Development of Multi-Temporal Landslide Inventory Information System for Southern Kyrgyzstan Using GIS and Satellite Remote Sensing

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Summary: In Southern Kyrgyzstan, landslides regularly endanger human lives and infrastructure. They are a very dynamic phenomenon with significant variations of the process activity in different years. This creates a need for the development of new methods of dynamic and spatially differentiated landslide hazard assessment at a regional scale. Because of the large size of the study area (over 12,000 km²), remote sensing data are a valuable and reliable source of detailed and consistent spatial information for landslide investigations in Southern Kyrgyzstan. The paper demonstrates how GIS and remote sensing techniques are used for the acquisition, verification and homogenization of heterogeneous multi-source landslide data with the goal of generating a multi-temporal landslide inventory. Special emphasis is placed on the spatial data consistency, the documentation of temporal information and the possibility to document repeated slope failures within the same slope. The multi-temporal landslide inventory is an integral part of a landslide inventory information system, which is implemented in the QGIS environment and provides self-customized functionality for data queries and spatial analysis including the derivation of landslide attributes. The information system contains additional spatial base data such as a spatially consistent multi-temporal archive of satellite images and topographic maps.

Zusammenfassung: *Entwicklung eines Informationssystems zur multitemporalen Inventarisierung von Hangrutschungen für Südkirgistan unter Verwendung von GIS und Satellitenfernerkundung.* In Südkirgistan werden durch Hangrutschungsereignisse regelmäßig Menschenleben sowie technische und soziale Infrastruktur gefährdet. Da die Hangrutschungsaktivität in dieser Region zwischen den Jahren sehr variiert, besteht der dringende Bedarf, Methoden zu entwickeln, welche eine dynamische und räumlich differenzierte Einschätzung der Hangrutschungsgefährdung auf regionaler Ebene erlauben. Aufgrund der Größe des Untersuchungsgebietes von über 12.000 km² sind für die Entwicklung dieser Methoden satellitengestützte Fernerkundungsdaten besonders geeignet, da sie die einzige räumlich kontinuierliche und zeitlich wiederholbare Informationsbasis für die gesamte Region darstellen. In diesem Paper wird gezeigt, wie GIS- und Fernerkundungsverfahren für die Erfassung, Überprüfung und Homogenisierung heterogener Hangrutschungsdaten aus mehreren Quellen verwendet werden, um eine multitemporale Inventarisierung von Hangrutschungen zu ermöglichen. Besonderer Wert wird dabei auf die räumliche Konsistenz der Daten, die Dokumentation des zeitlichen Auftretens und die Erfassung von wiederholten Hangrutschungsereignissen innerhalb desselben Hangs gelegt. Um die multitemporale Hangrutschungsinventarisierung zu unterstützen, ist ein QGIS-basiertes Informationssystem entwickelt worden, welches mit angepassten Datenabfragen und räumlichen Analysen zur Ableitung von Hangrutschungsattributen beiträgt. Das Informationssystem beinhaltet zusätzliche Geobasisdaten wie ein räumlich konsistentes multitemporales Archiv von Satellitenbildern und topographische Karten.*

1   Introduction

The foothills of the Tien Shan mountain ranges along the eastern rim of the Fergana basin in Southern Kyrgyzstan are subject to high landslide activity as a result of pronounced relief and ongoing tectonic activity. Furthermore, the topographically rising eastern rim of the Fergana basin represents a barrier to the prevailing westerlies leading to increased precipitation levels in comparison to areas that are situated further east (Kalmetyeva et al. 2009). All of these factors create favourable conditions for the intense and frequent occurrence of landslides in this area of about 12,000 km² administratively covering the Osh and Dzhalal-Abad provinces (oblasts), presenting an important human living space in this mountainous country (Fig. 1). Large landslides occur mostly within weakly consolidated Mesozoic and Cenozoic sediments at elevations between 800 m and 2,000 m a.s.l. Slope failures in massive Quaternary loess sediments are especially dangerous due to their very rapid and destructive avalanche-like movement. Another type of landslides develops in more clay-

rich sediments and is characterized by lower movement rates but can nevertheless affect large areas (Roessner et al. 2014, Roessner et al. 2005, Wetzel et al. 2000). Since landslides represent a major threat to the local population frequently causing fatalities and severe economic losses, observations of landslide activity in Southern Kyrgyzstan have been carried out by local organizations since the 1950s. Between 1969 and 2010, approximately 4,500 landslides were recorded in Southern Kyrgyzstan (Ibatulin 2011). Since 1993, over 250 persons have died as a result of catastrophic slope failures in Kyrgyzstan (Torgoev et al. 2010). Landslide activity in this region is characterized by frequent and at the same time sporadic occurrence of events. This creates a strong need for a spatially differentiated assessment of landslide hazard and risk.

A landslide inventory is one of the main prerequisites for an objective landslide hazard assessment, which includes both the spatial and the temporal aspects of the probability of landslide occurrence (Guzzetti et al. 2005). A landslide inventory is a register of the distribution of landslides and their characteristics (Hervás
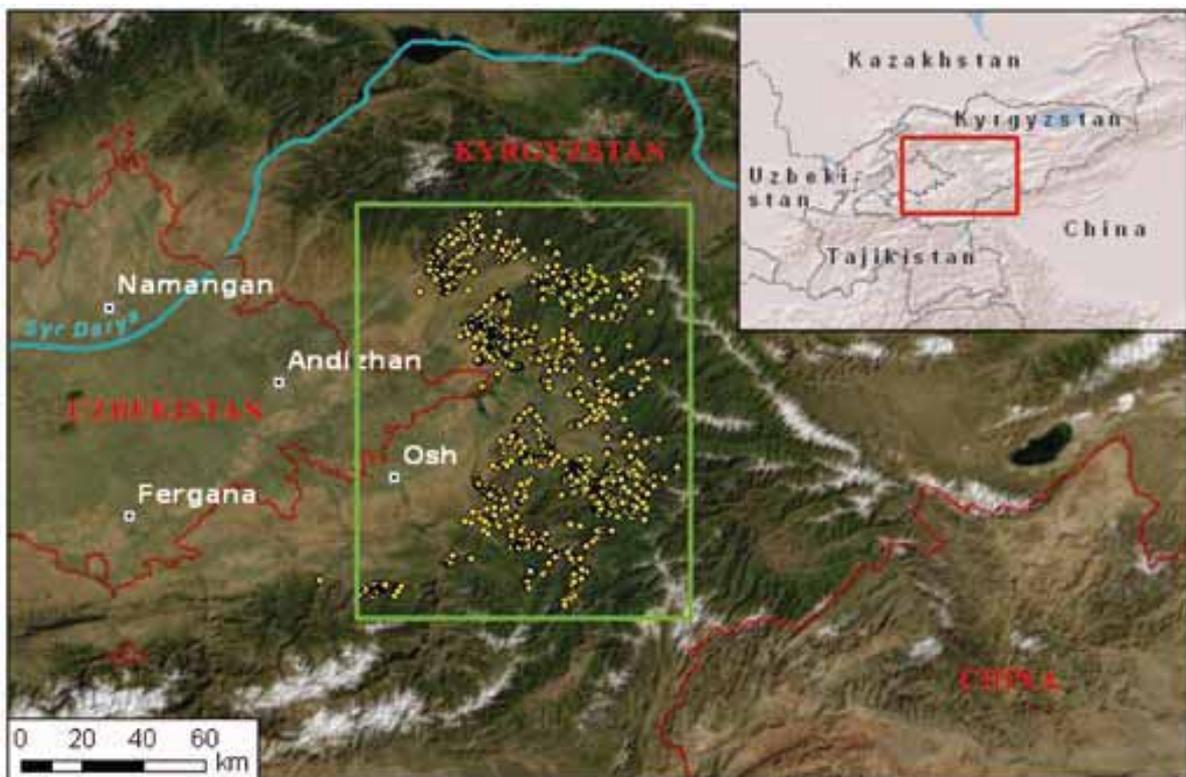

Fig. 1: Study area in Southern Kyrgyzstan (green) with landslide locations (yellow) according to data obtained from Yerokhin (1999). Spatial base data from Esri.

2013, Guzzetti et al. 2012). The latter usually include the landslide id, location, dates of first occurrence and reactivations, type, state of activity, area and volume. Additionally, information on landslide geometry, geo-environmental characteristics at landslide site, triggering factors, landslide impact, monitoring data, etc. can be incorporated. The set of recorded characteristics may differ depending on the scale and method used to create the inventory, on properties of the study area as well as on the project goals. An overview of the most common landslide attributes is presented in Tab. 1.

A wide range of methods have been developed in order to generate landslide inventories discussed in Van Westen et al. (2008) and Guzzetti et al. (2012). These methods include visual and (semi-) automated interpretation of optical, lidar and radar remote sensing data, geomorphological field mapping and archive studies. Geomorphological field mapping and visual interpretation allow integrating expert knowledge on the geological set-

ting in the region into the mapping process but these methods are prone to subjectivity and are only suitable for mapping areas of limited size. Visual interpretation of optical aerial and satellite images, sometimes combined with a DEM, remains a widely used technique for landslide mapping. In the recent years, approaches have been developed for automated and semi-automated landslide detection from high-resolution multi-spectral satellite images based on the classification of a single image or combined analysis of pre-event and post-event images. These approaches can be pixel-based or object-based. Whereas optical remote sensing enables the detection of slope failures that have already occurred, InSAR techniques allow detecting small surface deformations. In case of landslides, these deformations mainly indicate reactivations of previously active slopes that precede a new failure (Motagh et al. 2013, Wasowski & Bovenga 2014). Overall, applications of satellite remote sensing for landslide mapping have become more im-

Tab. 1: Overview of landslide attributes: '++' = 'very suitable', '+' = 'suitable', '-' = 'unsuitable' (after Van Den Eeckhaut & Hervás 2012, WP/WLI 1993, USGS 2004, Hervás 2013, Wieczorek 1984).

Attribute Group	Selected Attributes	Methods for Derivation		
		Terrestrial	*Map / GIS*	*Remote Sensing*
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 part Volume Area, perimeter / area ratio 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	Relief: 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 preceeding 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	- ++	- ++	- +

portant in the last decade due to the substantial increase in the satellite data availability, their spatial resolution and the development of hardware and software for image processing. The ongoing nature of satellite data acquisition permits going beyond producing a single landslide inventory map towards an information system with capabilities for future data updates as indicated by Van Westen et al. (2006). Such dynamic landslide inventories can serve as the basis for improved landslide hazard assessment that can incorporate input data updates and be carried out repeatedly, e.g. upon the availability of new data. GIS tools can be used for an efficient derivation of many of the landslide attributes from vector and raster data (Tab. 1).

Objective landslide hazard assessment for the study area requires a systematic landslide record in form of a multi-temporal landslide inventory, which documents slope failures over a long period of time including the dates or periods of their occurrence. The goal of this study is the establishment of a landslide inventory information system for Southern Kyrgyzstan enabling convenient data access and analysis and serving as the basis for subsequent landslide hazard assessment at a regional scale. Due to the highly dynamic nature of the landslide activity in this region and its complex interrelations with factors that cause its differentiation in space and time, we aim at establishing a GIS-based multi-temporal landslide inventory enabling efficient derivation of landslide attributes and subsequent hazard analysis. For this purpose, we develop a GIS and remote sensing based approach for the generation of the inventory from multiple information sources with the possibility of future data updates. The resulting inventory contains spatially explicit and consistent information about landslide activity with the best possible temporal resolution. This information includes single landslide events as well as complex landslide-prone slopes, which have been subject to several phases of reactivation. Such a comprehensive inventory has not yet been compiled for the area of high landslide activity in Southern Kyrgyzstan and, when completed, can serve as an example of multi-source landslide inventory mapping in a data-scarce environment.

The use of customized GIS tools makes it possible to develop a spatial information system for landslide hazard assessment accommodating the heterogeneous data on landslides, their predisposing and triggering factors and other supplementary information as well as functionality adapted to the procedures of landslide hazard assessment. Such a system has the potential to provide more consistent data storage, efficient data access, systematic data update procedures and customized tools for spatial and statistical analysis. Due to the advances in open-source GIS, it is possible to implement the system in the framework of already existing software packages. This allows using already available GIS functionality and taking advantage of the benefits of open-source software, such as the possibility of customization, minimization of costs and flexibility. We implement the landslide inventory information system in the QGIS environment including self-customized functionality for efficient access to the landslide inventory data and derivation of additional landslide information.

2 Data Sources

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. We consider all available sources of landslide data including information from local organizations, field work as well as results of multi-temporal satellite remote sensing analysis. The preparation of the landslide data from various sources for integration into the inventory and their verification requires the use of spatial base data of different kinds. In this section, we give an overview of the available sources of spatial base data and information on landslide occurrence.

2.1 *Spatial Base Data*

Spatial base data are needed for the derivation of the spatial location and extents of the landslides that originally did not have an explicit spatial reference and for the verification of

existing spatio-temporal information on slope failures. They are an integral part of the data provided by the landslide inventory information system and are used to derive landslide attributes, e.g. landslide dimensions, the reference to the river valley, settlement and administrative unit where the landslide is located, etc.

In order to obtain a consistent archive of surface conditions over large areas with the best temporal resolution possible and to provide common spatial reference for multi-source landslide data, a multi-temporal database of optical remote sensing imagery has been created (Behling et al. 2014a). It contains 592 multi-spectral middle- and high-resolution remote sensing datasets. This database includes Landsat (E)TM, ASTER, SPOT and RapidEye images acquired in 1986 − 2013 with the spatial resolution ranging between 5 m and 30 m. Standard orthorectified products from the providers were used to minimize the preprocessing effort. Even though the sensors record data in different channels, the combination of the green, red and near-infrared spectral bands is the least common spectral denominator which enables multi-sensor analysis of landslide-related surface changes. In order to ensure spatial consistency between the standard data products required for their automated analysis, they were co-registered to the Landsat reference using a fully automated approach. Overall accuracy has resulted in a high relative image-to-image accuracy of 17 m (RMSE) and a high absolute accuracy of 23 m (RMSE) for the whole co-registered database. Further details regarding the automated co-registration of the included 592 satellite images can be found in Behling et al. (2014a).

Derivation of landslide attributes, clarification of ambiguities related to landslide data and general orientation in the study area require the use of topographic data. We have used the 1:100 000 Soviet ordnance survey maps that were originally produced in the 1950s and 1960s and updated in the 1970s and 1980s. These topographic maps are consistently based on a transverse Mercator projection and represent a high level of spatial detail. However, they are in part outdated and many of the settlement names have changed since the independence of Kyrgyzstan in 1991.

Furthermore, digital elevation data have been used in this study to derive relief-related landslide characteristics and for perspective visualization. These data include an SRTM X-band DEM (Rabus et al. 2003), which was obtained from the German Aerospace Center (DLR) in a spike-removed form, and the freely available ASTER GDEM Version 2 (2011). These digital surface models largely correspond to the Earth's surface topography due to the predominantly treeless character of the vegetation in the study area.
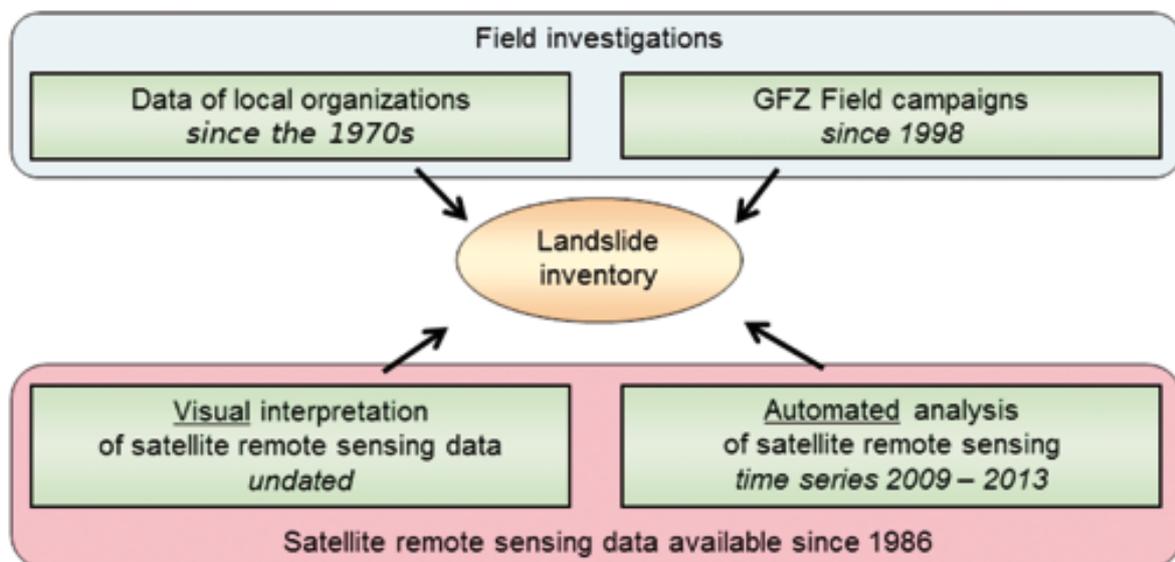

Fig. 2: Overview of main sources of data on landslide occurrence in Southern Kyrgyzstan.

2.2 Landslide Information

Multiple sources of landslide data are available (Golovko et al. 2014). They include data obtained from local 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. However, these sources vary in their temporal coverage, their spatial and temporal completeness as well as their accuracy (Fig. 2). Furthermore, these landslide data are of analogue and digital origin. They have different formats, such as verbal description, tabular data, and vector information.

2.2.1 Information obtained from local organizations

From the 1960s until the breakup of the Soviet Union, regular landslide monitoring was conducted by local authorities for the most endangered areas in the region focusing on settlements and their surroundings (Roessner et al. 2005, Roessner et al. 2014). After the independence of Kyrgyzstan, these activities have continued; however, they decreased due to shortage of funding. The landslide records of local organizations are therefore a valuable source of landslide information covering the time period before regular satellite remote sensing data acquisition. 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 extensive field investigations carried out between the 1970s and 2004. 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 whereby 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 slope failures. Instead, the landslide locations are described verbally in relation to significant topographic features. Overall, the report focuses on large landslides

in the vicinity of inhabited areas. Thus, it contains episodic rather than systematic landslide inventory information.

A less recent but more extensive and systematic 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 landslides. It represents the cumulative assessment of the landslide situation by the end of the 1980s without specifying the dates of documented slope failures. Although this report contains spatially explicit information, the mapped landslides needed to be evaluated and spatially adjusted using satellite remote sensing data due to the coarse spatial resolution of the maps included into the report (Fig. 3). The report documents a number of landslide attributes including dimensions, position on the slope and activity stage making it the most comprehensive source of information on the properties of landslides in Southern Kyrgyzstan. Thus, the distribution of landslide attributes derived within a GIS can be validated against statistics calculated using this report.

Moreover, employees of the Ministry of Emergency Situations of Kyrgyzstan visited selected areas affected by landslides between the years 2002 and 2010 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. 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.

2.2.2 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 with the purpose of selective landslide mapping and verification of data from other sources. 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. Field work has been extensively supported by satellite remote sensing analysis in order to efficiently cover large areas, especially for structural geological and landslide mapping. The findings were recorded in GPS-waypoint-oriented field documentation, satellite remote sensing based maps and field photographs. Furthermore, high-accuracy measurement with differential GPS were carried out for selected topographic features and spatial reference points.

2.2.3 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 bodies 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.

However, visual mapping is labour-intensive and thus could only be carried out for subsets of the study area. In order to perform multi-temporal analysis for the whole study area, an approach for automated landslide detection has been developed based on the spatially aligned multi-temporal satellite remote sensing database (BEHLING et al. 2014a). This approach allows analysing large areas in multiple time steps. Applying this approach to the complete study area has resulted in automated detection of over 600 landslides that occurred between 2009 and 2013 (BEHLING et al. 2014b, ROESSNER et al. 2014). The obtained results, which were visually verified in the field, have revealed a constantly ongoing process activity in this region requiring regular and systematic landslide monitoring.

3 Methodology

The landslide inventory information system includes a landslide inventory and a spa-

tial base as well as standard and customized functionalities for data querying and analysis as part of a GIS. We have implemented the landslide inventory information system in the QGIS environment because QGIS is a well-developed open-source software package with an easy interface for the incorporation of new plugins (QGIS DEVELOPMENT TEAM 2014). 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, such as Google Satellite and OpenStreetMap, or plugins that integrate R scripts for statistical analysis.

Fig. 3 gives an overview of the steps necessary for the generation of the multi-source landslide inventory for Southern Kyrgyzstan. Most of the input data underwent preparatory processing such as digitalization, data verification and other procedures necessary to bring them to a spatially consistent form. Spatial base data were required at this stage. After the multi-source landslide inventory has been generated, it can be used for further analyses, such as derivation of landslide attributes and data preparation for landslide hazard assessment. In the following, we discuss particular steps of this workflow in more detail. They include the creation of common spatial reference, derivation of spatial mapping units, preparation of the multi-source landslide data for GIS-based integration into the resulting landslide inventory and the development of a customized functionality in the QGIS environment for efficient data access and derivation of additional landslide information.

3.1 *Creation of a Common Spatial Reference*

The integration of all described landslide information sources into a single system requires the establishment of a common spatial reference. For this study, the multi-temporal satellite remote sensing database (section 2.1) represents the common spatial reference. UTM/WGS84 was used as the common map projection. The resulting spatially adjusted multi-temporal satellite remote sensing data-

base is characterized by a high relative spatial accuracy between the image datasets amounting to less than the pixel size of the Landsat reference. Moreover, the absolute positional accuracy of this database has been assessed using high-accuracy differential GPS measurements. This investigation has revealed a systematic offset of the multi-temporal image database comprising 22 m in western and 5 m in northern direction (BEHLING et al. 2014a). Due to the use of orthorectified input imagery, this displacement can be regarded as a shift. The database was shifted accordingly in order to eliminate these systematic errors and ensure compatibility with spatial information originating from other sources. As a result, a consistent area-wide database of multi-temporal and multi-resolution images with a common

spatial reference has been created. All other spatial data used for the generation of the multi-source landslide inventory information system have been checked in regard to their spatial fit to this common spatial reference system. The positional accuracy of the DEMs was checked using drainage network analysis and no systematic shifts could be identified. Thus, the DEMs can be used in their original form. The scanned topographic maps were georeferenced to the common UTM/WGS projection based on their corner coordinates. In a next step, the topographic maps were used to geocode the scanned paper maps contained in the report by YEROKHIN (1999). Thus, conformity of all used spatial data with the common spatial reference has been achieved.
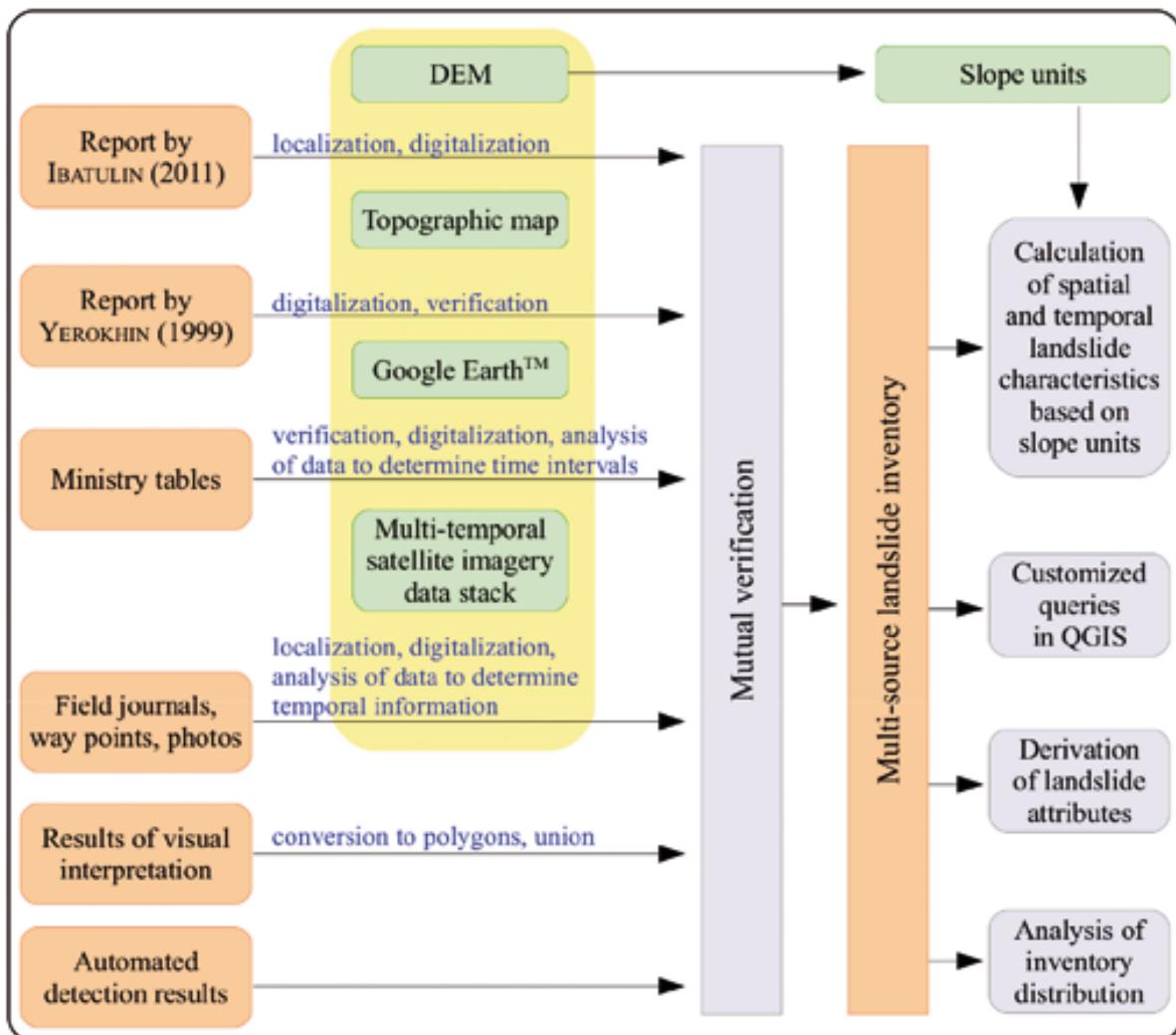

Fig. 3: Workflow for the generation of the multi-source landslide inventory.

3.2 *Derivation of Spatial Mapping Units*

Some of the landslide data sources provide information on single landslide 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 analysed 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, Erener & Düzgün 2012, Süzen & Doyuran 2004). For this study, morphologically-based slope units which can be 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). For the study area, they were derived from the SRTM DEM and the ASTER digital elevation data and are shown in an exemplary way in Figs. 5 and 6.

3.3 *Landslide Data Preparation and Integration*

Landslide data from each of the sources described above differ in their properties and had to undergo a plausibility check due to imprecision, uncertainty or errors in the data. Additional data preparation was necessary to transfer landslide data from the different sources to a consistent vector form. Fig. 4 illustrates the initial situation of the landslide information availability and the outcome of the multi-source data integration for landslide inventory mapping using the example of a complex landslide-prone slope in the Kara-

Tuz river valley. Only slope failures detected automatically from multi-temporal satellite imagery in an object-based way were available in form of polygons that can be integrated into the inventory information system without further preprocessing (Fig. 4a). In case of this data source, the temporal information on the landslide occurrence was provided in form of a time interval between two image acquisition dates within which the slope failure occurred. This format was chosen for the resulting inventory to ensure comparability of data from the different sources. When the exact failure date was known, the start of the time interval was the same as its end.

Incorporating landslide information from verbal descriptions such as the report by Ibatulin (2011) required primary approximate localization of landslides using the topographic maps. Afterwards, the precise localization of the failures within the slope and the determination of their spatial extent were carried out using post-event satellite images. Sometimes, verbal information from reports concerning additional features such as landslide-dammed lakes or damage to buildings was helpful to localize the landslide in imagery acquired soon after the landslide failure. The longer the time between the slope failure and the image acquisition the more the landslide features have already been subject to erosion, revegetation and reactivations within the same slope. Often, Google Earth™ was used to supplement the multi-temporal satellite imagery due to the higher spatial resolution, convenient functionality for generating perspective views and easy-to-use digitalization tools offered by this software package.

Slope failures documented in multiple data sources were used to verify the data, correct inconsistencies, improve localization of the landslides and determine the time of their failure with higher accuracy and reliability. Even though the heterogeneous landslide data could be processed to a more consistent and mutually comparable form, differences between the data from the various sources could not be completely eliminated. Therefore, it is important to document the data source for each landslide as part of the metadata, which allows judgments about the properties and precision of the data.
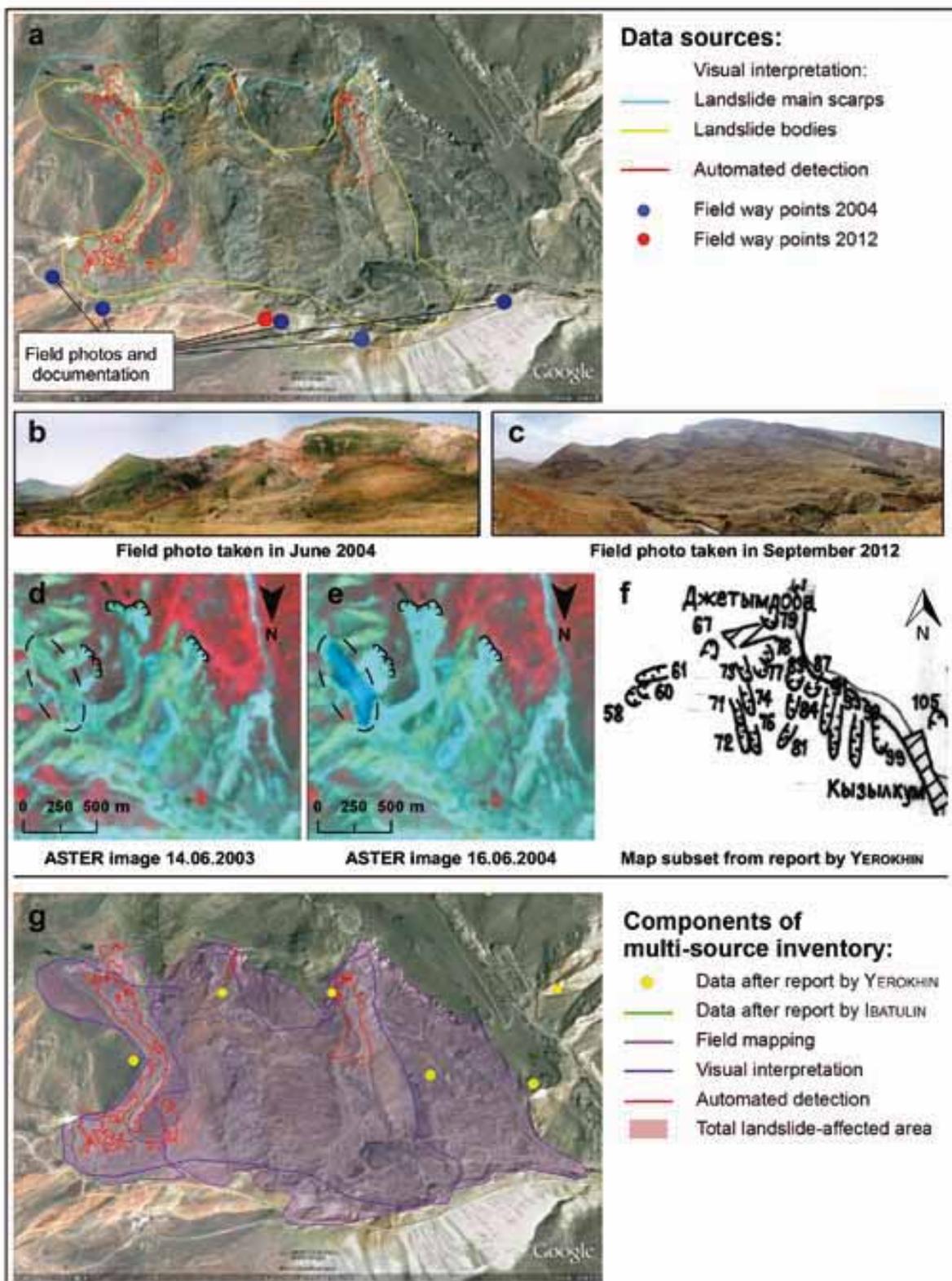
Fig. 4: (a–f) Input data from various sources of landslide information including field photos, pre-event and post-event ASTER images from the multi-temporal satellite remote sensing database and maps from the report by Yerokhin (1999), (g) results of multi-source landslide mapping for a landslide-prone slope in the Kara-Tuz river valley. Google and the Google logo are registered trademarks of Google Inc., used with permission.

Additional information, such as photos, descriptions and other types of metadata, can be linked to the spatial landslide data via ids or using spatial proximity. We used ids to link attribute tables from the report by YEROKHIN (1999) to landslide locations and a spatial link between landslides and GPS waypoints recorded during field surveys, which, in turn, contain references to field photos and landslide descriptions from field journals.

The data contained in the resulting multi-source landslide inventory for the landslide-prone slope in the Kara-Tuz river valley are illustrated in an exemplary way in Fig. 4. The report by IBATULIN (2011) documents a failure which occurred in 2004 within this slope. This description contains additional information that the landslide dammed the river and formed a lake. This failure could be localized in the left part of the slope due to the availability of a post-event ASTER image where the lake is clearly visible. The location of the lake is indicated in the pre-event (Fig. 4d) and post-event image (Fig. 4e) with an ellipse. Landslides recorded in the report by YEROKHIN (1999) (Fig. 4f) prove that all parts of the slope had already been subject to landsliding prior to the 2004 event. The results of automated landslide detection show that there were further activations within this slope in the period between 26.5.2009 and 14.5.2011 (red outlines in Fig. 4). This location was visited in 2004 and 2012 during field work when field photographs were taken and subsequently integrated into the GIS-based photo archive (Fig. 4b, c). This archive allows a better understanding of spatio-temporal dynamics of landslide-prone slopes. During field work, the whole landslide-affected slope was mapped as a single polygon because it was not possible to distinguish between individual failures. Thus, the dated landslide events occupy a relatively small area within the landslide-prone slope. However, this information is valuable for the evaluation of landslide activity in this area, and the undated landslide information allows mapping larger landslide-affected areas. The total extent of the landslide-affected area within the slope was derived as a spatial union of all landslide polygons described above and used for the calculation of landslide density as shown in Fig. 6b.
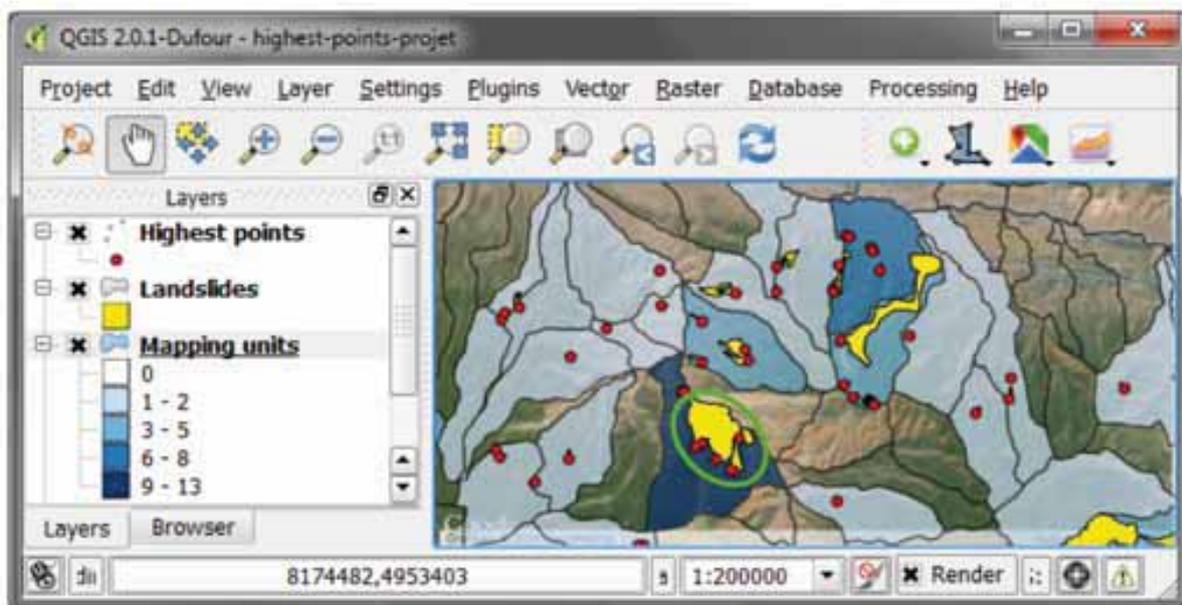

Fig. 5: QGIS window with landslides south of the Tar river (mapped after report by IBATULIN (2011), results of field surveys, visual and automated analysis of satellite imagery), landslide highest points and spatial mapping units indicating the number of landslides assigned to them. The green circle shows the position of the complex landslide-prone slope in the Kara-Tuz river valley used as example in the methodological description of section 3. Satellite imagery by Google via OpenLayers plugin. Google and the Google logo are registered trademarks of Google, Inc., used with permission.

3.4 *Derivation of Additional Landslide Information*

One of the components of the landslide inventory information system is a QGIS plugin written in the Python programming language. The plugin contains a set of customized functions implemented for the needs of working with the multi-temporal landslide inventory. It enables customized queries of the multi-source landslide data with an emphasis on temporal attributes. Furthermore, it provides spatial functionality for the derivation of landslide attributes, e.g. by automated referencing of landslides to spatial mapping units or finding highest points within a landslide body as an approximation of the landslide main scarp location. This type of analysis is based on the combination of vector data on landslides and spatial mapping units with a DEM. An exemplary result is shown in Fig. 5.

4   Results and Discussion

The resulting multi-temporal landslide inventory contains over 1.200 landslides which could be mapped as polygons based on the various sources of information (Tab. 2). The summary table also contains the total area covered by complex sequences of failures, where it has not been possible to identify individual landslides due to long-term process activity within these landslide-affected slopes. The table also shows differences in the size of the mapped landslides, e.g. the report by IBATULIN (2011)

documents a limited number of large slope failures, whereas automated landslide detection from multi-temporal satellite imagery has made it possible to map systematically landslides of all sizes including the small ones. Visual image interpretation allows mapping complex landslide-affected areas of large spatial extent, although individual failures cannot be distinguished. Automated detection enables reliable identification of the spatial extent of single slope failures. The level of detail for the temporal information depends on the availability of satellite imagery, which determines the length of the time interval between the pre-event and post-event satellite images used for dating automatically detected slope failures. The most detailed temporal information (exact day of the failure) is provided by the report by IBATULIN (2011), although the landslide extents are imprecise. Results of visual interpretation of landslide-prone slopes from satellite images and the information from the report by YEROKHIN (1999) contain no temporal information on landslide occurrence but document more landslides and a larger landslide-affected area than other sources. Thus, a trade-off between the inventory completeness, spatial and temporal information content can be observed. The integration of landslide information from multiple sources provides a way of improving the quality of the resulting inventory on these three aspects.

Fig. 6a shows the complete content of the multi-source landslide inventory for a 20 by 20 km² subset of the study area situated south of the Tar river and characterized by high re-

Tab. 2: Summary statistics representing the current stage of the landslide inventory according to different data sources.

| Source	Period of assessment	Number of landslides	Landslide area, km²	Landslide type
Report by IBATULIN (2011)	1970s – 2004	67	22.0	Single failures
Report by YEROKHIN (1999)	1956 – 1986	1532	n/a	Single and complex failures
Ministry tables	2002 – 2011	73	n/a	Single failures
Field mapping by GFZ (status 2014)	not dated	555	119.9	Single and complex failures
Visual interpretation	not dated	n/a	172.9	Complex failures
Automated detection	2009 – 2013	625	8.2	Single failures
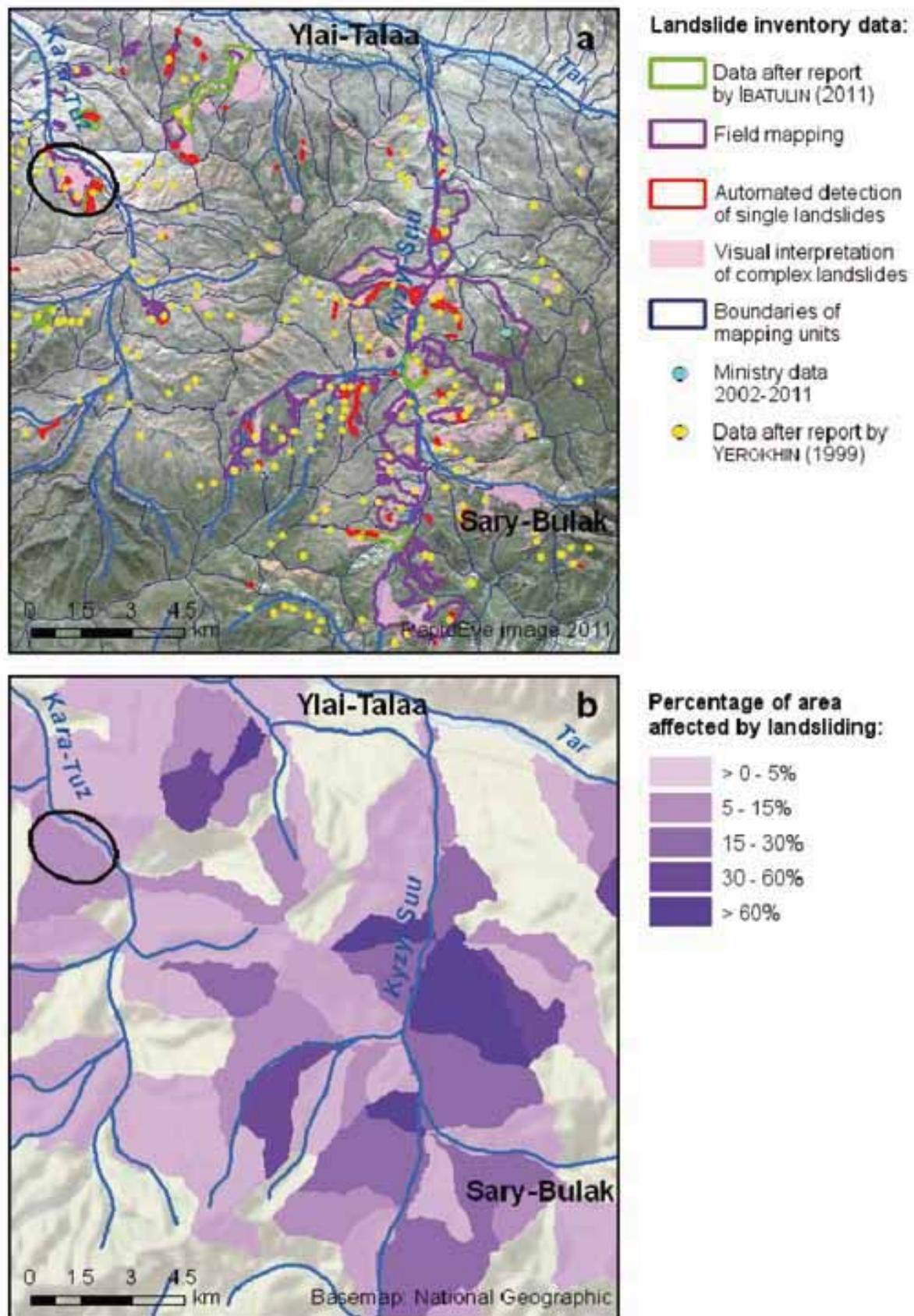
Fig. 6: Results of multi-source landslide mapping: (a) according to available data sources, (b) percentage of landslide-affected area per spatial mapping unit calculated using data from report by IBATULIN (2011), field mapping, visual interpretation of satellite imagery and automated landslide detection. The black ellipse shows the position of the landslide-prone slope in the Kara-Tuz river valley used as example in the methodological description of section 3.

cent landslide activity. The largest part of the mapped landslide area has been derived by visual interpretation of satellite remote sensing data in combination with field mapping (areas outlined in purple and filled in pink). Using the same combination of data sources, it has been possible to map selected large landslides contained in the report by Iʙᴀᴛᴜʟɪɴ (2011) in a spatially explicit way (landslides outlined in green). For these cases, the failure dates are known, all of them occurred before 2005. The areas outlined in red depict the landslide objects that have been automatically detected based on the multi-temporal Rapid-Eye data available for the time period between 2009 and 2013. These objects include areas of fresh failures as well as areas of reactivation within previously active landslide-prone slopes.

In a second step, the total area which has been mapped as affected by landslides was derived and related to the spatial mapping units outlined in blue in Fig. 6a by calculating the landslide density as the ratio between the landslide-affected area and the total area of the respective mapping unit (Gʜᴏꜱʜ et al. 2012). The results shown in Fig. 6b indicate an especially high concentration of landslide-affected areas on the slopes along the Kara-Darya, Kyzyl-Suu and Kara-Unkyur river valleys. Overall, higher landslide densities can be observed for slopes of northern, northwestern and northeastern expositions.

The use of a common spatial reference has enabled the detection of surface cover changes in a more precise way allowing the assessment reactivations within an already known landslide complex. The precise spatial location of landslide-affected areas within a slope unit indicates the potential for the continuation of landslide activity within that slope unit. In the case of the landslide in the Kara-Tuz river valley, mass wasting has not affected the upper part of the slope unit yet, and that landslide activity may advance towards the watershed.

Although multiple sources of data on landslides have been used, each of them only provides information on a subset of the slope failures that have occurred in the study area. The degree of completeness varies depending on the examined period of time and the available data sources. Visual interpretation and auto-

mated landslide analysis based on satellite imagery allows the systematic detection of landslides independently of their proximity to settlements, whereas the completeness depends on their detectability in the image data and the temporal sequence of the imagery. However, due to the limited temporal resolution of the satellite imagery before the availability of multi-temporal RapidEye data, temporal information derived from satellite remote sensing data represents longer periods of occurrence ranging from several months to several years.

In contrast, the report by Iʙᴀᴛᴜʟɪɴ (2011) contains temporally explicit information on failure dates exceeding the time span which is covered by satellite remote sensing data. In case of failures that occurred before 1990, it represents the only source of temporal information on landslide events unless they have been documented otherwise. However, this information lacks explicit spatial reference and most of it has been acquired in the vicinity of settlements. Such explicit spatial information and extent of slope failures can be derived from remote sensing data, whereas the resulting accuracy is highest if the satellite imagery was acquired shortly after the occurrence of the failure. However, visual interpretation of satellite remote sensing data also allows mapping of older landslides which already have experienced several stages of revegetation and in parts have been affected by subsequent reactivations. In fact, this is the only way of mapping old landslides that had failed even before the start of landslide observations in the study area. Due to the use of the results of visual interpretation of satellite imagery, the resulting multi-source inventory combines features of both multi-temporal and historical landslide inventory mapping. The resulting spatially explicit assessment of landslide-affected areas can be used for subsequent GIS-based landslide susceptibility mapping.

5 Conclusions and Outlook

In this paper, we have demonstrated the use of remote sensing and GIS technologies for the development of a landslide inventory information system which is capable of integrating

multi-source information on landslide activity 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 this study area, satellite remote sensing data represent a valuable source of spatial and temporal information on landslide activity. 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 have been 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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References

ASTER GDEM Version 2, 2011: http://gdem.ersdac.jspacesystems.or.jp/ (18.7.2014).

Behling, R., Roessner, S., Segl, K., Kleinschmit, B. & Kaufmann, H., 2014a: Automated Spatio-temporal Landslide Mapping over Large Areas Using RapidEye Time Series Data. – Remote Sensing **6** (3): 2572–2600.

Behling, R., Roessner, S., Kaufmann, H. & Kleinschmit, B., 2014b: Robust Automated Image Co-Registration of Optical Multi-Sensor Time Series Data: Generation for Multi-Temporal Landslide Detection. – Remote Sensing **6** (9): 8026–8055.

Calvello, M., Cascini, L. & Mastroianni, S., 2013: Landslide zoning over large areas from a simple inventory by means of scale-dependent terrain units. – Geomorphology **182**: 33–48.

Erener, A. & Düzgün, H.S.B., 2012: Landslide susceptibility assessment: what are the effects of mapping unit and mapping method? – Environmental Earth Sciences **66**: 859–877.

Ghosh, S., van Westen, C.J., Carranza, E.J.M., Jetten, V.G., Cardinali, M., Rossi, M. & Guzzetti, F., 2012: Generating event-based landslide maps in a data-scarce Himalayan environment for estimating temporal and magnitude probabilities. – Engineering Geology **128**: 49–62.

Golovko, D., Roessner, S., Behling, R., Wetzel, H.-U. & Kaufmann, H., 2014: GIS-Based Integration of Heterogeneous Data for a Multi-temporal Landslide Inventory. – Sassa, K., Canuti, P. & Yin, Y. (eds.): Landslide Science for a Safer Geoenvironment, Volume **2**: Methods of Landslide Studies: 799–804.

Guzzetti, F., Carrara, A., Cardinali, M. & Reichenbach, P., 1999: Landslide hazard evaluation: a review of current techniques and their application in a multi-scale study, Central Italy. – Geomorphology **31**: 181–216.

Guzzetti, F., Reichenbach, P., Cardinali, M., Gali, M. & Ardizzone, F., 2005: Probabilistic landslide hazard assessment at the basin scale. – Geomorphology **72**: 272–299.

GUZZETTI, F., MONDINI, A.C., CARDINALI, M., FIORUC-CI, F., SANTANGELO, M. & CHANG, K., 2012: Land-slide inventory maps: New tools for an old prob-lem. – Earth Science Reviews **112** (1–2): 42–66.

HERVÁS, J., 2013: Landslide Inventory. – BO-BROWSKY, P.T. (ed.): Encyclopedia of Natural Hazards: 610–611.

IBATULIN, K.V., 2011: Monitoring of Landslides in Kyrgyzstan. – Ministry of Emergency Situations of the Kyrgyz Republic, Bishkek, Kyrgyzstan (in Russian).

KALMETYEVA, Z.A., MIKOLAYCHUK, A.V., MOLDOBE-KOV, B.D., MELESHKO, A.V., ZHANTAEV, M.M. & ZUBOVICH, A.V., 2009: Atlas of Earthquakes in Kyrgyzstan. – CAIAG, Bishkek, Kyrgyzstan.

MOTAGH, M., WETZEL, H.-U., ROESSNER, R. & KAUFMANN, H., 2013: A TerraSAR-X InSAR study of landslides in southern Kyrgyzstan, Cen-tral Asia. – Remote Sensing Letters **4** (7): 657–666.

QGIS DEVELOPMENT TEAM, 2014: QGIS Geographic Information System. Open Source Geospatial Foundation Project. – http://qgis.osgeo.org (9.12.2014).

RABUS, B., EINEDER, M., ROTH, A. & BAMLER, R., 2003: The shuttle radar topography mission – a new class of digital elevation models acquired by spaceborne radar. – ISPRS Journal of Photo-grammetry and Remote Sensing **57** (4): 241–262.

ROESSNER, S., WETZEL, H.-U., KAUFMANN, H. & SAR-NAGOEV, A., 2005: Potential of satellite remote sensing and GIS for landslide hazard assessment in Southern Kyrgyzstan (Central Asia). – Natu-ral Hazards **35** (3): 395–416.

ROESSNER, S., BEHLING, R., SEGL, K., GOLOVKO, D., WETZEL, H.-U. & KAUFMANN, H., 2014: Automat-ed Remote Sensing Based Landslide Detection for Dynamic Landslide Inventories. – SASSA, K., CANUTI, P. & YIN, Y. (eds.): Landslide Science for a Safer Geoenvironment, Volume **2**: Methods of Landslide Studies: 345–350.

SÜZEN, M.L. & DOYURAN, V., 2004: Data driven bi-variate landslide susceptibility assessment using geographical information systems: a method and application to Asarsuyu catchment, Turkey. – Engineering Geology **71**: 303–321.

TORGOEV, I.A., ALESHIN, Y.G., MELESHKO, A. & HA-VENITH, H.-B., 2010: Landslide hazard in the Tien Shan, Kyrgyz Republic. – International Confer-ence Mountain Risk: Bringing Science to Soci-ety **2010**: 171–174, Firence, Italy.

USGS, 2004: Landslide Types and Processes: http://pubs.usgs.gov/fs/2004/3072/ (29.6.2014).

VAN DEN EECKHAUT, M. & HERVÁS, J., 2012: State of the art of national landslide databases in Eu-rope and their potential for assessing suscepti-bility, hazard and risk. – Geomorphology **139–140**: 545–558.

VAN DEN EECKHAUT, M., REICHENBACH, P., GUZZETTI, F., ROSSI, M. & POESEN, J., 2009: Combined land-slide inventory and susceptibility assessment based on different mapping units: an example from the Flemish Ardennes, Belgium. – Natural Hazards and Earth System Sciences **9**: 507–521.

VAN WESTEN, C.J., VAN ASCH, T.W.J. & SOETERS, R., 2006: Landslide hazard and risk zonation – why is it still so difficult? – Bulletin of Engineering Geology and the Environment **65**: 167–184.

VAN WESTEN, C.J., CASTELLANOS, E. & KURIAKOSE, S., 2008: Spatial data for landslide susceptibility, hazard, and vulnerability assessment: An over-view. – Engineering Geology **102**: 112–131.

WASOWSKI, J. & BOVENGA, F., 2014: Investigating landslides and unstable slopes with satellite Multi Temporal Interferometry: Current issues and future perspectives. – Engineering Geology **174**: 103–138.

WETZEL, H.-U., ROESSNER, S. & SARNAGOEV, A., 2000: Remote sensing and GIS based geological mapping for assessment of landslide hazard in Southern Kyrgyzstan (Central Asia). – BREBBIA, C.A. & PASCOLO, P. (eds): WIT-Press: 355–366.

WIECZOREK, G.F., 1984: Preparing a Detailed Land-slide-Inventory Map for Hazard Evaluation and Reduction. – Bulletin of the Association of Engi-neering Geologists **21** (3): 337–342.

WP/WLI (International Geotechnical Societies = UNESCO Working Party on World Landslide Inventory), 1993: Multilingual Landslide Glos-sary. – BiTech Publishers Ltd.

YEROKHIN, S.A., 1999: Investigation of Landslide Occurrence in Osh and Dzhalal-Abad Provinces of the Kyrgyz Republic. – Bishkek, Kyrgyzstan (in Russian).

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