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Satellite remote sensing for detailed landslide inventories using change detection and image fusion

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The availability of high spatial and spectral resolution remote sensing systems may be accompanied by changes in techniques for applying the data if appropriate data processing methodologies can be demonstrated. Landslide monitoring, which requires large areas to be surveyed at a detailed level, has previously been unsatisfactory due to its reliance on air photograph interpretation. This study demonstrates the synergistic use of medium resolution, multitemporal Satellite pour l'Observation de la Terre (SPOT) XS, and fine resolution IKONOS images for landslide inventories. The post-classification comparison method of change detection using the Maximum Likelihood classifier with SPOT XS images was able to detect approximately 70% of landslides, the main omissions being those smaller than approximately half a pixel wide. The visual quality of images obtained from Pan-sharpening of IKONOS images was comparable to that obtainable from 1 : 10 000 scale air photographs, enabling detailed interpretation of landslides and associated environmental features. A methodology combining the two levels of survey is proposed for regional scale landslide monitoring.

1. Background

Most of the Hong Kong Special Administrative Region (HKSAR) can never be built on because of landslide hazard. The Hong Kong government has established the Geotechnical Engineering Office (GEO), which has created the Natural Terrain Landslide Inventory (NTLI): a database of past landslides and their characteristics. The inventory is based mainly on the study of medium (1 : 20 000) scale aerial photographs and documents a total of over 26 000 landslides that have occurred in Hong Kong since 1945. Accuracy assessments using larger scale air photographs indicate that 80% of Hong Kong's landslides can be identified (Evans *et al.* 1997) but almost all, if multiple scarps are recorded as one. Since the early 1990s larger (1 : 10 000) scale colour air photographs have been used. This, as well as discussions with GEO staff, indicate that the accuracy in recent years is approaching 100%. These air photographs are flown annually by the Lands Department, and provided free of charge, as prints, or softcopy orthorectified mosaics, to all government departments for a variety of uses, as well as to the GEO for landslide monitoring.

With such high quality data available, there is little need for other more, or equally efficient methods for landslide monitoring in Hong Kong. However, most neighbouring Asian countries are undergoing rapid development, much of it in

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mountainous landscapes similar to those in the HKSAR, but do not have the resources, and are too large, to obtain regular air photograph cover. A cheaper and faster methodology based on satellite imagery would therefore be useful for such countries, as well as to supplement air photograph-based methods in Hong Kong, if the results were of comparable accuracy.

The high quality of landslide data in the HKSAR recommends its use as a reference for the testing of other more cost- and time-effective inventory methods. Thus the main objective of this study is to evaluate satellite imagery as a substitute for large to medium scale aerial photographs for landslide inventories, using the existing Hong Kong landslide database as a reference. The techniques used include change detection for automated landslide mapping using multi-date Satellite pour l'Observation de la Terre (SPOT) images, and image fusion of IKONOS images for improving the spatial resolution while retaining the spectral data quality.

1.1 *The need for landslide inventories*

There are two approaches to the generation of landslide hazard maps: simple inventories and multivariate models. Simple inventories are based on the premise that an area where a landslide occurs is a landslide-prone area. Thus inventories showing the locations of past landslides are the basis for most hazard zoning techniques (Evans *et al.* 1997) and can be used as a form of elementary hazard map. Multivariate models combine inventories with other data, allocating weightings to environmental parameters such as slope, land cover and geology based on the known frequency of past landslides associated with those parameters (see, for example, Nagajaran *et al.* 1998, Odajima *et al.* 1998, Saha *et al.* 2002). However, their application over large areas, and in developing countries, is limited by the non-availability of environmental data. If simple inventories can be derived from satellite sensor data, this may be a more feasible approach for regional scale studies.

1.2 *Previous satellite-based studies*

The lack of fine resolution satellite data until recently has confined most satellite-based landslide studies to regional scale assessments. For example, Röessner *et al.* (2002) give an overview of platforms and sensors for monitoring large landslides in Central Asia. They emphasize the importance of developing automated techniques for landslide detection based on multitemporal images. However, apart from Yamaguchi *et al.*'s (2003) use of multitemporal SPOT data to detect slow movement in a large landslide, there is currently no research supporting the multitemporal approach for regional scale mapping. Furthermore, there is no evidence that modern high-resolution satellite images are able to replace air photographs for interpreting landslides at detailed level. For example, Marcelino *et al.* (2003) were only able to identify landslides 'a few pixels wide' (i.e. a few tens of metres wide) using SPOT and Landsat images. Petley *et al.* (2002), using Landsat ETM+ images in the Himalayas, were only able to identify 25% of the total number of landslides, i.e. those over 50 m wide, even when the multispectral bands with 30 m resolution were Pan-sharpened to a resolution of 15 m. Furthermore, although the authors state that high resolution satellite sensors show the potential for delineation of small landslides, they are only able to visually identify slides over 10 m wide using IKONOS panchromatic images with 1 m spatial resolution.

This would suggest that satellite sensors, even those with 1 m spatial resolution such as IKONOS are not suitable for landslide mapping in Hong Kong where 80% of landslides are less than 10 m wide (Evans *et al.* 1997). Since such landslides may be as long as 200 m and can be very destructive due to down-slope acceleration, they should be included in landslide inventories. Thus, there is a need for a technique or data source that can enable such small landslides to be identified over large areas, i.e. at regional scale.

2. Objectives

The present study aims to demonstrate:

(i) the identification of small landslides using automated change detection techniques with medium resolution SPOT images, and
(ii) that IKONOS satellite images can provide a similar level of spatial and spectral detail as available on aerial photographs for the qualitative interpretation of landslides and their associated features, and that this high level of detail can be provided by image fusion.

3. Study area and images

The study area is a 36 km^2 landslide-prone area on Lantau island, Hong Kong. It is used as a test-bed for the development of the methodology. The terrain is steep and mountainous, attaining heights of over 800 m only 3 km inland from the coast (figure 1). The vegetation comprises lowland forest in the valleys with shrub and grassland at the higher levels and on ridges and summits. Since summits, steep slopes and rock outcrops are only sparsely vegetated, there are many areas spectrally similar

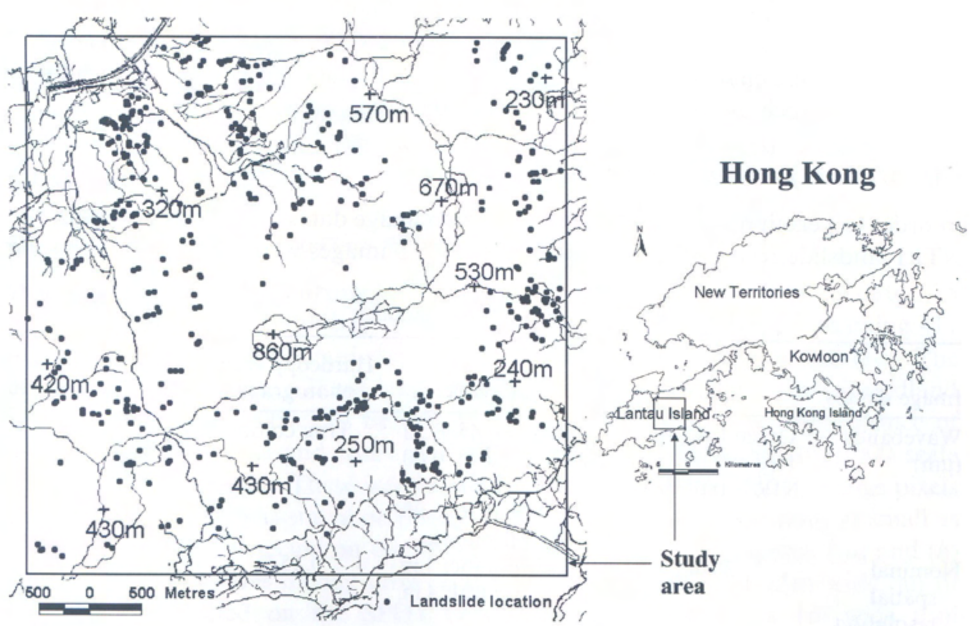

Figure 1. Location of study area in Lantau Island, Hong Kong, and the distribution of landslides during the study period, 1991–1995, and terrain elevations.

to landslides, making it impossible to identify landslides spectrally on a single date image. Geologically the area consists of volcanic tuff and lava of Jurassic age.

For this area, two wintertime SPOT images, of 21 December 1991 and 5 February 1995, were obtained (table 1). The images pre- and post-date a serious rainstorm-induced landslide event of November 1993, wherein 551 landslides occurred. Although re-vegetation of landslide tracks may be rapid, and experience from Hong Kong (Evans *et al.* 1997) suggests that on average, landslide tracks are 70% re-vegetated after 5 years, the landslide event occurred only 15 months before the date of the second SPOT image.

An IKONOS image of January 2003 was also obtained for the second part of the study on image fusion. Since IKONOS is a new sensor it was not operating in 1993 at the time of the landslide event studied on the SPOT images, therefore its evaluation was based on more recent landslides in the study area. Colour aerial photographs were available at dates close to both sets of satellite images to verify and compare the capabilities of the satellite data (table 1).

4. Change detection using multi-date SPOT images

Since the study area is a natural area, 80% within a country park, any change in land cover from vegetation to rock or soil between the two image dates may be assumed to be due to natural earth movements such as landslips and landslides. Contextual indicators used in traditional landslide interpretation from air photographs such as position, shape, direction and shadow are not necessary in the automated approach. Thus the task of identifying landslides may be simplified to mere detection using the tonal change of single pixels between image dates. Moreover, since contextual indicators require many ground resolution cells for interpreting a landslide in its environmental setting, sensors with large pixel sizes are unable to identify small landslides. However, change detection is based on single change pixels and can operate at pixel or even at sub-pixel level given high contrast between the object (landslide) and its background. Planning data in a GIS are available to verify the assumption that change pixels that are not actually landslides are due to human development such as roads and buildings in the study area.

4.1 *Methods for change detection*

In order to permit direct comparison of the two image dates and for overlay with the NTLI landslide records, the 1991 and 1995 SPOT images were orthorectified to the

Table 1. Image details.

Image details	SPOT	IKONOS	Hardcopy aerial photographs	Digital orthophotograph
Wavebands (μm)	Green 0.43–0.47 Red −0.50–0.59 NIR −0.61–0.68	Blue −0.45–0.52 Green −0.25–0.60 Red −0.63–0.69 NIR −0.76–0.90 Panchromatic	True colour	Blue Green Red
Nominal spatial resolution	20 m	Panchromatic: 1 m Multispectral: 4 m	0.25 m	0.35 m
Date	21 December 1991 5 February 1995	28 January 2003	20 December 1994	4 November 2002

Hong Kong 1980 Grid Coordinate System using the rational functions method in PCI Geomatica's OrthoEngine (Tao and Hu 2001). The DEM used in the ortho-rectification was created from contour maps with a 10 m contour interval, and a grid resolution of 5 m. Since the study area is extremely rugged, 350 GCPs were selected for the 1991 image and 460 for the 1995 image, from a range of elevations in the landscape. A root mean square error (RMSE) of 0.5 pixel was achieved for each image.

Methods for change detection are generally regarded as being of two types: image subtraction and post-classification comparison. For this study, several methods within each type were tested, including subtraction of single bands and band ratios, and post-classification comparisons using the Neural Network classifier and the Maximum Likelihood classifier (MLC). Overall the method of post-classification comparison using the MLC was found to be the most accurate and objective when the results were compared with the landslides recorded in the NTLI database over the same time period. For the MLC, all significant land cover types in the image were designated as classes, including shadow, which was a significant component of the images due to the steepness of terrain combined with the low Sun angle in winter. Its inclusion as a class reduced the classification confusion between dark shadowed areas and forest and water which had similar spectral characteristics. The overall classification accuracy was assessed by comparison of 100 random sample points with the orthorectified air photographs, and the overall class accuracies were 85% for the 1991 classified image and 87% for the 1995 classified image. The classified images for each date were combined into one file and two change images were created representing pixels that changed from grassland to soil, and those that changed from woodland to soil over the time period. This was done for each pixel using the following conditional filters in ER Mapper:

IF input91 = 'grassland' AND IF input95 = 'soil' THEN output = 'grassland_to_soil'

IF input91 = 'woodland' AND IF input95 = 'soil' THEN output = 'woodland_to_soil'

The NTLI data showing the positions of landslides were then overlaid onto each change image and the landslides whose crowns and/or trails were seen to be overlapping by more than 60% with change pixels were flagged as successfully detected.

4.2 *Results of change detection of landslides*

Of the 551 landslides occurring in the study area between the two image dates, 75 were in grassland and 59 in bare soil areas on the upper slopes. The remaining 417 occurred in woodland on mid-slopes, which tend to be the steepest (table 2). The detection rate was high: 67% of landslides in grassland areas and 71% in woodland areas were detected. This can be seen in figure 2, which shows the appearance of landslides with crowns and trails of different widths on the same 1 : 10 000 scale colour air photographs. These were matched visually with the SPOT change pixels and their detectability is stated on the figure. Generally crowns and trails as small as 7–10 m width were detected on the SPOT change images. Thus figures 2(*a*) and (*b*) indicate five landslides having crowns and trails between 7 and 13 m wide, all of which were detected on the SPOT change images. However, a 1m wide trail (figure 2(*b*)) was not detected. Thus the threshold of detectability of landslides on the SPOT images appears to be at sub-pixel level.

Table 2. Results of landslide detection on SPOT change images.

Land cover in 1991 by ML Classifier	Landslides by land cover type (by overlay of classified image with NTLI data)	Change detection image	Landslides detected by MLC number (%)
Grassland	75	Grassland to soil	50 (67%)
Woodland	417	Woodland to soil	296 (71%)
Soil/rock	59		

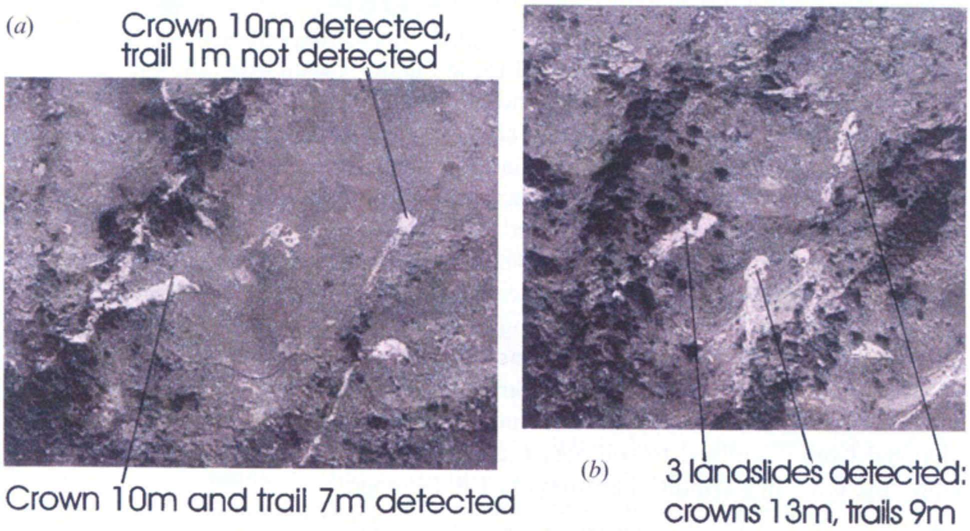

Figure 2. Extracts from 1 : 10 000 scale air photographs showing landslide scars in study area, their width, and their detectability on SPOT change images.

4.2.1 Errors of omission. Errors of omission (those not detected on the SPOT image) are due to small landslides under 10 m in width, e.g. the trail measuring 1m in width on figure 2(*a*). Additionally, the requirement that a pixel or group of pixels should be overlapping by at least 60% with an NTLI landslide in order to be identified, actually excludes some correctly identified pixels that could not be exactly matched, given the unavoidable errors of orthorectification due to the large (20 m) pixel size of SPOT.

Since the NTLI landslides are represented as single lines (figure 3) not areas, the 0.5 pixel RMSE of image rectification means that some pixels representing landslides displaced by up to 12 m from the line representing the true position were not counted. Visual inspection (figure 3) shows that some of these omitted are clearly matched with landslides but do not meet the criteria, and if they were included the detection rate would increase to 80% for grassland and 82% for woodland. Other cases of omission were landslides in shadow areas and those that recurred on the same track, and thus were classed as bare soil on both image dates. Classification errors, especially confusion between grassland and soil may also account for some omissions, but since most landslides are in woodland this is considered to be insignificant.

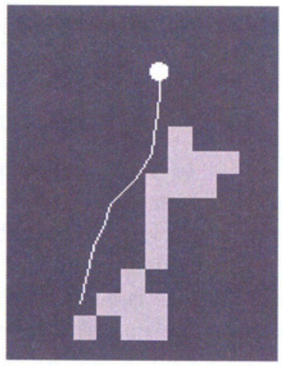

Figure 3. Change pixels on 'woodland_to_soil' image not detected because less than 60% of the landslide crown and trail (from NTLI database) overlaps with change pixels. In this case 0% overlap occurs thus the landslide is not detected.

4.2.2 Errors of commission. Errors of commission (i.e. change pixels which were actually not landslides) were mainly due to human-induced terrain disturbance or building during the study period. Thus some areas with new roads or building development are shown as change pixels, and they represent 'false alarms' in the data. Overall the result, showing approximately 70% of landslides detected by SPOT is surprisingly good given the constraints of the spatial resolution and the relatively small size of landslides in the study area. It can be explained by the very high contrast between landslides and their background, especially in the SPOT green and red bands on these winter-time images, such that the overall reflectance value of a 20 m pixel is 'contaminated' by the small bright feature within it. Additionally, it is due to the 'Point Spread Function' (Mather 1999) whereby light from a very bright ground object may diffuse into surrounding areas.

5. Pan-sharpening of IKONOS images by image fusion

5.1 *Rationale for visual interpretation using fine resolution images*

Traditionally, landslides are visually interpreted in their environmental context using a variety of parameters. This requires higher spatial and spectral resolution than for automated change detection, and generally twice as many Ground Resolution Cells (GRCs) are required for interpretation than for mere detection (Strandberg 1967). The present study shows that the additional qualitative information, similar to that on air photographs can be obtained by Pan-sharpening of IKONOS multispectral images.

5.2 *Images used*

IKONOS by Space Imaging® is one of the new generation of high resolution satellite sensors. Sensor details are given in table 1. The non-nadir look angle of the system makes frequent revisits possible, varying between 1.5 and 3 days according to the spatial resolution. Its currently high cost precludes its use for regular monitoring but the high revisit rate means that images may be available if required, e.g. following major rainstorm-induced landslide events.

A digital orthophotograph dated only three months earlier than the IKONOS image, having spatial resolution of 0.35 m, and in true colour was created. It was used for visual, qualitative comparison with the original and processed IKONOS images.

5.3 *Fusion methods*

The objective of image fusion is to take advantage of the synergy between multispectral images that are of lower spatial resolution, and a single broad (panchromatic) band covering the whole of the visible spectrum that has higher spatial resolution. For IKONOS it is also important to preserve the high (11-bit) radiometric resolution of the data, which is not achieved by some fusion algorithms that were devised for 8-bit imagery such as SPOT. In this study four methods of combining the IKONOS wavebands were tested for achieving the above objectives. They were Intensity, Hue and Saturation (IHS), Brovey Transform, Smoothing filter based modulation (SFIM), and Pan-sharpening by PCI Geomatica. These are briefly described below.

5.3.1 IHS method (Carper *et al.* 1990). The formula for the IHS transform is well known, e.g. Mather (1999). Disadvantages include a limitation to three input bands, and although the 11-bit radiometric resolution is preserved, some colour imbalance results from a mis-match between the image histograms of the intensity component and the panchromatic image that replaces it, since the IKONOS panchromatic band has extended wavelength sensitivity up to 0.90 μm, beyond the red–green–blue (RGB) range.

5.3.2 Brovey Transform method. The Brovey Transform is described by Gillespie *et al.* (1987). Its disadvantages are similar to those of the IHS method, since it makes use of the intensity component of the colour space transform, and the spectral properties of the panchromatic band are also included in the output image bands.

5.3.3 Smoothing filter-based modulation (SFIM) method (Liu 2000). The SFIM method is described by Liu (2000). Unlike the IHS and Brovey methods it can be performed on any number of wavebands. It maintains more of the true spectral qualities than the IHS and Brovey methods because the spectral properties of the panchromatic band are cancelled out by the ratio formula, and only the high spatial resolution edge information is retained.

5.3.4 Pan-sharpening (PCI Geomatica) (Zhang 2002). Like the SFIM method, the pan-sharpening method is more suitable for use with IKONOS images than other methods that assume that the panchromatic band covers only the visible spectrum, and it can operate on more than three bands. The method uses least squares to retain the true greyscale value relationship between the IKONOS panchromatic and multispectral bands. It thus preserves the colour of the original multispectral images as well as the spatial detail of the panchromatic image.

5.4 *Results of fusion: visual*

Figure 4 shows the visual results of the four methods of image fusion, as compared to the digital orthophotograph (figure 4(*b*)). The area is a partially forested slope with grassland at the upper levels (top of image) having two landslides of width 32 m and 19 m. There is an obvious difference in image quality between the original IKONOS multispectral (figure 4(*c*)) and panchromatic images (figure 4(*d*)), and both individually are inferior to the digital orthophotograph. However, all of the fused

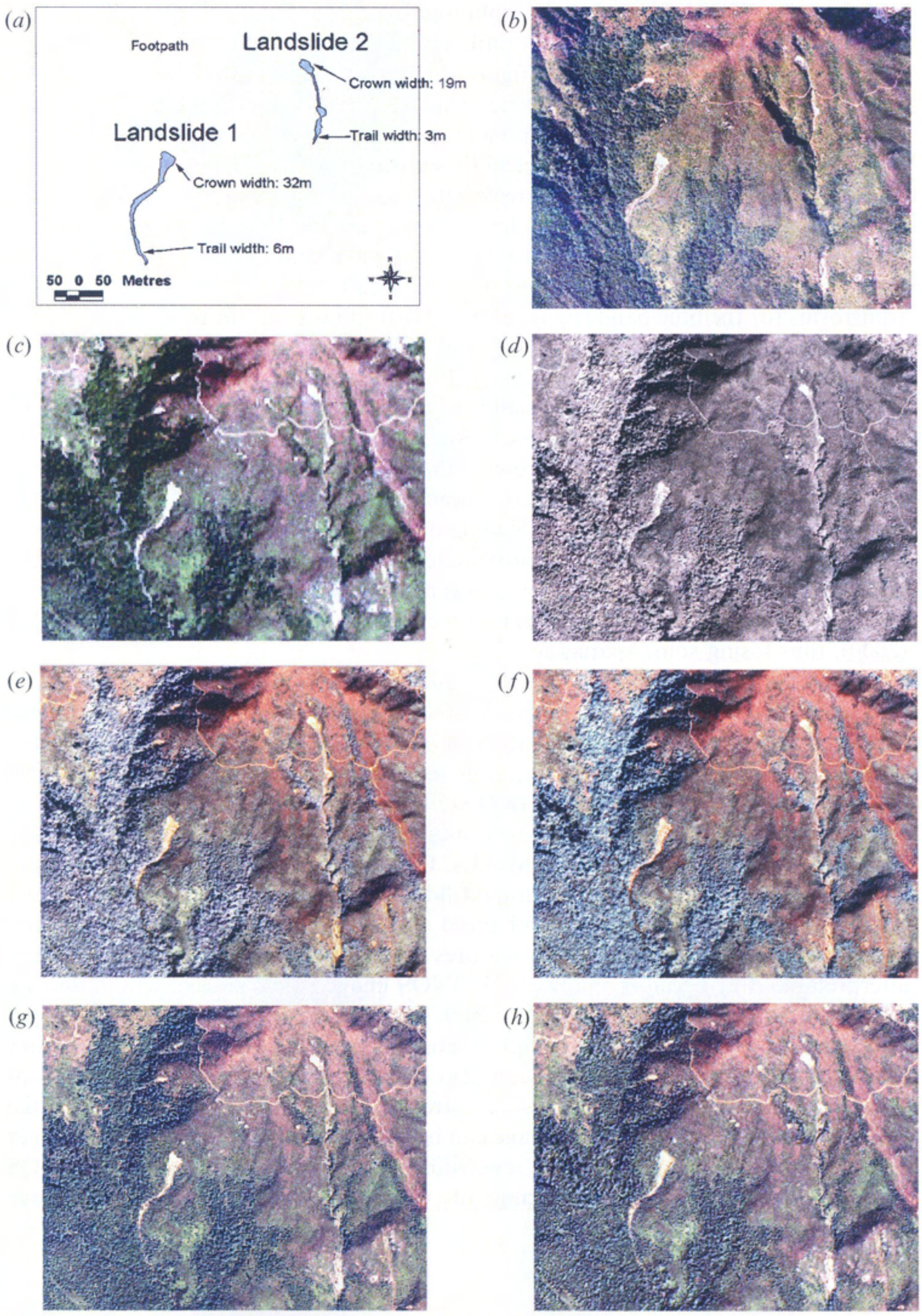

Figure 4. Extract of study area comparing the appearance of two landslides between different images: (*a*) legend; (*b*) orthophotograph; (*c*) IKONOS multispectral image; (*d*) IKONOS panchromatic image; (*e*) IHS fused image; (*f*) Brovey fused image; (*g*) SFIM fused image; (*h*) Pan-sharpened fused image.

images compare favourably in both tonal contrast and spatial definition (sharpness of boundaries) with the digital orthophotograph.

The spectral information content differs between the four fused images. The IHS (figure 4(*e*)) and Brovey methods (figure 4(*f*)) were unable to preserve the spectral information (true colour) of the scene. This is probably due to the histogram mismatch between the intensity component and the IKONOS Panchromatic band, resulting from the extended wavelength sensitivity of the latter. This results in objects such as vegetation, which are sensitive to this extended near-infrared (NIR) region exhibiting boosted intensity levels: in the present case the forested areas of figure 4(*e*) and (*f*) appear blue, since the lowest waveband input to the colour space transform (blue) is extended further. Thus the scatterplots of the IHS and Brovey transforms for the blue band (figure 5(*a*) and (*b*)) show a shift of the dense cluster of pixels, upwards from the leading diagonal and a stretching of the input range (x axis) to a wider output range (y axis). Figure 5(*e*) and (*f*), which represent the scatterplots for the green and red bands of the Brovey transform do not show this shift, and the scatter is more diagonal, especially for the red band.

The SFIM method was able to preserve the spectral (colour) information, with the output bands spectrally the same as the input bands. Thus figure 5(*c*) shows a scatter of image pixels generally along the leading diagonal, with the dense cluster of pixels occupying the same DN range (approximately 200–380) for the x axis (input band) and the y axis (output band). However, this method resulted in an overall smoothing of the image due to its sensitivity to minor co-registration errors, as discussed by Liu (2000), thus losing some spatial detail.

Overall the Pan-sharpened image (figure 4(*h*)) using PCI Geomatica software was judged visually to be the most satisfactory and compared well with the orthophotograph. The scatterplot (figure 5(*d*)) shows a generally diagonal distribution of the dense cluster, with output values occupying a similar DN range (230–350) to the input. In some respects this IKONOS Pan-sharpened image was superior to the orthophotograph. This can be seen more clearly in figure 6 (*a*) and (*b*), which shows an area with many small landslides. On the Pan-sharpened IKONOS image (figure 6(*b*)) the boundaries between landslides and their vegetated background are sharper and the image texture is enhanced e.g. individual tree crowns are clearer, and other small disturbed ground features have a higher contrast and are more interpretable. Furthermore the fused IKONOS image is less subject to shadow: an effect, which is also noted by Zhang (2002). The shadowed area covering the upper right portion of the orthophotograph is absent on the IKONOS image. Features normally requiring stereo viewing can also be interpreted using a combination of shadow, positional relationship to the stream, and lightness of tone; thus the features in the lower right of the image can be identified as multiple crests of former landslides. Additionally the colour spectrum is constant over the whole IKONOS image area whereas the mosaicing of the orthophotograph creates colour discontinuities.

5.5 *Results of fusion: statistical*

The correlation coefficient was used to compare the digital numbers (spectral values) of each fused band with the unfused original band, for each fusion method (table 3). The total of the correlation coefficients for each of three bands is highest for the Pan-sharpening method, meaning that this fused image is the least degraded spectrally by the fusion operation and thus the information contained in it is the highest.

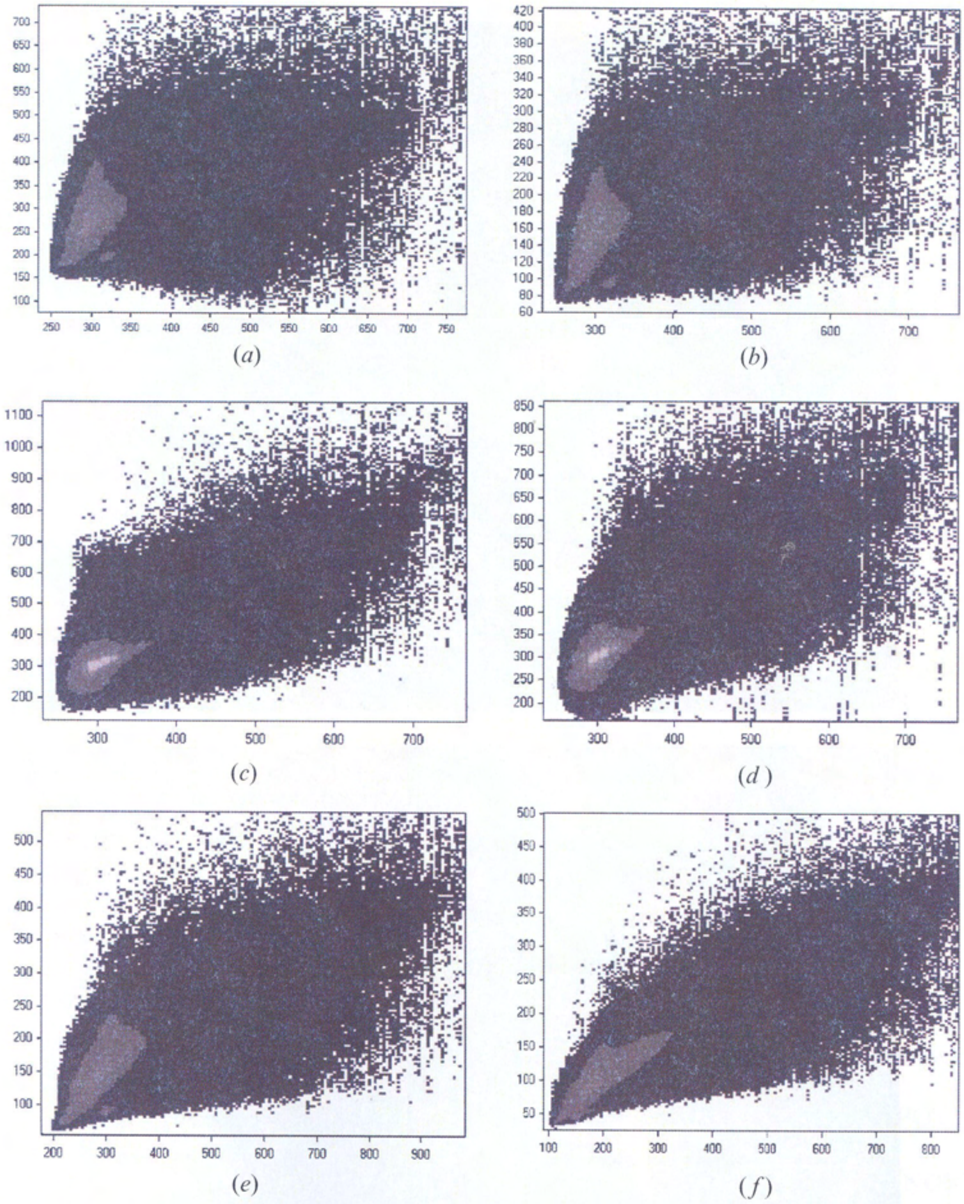

Figure 5. Scatterplots of the raw image data on the x axis and the output (fused) image data on the y axis. Blue band: (*a*) raw versus IHS fused, (*b*) raw versus Brovey fused, (*c*) raw versus SFIM fused, (*d*) raw versus Pan-sharpened fused. Green band: (*e*) raw versus Brovey fused. Red band: (*f*) raw versus Brovey fused.

6. Conclusion

The study demonstrates that satellite images can be used for detailed landslide inventories. Due to the generally high contrast between a landslide and its background, those of sub-pixel width, down to a size of 7 m, can be detected on medium (20 m) resolution SPOT images, with a detection rate of approximately 70%.

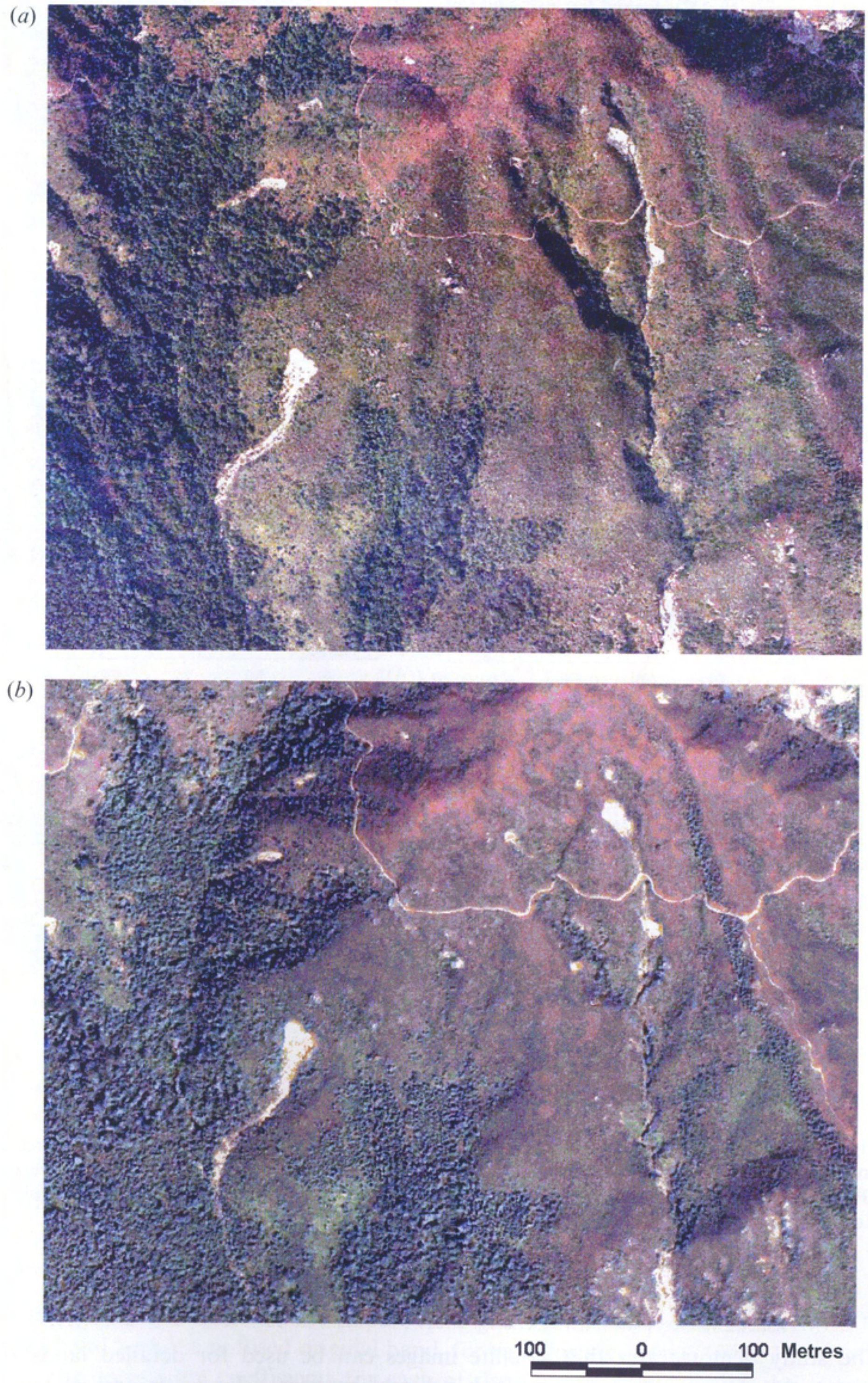

Figure 6. Comparison between (*a*) orthophotograph and (*b*) Pan-sharpened fused images showing landslide scars and patches of disturbed ground.

Table 3. Correlation coefficient for different fused images.

	IKONOS waveband (μm)				
Fusion method	1 (0.45–0.52)	2 (0.52–0.6)	3 (0.63–0.69)	4 (0.76–0.9)	Total (1st 3 bands)
Raw versus IHS	0.82	0.86	0.84		2.52
Raw versus Brovey Transform	0.88	0.84	0.81		2.53
Raw versus SFIM	0.92	0.91	0.91	0.90	2.74
Raw versus Pan-sharpening	0.94	0.94	0.94	0.94	2.82

If multi-date images are available, the task of identifying landslides may thus be simplified to automated change detection in a known context such as remote areas, country parks, or areas where all human-induced changes are recorded in a GIS. This would avoid errors of commission (or 'false alarms'). SPOT multispectral images with 20 m resolution can thus be used to map small landslides over large areas at reasonably low cost, since a single SPOT image covering an area of 60 km × 60 km (approximately the size of Hong Kong) is priced at $US 1200.

Due to the favourable results of image fusion it is possible to substitute high resolution satellite images for air photographs in detailed landslide inventories. The Pan-sharpening method of image fusion permits most of the qualitative (spatial and spectral) parameters used in air photograph interpretation to be available on satellite images. Even those parameters requiring stereo viewing can to some extent be obtained from 2-dimensional satellite images by the use of evidence such as shadow, and positional relationships to streams and ridges, as well as by draping the image over a DEM. Moreover the new generation of advanced satellite sensors, including SPOT, ASTER and IKONOS have stereo capabilities, which should be realized if the cost of images continues to fall. Currently IKONOS imagery of an area 60 km × 60 km. would cost $US 65 000, and twice this for stereo cover. But with reduced data costs, and advances in hardware and software, customized landslide monitoring systems using multi-temporal, stereo satellite imagery are achievable in the near future.

Given the current state of the art, the results of this study suggest a potential scenario for regional scale landslide inventories as follows:

- remote areas are surveyed by multi-temporal change detection using SPOT, for a reconnaissance overview of landslide-prone areas
- this is followed by more detailed mapping and interpretation using IKONOS in areas of immediate interest for development projects.

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References

Carper, W.J., Lillesand, T.M. and Kiefer, R.W., 1990, The use of Intensity-Hue-Saturation Transform for merging SPOT Panchromatic and multi-spectral image data. *Photogrammetric Engineering and Remote Sensing*, **56**, pp. 459–467.

EVANS, N.C., HUANG, S.W. and KING, J.P., 1997, The natural terrain landslide study—Phases I and II. Special Project Report SPR 5/97, Geotechnical Engineering Office, Hong Kong.

GILLESPIE, A.R., KAHLE, A.B. and WALKER, R.E., 1987, Color enhancement of highly correlated images—channel ratio and 'chromaticity' transformation techniques. *Remote Sensing of Environment*, **22**, pp. 343–365.

LIU, J.G., 2000, Smoothing filter based intensity modulation: a spectral preserve image fusion technique for improving spatial details. *International Journal of Remote Sensing*, **21**, pp. 3461–3472.

MARCELINO, E.V., FONSECA, L.M.G., VENTURA, F. and SANTA ROSA, A.N.C., 2003, Evaluation of the IHS and wavelet transform fusion techniques for the identification of landslide scars using satellite data. *Proceedings of the Anais XI SBSR Symposium, Belo Horizonte*, Brazil, 5–10 April 2003 (Brazil: National Institute of Space Research), pp. 487–494.

MATHER, P., 1999, *Computer Processing of Remotely Sensed Images*, 2nd edn (New York: John Wiley & Sons).

NAGARAJAN, R., MUKHERJEE, A., ROY, A. and KHIRE, M.V., 1998, Temporal remote sensing data and GIS application in landslide hazard zonation of part of Western Ghat, India. *International Journal of Remote Sensing*, **19**, pp. 573–585.

ODAJIMA, T., TSUCHIDA, S., YAMAGUCHI, Y., KAMAI, T. and SIAGIAN, Y.O.P., 1998, GIS and remote sensing based analysis of landslide hazards in Cianjur West Java, Indonesia. *Proceedings of International Symposium on Application of Remote Sensing and Geographic Information System to Disaster Reduction (ITIT International Symposium)*, 3–4 March 1998 (Japan: Institute for Transfer of Industrial Technology), pp. 185–190.

PETLEY, D.N., CRICK, W.D.O. and HART, A.B., 2002, The use of satellite imagery in landslide studies in high mountain areas. *Proceedings of the 23rd Asian Conference on Remote Sensing (ACRS 2002)*, Kathmandu, November 2002 (Kathmandu: ACRS).

RÖESSNER, S., WETZEL, H., KAUFMANN, H. and SAMAGOEV, A., 2002, Satellite remote sensing for regional assessment of landslide hazard in Kyrgyzstan (Central Asia). *Proceedings of Second Symposium on Katastrophenvorsorge*, Leipzig, 24–25 September 2001, pp. 433–441.

SAHA, A.K., GUPTA, R.P. and ARORA, M.K., 2002, GIS-based landslide hazard zonation in Bhagirathi (Ganga) valley, Himalayas. *International Journal of Remote Sensing*, **23**, pp. 357–369.

STRANDBERG, C.A., 1967, *Aerial Discovery Manual* (New York: John Wiley & Sons).

TAO, C.V. and HU, Y., 2001, A comprehensive study of the rational function model for the photogrammetric processing. *Photogrammetic Engineering and Remote Sensing*, **67**, pp. 1347–1357.

YAMAGUCHI, Y., TANAKA, S., ODAJIMA, T., KAMAI, T. and TSUCHIDA, S., 2003, Detection of a landslide movement as geometric misregistration in image matching of SPOT HRV data of two different dates. *International Journal of Remote Sensing*, **24**, pp. 3423–3534.

ZHANG, Y., 2002, Problems in the fusion of commercial high-resolution satellite as well as Landsat 7 images and initial solutions. *Proceedings of Symposium on Geospatial Theory, Processing and Applications of ISPRS*, Ottawa, Canada, 8–12 July 2002.