Remote Sensing and GIS based Approach for Multi-Source Landslide Mapping in Southern Kyrgyzstan

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Southern Kyrgyzstan is a region of high landslide activity frequently endangering human lives and infrastructure. So far, precise spatio-temporal information on landslide occurrence has been limited, although in this region landslide activity has been investigated for the last 60 years by local authorities with the goal of protecting people from the consequences of catastrophic slope failures. The objective of the presented research is the development of a satellite remote sensing and GIS-based approach for the establishment of a spatially and temporally consistent multi-temporal landslide inventory at a regional scale for the area of approx. 12000 sq km characterized by high landslide activity. Such an inventory is one of the main prerequisites for probabilistic landslide hazard assessment. For this purpose, multiple sources of information about slope failures have been analyzed in regard to their GIS-based integration into a single system with a common spatial reference. They include information collected by local authorities and residents, results from field mapping and visual interpretation of satellite remote sensing data as well as automated landslide detection based on a multi-temporal and multi-sensor satellite remote sensing database covering the last 25 years. These multi-source landslide data have been geometrically adjusted to a multi-temporal RapidEye data stack allowing their comprehensive analysis. As a result, landslide information could be verified, checked for consistency and in parts spatial and temporal characterization of the documented slope failures has been extended and improved. The resulting landslide inventory information system contains approx. 900 landslides. This inventory also distinguishes between different phases of landslide activation along the same slopes whereas temporal and spatial characterizations of the different mass wasting events have been mostly derived from automated multi-temporal analysis of satellite remote sensing data. This way, the developed GIS-based approach is based on the combination of a variety of remote sensing techniques allowing the establishment of a multi-temporal landslide inventory which is required for dynamic landslide hazard assessment.

1 Introduction

Southern Kyrgyzstan is an area of high landslide activity frequently resulting in the loss of human lives and damage to buildings and infrastructure. Landslides are especially concentrated along the Eastern rim of the Fergana Basin (Fig. 1). This area of about 12,000 km^2 administratively covers the Osh and Jalalabad districts (oblasts). The region belongs to the foothill zone of the adjacent high mountain areas and is situated at elevations between 700 and

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2000 m a.s.l. Large landslides occur mostly within weakly consolidated Mesozoic and Cenozoic sediments which have been subjected to ongoing tectonic deformation (Roessner et al. 2005, Wetzel et al. 2000). The topographically rising rim of the Eastern Fergana Basin represents a barrier to the prevailing westerlies leading to increased precipitation levels in comparison to the areas that are situated further east. All of these factors create favorable conditions for the vast development of landslides in this area. At the same time, the region represents an important human living space. Therefore, there is a big need for a spatially differentiated assessment of landslide hazard and risk. The establishment of a spatially and temporally consistent multi-temporal landslide inventory is of high importance.

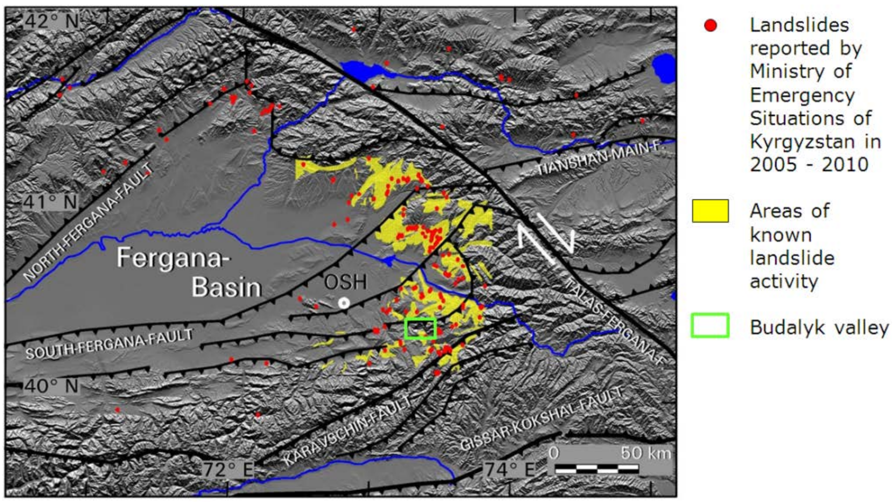

Fig. 1: Study area (yellow) and Budalyk valley (green) in Southern Kyrgyzstan

A wide range of methods and approaches have already been developed in order to carry out landslide inventories. They are comprehensively discussed by Guzzetti et al (2012) distinguishing between archive-based, historical, event-based, seasonal and multi-temporal inventories. Since most slope failures in Southern Kyrgyzstan are a result of complex interplays between different predisposing and triggering factors rather than of major triggering events (e.g. strong earthquakes or typhoons), a multi-temporal inventory for the area is required.
Because the area affected by landslides is large (regional scale) and some of its parts are difficult to access, field-based landslide mapping is very time-consuming and difficult in the study area. Therefore, the establishment of a comprehensive multi-temporal landslide inventory requires incorporating information from all available sources as well as using multi-temporal satellite remote sensing data as a consistent archive of surface conditions over large areas.
The objective of this study is the establishment of a multi-temporal landslide inventory for the area of high landslide activity in Southern Kyrgyzstan using a satellite remote sensing and GIS-based approach. The inventory should contain spatially and temporally explicit information about single landslide events as well as complex landslide-prone slopes which have been subject to several phases of reactivation. The resulting GIS-based multi-temporal landslide inventory is required for deriving spatial and temporal probabilities for probabilistic landslide hazard assessment (Guzzetti et al. 2005). Such an inventory has not been compiled yet for this region.

2 Data Sources of Landslide Information

The establishment of a multi-temporal landslide inventory for Southern Kyrgyzstan is a challenging task since the existing information on landslide failures is very heterogeneous. On the one hand, multiple sources of landslide data are available. They include data obtained from Kyrgyzstan's authorities, landslide mapping conducted during field campaigns, results of manual interpretation of mono- and multi-temporal satellite images as well as landslides which have been automatically detected from a multi-temporal satellite image database (Fig. 2). On the other hand, these sources vary in the time periods they cover, their spatial and temporal completeness as well as their accuracy. Furthermore, these landslide data are of analogue and digital origin and they have different formats, such as verbal description, tabular data, and vector information (points and polygons). In the following sections, we give a detailed overview of the available sources of landslide information. This description is illustrated in an exemplary way showing the data situation for the Budalyk valley next to the town of Gulcha in Osh district. Its location within the study region is shown in Fig. 1. However, information assessment has been carried out for the entire area of high landslide activity.

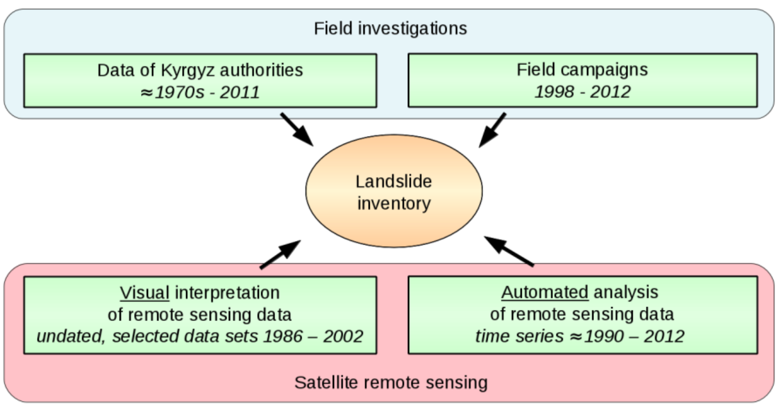

Fig. 2: Overview of main sources of data on landslide occurrence for Southern Kyrgyzstan

2.1 Landslide Data from Kyrgyzstan's Authorities

Since the 1950's, landslide investigations have been carried out in this region (Roessner et al. 2005). Regular monitoring of endangered areas was conducted form the 1960's until the break-up of the Soviet Union at the beginning of the 1990's. These activities also included extensive field-based mapping of landslides as well as detailed engineering-geological investigations. The main goal had been the timely warning of the population and, if necessary, their evacuation and resettlement. However, after the independence of Kyrgyzstan, the possibilities for landslide investigations and monitoring have drastically reduced. Furthermore, significant parts of the already existing data (e.g. maps and reports) are not available anymore or their use is limited because of the loss of accompanying information related to methodology, data sources, etc.

An important source of information on past landslide failures is the report "Monitoring of Landslides of Kyrgyzstan" (Ibatulin 2011). The report presents a description of selected landslide failures which have been observed mainly during field investigations between the

1970's and 2005. For some of the landslides, the report contains a very detailed verbal description including results from geotechnical investigations of the potentially dangerous slopes. The report also includes precise temporal information about landslide events whereas in most of the cases the day of failure is known, for some events even the hour of the day. In case of failures occurring before 1990, the report is the only source of temporal information on slope failures which has not been documented otherwise.
However, using data from the report is problematic because of the verbal description of the landslide information. It is difficult to find the location of some of the described landslides, and for most of the cases it is impossible to determine the spatial extent of the slope failures. Another problem is that the report only documents large landslides, landslides in inhabited areas and areas visited by landslide experts responsible for monitoring. Therefore, the resulting landslide information is biased towards the needs of civil protection. In Fig. 3 the landslides contained in the report are outlined in orange. They represent only a subset of slope failures in this area.

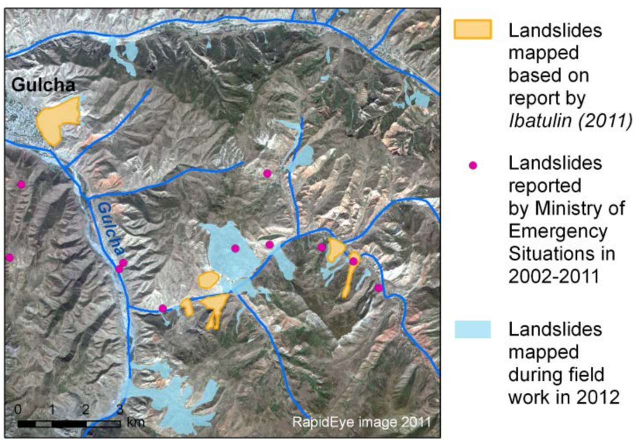

Fig. 3: Landslides reported by the Ministry of Emergency Situations of Kyrgyzstan and landslides mapped during field work

Moreover, employees of the Ministry of Emergency Situations of Kyrgyzstan visited selected areas affected by landslides between the years 2002 and 2011 and recorded new landslides. The results of these surveys are available in form of tables. They represent only a small number of landslides which occurred in inhabited areas. In Fig. 3 they are shown by pink dots. Their location is represented in the table by a pair of x- and y-coordinates. However, their spatial extent is not documented. Temporal information is only contained in form of the date of field mapping whereas the time of the actual failure is mostly unknown.

2.2 Landslide Data from Field Mapping

The Remote Sensing section of the German Research Centre for Geosciences (GFZ) has been conducting field work in Southern Kyrgyzstan since 1998 in cooperation with the Ministry of Emergency Situations of Kyrgyzstan. During this time, repetitive field work has been carried out including selective landslide mapping. Landslide locations were recorded by GPS and documented by field photos. They have been spatially referenced by linking them to the GPS waypoints and integrated into the GIS using the extension ArcPhoto in ArcGIS. During these field investigations, additional information about the landslides, such as date of failure, mechanism, estimated volume and state of investigation were provided by the experts of the

Ministry of Emergency Situations of Kyrgyzstan as well as by local residents. Field mapping was supported by satellite remote sensing data in order to map the spatial extent of the landslides which often could not be determined in the field due to the large extent and difficult accessibility of the landslides. Because of the large area affected by landslides, each of these field campaigns could only cover selected parts. However, many landslide prone slopes have been revisited several times and thus the resulting photo documentation allows analyzing the temporal development of these slopes (e.g., revegetation).

2.3 Expert Interpretation of Satellite Images

Landslide mapping conducted during field investigations has been extended by expert interpretation of satellite remote sensing data in combination with a DEM using the perspective visualization capabilities of a GIS (Roessner et al. 2005). As a result, landslide scarps and masses have been determined systematically for the whole area of interest (Fig. 4). The expert also includes information about geological structures and other landslide predisposing factors in the analysis. This method is especially suitable for mapping landslide-prone slopes which have experienced several phases of reactivation resulting in complex morphological structures. However, this integrative mapping method cannot provide differentiated information on the dates of slope failures. They have to be added from other sources when available. Furthermore, the method is labor-intensive and mostly used for initial landslide mapping.

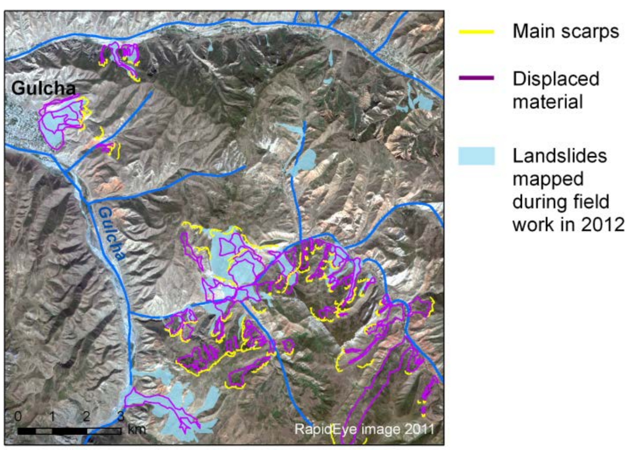

Fig. 4: Results of landslide scarps and masses interpreted from mono-temporal satellite images

2.4 Multi-temporal Analysis of Satellite Images

In order to establish a dynamic landslide inventory containing the temporal evolution of landslide-prone slopes, multi-temporal analysis of satellite remote sensing data has to be carried out. For the area of high landslide activity, a multi-temporal and multi-sensor satellite remote sensing database has been established starting 1986 (Behling et al. 2012). It enables analysis of landslide occurrence in multiple time steps with higher temporal and spatial precision allowing spatio-temporal reconstruction of the evolution of landslide-prone slopes. The temporal resolution is determined by availability of satellite images which is better in recent years since 2000 and more limited for the years before. However, interpreting these sequences of images visually is very labor-intensive and could only be carried out for a small subset of the study area.

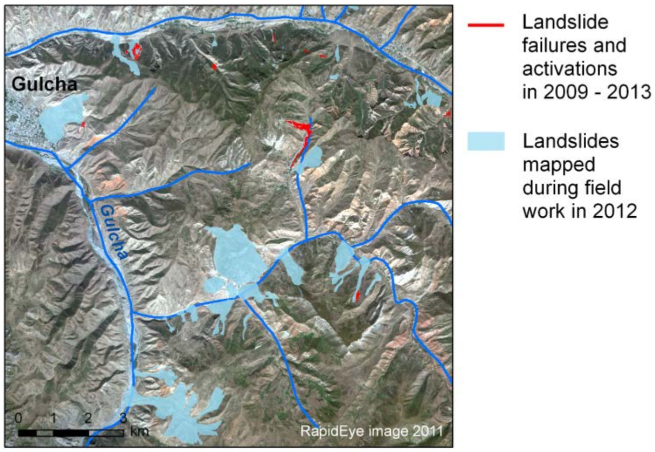

Fig. 5: Results of automated landslide detection from RapidEye data in 2009 - 2013

In order to solve this problem, an automated approach for landslide detection has been developed at the Remote Sensing Section of the German Centre for Geosciences using the established multi-temporal satellite remote sensing database (Behling et al. 2013). This approach allows analyzing large areas in multiple time steps. Fig. 5 shows the results which have been obtained for the area of the Budalyk valley from high-resolution RapidEye satellite data acquired between 2009 and 2013. In this relatively small area, multiple small mass movements and one large slope failure could be detected that had not been known otherwise. Using this method for the complete study area, about 625 landslides have been detected automatically. During the same period, the Ministry of Emergency Situations only reported about 40 landslide events. Thus, the developed approach yields excellent possibilities for efficient landslide detection over large areas allowing regular updates of existing landslide inventories as new satellite remote sensing data become available.

3 Approach for GIS-based Data Integration

Integration of all of the described landslide information sources into a GIS-based system requires the establishment of a common spatial reference. In this study, the spatially adjusted multi-temporal RapidEye data stack has been used as spatial reference (Behling et al. 2012). In case of the report by Ibatulin (2011), the verbal landslide descriptions were transformed into spatially explicit information using high-resolution RapidEye satellite imagery in combination with a scanned 1:100,000 topographic map. Some of the described slope failures were difficult to localize because distinct morphological features could not be visually interpreted from the remote sensing data since these traces had largely been eroded. Furthermore, the names of some of the villages had changed after the collapse of the Soviet Union. For spatial localization of landslide events contained in the report we also used the results of our own field-based mapping. Landslide localization has often required careful consideration of slope failures documented in multiple data sources. In such cases, we used these repeated entries to verify the data, correct possible errors, improve localization of the landslides and determine the time of their failures with higher precision. After all data sources were converted into a spatially explicit form, they were transformed to UTM/WGS84 as the common spatial projection.

Even though multiple sources of data on landslides have been used, all of them only provide information on a subset of slope failures in the study area. The degree of completeness varies with time for different sources. For example, remote-sensing-based landslide identification can deliver data on recent slope failures, whereas the report by Ibatulin (2011) is suitable for extracting historical information. The landslide report by Ibatulin (2011) contains detailed information on the dates of slope failures in inhabited areas, but the location and spatial extent of the described landslides are often ambiguous. On the other hand, visual and automated landslide detection from satellite images offers higher spatial precision but less precise dating of landslide events, regardless of their proximity to settlements.

4 Results and Discussion

As a result of the GIS-based integration of the landslide data with careful consideration of temporal information and documentation of repeated landslide failures within the same slope, we have obtained a multi-temporal landslide inventory system for Southern Kyrgyzstan. Due to the use of remote sensing, it has been possible to produce an inventory of an objective and regional character. This inventory contains a total of over 900 landslides which were identified by different methods from various sources of information. Tab. 1 gives an overview of the results.

Tab. 1: Components of landslide inventory obtained from different data sources and their properties

Source	Period covered	Number of landslides	Landslide area, km²
Report by Ibatulin (2011)	1970's – 2005	72	25.4
Ministry tables	2002 – 2011	73	point data
Field mapping	not dated	263	105.8
Expert interpretation	not dated	n/a	172.9
Automated detection	2009 – 2013	625	8.2

Besides the data on the location of a given landslide and known dates of its failure, the landslide inventory information system is capable of storing commonly assessed landslide attributes, such as area, length, slope angle and exposition, etc. Many of these values can be calculated within a GIS. Furthermore, the landslide inventory information system will include data on landslide triggering and predisposing factors within the same spatial reference. The described GIS-based system facilitates the joint analysis of the available spatial data on landslides as the basis for a regional landslide hazard assessment.

The automated method for landslide detection from multi-temporal satellite images enables updates of existing landslide inventories that are more precise and less time-consuming compared to other methods. The updated inventory is the basis for carrying out repeated hazard assessment and verifying results of previous analyses. This way it has been possible to establish a dynamic landslide inventory as a main prerequisite for dynamic landslide hazard assessment.

Satellite remote sensing plays an important role in the compilation of a multi-temporal landslide inventory at a regional scale. Firstly, it is the central source of objective information on land cover change at the regional level. It is the basis for both manual and automated landslide detection and thus enables a significantly higher level of inventory completeness. Secondly, satellite images and DEMs provide the common spatial reference for adjusting heterogeneous landslide data and enable an improved spatial and temporal characterization of landslides. Thirdly, new satellite images can be acquired in order to update an already existing inventory and thus be a step towards a continuous monitoring system of landslide activity.

In our future work, we plan to use the compiled landslide inventory for landslide hazard assessment, which will include the analysis of spatial and temporal probability of landslide failures. Furthermore, we plan to continue updating the established landslide inventory using newly available satellite remote sensing data. This way, we will contribute to an improved process understanding in this area of high landslide activity which in a next step can be related to landslide predisposing and triggering factors, such as precipitation, seismic and tectonic activity as well as lithological and structural conditions.

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