DEMs can be performed rapidly by using softcopy workstations; however, these systems lack the ability to reliably detect blunders. The extraction of a model of the bare earth surface by employing digital photogrammetric workstations can be performed through semi-automatic procedures. Different strategies for the automatic generation of DEM can be chosen, including the automatic filtering of spatial objects. Generally, comparisons with reference datasets are made and stereo inspection of the models is conducted to check the matching accuracy. In most cases, a series of time consuming editing operations are required to achieve the maximum allowed accuracy.

Spatial analysis techniques and GIS tools are extremely helpful in estimating the morphometric parameters that characterize the DEMs and an interesting complement in checking dataset quality. The application of morphometric parameterisation to bare earth surface models allows the recognition of possible artefacts which originate because of problems associated with data collection and/or management and/or processing. In the presence of artefacts that modify the representation of the ground surface, several filtering methods can be used. These methods reduce their effects. The use of a qualitative sensitivity analysis approach to morphometric parameters can result in highly effective selection of smoothing methods and values. The evolution of study areas can be evaluated by directly comparing the elevations of co-registered multitemporal datasets. The statistical significance of elevation variations in a time series of DEMs must be considered and weighted taking into account the elevation accuracy of each dataset. Statistics of the datasets and differential elevation maps represent powerful tools for identifying the presence of significant morphologic trends.

REFERENCES

ACHILLI V., ANZIDEI M., BALDI P., MARSELLA M., MORA P., TARGA G., VETTORE A. & VITTUARI L. (1997) - *GPS and digital photogrammetry: an integrated approach for monitoring ground deformation on a volcanic area*. International Archives of Photogrammetry & Remote Sensing, 32 (6W1), 1-5.

ACHILLI V., BALDI P., BARATIN L., BONINI C., ERCOLANI E., GANDOLFI S., ANZIDEI M. & RIGUZZI F. (1998) - *Digital photogrammetric survey on the island of Vulcano*. Acta Vulcanologica, 10 (1), 1-5.

ACKERMANN F. (1996) - *Some considerations about feature matching for the automatic generation of digital elevation models*. In: Kolbl O. (ed.), «Proc. OEEPE Workshop on the Application of digital Photogrammetric Workstations», 4-6 March 1996, Lausanne, Switzerland. OEEPE - European Organization for Experimental Photogrammetric Research, Official Publication, 33, IfAG, Frankfurt, 231-240.

ACKERMANN F. & SCHADE H. (1993) - *Applications of GPS for Aerial Triangulation*. Photogrammetric Engineering & Remote Sensing, 59 (11), 1625-1632.

ARBIA G., GRIFFITH D. & HAINING R. (1998) - *Error propagation modelling in raster GIS: overlay operations.* International Journal of Geographical Information Science, 12 (2), 145-167.

ARRELL K.E. (2002) - *Geographical Information Systems (GIS): A useful tool for Geomorphologists?* Journal of the Durham University Geographical Society. http://www.geog.leeds.ac.uk/people/k.arrell/GeomorphologyAndGIS.pdf visited on 30 November 2004.

BACHER U. (1998) - *Experimental studies into automated DTM generation on the DPW770*. International Archives of Photogrammetry & Remote Sensing, 32 (4), 35-41.

BALDI P., BONVALOT S., BRIOLE P., COLTELLI M., GWINNER K., MARSELLA M., PUGLISI G. & RÉMY D. (2002) - *Validation and comparison of different techniques for the derivation of digital elevation models and volcanic monitoring (Vulcano Island, Italy)*. International Journal of Remote Sensing, 23 (22), 4783-4800.

BALDI P., BONVALOT S., BRIOLE P. & MARSELLA M. (2000) - *Digital photogrammetry and kinematic GPS for monitoring volcanic areas*. Geophysical Journal International, 142 (3), 801-811.

BALTSAVIAS E.P. & KÄSER C. (1998) - *DTM and orthoimage generation - A thorough analysis and comparison of four digital photogrammetric systems*. International Archives of Photogrammetry & Remote Sensing, 32 (4), 42-51.

BALTSAVIAS E.P., FAVEY E., BAUDER A., BOESCH H. & PATERAKI M. (2001) - *Digital surface modelling by airborne laser scanning and digital photogrammetry for glacier monitoring*. Photogrammetric Record, 17 (98), 243-273.

BALTSAVIAS E.P., MASON S. & STALLMANN D. (1995) - Use of DTMs/DSMs and Orthoimages to Support Building Extraction. In: Gruen A., Kübler O. & Agouris P. (eds.), «Proc. Int. Workshop on the Automatic Extraction of Man-Made Objects from Aerial and Space Images», 24-28 April 1995, Ascona, Switzerland. Birkhäuser Verlag, Basel, 199-210.

BERTOLINI G. & PELLEGRINI M. (2001) - *The landslides of the Emilia Apennines (northern Italy) with reference to those which resumed activity in 1994-1999 period and required Civil Protection interventions*. Quaderni di Geologia Applicata, 8 (1), 27-74.

BETTELLI G. & PANINI F. (1989) - *I melanges dell'Appenino settentrionale dal T. Tresinaro al T. Sillaro*. Memorie della Società Geologica Italiana, 39, 187-214.

BETTELLI G. & PANINI F. (1992) - *Liguridi, melanges e tettoniti nel Complesso caotico lungo la «linea del Sillaro» (Appennino settentrionale, Province di Firenze e Bologna)*. Memorie Descrittive della Carta Geologica d'Italia, 46, 387-415.

BORTOLOTTI V., PRINCIPI G. & TREVES B. (2001) - *Ophiolites, Ligurides and the tectonic evolution from spreading to convergence of a Mesozoic western Tethys segment*. In: Vai G.B. & Martini I.P. (eds.), «Anatomy of an Orogen - The Apennines and Adjacents Mediterranean Basins». Kluwer Academic Publishers, Dordrecht, 151-164.

BOSSARD M., FERANCEC J. & OTAHEL J. (2000) - *CORINE land cover technical guide - Addendum 2000*. Technical report, 40. EEA - European Environment Agency, Copenhagen, 105 pp. http://reports.eea.eu.int/tech40add/en/tech40add.pdf visited on 30 November 2004.

BRASSEL K. (1974) - *A model for automatic hill shading*. The American Cartographer, 1(1), 15-27.

BROVELLI M.A., SANSÒ F. & TRIGLIONE D. (1999) - *Different Approaches For Outliers Detection In Digital Terrain Models And Gridded Surfaces Within The GRASS Geographic Information System Environment*. International Archives of Photogrammetry & Remote Sensing, 32 (4W12), 1-8.

BROVELLI M.A., TRIGLIONE D. & VENUTI G. (2000) - *GIS techniques for digital surface models outlier detection*, Geomatics Workbooks, 1. http://geomatica.como.polimi.it/workbooks/n1/pref.php visited on 30 November 2004.

BURROUGH P.A. (1986) - *Principles of Geographical Information Systems for Land Resources Assessment*. Oxford University Press, New York, 193 pp.

BURROUGH P.A. & MCDONNEL R.A. (1998) - *Principles of Geographical Information Systems*. Oxford University Press, New York, 336 pp.

CARMIGNANI L., DECANDIA F.A., DISPERATI L., FANTOZZI P.L., KLIGFIELD R., LAZZAROTTO A., LIOTTA D. & MECCHERI M. (2001) - *Inner Northern Apennines*. In: Vai G.B. & Martini I.P. (eds.), «Anatomy of an Orogen - The Apennines and Adjacents Mediterranean Basins». Kluwer Academic Publishers, Dordrecht, 197-213.

CARTER J. (1992) - The *effect of data precision on the calculation of slope and aspect using gridded DEMs*. Cartographica, 29 (1), 22-34.

CASTELLARIN A. & PINI G.A., with the contribute of BORSETTI A.M. & RABBI E. (1989) - *L'arco del Sillaro: la messa in posto delle Argille Scagliose al margine appenninico padano (Appennino bolognese)*. Memorie della Società Geologica Italiana, 39, 127-142.

CERRINA FERONI A., OTTRIA G., MARTINELLI P. & MARTELLI L. (2002) - *Structural Geological Map of the Emilia-Romagna Apennines, 1:250.000 scale.* Selca, Firenze.

CHANG K. & TSAI, B. (1991) - *The effect of DEM resolution on slope and aspect mapping*. Cartography and Geographic Information Systems, 18 (1), 69-77.

CHURCH M. & MARK D.M. (1980) - *On size and scale in geomorphology.* Progress in Physical Geography, 4, 342-390.

COLLINS S.H. (1975) - *Terrain parameters directly from digital elevation models*. Canadian Surveyor, 29 (5), 507-518.

COWAN D.S. & PINI G.A. (2001) - *Disrupted and chaotic rocks in the Apennines*. In: Vai G.B. & Martini I.P. (eds.), «Anatomy of an Orogen - The Apennines and Adjacents Mediterranean Basins». Kluwer Academic Publishers, Dordrecht, 165-176.

CRAMER M. (2004) - *Eurosdr Network On Digital Camera Calibration*. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 35 (B6), 204-209.

CRUDEN D.M. & VARNES D.J. (1996) - *Landslide types and processes*. In: Turner A.K. & Schuster R.L. (eds.), «Landslides: investigations and mitigation», Spec. Rep., 247, Transportation Research Board, National Research Council, National Academy Press, Washington, DC, 36-75.

CHANDLER J.H. (1999) - *Effective application of automated digital photogrammetry for geomorphological research*. Earth Surface Processes and Landforms, 24, 51-63.

DOWMAN I. (1998) - *Automating image registration and absolute orientation: solutions and problems*. Photogrammetric Record, 16 (91), 5-18.

DOWMAN I., EBNER H. & HEIPKE C. (1992) - *Overview of European developments in digital photogrammetric workstations*. Photogrammetric Engineering & Remote Sensing, 58 (1), 51-56.

DYMOND J.R., DEROSE R.C. & HARMSWORTH G.R. (1995) - *Automated Mapping of Land Components from Digital Elevation Data.* Earth Surface Processes and Landforms, 20, 131-137.

ELTER P., GRASSO M., PAROTTO M. & MEZZANI L. (2003) - *Structural setting of the Apennine-Maghrebian thrust belt*. Episodes, 26 (3), 205-211.

EEA (2001) - *Towards agri-environmental indicators. Integrating statistical and administrative data with land cover information*. Topic report, 6. EEA - European Environment Agency, Copenhagen, 133 pp. http://reports.eea.eu.int/topic_report_2001_06/en/Topic_6_2001.pdf visited on 30 November 2004.

ESRI, INC. (1996) - *Dictionary of GIS Terminology.* Environmental Systems Research Institute, Inc., Redland, California. http://support.esri.com/index.cfm?fa=knowledgebase.gisDictionary.gateway visited on 30 November 2004.

ESRI, INC. (2004a) - *ArcGIS 9 - Getting started with ArcGIS*. Environmental Systems Research Institute, Inc., Redland, California, 272 pp.

ESRI, INC. (2004b) - *ArcGIS 9 - Using 3d Analyst*. Environmental Systems Research Institute, Inc., Redland, California, 70 pp.

EVANS I.S. (1972) - *General geomorphometry, derivatives of altitude and descriptive statistics*. In: Chorley R.J. (ed.), Spatial analysis in Geomorphology. Methuen and Co., Ltd., London, 17-90.

EVANS I.S. (1980) - *An Integrated System for Terrain Analysis and slope mapping*. Zeitschrift für Geomorphologie, Supplementbände, Band 36, Perspectives in Geomorphology, 274-290.

EVANS I.S. (1981) - *General geomorphometry*. In: Goudie A.S. (ed.), Geomorphological Techniques. George Allen and Unwin Publishers, London, 31-37.

EVANS I.S. (1998) - *What do terrain statistics really mean?* In: Lane S.N., Richard K.S. & Chandler J.H. (eds.), «Landform Monitoring, Modelling and Analysis». J. Wiley & Sons, Chichester, England, 119-138.

FERRANO G., NEUMANN K.J. & DOERSTEL CH. (2004) - *New Quality Standards for Digital Images*. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 35 (B2), 245-248.

FELICÍSIMO A.M., CUARTERO A. & ARIZA F.J. (2004) - *A Method for the improvement elevation data generated from automated photogrammetric methods into SIS*. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 35 (B4), 255-260.

FOWLER R.J. & LITTLE J.J. (1979) - *Automatic extraction of irregular network digital terrain models*. ACM SIGGRAPH Computer Graphics, 13 (2), 199-207.

GARDNER T.W., SASOWSKY K.C. & DAY R.L. (1990) - *Automated extraction of geomorphometric properties form digital elevation data*. Zeitschrift für Geomorphologie, Supplementbände, Band 80, «Geomorphology and Geoecology: Geomorphological mapping, remote sensing and terrain models», 57-68.

GOOCH M.J. & CHANDLER J.H. (2001) - *Failure prediction in automatically generated digital elevation models*. Computers & Geosciences, 27 (8), 913-920.

GUTH P. (1992) - Spatial analysis of DEM error. ASPRS/ACSM/RT - American Society for Photogrammetry and Remote Sensing/American Congress on Surveying and Mapping/Resource Technology, Washington, DC, 2, 187-196.

HABIB A., LEE Y.R. & MORGAN M. (2001) - *Surface matching and change detection using modified Hough transformation for robust parameter estimation*. Photogrammetric Record, 17 (98), 303-315.

HAMBY D.M. (1994) - *A review of techniques for parameter sensitivity analysis of environmental models.* Environmental Monitoring and Assessment (32), 135-154.

HAWKINS D.M. (1980) - *Identification of Outliers - Monographs on applied probability and statistics*. Chapman and Hall, London, 188 pp.

HEIPKE C. (1995) - *State-of-the-art of Digital Photogrammetric Workstations for Topographic Applications*. Photogrammetric Engineering & Remote Sensing, 61 (1), 49-56.

HEIPKE C. (1997) - *Automation of interior, relative, and absolute orientation*. ISPRS Journal of Photogrammetry and Remote Sensing, 52 (1), 1-19.

HELAVA U.V. (1988a) - *Object space least square correlation*. Photogrammetric Engineering & Remote Sensing, 54 (6), 711-714.

HELAVA U.V. (1988b) - *On system concepts for digital automation*. International Archives of Photogrammetry & Remote Sensing, 27 (B2), 171-190.

HELLWICH O., HEIPKE C., TANG L., EBNER H. & MAYR W. (1994) - *Experiences with automatic relative orientation*. International Archives of Photogrammetry & Remote Sensing, 30 (3/1), 370-378.

JANESICK J.R. (2001) - *Scientific Charge Coupled Devices*. SPIE PRESS Monograph PM83, SPIE - The International Society for Optical Engineering, Bellingham, Washington, 920 pp.

KÄÄB A. & FUNK M. (1999) - *Modelling mass balance using photogrammetric and geophysical data: a pilot study at Griesgletscher, Swiss Alps*. Journal of Glaciology, 45 (151), 575-583.

KARRAS G.E., MAVROGENNEAS N., MAVROMATI D. & TSIKONIS N. (1998) - *Tests on automatic DEM generation in a digital photogrammetric workstation*. International Archives of Photogrammetry & Remote Sensing, 32 (2), 136-139.

KRAUS K. (1993) - *Photogrammetry, volume 1: Fundamentals and Standard Processes*. Ferd. Dümmlers Verlag, Bonn, 397 pp.

KRAUS K. (1997) - *Photogrammetry, volume 2: Advanced Methods and Applications*. Ferd. Dümmlers Verlag, Bonn, 466 pp.

KRZANOWSKI R.M., PALYLYK C.L. & CROWN P.H. (1995) - *Lexicon of Terms for Users of Geographic Information Systems*. In: Bonham-Carter G.F., «Geographic Information Systems for Geoscientists: Modelling with GIS», Pergamon Press, Inc., Oxford, New York, 398 pp.

KUMLER M.P. (1994) - *An intensive comparison of triangulated irregular networks (TINs) and Digital Elevation Models (DEMs)*, Cartographica, 31(2), Monograph 45, 48 pp.

LAM N. (1983) - *Spatial Interpolation methods: A review*, The American Cartographer, 10 (2), 129-149.

LH SYSTEMS, LLC (1999) - *SOCET SET - User's Manual*. LH Systems, LLC, San Diego, 786 pp.

LI Z., XU Z., CEN M. & DING X. (2001) - *Robust surface matching for automated detection of local deformations using least-median-of-square estimator*. Photogrammetric Engineering & Remote Sensing, 67 (11), 1283-1292.

LONGLEY P.A., GOODCHILD M.F., MAGUIRE D.J. & RHIND D.W. (2001) - *Geographic Information Systems and Science*. John Wiley & Sons, New York, 472 pp.

MCGWIRE K. & ESTES J.E. (1991) - *The Class Dependent Nature of Error in Machine Assisted Land Cover Classification.* In: Star J.L. (ed.), Proc. ACSM-ASPRS Annual Convention, Spec. Session The Integration of Remote Sensing and Geographic Information Systems, Baltimore, USA, 1991. ASPRS - American Society for Photogrammetry and Remote Sensing, Bethesda, Maryland, 117-128.

MARTINI I.P., SAGRI M. & COLELLA A. (2001) - *Neogene-Quaternary basins of the inner Apennines and Calabrian arc.* In: Vai G.B. & Martini I.P. (eds.), «Anatomy of an Orogen - The Apennines and Adjacents Mediterranean Basins». Kluwer Academic Publishers, Dordrecht, 375-400.

MITCHELL H.L. & CHADWICK R.G. (1999) - *Digital photogrammetric concepts applied to surface deformation studies*. Geomatica, 53 (4), 405-414.

MITCHELL H.L., FRYER J.G. & PÂQUET R. (2002) - *Integration and filtering of 3D spatial data using a surface comparison approach*. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 34 (4), 6 pp.

MORA P., BALDI P., CASULA G., FABRIS M., GHIROTTI M., MAZZINI E. & PESCI A. (2003) - *Global Positioning Systems and digital photogrammetry for the monitoring of mass movements: application to the Ca' di Malta landslide (northern Apennines, Italy)*. Engineering Geology, 68, 103-121.

NETELER M. & MITASOVA H. (2004) - *Open Source GIS: a GRASS GIS Approach*. The Kluwer international series in Engineering and Computer Science, Vol. 773, Kluwer Academic Publishers, Boston/Dordrecht, 424 pp.

NOAA (2004) - *Benthic Habitat Mapping - GIS basics*. NOAA - National Oceanic and Atmospheric Administration Coastal Service Center. http://www.csc.noaa.gov/benthic/mapping/analyzing/gis.htm, visited on 30 November 2004.

ORI G.G. & FRIEND P.F. (1984) - *Sedimentary basins formed and carried piggy-back on active thrust sheets*. Geology, 12, 475-478.

PESCI A., BALDI P., BEDIN A., CASULA G., CENNI N., FABRIS M., LODDO F., MORA P. & BACCHETTI M. (2004) - *Digital elevation models for landslide evolution monitoring: application on two areas located in the Reno River Valley (Italy)*. Annals of Geophysics, 47 (4), 1339-1353.

PEUCKER T.K., FOWLER R.J., LITTLE J.J. & MARK D.M. (1978) - *The Triangulated Irregular Network.* In: «Proc. ASP Digital Terrain Models (DTM) Symposium», 9-11 May 1978, St. Louis, Missouri. ASP - American Society of Photogrammetry, Falls Church, Virginia, 516-540.

PFALTZ J.L. (1976) - *Surface networks*. Geographical Analysis, 8 (1), 77-93.

PIERI M. & GROPPI G. (1981) - *Subsurface geological structure of the Po Plain, Italy*. Publication 414, P.F. Geodinamica, CNR - Consiglio Nazionale delle Ricerche, Roma, 23 pp.

PIKE R.J. (1988) - *The geometric signature: quantifying landslide-terrain types from digital elevation models*. Mathematical Geology, 20 (5), 491-510.

PIKE R.J. (1993) - *A bibliography of geomorphometry with a topical key to the literature and an introduction to the numerical characterization of topographic form*. Open-File Report 93-262-A, USGS - U.S. Geological Survey, Menlo Park, California, 132 pp.

PIKE R.J. (1995) - *Geomorphometry-process, practice and prospects*. Zeitschrift für Geomorphologie, Supplementbände, Band 101, «Advances in Geomorphometry» - Proceedings of the Walter F. Wood Memorial Symposium, 221-238.

PIKE R.J. (2000) - *Geomorphometry - diversity in quantitative surface analysis*. Progress in Physical Geography, 24 (1), 1-20.

PILGRIM L.J. (1996) - *Surface matching and difference detection without the aid of control points*. Survey Review, 33 (259), 291-304.

PINI G.A. (1999) - *Tectonosomes and Olistostromes in the Argille Scagliose of the northern Apennines, Italy*. Geological Society of America, Spec. Pap., 335, 73 pp.

PINI G.A., LUCENTE C.C., COWAN D.S., DE LIBERO C.M., DELLISANTI F., LANDUZZI A., NEGRI A., TATEO F., DEL CASTELLO M., MORRONE M. & CANTELLI L. (2004) - *The role of Olistostromes and Argille Scagliose in the structural evolution of the northern Apennines*. Field Trip Guide Book - B13. APAT - Italian Agency for the Environmental Protection and Technical Services, Roma, 40 pp.

REGIONE EMILIA-ROMAGNA (1999) - *I numeri sulle frane*. Pendragon Ed., Bologna, 94 pp.

REGIONE EMILIA-ROMAGNA (2004) - *Some examples of landslides in the Emilia Apennines*. Industrie Grafiche Labanti e Nanni, Bologna, 40 pp.

RICCI LUCCHI F. (1986) - *The Oligocene to Recent foreland basins of the northern Apennines.* IAS - International Association of Sedimentologists, Spec. Publ., 8, 105-139.

SCHENK T. (1999) - *Digital Photogrammetry, volume 1. TerraScience, Laurelville, Ohio. 428 pp.*

SCHENK T., KRUPNIK A. & POSTOLOV Y. (2000) - *Comparative study of surface matching algorithms*. International Archives of Photogrammetry & Remote Sensing, 33 (B4), 518-524.

SCHUMM S. & LICHTY R. (1965) - *Time, space and causality in Geomorphology*. American Journal of Science, 263, 110-119.

SIMONI A., BERTI M., GENERALI M., ELMI C., & GHIROTTI M. (2004) - *Preliminary result from pore pressure monitoring on an unstable clay slope*. Engineering Geology, 73, 117-128.

SPEIGHT J.G. (1974) - *A parametric approach to landform regions*. In: «Progress in Geomorphology», Institute of British Geographers, Spec. Publ., 7, Alden & Mowbray Ltd. at the Alden Press, Oxford, 213-230.

TANG L. & HEIPKE C. (1996) - *Automatic relative orientation of aerial images*. Photogrammetric Engineering & Remote Sensing, 62 (1), 47-55.

THOMPSON M.M. & GRUNER H. (1980) - *Foundations of photogrammetry.* In: Slama C.C. (ed.), «Manual of Photogrammetry». ASP - American Society of Photogrammetry, Falls Church, Virginia, 1-36.

TURNER A.K. (1997) - *What's the Difference Among 2-D, 2.5D, 3-D, and 4-D?* Geo World, 10 (3), 54.

USACE (2002) - *Engineering and Design - Photogrammetric Mapping*. Manual, EM 1110-1-1000. CECW-EE, USACE - U.S. Army Corps of Engineers, Department of the Army, U.S., Washington, DC, 371 pp.

VAI G.B. (2001) - *Structure and stratigraphy: an overview*. In: Vai G.B. & Martini I.P. (eds.), «Anatomy of an Orogen - The Apennines and Adjacents Mediterranean Basins». Kluwer Academic Publishers, Dordrecht, 15-31.

VAI G.B. & CASTELLARIN A. (1993) - *Correlazione sinottica delle unità stratigrafiche nell'Appennino Settentrionale*. Studi Geologici Camerti, Vol. Spec., 1992/2A, 171-185.

VERBYLA D.L. (2002) - *Practical GIS analysis*. Taylor & Francis, London, 294 pp.

WEHRLI & ASSOCIATES, INC. (2000) - *RasterMaster PHOTOSCANNER*. Wehrli & Associates, Inc., Valhalla, New York, 47 pp.

VAN WESTEN C.J. & LULIE GETAHUN F. (2003) - *Analyzing the evolution of the Tessina landslide using aerial photographs and digital elevation models*. Geomorphology, 54 (1-2), 77-89.

WOOD J. (1996a) - *The Geomorphological Characterisation of Digital Elevation Models*. PhD Thesis, University of Leicester, England, 185 pp.

WOOD J. (1996b) - *Scale-based characterisation of Digital Elevation Models*. In: Parker D. (ed.), «Innovations in GIS», Vol. 3. Taylor and Francis, London, 163-175.

WOOD J. (1998) - *Modelling the continuity of surface form using digital elevation models.* In: Poiker T. & Chrisman N. (eds.), «Proc. IGU 8th Int. Symposium on Spatial Data Handling», 11-15 July 1998, Vancouver, BC, Canada, 725-736.

WOOD J. (2004) - *Landserf 2.1 Documentation*. http://www.landserf.org, visited on 30 November 2004.

WP/WLI (1993a) - *A suggested method for describing the activity of a landslide*. Bulletin of the International Association of Engineering Geologists, 47, 53-57.

WP/WLI (1993b) - *Multilingual Landslide Glossary*. BiTech Publishers, Richmond, 59 pp.

YOELI P. (1967) - *Mechanisation in analytical hill-shading*. Cartographic Journal, 4 (2), 82-88.

ZEVENBERGEN L.W. & THORNE C.R. (1987) - *Quantitative analysis of land surface topography*. Earth Surface Processes and Landforms, 12, 47-56.

ZIEMANN H. & GROHMANN D. (2003) - *Photogrammetric Procedures for Digital Terrain Model Determination.* In: Buhmann E. & Ervin S.M. (eds.), Proc. 4th Conference on Information Technologies in Landscape Architecture at Anhalt University of Applied Sciences, Dessau, Germany, 15-16 May 2003, «Trends in Landscape Modeling». Herbert Wichmann Verlag. Heidelberg, 275 pp.

ZIEMANN H. & GROHMANN D. (2004) - *The Eurosdr Digital Camera Project*. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 35 (B6), 210-213.