THE USE OF SATELLITE IMAGERY IN LANDSLIDE STUDIES IN HIGH MOUNTAIN AREAS

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ABSTRACT

Landslides represent a serious threat to human life and activities in most high mountain chains. However, due to the difficult nature of such terrain, it is often difficult to assess directly the susceptibility of slopes to landsliding. Hence, remote sensing offers many attractions for the examination of landslide potential in such environments, especially in less developed nations in which resources are stretched and levels of environmental information are limited. However, there is a need to ensure that the techniques are effective, reliable, and offer value for money in terms of the amount and accuracy of data that can be extracted. Using a case-study, this paper compares the applicability of Landsat ETM+ and IKONOS imagery for the assessment of landslide susceptibility in natural terrain. This has been undertaken on the basis of six study areas located in upland areas of Nepal and Bhutan. In each case, the imagery has been used both to directly map landslides and to examine the occurrence of factors that might be important in landslide initiation, such as water seepage. The results from the imagery have been bench-marked using field surveys. The study has demonstrated that at present Landsat ETM+ remains the most cost-effective tool for mapping landslide susceptibility, due to its relatively low cost and high spectral resolution. However, its spatial resolution remains a significant limitation. This limitation is avoided by high resolution, multispectral IKONOS imagery, which finally allows even small landslides to be mapped in detail. However, the more limited spectral resolution is less useful for factor type mapping. Unfortunately, the high cost of this imagery will continue to preclude the development and use of this technique in developing countries.

1. INTRODUCTION

Recent research has demonstrated that in mountain chains undergoing high rates of uplift, landslides are an inevitable and essential environmental process (Petley and Read 1999 for example). Unfortunately this has important implications for humans, who are often adversely affected by landslides. As a result, the delineation of landslides is extremely important, but there is a general recognition that the process is difficult, especially where the slopes are covered in dense vegetation or are cultivated.

This is particularly the case in the Himalayas, where the on-going collision has allowed the generation of a high mountain chain characterised by steep, unstable slopes. The monsoonal climate allows the rapid growth of vegetation, although the environment is considerably altered by the activities of humans, in particular with respect to the drainage pattern and the landuse. Consequently landslides occur throughout the Himalayas. Unfortunately, landslide identification and delineation in this environment is problematic. The high, steep terrain means that the identification of mass movement features is difficult, especially where the features are not presently active. Many slopes are covered in forest or have been terraced for cultivation, meaning that surface forms are hard to identify. Finally, from a practical perspective, access to the mountain areas is hindered by the absence of good quality roads – a Catch 22 situation given that the lack of roads is due in part to the problems associated with landslides.

Satellite remote sensing potentially offers a solution to at least some of these problems. Good quality, multispectral imagery can allow landslides to be identified using a combination of direct inspection and computer-based analyses. The availability of imagery with a sub-metre resolution means that even small landslides are potentially observable. However, research into the use of such techniques for landslide delineation has so far been limited. In this paper, the results of the application of various remote sensing methods for the delineation of landslides in the mountains of Nepal and Bhutan are described, demonstrating the very high potential that these techniques now offer.

2. SATELLITE REMOTE SENSING FOR LANDSLIDE MAPPING

Satellite imagery has been used in the analysis of landslide occurrence primarily through the analysis of colour composites. Several studies have experimented with the use of a true colour composite (TCC) (e.g. Sauchyn and Trench 1978; Greenbaum *et al.* 1996). In most cases the primary restriction has proven to be spatial resolution, with only landslides of approx. 50 m x 50 m or larger being easily resolved. Rather better results were achieved using the 5.8 m spatial resolution of the IRS-1 instrument however (Nagarajan *et al.* 1998).

False colour composite (FCC) images have proven useful in some cases, especially where a landslide scar provides a clear change in the surface properties, such as the removal of forest to expose bare soil. Greenbaum *et al.* (1995) successfully used this technique for the examination of landslides in Papua New Guinea for example. Similar results were also achieved by Rothery (1987) to identify rock avalanche deposits.

Mixed success has been achieved with the use of more complex analyses techniques. For example, Huang and Chen (1991) reported considerable success using a principal components analysis. Kusaka *et al.* (1996) on the other hand used the LANDSAT thermal bands to identify areas of perennially wet soil, which were linked with potential landslides. In all cases, spatial resolution has proven to be a key limitation, and shadows cause considerable problems.

3. THE STUDY SITE

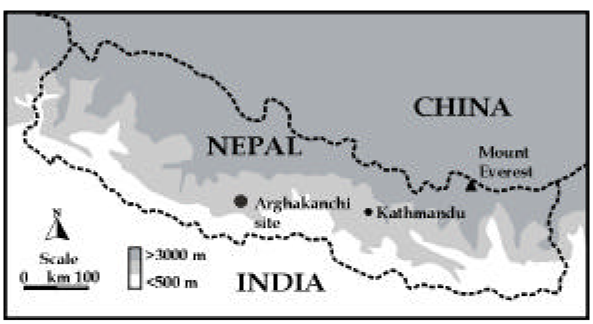

Figure 1: Field site location map

This study has examined the use of satellite imagery in six study areas within Nepal and Bhutan. However, this paper will concentrate upon one of the sites, located within the Arghakhanchi district of Nepal at approx. 83° 10'E, 27° 55'N (Figure 1). The study site has a surface area of 340 km^2, surrounding an existing agricultural road that has been severely affected by landslides. The road is orientated broadly north-south, running across terrain formed from young sedimemts including shales, sandstones, limestones, mudstones; and older metamorphosed rocks including quartzites, and schists. The area is forested, although there are extensive areas of cultivation and some and medium-sized settlements. The relief of the area extends from about 100 m above sea level on the Ganges plain to the south of the study area up to 2500 m in a ridgeline across which the road passes.

4. THE SATELLITE IMAGERY

This study has concentrated on the use of LANDSAT 7ETM+ and IKONOS imagery.

4.1 Landsat ETM+ imagery

A description of the Landsat 7ETM+ imagery can be found in table 1. In general the image is of very good quality, with no visible cloud, haze, distortions or noise. The image was referenced to the local Custom Transverse Mercator (Everest 1830) map projection system using quadratic polynomial rectification. High quality, scanned and mosaiced 1:25000 FinMap topographic maps were used for ground control points. The rectified image was checked against the base map. As the maximum error was 10 m the rectification was deemed to be acceptable. A sub-scene of the image to remove all but the study area was taken for ease of processing.

4.2 IKONOS imagery

IKONOS imagery has been acquired for 100 km² in the centre of the 340 km² study area. The imagery is formed from two north-south orientated, parallel strips (Table 2). Unfortunately, the two strips of data were noticeably difference in contrast and clarity, with strip 2 being considerably clearer than Strip 1. In addition, Strip 1 was affected by haze and had some thick cloud cover (7% of image). Overall however the terrain features were clearly visible, with individual houses, trees, terraces, water courses and roads being easy to identify. In many respects the image was similar to digital black and white aerial photography.

Date/Time of acquisition:		13th December 2000 c.09:30 local time
Path/Row:		142-41
Sun azimuth:		SSE
Cloud cover (%):		1
Bands		**Resolution**
B1	Visible blue	30 m
B2	Visible green	30 m
B3	Visible red	30 m
B4	Near infrared	30 m
B5	Mid Infrared	30 m
B6	Thermal Infrared	60 m
B62	Thermal Infrared	30 m (sub-sampled to 30m from B6)
B7	Mid Infrared	30 m
B8	Panchromatic	15 m

Table 1: Landsat ETM+ metadata

Both images were taken in the late afternoon so shadowing on northern and eastern slopes was a problem, but the shadow on northern, western, southern and south eastern slopes acted to highlight ground morphology. Both strips were georeferenced using quadratic polynomial rectification to the local coordinate system (as per the Landsat imagery) using scanned and mosaiced 1:25 000 topographic maps of the study area. The two images were then combined to form a single image and colour matched by contrast stretching.

Strip 1 (Western)		**Strip 2 (Eastern)**	
Date / Time:	24th January 2000, 17:12 (local)	Date / Time:	19th October 2000, 17:13 (Local time)
Sun Azimuth / Angle:	147°, 36°	Sun Azimuth / Angle:	152°, 48°
Cloud cover:	7%	Cloud cover:	0%
Bands	**Resolution**	**Bands**	
B1 (Panchromatic)	1m	B1 (Panchromatic)	1m

Table 2: IKONOS metadata

5. RESULTS

5.1 Landslide Mapping

5.1.1 Landsat 7 ETM+ Direct landslide mapping has been tested using both the Landsat and the IKONOS imagery. For the Landsat imagery this was undertaken using the false colour composite images. Comparison with the field landslide map suggested that the most effective technique utilises the RGB 457 FCC, pan sharpened using the panchromatic Band 8 and contrast stretched with a 99.9% transform in all bands. A 3x3-edge enhancement filter kernel was applied to increase the contrast. Bare soil in the resulting image varied from light to dark blue depending on light incidence and moisture content, meaning that landslides and areas of erosion were clearly highlighted. These were easy to differentiate from areas of forest (deep red) and cultivation (bright pink/orange). Little difference in colour was noted between landslides and other areas of bare soil. However, morphological evidence could be used to support the classification, including morphology (landslides typically have an arcuate back (upslope) scarp and a convex form) and slope (shadowing assisted in the elimination of areas of flat ground).

Some success was also achieved trough the use of the RGB 542 FCC, created using Pan sharpening from the panchromatic band, and enhanced with a 3x3 edge filter kernel and contrast stretching in each band. This composite highlighted wet, bare soil as blue tones, with increases in moisture content leading to a darkening of the blue colour. Vegetation appeared as a bright green and dry bare soil as brown tones. Thin vegetation representing areas of well-managed paddy cultivation (Khetland) were highlighted as purple colours. Other vegetation was represented by dark green colours and bare ground by deep brown colours. Areas of gravel alluvium were represented by a light pink colour. Water appeared dark blue. The ability to ascertain the soil moisture level of bare soil greatly assisted the interpretation. Best results were achieved where the RGB 542 and RGB 457 FCCs were examined together using a GIS.

The usefulness of a Principal Components Analysis (PCA) approach using an RGB 123 FCC was also tested. Again, this image was pan sharpened to increase clarity. The resulting image exhibited a very diverse range of colours (see fig 2). Areas of bare soils and landslides were particularly distinct and appeared almost white. In contrast to this all other colours were relatively dark. This was particularly useful for resolving relatively small finding small landslides.

Finally, testing was undertaken of the useful ness of the clay ratio, the iron oxide ratio and the Abrams ratio. In the Himalayan region the clay ratio was found to be of limited use as it did not distinguish adequately between vegetation and areas of clay rich soils. The iron oxide performed rather better, clearly differentiating between areas of vegetation and areas of bare soil. However, there was little advantage over the FCC approach. Finally, the Abrams Ratio, which projects the clay ratio, the iron oxide ratio and the NDVI (vegetation) ratio into the red green and blue colour guns respectively, was found to be rather more useful. The resulting image had an extremely diverse range of colours and was very good at distinguishing bare soil types from vegetation. Clay rich soils appear as red colours, whilst iron oxide-rich soils were seen as green colours and vegetation appears as blue. A mixture of iron soils and thin vegetation show as a cyan tone and granite soils with thin vegetation as magenta. Thus, this ratio appeared to give rather promising results and is worthy of further development.

After ground truthing, and through the use of the RGB 457 and RGB 457 FCCs, the RGB 123 PCA and the Abrams ratio a total of 67 landslides were identified from the imagery. The ground mapping detected a total of 388 landslides. Thus, although the imagery allowed the detection of a significant proportion of the total landslide population, more than 75% of the total were not detected. The reasons for this anomaly are:

- Landslides on the shadowed slopes in the imagery were consistently under represented. In areas affected by shadows the unvegetated slopes had a similar appearance to those that had vegetation due to their low reflectance in many of the bands.
- The spatial resolution of the Landsat 7 ETM+ instrument is still too low to allow the detection of many of the smaller landslides. Based upon the results from this study, 50 m remains the smallest landslide width and length that can be resolved confidently using this instrument. Unfortunately, although many landslides have a length in excess of 50 m, their width is very often less than this, such that the slide cannot be delineated.
- The spectral resolution is still not really good enough to be able to produce finely-tuned, high quality FCC images.

However, the results did show that for very large, relict landslides the use of Landsat 7 ETM+ produced better results than did ground mapping. Such very large slides are difficult to detect from the surface, but proved to be very obvious in FCC images.

Based upon the ground mapping and the satellite image interpretation, an analysis has been conducted of the typical spectral range of landslides in the Arghakanchi study area (Table 3). Using an algorithm based upon these parameters, and excluding areas with a slope angle of less 15°, it would be possible to delineate 21 of the 30 active landslides within the study area.

Band number	DN value
1	60-100
2	60-100
3	50-120
4	70-130
5	80-140
6	140-190
7	60-110

Table 3: Active landslide band ranges

The increase in accuracy of this classification was tremendous and 21 of the 30 active landslides were classified. 2 small debris flows were also identified. It also helped in the mapping of areas of erosion, discussed later.
In total 32 landslides were mapped by a combination of the techniques listed below before any ground truthing was completed. After some ground truthing this number was increased to 67 (details of the ground truthing exercise can be found in this section).

5.1.2 IKONOS Due to the high cost, for this study only the 1 m panchromatic imagery was acquired. Of course, this has restricted this part of the study to direct examination of the imagery (Figure 2). The black and white images were plotted onto high resolution paper at a scale of 1:5000 and 1:10 000 and interpreted much the same as regular aerial photography in conjunction with the digital imagery on screen.

Use of the IKONOS imagery proved to be very straightforward. Ridges, valleys and rivers were clearly evident, whilst land cover information such as vegetation type, soil type and rock outcrops were also visible. Areas of bare soil were bright and lighter in comparison with the surrounding darker vegetation, so recent and active landslides were visible. The smallest landslides that could be mapped were in the order of 10m in width and length. Relict (inactive) landslides were much more difficult to spot, and in particular the very large, relict features identified with Landsat 7 ETM+ and in the field were not visible.

Overall because of the crispness of the imagery medium sized recent landslides were mapped very easily. Improvements could be achieved with the availability of stereo images, which would have meant that the imagery is the equivalent of 1:5000 scale aerial photography, which is known to have great potential for landslide mapping.

In total 74 landslides were mapped using the IKONOS imagery, although the imagery covered only 50% of the study area. Thus, the effectiveness of the higher resolution of this imagery is clearly evident, demonstrating that the imagery offers great potential. Indeed, if stereo coverage were freely available the imagery would offer better potential than the standard 1:25 000 or 1:50 000 scale aerial photography.

For the Arghakanchi area multispectral IKONOS imagery were not available. For other study areas this imagery has been acquired. The construction of a FCC improved the visual appearance of the imagery but offered little in terms of improving the ability to resolve landslides, especially in view of the lower spatial resolution. The construction of other FCCs, using the VNIR band, proved to provide little advantage. Unfortunately, the limited spectral resolution remains a problem with the IKONOS instrument. The availability of mid IR and thermal IR bands would potentially improve the instrument very considerably.

5.2 Factor Mapping
Satellite imagery has the potential to allow the identification of factors that are important in the initiation of landslides, such as areas of increased soil moisture content and of disturbed ground. If this is possible,

then the imagery can potentially be used to delineate areas of high landslide susceptibility rather than just those that have already suffered slope failure.

5.2.1 Landsat 7 ETM+ A multispectral analysis of the Landsat imagery can allow landslide factor mapping to be completed. The presence of disturbed ground is frequently taken to be an indication of the presence of slow landslide processes such as creep (Dearman and Fookes 1974). In many cases this is an indication of incipient or ongoing failure. The use of the RGB 457 and RGB 542 FCC images allowed the identification of the morphological characteristics of creep, such as slopes with mottled texture and disrupted vegetation. In addition, colluvium was clearly identifiable on the RGB 457 image as it appeared as bright blue tones. In the PCA 123 image bare colluvium and alluvial fans appeared as green colours when in shadow, and as orange colours where there was bright sunlight, although some variation across the image was noted, presumably reflecting lithological differences.

Considerable success was also achieved in the identification of areas of high moisture content or water seepage. Based on a training area identified during a field visit, a wet are algorithm was constructed based upon the band parameters given in Table 4. This was completed by identifying potential areas with high moisture content. The spectral responses of these areas were then deduced to produce minimum and maximum ranges of DN values, from which classification algorithm was created using minimum and maximum values.

Band number	DN value
1	53-120
2	35-67
3	32-90
4	40-70
5	35-95
6	130-149
7	21-90

Table 4: Wet Area Secondary Classification Parameters

This classification highlighted irrigated paddy fields, shadowed hollows, areas of ponding, and river alluvium. Whilst in a number of cases this was successful in the identification of areas that are prone to landslides, this tended to be swamped by the occurrence of high moisture content for other (i.e. non landslide-related) reasons. For this reason, such an analysis has proven to be of limited use.

5.2.2 IKONOS For the Arghakanchi area multispectral imagery was not available, so similar factor analyses approaches were not possible. However, mapping of disturbed ground from the panchromatic imagery was possible based upon texture and ground cover type. This could have been enhanced through the analysis of ,the multispectral imagery, but the improvement would have been limited given the low spectral resolution. The high spatial resolution of the IKONOS imagery could also be used to map elements that are vulnerable to the effects of landslides, which could greatly assist in the compilation of a landslide risk map.

6. CONCLUSIONS

LANDSAT 7 ETM+ offers many advantages in the mapping of landslides in high mountain chains, especially with respect to large features that are difficult to detect on the ground. The use of FCCs, and in particular the combination of the RGB 457 and the RGB 542 FCCs, PCA RGB 123 highlighted landslides well. However, the combination of the all of the techniques still allowed the delineation of only about 25% of the total number of landslides in the study area, the major limitation being the spatial resolution.

The results achieved using the IKONOS panchromatic imagery are very promising. The 1m spaltial resolution allows even small landslides to be mapped, with failures as small as 8 m length and width being identified. At present the multispectral capability of the instrument appears to offer relatively small advantage due to the limitations in spectral resolution. However, the greatest restriction in the use of this technique is the high acquisition cost of the imagery, which will prevent its widespread use in less developed countries.

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