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Lineament mapping and its application in landslide hazard assessment: a review

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Abstract This paper presents an overview of the use of lineaments in landslide hazard mapping. The lineaments are normally derived either from aerial photographs or satellite imagery. The relative advantages and disadvantages of digital image processing and manual (visual) lineament interpretation are discussed. Most researchers prefer the manual technique, despite the fact it is more time-consuming and subjective, as it allows a higher degree of operator control. Ways of increasing objectivity in the interpretation are suggested. It is hoped that lineament mapping will increasingly be incorporated in landslide hazard assessment hence the paper emphasizes the need for care and a proper understanding of these methods and their limitations.

Keywords Landslide hazard · Lineament · Subjectivity · Remote sensing imagery

Résumé L'article présente une revue sur l'utilisation des linéaments pour la cartographie de l'aléa de glissement de terrain. Les linéaments sont normalement obtenus à partir de photographies aériennes ou d'images satellitaires. Les avantages et inconvénients des traitements numériques des images et des interprétations manuelles (visuelles) des linéaments sont discutés. La plupart des chercheurs préfèrent les techniques manuelles, malgré le fait qu'elles sont longues et subjectives, considérant qu'elles permettent un meilleur contrôle par l'opérateur. Des moyens d'améliorer l'objectivité dans l'interprétation sont suggérés. On peut espérer que la cartographie de linéaments sera incorporée de façon plus importante dans l'évaluation des aléas de glissement de terrain. C'est pourquoi l'article met l'accent sur la nécessité de bien maîtriser ces méthodes et connaître leurs limites.

Mots clés Aléa de glissement de terrain · Linéament · Subjectivité · Imagerie à distance

Introduction

The structural geology of the area has a significant influence on the occurrence of landslides. One way of incorporating structural information into the landslide hazard assessment is by utilizing lineament mapping (Anbalagan and Singh 1996; Atkinson and Massari 1998; Nagarajan et al. 2000; Temesgen et al. 2001; Saha et al. 2002; Lin and Tung 2003 and many others). Lineament mapping needs to be undertaken with care and with a proper understanding of its methods and limitations. Thus the main objectives of this paper are to review the methods of lineament detection and to suggest the best practice in lineament mapping to be used as part of a landslide hazard assessment.

Lineaments and remote sensing

Numerous terms have been used to describe lineaments, e.g. geologic lineaments, tectonic lineaments, photo lineaments, fracture traces and photo linear or geophysical lineaments, based on the assumed origin of the feature or sometimes the data source from which it has been derived (Sander 2007).

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Hobbs (1904) originally proposed the term lineament for significant lines of landscape caused by joints and faults, revealing the architecture of the rock basement. The most widely used definition is by O'Leary et al. (1976) who described a lineament as a mappable, linear feature of a surface whose parts are aligned in a rectilinear or slightly curvilinear relationship and which differ from the pattern of adjacent features and presumably reflect some subsurface phenomenon. Haeberlin et al. (2004) and Gomez and Kavzoglu (2005) refer to a surface expression that may reveal the hidden architecture of the rock basement. Remote sensing indicates lineaments as lines or linear formations with either lighter or darker pixels compared to the background pixels (Vassilas et al. 2002; Kocal et al. 2004). However, sometimes a lineament is clearly shown on the imagery but does not appear to correspond to any observable physical feature. There are sound reasons for assigning a geological meaning to some lineaments even if they do not always correspond to features in the field (Campbell 1987), as the feature may be deep seated or partially covered by unrelated strata (Richards 2000). Where these unrelated younger strata obscure the geological lineaments in the deep bedrock, with reactivation they often result in an array of brittle fractures on the surface (Leech et al. 2003).

There are two main types of lineament—positive and negative, referring to ridge trends and river valleys respectively. Whilst the topographically negative straight lineaments may represent joints, faults and shear zones, the topographically positive straight lineaments may be interpreted as dykes and dyke swarms (Koch and Mather 1997; Solomon and Ghebreab 2006). The slightly curved and sub-parallel lineaments indicate foliation or bedding trends, depending on rock type (crystalline or limestone) while circular features may delineate ring dykes (Koch and Mather 1997).

As far as landslides are concerned, negative lineaments are more important as the fractures which produce them cause weak lines and increase the probability that a landslide will occur.

Lineaments may be continuous or discontinuous and, under certain circumstances, may be regarded as the surface manifestation of fault and fracture zones (Pal et al. 2006). Furthermore, good correlation between structures mapped in the field and lineament systems has suggested lineaments may be regarded as representative of fracture networks (Morelli and Piana 2006). However, the presence of a dense vegetation canopy, extensive weathering and recent non-consolidated deposits (fluvial terraces, pediments or alluvial sediments) may prevent the identification of lineaments (Cortes et al. 1998; Gustafsson 1994) whilst not all faults are expressed topographically (Novak and Soulakellis 2000). As a consequence, the lack of expression of a lineament in remote-sensed imagery does not necessary mean that there is no joint or fault in the particular areas. Nevertheless, remote sensing (e.g. aerial photo or satellite imagery) is generally better at identifying these linear or slightly curvilinear features compared with field inspection. The continuity of a fault may also be better shown in satellite imagery because the "noise" caused by the high detail offered by aerial photos disappears (Arlegui and Soriano 1998).

Remote sensing has been widely used in lineament studies since the introduction of Landsat MSS in 1980. Among the types of remote sensing imagery that have been used for landslide hazard assessment studies are Landsat, IRS, LISS, ASTER, aerial photo, and Spot (Table 1). Where possible, the conventional aerial photo is complemented with satellite imagery as a wider synoptic view is more likely to allow long lineaments to be detected. Currently, most researchers use middle resolution satellite imagery which is easier to use and cheaper than aerial photos. Unless archived aerial photos are available, it is expected that this trend will continue, especially as the cost of satellite imagery is expected to decrease in the future.

In addition to landslide hazard assessment, where often the lineament mapping is only briefly referred to, in geological studies there is generally a more extensive discussion of the lineaments. In economic geology, for example, lineaments may indicate natural stopes where minerals are found, while in structural geology they give an almost unparalleled overview of the large structural features, the trends of which may be difficult to identify in the field. An indication of the kind of studies which have used lineament mapping is given in Table 2.

Generally, Landsat is the most popular satellite imagery (see Table 2), probably due to its relatively cheap cost; indeed the archive of Landsat imagery may be downloaded free from the internet. An advantage of the older archival imagery is that it may indicate features not so obvious on the more recent imagery, due to increasing urbanization etc. It should be stressed, however, that where possible the lineament should be "ground-truthed".

Lineament interpretation

Two main types of interpretation are used: manual interpretation based on visual interpretation and automatic interpretation utilizing computer algorithms.

Manual lineament interpretation

Conventional lineament interpretation was originally undertaken using hardcopy aerial photos under the stereoscope, where the visually interpreted lineaments are

Table 1 The application of lineament in landslide susceptibility/hazard assessment

Author	Imagery/scale	Place	Lineament application	Comment
Pachauri and Pant (1992)	(i) Aerial photos (ii) Landsat MSS	Aglar river, Himalaya, India	Lineament buffer (2,000 m) and density	Good relationship between lineament distance and landslides
Atkinson and Massari (1998)	Two aerial photos (i) colour/1:12,000 (ii) pan/1:33,000	Central Apennines, Italy	Lineament density No field verification	Slope movements are highly correlated with the density of lineaments
Nagarajan et al. (1998)	IRS	Western Ghat, India	Lineaments within 100 m buffer zones were given zero values, whereas the surroundings were given values other than zero using range classification Field verified	Most of the existing slides are associated with lineaments. 100 m wide buffer zone representing the influence of lineaments on the sliding event was generated
Pachauri et al. (1998)	(i) Aerial photo 1:40,000 (ii) Landsat/1:250,000	Part of Gharwals of Himalaya, India	Lineament buffer (1,000 m) and density Only lineaments conform to major faults were utilised	Good relationship between lineament distance and landslides
Nagarajan et al. (2000)	IRS	Konkan Coast, India	Lineament buffer 5 m Field mapping showed that their influence extends for some 3–5 m either side of the fracture itself where they appear as fragmented rock	Intersection of lineament, fragmented rock surface in the adjacent area or sheared/crushed material at the intersection of two such lineaments. The highest incidence of landsliding is found in areas where such a linear pattern is interpreted from satellite data
Rautela and Lakhera (2000)	(i) IRS 1 D (ii) LISS III	Himachal, Himalaya, India	Lineament delineation and then classified into minor and major faults Buffer distance is not mentioned Field verified	Severe mass wastage was observed to be taking place along the trace of major lineaments in the PAN stereo pair and in the aerial photographs, these zones are clearly demarcated; and in the field, sag ponds and shutter ridges were observed along the trace of these lineaments
Temesgen et al. (2001)	(i) Landsat TM (ii) SPOT Pan	Wondogenet Area, Ethiopia	Geological structure consists of collapse structure; lineament and normal faults were buffered with 500 m Limited field verification	The maximum number of landslide sites were observed within a distance of approximately 0–500 m from a given geological structure. Farther away from the structural features, landslide occurrences gradually decrease
Pistocchi et al. (2002)	Structural map/ 1:50,000	Northern Apennines, Italy	Lineament buffer (The legend in the lineament map showing distance of the buffer is not clear)	Distance from the geological lineaments was also calculated in order to appreciate the possible effect of structural disturbance on slope stability Lithology, land cover and rainfall are found to be the most important parameters
Saha et al. (2002)	(i) IRS-1B (ii) LISS-II 36.25 m	Bhagirathi Valley, India	Lineament buffer 500 m Apart from major known thrust, photo lineament is not field verified	The distance from these structural features suggests likelihood of occurrence of landslides may increase with the proximity to the lineaments

Table 1 continued

Author	Imagery/scale	Place	Lineament application	Comment
Lee (2004)	IRS pan/5 m	Boun, Korea	Lineament buffer 50 m Not field verification	Distance of lineament was classified for convenience. Proximity to a lineament seems to influence landslides. As the distance from lineament decreases, the extent of fracturing of the rock and the degree of weathering increases
Liu et al. (2004)	(i) Published maps (ii) ASTER (iii) DEM derived from 1:50,000 topographical map	Zigui–Badong, China	Fault and lineament buffer 500 m No field verification	
Sarkar and Kanungo (2004)	IRS-1C LISS III and IRS-1D PAN satellite data	The Darjeeling Himalaya, India	Lineament density Limited field verification	
Süzen and Doyuran (2004)	(i) Geological map (ii) Aerial photos	Asarsuyu catchment, Turkey	Fault buffer (range from 0 to 4,791 m) and fault density Field verified	The density of fault map involves the probability of the presence of micro tremors and gives an indication of the degree of shearing of the rocks, whereas the distance to fault map indicates the presence of joints-fractures affecting the strength
Ayalew and Yamagishi (2005)	Aerial photos/1:20,000	Kakuda-Yahiko Mountains, Japan	Lineament buffer 100 m Landslide density was assumed to be 100% within the buffer zones and 0% outside Field verified	This diameter is an average threshold set based on a comprehensive assessment of how far slope failures extend from mountain scarps, topographic breaks and any other linear futures The proximity to roads parameter was found to have the strongest relationship with slope failures, whereas lineaments portrayed a negative correlation and elevation had a small role in landslide occurrences
Gomez and Kavzoglu (2005)	Landsat TM band 4 the best	Jabonosa River Basin, Venezuela	Lineament buffer (Buffer distance not mentioned) No field verification	
Lee and Jasmi (2005)	Geologic database 1:50,000	Penang, Malaysia	Lineament buffer 200 m	The closer the distance to a lineament, the greater the landslide-occurrence probability. As the distance from a lineament decreases, the fracture of the rock and the degree of weathering increases
Lee (2005)	Geologic database 1:50,000	Penang, Malaysia	Lineament buffer 200 m	
Saha et al. (2005)	IRS-LISS	Himalaya, India	Thrusts, faults and lineament buffer 500 m Beside major known thrust, lineament is not field verified	
Kim et al. (2006)	1:50,000 Geological map	Samcheok City, Korea	Lineament buffer 100 m	

Table 1 continued

Author	Imagery/scale	Place	Lineament application	Comment
Lee and Lee (2006)	Pan IRS and Landsat TM	Gangneung, Korea	Lineament buffer 100 m No field verification	The closer the distance to a lineament, then the greater the landslide-occurrence probability The distance from a lineament decreases, the fracture of the rock and the degree of weathering increases
Van Den Eechaut et al. (2006)	Geological map	Flemish Ardennes, Belgium	Fault buffer Buffer distance as continuous data	
Fourniadis et al. (2007)	Aster Band 2 (15 m)	Wushan-Badong, China	Buffer zones to lineament length with two classes, 'Near' and 'Distant' 100 m No field verification	Higher hazard areas are associated with steep slopes formed in less competent lithologies and in proximity to drainage streams and lineaments
Mathew et al. (2007)	The LISS III	Part of Garhwal Himalaya	Lineament classified as major (if length >2 km) and minor (if length <2 km) Major lineament buffer 300 m Minor lineament buffer 100 m Field verification	This distance is based on the assessment of proximity of existing landslides from the lineaments Proximity to geologically important lineaments found to be the most critical parameter in creating slope instability
Ruff and Czurda 2008	Field mapping	Hochtannberg/Arlberg region, Germany	Fault buffer and differentiate between nappe, thrust and strike-slip fault Bedding orientations	Nappe thrusts were observed in the field as 10–100 m broad thrust zones. Within these zones the bedrock is tectonically stressed and highly unstable. Minor thrust and strike-slip faults show fault zones only a few meters wide. Therefore the susceptibility was assigned to three buffer regions. The smaller the distance to the fault the higher the tectonic influence the greater the index

Table 2 The application of lineament in geological studies

Author	Imagery/scale	Place	Type of studies	Image processing	Filter
Isiorho (1985)	Landsat MSS and Radar	Benua trough, Nigeria	Structural geology	Standard photogeologic routine using light table	
Karpuz et al. (1993)	Landsat TM	Northern Norway	Structural geology	RGB 453, RGB 457 and individual band	Directional filter and Wallis operator
Juhari and Ibrahim (1997)	Landsat TM	Kedah, Malaysia	Structural geology	Band 4	Non-directional filters (Laplacian) Directional filters, 3 × 3 kernel, EW, NS, NE-SW and NW–SE
Venkataraman et al. (1997)	Landsat TM	Rajashtan, India	Mineral Geology	RGB PC1, PC2 and Band 4 NE directional filtered composite image	NE directional filtered
Arlegui and Soriano (1998)	Landsat TM	NE Spain	Structural geology	Band 5 an automatic scanning	
Bense (1998)	Landsat TM	Namaqualand, South Africa	Hydrogeology	RGB 147	
Mountrakis et al. (1998)	Aerial photographs 1:50,000 Landsat TM	Western Macedonia, Greece	Structural geology	Contrast stretching, ratioing of the spectral bands, principal component analysis (PCA) and false colour composite (FCC) images, either by various original TM bands or by ratioing images and PC images RGB PC1, PC2, TM7	
Süzen and Toprak (1998)	Landsat TM	Central Turkey	Structural geology	Band 7 PCA	Directional high pass filters Prewitt kernels (N–S, NE-SW, E-W, NW–SE) Sobel filter
Novak and Soulakellis (2000)	Landsat TM	Lesvos, Greece	Structural geology	RGB TM-band 3, PC-1, and PC-2; RGB TM-band 7, PC-1, and PC-2	
Sahoo et al. (2000)	IRS-1B LISS-I	NW Himalaya, India	Structural geology	Band 4 FCC	Directional high pass filters in N–S, NE-SW, E-W, NW-SE)
Saha et al. (2002)	IRS-1B LISS-II image	Bhagirathi Valley, India	Landside hazard assessment	–	Non-directional (Laplacian)
Cortes et al. (2003)	Landsat TM	North Spain	Structural geology	RGB 542 contrast stretch of 1%	
Akman and Tüfekçi (2004)	ASTER LANDSAT-TM	Southwestern part of Turkey	Structural geology	Anaglyph DEM from ASTER draped over LANDSAT-TM. The relief was exaggerated by 3 times RGB 432	
Ali and Pirasteh (2004)	Landsat TM	South-west Iran	Structural geology	RGB 4-3-2 and RGB 741 Band 4	Directional Non-directional (Laplacian)

Table 2 continued

Author	Imagery/scale	Place	Type of studies	Image processing	Filter
Kocal et al. (2004)	Ikonos	Ankara, Turkey	Structural geology		First smoothed with an average low pass filter in order to eliminate the noise Following the smoothing process, directional filtering (Sobel)
Gomez and Kavzoglu (2005)	Landsat TM	Jabonosa River Basin, Venezuela	Landside hazard assessment	Band 4	Filtering analysis (no detail given)
Kavak (2005)	Landsat TM	Western Turkey	Structural geology	Band 5	Directional filters such as NW, N–S and E–W based on the structural and tectonic features
Ricchetti and Palombella (2005)	Landsat ETM+	Southern Italy	Structural geology	Panchromatic and multispectral bands were fused RGB 247 RGB 457	Direction filters (EW, NS, NE-SW and NW–SE) were used Non-directional of Laplacian, Sobel and Prewitt edge filters Edge detection of top hat transformation
Pena and Abdelsalam (2006)	SRTM DEMs	Southern Tunisia	Geological Mapping	Hill-shading DEMs with different azimuth direction and sun angle Illumination sun angles of less than 20 are the most effective in enhancing topography in low relief areas Hill-shading DEMs generated at 15 azimuth increments and an illumination sun angle of 10 have been the most useful in bringing out subtle morphological variations	
Pal et al. (2006)	ERS-2 SAR	Singhbhum shear zone, India	Structural geology	Fast Fourier transform (FFT)	
Rao (2006)	IRS LISS III	Andhra Pradesh, India	Hydrogeology	RGB 234	
Sarup et al. (2006)	IRS 1D LISS III	Maharashtra, India	Structural geology	RGB	Edge enhancement
Solomon and Ghebreab (2006)	Landsat TM	Central highlands of Eritrea	Structural geology	Band 5 RGB 541 RGB PC1–PC2–PC3	A kernel of 3 × 3 pixel size was selected and employed along directions N, NW, NE and E
Srivastava and Bhattacharya (2006)	IRS LISS III	Orrisa, India	Hydrogeology	PCA Histogram equalization	3 × 3 high-pass directional filtering (NS, ES, NE-SW and NW–SE)
Warner (1997)	Landsat TM	West Virginia, USA	Geobotanical	FCC	3 × 3 high pass filter was multiplied by 0.2 and combined with the original image data multiplied by 0.8

Table 2 continued

Author	Imagery/scale	Place	Type of studies	Image processing	Filter
Pradhan et al. (2006)	IRS-1B LISS 1	A part of the Himalaya belt, India	Landslide studies using remote sensing	FCC image Histogram equalisation	Spatial domain filtering Prewitt and Sobel convolution kernels
Cengiz et al. (2006)	Landsat ETM+	Isparta, SW Turkey)	Structural geology		Directional filters NS, ES, NE-SW and NW–SE
Virdi et al. (2006)	IRS-1D-LISS-III and PAN SRTM	Northwest Himalaya, India	Structural geology	IRS-1D-LISS-III merged with PAN Satellite images draped over Digital Elevation Model (DEM)	
Mathew et al. (2007)	The LISS III	Part of Garhwal Himalaya, India	Landslide hazard assessment	Decorrelation-stretched FCC merge with PAN from the IHS transformation	Edge-enhancement
Lin et al. (2007)	1:20,000 aerial photos and the DTM	Chiayi-Yunlin, Taiwan	Structural geology	Shaded relief images were produced from the DTM with illumination	

delineated on the transparent overlays and transferred to a map. Advances in technology have allowed digital manipulation of the satellite imagery and the exploitation of the 3D environment. The basis of visual interpretation is generally tonal contrast and/or textural pattern (Akman and Tüfekçi 2004; Gomez and Kavzoglu 2005; Sarup et al. 2006). These patterns mainly relate to geomorphological features (Table 3).

It is suggested that before lineament delineation is undertaken, the general orientation of the drainage pattern should be considered. As most drainage patterns follow the major lineament trends (Süzen and Toprak 1998; Devi and Singh 2006; Sarup et al. 2006), this will give some indication as to the general structural orientation.

The review of the digital processing for visual interpretation summarized in Table 2 indicates that most researchers utilize standard image processing such as image enhancement and filtering. The techniques include: the application of false colour (Karpuz et al. 1993; Venkataraman et al. 1997; Warner 1997; Bense 1998; Mountrakis et al. 1998; Cortes et al. 2003; Akman and Tüfekçi 2004; Ali and Pirasteh 2004; Ricchetti and Palombella 2005; Rao 2006; Sarup et al. 2006; Solomon and Ghebreab 2006; Pradhan et al. 2006); the application of principal component analysis in RGB (Mountrakis et al. 1998; Solomon and Ghebreab 2006; Srivastava and Bhattacharya 2006); the combination of satellite bands and principal component band (PC) (Venkataraman et al. 1997; Mountrakis et al. 1998; Novak and Soulakellis 2000). Some researchers prefer the use of only individual bands; the most popular bands for Landsat TM are band 4 (Sahoo et al. 2000; Ali and Pirasteh 2004; Juhari and Ibrahim 1997; Gomez and Kavzoglu 2005; Solomon and Ghebreab 2006), band 5 (Arlegui and Soriano 1998; Kavak 2005) and band 7 (Süzen and Toprak 1998) or band ratio (Mountrakis et al. 1998). Other techniques include a combination of satellite imagery draped over a digital elevation model (DEM) (Akman and Tüfekçi 2004); fusing of the relatively lower multispectral resolution with the higher resolution pan imagery (Ricchetti and Palombella 2005; Mathew et al. 2007); the utilization of a DEM (Pena and Abdelsalam 2006; Lin et al. 2007); and a fusion of the relatively lower multispectral resolution with the higher resolution pan imagery draped over the DEM (Virdi et al. 2006).

Some researchers preferred the analysis to be undertaken using an RGB environment which is in colour and different textural information from three bands can be simultaneously analysed (Karpuz et al. 1993; Venkataraman et al. 1997; Bense 1998; Mountrakis et al. 1998; Cortes et al. 2003; Akman and Tüfekçi 2004; Ali and Pirasteh 2004; Ricchetti and Palombella 2005; Rao 2006; Sarup et al. 2006; Solomon and Ghebreab 2006; Warner

Table 3 The geomorphologic characteristic of lineaments that can be used in lineament interpretation (after Akman and Tüfekçi 2004; Gomez and Kavzoglu 2005; Sarup et al. 2006)

Geomorphological characteristics	
Structural alignments	Straight arrangement of triangular surfaces
Existence of fault-scarp	Displacement of ridge lines and river passages
Straight valley	Drainage anomaly
Extra-ordinary straight arrangement of river passages	Straight arrangement of lakes, hot springs, volcanic vents, water wells, slope failures, landslides, alluvial fan gaps and vegetation
Straight arrangement of the conversion points on the inclination of sedimentary rocks where the gentle inclination changes to a steep one	Vertical or horizontal linear displacement drainage patterns and density, rock resistance, landforms and development of bedding, and also superficial cover such as vegetation and cultivation
Straight arrangement of the conversion points on the slope inclination	Topographic breaks
Existence of kerncol and kernbut	

1997; Pradhan et al. 2006). However a number of researchers have preferred to use the individual band in the greyscale environment (Sahoo et al. 2000; Ali and Pirasteh 2004; Juhari and Ibrahim 1997; Gomez and Kavzoglu 2005; Kavak 2005; Solomon and Ghebreab 2006). The main reason is probably individual preference, but it has been shown that the human retina has a high response to high frequency images in black and white, whereas the retina response to colour image is poor at high frequency, improving for broad, spatial features (Pratt 1978). This would suggest that interpretations for structural studies such as lineament mapping, where image features are of relatively high spatial frequencies, are better performed on black and white images as opposed to colour images (Drury 1986; Rothery 1987; Greenbaum 1987).

The combination of the relatively higher resolution pan imagery with multispectral imagery has also been undertaken (Ricchetti and Palombella 2005; Virdi et al. 2006; Mathew et al. 2007). This gives higher resolution data that may improve the interpretation. DEM, from either topographical maps, SRTM or aerial photos, has also been utilized (Pena and Abdelsalam 2006; Lin et al. 2007). The application of DEM will undoubtedly improve the interpretation because the introduction of the 3D aspect will enhance the understanding of the topography, which is crucial in lineament interpretation. Thus, draping the satellite imagery over the DEM will introduce a stereo view which may increase the interpretation capability (Akman and Tüfekçi 2004; Virdi et al. 2006).

Another useful application of DEM for delineating lineaments is by utilizing analytical hill shading. This is a technique for generating shaded topographic images of the earth's surface elevations where the reflection of artificial light arriving from a point source of illumination from a given altitude (inclination) and azimuth (declination) is simulated (Masoud and Koike 2006). A DEM could be artificially illuminated from any direction desired, which is not possible in optical satellite imagery. This capability is important where the lighting may be in a perpendicular direction in order to enhance any suspected lineament. Another advantage of the shaded-relief image is that as it only shows bare-ground surfaces, unobscured by any vegetation or land use, lineaments that are difficult to see by the usual methods of aerial photo or satellite imagery interpretation may be identified (Oguchi et al. 2003).

Lineament mapping using hillshade by DEM has been successfully utilized by Oguchi et al. (2003), Norini et al. (2004), Concha-Dimasa et al. (2005), and Andreas and Allan (2007). However caution is required when utilizing the hillshade illumination as it may general a "false lineament". In addition, landforms—which are crucial in lineament identification—are known to appear differently with different solar illumination directions. Smith and Clark (2005) noticed that a drumlin viewed side on will appear linear, but when viewed head-on can look like a circular hill.

Surprisingly, many of the researchers did not undertake any spatial feature manipulation to filter the image and use the imagery but employed only contrast stretching (Bense 1998; Mountrakis et al. 1998; Novak and Soulakellis 2000; Cortes et al. 2003; Akman and Tüfekçi 2004; Pena and Abdelsalam 2006; Rao 2006; Virdi et al. 2006; Lin et al. 2007). This is probably because they preferred to keep the image in the original condition (rather than filtered) to avoid confusion as the image is maintained as it is visually experienced.

Filtering can be either directional (Karpuz et al. 1993; Venkataraman et al. 1997; Süzen and Toprak 1998; Sahoo et al. 2000; Kocal et al. 2004: Kavak 2005; Solomon and Ghebreab 2006; Srivastava and Bhattacharya 2006; Cengiz et al. 2006) or non-directional (Saha et al. 2002; Sarup et al. 2006; Mathew et al. 2007) or both (Ali and Pirasteh 2004; Juhari and Ibrahim 1997; Ricchetti and Palombella 2005; Pradhan et al. 2006). Most researchers used a high pass filter except Süzen and Toprak (1998) and Kocal et al.

(2004) who used a combination of low and high pass filters. The application of the low pass filter before the high pass filter is to filter out the noise first before the high spatial frequency is enhanced (Avery and Berlin 1985; Süzen and Toprak 1998). However, the user should be aware that the application of a directional filter may introduce artefacts as a result of the digital processing of the filter itself and it is sometimes difficult to differentiate between the "true" lineament trends and the artefact (Avery and Berlin 1985; Drury 1986; Gupta 1991).

Subjectivity

The subjective nature of any visual interpretive technique, including lineament mapping, means that the result may be controversial (Mabee et al. 1994; Gomez and Kavzoglu 2005). To a large extent, the results cannot be reproduced because the identification criteria are not agreed upon by different analysts and usually cannot be expressed in quantitative terms but rather are based on sensory impressions (Wladis 1999). Subjectivity is involved in the identification of the lineament itself, whether it is a lineament or not, and how far the lineament extends. In particular, it may be difficult to position the lineament in a satisfactory manner, especially in highly vegetated or wide valley areas (Gustafsson 1994).

While most researchers are aware of this problem, measures to minimize subjectivity are seldom employed (Mabee et al. 1994). This was found to be generally true in the review undertaken for landslide hazard mapping (Table 1); although the subjectivity issue is sometimes mentioned, the measures undertaken to overcome the problem (if any) are not stressed.

The subjectivity can be minimized and confidence in the lineament maps increased through the integration of results from multiple observers (Mabee et al. 1994; Sander et al. 1997), or multiple observer trials (Mabee et al. 1994). The latter authors suggest that several operators map the same/similar locations and that one operator could also observe similar imagery twice with a minimum of one week break between the observations, and that the results are compared, with only the lineaments identified by more than one observer or at least twice by the same observer being used. Such reproducibility tests provide confidence that the feature being mapped is "real" because it can be detected in the repeated trial or by several observers (Mabee et al. 1994).

Automatic lineament extraction

One of the main advantages in the automatic identification of lineaments is its objectivity as it uses computer algorithms. The algorithm may be based on edge enhancement and filtering techniques such as Hough and Haar transforms (Cross 1988; Wang and Howarth 1990; Karnieli et al. 1996; Majumdar and Bhattacharya 1988; Vassilas et al. 2002). The principle of these methods is to detect adjacent pixels which abruptly change in grey level by the use of a differential operation (Koike et al. 1995). The Hough Transform is a powerful tool in edge linking for line extraction; the main advantages being its insensitivity to noise and its capability to extract lines even in areas with pixel absence/pixel gaps (Argialas and Mavrantza 2004). The transform detects the collinear sets of edge pixels in an image by mapping these pixels into a parameter space (the Hough space) defined in such a way that collinear sets of pixels in the image give rise to peaks in the Hough space (Karnieli et al. 1996). The Hough Transform has been utilized successfully in delineating lineaments in many areas, see for example Cross 1988; Wang and Howarth 1990; Karnieli et al. 1996; Vassilas et al. 2002; Argialas and Mavrantza 2004 (Table 4).

The Haar Transform provides a transform domain in which differential energy is concentrated in localized regions. It has low and high frequency components and therefore may be used for image enhancement (Majumdar and Bhattacharya 1988). This method was successfully used to delineate the major drainage and lineament patterns in part of Cambay Basin in India (Majumdar and Bhattacharya 1988).

The main problems with automatic lineament extraction procedures are that in some situations the filtering technique generates segmented images containing numerous spurious lineament pixels that must be eliminated using complicated edge-linking algorithms; and these lineament extraction routines perform indiscriminate extraction of edge pixels without considering the topographic information inherent in remotely sensed images (Raghavan et al. 1995). In addition, these techniques cannot effectively extract lineaments from low-contrast areas and in mountain shadows which produce short dense lineaments that are difficult to relate to tectonically significant structures (Koike et al. 1995). In order to overcome these problems, the non-filtering technique of the Segment Tracing Algorithm (STA) may be utilized (Koike et al. 1995). The principle of the STA is to detect a line of pixels as a vector element by examining local variance of the grey level in the digital image and to connect retained line elements along their expected directions. The threshold values for the extraction and linkage of line elements are direction dependent. The advantages of the proposed method over usual filtering methods are its capability to trace only continuous valleys and extract more lineaments parallel to the sun's azimuth and located in shadow areas (Koike et al. 1995). Raghavan et al. (1995) combined the STA method with the Hough Transform to scan a line-element image in

Table 4 Lineament detection utilizing automatic method

Author	Imagery/scale	Place	Type of studies	Automatic methods
Cross (1988)	Landsat TM	Egyptian/Sudanese border	Lineament testing	Hough transform
Wang and Howarth (1990)	Landsat TM	Canadian Shield	Lineament testing	Hough transform
Koike et al. (1995)	Landsat TM	Kyushu district	Lineament testing	Segment Tracing Algorithm (STA) is utilized. The STA is utilized to detect a line of pixels as a vector element by examining local variance of the gray level in the digital image, and to connect retained line elements along their expected directions. The threshold values for the extraction and the linkage of line elements are direction dependent
Raghavan et al. (1995)	LANDSAT MSS and TM, DEM	Southwestern Japan	Lineament testing	Segment Tracing And Rotation Transformation (START) algorithm adopts a non-filtering approach to detect gray-level boundaries in a digital image. The topographic information revealed by the direction of shadows in digital images is taken into account in the extraction procedure
Karnieli et al. (1996)	Aerial photo	Negev, Israel	Lineament testing	Hough transform
Zlatopolsky (1997)	Radar	Taiwan	Lineament testing	LESSA (Lineament Extraction and Stripe Statistical Analysis) based on textural orientations
Majumdar and Bhattacharya (1988)	ISRO Multispectral Scanner (MSS)	Cambay Basin in India	Lineament testing	Haar transform
Costa and Starkey (2001)	Landsat TM, a topographic map, and aerial photograph	Southeastern Brazil and northwestern Ontario, Canada	Lineament testing	Photolin software where the image file is binarized and segmented using a threshold to identify features of interest. The median axes of the features are located using a thinning algorithm and they are represented as a lineament map
Vassilas et al. (2002)	Landsat TM	Vermion, Greece	Lineament testing	Hough transform
Hung et al. (2005)	Landsat TM and VNIR ASTER	Suoimuoi, Vietnam	Hydrogeology	LINE module of the PCI Geomatica
Hung and Batelaan (2003)	Landsat ETM+	Northwest Vietnam	Environmental geology	Panchromatic fused with multispectral bands LINE module of the PCI Geomatica
Argialas and Mavrantza (2004)	Landsat TM, topographic map, and DEM	Nisyros Island, Greece	Lineament testing	Hough transform
Kocal et al. (2004)	Ikonos	Ankara, Turkey	Structural geology	LINE module of the PCI Geomatica
Mostafa and Bishta (2005)	Landsat ETM+	Gebel Gharib-Dara, Egypt	Mineral exploration	LINE module of the PCI Geomatica
Masoud and Koike (2006)	Landsat ETM+ SRTM	Libyan–Egyptian border	Hydrogeology	A segment tracing algorithm (STA) as in Koike et al. (1995)

order to detect continuous grey-level boundaries and generate their final lineament map. This algorithm was named Segment Tracing And Rotation Transformation (START).

In geological studies, the most popular software is the LINE module of the PCI Geomatica which has a similar approach to STA and has been used in hydrogeological, environmental, structural and mineral exploration studies (Hung and Batelaan 2003; Kocal et al. 2004; Hung et al. 2005; Mostafa and Bishta 2005; Sarp 2005). With automated extraction, an understanding of the parameter setting for lineament extraction optimization is crucial (Mostafa and Bishta 2005; Sarp 2005). Sarp (2005) compared the accuracy achieved by manual and automatic lineament extraction and found that the reliability of the automatic extraction in identifying faults was much lower than with manual interpretation.

Not surprisingly, none of the landslide hazard assessments reviewed utilized automatic lineament mapping; indeed, as seen in Tables 1, 2 and 4, at present more researchers use manual extraction and automatic extraction is generally only used for testing purposes.

In addition to being relatively less reliable than manual interpretation, another reason why automatic extraction is less frequently used is that the program for automatic lineament mapping is still not widely embedded as an option or part of the image processing in commercial remote sensing software. Only PCI Geomatica bundled the automatic lineament extraction, which is probably the reason it is so popular in automatic lineament extraction. It is likely that the automatic lineament program will become more popular if it is available as an option inside general remote sensing software packages rather just with standalone software. It is obviously much easier for the user to just complete the process within an already familiar remote sensing environment and the time taken for researchers to become familiar with a new software environment is undoubtedly a hindrance. In addition, incorporation into general remote sensing software would reduce the need for data conversion as new software frequently only accepts its own image format for a standalone software.

As noted above, automatic mapping requires an understanding of the complex parameter setting that needs to be used in lineament extraction. Adjustments and proper settings are essential so that the optimum parameters are utilized in different illumination conditions and also in different terrain (Argialas and Mavrantza 2004; Kocal et al. 2004). The variation in the parameter settings chosen by different researchers may also reduce the objectivity of the interpretation. Most of the previous studies utilizing automatic lineament detection have considered the evaluation of the optimum parameter to be utilised in the lineament mapping algorithm (Table 4).

In summary, the automatic method seems still in its early stages compared with the manual method and Gustafsson (1994) found it could not identify false lineaments related to roads, power lines and other man-made features which are time consuming to edit.

Lineament and landslide hazard map

Landslide hazard assessment is considered as one of the main aspects of landslide management and can assist in proper urban development and land use planning, avoiding or regulating development in areas which are prone to landslides.

Only a brief discussion on landslide susceptibility or hazard assessment is given here, as the main intention of the paper to discuss the application of lineament mapping and not the landslide susceptibility or hazard assessment itself. For an excellence discussion on landslide hazard assessment, the reader's attention to drawn to Aleotti and Chowdhury (1999), Dai et al. (2001), Van Westen et al. (2006) and Chàcon et al. (2006).

It is appreciated that there is a difference between hazard and susceptibility maps; the term hazard including the likelihood of the occurrence of a landslide where triggering variables are considered, while the susceptibility map does not includes the triggering variables (Dai et al. 2002). Strictly following these definitions, the terms susceptibility and hazard should not be used synonymously, as often observed in literature (Parise 2001). However for ease of discussion, only the term landslide hazard will be utilized in this paper.

One of the main aspects in landslide hazard assessment is the combination of pre-disposing factors that contribute to landslide occurrences. The determining factors may be grouped into two categories: (1) the intrinsic variables that contribute to landslide susceptibility, such as geology, slope gradient, slope aspect, elevation, soil geotechnical properties, vegetation cover and long-term drainage patterns; and (2) the extrinsic variables or triggering variables that tend to trigger landslides in an area of given susceptibility, such as heavy rainfall and earthquakes (Dai et al. 2001). It is believed that the accuracy of susceptibility mapping increases when all determining parameters are included in the analytical process; however, in reality this is rarely achieved because of the difficulty of obtaining all these data (Ayalew et al. 2004) and/or the data are available at very low resolution or at very high cost (Conoscenti et al. 2008).

The most common factors that are incorporated to represent geology in landslide hazard assessment are lithological and structural information on the study area. Generally, a very accurate lithology map is relatively easier to prepare (and more commonly available) than a structural geology map, but the structural geology of the particular area is known to be one of the main controlling factors in landslide occurrence (Cooke and Doornkamp 1990). Structural discontinuities such as joints, faults, foliation and bedding planes form the pre-existing lines of weakness in a rock body. These lines of weakness, often in a fractured zone, are likely to be areas where moisture accumulates and vegetation grows. In addition to indicating lineaments, they affect surface material structures and have a significant influence on terrain permeability and thus slope stability (Nagarajan et al. 1998, 2000; Gomez and Kavzoglu 2005). The presence of moisture will also increase the rate of weathering, further exacerbating the problem of instability. The weak areas commonly are opened up and enlarged by erosion and some may even become small valleys (Ali and Pirasteh 2004). The weakness of this line is demonstrated in semi- arid areas where weathering is concentrated around the lineament (Carruthers et al. 1991 in Gustafsson (1994)).

It is still not common for detailed structural mapping to be undertaken as part of a landslide hazard assessment. Ideally this would involve a detailed survey of the orientation of structural features, but the high cost and difficulty/lack of accessibility to reasonably unweathered outcrops (especially in tropical countries) are significant deterrents. Many other factors, such as rainfall, land use, landslide distribution and landform mapping should also be incorporated, hence landslide hazard assessment is laborious and time-consuming, especially when manual handling and processing of the data is required (Dai et al. 2001). As a consequence, a pragmatic approach has to be taken, with a certain "give and take" in balancing the parameters incorporated and the accuracy achieved.

One way of incorporating the structural elements in landslide hazard assessment is by lineament mapping. Although lineament pattern has been shown to be well correlated with landslides (e.g. Atkinson and Massari 1998; Nagarajan and Khire 1998; Nagarajan et al. 2000; Temesgen et al. 2001; Saha et al. 2002; Ambrosi and Crosta 2006; Lee and Lee 2006; Pradhan et al. 2006; Yilmaz and Yildirim 2006), it is not clear whether lineaments presumed to be of geological origin play an active or passive role in the slope movements, i.e. whether they coincide with a zone of stress concentration, or are simply a zone of weak rock (Ambrosi and Crosta 2006).

It is widely observed in the Himalayas that landsliding phenomena are particularly severe close to regional geological lineaments (Pachauri and Pant 1992; Mathew et al. 2007). However, the relationship is confusing as in some (other) areas, lineaments do not appear to be the main controlling factor. Dai et al. (2001) and Dai and Lee (2002) did not use structural information in their study of hazard assessment in Lantau Island, Hong Kong because the spatial distribution suggested that the correlation between landslides and mapped linear structural features is not good. Many other landslide hazard assessments which did not include structural information have also been reported, e.g. Barredo et al. 2000; Dai et al. 2001; Dai and Lee 2002; Ohlmacher and Davis 2003; Perotto-Baldiviezo et al. 2004; Ermini et al. 2005; Ercanoglu 2005; Guzzetti et al. 2006; Conoscenti et al. 2008; Nefeslioglu et al. 2008; Thiery et al. 2007 (see Table 5).

In view of the complex inter-relationships involved in landslides, it is perhaps not surprising that the causative factors included in landslide hazard assessments are not consistent between researchers (Rautela and Lakhera 2000). Clearly, there is no general agreement on the scope, techniques and methodologies for landslide hazard evaluation (Guzzetti et al. 1999) as in some areas a certain factor is important while in another region it is not so significant (Nefeslioglu et al. 2008). Thiery et al. (2007) stressed that the inclusion of more detailed structural maps (fault and tectonic maps) would give more accurate results. However, where the scale is more than 1:10,000 and for large, complex environments, structural features may be extremely difficult to record because of their spatial variability.

Some of the difficulties involved in preparing detailed structural maps may be overcome by utilising lineament mapping. Lineament studies may help reveal generalities that may assist in understanding the cause of landslides (Ayalew and Yamagishi 2005); most medium to large scale landslides studies tend to focus on general aspects of each of the pre-disposing factors.

Where reliable published structural mapping does not exist, large scale lineaments are commonly extracted through visual interpretation of digital satellite imagery (Fourniadis et al. 2007). The fault patterns provide basic information about tectonics, because many faults and crustal fractures correspond with lineaments (Koike et al. 1995). A review of the incorporation of lineament information in landslide studies has shown that the most popular representation of lineament analysis is the lineament (or fault or structural) buffer (Table 1) with only Atkinson and Massari (1998), and Sarkar and Kanungo (2004) utilizing lineament density and Pachauri and Pant (1992), Pachauri et al. (1998) and Süzen and Doyuran (2004) using both lineament buffer and density.

The distance of the buffer zones chosen varies from as small as 5 m (Nagarajan et al. 2000) up to 2,000 m (Pachauri and Pant 1992). Although most researchers did not given their reasons for selecting a particular distance for the buffer zone, a few explained their choice (Table 1) was based on such factors as: field evidence of the extent of fragmented rock either side of the fracture itself (Nagarajan et al. 2000); the maximum landslides were observed to be within the determined distance from a lineament (Temesgen et al. 2001); an average threshold based on a comprehensive assessment of the distance of slope failures from mountain scarps, topographic breaks and any other linear futures (Ayalew and Yamagishi 2005); proximity of existing landslides to lineaments (Mathew et al. 2007); field observation of such effects as nappes, thrusts and strike-slip faults (Ruff and Czurda 2008). The latter authors reported nappe thrusts were observed in the field as 10–100 m broad thrust zones within which the bedrock was tectonically stressed and highly unstable while minor thrusts and strike slip faults indicate fault zones only a few meters wide. Lee (2004) gave convenience of calculation as the reason for choosing the buffer distance when producing a landslide hazard assessment in Boun, Korea; this may also be the explanation for the choice made by researchers who did not give a reason.

Apart from the lineament buffer, lineament density is also used in landslide hazard assessment (Atkinson and Massari 1998; Pachauri et al. 1998; Sarkar and Kanungo 2004; Süzen and Doyuran 2004) as it is generally considered the probability of landslides occurring is greater in highly fractured areas (often associated with thrusts and folds; Cortes et al. 2003) compared to those with a lower fracture density. Morelli and Piana (2006) recognized two distinct lineament density patterns in Monferrato, Italy: a high density of long lineaments could correspond to long major fault zones/deep tectonic structures; and short lineaments, especially if widely distributed, are likely to be associated with poorly defined areas where movement at various times has resulted in "overprinting"/superimposition of several structures.

Lineament density has also been used widely in groundwater studies because of the relationship between fractures and sub-surface permeability (Raju and Reddy 1998; Lee 2003; Andreas and Allan 2007; Münch and Conrad 2007; Srivastava and Bhattacharya 2006) which will increase the probability of landslides occurring. In groundwater studies, however, lineament density is a positive effect because of the secondary porosity associated with joints and fracture density (Sree Devi et al. 2001) and the correlation between a high density of lineaments and good groundwater potential (Raju and Reddy 1998).

It is often not clear why different researchers have used lineament buffer, lineament density or both. This may be simply convention in that particular area. However, it would appear that utilizing both lineament buffer and density may both produce a more accurate landslide hazard assessment and also introduce more uncertainty. The significance of using either one or both factors when undertaking hazard mapping would be a useful topic for further study.

Apart from those reported by Atkinson and Massari (1998), Lee (2004), Gomez and Kavzoglu (2005), Lee and Lee (2006) and Fourniadis et al. (2007), most of the studies undertaken included some form of field checking to reduce some of the "uncertainty" in lineament mapping (Table 1). Field checking is crucial in lineament mapping as "false" lineaments such as roads, field boundaries or other man-made features can be mistakenly identified. Nagarajan et al. (1998, 2000) and Rautela and Lakhera (2000) checked the lineaments in the field. Pachauri et al. (1998) only used lineaments which conform to major faults. Limited field verification was also undertaken by Pachauri and Pant (1992), Temesgen et al. (2001) and Sarkar and Kanungo (2004). Saha et al. (2002) and Saha et al. (2005) checked their results against major known thrusts but did not actually check the lineaments in the field. A combination of published maps and ASTER and DEM derived from the 1:50,000 topographical map was used by Liu et al. (2004) while Süzen and Doyuran (2004) verified their work against the geological map, aerial photos and field mapping. Aerial photos at a scale of 1:20,000 and field verification was also used by Ayalew and Yamagishi (2005).

Perhaps the choice of different methods was related to budget constraints and/or field conditions; some studies only used current geological or structural maps (e.g. Pistocchi et al. (2002), Lee and Jasmi (2005), Lee (2005), Van Den Eechaut et al. (2006) and Kim et al. (2006). However the user must aware that some of the geological maps, especially in developing countries have not been updated. For example in Malaysia, some of the geological maps have not been reassessed since 1985 and the original map was based on aerial photo interpretation which could not be field checked due to thick vegetation. From the authors' experience, the geological map published by the Malaysian Mineral and Geosciences Department (1985) showed the stretch of highway from Simpang Pulai to Pos Selim to be on granite, but field observations after the hillslope had been excavated for the highway construction proved some areas of metasedimentary rock.

It is suggested that lineament mapping is updated either by aerial photo or satellite imagery, ideally followed by field mapping. In reality, however, cost and the lack of availability of fresh outcrops may hinder the field verification. If the lineament been interpreted using satellite imagery, it is crucial that it is subjected to some form of field verification, or at least cross-checked with the geological map in order to reduce the uncertainty, which will affect the quality of the landslide hazard assessment.

Discussion and conclusions

Manual mapping of lineaments requires a high degree of skill and experience in the visual interpretation process and being to a large extent subjective, has limited

Table 5 The application of landslide susceptibility/hazard assessment without using lineament analysis

Author	Place	Comment on the geological information used
Anbalagan (1992)	Himalaya	Used detailed structural discontinuities within slope Lithology is used
Barredo et al. (2000)	Gran Canaria Island, Spain	Only used material types which are classified into bedrock, alluvial–colluvial deposit, residual soil and landslides deposit
Dai et al. (2001)	Lantau Island, Hong Kong	Lithology is used. Qualitative examination of spatial distributions suggests that the correlation between landslides and mapped linear structural features is not good, thus the structural information is excluded in this study
Gritzner et al. (2001)	Payette River, Idaho, United States of America	No geological information is used because the geology and soil characteristics are relatively homogenous
Dai and Lee (2002)	Lantau Island, Hong Kong	Only lithology is used. The structural information is not used because the correlation between landslides and mapped linear structural features at the 1:20,000 scale is not good
Ohlmacher and Davis (2003)	Northeastern Kansas, United States of America	Only lithology is used
Alcantara-Ayala (2004)	States of Puebla, Veracruz and Hidalgo	Only lithology is used
Ayalew et al. (2004)	Niigata prefecture, Japan	Only lithology is used because of lack of data
Perotto-Baldiviezo et al. (2004)	Namasigue and El Triunfo watersheds, Honduras	No geological information is used because of the unavailability of the data
Can et al. (2005)	Western Black Sea Region of Turkey	Only lithology is used
Ercanoglu (2005)	West Black Sea region of Turkey	No geological information is used because landslides occurred only in one lithological unit
Ermini et al. (2005)	Northern Apennines, Italy	Only lithology is used
Gomes et al. (2005)	S.Miguel Island, Azores	Only lithology is used
Dymond et al. (2006)	Manawatu–Wanganui, New Zealand	Only lithology is used
Guzzetti et al. (2006)	Umbria, Italy	Only bedding orientation is utilised
Conoscenti et al. (2008)	NW Sicily, Italy	Only lithology is used because this study involves flow and rotational slide landslides only, excluding falls and translational slides that affect carbonate slopes and fluvial scarps (i.e. these landslide typologies would require knowledge of structural data)
Coelho-Netto et al. (2007)	Rio De Janeiro, Brazil	Only lithology is used
Domínguez-Cuesta et al. (2007)	Northwest Spain	Only lithology is used
Saldivar-Sali and Einstein (2007)	Bagiou, Philippines	Only lithology is used
Thiery et al. (2007)	Barcelonnette Basin, France	Only lithological data and thickness and bedding map are used
Budetta et al. (2008)	Cilento region, Italy	Attitude of bedding planes (P4) and structural jointing is used
Conoscenti et al. (2008)	Northwestern Sicily, Italy	Only lithology is used
Nefeslioglu et al. (2008)	Eastern Black Sea region, Turkey	Only lithology is used

reproducibility (Gupta 1991; Mabee et al. 1994; Warner 1997; Hung et al. 2005; Gomez and Kavzoglu 2005). The advancement of technology has allowed the interpretation to be undertaken automatically and with more objectivity. In addition it is quicker than the manual technique, which is very time consuming especially if regional mapping is concerned (Masoud and Koike 2006). However, the manual method has the advantage of a high degree of fault tolerance and the operator can learn to re-check and distinguish true geological lineaments from non-geological features such as roads, railway lines, power-cables, canals and crop-field boundaries such that, with skill and experience, these will be omitted from the interpretation (Richetti 2001; Ali and Pirasteh 2004; Kocal et al. 2004; Yassaghi 2006). A comparison between the manual process (visual interpretation) and automatic interpretation is in Table 6.

Table 6 Comparison between visual and the automatic (digital) lineament extraction methods after (Zlatopolsky 1997; Hung et al. 2005 and Yassaghi 2006)

Visual process	Digital process
Depends on the quality of the performance of the image (on paper and/or screen)	Depends only on the quality of the image
Partly depends on the complexity of the research area	Totally depends on the complexity of the research area
Strongly dependent on human experience and ability	Totally depends on the mathematical function of the software
Takes a lot of time	Very quickly
Strong effect of human subjectiveness	Little effect of human subjectiveness
Easy to distinguish type of lineament (tectonic origin or man-made)	Cannot recognize the type of lineament, so the result may be confused
Simple but subjective method	Complex but objective
The operator can learn	Training areas such as training for algorithms
Non-uniform approach to different images	Uniform approach to different images

It is anticipated that in the near future lineament mapping will be increasingly used in landslide hazard assessment, especially for moderate and small scale studies. The price of satellite imagery such as Landsat, ASTER and SPOT, Quickbirds and Ikonos is expected to decrease while the cost of the relevant software and easy access of global positional system technology will definitely reduce the cost of this form of lineament mapping.

Concurrent with this trend, it is likely that there will be more studies utilising not only moderate resolution imagery but also high resolution imagery for lineament studies. However, until automatic lineament mapping is more widely available as an option within the commonly used remote sensing software, the manual technique will remain popular. In addition, until automatic processing can take into account such factors as texture, pattern and shape (which may be important in lineament detection), user observation will probably continue to provide the best results (Sarp 2005).

Although it is understood that there are many other factors which need to be taken into account in landslide assessment, it is considered that lineament interpretation has a vital role to play and is probably worth more effort in terms of its interpretation. It is suggested that before lineament interpretation is undertaken, the drainage pattern is first analysed so that general lineament pattern of the area is known. The user should also be aware of the advantages and disadvantages of manual and automatic lineament extraction. If manual interpretation is chosen, efforts should be made to reduce the subjectivity inherent in this method, while with automatic lineament mapping, care must be taken in the selection of the parameters to be used. In both cases, ground-truthing should be undertaken.

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