GIS Methods and Multi-Temporal Remote Sensing Data for Improved Landslide Hazard Mapping in Southern Kyrgyzstan

Golovko, D.,[1] **Behling, R.,**[2] **Wetzel, H.-U.**[3] **and Roessner, S.**[4]
GFZ German Research Centre for Geosciences Potsdam, Section 1.4 – Remote Sensing
E-mail: dgolovko@gfz-potsdam.de,[1] behling@gfz-potsdam.de,[2] wetz@gfz-potsdam.de,[3] roessner@gfz-potsdam.de[4]

Abstract

In Southern Kyrgyzstan, large landslides frequently occur with a high potential for endangering human lives and infrastructure. Landslides are especially concentrated along the eastern rim of the Fergana basin, which represents an important human living space in this mountainous country. The relationships between landslide occurrence and predisposing and triggering factors have not been completely understood yet. An objective and comprehensive landslide inventory is a prerequisite for these analyses. The paper shows how the use of multi-temporal remote sensing data combined with landslide information from other sources allows to create a multi-temporal landslide inventory for the data-scarce study area in Southern Kyrgyzstan. The application of GIS methods enables an efficient data integration and access as well as automated derivation of landslide attributes.

1. Introduction

The foothills of the Tian Shan mountain ranges along the eastern rim of the Fergana basin in Southern Kyrgyzstan are subject to high landslide activity. Since this region is an important human living space in the mountainous country, landslides represent a major natural hazard here causing fatalities and severe economic losses. This area of about 12 000 km^2 administratively covers the Osh and Jalalabad provinces (oblasts). Large landslides occur mostly within weakly consolidated Mesozoic and Cenozoic sediments which have been subjected to ongoing tectonic deformation (Roessner et al., 2005 and Roessner et al., 2014) at elevations between 900 and 2 000 m a. m. s. l. The topographically rising eastern rim of the 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 intense and frequent occurrence of landslides in this area. Landslides are a severe threat to the local population, which creates a strong need for a spatially differentiated assessment of landslide hazard and risk. A landslide inventory is a prerequisite for a landslide hazard assessment, which includes an evaluation of the spatial and temporal probability of landsliding (Guzzetti et al., 2005). The spatial probability of landslide occurrence, also referred to as landslide susceptibility, is determined by establishing a spatial relationship between the distribution of landslides and the characteristics of predisposing factors. Predisposing factors include properties of the environment that are relevant for the occurrence of landslides and remain constant over long periods of time, e.g. geological structures, faults and relief parameters. The temporal probability of landslide occurrence is studied by analyzing the landslide intensity in relation to changes in triggering factors. Triggering factors represent processes that change dynamically and cause the temporal onset of slope, such as rainfall, snowmelt and seismicity. The use of remote sensing and GIS technologies allows carrying out the landslide hazard assessment in an efficient and spatially consistent way. They contribute to every component of landslide hazard assessment. Remote sensing data are a valuable source for obtaining landslide inventory data and serve as common spatial reference for the heterogeneous information on landslides, predisposing and triggering factors that originates from different sources. The characterization of predisposing and triggering factors is also supported by these technologies. ASTER GDEM is used for the calculation of relief parameters. Optical imagery is used for verifying and improving the information on geological characteristics of the study area, e.g. a more precise localization of the boundaries of stratigraphic or lithological units.

Hydrometeorological information on precipitation and surface temperature is also derived with the support of remote sensing data. E.g. the information on precipitation delivered by the TRMM mission and the data on precipitation, snow cover and surface temperature provided by the MODIS sensors can be used for landslide studies. The continuous nature of satellite imagery acquisition creates the basis for future updates of the information on slope failures and landslide triggering factors. Thus the use of remote sensing represents one of the main prerequisites for dynamic landslide hazard assessment and the establishment of a landslide monitoring system in this region. The preparation of landslide data for the hazard assessment and the derivation of landslide attributes can be carried out in a more efficient and objective way using GIS. This is especially important due to the large size of the study area and the limited data availability, which requires combining data from multiple information sources. In the following, we present a GIS and remote sensing based approach for the compilation of a multi-temporal multi-source landslide inventory for Southern Kyrgyzstan with the possibility for data updates. The resulting inventory contains spatially explicit and consistent information on landslide activity with the best possible temporal resolution. In the next step, we derive a number of landslide attributes characterizing the location, geometrical and geo-environmental properties of landslides.

2. Sources of Landslide Data

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 (Golovko et al., 2014). They include data obtained from Kyrgyzstan's organizations, landslide mapping conducted during field campaigns, results of visual interpretation of mono- and multi-temporal satellite images as well as landslides which have been automatically detected from a multi-temporal satellite image database. On the other hand, these sources vary in their temporal coverage, 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, we give a detailed overview of the used sources of landslide information. In order to determine and verify the spatial position and extent of landslides documented in the various information sources, supplementary data were used.

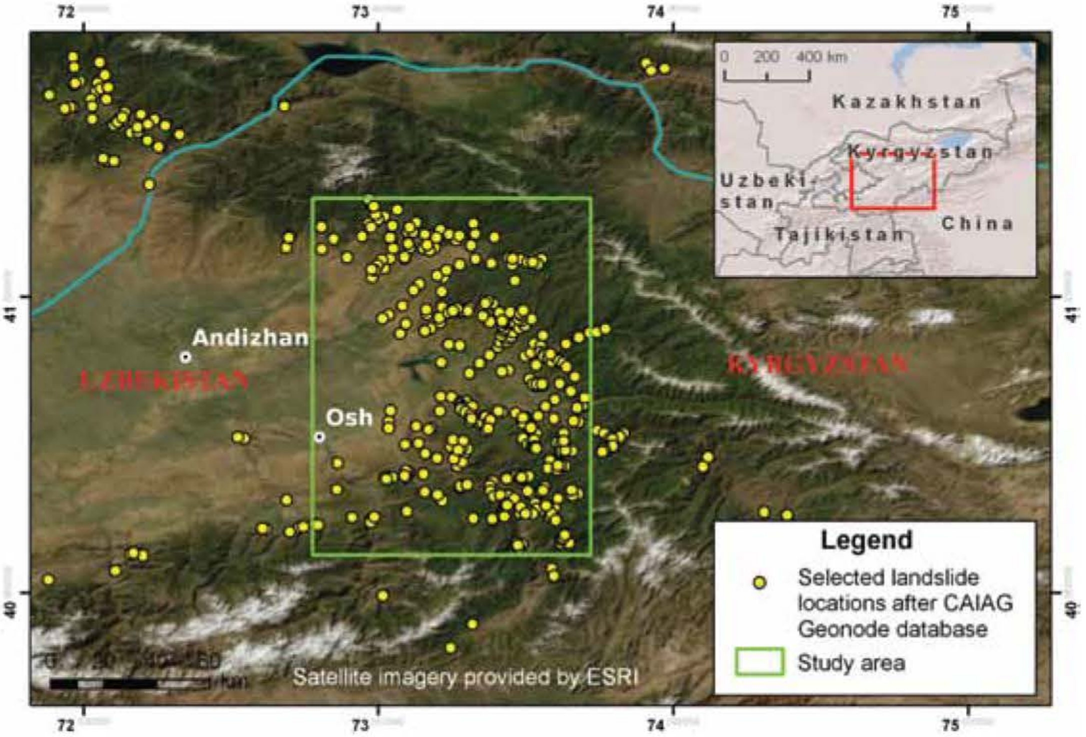

Figure 1: Study area in Southern Kyrgyzstan with selected landslide locations according to data obtained from CAIAG Geonode database (geonode.caiag.kg). Basemap data by ESRI

They include a multi-temporal spatially adjusted data stack of optical satellite images (Behling et al., 2014a), high-resolution multi-sensor imagery made available by Google Earth^{TM}, a DEM (ASTER GDEM), scanned 1:100 000 topographic maps used when the landslide location is specified in relation to settlements or rivers, and GPS-based documentation of field investigations. These data have been particularly valuable for the derivation of the spatial location or extent of the landslides that originally did not have an explicit spatial reference and for the verification and homogenization of existing spatio-temporal information on slope failures.

2.1 Information Obtained from Local Organizations

Observations of landslide activity in Southern Kyrgyzstan have been carried out by local organizations since the 1950s (Roessner et al., 2005). From the 1960s until the breakup of the Soviet Union, regular monitoring was conducted for the most endangered areas focusing on settlements and their surroundings. These investigations also included extensive field-based mapping of landslides as well as detailed engineering-geological analysis of selected slopes. The main goal of these activities was the timely warning of the population and, if necessary, their evacuation and resettlement. After the independence of Kyrgyzstan, these efforts have continued; however, they have decreased due to the shortage of funding. In this context, it has been important to include all accessible information on past landslide activity in Southern Kyrgyzstan. One recent source of information on slope failures is the report by Ibatulin (2011) containing descriptions of selected landslide failures which have been documented mostly as the result of field investigations carried out between the 1970s and 2005. The report comprises detailed verbal descriptions of the slope failures including results from geotechnical investigations of potentially endangered slopes. The report also contains precise temporal information on single landslide events whereas in most of the cases the exact day of the failure is known. However, it does not include explicit coordinate or map-based spatial information on the location of the described slope failures. This information is provided in the form of verbal descriptions related to significant features contained in topographic maps. Therefore, reliable localization of the described landslides has required the use of additional data, such as optical satellite imagery covering multiple time steps. However, since most of these landslides occurred quite some time ago, it is difficult to determine their original spatial extent. For this purpose, additional field investigations have been carried out in combination with the analysis of archived remote sensing data. Overall, the report focuses on large landslides in the vicinity of inhabited areas. Thus it contains episodic rather than systematic landslide inventory information. Another source of information on past landslide activity is the report by Yerokhin (1999) consisting of verbal descriptions accompanied by tabular and map-based information on single landslide events. For this report, landslide mapping was carried out in a systematic way representing the cumulative assessment of the landslide situation by the end of the 1990s. Although this report contains spatially explicit information, the mapped landslides needed to be evaluated and spatially adjusted using satellite remote sensing data.

2.2 GFZ Field Campaigns

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 and the Central-Asian Institute for Applied Geosciences (CAIAG) in Bishkek. Because of the large area affected by landslides, each of these field campaigns has covered selected parts of the study area. However, many of these areas have been visited multiple times. These investigations have been focusing on comprehensive understanding of the landslide processes with special emphasis on recent tectonic activity as one of the main predisposing factors for slope failures in this region. Field work has been extensively supported by satellite remote sensing analysis in order to efficiently cover large areas, especially in the fields of structural geology and landslide mapping. The findings were recorded in waypoint-oriented field documentation, satellite remote sensing based maps and field photographs, whereby all of them were geo-located by field-based geodetic and hand-held GPS measurements.

2.3 Satellite Remote Sensing Analysis

Landslide mapping conducted during field investigations has been extended by expert interpretation of satellite remote sensing data in combination with digital elevation data and geological information 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. This method has proven to be especially suitable for mapping landslide-prone slopes which have experienced several phases of reactivation resulting in complex morphological structures. 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 been carried out. For the area of high landslide activity, a multi-temporal and multi-sensor satellite remote sensing database with over 700 images has been established starting from 1986. The composition of the database including the properties of the different sensors is described in detail in Behling et al., (2014a). The database enables analysis of landslide occurrence in multiple time steps with higher temporal resolution in a spatially explicit way allowing spatio-temporal reconstruction of the evolution of landslide-prone slopes. The temporal resolution is determined by availability of the satellite imagery which has significantly increased since 2000 for this region. However, visual interpretation of these multi-temporal image data is very labor-intensive and could only be carried out for subsets of the study area. In order to perform multi-temporal analysis for the whole study area, an automated approach for landslide detection has been developed based on the established multi-temporal satellite remote sensing database (Behling et al., 2014b and Roessner et al., 2014). This approach is based on analyzing temporal NDVI trajectories to separate landslides from other land cover changes and allows working with large areas and multiple time steps. Applying this approach to the complete study area has resulted in automated detection of more than 600 landslides for the period between 2009 and 2013. Furthermore, over 1 500 slope failures have been identified for the period between 1986 and 2013 for a subset of the study area. The obtained results have revealed a constantly ongoing process activity in this region requiring regular and systematic landslide monitoring.

3. GIS-Based Data Integration

Integration of all of the described landslide information sources into a spatial information system requires the establishment of a common spatial reference. In case of the report by Ibatulin (2011) and the field mapping results, the verbal landslide descriptions were transformed into spatially explicit information using a mosaic of scanned 1:100 000 topographic maps for the initial localization of the described landslides in combination with high-resolution RapidEye satellite imagery for the subsequent determination of their more precise position and spatial extent. 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 inconsistencies, improve localization of the landslides and determine the time of their failure with higher accuracy and reliability. After all data sources had been converted into a spatially explicit form, they were transformed to UTM/WGS84, zone 43N used as the common spatial projection. The resulting multi-source landslide inventory contains over 2 500 individual landslides mapped as polygons, over 1 600 landslides mapped as points and over 170 km² of mapped landslide bodies with no differentiation of individual objects. Figure 2a shows landslides stored in the inventory in form of polygons for a 20 by 20 km subset of the study area. Some of the landslide data sources provide information on single slope failures, whereas the others document complex landslide-prone slopes, which are a result of a large number of landslide events. Both types of data need to be analyzed in a combined way in order to reconstruct the spatial and temporal evolution of landslide activity for distinct slopes. This requires the determination of adequate spatial mapping units, which also form the basis for subsequent hazard assessment. They can comprise cells of a regular grid, slope units, unique condition units, seed cells and other spatial units (Guzzetti et al., 1999, Van Den Eeckhaut et al., 2009 and Süzen and Doyuran, 2004). For this study, morphologically-based slope units derived from DEM-based watershed delineation have been chosen as the most suitable mapping units because they reflect the physical properties of the relief as the main landslide predisposing factor and have the potential for handling the remaining spatial uncertainties contained in the landslide data. Due to the fractal nature of these units, their size can be adjusted to the different mapping scales by varying the parameters for watershed delineation, e.g. the stream orders or the minimum basin size (Calvello et al., 2013). Figure 2b demonstrates the landslide density per slope unit for the study area. Similar maps can be prepared for different time intervals to trace changes in the landslide activity patterns within the study area over time. In order to enable convenient querying and analysis of the spatial information on landslides and landslide factors that originated from multiple sources and is subject to future updates, a QGIS plugin (not yet distributed online) has been designed and partially implemented in Python. QGIS is a well-developed open-source software package with an easy interface for the incorporation of new plugins (QGIS Development Team, 2015). Furthermore, working in the framework of QGIS allows using its available core functionality and many already existing plugins, e.g. the OpenLayers plugin for convenient visualization of data served by a Web Map Service, e.g. data of Google or OpenStreemMap, or plugins that integrate R scripts for statistical analysis.

The implemented functionality of the plugin enables such actions as selecting all known landslides that occurred within a given time interval, deriving the highest point within a landslide polygon as an approximation of the landslide main scarp or assigning landslides to mapping units as demonstrated in Figure 3.

4. Derivation of Landslide Attributes using GIS

Besides the information on the spatial dimensions of a slope failure, landslide inventories typically include a variety of further landslide attributes. GIS and remote sensing can be very helpful for the derivation of many of the attributes.

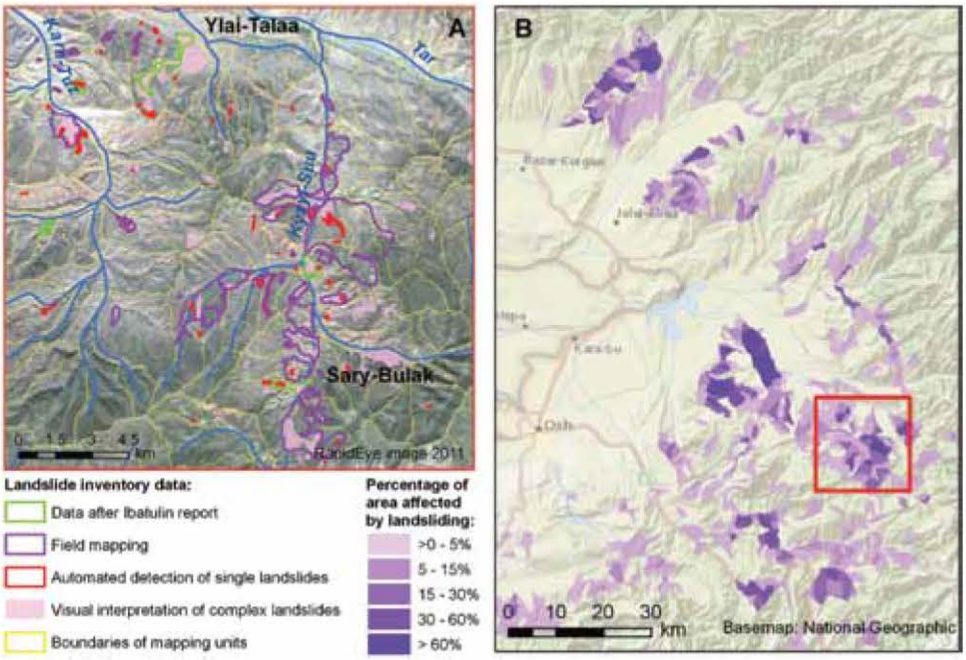

Figure 2: Results of multi-source landslide mapping (A) and (B) percentage of landslide-affected area per spatial mapping unit. The red rectangle indicates the position of the subset shown in map A.

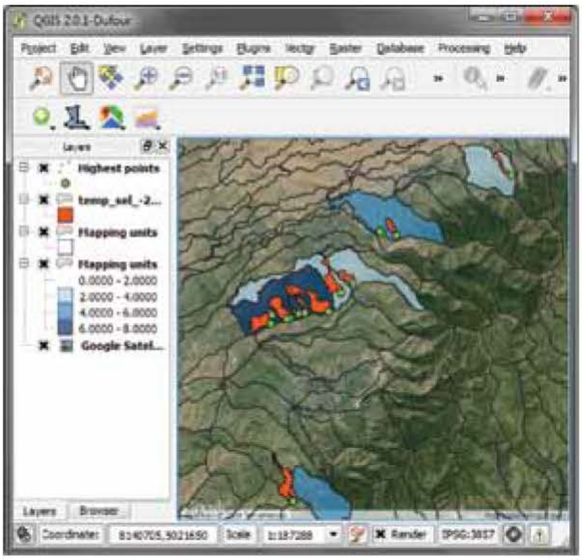

Figure 3: QGIS window with landslides (orange), their highest points (green) and spatial mapping units indicating the number of landslides assigned to them (blue)

Figure 4: Landslide polygon (red) and its length line (yellow) derived automatically with QGIS plugin

The main groups of attributes commonly included into landslide inventories (with attribute examples) are:

- General information: ID, reporter, photographs, bibliography;
- Landslide location: coordinates, reference to river valley or settlements, administrative units;
- Landslide dimensions: length / width / depth at head / middle / toe parts, volume, area, perimeter, compactness, elevation drop;
- Landslide classification: type of movement (e.g. flow, rotational or translational slide), slope material (e.g. rock / debris / mud flow);
- Geo-environmental characteristics: slope, aspect, curvature and derivatives, lithology, tectonic structures, land use, distance to roads;
- Landslide history and activity: known failure and reactivation dates, state of activity (e.g. active / dormant / relict landslide);
- Causes: hydrometeorological, seismic and other conditions preceding the failure;
- Consequences and elements at risk: fatalities and injuries, building damages, road closures, loss of arable land, number of people and buildings at risk.

We use standard GIS functionality for the calculation of the landslide area and perimeter. The ratio of these two indicators, which is the measure of the polygon compactness, will be used for an approximation of the landslide movement type. In order to calculate the landslide length, we have implemented customized functionality as part of the QGIS plugin, which enables the calculation of the length of complex polygons by combining a landslide vector layer with digital elevation data. The algorithm draws a line between the highest and the lowest points of a landslide polygon. If that line is (partly) outside the landslide polygon, additional points are added until the line passes inside the polygon (see example in Figure 4). Digital elevation data is used to derive landslide relief parameters, e.g. the mean slope of a landslide polygon and the dominating aspect. The latter was calculated using the zonal statistics majority function. The calculation has shown a tendency towards the northern and northwestern exposition of landslide-affected slopes, which can be explained by the influence of the hydrometeorological factors and the accumulation of loess sediments on northwestern slopes. The dominant geology was determined for each landslide polygon as the geology class that occupies the largest area within the polygon. Most landslides occur within the Jurassic-Oligocene folding.

Significant differences in landslide attribute values by data source were identified. They are related to the fact that automated detection results enable a systematic record of single landslide events, whereas landslides documented in the report by Ibatulin (2011) represent a small selection of especially large and/or destructive events in the vicinity of settlements.

5. Conclusions

In this paper, we have demonstrated the use of GIS technologies and remote sensing data for the compilation of a landslide inventory based on multiple information sources for the study area in Southern Kyrgyzstan. Special attention has been paid to spatially explicit landslide mapping and to the temporal dimension of landslide information in order to create a GIS-based multi-temporal landslide inventory. In this study area, satellite remote sensing data represent a valuable source of spatial and temporal information on landslide activity, whereas visual interpretation is especially suitable for mapping complex slope failures. Automated analysis allows the detection of single landslide events in an object-based form for the most recent period of time. Since none of the used sources is capable of providing a complete inventory, the combination of all of them has been required in order to derive a comprehensive landslide inventory. In this context, GIS-based data integration including homogenization and evaluation played an important role in the derivation of consistent and reliable multi-temporal information, which can be used in subsequent susceptibility and hazard analysis. Moreover, multi-temporal satellite remote sensing data are used as spatial reference information for establishing the multi-source GIS database since they are available in high spatial resolution and consistency for the complete study area. GIS technologies have also enabled efficient customized data access and joint processing in order to prepare all available information for subsequent landslide hazard assessment. For this purpose, a QGIS plugin is under development. Future work will focus on the development of GIS-based methods for susceptibility and hazard assessment which are capable of accommodating the spatially and temporally differentiated input information into the analysis including the results of ongoing monitoring of landslide activity in this area. In this context, special attention will be paid to the spatio-temporal assessment of landslide triggering factors, such as precipitation and seismicity in their relation to landslide activity.

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