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SATELLITE REMOTE SENSING AND GIS FOR ANALYSIS OF MASS MOVEMENTS WITH POTENTIAL FOR DAM FORMATION

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(**) Ministry of Ecology and Emergency (MEE), Center for Monitoring, Prognosis of Natural Hazards and Management of Mining Tailings, 720055 Bishkek, Kyrgyzstanvaluable source of information for analyzing landslides in Kyrgyzstan.

INTRODUCTION

Mass movements are an important factor in shaping the Earth's surface. They result in changes of the morphology and the surface cover as well as the near-surface underground. In dependence on the varying terrestric and atmospheric conditions a wide range of different mass movements has been observed, described and classified, e.g., (Cruden & Varnes, 1996). Under certain natural conditions most of them have the potential for forming landslide dams whereas their majority results from rotational and translational slides followed by rockfalls (Costa & Schuster, 1988; Ermini & Casagli, 2003). These predominantly unstable dams represent a high natural hazard especially to the downstream areas mainly by their potential for rapid release of the impounded waters with a high risk of subsequent extensive flooding , e.g. (Schuster, 1994).

There has been a wide range of studies analyzing present and past landslide dams with the goal of understanding the natural conditions for their formation and failure. Subsequently, the results of these studies have been summarized and analyzed in inventories in order to develop classifications of characteristic parameters and derive criteria for forecasting landslide dam evolution, e.g. (Clague & Evans, 2000; Costa & Schuster, 1988; Ermini & Casagli, 2003; Korup, 2002).

These studies have revealed the necessity for standardized description of events with quantifiable key parameters including homogenization of the already existing investigations which are mostly descriptive and very heterogeneous in their methodology. These inventories also show that the existing database is still limited for many parts of the world often representing areas of high process activity (e.g., Asia). However, even in the comparably well investigated areas, of Europe, Northern America and New Zealand past process activity is often hard to assess due to the short-term existence of many of these dams. Such event-related information are crucial for magnitude-frequency analysis as an important part of objective hazard assessment.

Since mass movements and their resulting potential of dam formation represent complex phenomena a wide range of methods is involved in their investigation. During the last years remote sensing techniques have become an integral part of the methodological spectrum. They are especially suitable for analyzing the spatial evolution and predisposing factors of such processes. In areas of limited data coverage satellite remote sensing data often present the only spatial-temporal archive of surface conditions. Its analysis can reveal important characteristics of recent events which otherwise would have not been documented. This technology has also developed a rapidly growing potential for the well investigated parts of the world due to improved sensor systems which became available during the last 5 years.

In its first part the paper reviews currently available satellite remote sensing data as well as methods and applications using these data for investigation of mass movements. In this review all types of gravitational mass movements are considered since most of them have the potential for dam formation and the methodological outcomes are often applicable to different types of mass movements. Additionally, the number of studies dealing with specific methodological developments for analyzing mass movements is still small compared to total number of remote sensing application in geosciences.

In the second part of the paper results of satellite remote sensing based information extraction are presented for an area of high landslide activity in Southern Kyrgyzstan (Central Asia). This region shown in Figure 1 is affected by the ongoing collision of the Indian sub-continent with Southern Eurasia leading to rapid uplift of the Earth's largest mountain belts (Himalaya, Pamir, Tienshan). In the result 90% of the Kyrgyz territory has an elevation higher than 1000 m a.s.l. and is frequently affected by extreme natural processes, such as mass movements, floods, avalanches and earthquakes. Among them large landslides are one of the major natural hazards due to their frequent seasonal occurrence within large areas along the Eastern rim

Figure 1 - Kyrgyzstan in Central Asia – white box indicates area of high landslide activity

of the Fergana Basin (Figure 1) representing a comparably densely settled area in Kyrgyzstan.

REVIEW OF DATA AND METHODS FOR SATELLITE REMOTE SENSING BASED INFORMATION EXTRACTION

Since the beginning of their availability for civilian use remote sensing data have been an useful information source for mapping of mass movements and related features as well as factors predisposing these processes. With the existence of satellite remote sensing systems providing global coverage, such information have been available for most parts of the world forming a steadily growing archive of surface conditions containing important indicators for mass wasting processes. In the following the currently available satellite remote sensing data are reviewed in regard to their suitability for analyzing mass movements. Special emphasis is put on their potential for generation of topographic information, identification of mass movements and monitoring their evolution.

AVAILABLE OPTICAL SATELLITE REMOTE SENSING DATA

Since the beginning of the 1980's operational optical satellite remote sensing systems have been recording data with a spatial resolution of 30 m and better. Table 1 gives an overview about the presently available systems. Among them the longest archive is provided by the Landsat-(E)TM system which has been acquiring data since 1984 with a revisiting cycle of 16 days.

Most of these systems are equipped with multispectral sensors recording the spectral reflectance characteristics of the Earth's surface within discrete spectral bands throughout the solar reflected part of the electromagnetic spectrum (Figure 2). The obtained spectral reflectance characteristics contain indicators for mass movement related phenomena, such as scarps, faults and changes in surface cover and vegetation patterns caused by slope failures.

The quality of the spectral information depends on the sensor characteristics, suchas number, spectral width and position of the bands within the solar reflected spectrum. The Landsat-(E)TM sensor (Table 1, Figure 2) represents a broad-band instrument which is sensitive to wider spectral absorption zones, such as the iron bands in the visible part of the spectrum. However, the narrow diagnostic absorption features of calcite and kaolinite within the short-wave infrared range of the spectrum cannot be resolved.

Recently, new opportunities have been opened up with the availability of the ASTER instrument recording spectral information in 9 reflective and 5 thermal bands (Table 1, Figure 2). This spectral configuration allows a better assessment of spectral absorption features in the short-wave infrared playing a key role for lithological differentiation and thus improving the possibility for investigations of mass movements.

Exploitation of the full potential of spectral information for surface characterization requires hyperspectral instruments. The first satellite-based sensor of this kind – Hyperion - records the solar reflected part of the spectrum in 220 bands and has been operational since the end of 2001. However, limited data availability and narrow swath width (7.5 km) only have been allowing methodological studies so far.

The suitability of optical satellite remote sensing data for landslide analysis is also determined by their spatial resolution currently ranging between 2.8 and 30 m for multispectral sensors and between 0.7 and 18m for panchromatic ones. Right now highest satellite-based spatial resolution is achieved by the QuickBird and the IKONOS systems (Table 1). However, narrow swath width, limited spectral resolution and high data costs limit their use for multitemporal investigations at a regional scale covering areas with an extent of several tens up to hundreds of kilometers.

GENERATION OF DIGITAL TOPOGRAPHIC INFORMATION

Presently, three of the optical satellite remote sensing systems – SPOT, ASTER, IKONOS - simultaneously record stereo image data for generation of topography and multispectral data for characteriza-

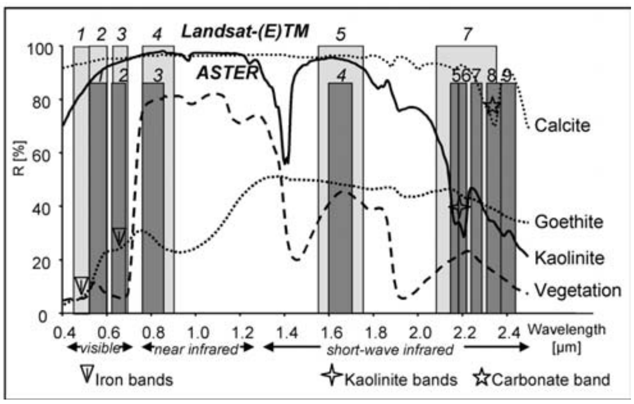

Figure 2 - Spectral bands of Landsat-ETM and ASTER sensors with spectral reflectance characteristics of minerals and vegetation

Parameter	Multispectral							
	LANDSAT-TM	LANDSAT-ETM	MOMS-2P*	ASTER	IRS-C	SPOT-5	IKONOS	QuickBird
I General								
Launch date	March 84	Apr 99	Apr 96	Dec 99	Jan 96	May 02	Sep 99	Oct 01
Mode	operational	operational	out of service	operational	operational	operational	operational	operational
Revisiting cycle	16 days	16 days	variable	variable	variable	variable	variable	variable
Swath width (km)	185	185	105	60	63 -141	60 - 120	11	16,5
Stereo capability	no	no	yes	yes	no	yes	yes	no
Stereo resolution (m)	N/A	N/A	18	15	N/A	10	1	N/A
II Reflected spectrum								
Spatial resolution (m)	30	30	18	15 - 30**	23 - 70***	10 - 20****	4	2,8
Spectral range (µm)	0.4 - 2.4	0.4 - 2.4	0.4 - 0.8	0.5 - 2.4	0.5 - 1.7	0.5 - 1.7	0.4 - 0.9	0.4 - 0.9
Number of bands	6	6	4	9	4	4	4	4
Spectral resolution (nm)	60 - 270	60 - 270	35 - 66	40 - 100	60 - 90	70 - 170	60 - 140	60 - 140
IV Thermal spectrum								
Spatial resolution (m)	120	60	N/A	90	N/A	N/A	N/A	N/A
Spectral range (µm)	10.4 - 12.5	10.4 - 12.5	N/A	8.1 - 11.6	N/A	N/A	N/A	N/A
Number of bands	1	1	N/A	5	N/A	N/A	N/A	N/A
Spectral resolution (nm)	2100	2100	N/A	300 - 700	N/A	N/A	N/A	N/A
III Panchromatic band								
Spatial resolution (m)	N/A	15	6	N/A	6	2.5 - 5	1	0,7
Spectral range (µm)	N/A	0.5 - 0.9	0.5 - 0.8	N/A	0.5-0.7	0.5 - 0.7	0.4 - 0.9	0.4 - 0.9

* shutdown of Russian MIR space station in March 2001
** visible/near infrared: 15m, short-wave infrared: 30m
*** visible/near infrared: 23m, short-wave infrared: 70m
**** visible/near infrared: 10m, short-wave infrared: 20m

Table 1 - Technical parameters of selected optical satellite remote sensing systems

tion of surface conditions (Table 1). This is especially important for analyzing mass movements since these processes change topographic relief as well as surface coverage within the affected areas.

DEM's from ASTER stereo data are generated in an operational way by the US/Japan ASTER Science Teams in form of relative and absolute DEM's. The resulting 30-m-resolution datasets can be ordered through the internet from data centers in both countries at comparably low cost. Quality assessment ASTER DEM's has been performed in a number of studies for different parts of the world resulting in height accuracies between 7 and 60 meters depending on the terrain type (Hirano *et alii*, 2003; Kaeaeb, 2002).

Another comparable along-track stereo system became available in 2002 with the launch of the SPOT-5 satellite (Table 1). This 3-fold stereoscopic system allows incorporation of three viewing directions in the process of DEM generation improving quality above all in mountainous terrain (Kornus *et alii*, 2004). Achieved height accuracies vary between 4 and 17m (Kornus *et alii*, 2004; Reinartz *et alii*, 2004). Based on high resolution IKONOS stereo satellite data DEM's of various accuracy levels are produced on a commercial basis by the Space Imaging company (Dial *et alii*, 2003). Highest quality products reach height accuracies between 1 and 2 m for flat terrain.

In comparison to optical systems radar instruments have the big advantage of being able to penetrate clouds. This makes them favorable for global mapping projects, such as the Shuttle Radar Topography Mission (SRTM) which took place in February 2000. Based on the NASA-operated C-Band instrument a nearly global database of highly accurate elevation data has been produced with a resolution of about 30 meters being released only for the U.S. Most of the data for the remaining world is restricted to a grid spacing of about 90 meters by the U.S. National Imagery and Mapping Agency (NIMA). The new global SRTM database is of homogenous and high quality resulting in height accuracy between 4 and 6 meters for areas of moderate relief (Smith & Sandwell, 2003).

During the same mission the German/Italian X-band system has been operated by the DLR (Deutsches Zentrum fuer Luft- und Raumfahrt e. V.). The coverage of the resulting X-Band DEM processed by the DLR is only half in comparison to the C-Band database due to its smaller swath width. The value of this database consists of a higher relative vertical accuracy and a complete availability of the 30 m resolution DEM for civilian use. In Rabus *et alii* (2003) height accuracy is analyzed across the entire mission varying between 6 and 16 meters. Heipke & Koch (2002) determined height accuracy of about 3 meters for flat to moderate terrain in Germany.

IDENTIFICATION OF MASS MOVEMENTS FROM OPTICAL REMOTE SENSING DATA

In the recent past, satellite remote sensing data have played a minor role in the analysis of mass movements because of their limited spatial resolution. They have been mostly used for investigations at a regional scale in areas with limited availability of base information, e.g., (MANTOVANI *et alii*, 1996; SOETERS & VAN WESTEN, 1996). Traditionally, panchromatic aerial photographs have been most widely used and analyzed by visual photointerpretation supported by stereoscopic techniques. This approach works well for comparably small areas where mass movements show a significant brightness and relief contrast to their surroundings. However, aerial photograph-based investigations at a regional scale are very resource-consuming. For example, within the Umbria-Marche landslide hazard assessment project in Italy 2100 aerial photographs were analysed for an area of 18125 km^2 requiring 5 person/years (GUZZETTI *et alii*, 1999).

New opportunities have been opened up with the availability of multispectral satellite remote sensing data covering the visible, shortwave and thermal infrared parts of the spectrum. So far, these data have been mostly used for visual interpretation in form of true (TCC) and false color composites (FCC) visualizing three multispectral bands the same time. The potential for identification of mass movement related features depends on the their spectral contrast to the undisturbed surroundings which is influenced by a variety of factors, such as degree of re-vegetation, lithological composition and moisture content. For analyzing the latter one the shortwave and thermal infrared parts of the spectrum are especially useful. However, since moisture content is only one parameter determining the spectral reflection at a given location, its influence can only be assessed in case of an otherwise homogenous background or on the basis of a time series of remote sensing data.

Spatial resolution is still the main factor limiting use of satellite remote sensing data for visual analysis of mass movements, especially in the shortwave and thermal infrared wavelength ranges (Table 1). However, most of the presently available optical satellite remote sensing systems simultaneously record higher resolution spectral bands in the visible and near infrared parts of the spectrum (ASTER, SPOT) or an additional high-resolution panchromatic band (Landsat-ETM; SPOT). Using special image processing techniques allows a resolution merge of data with different spatial resolutions, e.g., (LIU, 2000). Additionally, the contrast of the high resolution band is often further enhanced by edge sharpening filter techniques (MASON *et alii*, 1998).

The increasing number of spectral bands (e.g., 14 bands in case of the ASTER system) limits the opportunity for full exploitation of their information content based on visual analysis of color composites. Under these conditions a number of techniques for information reduction has been developed including band-ratios and principal component analysis (PCA). Additionally, methods for automated information extraction are capable of analyzing multidimensional feature spaces originating from different spectral bands and acquisition times. A wide range of such methods has already been developed for the analysis of landcover types and landuse changes in different natural and urban environments. So far, their application to mass movement related identification task is still rare (CHENG *et alii*, 2004).

MONITORING OF MASS MOVEMENT RELATED SURFACE CHANGES

Satellite remote sensing data have also been successfully applied for monitoring existing mass movements representing long-term hazards to their surroundings. In this connection remote sensing represents a complementary approach to widely implemented field based monitoring techniques, such as geodetic, geotechnical and geophysical surveying. With these methods different parameters can be measured with high accuracy and temporal resolution mostly at point locations or along line profiles. Remote sensing allows derivation of spatially continuous information over large areas at the same acquisition time. During the last years a variety of methods has developed for quantitative analysis of mass movement related displacement fields representing important information for an improved processes understanding.

Photogrammetric methods have been most widely used for determination of horizontal and vertical displacements based on time series of aerial photographs using manual interpretation (SOETERS & VAN WESTEN, 1996), and quantitative stereo analysis (KAEAEB, 2002). Recent examples for he latter technique are the determination of the velocity field for the La Clapiere landslide between 1983 and 1999 (CASSON *et alii*, 2003) and the analysis of the Tessina landslide with special emphasis on the detection of volumetric changes related to several phases of landslide reactivation (VAN WESTEN & GETAHUN, 2003).

KAEAEB (2002) represents one of the rare studies of photogrammetric analysis of rockslide displacement. These processes are more difficult to monitor by remote sensing methods because deformation is much less coherent than for other types of mass movements formed in weakly consolidated sediments or ice. The analysis of a rockslide near the Aletsch glacier in the Swiss Alps revealed a maximum terrain deformation of 2 meters between 1976 and 1995 as a stress-relief response due to the retreat of the Aletsch glacier. So far, there have been no examples for this kind of analysis using stereoscopic satellite remote sensing data because suitable data have only been available for a short period of time (Table 1).

In the past non-stereoscopic optical satellite remote sensing data have rarely been used for direct landslide monitoring because of their limited spatial resolution. New opportunities have been opening up with the availability of high-resolution IKONOS and Quickbird data. HERVAS *et alii* (2003) have developed a digital method for change detection including a subsequent thresholding algorithm in the area of the Tessina landslide using aerial photographs and IKONOS data.

Another opportunity for quantitative monitoring of mass movement related surface deformations is the differential InSAR method (D-InSAR) using interferometric SAR data. This technique allows satellite remote sensing based assessment of surface changes in the scale of a few centimetres, e.g., (FRUNEAU *et alii*, 1996; MASSONNET & FREIGL, 1998; XIA *et alii*, 2004). SINGHROY & MOLCH (2004) present results for D-InSAR based post-slide detection of gradual motion for the Frank rockslide in the Canadian Rockies in the vegetation-free detachment zone prior to the 2001 rockfall amounting to 6000 tons.

These studies have also revealed a number of constraints for the D-InSAR method. Motion detection is restricted to movements in the direction of the radar signal. This limitation can be overcome by simultaneous ground-based GPS measurements for derivation of the vertical and horizontal components of these movement (XIA *et alii*, 2003). Another problem is unfavourable orientation of slopes with respect to the radar signal and the availability of interferometric radar data with suitable baselines and sufficient coherence between images. The latter requirement has been fulfilled best by the ERS-1/2 tandem system. Since ERS-1 went out of service in 1999 no comparable interferometric satellite radar system has been in operation anymore. The remaining operational systems ERS-2, ENVISAT and RADARSAT are not optimal for interferometric applications.

In summary this technique works best for monitoring of continuously and moderately moving slopes without sudden occurrence of large surface disruptions in mostly vegetation-free areas since these phenomena lead to a loss of coherence and thus the possibility for interferometric change detection. Some of the drawbacks of the D-InSAR method have recently been overcome by the Permanent Scatterer Technique which identifies so called Permanent Scatterers (PS) represented by radar-bright and phase-stable targets, such as buildings, bridges and rock outcrops. Based on this subset of image pixels deformation rates are interferometrically determined (FERRETTI *et alii*, 2001). This way long time series can be established for areas where deformation detection had been limited or made impossible before because of phase decorelation.

Using this PS-technique COLESANTI *et alii* (2003) have investigated the evolution of the Ancona landslide in Italy between 1992 and 2000 based on 61 ERS- images. The results showed a good agreement with displacement data obtained from optical leveling. HILLEY *et alii* (2004) have constructed a range-change time series between 1992 and 2001 for the Berkley vicinity in the eastern San Francisco Bay area with special emphasis on slow-moving landslides using 46 ERS-scenes. They have also analyzed the obtained sliding velocities in relationship with precipitation data for a better understanding of factors influencing landslide activity in this area.

MASS WASTING PROCESSES IN KYRGYZSTAN AND DESCRIPTION OF STUDY AREA

According to the Ministry of Ecology and Emergency (MEE) which is responsible for hazard assessment and operational disaster mitigation mass movements have the highest hazardous potential in Kyrgyzstan since they often occur in the vicinity of settlements or affect populated areas with their extensive runout zones. Frequently occurring processes are landslides, rockslides, mudflows, debris flows and glacier lake outbursts (MOLDOBEKOV *et alii*, 1997). In Kyrgyzstan these processes have been studied and documented for more than 50 years. Most of the investigations have been published in Russian in form of internal reports. Only a few results have appeared in the international literature for Kyrgyzstan - e.g., (STROM, 1996; STROM, 1998; TORGOEV *et alii*, 1999) - and Central Asia - e.g., (NIYAZOV, 2002; SALIKHOVA, 1992).

In Kyrgyzstan highest process activity is observed for deep-seated landslides which occur most frequently in spring between March and April with varying intensity between the years mainly depending on precipitation characteristics of the previous winter season. During the last 10 years more than 2000 landslides have occurred. Highest activation was observed in 1994 when about 1000 landslides failed and 115 people were killed. The most recent period of intense landslide formation has been taking place between 2002 and 2004 (see Figure 3 for location of main landslides) with highest activity in 2004 (about 400 landslides) leading to 45 people being killed.

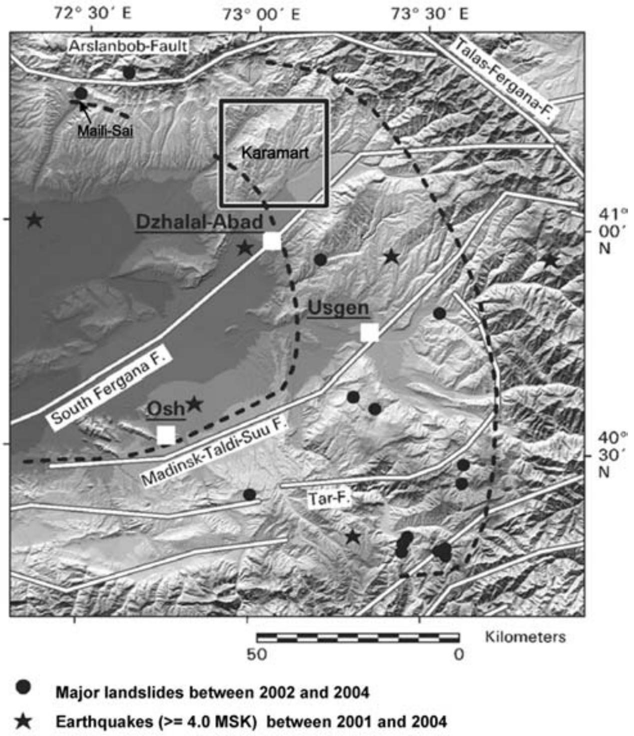

Figure 3 - Shaded relief of Eastern rim of Fergana Basin based on SRTM DEM data overlaid by main faults (white lines) and zone of high landslide activity (black dashed lines)

LANDSLIDE PROCESSES AND STATE OF INVESTIGATION IN SOUTHERN KYRGYZSTAN

In Kyrgyzstan about 5000 landslides have been recorded based on field investigations and analysis of aerial photographs for selected areas of high landslide activity. They are mainly concentrated along the topographically rising Eastern rim of the Fergana Basin below its transition into the high mountainous terrain at elevations between 700 and 2000 m (Figure 3). The majority of landslides occur in form of rotational and translational slides in weakly consolidated Quaternary and Tertiary sediments consisting of loess, sand- and siltstones, clays, loams and carbonates AITMATOV *et alii*, 1999; KOSHOGULOV *et alii*, 1999; SARNAGOEV & KRAVCHENKO, 2000a and 2000b).

One type of landslides is related to massive Quaternary units mostly consisting of loess reaching up to 50m thickness. It is characterized by very rapid avalanche-like mass movements which can amount to several meters per second. These landslides often occur as a combination of rotational slide and dry flow resulting in long runout zones. They are especially dangerous because of their great destructive power and their sudden occurrence after longer periods of subsurface destabilization which is indicated by cracks developing subparallel to hill slope crests. Figure 4 shows the upper part of the Kotchkor-Ata landslide in the Upper Maili-Suu river basin (Figure 3). The main displacement took place within a few days in spring 1994 in form of a combined rotational slide and flow within Mid-Quaternary loess and weakly consolidated Tertiary sediments and represents a volume of more than 10 Million m^3. The distance between the main scarp and the toe of the landslide amounts to about 4 km.

Another type of landslides occurs in Mesozoic and Cenozoic sediments with intercalated clays. These environments lead to complex mass movements mostly in form of deep-seated landslides with long periods of activity and maximum movement rates of several meters per day. They are also preceded by the formation of cracks. Figure 5 shows the western part of the landslide complex of Sary Bulak where a total failure of 15 Millions m^3 of Neogene and Paleogene clay-rich sediments occurred in form of several translational slides mainly during June 1998.

Both types of landslides affect large areas in the foothills of the high mountain ranges representing an important human living space

Figure 4 - Landslide Kotchkor-Ata – view to main scarp (width ca. 500m) – picture taken in July 1999

Figure 5 - Translational landslide complex Sary Bulak – picture taken in July 1999

in Kyrgyzstan. They result in formation of temporary dams, diversion of river courses and the destruction of buildings, roads and bridges. So far, this region of high landslide activity has been lacking a consequential spatial analysis of landslide processes in relation to their predisposing and triggering factors at a regional scale. Previous investigations had been focused on single events in context of their local environments. The obtained results could only partially explain the occurrence of landslides over larger areas representing a main prerequisite for spatially differentiated regional hazard assessment.

GOAL OF SATELLITE REMOTE SENSING BASED INVESTIGATIONS AND DESCRITPION OF STUDY AREA

Under the specific conditions in Kyrgyzstan, satellite remote sensing data represent the only available source of multitemporal and spatially continuous information about surface conditions covering large areas with relatively high spatial detail. Against this background, the Remote Sensing Section of the GFZ Potsdam and the MEE in Kyrgyzstan have been collaborating on a project with the goal of developing a satellite remote sensing and GIS based system for objective and spatially differentiated landslide hazard assessment for the area of high landslide activity in Southern Kyrgyzstan.

So far main emphasis has been put on the evaluation of the information potential of various types of satellite remote sensing data for landslide identification and characterization of predisposing factors. Research has been carried out in an exemplary way for several test sites along the Eastern rim of the Fergana Basin including the Upper Maili-Suu river basin (ROESSNER *et alii*, 2000) and the Karamart area at the northern rim of the Fergana Basin (Figure 3).

The Karamart study area is situated between the Kugart river in the east and the Kara-Unkjur River in the west in the foothills of the Fergana range. The area shown in Figure 6 is mainly considered as one structural block which has been predominantly formed by the older Alpidic structural phase and mostly consists of Meso-Cenozoic sediments. In the Eastern part (settlement Karamat) these structures are overlaid by a younger N-S oriented brachysyncline which is predominantly filled by loess units of the Lower Quaternary (Q_1). Figure 6 shows the main geological units of this area modified after the Kyrgyz Geological Map (1:200000). Table 2 contains a more detailed description of these units.

During the older structural development folding of the sediments along a NE-SW axis took place first and was related to a cross-folding (NW-SE). Additionally, several NW-SE oriented structural zones could be identified based on the interpretation of satellite remote sensing data (WETZEL *et alii*, 2000). In Figure 6 they are indicated as main fault zones dissecting the area between the Kara-Unkjur valley in the northwest and the loess-filled brachysyncline in the southeast.

According to our geological field investigations, these older structural elements are reactivated due to recent tectonic deformation leading to a destabilization of the weakly consolidated sediments. In the result, this area is affected by high landslide activity (see Section 4.3 for more details). Due to its moderate elevations ranging between

Geological period	Map	Lithological units
Recent	Q4	alluvial sediments
Upper Quaternary	Q3	glacial moraines, loesses, alluvial sediments
Middle Quaternary	Q2	glacial moraines, loesses, alluvial sediments
Lower Quaternary	Q1	grey conglomerates, loesses
Tertiary - Neogene (Pliocene)	N2	conglomerates, gravels, loess-type loams
Tertiary: Paleogene (Oligocene) - Neogene (Miocene)	PG3-N1	red sandstone, conglomerates, clays
Tertiary: Paleogene (Lower Eocene - Oligocene)	PG1-2	sandstones, gypsolytes, limestones, marls, clays, aleurolites
Upper Cretaceous (Cenomanian) - Paelogene (Lower Eocene)	CR2-PG1	sandstones, limestones, dolomites, marls, gypsolytes, conglomrates, gravels, clays
Lower Cretaceous - Upper Cretaceous	CR-CR2	Red sandstone, conglomerates, gravels, gypsolytes, limestones, clays, aleurolites
Upper Jurassic - Middle Jurrasic	J1-J2	sandstones, aleurolites, slates
Lower Permian	P1	red conglomerates, sandstones

Table 2 - Lithological units modified after geological base maps of Kyrgyzstan used in Figures 6 and 10

800 and 1800m a.s.l. (Figure 6) all of the wider valleys are occupied by permanent settlements (e.g., Karamart and Ak-Shaluu) reaching up to elevations of 1600m a.s.l. Thus, many of these villages are situated in areas of high landslide hazard.

SATELLITE REMOTE SENSING AND GIS BASED ANALYSIS OF LANDSLIDE SITUATION

The goal of spatially differentiated regional landslide hazard assessment requires the establishment of a suitable digital database containing detailed information about landslide occurrence and factors predisposing these events. In the following methods and results of satellite remote sensing and GIS based information extraction are presented in an exemplary way for the Karamart study area (Figure 6) focusing on landslide identification, derivation of topographic information and the analysis of the geological setting as the main predisposing factor for landslide formation in this area of high recent tectonic activity.

LANDSLIDE IDENTIFICATION

The landslide investigations along the Eastern rim of the Fergana Basin in Southern Kyrgyzstan are based on Landsat-(E)TM, MOMS-2P and ASTER data (Table 1). Best multitemporal coverage is available for the Karamart area including Landsat-E(TM) data of June 1993, July 1994, August 1998 and September 1999 as well as MOMS-2P data of June 1998 and ASTER data of June 2001. This time series allows analysis of landslide formation during the period of highest recent activity in spring 1994.

For landslide identification the different images were geometrically corrected using the orthoimage generated from the MOMS-2P data as the master scene. Despite the different sensor systems high relative geometric accuracy between the scenes was achieved amounting to RMS-errors of about half of the respective pixel sizes.

Visual image analysis was performed based on RGB (Red-Green-Blue)-visualization of false-color-composites (FCC). Different image processing techniques have been applied to generate multispectral images of enhanced spatial resolution. In case of ASTER data the 30m bands of the short-wave infrared (SWIR) part of the spectrum have been resampled to a 15m pixel size and combined with the original bands of the visible (VIS) and near infrared (NIR) wavelength ranges. High resolution multispectral image data were also obtained by an IHS (Intensity-Hue-Saturation)-based resolution merge of the 30m bands with band 1 (VIS). The same technique was applied to Landsat-ETM data using the 15m panchromatic band for resolution enhancement. In comparison to simple resampling the merging technique results in a more detailed spatial impression.

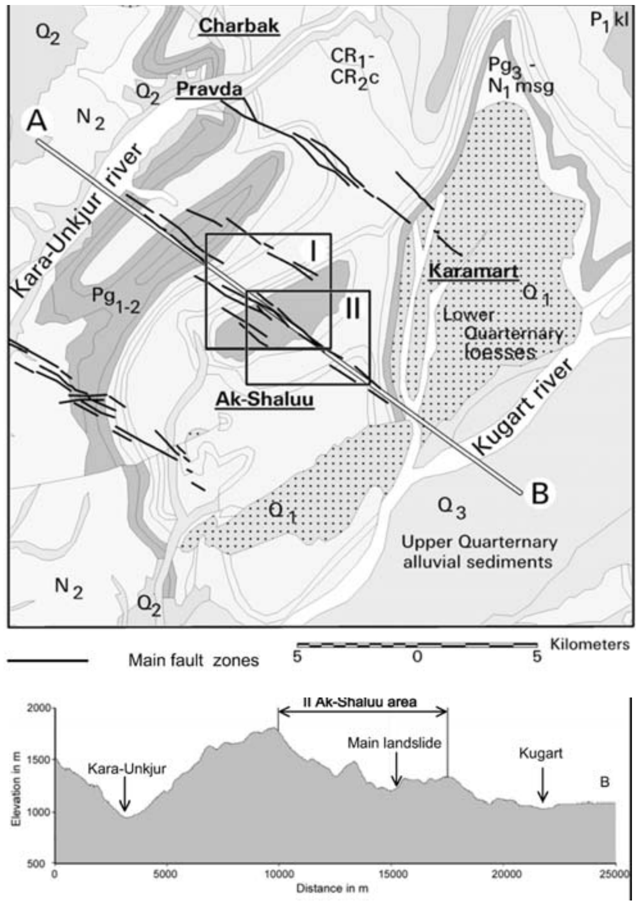

Figure 6 - Geological base map for the Karamart area – see Table 2 for explanation of lithological units

Based on these image products the potential for direct landslide identification was investigated. Highest color contrast between displaced material and undisturbed surroundings was observed for Landsat RGB 542 and 752 FCC's corresponding to ASTER RGB FCC's of any of the SWIR bands (5 through 9) displayed in combination with band 3 or 4 and band 1 (Figure 2). This shows that

SWIR data greatly improve the possibilities for landslide identification. However, the narrower bandwidth of the ASTER SWIR bands did not lead to an improved color differentiation.

Including the NIR-band in the FCC enhances chlorophyll-rich vegetation but often leads to color saturation in these areas. This may result in suppression of finer differences in vegetation cover as indicators for different stages of re-vegetation of displaced material. For the Karamart area simultaneous use the of 542 and 752 FCC led to the most reliable visual identification of landslides based on the multitemporal image data. In the July 1994 data landslides show especially distinct color characteristics since they had been formed only some months before data acquisition. Under these conditions even small landslides with an extent of two to three pixels (between 50m and 100m) could be identified. However, the 30m resolution data do not allow derivation of shape characteristics for these small features.

Comparing 30m Landsat-ETM data (Figure 7d) with resolution-merged 15m ETM image data (Figure 7c) shows a significantly more detailed representation of landslide features and morphological structures in case of the latter one. However, Landsat-TM data have the advantage of dating further back in time. This is illustrated in Figure 7 showing the area of the Ak-Shaluu landside for different acquisition dates (see also Figure10 for larger spatial context). The grayscale visualization is based on band 4 (NIR) characterized by high reflectance of green vegetation (bright areas) and strong absorption of water bodies (dark areas).

The landslide occurred in April 1994 in form of a rotational slide in Mid-Quaternary loess (Q_2). In the zone of accumulation the displaced material covered the lower part of the Ak-Shaluu village along the Achy-Sai river. The settlement structure can be seen in the June 1993 Landsat data (Figure 7a). Thanks to early warning of the MEE all of the inhabitants were evacuated before the failure. Figure 8 shows a field picture of the main scarp of the landslide and the displaced material which dammed the Achy-Sai river leading to the formation of a lake (Figure 7b). It mostly got drained later on by an erosion channel except for a small water body at the Eastern edge of the former lake which was revealed during field investigations in August 1999. The 15m Landsat-ETM resolution merge (Figure 7c) also resolves the dirt road (bright linear feature) which has been put through the accumulation zone (see also Figure 8).

The results for the Ak-Shaluu area (Figures 7, 10) show that available satellite remote sensing data are suitable for initial landslide identification in Kyrgyzstan due to the fairly large spatial extent of these phenomena and their good spectral contrast to the surroundings which is preserved at least over a decade. Remote sensing based landslide analysis requires multitemporal coverage allowing assessment of interannual and seasonal changes in surface conditions as well as variations in illumination.

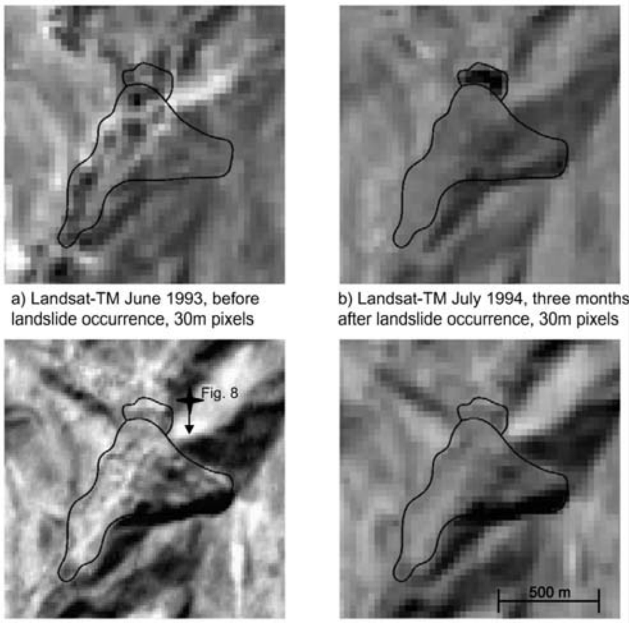

Figure 7 - Representation of Ak-Shaluu landslide in multitemporal Landsat-(E)TM remote sensing data used for landslide identification - greyscale image based on band 4: near infrared (NIR)

Figure 8 - Ak-Shaluu landslide – view to main scarp and displaced material with new dirt road – picture taken in July 1999 (for position and look direction see Figure 7)

GENERATION AND ANALYSIS OF DIGITAL TOPOGRAPHY

In Kyrgyzstan satellite remote sensing data are the only possible source for effective generation of high resolution topographic information for large areas. So far, DEM's have been derived from data acquired by the experimental MOMS-2P and the operational ASTER sensors. The 30m resolution MOMS-2P DEM was generated for a 150 km long image strip covering the Northeastern part of the area of high landslide activity including the Maili-Sai and Karamart study areas. Absolute DEM generation was performed using high accuracy geodetic GPS measurements as ground control points and is described in detail in Roessner *et alii* (2000).

Determination of height accuracy was based on high accuracy GPS check points and ranges between 10 and 20m depending on relief characteristics. Since the usability of the DEM for landslide analysis is also determined by its morphological correctness, the representation of morphological structures in the DEM has been analyzed by automated extraction of drainage networks and watersheds using the surface hydrological analysis tool of the ARC/INFO software (ROESSNER *et alii*, 2004). Figure 9 shows the result for a subset of the Karamart study area marked as Box I in Figure 6.

The derived drainage pattern reflects the present stage of relief development as a result of the interaction between tectonic activity and erosion. The semicircular structure in the center of the subset depicted by the dashed line has been formed by ancient landslide activity. The internal differentiation of this structure into subordinate NW-SE oriented watersheds corresponds in its direction to the main fault zones of this area shown in Figure 6. These findings support the hypothesis of tectonic activity as a main factor predisposing landslides in Southern Kyrgyzstan (see also Section 4.3).

These results show that the MOMS-2P DEM is of sufficient quality for analyzing landslide activity in this area. Presently, it is extended using ASTER stereo data. First results of GPS-based absolute DEM generation have been obtained for the Eastern part of the area of high landslide activity. Height accuracy of the 30m resolution DEM amounts to 12m and has been determined using a subset of GPS check points originally measured in the field for generation of the MOMS-2P DEM.

Additionally, digital topography derived from interferometric SAR data is available for Southern Kyrgyzstan. C-band SRTM DEM data (Section 2.2) have been incorporated into the existing GIS database for the whole Eastern rim of the Fergana Basin. Due to its limited 90m resolution these data have been mainly used for visualizations of large areas (Figure 3). InSAR based DEM's were also generated from ERS-1/2 data. They were acquired for the first time for Central Asia by a mobile satellite receiving station operated by the GFZ Potsdam and the DLR in Kitab (Uzbekistan) between March and July 1999. Interferometric analysis of these data allowed a first evaluation of this technique under the specific conditions in Central Asia (XIA, 2001).

CHARACTERIZATION OF GEOLOGICAL SETTING AS MAIN PREDISPOSING FACTOR

Our remote sensing based geological field investigations have revealed the great importance of recent tectonic activity as a main factor predisposing landslides in Southern Kyrgyzstan. Information about relevant tectonic structures are not contained in the existing geological maps of Kyrgyzstan and had not been taken into account in the frame of the already existing landslide investigations. They were focused on engineering geological and hydrogeological aspects resulting in a good local understanding of landslide mechanisms. However, they could only partially explain the spatial distribution of landslides at a regional scale.

Combining our geological field observations with information derived form the previously described satellite remote sensing data and existing geological maps a new model for landslide formation in Southern Kyrgyzstan has been developed including recent tectonic activity as a main predisposing factor. For analyzing of the geological setting over large areas a GIS approach was developed for visual

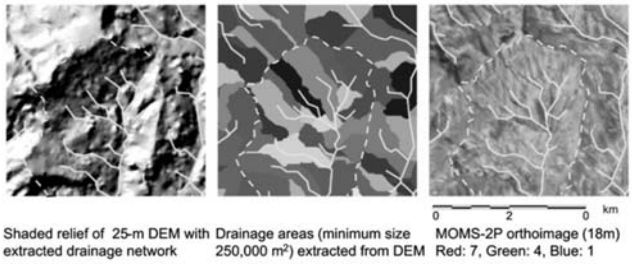

Figure 9 - Automated extraction of drainage network and watersheds based on MOMS-2P DEM – Dashed line depicts semicircular structure resulting from ancient landslide activity

interpretation and mapping based on 2-D profiles (Figure 6) and 3-D perspective views (Figure 10) allowing combined visual analysis of different information of the GIS database.

Based on these visualizations young tectonic structures have been identified in their spatial relationship to landslide occurrence. Further geological analysis has aimed at the assessment of the mechanical functions of these structures in the frame of the recent tectonic stress field. They are assumed to be responsible for providing the tectonic impulse for landslide formation in this area of high recent tectonic activity.

Figure 10 illustrates this approach for a subset of the Karamart study area marked as Box II in Figure 6. In the lower part the geological base map (modified after the existing 1:50000 geological map) is overlaid by landslides and tectonic structures as they were interpreted from satellite remote sensing data. In the upper part of the Figure these information on top of a RGB 542 FCC of the September 1999 Landsat-ETM data are draped over a perspective view of the MOMS-2P DEM.

These GIS-based visualizations show that all of the identified landslides have developed their main scarps in Mid-Quaternary loesses (Q_2) overlaying tertiary and cretaceous sediments which are exposed to the surface in some areas (see Table 2 for lithological details). The majority of landslides occurs in form of rational slides. Sliding planes mostly develop within loess, in some cases they also form in the contact zone between the loess accumulations and the underlying meso-cenozoic sediments.

The spatial distribution of landslides is mainly controlled by tectonic structures forming a dextral shear zone of about 2km width. In this area older tectonic fracture elements dating back to the Alpidic structural phase have been reactivated under the influence of the recent tectonic stress field in form of diletation or shear elements. In the result landslides have developed in close spatial relationship to these second order structures. It is assumed that they represent preferred zones of surface water infiltration leading to ground water conditions being especially prone to the formation of slope failures under the given lithological conditions.

The revealed tectonic control on the spatial distribution of landslide has also been observed for other study sites within the area of high landslide activity in Southern Kyrgyzstan (ROESSNER *et alii*, 2004; WETZEL *et alii*, 2000) leading to the assumption that the devel-

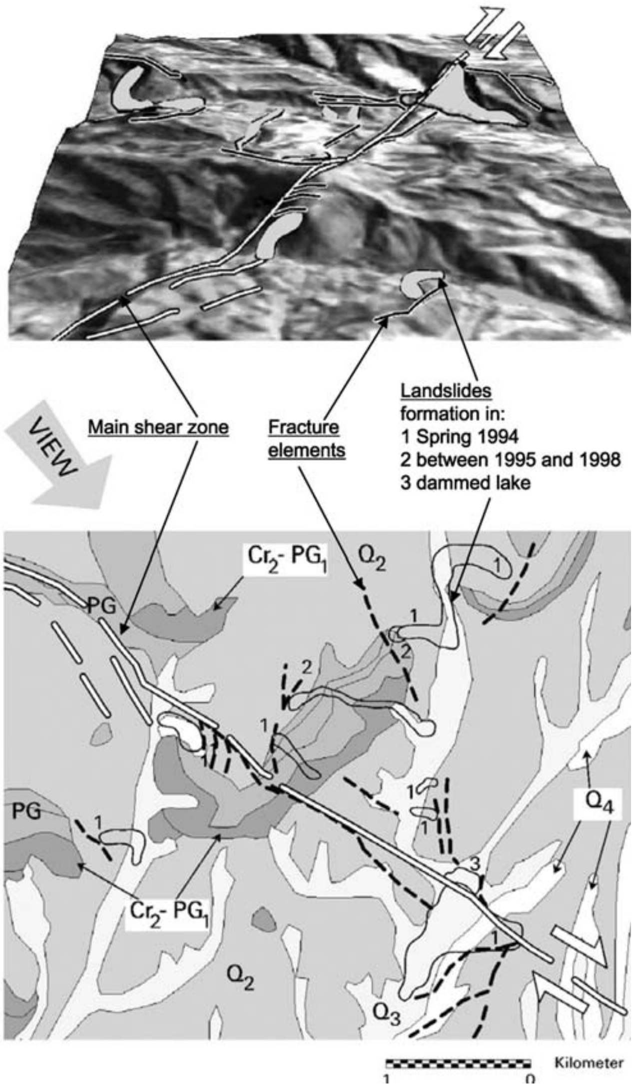

Figure 10 - Identification of young tectonic structures in relationship to landslide occurrence

oped model can be applied to larger areas. Thus, remote sensing and GIS based methods provide important information about landslide processes at a regional scale representing a main prerequisite for landslide hazard assessment in this area.

CONCLUSIONS AND OUTLOOK

Satellite remote sensing based information extraction has become an integral part of many studies analyzing slope failures in different parts of the world. With the recent availability of new high resolution sensor systems these data have started to replace the traditional use of aerial photographs which are hard to access for many parts of the world. In contrast, satellite remote sensing data are stored in centralized archiving facilities operated by the owners of the systems who are interested in distributing the data as widely as possible. In the result a wide range of methods and applications using these data for analyzing mass movements has developed during the last years.

Their outcomes have showed that satellite remote sensing data allow identification and monitoring of mass movements as well as characterization of predisposing factors. For identification purposes best results are obtained using multispectral data covering not only the visible and near infrared part of the spectrum but also the short-wave infrared wavelength range containing important spectral features for characterizing lithological conditions. However, spatial resolution is still the main factor limiting the use of multispectral satellite remote sensing data. Against this background techniques for merging remote sensing data of different spatial resolution have developed and successfully applied for analyzing mass movements.

Investigations of slope failures and related phenomena, such as temporary river blockage always require incorporation of topographic information. With the recently available stereo satellite remote sensing data a long-time existing bottleneck of digital topographic data of sufficient spatial resolution and height accuracy has been overcome for most parts of the world. Another advantage of these systems is the simultaneous recording of stereo and spectral information opening up new opportunities for analyzing surface characteristics in relationship to underlying relief properties.

Optical stereo data as well as interferometric SAR data allow quantitative monitoring of mass movement related surface changes. The obtained spatially continuous displacement fields represent important information for a better process understanding. Currently, the great potential of these methods cannot fully develop due to insufficient temporal availability of these data. This problem can only be overcome with data acquisition schemes of higher spatial and temporal flexibility.

Applying some of the discussed satellite remote sensing data and methods for information extraction to the investigation of landslide processes in Southern Kyrgyzstan shows that these data are a valuable source of information allowing the creation of an improved knowledge base for landslide analysis. Successful information extraction requires the combined analysis of satellite remote sensing data with other thematic information using the analytical environment of a GIS. Such an approach was applied to the analysis of the geological setting revealing young tectonic structures as the main factor controlling the spatial distribution of landslides.

Full exploitation of the spatial, spectral and temporal information content of the available satellite remote sensing data requires the combination of interactive interpretation with methods for automated information extraction. Future work will focus on the development of such remote sensing and GIS-based approaches for systematic landslide identification and characterization factors predisposing landslides. The results will lead to an improved process understanding forming the main prerequisite for regional landslide hazard assessment in Southern Kyrgyzstan.

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