Multi-temporal satellite remote sensing for dynamic landslide hazard assessment in Southern Kyrgyzstan

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The presented work has investigated the potential of optical and radar satellite remote sensing for enabling dynamic landslide hazard assessment at a regional scale. For this purpose a large multi-temporal satellite remote sensing database has been established for a 12000 km^2 study area in Southern Kyrgyzstan including a multitude of optical data covering the last 25 years as well as TerraSAR-X and ALOS-PALSAR radar data which have been available for this region since 2007. Optical data have been mainly used for the establishment of a GIS-based dynamic landslide inventory and spatially differentiated characterization of pre-disposing factors with emphasis on structural and tectonic control of landslide occurrence. Radar data analysis has been focused on SAR Interferometry (InSAR) in order to detect surface deformation related to mass movements. The used GIS-based system allows combination of all of the obtained landslide-related information regardless of their initial source and method generation for subsequent landslide hazard assessment.

1 Introduction

In Kyrgyzstan landslides are especially concentrated in the Southern part of the country along the Eastern rim of the Fergana Basin. In this densely populated mountainous region almost every year large landslides endanger human lives and infrastructure. Therefore local authorities responsible for disaster management and risk reduction have a big need for objective hazard and risk assessment covering large areas in a spatially differentiated way. Enabling objective hazard assessment requires profound knowledge about spatiotemporal distribution and evolution of landslides in order to improve understanding of regional processes activity in its links to predisposing and triggering factors. In this context, multi-temporal landslide inventories are of special importance (FELL ET AL., 2008; VAN WESTEN ET AL., 2008). However, their initial generation and subsequent updates represent big challenges especially in case of large areas where they require the combination of different approaches and data sources as well as incorporation of results into common spatial databases within a GIS environment (GUZETTI ET AL., 2012).

In Kyrgyzstan, landslide inventories have been carried out since the 1950s, whereas approx. 5000 landslides have been recorded by the local authorities. However, regular inventories have been limited to the time period between 1968 and 1992 and focused on areas in the vicinity of settlements. Most of the still available documentations comprise verbal descriptions of main events (e.g., IBATULIN, 2011) whereas in most of the cases precise geographic locations are missing. Thus, the existing knowledge on landslide events is incomplete in space and time and leaves the need for establishing a systematic multi-temporal landslide inventory.

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Because of the limited information base and the large areas which are affected, satellite remote sensing data represent the only consistent, reliable and up-to-date source of spatial information in Kyrgyzstan. Since optical imagery has already been archived for several decades, it enables longer term analysis required for reliable investigation of landslide occurrence. This situation got further improved by opening the Landsat archive in early 2009 providing free access to a profound data pool of widely available optical multi-temporal data (WULDER ET AL. 2012) for large parts of the world including Central Asia. Since landslides are a phenomenon which often significantly changes earth surface characteristics, usually they are well detectable in optical imagery which therefore is suitable for post-failure detection of landslides. In this paper a new approach for automated landslide detection is presented which has the potential for analysis of an optical multi-sensor multi-temporal satellite remote sensing database at a regional scale.

Besides landslide inventories, there is also a big need for quantitative analysis of process parameters and precursors for the onset of slope failures. Such landslide related surface deformation can be derived in high spatial and temporal detail using Differential Radar Interferometry (InSAR) techniques (COLESANTI AND WASOWSKI, 2006, STROZZI ET AL., 2010). In this paper Synthetic Aperture Radar (SAR) imagery acquired by the German X-band TerraSAR-X and the Japanese L-band ALOS/PALSAR satellites are used for detecting slope movements in Southern Kyrgyzstan.

2 Multitemporal satellite remote sensing database

For the study area in Southern Kyrgyzstan a multi-temporal satellite remote sensing database has been established consisting of optical and radar data. The optical database contains 592 multispectral mid- and high-resolution satellite remote sensing images acquired by the Landsat-TM and ETM+, SPOT-1 and 5, ASTER, and RapidEye sensors during the last 25 years. The first image was acquired on the 12th of July 1986 by SPOT-1 followed by a Landsat TM image of 3rd of September 1989, whereas complete annual coverage of the region of interest has been achieved since 1996. The contributing sensors differ widely in their spatial resolution ranging between 30 m for Landsat and 6.5 m for RapidEye data. They also cover different spectral ranges by varying spectral bands and resolutions. However, all of these sensors represent multispectral instruments comprising the green, red, and NIR spectral bands as lowest common denominator forming the basis for comprehensive multi-sensor analysis of landslide related surface changes.

Remote sensing datasets were mostly acquired in form of orthorectified standard data products in order to minimize geometric preprocessing effort and to facilitate operational suitability of the developed approach independent from local ground truth information, such as GCPs. RapidEye data have been acquired in the frame of the RESA (RapidEye Science Archive) program allowing customized tasking of data acquisition during pre-defined time periods. Due to the five independent satellites of the RapidEye system, a database of high spatial and temporal resolution could be established containing approx. 20 complete RapidEye coverages for the four-year period between 2009 and 2012. In total, it comprises of 503 level 3A standard orthorectified data products resampled to 5 m pixel size. Landsat TM and Landsat ETM+ data were obtained from the U.S. Geological Service Global Land Survey (USGS GLS) in form of orthorectified Level 1T data products. In the result the established multi-temporal and multi-sensor satellite remote sensing database solely contains orthorectified datasets.

Radar images were acquired by the ALOS/PALSAR sensor with 46 days repeat cycle during the time period between 2007 and 2010. In total, 38 InSAR ALOS/PALSAR pairs from the ascending mode with an off-nadir angle of 34.3 degrees were processed. TerraSAR-X images have been acquired with 11 days repeat cycle during a time period between May 2009 and May 2010. For this time interval 31 ascending and 25 descending TerraSAR-X data were obtained from the German Aerospace Agency (DLR) with a horizontal resolution of 3 meters, making it an ideal data source to detect small-scale deformation in the order of 2 -3 meters or greater associated with landslide activity.

3 Automated approach for landslide identification

The established multi-temporal satellite remote sensing database forms the basis for the development of an automated approach for landslide identification in order to derive a GIS-based multi-temporal landslide inventory in an object-based form including the potential for qualitative and quantitative characterization of the identified landslide events. The main part of the approach is represented by multi-temporal change detection allowing separation between changes caused by landslide activity from other land cover changes (e.g. agriculture) as well as from artifact changes caused by geometric mismatches and radiometric differences between image data of different acquisition properties. In order to minimize such artifacts, automated change detection requires adequate pre-processing of the multi-temporal image database. Taking into account the high number of more than 500 datasets, pre-processing has to be carried out in an automated and robust form.

3.1 Geometric correction

Since for this area a continuous and consistent external topographic reference, such as large-scale topographic maps has not been available, the free of charge and widely available terrain corrected Landsat Level 1T data are used as topographic reference. The Landsat Level 1T data are characterized by sub-pixel image-to-image registration geolocation accuracy enabling implementation of multiple reference scenes into the co-registration procedure. Using multiple reference scenes of different acquisition dates is advantageous, because it accommodates multi-temporal effects, such as seasonal and long-term land cover changes which often reduce the accuracy of co-registration (GAO ET AL., 2009). Moreover, the used Landsat Level 1T reference enables co-registration independent from the availability of other topographic reference data. Thus, the approach can be applied worldwide under the prerequisite that Landsat Level 1T data are available.

A special image-to-image co-registration approach (BEHLING ET AL., 2012) has been developed in order to correct for the remaining geometric shifts occurring between the standard orthorectified datasets contained in the multi-temporal and multi-sensor database. The approach assumes that the orthorectified standard data products of the various sensors only differ by global shifts in x and y direction which are constant for the whole dataset. Checking the fulfillment of this condition for each dataset is part of the developed approach. The final result includes two co-registered images - one adapted to the grid and spatial resolution of the reference data and one maintaining the spatial resolution of the original data with improved map coordinates in the header file.

The co-registration approach builds on an area based cross-correlation algorithm (DAWN ET AL., 2010) requiring the same spatial resolution for the reference image and the warp image. Resampling of the warp image to the spatial resolution of the reference dataset is a critical step for the performance of the correlation process because different interpolation approaches used for resampling lead to different results. The developed approach simulates realistic Landsat pixels by applying a Gaussian filter kernel taking into account the spatial resolution of both sensors following the approach described in (MUELLER & SEGL, 1999).

The developed co-registration approach has been applied to all of the 592 image datasets resulting in specific shifts for all of them. No image had to be rejected because of the affine criterion in the validation step implying that the previously orthorectified standard image products are characterized by high internal geometric stability. The obtained shifts vary widely between more than 400 m for selected SPOT-1 data and 5 m for the lastest RapidEye data. Typically, shifts of several tens of meters had to be applied during co-registration (BEHLING ET AL., 2012). Assessment of the relative image-to-image accuracy based on time-invariant check points (CPs) has resulted in an overall accuracy of 17 m (RMSE) and maximum remaining offsets of 20 m to the Landsat reference.

Taking into account the 30 m resolution of Landsat, these results show a sub-pixel image-to-image accuracy of the whole multi-sensor database. For the 503 RapidEye data sets sensor-internal image-to-image accuracies of less than 5 m have been achieved. Absolute accuracy of the co-registered database has been evaluated based at 52 differential GPS (DGPS) points showed an overall accuracy of 23 m (RMSE) and a maximum position error (PE) of 29 m with a systematic shift in western direction. The obtained results have proven the robustness of the developed co-registration approach against variabilities in the image data resulting from various multi-sensor and multi-temporal effects often impeding the applicability of already existing co-registration approaches.

3.2 Multi-temporal Change Detection

The developed multi-temporal change detection approach (BEHLING ET AL., 2013) is based on the analysis of temporal trajectories of NDVI time series derived from the pre-processed multi-temporal satellite remote sensing data stack. These temporal trajectories are derived for every pixel across the time span of the entire data archive and thus allow analysis of vegetation cover changes over longer periods of time rather than solely assess the absence of vegetation in a single dataset or the loss of vegetation between two datasets. These specific temporal footprints of vegetation changes enable identification of landslide events due to the temporal characteristics of destruction and regeneration of the vegetation cover caused by the landslide event itself as well as by longer-term processes of (re)activation of landslide-prone slopes. They need to be distinguished from temporal changes of the vegetation cover caused by other processes, such as agricultural land use.

For this purpose a combined pixel- and object-based approach has been developed which is divided into three main steps: 1) bi-temporal change detection, 2) segmentation based on the bi-temporal change result and 3) object-based multi-temporal change detection for final delineation of landslide events (BEHLING ET AL., 2013). So far, this approach has been applied to the entire multi-temporal RapidEye image database containing 20 complete temporal coverages for the whole study area between the years 2009 and 2012. For every analyzed time period a shapefile has been produced containing the image-intrinsic likelihoods for a landslide occurring within this time period.

Visual evaluation of the derived objects resulted in the selection of about 250 objects most likely representing surface changes related to landslides. The size of these objects is ranging between 500 and 250,000 square meters and the total area affected by these landslide-related changes amounts to 5.5 million square meters. About half of these changes happened between 2009 and 2010. For the analyzed time period between 2009 and 2012 the Ministry of Emergency Situations of Kyrgyzstan has only reported 40 events.

The obtained results have been verified during a four-week field survey which took place in September 2012. During this survey about 100 of the 250 detected landslides have been visited and in almost all of these cases the field checks confirmed recent surface changes related to landslides. Exceptions were primarily caused by the extraction of construction material (e.g., clay and gravel) at the bottom of hillslopes representing artificial mass movements. This field survey has revealed that the developed approach is capable of automatically detecting different kinds of mass movements caused by a variety of slope processes, such as rotational and translational landslides as well as debris flows under diverse natural conditions. Thus, it could be shown that the approach can be used for reliable automated landslide detection at a regional scale.

4 InSAR based deformation analysis

Applying InSAR methodS, only one-dimensional displacements in the satellite's line of sight can be observed. Therefore, the SAR interferograms only show such displacements where the surface moves towards or away from the satellite along this line of sight. InSAR data were processed by repeat-pass interferometry technique using the DORIS and SARScape software. The topography-related phase in the interferometric processing was estimated and removed from the interferograms using a 3 arcsec digital elevation model from the Shuttle Radar Topography Mission (SRTM). The differential interferograms (complex wrapped images) were low-pass filtered using a multi-looking factor of 10 by 10 to mitigate the impact of high-frequency phase variation due to water vapor variation. The results have been used for landslide surveys covering larger parts of the study area. Moreover, to better assess and analyze ground deformation that may affect individual landslide-related features at local scale, InSAR time-series analysis was applied using the Small Baseline Subset (SBAS) method (MOTAGH ET AL., 2013).

4.1 TerraSAR-X analysis

The X-band interferograms showed a wide range of variation in the phase coherence: the interferometric coherence in the region proved to be generally good for short-term (~1-2 repeat cycles) summer and fall interferograms, but degraded quickly in the winter and early spring period even for images separated by a single repeat cycle of TerraSAR-X satellite (11 days), presumably because of continuous snow cover, rainfall or starting of vegetation growth.

In order to detect surface deformation related to mass movements, consistent phase change variations were identified in multiple coherent interferograms in order to avoid misinterpretation of atmospheric artifacts and other error sources as displacement. Using descending and ascending interferograms, mass movements occurring on slopes facing towards the west and east could be identified. Subsequent InSAR time-series analysis provided a much more detailed overview of landslide phenomena in the region than what was inferred from repeat-pass interferometry (MOTAGH ET AL., 2013).

4.2 ALOS/PALSAR analysis

The interferograms obtained by ALOS/PALSAR for SAR interferometry analysis show very good coherence even for image pairs of more than 2 years temporal resolution covering mountainous and vegetated terrain. This way, numerous slope instabilities have been identified for the analyzed three years period of time of ALOS-PALSAR data availability. The obtained results have been verified by field investigations carried out in September of 2011 and 2012.

5 Discussion and outlook

The developed approach for automated landslide detection has been applied to the entire optical RapidEye database enabling systematic derivation of a multi-temporal landslide inventory for the 12000 km^2 study area along the Eastern rim of the Fergana Basin which is required for objective hazard and risk assessment. Although compared to previous years process activity had been rather low during the analysed time period between 2009 and 2012 and no specific triggering event has been known, a total of about 250 landslides could be automatically detected. This shows the constant ongoing process activity occurring independently from distinct triggering events in this area. This situation emphasizes the need for systematic multi-temporal landslide inventories in regions dominated by complex slope failures, such as the Eastern rim of the Fergana Basin. In a next step the developed approach will be applied to a longer-term time series containing multi-temporal image data acquired by a variety of optical sensor starting from 1986 whereas annual coverage for the complete study area has been available since 1996.

In contrast to the very good long-term coherence of the ALOS/PALSAR interferograms, coherence of TerraSAR-X interferograms is generally sufficient for shorter-term summer interferograms, whereas coherence degrades quickly during winter season even for image pairs only separated by a single repeat cycle of 11 days. This loss of coherence is most likely caused by snow cover influencing strongly the X-band signal. However, during summer season the high temporal resolution of the TerraSAR-X interferograms allow a more detailed process analysis in comparison to the L-band results. Overall, time-series analysis for mapping and measuring of landslide movements on a regional scale was found to be straightforward and reliable on the basis of field observations and comparison with high-resolution optical remote sensing data. The use of SBAS method proved to have greater value for both qualitative and quantitative distinction between stable and unstable slopes, thereby allowing detailed instrumental monitoring is focused on areas where we have heightened potential for slope movement.

Field-based verification and further optical remote sensing analysis of the InSAR results have revealed that the detected phenomena most likely correspond to slow movements being characteristic for reactivation processes of previously occurred slope failures. Since landslide-prone areas in Southern Kyrgyzstan are mostly subject to long-term reoccurring failures, our findings can contribute to the recognition of landslide activation processes with high temporal and spatial resolution. Thus, these results have demonstrated the potential of the applied InSAR techniques for regular monitoring of slope movements covering larger areas in Southern Kyrgyzstan which are strongly affected by landslides. Future work will investigate the synergetic use of optical and radar satellite remote sensing data for comprehensive multi-temporal assessment of landslide activity as a main prerequisite for dynamic hazard assessment

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